The front cover shows a satellite image (NOAA 10) of the flood situation on 8 October 1988. This was one of the worst flood years of the twentieth century in Bangladesh. The flood was at its maximum extent between 20 August and 5 September. Thus, the satellite image illustrates the receding water levels at the end of an extreme flood year. The three main rivers reveal typical aspects of many flood situations in the twentieth century: the extensive flooded areas to the south of the Meghalaya Hills, illustrating the direct effect of this first orographic barrier on the humid monsoon winds blowing from the Bay of Bengal towards the north, which produces precipitation, discharge and floods in the forelands; the uninterrupted flood along the Brahmaputra from eastern Assam down to central Bangladesh, which strikingly disappears towards southern Bangladesh; rainfloods in Bangladesh itself, evidenced in the flood-affected area to the west of the main course of the Brahmaputra; only isolated flood patches in the Ganga Plain between Patna, Allahabad and Dehli and in the far west of the basin, but interestingly not upstream of the confluence with the Brahmaputra. The NOAA data were acquired by the Bangladesh Space Research and Remote Sensing Organization (SPARRSO); the image was obtained through the International Institute for Geo-Information Science and Earth Observation (ITC), Enschede, the Netherlands.

The back cover shows satellite images (LANDSAT MSS) illustrating the impressive contrast between the dry season (left-hand picture, recorded on 7 February 1987) and the wet season (right-hand picture, recorded on 18 August 1987, the approximate peak of the 1987 flood). Along certain stretches within Bangladesh, the Brahmaputra is a river system of 13 km width. During the monsoon season it forms more or less one large water body, and during the dry season it is divided into a number of distinct channels. The copyright for the reproduction of the two images was kindly provided by the Bangladesh Space Research and Remote Sensing Organization (SPARRSO).

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Floods in Bangladesh

The research in this book originates in The United Nations University Mountain Programme, a long-standing network of natural and social scientists, development practitioners, and stakeholder communities seeking sustainable solutions to the urgent local problems facing mountain people and ecosystems, while mitigating their wide-ranging regional and global implications. Launched in 1978, the programme has come to encompass targeted research and capacity-building activities supporting theoretical and practical approaches to improving human livelihoods and environmental sustainability in vulnerable mountain areas in South and East Asia, Latin America, and Africa and more recently in the countries in transition in the Balkans and Central Asia.

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Floods in Bangladesh: History, dynamics and rethinking the role of the Himalayas

Thomas Hofer and Bruno Messerli

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Preface

Floodplain management has become an increasingly fundamental topic world-wide. Under certain climatic conditions, floodplains – from valley bottoms in mountain areas to large-sized plains such as those of the Brahmaputra and the Ganga in India and Bangladesh – offer a special potential for food production. As a consequence, high population density, growing urbanization and industrialization, and a high investment in infrastructure and transport systems can be observed in all these areas. Accordingly, the dilemma between increasing population and greater intensity of land use on the one hand, and susceptibility to floods and other hazards on the other, is increasing as well. Devastating events have occurred in the recent past in the floodplains of the Mississippi (1993), the Rhine (1993, 1995), the Yangtze (1998) and the Ganga–Brahmaputra (1987, 1988, 1998).

Bangladesh is certainly one of the most impressive floodplain and delta areas in the world. The interaction between the rapidly increasing population, the intensity of agricultural production, the extreme variability of precipitation in the monsoon circulation, and the scale and dynamics of the river systems makes floodplain management in Bangladesh a truly challenging task. We are well aware of the fact that a large number of highly qualified institutions and authors have tackled issues concerning monsoonal floods in Bangladesh, not only from the natural and social science side but also from the technical and engineering science side. Taking into account this broad base of information and experience, including, in particular, the knowledge created during the International

Year of Mountains 2002 and the International Year of Freshwater 2003, we see many misunderstandings and misinterpretations of the following problem: how far is deforestation in the Himalayas responsible for the floods in Bangladesh and, as a consequence, is it really true that the frequency and intensity of floods have increased owing to human-induced degradation in mountain areas? In our project on floods in Bangladesh, which was mainly implemented in 1992–1996 and which is presented in this book, we therefore tried to widen the temporal and spatial dimensions of this very complex topic: we analysed the regional flood history back to the eighteenth century; we tried to understand the flood processes by enlarging the scale from some small test sites in Bangladesh to the entire Ganga–Brahmaputra–Meghna basin, with the overarching highland–lowland linkages as the focal theme. This concept required considerable effort in terms of data and information collection, analysis, learning from experts, teamwork and attracting financial support. Figure P.1 presents the variety of partner institutions that collaborated on our project and supported our activities. Without this network of core institutions for the project implementation (Table P.1), key institutions for the data collection (Table P.2) and project partners with in-depth expertise and experience in flood-related issues (Table P.3), we would never have managed to gather the basic documentation needed for a meaningful interpretation of the available data, and to achieve the project's goals. We would like to express our deep gratitude and great appreciation for the stimulating cooperation and outstanding contributions of the participating institutions and partners.

The core institutions (Table P.1)

Four institutions were responsible for the funding, implementation and documentation of the project.

Since 1979, the United Nations University (UNU) has been the key partner and supporter in all research activities in the Himalayas within the framework of the overall topic "Highland–Lowland Interactive Systems". In the High and Middle Mountains of Nepal, we began to understand mountain hazards and erosion processes, particularly the impacts of intense monsoon precipitation on bare ground, agricultural terraces, and forested land. We observed sedimentation in various basins within the mountain ranges and we became more and more sceptical about generalized and simplified theories about environmental degradation in the Himalayas and about statements that link the floods in the Indo-Gangetic Plain to this so-called Himalayan degradation (Ives 1987).

For the International Year of Mountains 2002, UNU published a small report entitled "Mountain research in south-central Asia: An overview of

Table P.1 The core institutions and the project team

United Nations University (UNU), Tokyo	
Juha Uitto	Senior Academic Officer
Libor Jansky	Senior Academic Programme Officer
Swiss Agency for Development and Cooperation, Bern and Dhaka	
Niklaus Zingg	Desk Officer in Bern (first project period)
Peter Tschumi	Program Officer in Dhaka and Desk Officer in Bern
Peter Arnold	Resident Coordinator in Dhaka
Henri Morrand	Program Officer in Dhaka
Institute of Geography, University of Bern	
Swiss team	
Bruno Messerli	Project Leader
Thomas Hofer	Project Coordinator PhD: *Floods in Bangladesh: A highland–lowland interaction?* (Hofer 1998a)
Rolf Weingartner	Technical Project Adviser (hydrology, meteorology)
Regina Liechti	Master's student Thesis: "Ganges und Brahmaputra nahe ihres Zusammenflusses – Flussdynamik und menschliche Reaktionen" (Liechti 1996) Input into the synthesis work
Barbara Schneider	Master's student Thesis: "Drei Fallstudien von Niederschlagsereignissen der Überschwemmungs-jahre 1987/88 in Bangladesch. Eine Analyse von Wolkenstrukturen auf NOAA-Satellitenbildern und klimatologischen Daten" (Schneider 1996) Input into the synthesis work
Susanne Zumstein	Master's student Thesis: "Flusslaufveränderungen des Jamuna in Bangladesch – Dynamik eines Lebensraumes" (Zumstein 1995)
Robeen Dutt	Master's student Thesis: "Überschwemmungen in Bengalen vor 1950. Fallstudien (1891–1909) und Zeitreihenanalysen (1891–1950)" (Dutt 1995)
Roland Guntersweiler	Master's student "Überschwemmungen in Bengalen vor 1950. Fallstudien (1910–1930) und Zeitreihenanalysen (1891–1950)" (Guntersweiler 1995)
Hansjoerg Kuster	Master's student "Überschwemmungen im Einzugsgebiet des Yamuna, NW-Indien" (Kuster 1995)
Francesca Escher	Publication editor
Bangladesh team	
Talim Hossain	Team coordinator for fieldwork Report: "Landscape, land use and settlement dynamics and flooding" (Hossain 1994)

Table P.1 (cont.)

Jahan Akter Seema	Research collaborator, test areas
Monica Nahar	Research collaborator, test areas
Qumrun Nahar	Research collaborator, test areas
Mahbuba Matin	Research collaborator, office
Sayd Ferdous	Research collaborator, test areas
Support team	
Christian Pfister	Technical Project Adviser (history of flooding)
Martin Grosjean	Soil analysis expert
Thorbjoern Holzer	Remote-sensing specialist
Dominic Blaettler	Data-processing assistant
Andreas Brodbeck	Cartography
Alex Herrmann	Cartography
Ted Wachs	Language editing
Many students	Seminar studies on specific project elements
Food and Agriculture Organization of the United Nations (FAO)	
El Hadji Sène Jose-Antonio Prado	Directors, Forest Resources Division
Tage Michaelsen Jean-Prosper Koyo	Chiefs, Forest Conservation Service
Douglas McGuire	Senior Forest Conservation Officer
René Gommes	Senior Agrometeorologist

25 years of UNU's Mountain Project'' (Ives et al. 2002). Behind this impressive title stands a unique friendship with Jack Ives, which began before the joint research project in the Nepal Himalayas from 1979 to 1989. After this project we continued on separate research paths, always with support from UNU, without neglecting our cooperation and friendship: Jack Ives with his US team continued his research in the Chinese mountains and we, the Swiss team, moved downstream with a new focus on the floods in Bangladesh. UNU gave its full support to the project presented in this volume, in particular by providing funding for the editing, printing and dissemination of the publication.

The Swiss Agency for Development and Cooperation (SDC) was the main funding institution for the project. Its financial support covered all project activities as well as the printing of two editions of a first synthesis document (Hofer and Messerli 1997). In addition, SDC was the main partner of the University of Bern team for the conceptual evolution of the project and for permanent discussions on development-oriented components. The logistical support provided by SDC's Coordination Office in Dhaka for all field activities and official contacts in Bangladesh was of fundamental importance.

The Institute of Geography of the University of Bern was responsible for all aspects of the project implementation, which included fieldwork, data collection, analysis and interpretation, project synthesis, reporting and publication of results. The project was administered through the Centre for Development and Environment (CDE), which is the focal point within the Institute of Geography for the links between the University and SDC.

In the initial phase, the project team was small and comprised Thomas Hofer, Bruno Messerli, Rolf Weingartner, Francesca Escher and Talim Hossain, the collaborator in Bangladesh. Very soon the team had to be expanded: a series of master's theses were initiated (by Robeen Dutt, Roland Guntersweiler, Hansjoerg Kuster, Regina Liechti, Barbara Schneider and Susanne Zumstein), the field team in Bangladesh was considerably enlarged, and a support group for specialized inputs was created (Martin Grosjean and Christian Pfister). In addition, the project became part of the Institute's programme for advanced studies, which attracted a large number of students. Their contributions in data analysis and interpretation were substantial. Wherever appropriate, reference will be given in this book to the original documents (partly unpublished, but available in the library of the Institute of Geography, University of Bern). Andreas Brodbeck, the cartography expert from the Institute of Geography in Bern, joined the team in the publication phase.

Apart from providing access to the agro-climatological database for Asia in the early stage of the project, the Food and Agriculture Organization of the United Nations (FAO) came prominently into the picture in the preparation phase of this book: in late 1998, Thomas Hofer joined the Mountain Programme of the FAO at its headquarters in Rome. The FAO, having served as Task Manager of Chapter 13 ("Managing Fragile Ecosystems – Sustainable Mountain Development") of *Agenda 21* as well as Lead Agency for the International Year of Mountains 2002 (IYM), and being the host of the secretariat of the Mountain Partnership, is very interested in questions related to interactions between highlands and lowlands and, obviously, in the experiences and the results of this project. Therefore the realization of this publication was incorporated into the work programme of Thomas Hofer in his capacity as sustainable mountain development officer at FAO over recent years. Accordingly, the contribution of FAO to the documentation of the project and dissemination of its results was substantial in terms of human resources input, logistics and institutional support.

The key institutions for data collection (Table P.2)

Flood processes were analysed at different geographical scales. Therefore, a variety of information had to be collected, such as:

- long-term discharge and rainfall data series for the Ganga–Brahmaputra–Meghna basin;
- tidal and groundwater data for Bangladesh;
- recent and historical maps of Bangladesh;
- satellite images of Bangladesh as well as the whole Ganga–Brahmaputra–Meghna basin;
- literature on flooding in Bangladesh and India;
- information on flood perception and on strategies for coping with floods by the affected people.

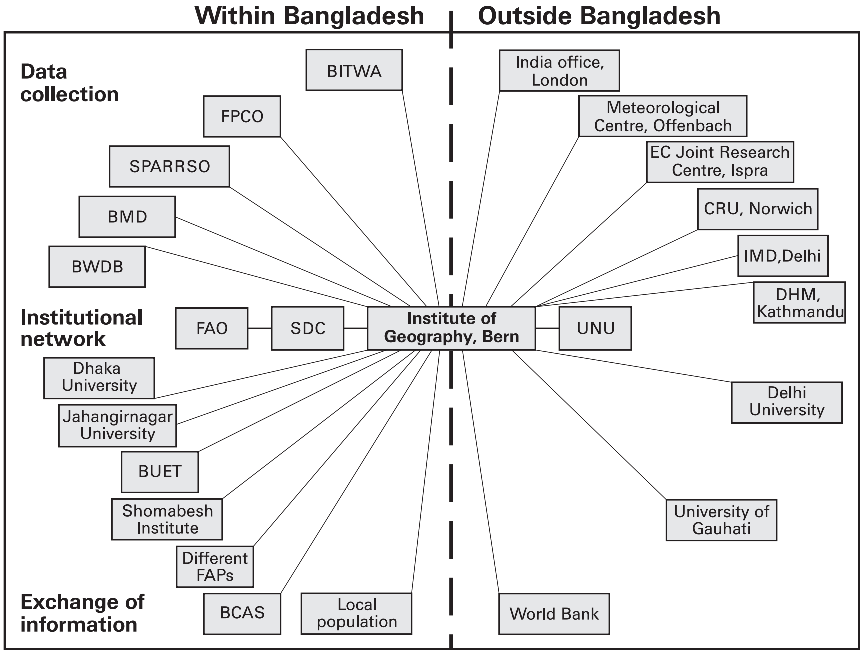
It is obvious that the information had to be collected from a variety of sources within Bangladesh, in other parts of the Indian subcontinent, or, in the case of historical information from the British period, even in Europe (Figure P.1). This data collection was time consuming, not only because of the number of different institutions that had to be contacted, but also because of bureaucracy and the sensitivity of the information.

In Table P.2, key institutions and resource persons for the data collection are listed and briefly characterized. There are two institutions we would particularly like to highlight:

- The Bangladesh Water Development Board (BWDB) was the primary source of hydrological and meteorological information. Our cooperation with this government agency, however, went far beyond the collection of data: in many meetings with BWDB staff members, discussions were held on the causes of floods, the history of floods, flood management scenarios and approaches, etc., which proved crucial for the project. In addition, on several occasions we had the unique opportunity to participate in hydrological measurement campaigns on the Brahmaputra, the Meghna and the Padma rivers as well as to discuss the problems of data-recording in the complex hydrological conditions of Bangladesh.
- For the collection of historical data (basically before 1950), the India Office Library and Records of the British Library in London was the key institution. This library has a wealth of documentation from the British period for the entire Indian subcontinent. Through this institution and its very cooperative staff we had access to old maps for the investigation of river course changes as well as to daily rainfall data, district gazetteers and newspaper articles for the reconstruction of the extent and dimension of historical floods.

Partner institutions and resource persons for information exchange (Table P.3)

One of the main approaches of the project was to look into flood issues from different angles: through the analysis of raw data, through the per-



Legend:

BCAS:	Bangladesh Centre for Advanced Studies
BITWA:	Bangladesh Inland Water Transport Authority
BMD:	Bangladesh Meteorological Department
BUET:	Bangladesh University of Engineering and Technology
BWDB:	Bangladesh Water Development Board
CRU:	Climate Research Unit
DHM:	Department of Hydrology and Meteorology
EC:	European Commission
FAO:	Food and Agriculture Organization of the United Nations
FAPs:	different components of the Flood Action Plan
FPCO:	Flood Plan Coordination Organization
IMD:	Indian Meterological Department
SDC:	Swiss Agency for Development and Cooperation
SPARRSO:	Space Research and Remote Sensing Organization
UNU:	United Nations University

Figure P.1 The collaborating institutions of the ‘‘Floods in Bangladesh’’ project.

Table P.2 The key institutions for data collection

Institution	Focal person(s)	Sources for
Bangladesh Meteorological Department (BMD), Dhaka	M. H. Khan Chowdhury, Director	Daily rainfall data for Bangladesh
Bangladesh Water Development Board (BWDB), Dhaka	A. K. M. Shamsul Hoque, Chief Engineer Hydrology A. Alam Mia, Director Surface Hydrology 1 A. N. H. Akhtar Hossain, Executive Engineer	Daily discharge and rainfall data for Bangladesh Groundwater data for Bangladesh Data on suspended sediment load of the big rivers Discharge measurement techniques in Bangladesh
Space Research and Remote Sensing Organization (SPARRSO), Dhaka	A. M. Choudhury	LANDSAT images of Bangladesh for different years
Bangladesh Inland Water Transport Authority (BITWA), Dhaka		Tidal data
Flood Plan Coordination Organization (FPCO)	M. H. Siddiqui, Chief Engineer	Resource person for the Flood Action Plan and its different components and for access to hydrological and meteorological information
Indian Meteorological Department, (IMD), Delhi		No success in data collection from this source
Department of Hydrology and Meteorology (DHM), Kathmandu	A. Pokharel, Deputy Director General	Monthly/daily rainfall and discharge data for a number of stations in Nepal
India Office Library and Records, British Library, London	Mr Bingle, Curator Mr Cook, Map section	Daily rainfall records 1890–1950 Maps of different time periods before 1950 Newspaper articles on floods before 1950 Water-level records for different stations on the Ganga before 1950
German Meteorological Centre, Offenbach	Library	Daily weather reports for India, 1987 and 1988
European Commission's Joint Research Centre, Ispra (Italy)	Jean-Paul Malingreau, Remote Sensing Institute Jean-Marie Grégoire, Remote Sensing Institute	Daily NOAA satellite images over the Indian subcontinent
University of East Anglia, Climate Research Unit (CRU), Norwich		Monthly rainfall data series for India

ception of the affected families, through the eyes of engineers, and finally by listening to the views of politicians. Continuous discussion of research results with experts was crucial and the interaction with local people in the flood-affected areas was fundamental for the progress and success of the project. The discussion partners can be grouped into four categories:

- universities in Bangladesh and India: Dhaka University, Jahangirnagar University, Gauhati University, Delhi University;
- non-governmental organizations: the Shomabesh Institute, the Bangladesh Centre for Advanced Studies;
- institutions in Bangladesh involved in the Flood Action Plan: the World Bank Resident Mission, components of the Flood Action Plan (FAP), the Flood Plan Coordination Organization (FPCO);
- the rural population of the test areas in the flood-affected areas.

The various contacts are further specified in Table P.3. We would like particularly to highlight four of them:

- *Jahangirnagar University*: the Department of Anthropology and the Department of Geography have particular experience in river geomorphology within Bangladesh as well as in the socio-economic aspects of flooding. N. S. Alam was our most important partner, and the project team significantly profited from his profound experience and advice. N. S. Alam is the former teacher and supervisor of Talim Hossain, the Bangladeshi field team leader of the project.
- *The Flood Plan Coordination Organization (FPCO)*: FPCO was, at the time of the study, the coordination office for the 26 studies carried out under the umbrella of the Flood Action Plan (World Bank 1989). M. H. Siddiqui, the head of FPCO, was very supportive of our project. He facilitated access to the raw hydrological data at the Bangladesh Water Development Board and opened the door to eminent FAP results, which provided insight into the negotiations over flood management in Bangladesh.
- *Gauhati University*: for many years D. Goswami has been a key contact for research activities throughout the Himalayan region. He has in-depth knowledge of the geomorphology of the Brahmaputra and of the highland–lowland linkages in the eastern Himalayan–Brahmaputra area. The collaboration was significantly intensified in September 1994 during a fascinating excursion through the project region. D. Goswami was the principal guide from Darjiling through Gauhati in Assam, to Shillong and Cherrapunjee in the Meghalaya Hills and down to the border of Bangladesh. The project team profited greatly from his deep and wide-ranging experience related to the hydro-ecology of the Brahmaputra basin.
- *The rural population in Bangladesh*: for over two years, intensive fieldwork was carried out in three test areas of Bangladesh that are affected

Table P.3 The main partner institutions and resource persons for information exchange

Partner	Focal person(s)	Expertise
Dhaka University	M. M. Miah Aminul Islam M. Abdul Baquee C. R. Abrar Tasneem Siddiqui	M. M. Miah, at that time Vice Chancellor of Dhaka University, is a senior expert in flood-related issues (Miah 1988) Aminul Islam is a senior geographer with extensive experience of historical and current aspects of hazards in Bangladesh (Islam 1995) Abdul Baquee was a very important resource person for field excursions C. R. Abrar and T. Siddiqui are experts on the political implications of flooding
Jahangirnagar University, Dhaka Savar	Nurul S. Alam K. Maudood Elahi M. Shamsul Alam	Nurul Alam was our most important partner for the social aspects of flooding M. Elahi and Shamsul Alam were important discussion partners mainly for the morphology and dynamics of the river systems in Bangladesh
Bangladesh University of Engineering & Technology (BUET), Dhaka	Ainun Nishat	A. Nishat (at that time a member of the Joint River Commission) was a key person for international issues related to the flood problem
Bangladesh Centre for Advanced Studies (BCAS), Dhaka	A. Atiq Rahman	BCAS is an important resource institution for environmental aspects of water issues in Bangladesh
Shomabesh Institute	Shapan Adnan	Shapan Adnan, a prominent fighter against technologically dominated approaches to flood management and an outspoken opponent of the Flood Action Plan, was a crucial discussion partner for many aspects of the project
World Bank Resident Mission, Dhaka	Ross Wallace	Resource person for the Flood Action Plan and for access to the World Bank Library in Dhaka
Different components of the Flood Action Plan (FAPs)		Discussion of different flood-related issues
University of Gauhati	Dulal C. Goswami	Expert on river morphology and ecology for the Indian Brahmaputra basin
Delhi University	R. B. Singh	Resource person for flood-related issues in the Indian Ganga basin
Population in the test areas of Bangladesh	Farmer families	Key informants on river dynamics, flood perception and indigenous strategies

by floods, by lateral river erosion, or by both. Through interviews and discussions with several hundred families, we gained in-depth insights into local hydrological and river-morphological processes, into the perception of the people with regard to natural hazards, and into their development priorities and strategies for surviving in a highly dynamic environment.

To the whole project team, the collaborating institutions, the large number of resource persons and, particularly, the people living in the test areas in the floodplains of Bangladesh, we would like to express our cordial thanks for the fruitful collaboration and for their important contributions to the success of the project.

Thomas Hofer
Food and Agriculture Organization of the United Nations, Rome
Bruno Messerli
Institute of Geography, University of Bern

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1

The project on Bangladesh floods: Background, framework and key questions

1.1. The theory of Himalayan degradation: Traditional understanding and emerging doubts

Almost every year during the monsoon season, floods in India and Bangladesh appear in the headlines of the media. The few examples quoted in Box 1.1 show that such news items are common in the national and international press as well as in international organizations. The headlines are noteworthy because they

- assume that the frequency and severity of flooding in Bangladesh have increased;
- state that there is a direct link between the hydro-meteorological processes in the Himalayas and the floods in the lowlands;
- state that it is the rapid forest removal in the mountains that is responsible for the intensification of the hydrological processes in the plains;
- accuse mountain people and other users of mountain forests of being responsible for the presumably increasing flood frequency in the surrounding lowlands; and
- state that floods are a key problem in Bangladesh that must and can be resolved.

This line of thinking regarding the impact of human activities in the Himalayas on the hydrological processes in the lowlands is politically very sensitive, because the Ganga and the Brahmaputra are international river systems. The assumptions are based on the following traditional and superficially convincing understanding of the sequential processes:

Box 1.1 Media headlines referring to Bangladesh floods

- “Nepal has lost half its forest cover within a thirty-year period (1950–1980) and by AD 2000 no accessible forest will remain.” (World Bank 1979)
- “The severity of the recent floods in Bangladesh has led the government to look for a flood plan which would, in the long term, provide a comprehensive and permanent solution to the recent flood problem and so to create an environment for sustained economic growth and social improvement.” (World Bank 1989)
- “Bangladesh in grave danger: deforestation in Himalayas aggravating floods.” (*Bangladesh Observer*, 2 June 1990)
- “When the Himalayas were covered in trees, Bangladesh suffered a major flood about twice a century; one every four years is now the average.” (UNEP 1992)
- “The severe floods in eastern India and Bangladesh are not the result of a natural disaster, but of a ruthless exploitation of wood which has been practised over centuries in the forests of the Himalayas.” (*Basler Zeitung*, 15 September 1998)

population growth in the mountains → increasing demand for fuel wood, fodder and timber → uncontrolled forest removal in increasingly marginal areas → intensified erosion and peak flows in the rivers → severe flooding and siltation on the densely populated and cultivated plains of the Ganga and Brahmaputra. These conclusions have been subscribed to by some scientists, have been adopted by many politicians, and have been used to derive development strategies (Ives and Messerli 1984, 1989). For politicians, this supposedly scientific chain of events has been useful in times of flood-related crises to pin the blame on the peasantry of remote mountain areas. The mountain population, meanwhile, has been acquiescent in accepting the blame because bad science was presented to them as a “fait accompli”, and also because development agencies funded reforestation programmes.

There is no doubt that the Himalayas and their forelands have undergone a dynamic change in land use in recent decades owing to rapid population growth. However, mainly in the scientific community, this “theory of Himalayan degradation” has been increasingly questioned (Ives 1987): Are the highland–lowland linkages really as simple as that? Do we have the scientific fundamentals needed to justify the politically explosive accusation that the mountain inhabitants are responsible for the apparently increasing flood processes in the lowlands? Furthermore, is it really true that the Himalayas are being deprived of their forest cover at a rapid rate? And, is it confirmed by the affected people in the floodplains of Bangladesh that inundations are their most severe problem?

1.2. The highlands – and their lowland linkages: Twelve years of research on Himalayan ecology

In 1979, the University of Bern and the University of Boulder, Colorado, together with many other institutions and individuals worldwide, joined in this discussion with the aim of promoting a more serious scientific analysis with regard to the crucial questions outlined above. The overall concern of this research, which from 1979 to 1991 focused primarily on the highlands, has always been the impact of human activities on the environment, together with the ecological interaction between the Himalayas and the adjacent lowlands of the Ganga and Brahmaputra. Most of the work has been carried out under the "Highland–Lowland Interactive Systems Project" of the United Nations University (UNU), a programme that was initiated by Jack Ives and Bruno Messerli. The main research activity under this project was entitled "Mountain hazards mapping in Nepal". It had one test area in the Middle Mountains in Kakani near Kathmandu and a second in the High Mountains in the Khumbu region. The publications and maps that resulted from these project activities are still of great value and interest today: they document various processes and particularly the changes in landscapes and hazardous areas during the past 20 years (Ives and Messerli 1981; Kienholz et al. 1983, 1984; Zimmermann et al. 1986; Vuichard and Zimmermann 1987). During this period of fieldwork, a new contact of cooperation and friendship was established with the Canadian team of Hans Schreier, who was working in the Jhikhu Khola, 40 km east of Kathmandu, in a highly interdisciplinary and integrated project (Schreier and Wymann von Dach 1996; Schreier et al. 2000; Carver and Schreier 1995). These projects and the growing field experience created new ideas, which we began to explore with several master's theses: erosion and sediment transport in relation to land use (Lauterburg 1985); the discharge characteristics of Himalayan rivers (Hofer 1989); forest cover change and forest history. Some of these efforts were general or large-scale studies (Wyss 1988); others concentrated on specific areas or case studies. Although the focus was on the highlands, an attempt was made to relate the findings to the processes in the plains, for example to flooding and sedimentation. The results of all these research activities were discussed in three major publications (Ives and Messerli 1989; Messerli et al. 1993; Ives 2004), as well as in a number of articles (Messerli and Hofer 1992, 1995; Hofer 1993). The findings presented in these publications received considerable support and confirmation from other authors, including Goswami (1983), Hamilton (1987), Bruijnzeel and Bremmer (1989), Rogers et al. (1989) and Agarwal and Narain (1991). In summary, all these authors agree on the following basic key points:

1. Highland–lowland interactive processes exist and they are fundamental. Without the Himalayas there would be only very low precipitation, no permanent rivers and only low-potential land on the plains.
2. It has not been possible to find a significant correlation between human activities in the mountains (e.g. forest removal) and catastrophes on the plains (e.g. floods).
3. The impact of human activities on physical processes seems to be specific to different geographical scales: human-induced ecological changes can be proven in some specific examples at the local, small-scale level; in medium-sized catchments, high levels of intense rainfall and natural hazards are much more significant; in large catchments, finally, human influences are concealed by the overwhelming dimensions of natural processes. It is therefore not admissible to extrapolate results from a small watershed in the Himalayas to the scale of the entire Ganga-Brahmaputra basin.
4. Eroded material in the mountains is moved into temporary storages in river beds, valleys and intramontane basins. Sediments produced through human-made degradation over recent decades will not reach the floodplain immediately, but will take decades or even centuries to get there. Accordingly, human activities in the highlands do not have an immediate effect on the floodplain in the lowlands.
5. Statements on forest removal and its effects should not be generalized: in certain areas of the Himalayas, forest cover has increased over the past few decades. Forest removal does not necessarily lead to degradation of soil and water resources. If forests are replaced by well-maintained agricultural terraces or other adapted and sustainably managed land-use systems, erosion and runoff are not greater than in a forested area.

These important and challenging results were very often based on short-term series of measurements, a few experimental plots, or case studies. It became very clear that more effort was needed to further verify, quantify and document these tentative conclusions in favour of a long-term sustainable development in the greater Himalayan region.

1.3. The lowlands – and their highland linkages: Research on ''Floods in Bangladesh''

As a follow-up to the research activities between 1979 and 1991 in the Himalayan highlands, in 1992 the focus was shifted to the lowlands of the Ganga, Brahmaputra and Meghna rivers. The most important and obvious objective was to verify the research findings in the highlands by focusing on the flood processes and flood history in the lowlands, and in Bangladesh in particular. However, there was a very important additional rationale: in 1988, Bangladesh was hit by one of the most severe floods of the twentieth century. This event aroused significant international concern and triggered the Bangladesh Action Plan for Flood Control (World Bank 1989; see also section 7.6). One important original objective of this plan was to control floods in Bangladesh by strengthening and expanding the embankment network along the main river courses. This approach, which today has fortunately been significantly modified, provoked vigorous debate and controversy between the various interested aid organizations and governmental institutions in the early 1990s (e.g. Adnan 1991, 1993; Adnan et al. 1992). Because of its strong commitment in Bangladesh, the Swiss Agency for Development and Cooperation (SDC) was confronted with this controversial discussion about flood management and was therefore particularly interested in obtaining more basic information on flood processes, on perceptions of floods by the affected people, and on their experiences with flood protection embankments. Accordingly, the resulting project document was a joint exercise between the University of Bern and SDC, in which R&D-oriented interests merged.

The overall approach of the project was to look at floods from different angles and perspectives (Figure 1.1), to satisfy both natural and social science enquiries and to accommodate, through this interdisciplinary approach, research as well as development interests. The analysis of flood processes and people's perceptions of floods were the core themes of the project. Based on an extended literature review, major knowledge gaps were identified for the following thematic areas:

- looking at Bangladesh floods on a broad geographical scale, in particular in the context of highland–lowland linkages;
- the thorough use of different historical sources and long-term records to understand the frequency of floods in Bangladesh;
- the investigation of different flood processes with the same methodological approaches in order to ascertain common or divergent key elements that lead to flooding.

In the course of the project, the very dynamic shifting of the main rivers in Bangladesh was identified as a major hazard for the affected population and therefore a component on river morphology was added to the agenda of the project activities.

The official launch of the project was preceded by an extended preparatory phase during which the feasibility of the project ideas was assessed in terms of data availability. Some milestones of this preparatory period were:

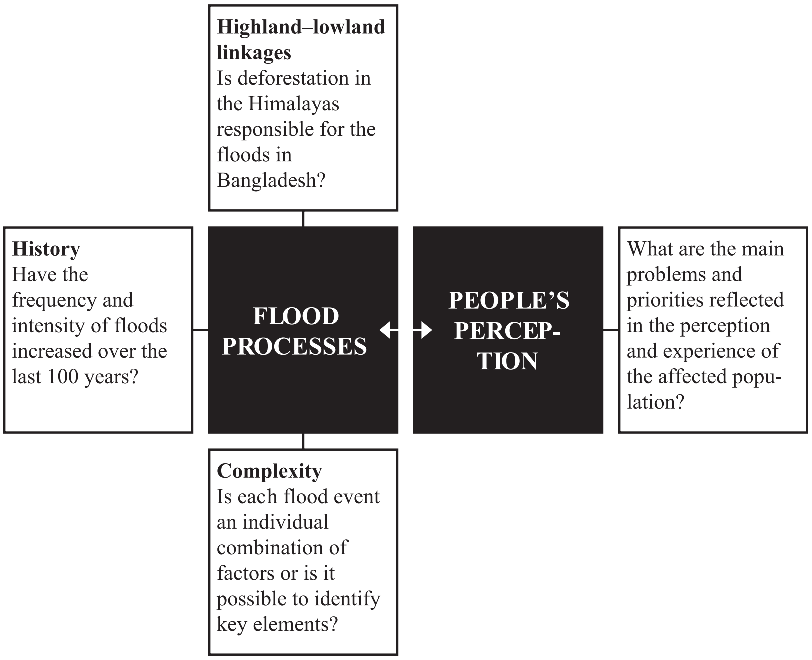

Figure 1.1 The ''Floods in Bangladesh'' project: The key questions.

- work at the East–West Center in Hawaii to establish important contacts and to collect key hydrological information for the Ganga–Brahmaputra basin;
- a visit to the NASA Space Flight Center in Washington DC, which provided access to an archive of NOAA Satellite images at the European Commission's Joint Research Centre in Ispra, Italy; and
- a visit to the India Office Library in London to collect historical rainfall data and flood descriptions in newspapers and maps.

The project officially started in July 1992 and ended in December 1996. Follow-up activities continued beyond the official project phase: the project synthesis was published in 1997 (Hofer and Messerli 1997) and the project was officially presented and discussed in Bangladesh in January 1998. Further data analysis for the updating of results and the inclusion of more recent flood events as well as editing work for the present publication continued steadily through mid-2004. During 2002 the editing process was delayed because of the International Year of Mountains, in whose implementation both of us were heavily involved.

The broad scope of the project goals, together with the approach of looking at flooding from different perspectives, imposed some important and interesting methodological challenges:

- Work had to be carried out at different geographical scales (Figure 1.2): for the investigation of Bangladesh floods in the context of highland–lowland linkages as well as for the analysis of flood history, the entire basin of the Ganga, Brahmaputra and Meghna rivers was taken into consideration (macro-scale); work related to the complexity of flooding and to river morphology focused on the territory of Bangladesh (meso-scale); the investigation of people's flood perceptions and of their indigenous strategies for flood management was carried out in three test areas located in the Bangladesh floodplains near the major river courses (micro-scale).
- The overall project objectives could be achieved only by applying interdisciplinary approaches. The combination of physical sciences for the investigation of the flood processes and social sciences for studies related to people's perceptions and experiences was particularly important. Similarly, the combination of both basic and applied research was of special importance as well.
- A variety of methodological approaches including statistical analysis, regionalization exercises, remote sensing, mapping and interview techniques had to be applied in the different project components. The investigation of floods in the context of highland–lowland linkages and of their complexity was based on case studies; the reconstruction of flood history was based on data series.
- In the framework of the research activities in the overall Himalayan area, fieldwork has always been a key component and accordingly was given high priority in this project. For almost two years, fieldwork in the three test areas within Bangladesh (Figure 1.2) was carried out with the specific intention of gaining an understanding of people's perceptions and experiences. A highlight in the final phase of the fieldwork was an expedition in September and October 1994 from the Darjiling Himalayas through Assam and the Meghalaya Hills down to the Bay of Bengal. During this expedition the entire project team had the unique opportunity to observe and discuss climatology, hydrology, geomorphology, floods and other hazards, agricultural systems, land-use techniques, indigenous strategies to cope with a dynamic environment, and so on, at the different zones and levels of the highland–lowland system. This lively outdoor seminar allowed every team member to develop the necessary overview and to rethink and integrate his or her highly specialized field of investigation into the complex and interdisciplinary framework of the whole project. The itinerary of the excursion is documented in Figure 1.3 (see also Hofer et al. 1996).

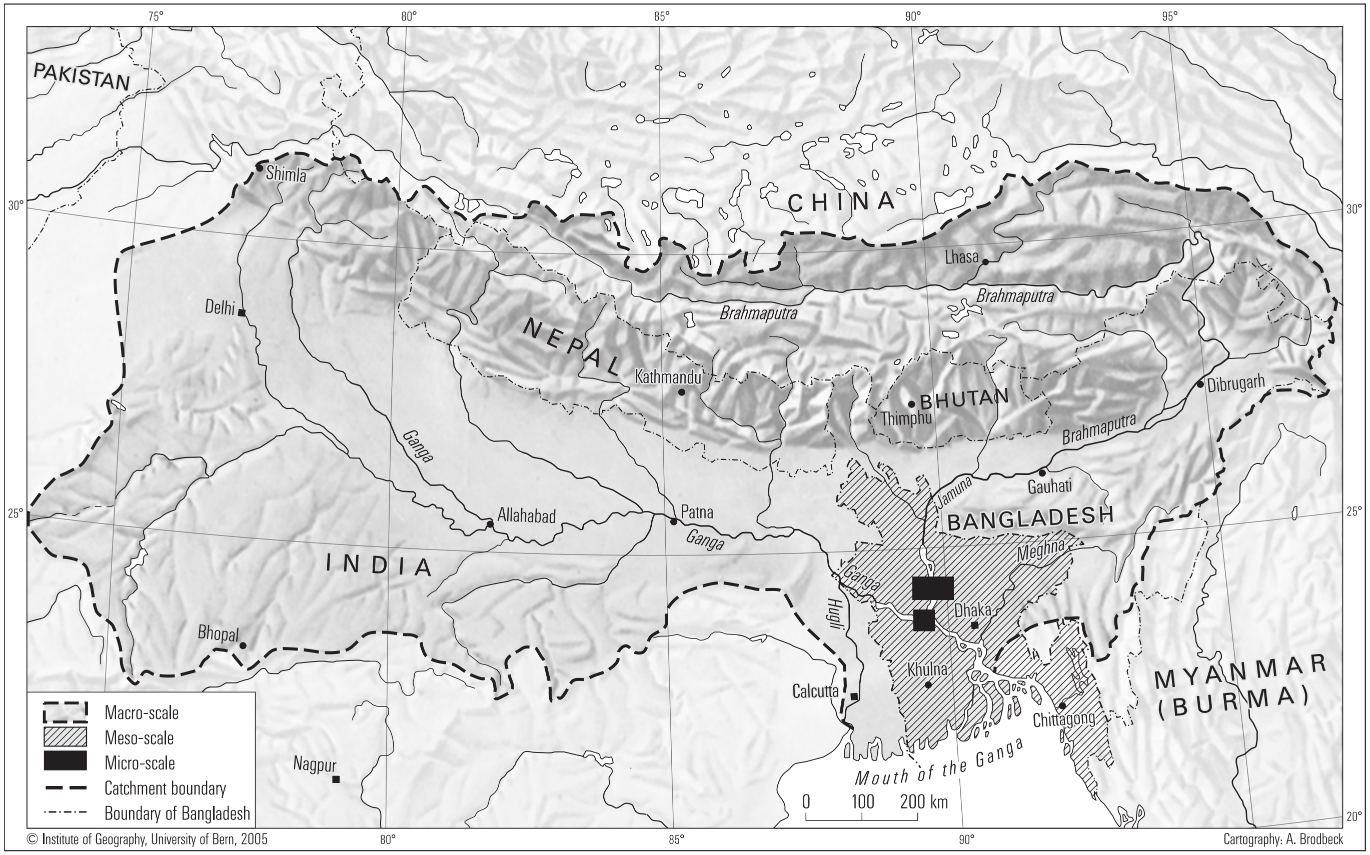

Figure 1.2 Three geographical scales of project activities.

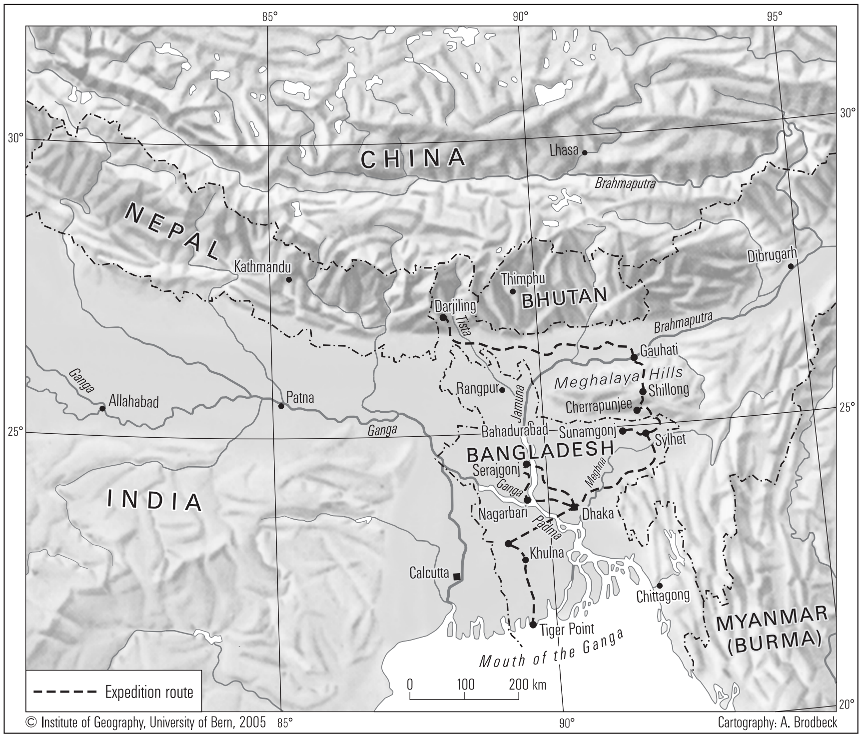

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Figure 1.3 From Tiger Hill (Darjiling Himalayas) to Tiger Point (Bay of Bengal): The route of a fascinating ‘‘seminar expedition’’ in 1994 for all project collaborators.

1.4. The structure of the book

This volume is structured as follows:

- Chapters 1–3 provide an introduction to the project, the basic characteristics of the study area, and the data situation.
- Chapters 4–5 are the key sections of the book in which the main research contributions of the project are presented. Flood history (Chapter 4) and Bangladesh floods in the context of highland–lowland linkages (Chapter 5) are the two issues in which the project has made the most important contributions to the discussion and the understanding of flooding in Bangladesh.
- The processes related to erosion, sediment transport and deposition in the large highland–lowland system and the uncertainties in understanding these processes were raised again and again as important issues, particularly during the presentations of the project results. Chapter 6

is dedicated to these very complex questions as well as to the very dynamic river morphology within Bangladesh.

- As discussed above, the human dimension of flooding was an important element of the project activities in the test areas. However, since there is a substantial literature on flood perception, Chapter 7 provides only a summary of some of the major issues and focuses on the highly divergent flood perceptions of different stakeholders.
- Chapter 8 provides a synthesis, takes a look at major flood events in other river basins and looks ahead to emerging issues of flood management and research priorities.

Floods have a large number of different facets and it would not be possible for this book to provide a complete understanding of their complexity. We focus strongly on the large-scale dimension of flooding, and intend neither to provide an understanding of location-specific flood processes nor to make specific recommendations for site-specific flood mitigation measures. This publication is targeted at different stakeholders, such as development authorities, politicians, journalists, scientists and engineers. It discusses research results and related development issues, which can be used both as background information and as useful tools for decision-making.

1.5. An important contribution to the International Year of Mountains

In 1992, during the United Nations Conference on Environment and Development (the Earth Summit) in Rio de Janeiro, sustainable mountain development received special attention, which is reflected in Chapter 13 of *Agenda 21* (“Managing fragile ecosystems – Sustainable mountain development”). In November 1998, the United Nations General Assembly declared 2002 as the International Year of Mountains (IYM) and designated the Food and Agriculture Organization (FAO) of the United Nations as the lead agency for the preparation of this event. One of the main objectives formulated for the IYM was to “[i]ncrease awareness of, and knowledge on mountain ecosystems, their dynamics and functioning, and their overriding importance in providing a number of strategic goods and services essential to the well being of both rural and urban, highland and lowland people, particularly water supply and food security” (FAO 2000a: 9). With its strong focus on the understanding of the flood processes in the context of highland–lowland linkages, this publication about “Floods in Bangladesh” is of global importance by providing a case study from one of the world’s most impressive highland–lowland interactive systems.

2

Floods in Bangladesh: Understanding the basic principles

2.1. Bangladesh: An unusual country profile (see front cover)

Bangladesh is generally known as a rather small developing country in South Asia with a very low average income, a high population density, a low literacy rate, a majority of the population depending on agriculture and a high frequency of disasters such as floods and cyclones (Table 2.1). The following discussion intends to broaden and differentiate this picture. This chapter also introduces the basic principles of the monsoon circulation as well as the flood processes in Bangladesh.

Bangladesh is located in the confluence and delta area of the Ganga, the Brahmaputra (which is called Jamuna within Bangladesh) and the Meghna rivers (Figure 2.1). An area of 147,570 km^2 is shared by 123.1 million inhabitants (2001). A flat, low-lying topography is the most characteristic geomorphological feature: 60 per cent of the country lies less than 6 metres above sea level (USAID 1988). The average river gradient in the delta is as small as 6 cm/km (GOB 1992a).

Bangladesh has to drain water from an area 12 times its own size (Miah 1988; Bingham 1991). According to Ahmad (1989), the amount of water that annually reaches Bangladesh from outside the country would form a lake of the size of the country and of 10.3 metres depth. Therefore, the particular physical features of Bangladesh can be understood only by looking over the national boundaries into the whole basin of the three

Table 2.1 Country profile of Bangladesh: Some basic facts

Area	147,570 km^2
Population (22 January 2001)	123.1 million
Population density	834 people/km^2
Annual growth rate (1991–2001)	1.47 per cent
Literacy rate (7 years and above, 2002)	51 per cent
Life expectancy at birth (1998)	61 years
Age group (2000)	45 per cent under 15 years
Main seasons	Winter (November–February) Summer (March–June) Monsoon (July–October)
Principal seasonal crops and fruits	Rice, wheat, jute, tea, tobacco, sugarcane, pulses, oilseeds, spices, potato, vegetables, banana, mango, coconut, jackfruit
Area of rice cultivation	89 per cent of total agricultural land
Principal exports	Garments, raw jute, jute manufactures, tea, fish, hides and skins, newsprint
Principal minerals	Natural gas, lignite coal, ceramic clay and glass sand
Per capita GDP at 2001–2002 market prices	US$361
Employment in the agricultural sector (agriculture, forestry, fishery)	51 per cent
Religion	87 per cent Muslim 12 per cent Hindu 1 per cent Buddhist and Christian

Sources: SDC (1990), Anwar (1993), Bangladesh Bureau of Statistics (1993, 2005).

big rivers and into its distinct geographical units (Figure 2.1 and front cover):

- Tibet, where the sources of the Brahmaputra and of several antecedent Himalayan rivers are located, is one of the most extended high plateau areas of the world and has a dry and cold climate. Most of the river flow results from snow and glacial melt.
- The springs of major tributaries to the Ganga and Brahmaputra as well as of the Ganga itself are located in the Himalayas, one of the biggest mountain systems of the world, which extends over some 2,000 km from north-west to south-east. It is estimated that 17 per cent (or 33,200 km^2) of the High Himalaya are covered by ice (Verghese 1990). Accordingly, glacial geomorphological processes and intensive weathering are widespread. The Middle Hills (600 to 4,000 metres above sea level) are characterized by steep slopes, intensive geomorphological and seismic activities and high rates of river downcutting. These areas are inten-

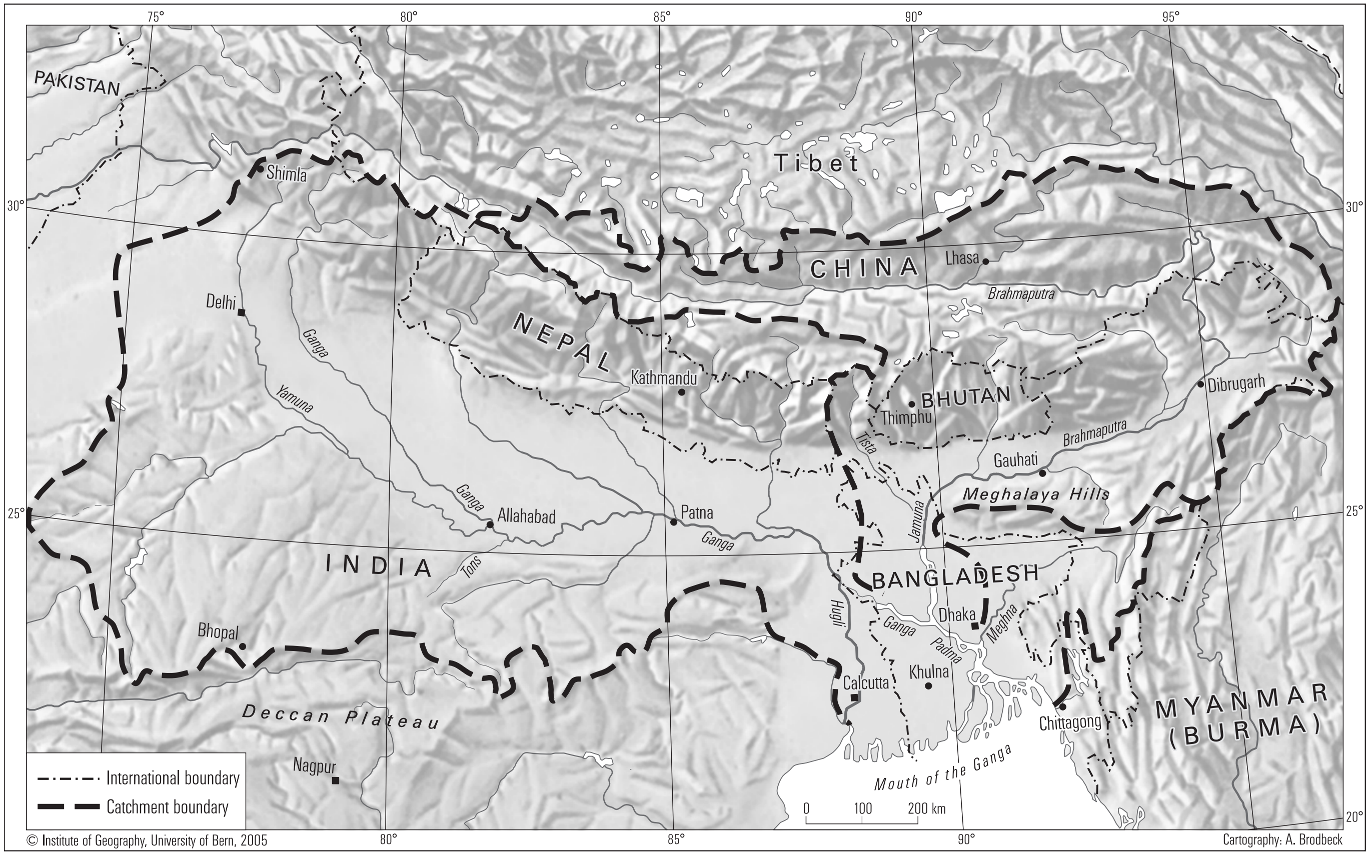

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Figure 2.1 Catchment area of the Ganga, Brahmaputra and Meghna rivers.

sively used for agriculture and there is considerable pressure on natural resources. The Siwalik Hills form the transition between the Middle Hills and the plains and reach maximum elevations of approximately 1,200 metres above sea level (masl). Owing to their unstable rock formations, the Siwaliks are characterized by high rates of erosion and sediment load in the rivers. The transition between the Himalayas and the plains is very sharp. The Himalayan rivers therefore lose their transport capacity, particularly of coarse material, over a very short distance. Dynamic sedimentation processes are very prominent in this transition zone.

- The Ganga Plain is one of the largest lowland areas in the world. It is a region of intensive agricultural production. There are a large number of tributaries to the Ganga from the Himalayas in the north as well as from the Deccan Plateau in the south. The rivers and the rich groundwater aquifers allow for widespread irrigation during the dry season. In the lowlands of the Brahmaputra the characteristics are similar, but the plain is considerably smaller.
- A particularly interesting area is the Meghalaya Hills, located between the vast floodplains of north-eastern Bangladesh and the Indian lowlands of the Brahmaputra (Assam). With the highest peaks reaching 2,500 masl, the Meghalaya Hills form a first barrier for the humid winds on their way from the Bay of Bengal to the Himalayas. Cherrapunjee, a small town on the southern slopes, has made the Meghalaya Hills famous: through the testimony of millions of schoolbooks, Cherrapunjee has attained mythic status as "the place where it rains the most in the world" (Hofer 1997): the average annual rainfall in this small town reaches 11,117 mm! The Meghalaya Hills have shallow soils and a rocky surface. When it rains, the runoff is immediately discharged in huge quantities over cascades into the floodplains of Bangladesh. The effect of this high discharge on the flood processes in Bangladesh is illustrated in the picture on the front cover.

Bangladesh and the Ganga–Brahmaputra–Meghna basin as a whole are dominated by the Asian monsoon system. In the summer months Bangladesh is a "water country": rivers, ponds, rising groundwater tables and the sea are interlinked and form large water bodies. Deepwater rice floats in the water, jute is harvested and a wide range of country boats ensure communication. In the winter season Bangladesh is a "dry country", with large sand bars, dry river courses and vast areas of irrigated agriculture.

The Ganga and Brahmaputra are two of the world's largest rivers in terms of catchment area, length and amount of flow (Table 2.2). The floodplains of the three big rivers, together with the large number of small rivers and streams, cover as much as 80 per cent of the total area

Table 2.2 Watershed characteristics of the Ganga and the Brahmaputra/Meghna rivers compared with other big river systems of the world

Characteristics	Ganga	Brahmaputra/Meghna	Nile	Amazon	Mississippi	Rhine
Basin area (km^2)	1,016,104	651,334	3,254,555	6,144,727	3,202,230	198,731
Length of river mainstem (km)	2,296	2,772	5,964	4,406	4,240	1,083
Average annual discharge (m^3/sec)	11,365 (Hardinge Bridge)	19,772 (Bahadurabad)	2,760 (Aswan Dam)	176,177 (Obidos)	17,600 (Vicksburg)	2,278 (Rees)
Population density (people/km^2)	375	174	44	4	21	304
Forest (per cent)	4	19	2	73	22	7
Cropland (per cent)	71	29	10	15	35	64
Cropland irrigated (per cent)	15	47	5	0	4	0
Grassland (per cent)	7	29	52	8	22	0
Large dams	6	0	7	2	2,091	6

Sources: BWDB (n.d.[b]), UNEP (1995), Revenga et al. (1998), Fekete et al. (2000).

of Bangladesh (Brammer 1990a). Regarding annual sediment discharge into the ocean, the Brahmaputra (with 540 million tons) and the Ganga (with 520 million tons) are ranked 4th and 5th in the world, respectively (UNEP 1995). The sediments are in the clay, silt or sand fractions and the soils formed in the clay and silt depositions can be fertile. Over millions of years these huge amounts of sediments carried by the rivers have led to the continuing formation of the vast delta. In the Sunderbans – the mouth of the Ganga–Brahmaputra–Meghna rivers – land and water are in a permanent exchange: land formation and erosion take place in the interactive zone of fluvial and tidal currents. "The Sunderbans is an extraordinary network of inter-connected waterways. It is the world's largest deltaic formation and hosts the greatest mangrove forest anywhere. The whole flat deltaic flood plain of the combined Ganga–Brahmaputra–Meghna system ranks only second to the Amazon and exceeds the Huang Ho in China in terms of sediment load" (Verghese 1990: 13). Owing to the flat topography, tides affect one-third of the territory of Bangladesh (Hossain et al. 1987).

The Ganga is typically a meandering river system and the Brahmaputra is a braiding river system. In certain stretches within Bangladesh, the Brahmaputra is a river system of 13 km width, which forms more or less one large water body during the monsoon season and which is divided into a number of distinct channels during the dry season (see back cover). The Ganga, and even more so the Brahmaputra, are characterized both by high rates of lateral erosion and by rapidly changing sedimentation processes. Erosion and deposition zones are very dynamic and continuously shifting. A prominent result of sedimentation in the Brahmaputra river bed is the large number of islands, or *chars*, which are inhabited by millions of people (for more in-depth reading on these topics, see section 6.4 in Chapter 6).

The Bangladeshi people are confronted with a highly dynamic and hazardous environment. Over generations they have developed sophisticated indigenous strategies to cope with extraordinary situations and to withstand difficult periods such as extreme monsoon floods, river erosion and cyclones. The seasonal abundance of water and the highly fertile soils make the plains of the Ganga–Brahmaputra–Meghna rivers favourable for agriculture: it is common in the floodplains of Bangladesh to grow three crops a year. As a result of the favourable conditions, these areas are inhabited by up to 1,000 people/km^2. The traditional crops grown in the monsoon season are adapted to flooding and to fast-rising water levels: the deepwater *aman* rice species are able to grow up to 20 cm a day; the harvesting of jute, a traditional export product of Bangladesh, depends on large standing water bodies (for more in-depth information on these topics, see Chapter 7).

Throughout the basin, the river systems have tremendous importance (Myint and Hofer 1998). They provide water for irrigation, for hydropower production and for groundwater recharge, as well as for daily economic and social life. They significantly contribute to the annual flooding (both beneficial and damaging) and to some extent to soil fertility. They host rich fishing grounds. They facilitate the transport of many goods. They are central to domestic use and for waste disposal. They host a number of very important sacred sites and they also have an important political dimension: the Ganga, the Brahmaputra and the Meghna are international and transboundary river systems (Hofer 1994): 7–8 per cent of the total catchment area is located within Bangladesh, 62 per cent in India, 18 per cent in China, 8 per cent in Nepal and 4 per cent in Bhutan (Hughes et al. 1994). Five countries have to manage and share the water resources of the Ganga–Brahmaputra–Meghna basin and the important services they provide. Bangladesh, being the lowest riparian country, is influenced by the sometimes adverse effects of interventions and activities higher up in the river system. The management of the water resources often results in difficult international negotiations or even political tensions, particularly regarding the sharing of the dry season flow.

This brief introduction has provided a first insight into a unique area of our planet:

- where the largest mountain system of the world interacts with one of the most extended lowland and delta areas;
- which drains some of the wettest and, in terms of seasonality, most contrasting areas of the world;
- which is the confluence and mouth of some of the world's largest and most dynamic rivers in terms of width, flow, sediment discharge and lateral shifting;
- which is highly influenced by tidal movements; and
- which has some of the world's highest population densities and cropping intensities.

In view of this list of superlatives and contrasting features that characterize the Ganga–Brahmaputra–Meghna basin, it is easy to understand that Bangladesh regularly and recurrently faces unusual situations. As elaborated in Chapter 1, this book addresses some aspects of the dynamic nature of the Ganga–Brahmaputra–Meghna basins, putting monsoonal floods into the centre of the discussion.

2.2. Mechanisms of the monsoon circulation

The rainy season has arrived. Rivers overflowed their banks. Peacocks danced at eventide. The rain quelled the expanse of dust as a great ascetic quells the tide of

> passion. The chataka birds were happy. Lightning shown like a bejewelled boat of love in the pleasure-pool of the sky; it was like a garland for the gate of the palace of paradise; like a lustrous girdle for some heavenly beauty; like a row of nail-marks left upon the cloud by its lover, the departing day. The rain was like a chess player, while yellow and green frogs were like chessmen jumping in the enclosures of the irrigated fields. Hailstones flashed like pearls from the necklace of heavenly birds. (Pandey 1977: 138)

This text, extracted from the ‘‘Vasavadatta’’ of the poet Subandhu in the late sixth century AD, highlights the importance of the monsoon circulation for the Indian subcontinent. It provides a flavour of the atmosphere prevailing at the onset of the summer monsoon after a long period of drought, heat and dust. In the following sections, we describe some basic mechanisms of the monsoon circulation. We do not provide a detailed, in-depth discussion of the physics of the monsoon, but select some key elements that are important in the context of this publication. The text, which was mainly compiled by project team member Barbara Schneider, is based on the following sources: Rao (1981), Hastenrath (1985), Fein and Stephens (1987), Webster (1987), Barry and Chorley (1992).

2.2.1. The monsoon and its formation

In the Indian subcontinent the monsoon is strongly developed. Hastenrath (1985: 177) writes: ‘‘nowhere else on the globe is the annual reversal of wind and rainfall regimes as spectacular as in the realm of the Indian Ocean and surrounding land areas. On the densely populated Indian subcontinent in particular, the monsoon rains are of vital social and economic consequence.’’ Because the maximum insolation of the sun during the northern summer occurs north of the equator, the strongest heating of air masses is found in the subtropical regions (Figure 2.2). The heating of air masses is stronger over land than over water. As a consequence, the air over the huge land masses of the Indian subcontinent and the Tibetan Plateau is heated considerably during the summer months. Low pressure areas are formed over land. The thermally induced low pressure area over the Indian subcontinent extends up to the middle troposphere (5,000–6,000 metres). In the upper troposphere, the low pressure area is overlapped by a strong high pressure area. A trough extends from the Bay of Bengal in a north-westerly direction to the dry region of Pakistan, the so-called monsoon trough. A large gradient exists between the low pressure over land and the higher pressure over the oceans. This pressure gradient extends from the tropics of the southern hemisphere over the equatorial region to the thermal heat low of the Indian subcontinent. Air masses originating in the subtropical high pressure belts of the southern hemisphere flow into the heat low of the northern hemisphere

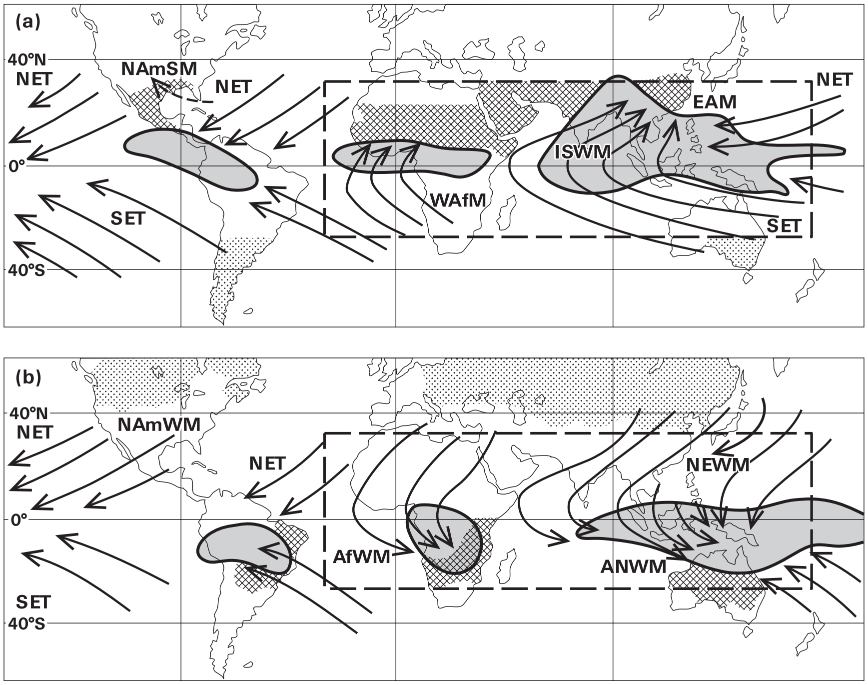

Figure 2.2 The domains of the principal monsoon systems of the atmosphere during the northern hemisphere summer (a) and winter (b).
Source: The figure is taken from Webster (1987).
Notes: Using the criteria of seasonal wind reversal and distinct summers and dry winters, the monsoon region is outlined by the dashed rectangle. The main surface wind and areas of maximum seasonal precipitation are indicated as arrows and shaded areas, respectively. The cross-hatching shows the land areas with maximum surface temperatures and the stippling indicates the coldest land surfaces. Key monsoon and tropical systems are indicated. NET and SET refer to the north-east and south-east trade-wind regimes. EAM, ISWM, WAfM and NAmSM indicate, respectively, the East Asia Monsoon, the Indian Southwest Monsoon, the West African Monsoon and the North American Summer Monsoon. NEWM, ANWM, NAmWM and AfWM show the locations of the Northeast Winter Monsoon, the Australian Northwest Monsoon, the North American Winter Monsoon and the African Winter Monsoon.

(Figure 2.2). Because of the Coriolis force, the winds are diverted in an easterly direction when crossing the equator. The resulting southwesterly winds are called monsoon winds. Monsoon winds contain a lot of moisture. These winds become unstable when they reach the continent because of mass convergence. As a result, condensation and precipitation processes are triggered.

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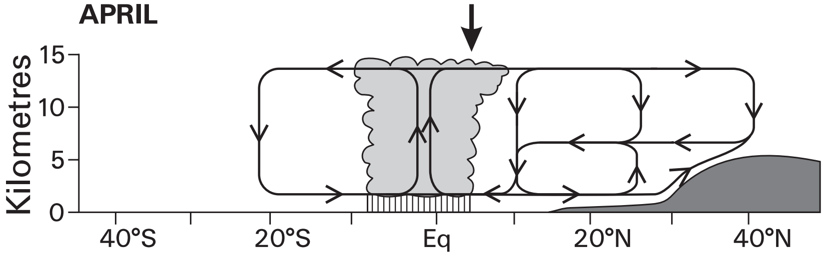

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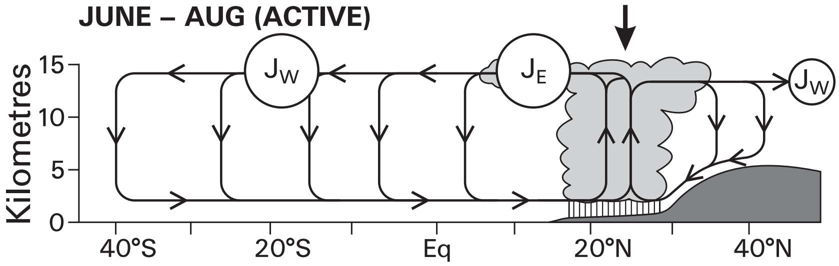

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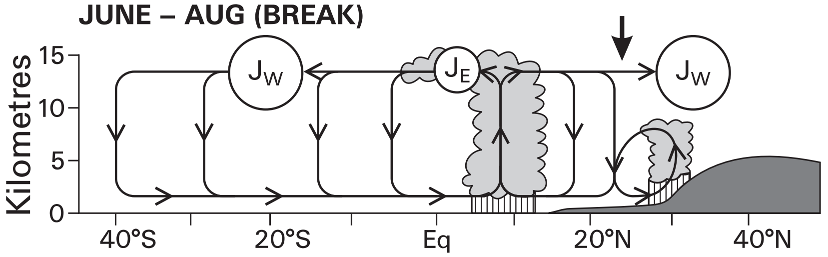

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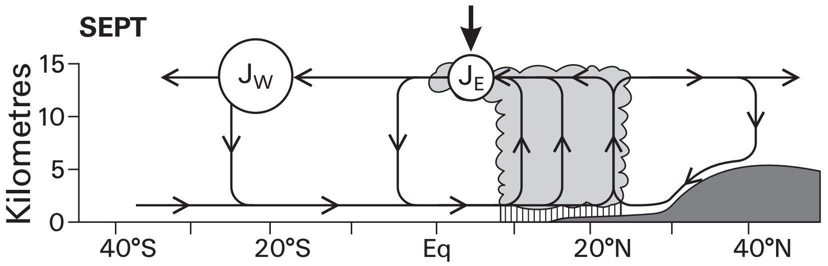

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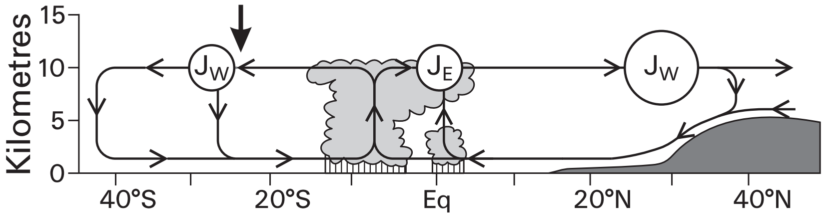


2.2.2. The cycle of the Indian summer monsoon

In the pre-monsoonal period (April–May), the heating of the land masses starts slowly. Convection is not yet developed, and descending air masses from the equator are still quite strong (Figure 2.3). Only small amounts of rainfall over the Indian subcontinent are expected during this period. The probability of rainfall is highest in the far north because of the coincidence of the warm, moist air in the lower troposphere with the dry and cold westerlies in the upper troposphere. In Bangladesh, Assam and the Meghalaya Hills, rainfall starts earlier than in the other regions.

> The early onset of summer rains in Bengal, Bangladesh, Assam, and Burma is favoured by an orographically produced trough in the westerlies at 300 mb, which is located at about 85–90° East in May. Low-level convergence of maritime air from the Bay of Bengal, combined with the upper-level divergence ahead of the 300 mb trough, generates thunder squalls. Tropical disturbances in the Bay of Bengal are another source of these early rains. (Barry and Chorley 1992: 244)

At the end of May and beginning of June, the heat low over India intensifies and convection increases. This is the beginning of the summer monsoon (June–August), known as the "burst of the monsoon". The onset of the monsoon is characterized by the arrival of humid air masses blowing from the south-west and by the formation of the eastern jetstream in the upper troposphere. Because of the significant northward shift of the whole circulation, the westerlies, which play an important role during winter, move northwards across the Himalayas, where they weaken considerably. Over the Tibetan Plateau a thermally induced heat low has developed.

By mid-July, the monsoon has arrived everywhere. The monsoon trough is situated at about 25° North. The pressure gradient between land and ocean is strongest during this time. In the upper troposphere the easterlies are well developed. The axis of the jetstream is located at about 15° North. Around the Bay of Bengal one of the most important phenomena of the monsoon is likely to develop: the monsoon depression (see section 2.2.3).

In the post-monsoonal period (September), the region with the strongest insolation is moving southward. The monsoon is losing its intensity.

◄

Figure 2.3 The annual cycle of the monsoon over the Indian subcontinent.
Source: Barry and Chorley (1992).
Notes: The black arrow indicates the maximum insolation of the sun. J_E and J_W show the position of the eastern and western jetstream.

In the upper troposphere the eastern jetstream is weakening. The westerlies are gradually being established again.

In the winter (December–February), the maximum insolation is located in the southern hemisphere. The land masses of the northern hemisphere (the subtropical region) are cooling down. The direction of the surface winds becomes north-west in India and veering north-east in Bangladesh and Burma.

2.2.3. The monsoon depression

Monsoon depressions develop over the relatively warm Bay of Bengal. They move north-westward (along the axis of the monsoon trough) towards the warmer and drier regions of western India. In the upper troposphere they are steered by the easterlies. As a result of the monsoon depression there is heavy rainfall in the regions where the depression moves across. The rainfall resulting from such a monsoon depression is considerable. The following factors are very important for the development of a monsoon depression:

- the sea surface temperature of the Bay of Bengal must be more than 29 °C;
- the monsoon trough must extend into the Bay of Bengal;
- a very large pressure gradient in the Bay of Bengal has to precede the formation of a monsoon depression.

2.2.4. Precipitation patterns in the Ganga–Brahmaputra–Meghna basin

Rainfall in the tropics is dominantly convective. Precipitation falls because of thunderstorms, gusts of wind and ordinary showers. The amount of rain resulting from the monsoon winds depends on the water vapour contained in the air masses. During the monsoon season there are four main currents in the Indian subcontinent that carry humid air:

- south-westerly currents flowing over the Deccan Plateau and the western Ghats (Indian Peninsula);
- southern currents moving from the Bay of Bengal towards the Meghalaya Hills, Assam and the eastern Himalaya;
- south-easterly currents, which are separated from the southern currents over the Bay of Bengal, flowing up the Gangetic Plain into the heat low of Pakistan; and
- a “weak” current blowing from the Arabian Gulf across the foothills and forelands of the Himalayas to Assam and the Meghalaya Hills.

Besides the water vapour content of the air, the position of the monsoon trough is most important. The intensity of rainfall depends on how strongly the monsoon trough has developed. "The variation of the rainfall in the Gangetic plain is known to be correlated with that of the vorticity around the monsoon trough, active spells being associated with high cyclonic vorticity and weak spells or breaks with anticyclonic vorticity in this region" (Gadgil 1977: 1413). The rainfall, which is induced by the processes in and around the monsoon trough, is often supplemented by precipitation produced by monsoon depressions that originate in the Bay of Bengal and move along the axis of the monsoon trough to the north (section 2.2.3).

If the humid monsoon winds are forced to rise because of mountain ranges, the air masses are further labilized. This labilization and rise lead to additional convection and to orographic rainfall, which intensifies the normal monsoon rainfall. Thus, areas lying in the southern slopes and adjacent foothills and forelands of mountain ranges receive enormous amounts of rainfall.

Pulsations in the monsoon current lead to active and inactive phases. The active period is characterized by frequent weather changes with heavy rain spells. The inactive phase is characterized by clear and warm weather, which can last for several weeks. The changes are probably induced by the position of the monsoon trough. During an active phase, the monsoon trough is positioned south of the Himalayas, so that there is rainfall in the north and in the central parts of India. During the inactive phase, the monsoon trough weakens. It is positioned further north and consequently there is rainfall along the forelands of the Himalayas and in Assam. Hastenrath (1985: 180) writes about the inactive phase: "in the course of the south-west monsoon, there are periods when the monsoon trough shifts northward to the foot of the Himalayas, and rains decrease over much of India except along the slope of the Himalayas and parts of Northeast India, and the Southern Peninsula. This synoptic situation is called 'break in monsoon'."

The complex and differentiated circulation mechanisms of the Asian monsoon system result in distinct precipitation patterns in the overall Himalayan region (Figure 2.4):

- Maximum rainfall is recorded from June to September and minimum precipitation from November to March.
- There is an increase in rainfall from west to east: the average annual rainfall in the catchment area of the Ganga reaches 1,400 mm, the Brahmaputra/Jamuna 2,100 mm and the Meghna 4,000 mm (Ahmad 1989). The lowest annual rainfall figures are recorded in the Upper Ganga Plain (Delhi with 712 mm); towards the western border of the basin, the annual precipitation falls as low as about 600 mm. By far the highest amount of rainfall is measured in the Meghalaya Hills (Cherrapunjee). The gradient is extraordinary: over a distance of only

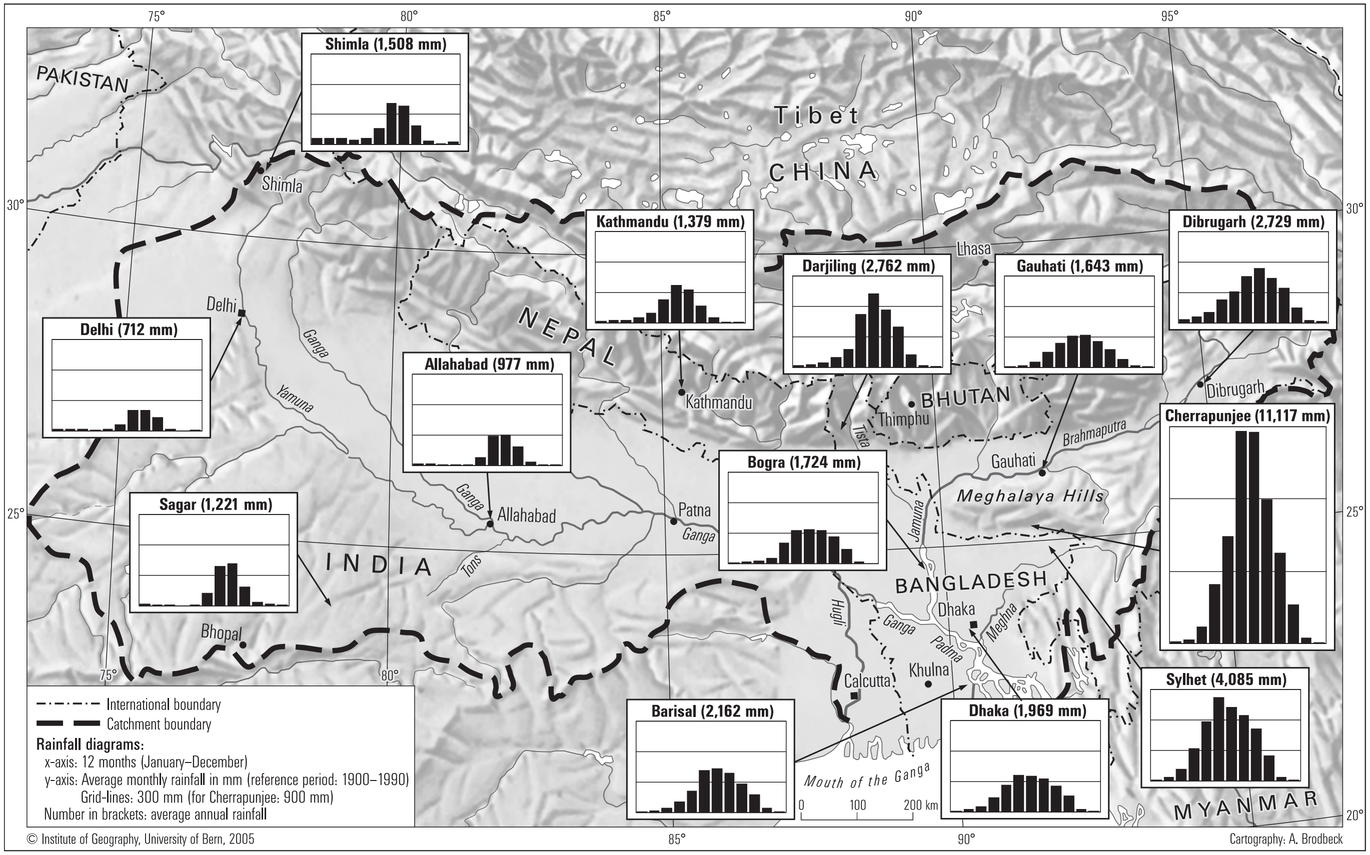


Figure 2.4 Average monthly rainfall at selected stations in the Ganga–Brahmaputra–Meghna basin.
Sources: For data sources, see Table 3.2.

250 km, the average annual precipitation increases from 1,724 mm in Bogra to 11,117 mm in Cherrapunjee. The western Himalaya (near Shimla) gets noteworthy precipitation between November and April, often in the form of snow. This precipitation is caused by western disturbances that originate in the Mediterranean–Caspian region and move east across Iran, Afghanistan and the southern part of the former USSR.

- As a result of the much earlier onset and more intensive monsoon in the east, the duration of the rainy season increases from west to east: whereas in the Ganga system the monsoon season concentrates in July and August, in the Meghna system high monthly rainfall totals are recorded from May to September, with the maximum in the first rather than the second part of the monsoon season.
- Owing to orographic effects there is an increase in rainfall from south to north. The very high rainfall in the Meghalaya Hills, which form the first significant barrier for the humid monsoon winds from the Bay of Bengal, has already been discussed. In the Himalayas, the maximum precipitation is recorded in the Middle Hills, beyond which there is some slackening, resulting in elements of desertification in rain-shadow inner valleys in the northernmost parts of the central and western Himalaya (Verghese 1990).

In the Himalayas, the proportion of the annual precipitation that falls in the form of snow decreases from 22 per cent in the far west to 2 per cent in the east (Verghese 1990).

The intensities of monsoonal precipitation can be very high, but are often rather localized. In the highlands, such rains may develop considerable erosive forces and in the lowlands they can lead to substantial accumulation of water masses.

2.2.5. River discharge patterns in the Ganga–Brahmaputra–Meghna basin

The complex circulation mechanisms of the Asian monsoon system and the differentiated precipitation patterns result in distinct discharge characteristics of the rivers in the Ganga–Brahmaputra–Meghna basin (Figure 2.5):

- The rivers flow at high water levels in the summer months and at low water levels in the winter months.
- Most of the graphs document an extraordinary difference between the dry season and the rainy season flow.
- The average flood flow of the Brahmaputra reaches 10 times its dry season flow, and that of the Ganga as much as 20 times its dry season flow (see also the images on the back cover).

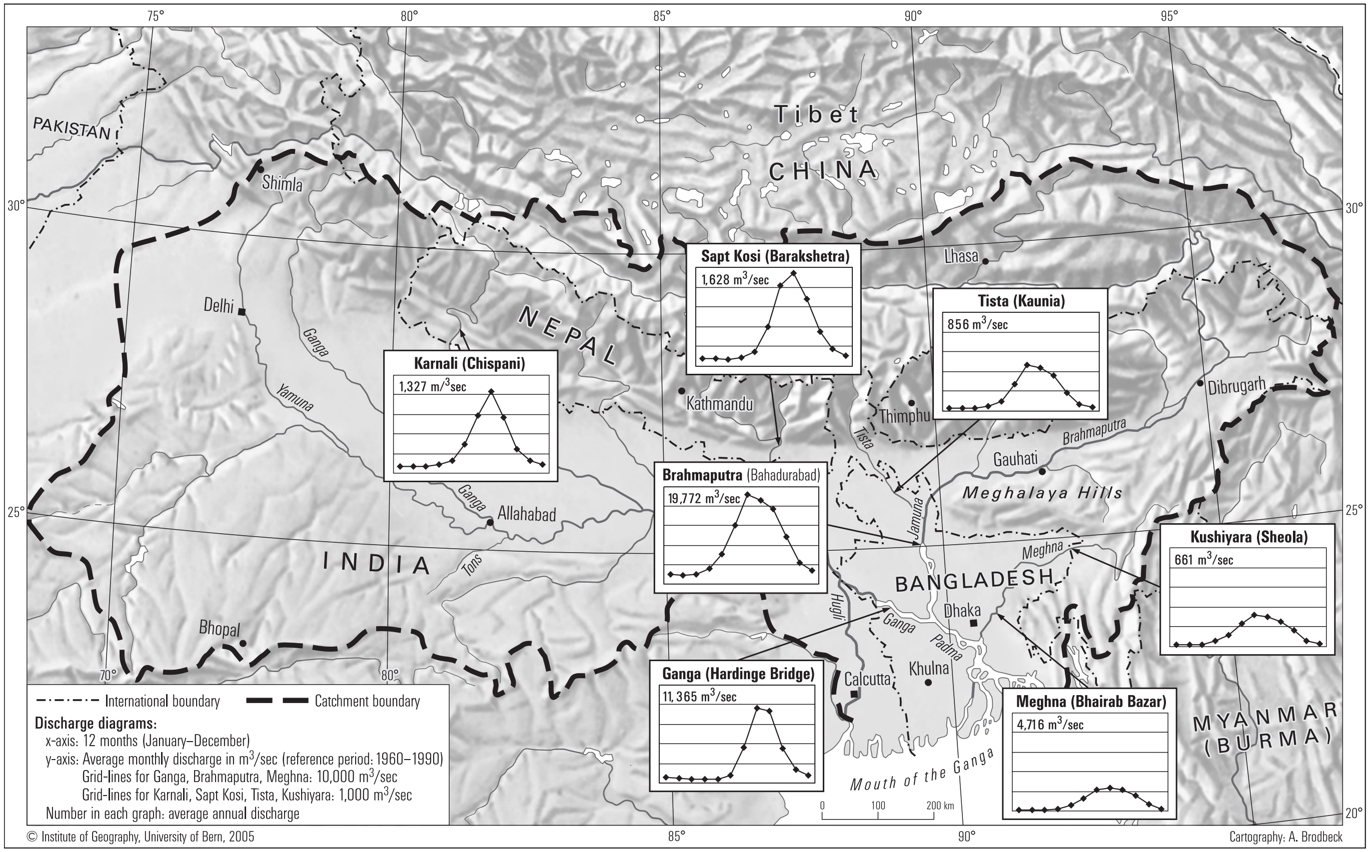


Figure 2.5 Average monthly discharge at selected stations in the Ganga–Brahmaputra–Meghna basin.
Sources: For data sources, see Table 3.4.

- Owing to the earlier onset of the monsoon in the east, the discharge hydrograph of the Brahmaputra rises much earlier, and normally reaches its peak one month before the Ganga. The duration of high river flow increases from west to east in the basin.
- In the Ganga system there is a marked difference between the hydrographs of the main river and those of its tributaries: whereas the discharges of the Karnali and the Sapt Kosi start rising in May as a result of snow and glacial melt, the flow of the Ganga remains rather low until June.

The amount of water flowing through Bangladesh is enormous. In addition to the big rivers, countless small streams and rivulets drain the territory of Bangladesh and nearby areas and add to the total amount of water that has to be discharged into the Bay of Bengal. Of the water carried by the river systems, 90 per cent (or 1,360,000 million m^3 of annual discharge) originates outside Bangladesh (Choudhury 1989; Boyce 1990). Of this amount, 50 per cent is contributed by the Brahmaputra, 40 per cent by the Ganga and nearly 10 per cent by the tributaries of the Meghna (BWDB 1975).

The flow patterns of the Brahmaputra within Bangladesh still reflect more or less the natural conditions. The discharge characteristics of the Ganga are influenced by engineering structures higher up in the catchment: the Farakka Barrage, located very near to the Bangladesh border on the Ganga in India, is a particularly important element in this respect (Box 4.3).

This general discussion of the monsoonal circulation and of the resulting complex hydrometeorological characteristics provides a very important background for understanding the flood processes in the basin and for the contents of the main chapters in this book.

2.3. Characteristics of Bangladesh floods

2.3.1. The main physiographical units

In order to understand the flooding conditions in Bangladesh, a short presentation of the principal physiographical units of the country is necessary (Figure 2.6). The following discussion of these units is compiled from Islam (1995) and Brammer (1994):

- Hills: hills, tertiary and older, exist only in the east and south-east of the country, in the Comilla and Chittagong areas, with maximum elevations of approximately 700 masl. The folded Chittagong Hill Tract Ranges are densely forested and sparsely populated. Shifting cultivation is a typical agricultural feature in the area.

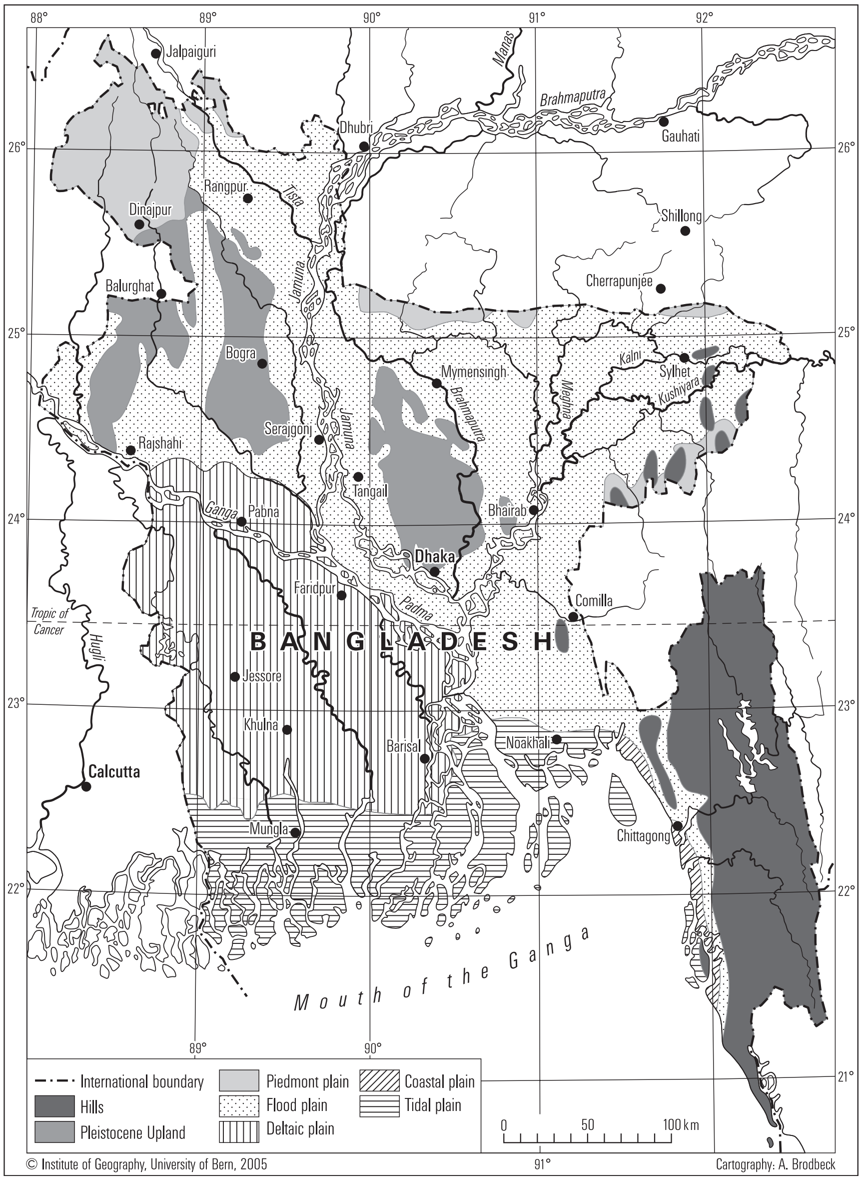


Figure 2.6 The main physiographical units of Bangladesh.
Source: Modified from Huq and Rahman (1994).

- Pleistocene upland: there are two major areas of pleistocene sediments within the Bengal basin. One is located to the north of Dhaka (Madhupur tract), with maximum elevations of approximately 15 masl, the other west of Bogra (Barind Tract), with maximum elevations of around 30 masl. These areas remain above the active floodplains and are usually not flooded during the rainy season. Pleistocene sediments are well oxidized and are typically reddish or brown; organic material is confined to the surface soil profile. Pleistocene areas do not allow for a very diversified cropping system.
- The floodplain: this land category occupies a large part of the country. The areas close to the major rivers host young alluvial lands with mixed sandy and silty soils. These lands continually change in extent and elevation owing to river bank erosion and new alluvial deposition. They are subject to annual flooding by the rivers. The areas of the floodplain located away from the main river courses are older and more stable. They are characterized by a micro relief, with 2–5 metres of difference between the ridge tops and the depressions, and by many active or old river channels. Flooding in these areas is mainly caused by rainwater; the highest ridge tops are submerged only in years with exceptionally high flooding. The soils are loamy on the ridges, clayey in the basins. The centres of particularly low-lying depressions in the old floodplain may remain inundated, mainly by ponded rainwater, even during the dry season.
- The deltaic plain: the deltaic plain is drained by innumerable distributaries off the Ganga. It is characterized by a gentle slope and a complex river system, the river courses criss-crossing each other. The topographic features are similar to those of the floodplains.
- Tidal floodplains: these consist of almost level lands with numerous tidal rivers and creeks, and predominantly clayey soils. "Under natural conditions, the land can be mainly shallowly flooded with silty river water at high tides, either throughout the year near the coast or only in the monsoon season further inland. Flooding is by fresh water inland and in the monsoon season near the coast, but in the dry season by saline water near the coast. Following the empolderment of much of the land, flooding is now mainly by ponded rainwater" (Brammer 1994: 5). A considerable part of the tidal floodplain is made up by the Sunderbans, which are almost devoid of habitation since they are not open to settlement.
- Piedmont plains: these areas are gently sloping alluvial plains at the foot of the hills, generally subject to flash flooding. They often have complex sandy and loamy soil patterns on higher land, grading into more silty and clayey soils in depressions.
- Coastal plains: the coastal plains in the Chittagong area occupy a nar-

row strip of land between the Chittagong Hills and the sea. The area is often subjected to shallow flooding and flash floods from the hills. It is also exposed to tropical cyclones and the associated storm surges. Ingress of saline water at high tides is a major handicap for agriculture.

Based on these physiographical units, it is evident that large parts of the territory of Bangladesh are potentially flood-affected areas and that the flooding characteristics need to be regionally differentiated.

2.3.2. The flood types in Bangladesh

"Rivers flood. None more so than in Asia. And none in Asia as much as the Ganga–Brahmaputra–Meghna system which drains a more populous basin than the Yangtze and carries a larger flood discharge than any other river, barring the Amazon, and immeasurably more silt than China's notorious Huang-Ho" (Verghese 1990: 121). According to Hossain et al. (1987), Miah (1988), Ahmad (1989) and Brammer et al. (1993), basically four flood types occur in Bangladesh (Figure 2.7):

- normal monsoon floods of major rivers, with the water level showing a slow rise and fall with pulsations;
- flash floods, where hydrographs rise and fall sharply;
- floods owing to excessive rainfall; and
- tidal floods as a result of cyclones and storm surges.

Inundations caused by river overflow or excessive rainfall make up the majority of the flood processes that occur in Bangladesh and are accordingly of main interest for this publication. In the field, when there is water all around, it is usually difficult to differentiate between rain and river floods. Flash floods and tidal floods are spatially limited to the forelands of the hills and the coastal areas, respectively.

Floods associated with the huge river systems of the Ganga and Brahmaputra build up gradually and often need time to reach their maximum extent. Floods associated with the much smaller, but for Bangladesh very important, Meghna catchment, usually build up faster and are, in the case of events occurring in the transition zones between the hills and the plain, often flashy and rather unpredictable. The big rivers, the regional rivers, the small rivers and the irrigation channels are interlinked. This strongly influences the development and the recession of floods.

2.3.3. The extent and range of flooding

Statistics on flood-affected areas or maps documenting the extent and degree of flooding are basic sources that are used to compare flooding patterns in different years, to plan and prioritize flood relief operations

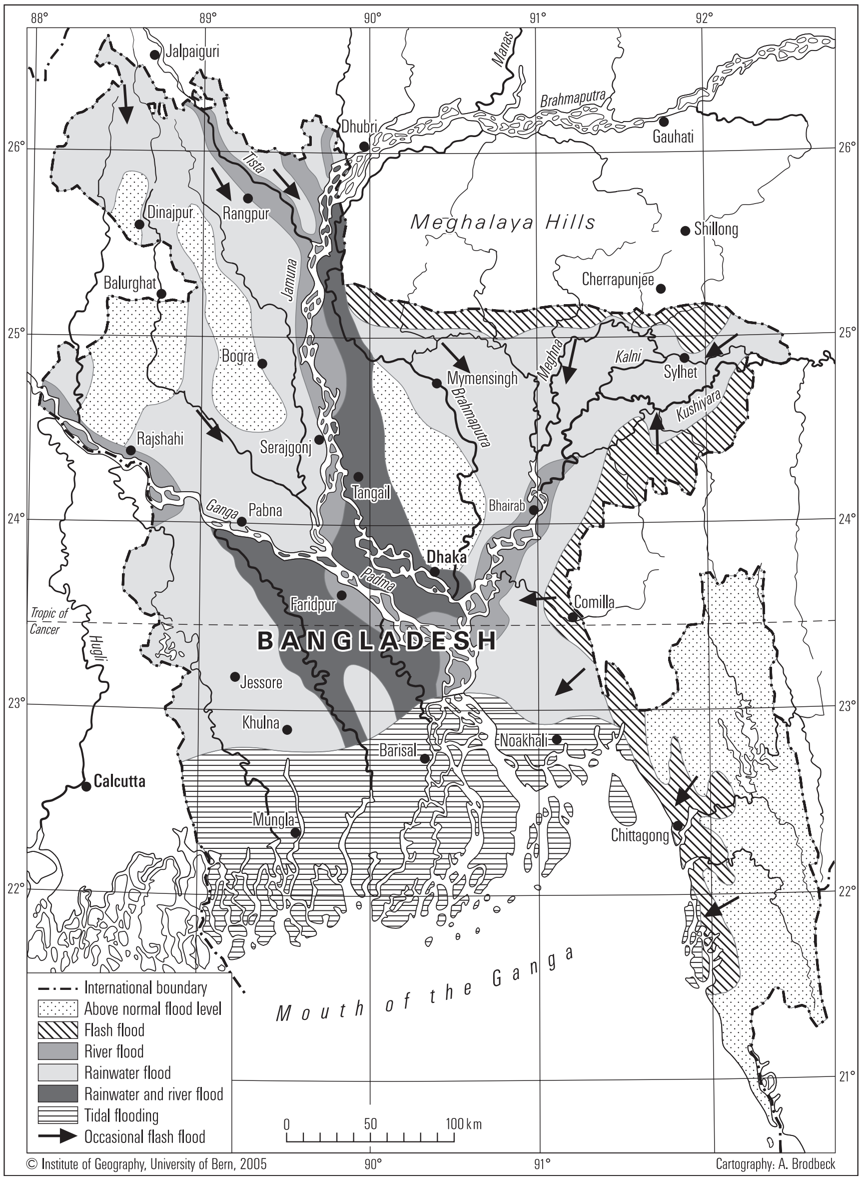


Figure 2.7 Flood types in Bangladesh.
Source: Brammer et al. (1993).

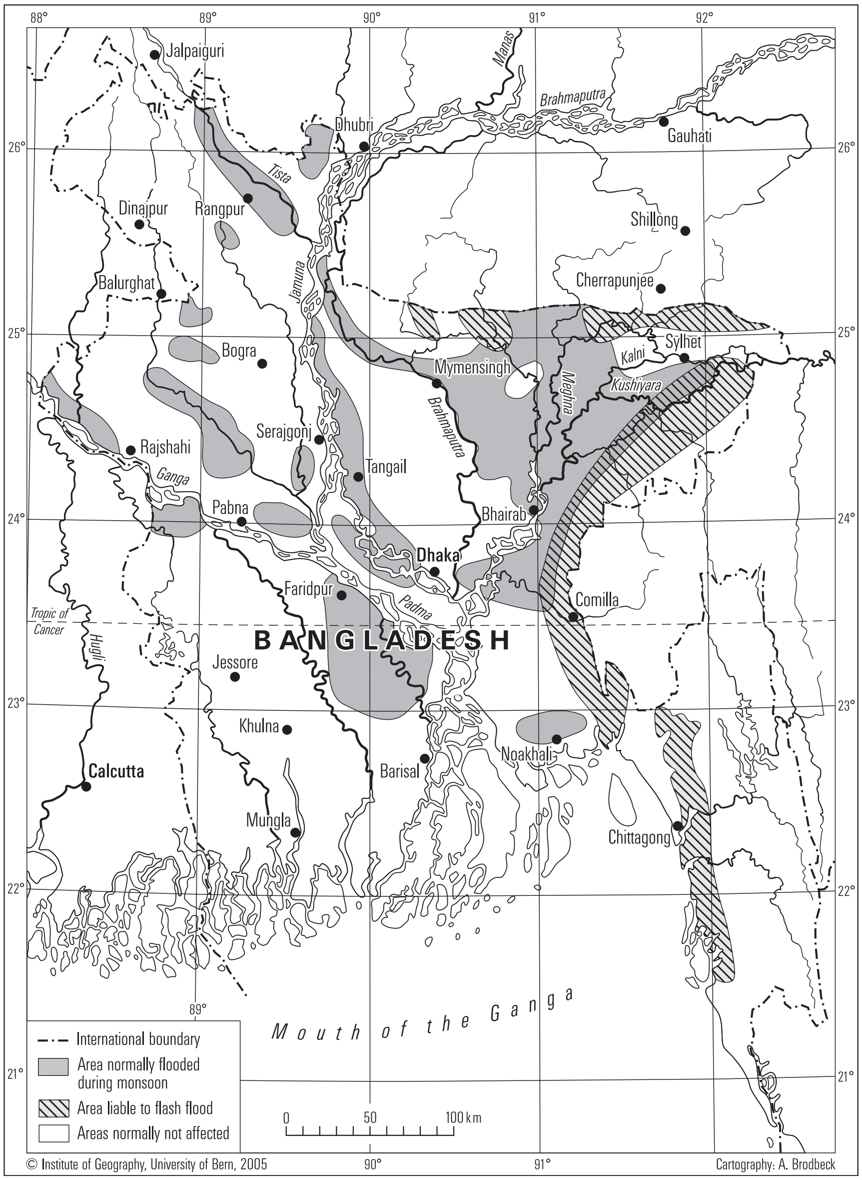


Figure 2.8 The extent of normal flooding in Bangladesh.
Source: BWDB (1991a).

or even for foreign aid institutions to decide on support to the country for rehabilitation activities.

Figure 2.8 reproduces the official map of those areas of Bangladesh that are flooded during a normal monsoon season. According to BWDB (1991a) and Pearce (1991), on average 20 per cent of Bangladesh is flooded annually (see also Table 4.1). Of the cultivable land, about two-thirds is classed as vulnerable to flooding, with one-fourth to one-third flooded every year (Dewan 1989; Miah 1988). These are the official figures. However, access to real data or to reliable and realistic mapping of flood-affected areas is a critical and difficult issue:

- Most of the official maps and statistics are produced by the Bangladesh Water Development Board. They are usually based on information provided to the head office by the regions. It is a major question whether the figures from the different areas are comparable and if the officers apply the same criteria when collecting the information. In a personal letter (20 July 1997), Hugh Brammer communicates the following very important message: "the map in Figure 2.8 reflects the responsibilities of the Bangladesh Water Development Board for protecting land from river floods. It ignores 'normal' rainwater flooding [Figure 2.7]. Soil surveys in the 1960s and 1970s calculated an area of 56 per cent of the country subject to 'normal' floods and flooding, including rainwater flooding; this proportion will now be less following empoldering of additional floodplain land." Personal comments made by Haroun er Rashid of the Independent University of Bangladesh in January 1998 point in the opposite direction: "the figures on flood affected areas listed in the reports of the Bangladesh Water Development Board (BWDB), even for years with average extent of flooding, are exaggerated since floods attract foreign aid money for relief". The arguments of Hugh Brammer and Haroun er Rashid, both of which are extremely valuable, relevant and convincing, draw attention to how controversial the "simple" question of the average flood dimension in Bangladesh is. If, as occurs in certain projects, flood maps are based on LANDSAT images, these problems are less inherent and a more objective documentation and realistic discussion of the flood situation is possible.
- Flooding does not necessarily imply that the affected people face problems. Based on maps and statistics, areas that are flooded every year may appear in the headlines, but the reader is unaware that this type of flooding may be more beneficial than harmful for agriculture. Maps and statistics may not provide sufficient information to pinpoint those areas that really suffer from flood and are in need of flood relief.
- The available records do not necessarily represent the maximum extent of flooding at a given time in a specific year. According to M. Miah, a retired officer of the Bangladesh Water Development Board, the an-

> nual figure for a specific year in the statistics represents the sum of all the different flood-affected areas that were reported during the monsoon season of that year. In the case of a nationwide flood, the figure might well represent the maximum extent of flooding at a specific time, whereas in other years it might be the total figure of regionally limited flood events with different timings. This type of constraint can be avoided only if flood mapping is based on a satellite image on a specific date.

These comments by no means question the usefulness of maps or statistics for flood-affected areas. However, they do imply that flood maps or statistics are not sufficient to get the full picture of the flood situation and that additional information needs to be collected.

The range of the flood dimension in different years is impressive. According to the Bangladesh Water Development Board, in 1994 only 419 km^2 of flood-affected area (0.28 per cent of the country) was reported, whereas in 1998 the area under floods exceeded 100,000 km^2 (68 per cent of the country; see also Table 4.1). The Bengali language reflects this range by using different words: the normal, beneficial floods are termed *barsha*; the harmful floods of abnormal depth and timing are termed *bonna* (see also section 7.3).

2.3.4. The depth, duration and timing of flooding

In terms of the impacts of floods on the affected people, the depth of inundation is a very important parameter that is usually not documented in flood maps or flood statistics. The differentiated pattern of the average flood depth shown in Figure 2.9 results from the physiographical units (section 2.3.1) and the micro-topography within the floodplains. There are basically four areas in which the depth of floods usually exceeds 1.8 metres: the Sylhet depression in the Meghna catchment; the area between Rajshahi and Bogra along the Atrai River towards the confluence of the Ganga and the Brahmaputra; the area between the Daleswari and the Padma south of Dhaka; and the area north of Khulna. The big depression in the Meghna catchment deserves particular attention: the area is flooded for approximately six months per year, when the villages are transformed into small islands. During the monsoon season, the region forms a vast ponding area where the water masses that are discharged from the surrounding areas can be temporarily stored.

Based on the average depth and duration of the flood, the appropriate cropping patterns are selected (see Brammer 1994: 8–12) and the minimum height of the house platforms or road embankments is defined. According to Brammer (1994), the land categories documented in Figure 2.9 are based on the farmers' own land classification. The indicated levels of

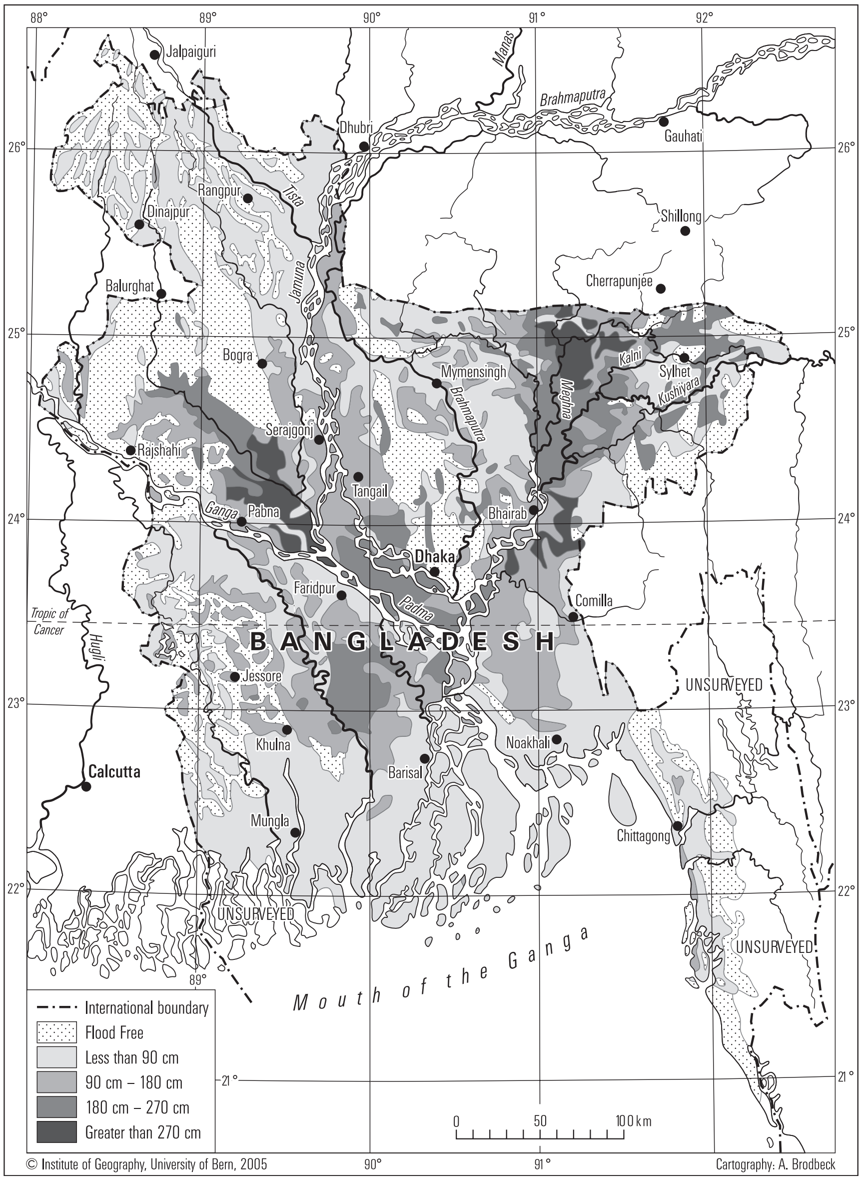
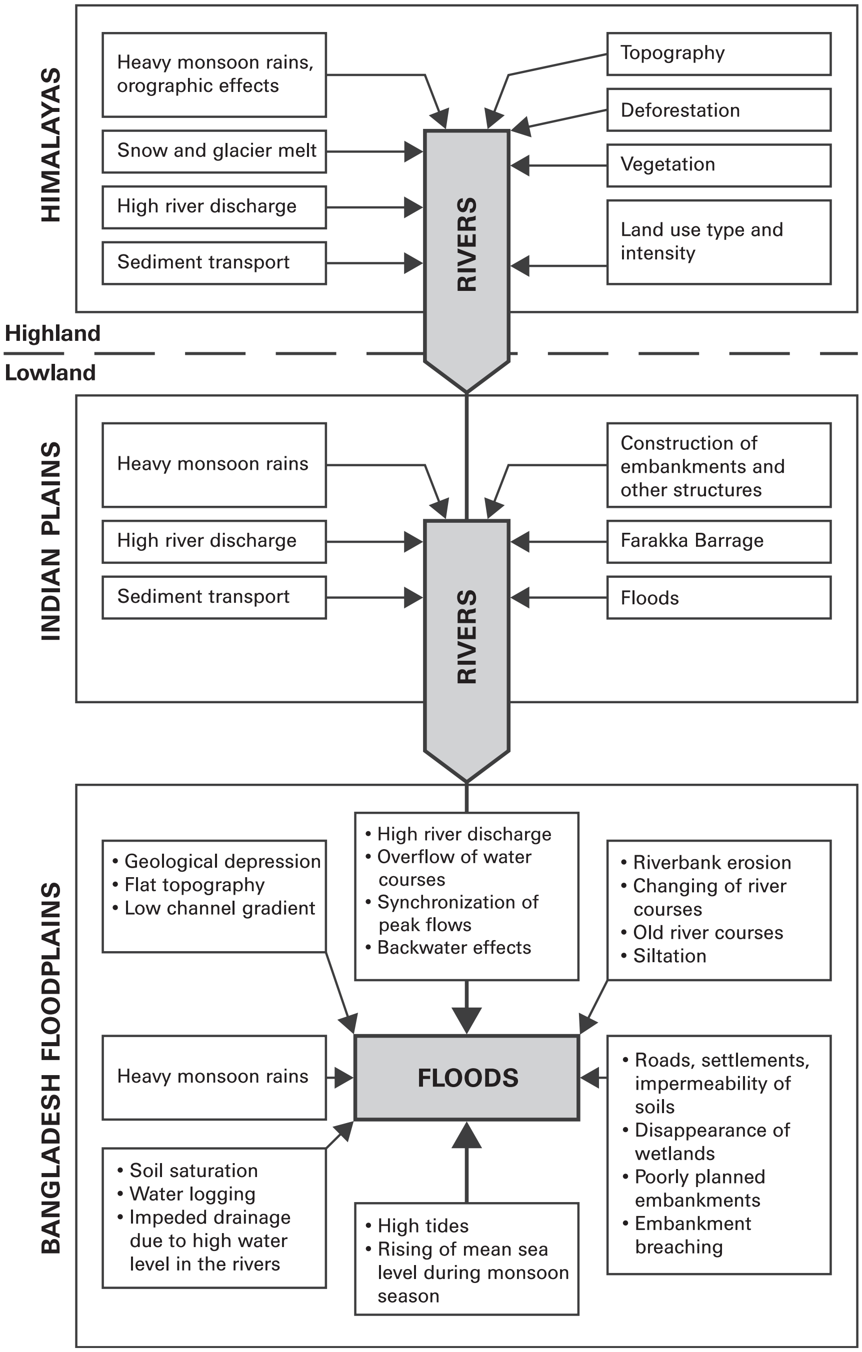


Figure 2.9 Average depth of inundation, slightly generalized.
Sources: Brammer (1994); Pasche (1990).


HIMALAYAS
Heavy monsoon rains, orographic effects
Snow and glacier melt
High river discharge
Sediment transport
RIVERS
Topography
Deforestation
Vegetation
Land use type and intensity
Highland
Lowland
INDIAN PLAINS
Heavy monsoon rains
High river discharge
Sediment transport
RIVERS
Construction of embankments and other structures
Farakka Barrage
Floods
BANGLADESH FLOODPLAINS
• Geological depression
• Flat topography
• Low channel gradient
• High river discharge
• Overflow of water courses
• Synchronization of peak flows
• Backwater effects
• Riverbank erosion
• Changing of river courses
• Old river courses
• Siltation
Heavy monsoon rains
FLOODS
• Roads, settlements, impermeability of soils
• Disappearance of wetlands
• Poorly planned embankments
• Embankment breaching
• Soil saturation
• Water logging
• Impeded drainage due to high water level in the rivers
• High tides
• Rising of mean sea level during monsoon season

flood depth represent the farmers' experiences of the "normal" flood situation. Based on this traditional knowledge, the farmers have developed highly adapted cropping patterns on their different types of land (see also section 7.4). In view of the large inter-annual range of flood extent and intensity, the depth of flood water on a specific plot can significantly vary from year to year. This requires a high degree of flexibility and adaptation by the farmers and can also create problems in specific cases.

In assessing the adverse effects of flooding, the timing of the inundations can be crucial: a moderate flood that occurs too early in the monsoon season or that recedes too late may be much worse for the crops than an extraordinary flood in the middle of the monsoon season. "Severity of flooding is a factor of timing and areal distribution rather than of volume" (BWDB 1991a: 48). For such temporal differentiation, neither maps nor statistical figures can provide sufficient information.

2.3.5. The causes of flooding

The causes of flooding and the processes leading to inundations were key topics of the project presented in this publication. In the following discussion it is intended only to provide a first and brief insight into the variety and complexity of flood-causing factors. Figure 2.10 is an attempt graphically to structure the different factors extracted and compiled from the vast available literature.

The causes of floods are numerous, heterogeneous and complex. Floods are often produced by a combination of factors that differ for each flood (GOB 1992a). Hughes et al. (1994) state that "a key feature of flooding in Bangladesh is that each flood is different. There are a number of reasons for that". In its flood report for 1991 (BWDB 1991a), specific aspects of the 1984, 1987, 1988 and 1991 floods are compared. According to this source, a standardization of floods is difficult because each flood event has specific conditions.

Figure 2.10 is divided into the three main regions of the basin in which the literature statements locate different causes of flooding: the highlands (almost exclusively the Himalayas, there being hardly any reference to the Meghalaya Hills); the Indian plains of the Ganga and the Brahmapu-

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Figure 2.10 The causes of floods in Bangladesh.
Sources: compiled from BWDB (1975), Brammer (1987), Hossain et al. (1987), Rasid and Paul (1987), Miah (1988), USAID (1988), Abbas (1989), Ahmad (1989), Ahmed (1989), Choudhury (1989), Dewan (1989), Haq (1989), Hossain (1989), Huda (1989), Khan (1989), Latif (1989), Shahjahan (1989), Adnan (1991), Ives (1991), Pearce (1991), GOB (1992a), Hughes et al. (1994).

tra; and the floodplains of Bangladesh. It is obvious that the factors located outside Bangladesh can have only an indirect impact on the flood processes in Bangladesh by in one way or another influencing the hydrological characteristics of the big river systems that ultimately flow through the floodplains of Bangladesh into the Bay of Bengal.

In the literature, the different flood-causing parameters are usually not quantified. Rarely is the attempt made to prioritize factors or to distinguish between key parameters and elements of lesser relevance. At this stage we cannot judge the appropriateness of each argument or prioritize them. However, we shall continue to discuss and specify certain processes in the following chapters, even if it will not be possible to deal with each factor in the framework of this publication.

3

The data situation: The need to compromise

> Any one, who has done some academic work in Bangladesh knows how difficult it is to collect necessary data and information. If these are to be obtained from the common run of people, through a questionnaire survey, one may land oneself in trouble to sift out facts from fiction unless one is careful enough. And if these are to be gathered from official sources, one may be stuck in the bureaucratic labyrinth. (Miah 1988: v)

The basic information required for the investigation of floods in the context of highland–lowland linkages, flood history and flood complexity (Figure 1.1 in Chapter 1) is time series of precipitation data and hydrological parameters (discharge, suspended sediment, groundwater and flood statistics). Accordingly, a hydro-meteorological database had to be established. The data situation for the Ganga–Brahmaputra–Meghna basin proved to be very difficult and data collection was time consuming and challenging for a number of reasons: restricted access to data and sensitivity of information; the need to collect data from many different sources; the large size of the study area; low station density in certain parts of the Ganga–Brahmaputra–Meghna basin; gaps in existing data series. In this chapter, we provide an overview of the data series that were accessible to the project, as well as of their sources.

3.1. Rainfall

In total, data series for 49 rainfall stations were used. These stations are not evenly distributed over the Ganga–Brahmaputra basin: the station density is much higher in Bangladesh than in India (see Figure 3.1). For the Himalayas, only three stations were available with sufficiently long records (Shimla, Kathmandu and Darjiling). For the eastern Himalaya (Arunachal Pradesh) and part of the upper Meghna catchment, data are missing. Very little information taken on an average basis is accessible for the upper Brahmaputra catchment in Tibet (FAO 1987). In the following paragraphs the main sources of rainfall data are briefly discussed.

Monthly precipitation data for India were provided by the Climatic Research Unit (CRU n.d.) of the University of East Anglia in the United Kingdom. The information is extracted from its Global Precipitation Data Set and includes more or less continuous information from the beginning of the twentieth century to 1990. For the years after 1990 the data were requested from the German Weather Service (DWD n.d.). The monthly records for Bangladesh are based on a report published by UNDP/FAO (1988). This report includes an extended climatic database for Bangladesh for roughly 200 stations, of course with different record lengths, all of them ending in 1979. The monthly records for 1980–1998 are based on information from the Bangladesh Meteorological Department (BMD n.d.) and the Bangladesh Water Development Board (BWDB n.d.[b]).

During the British period, daily precipitation was recorded at hundreds of stations in the Indian subcontinent, including modern Bangladesh and Pakistan. Rainfall data for the period 1891–1955 were published on an annual basis by the Indian Meteorological Department (IMD 1891–1955). After 1950 daily rainfall data are available for Bangladesh in electronic form (BMD n.d.; BWDB n.d.[b]) and were provided to the project by the two government agencies. The attempt to acquire daily rainfall data for India for the second half of the twentieth century failed: the head office of the Indian Meteorological Department did not respond to several requests sent by the project.

The combination of data from different sources and time periods of the twentieth century was a major challenge for the establishment of the rainfall database. Particularly in cases where there is a temporal overlap of information in the different sources, e.g. for Bangladesh after 1950 (BWDB n.d.[b]; BMD n.d.; UNDP/FAO 1988), the data are often not identical. Although minor inconsistencies were not a constraint for our investigations, as far as possible we attempted to use the same sources for specific blocks of analysis and to avoid too many switches from one source to another.

Another challenge for the establishment of the database was the gaps in the available time series (see Tables 3.1 and 3.2). Gaps at sites located in areas with a sufficiently high station density were either interpolated or

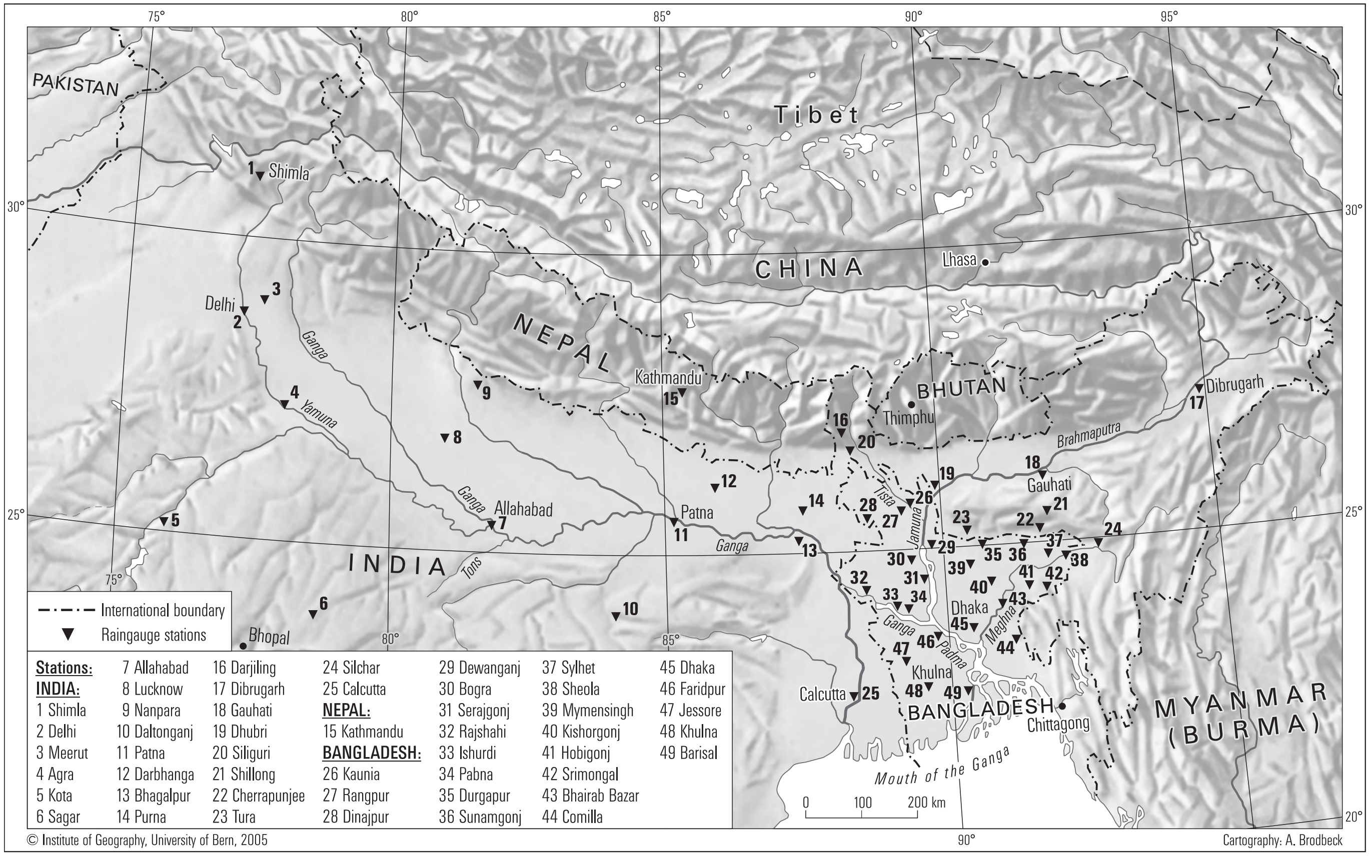
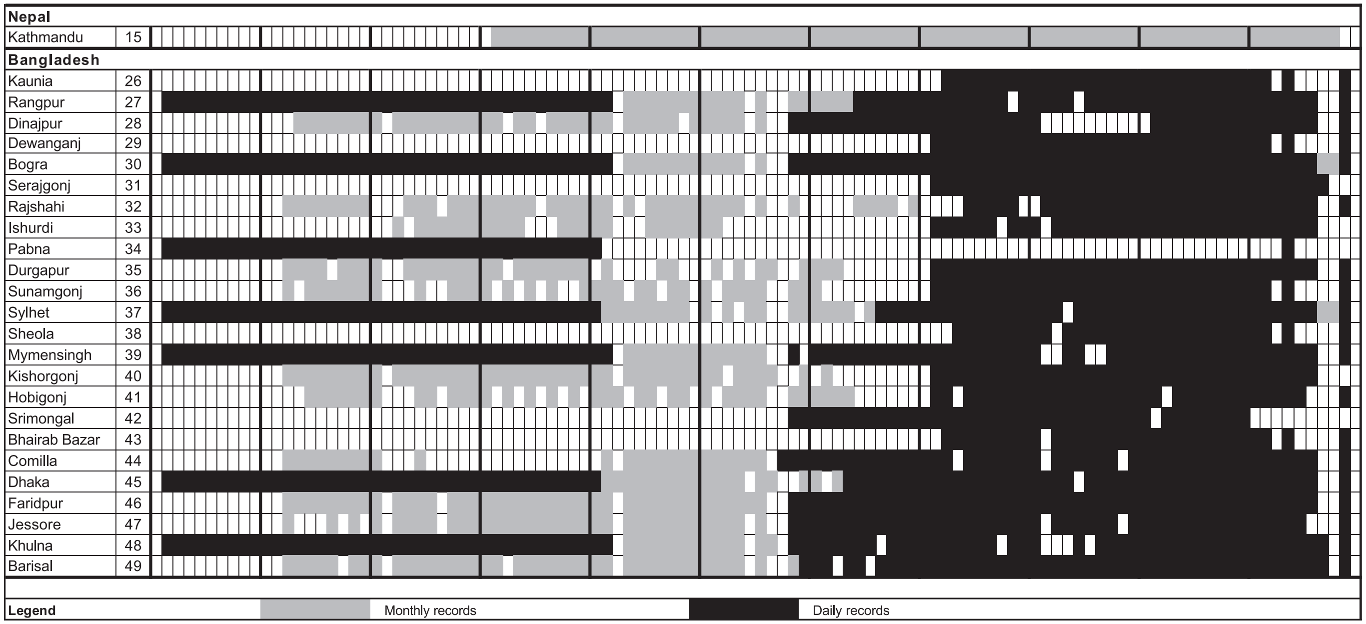


Figure 3.1 Location of raingauge stations.

Table 3.1 List of rainfall data available for the project

Station	No.	1890-1899	1900-1909	1910-1919	1920-1929	1930-1939	1940-1949	1950-1959	1960-1969	1970-1979	1980-1989	1990-1999
India												
Shimla	1	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒□□□□□□□□□	□□□□□□□□□□
Delhi	2	□□□□□□□□□□	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒□
Meerut	3	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□
Agra	4	□□□□□□□□□□	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒□□▒□▒□□▒□
Kota	5	□□□□□□□□□□	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒□▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒□□□▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒□
Sagar	6	□□□□□□□□□□	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒□▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒□
Allahabad	7	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒□□▒□▒▒▒▒□
Lucknow	8	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□
Nanpara	9	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□
Daltonganj	10	□□□□□□□□□□	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒□□□▒▒▒▒▒	▒▒▒▒▒▒▒▒▒□
Patna	11	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒□□□□□□□□□	□▒▒▒▒▒▒▒▒▒	▒□□□□□□□□□	▒▒▒□□□□□□□
Darbhanga	12	□□□□□□□□□□	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒□▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒□□□□▒▒▒▒▒	▒▒▒▒▒▒▒□□□
Bhagalpur	13	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□
Purna	14	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□
Darjiling	16	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒□	□□□□□□□□□□	□□□▒▒□▒□□□
Dibrugarh	17	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒□
Gauhati	18	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒□
Dhubri	19	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□
Siliguri	20	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□
Shillong	21	□□□□□□□□□□	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒□□□□□□□□□	□□□□□□□□□□
Cherrapunjee	22	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	□□▒□□□▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒□▒▒	□□□□□▒▒▒▒□
Tura	23	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□
Silchar	24	□■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■■■■■■■■■■	■□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□	□□□□□□□□□□
Calcutta	25	□□□□□□□□□□	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒▒	▒▒▒▒▒▒▒▒▒□

Table 3.1 (cont.)



Nepal	
Kathmandu	15
Bangladesh	
Kaunia	26
Rangpur	27
Dinajpur	28
Dewanganj	29
Bogra	30
Serajgonj	31
Rajshahi	32
Ishurdi	33
Pabna	34
Durgapur	35
Sunamgonj	36
Sylhet	37
Sheola	38
Mymensingh	39
Kishorgonj	40
Hobigonj	41
Srimongal	42
Bhairab Bazar	43
Comilla	44
Dhaka	45
Faridpur	46
Jessore	47
Khulna	48
Barisal	49

Legend ▨ Monthly records ■ Daily records

Table 3.2 Sources of rainfall data

No.	Station	Data sources
1	Shimla	IMD (1891–1955); CRU (n.d.)
2	Delhi	CRU (n.d.); DWD (n.d.)
3	Meerut	IMD (1891–1955)
4	Agra	CRU (n.d.); DWD (n.d.)
5	Kota	CRU (n.d.); DWD (n.d.)
6	Sagar	CRU (n.d.); DWD (n.d.)
7	Allahabad	IMD (1891–1955); CRU (n.d.); DWD (n.d.)
8	Lucknow	IMD (1891–1955)
9	Nanpara	IMD (1891–1955)
10	Daltonganj	CRU (n.d.); DWD (n.d.)
11	Patna	IMD (1891–1955); CRU (n.d.); DWD (n.d.)
12	Darbhanga	CRU (n.d.); DWD (n.d.)
13	Bhagalpur	IMD (1891–1955)
14	Purna	IMD (1891–1955)
15	Kathmandu	HMG (n.d.)
16	Darjiling	IMD (1891–1955); CRU (n.d.); DWD (n.d.)
17	Dibrugarh	IMD (1891–1955); CRU (n.d.); DWD (n.d.)
18	Gauhati	IMD (1891–1955); CRU (n.d.); DWD (n.d.)
19	Dhubri	IMD (1891–1955)
20	Siliguri	IMD (1891–1955)
21	Shillong	CRU (n.d.)
22	Cherrapunjee	IMD (1891–1955); CRU (n.d.); DWD (n.d.)
23	Tura	IMD (1891–1955)
24	Silchar	IMD (1891–1955)
25	Calcutta	CRU (n.d.); DWD (n.d.)
26	Kaunia	BWDB (n.d.[b]); BWDB (1993); BWDB (1998b)
27	Rangpur	IMD (1891–1955); UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]); BWDB (1998b)
28	Dinajpur	UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]); BWDB (1998b)
29	Dewanganj	BWDB (n.d.[b]); BWDB (1993); BWDB (1998b)
30	Bogra	IMD (1891–1955); UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]); BWDB (1998b)
31	Serajgonj	BWDB (n.d.[b])
32	Rajshahi	UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]), BWDB (1998b)
33	Ishurdi	UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b])
34	Pabna	IMD (1891–1955); BWDB (1993)
35	Durgapur	UNDP/FAO (1988); BWDB (n.d.[b]); BWDB (1998b)
36	Sunamgonj	UNDP/FAO (1988); BWDB (n.d.[b]); BWDB (1993); BWDB (1998b)
37	Sylhet	IMD (1891–1955); UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]); BWDB (1998b)
38	Sheola	BWDB (n.d.[b]); BWDB (1993); BWDB (1998b)
39	Mymensingh	IMD (1891–1955); UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]); BWDB (1998b)
40	Kishorgonj	UNDP/FAO (1988); BWDB (n.d.[b])

Table 3.2 (cont.)

No.	Station	Data sources
41	Hobigonj	UNDP/FAO (1988); BWDB (n.d.[b]); BWDB (1998b)
42	Srimongal	BMD (n.d.)
43	Bhairab Bazar	BWDB (n.d.[b]); BWDB (1993); BWDB (1998b)
44	Comilla	UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]); BWDB (1998b)
45	Dhaka	IMD (1891–1955); UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]); BWDB (1998b)
46	Faridpur	UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]); BWDB (1998b)
47	Jessore	UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]); BWDB (1998b)
48	Khulna	IMD (1891–1955); UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]); BWDB (1998b)
49	Barisal	UNDP/FAO (1988); BMD (n.d.); BWDB (n.d.[b]); BWDB (1998b)

substituted by a neighbouring site. However, data gaps were of concern for those sites located in the highlands that are of particular interest for the project and where the station density is very low (Shimla, Darjiling and Shillong after 1980). Fortunately, rainfall in Cherrapunjee and Shillong is well correlated and it was possible to interpolate the data gaps for Shillong. This approach failed for Shimla and Darjiling.

3.2. Discharge

With a few exceptions, hydrological data series for discharges are available only after 1965 (see Tables 3.3 and 3.4). For Bangladesh, the data situation and the density of the station network are fairly good. All the important rivers are represented by at least one discharge site (see Figure 3.2) and the data are available on a daily basis. The hydrological data series for the rivers in Bangladesh were provided by the Bangladesh Water Development Board (BWDB n.d.[b]). For some rivers, additional monthly data were available for the period before 1965 (Hossain et al. 1987).

For India (especially the Ganga system) and the Himalayas, the data situation is very poor. There is no officially accessible overall hydrological database. This situation has mainly political causes. The Ganga and the Brahmaputra are important international river systems, whose catchments are shared by Nepal, China, India, Bhutan and Bangladesh. Depending on the season, water is either abundant or scarce. As a conse-

Table 3.3 List of discharge data available for the project

River (station; country)	No.	1930-1939										1940-1949										1950-1959										1960-1969										1970-1979										1980-1989										1990-1999									
Ganga system																																																																							
Karnali (Chispani; Nepal)	1																																	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■	▨	▨	▨	▨	■						
Narayani (Narayangarh; Nepal)	2																																		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■	▨	▨	▨	▨	■						
Sapt Kosi (Barakshetra/Chatara-Kothu; Nepal)	3																		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■	▨	▨	▨	▨	■						
Ganga (inflow into Farakka; India)	4																				▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨														
Ganga (Hardinge Bridge; Bangladesh)	5					▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Brahmaputra system																																																																							
Jia Bharali (N.T. Road Crossing; India)	6																																										▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨														
Manas (Mathanguri; India)	7																																										▨	▨	▨	▨	▨	▨		▨	▨																				
Brahmaputra (Pandu; India)	8																										▨	▨	▨	▨	▨	▨	▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨																				
Tista (Kaunia; Bangladesh)	9																															▨	▨	▨	▨			■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Brahmaputra (Bahadurabad; Bangladesh)	10																											▨	▨	▨							■	■	■	■	■		■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■				
Meghna system																																																																							
Kushiyara (Sheola; Bangladesh)	11																																				■	■	■	■		■		■	■	■	■	■	■	■	■	■		■	■	■	■	■	■	■	■										
Surma (Sylhet; Bangladesh)	12																																				■	■			■	■		■	■	■	■	■	■				■	■	■	■	■	■	■	■	■										
Sameswari (Durgapur; Bangladesh)	13																																					▨		▨	▨	▨		▨	▨	▨	▨	▨	▨	▨	▨																				
Meghna (Bhairab Bazar; Bangladesh)	14																																				■	■	■	■	■	■		■	■	■	■	■					■	■	■	■	■	■	■	■	■	■	■	■	■						
Ganga-Brahmaputra system																																																																							
Padma (Baghyakul; Bangladesh)	15																																					■	■	■	■	■		■	■	■		■	■				■	■	■	■	■	■	■	■	■										

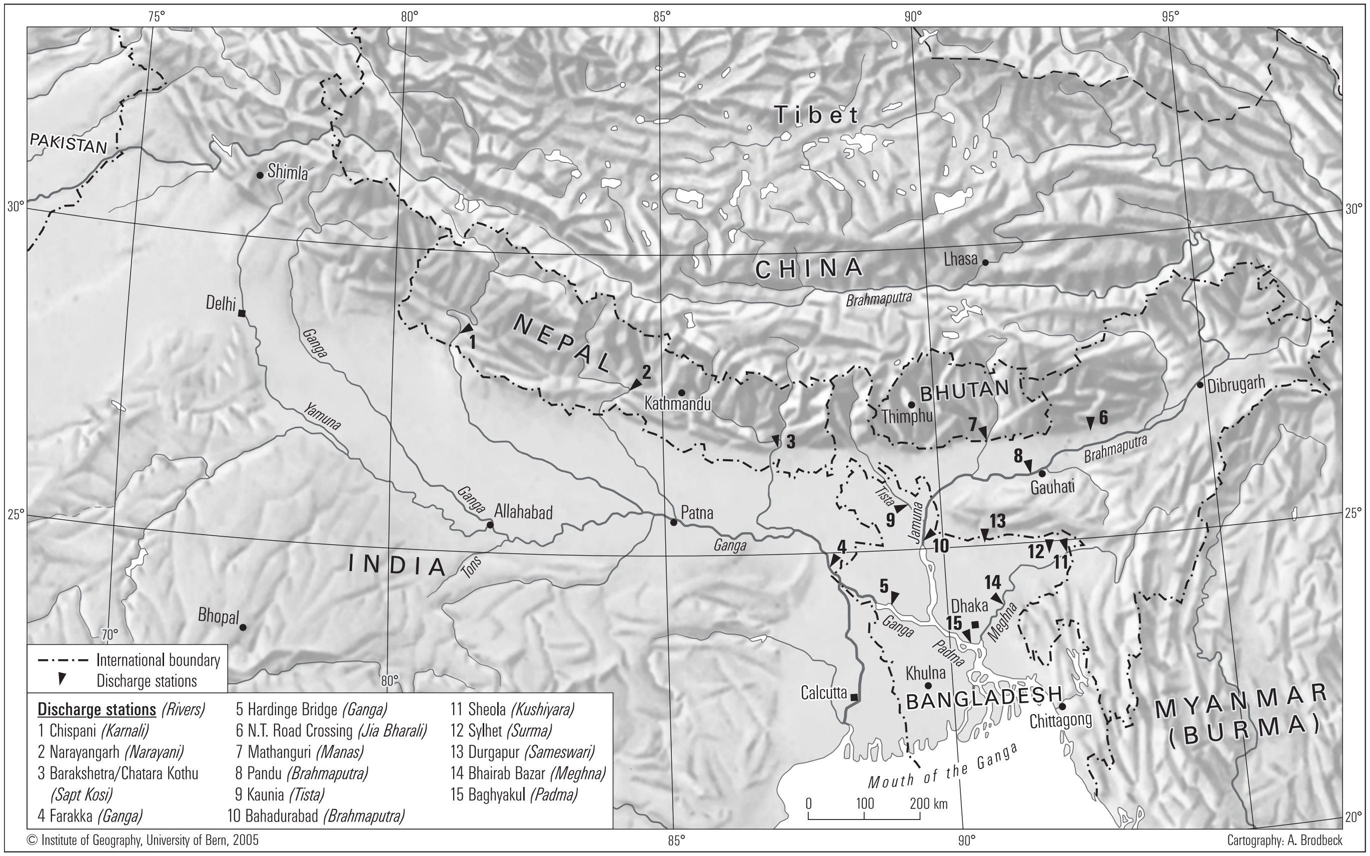
Legend ▨ Monthly records ■ Daily records

Table 3.4 Sources of discharge data

No.	River (Station)	Data sources
Ganga system		
1	Karnali (Chispani)	HMG (1982); HMG (n.d.)
2	Narayani (Narayangarh)	HMG (1982); HMG (n.d.)
3	Sapt Kosi (Barakshetra/ Chatara-Kothu)	HMG (1982); HMG (n.d.)
4	Ganga (Farakka)	BWDB (1986)
5	Ganga (Hardinge Bridge)	Hossain et al. (1987); BWDB (n.d.[b])
Brahmaputra system		
6	Jia Bharali (N.T. Road Crossing)	Ashok (1990)
7	Manas (Mathanguri)	IMD (1981)
8	Brahmaputra (Pandu)	Goswami (1983)
9	Tista (Kaunia)	Hossain et al. (1987); BWDB (n.d.[b])
10	Brahmaputra (Bahadurabad)	Hossain et al. (1987); BWDB (n.d.[b])
Meghna system		
11	Kushiyara (Sheola)	BWDB (n.d.[b])
12	Surma (Sylhet)	BWDB (n.d.[b])
13	Sameswari (Durgapur)	UN/BWDB (1983)
14	Meghna (Bhairab Bazar)	BWDB (n.d.[b])
Ganga–Brahmaputra system		
15	Padma (Baghyakul)	BWDB (n.d.[b])

quence, there is a lot of concern and political discussion about the sharing of water in the area and hydrological information in India is therefore generally not accessible. Under the Joint River Commission there is only limited data exchange between the countries concerned, which makes timely flood forecasting in the basin, as well as research and integrated watershed management, almost impossible. The Farakka Barrage on the Ganga, just upstream of the India–Bangladesh border (see Box 4.3 in Chapter 4), is a particular point of tension between India and Bangladesh. It was not until the end of 1996 that the two countries managed to take a first step towards a comprehensive contract for sharing the Ganga water (for more information on the problems of water-sharing and integrated watershed management in the Ganga–Brahmaputra basin, see, for example, Crow 1985; Begum 1987; Abrar 1994; Bandyopadhyay and Gyawali 1994a; Dixit and Gyawali 1994; Gyawali and Schwank 1994; Hofer 1994). In spite of this difficult situation it was possible to collect a few hydrological series for some Indian stations from different sources.

Hydrological information for Nepal is available from the Department of Hydrology and Meteorology of His Majesty's Government. For the



Cartography: A. Brodbeck

Figure 3.2 Location of discharge stations.

purposes of the project, data series were collected for a number of stations located on the transition between the mountains and the plains.

For a few years before 1950, water level data for specific stations on the Ganga and Brahmaputra and for specific dates were made available from the India Office Library and Records in London. Since this information is very scanty it is not included in this overview.

Discharge measurement in the big rivers of Bangladesh is a difficult and challenging task. As an example, the Brahmaputra at Bahadurabad is a river system of approximately 13 km width. Particularly in the dry season, the river is divided into a number of channels, which are very dynamic and frequently change their course. Each discharge measurement at this site, which involves two teams working simultaneously from both sides of the river bank, takes approximately five hours. The measurements by current meter are done from a catamaran, which, for each vertical, is positioned according to a defined angle between two flags on the river bank. The flow velocity at each vertical is measured at 20 per cent and 80 per cent depth. Based on a number of field visits, we are confident that the measurements are done with the greatest accuracy possible given the difficult circumstances at the measuring sites.

3.3. Suspended sediments

Series on suspended sediments available at the Bangladesh Water Development Board (BWDB n.d.[b]) were accessible only for the main hydrological stations of the big rivers in Bangladesh (Figure 3.2): Ganga at Hardinge Bridge (1966–1995), Brahmaputra at Bahadurabad (1968–1995), Meghna at Bhairab Bazar (1972–1994) and Tista at Kaunia (1993–1995). The calculation of the suspended sediment load at a particular hydrological station is based on samples taken during the discharge measurements at each measuring point of flow velocity. The records represent not average daily figures but specific, actual conditions at the time of the measurement. The frequency of the measurements is weekly, fortnightly or even less. The data records are usually differentiated into suspended sand discharge, suspended fine discharge and total suspended discharge.

3.4. Groundwater

Groundwater resources are very important in Bangladesh, particularly for irrigation and domestic purposes. In recent years groundwater resources have been shrinking and appear in the news headlines because

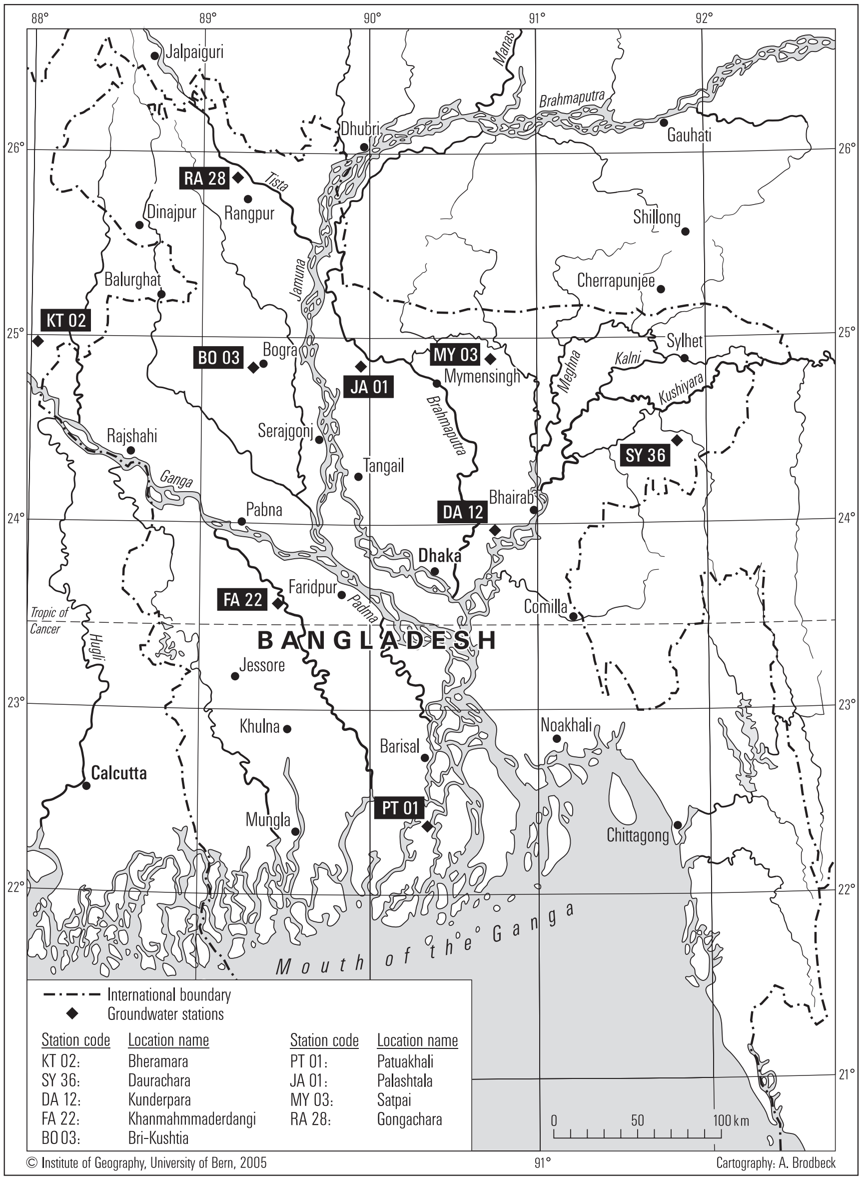


Figure 3.3 Location of groundwater stations.

of their high arsenic concentration. Since about 1970, the Bangladesh Water Development Board has been running a network of groundwater stations in order to monitor the trends in the subsurface water reservoirs (see Figure 3.3). The records (BWDB n.d.[b]), which indicate the depth of the groundwater level below the surface, are based on weekly readings. In the context of the project presented in this publication, the groundwater level is a very important parameter for assessing the storage potential of the ground for excess monsoonal rainfall as well as the liability to waterlogging.

3.5. Flood-affected areas

Data series on flood-affected areas were essential for the different parts of the project. The records were collected from a number of sources (Chaphekar and Mhatre 1986; Agarwal and Narain 1991; BWDB 1991a; Eriksen et al. 1993; BWDB n.d.[a]; CWC n.d.; Goswami 1998) and cover the following time periods: Bangladesh (1954–1998), Uttar Pradesh and Bihar (Indian Ganga Plain: 1954–1994), West Bengal (Indian Ganga Plain: 1954–1993) and Assam (Indian Brahmaputra plain: 1956–1994). Methodological issues and concerns with regard to flood statistics are discussed in Section 2.3.3 in Chapter 2.

3.6. Reflection on the data situation

Whereas the data situation is satisfactory for the investigation of flood processes in Bangladesh, the available information is indeed rather limited for a regional understanding of the processes in the context of highland–lowland interactions. However, the situation can also be perceived the other way round: given the large scale of the study area, the number of countries involved and the political sensitivity of the issues, it is in fact rather an opportunity to have some information available for most parts of the study area. The challenge for the project team was to do something useful with the available information and to develop some innovative methodological steps.

Chapters 1–3 have introduced the project team, the basic features of the monsoonal floods and the data situation, thus providing the background for understanding the following discussions. The next chapter dives into the first core part of the project: the floods in the Ganga–Brahmaputra–Meghna basin in a historical perspective.

4

The history of flooding in the lowlands of the Ganga, Brahmaputra and Meghna rivers

4.1. Introduction to the issue

In this chapter we discuss flooding processes in Bangladesh and, to some extent, also in the Indian lowlands of the Ganga and Brahmaputra from a historical perspective. The following newspaper headline is an appropriate introduction to this discussion: ‘‘Bangladesh in grave danger: deforestation in Himalayas aggravating floods’’ (*Bangladesh Observer*, 2 June 1990). Indirectly, the assumption expressed in this headline is that forest cutting in the Himalayas leads to

- intensified surface runoff, increased down-rush of water from the Himalayas and rising peak discharges of the rivers in the Ganga–Brahmaputra basins;
- intensified flood processes in Bangladesh (‘‘aggravation’’ may refer to flood frequency, flood intensity or the impacts of flooding); and
- intensified surface erosion in the Himalayas, a higher sediment load in the rivers, increased sedimentation on the plains and, as a consequence, aggravation of floods in Bangladesh.

If these assumptions do reflect the reality, then it should be possible to prove and document the trends with appropriate information and data series. Literature statements and newspaper reports in particular tend to be generalized, qualitative and, in some cases, even controversial. Very often they are not based on measured evidence and scientific fundamentals (see Box 4.1). The discussion in this chapter intends to contribute to clarifying this issue. The findings are presented in four time frames: the

Box 4.1 Literature statements on the history and frequency of flooding in Bangladesh

Literature statements on flood history in Bangladesh are numerous and are evidence of a great variety of opinions. In some cases (e.g. statement 3 in the list below) the statements are even contradictory within the same source! Several authors speak of non-existent or even declining trends of flooding; others support the assumption of increasing trends. The uncertainties with regard to this issue and the lack of basic research are clearly illustrated by wording such as ‘‘it appears that’’, ‘‘there are reasons to believe’’, ‘‘there is some evidence to suggest that’’ or ‘‘there is no published evidence that’’. Some authors suggest that floods have increased not in terms of dimension or frequency, but rather in terms of the impacts resulting from the extension of land use into flood-prone areas.

1. ‘‘History of flood, in this country, perhaps is inseparable from the history of this land. In every century, this delta witnessed the visit of nearly half a dozen floods, almost equal to the magnitude and intensity of the one in 1988 and of as many, with lesser magnitude.’’ (Rahman 1989b: 45)
2. ‘‘Flood is a natural calamity. We had it in the past, we have it now, and we will continue to have it in future also.’’ (Miah 1988: 88)
3. ‘‘Due to the activities of human beings floods have intensified in Bangladesh. The construction of railways, roads and homesteads in the flood plain obstruct the flow of the flood.’’ (Hossain et al. 1987: 17)

   ‘‘It appears that the frequency of floods has been decreasing in recent times.’’ (Hossain et al. 1987: 20)
4. ‘‘Each year’s highest flood record has been broken by the subsequent year’s.’’ (Rahman 1989a: 132)
5. ‘‘It appears from recent floods and the extent of their damages that the return period of catastrophic floods have been decreased.’’ (Ahmad 1989: 6)
6. ‘‘In fact it remains unclear whether an increase in the frequency of ‘abnormal flooding’ in Bangladesh has actually taken place. There is some evidence to suggest that an increase in the extent and duration of inundation has occurred during the period 1954–1988, but the reasons for this remain unclear.’’ (Hughes et al. 1994: 20)
7. ‘‘There are reasons to believe that the incidence of floods is declining in certain parts of Bangladesh due to changes in factors such as the condition of the river beds and the effect of manmade structures outside the borders of Bangladesh on water courses.’’ (Hossain et al. 1987: xiv)

Box 4.1 (cont.)

8. “The Bangladesh Flood Plan states that no rising or falling trend in flood levels is discernible in the records for the Brahmaputra-Jamuna, Padma and Meghna rivers, and that a rising trend in the Ganges within Bangladesh since 1975 is attributable to the Farakka Barrage completed in that year.” (Brammer 1990b: 164)
9. “Measurements at Bahadurabad have shown that the dominant low water level in the Brahmaputra of 11.9 m in the early 1950s had gradually gone up to 13.4 m, a rise of 1.5 m in the 1960s” (the impact of frequent earthquakes in Assam between 1951 and 1956). “However, since then a lowering trend can be observed.” (Agarwal and Narain 1991: 78)
10. “Claims that the 1988 flooding of Bangladesh was the worst in the century, that flooding is becoming progressively more serious, are, like the claims about soil erosion in the Himalayas, unsupported.” (Ives 1991: 37)
11. “Ives and Messerli state, that there is no published evidence for a recent increase in the magnitude of floods or in sediment loads on the Ganges-Brahmaputra floodplains.” (Brammer 1990b: 164)
12. “The two big consecutive floods (1987 and 1988) are coincidental, rather than being caused by well understood natural phenomena which are cumulative and repetitive, as in the 1950s flooding (earthquake in Assam). Therefore, I do not expect the big floods to continue as a regular annual occurrence, as most scientists seem to indicate.” (Timm 1989: 272)
13. “Data also shows that, notwithstanding 1987, 1988, 1995 and 1996, there is a declining trend in flood intensity.” (Gain 1998: 206)
14. “Former depressions of the 19th century (regions of Rajshahi, Pabna, Bogra, Faridpur, Kushtia, Jessore and Dhaka) are filled up with sediments. Due to filling up and flood control structures today only a few areas are flooded.” (Hossain et al. 1987: 55)
15. “Flood frequency may increase if a river creates a new course and its bed has not yet cut into the ground.” (Frisch 1988: enclosure 7).
16. “No clear link has been established between changes in land use in the mountains and changes in the flows and transfer of sediment in the Ganges and Brahmaputra on the plains.” (Ives 1991: 37)

Box 4.1 (cont.)

17. ‘‘Disastrous effects of floods have increased in recent years due partly to indiscriminate use of marginal and hill land areas for cultivation owing to population pressure and partly to an increasing number of settlements into flood-prone areas of the rivers.’’ (Dewan 1989: 17–18)
18. ‘‘Despite the two catastrophic floods of 1987 and 1988, there is no evidence of any significant trend to increased flooding, either natural or man-made. However, over time, the extent of damage has increased as new development activities have become established on the floodplains.’’ (World Bank 1989)
19. ‘‘The increase in flooded area correlates with a similar increase in the length of embanked river courses. This does draw attention to the point that despite a progressive increase in the length of embankments, polders, water regulation structures, the area and duration of inundation following major flood events still appear to be increasing.’’ (Hughes et al. 1994: 21)

longer-term geological evolution; the last 20,000 years; the eighteenth and nineteenth centuries; and the twentieth century.

Obviously, the sources used for the work in each of these four time frames differ significantly:

- New research into the geological evolution of the Bengal Basin was used to summarize and generalize some important results that are significant for understanding the long-term highland–lowland processes.
- For the investigation of the last 20,000 years, geological evidence in the form of stratigraphies from the Bengal delta were consulted.
- The flood history of the eighteenth and nineteenth centuries was analysed on the basis of descriptions from the British period in the Indian subcontinent as well as old maps documenting major changes in the main river courses during these two centuries.
- It might be expected that humans’ impact on ecological processes has been most prominent over the last 100 years and, in the light of the assumptions made above, should have had the most important impacts on flooding conditions during this period. Therefore the flood history of the twentieth century receives the greatest attention in this chapter. It is obvious that much more information is available for this time frame than for the others; the sources of information include not only written documents and descriptions but, more importantly, also quantitative data and statistics (see Chapter 3). Therefore a broader approach can

be applied that looks into not only the flood history per se but also possible trends in rainfall, discharge and the impacts of floods.

The forest history in the Himalayas is one of the main rationales for the historical discussion in this chapter and, as discussed in Chapter 1, for the entire project. Box 4.2 provides some facts and thoughts on this interesting and complex topic.

4.2. The evolution of the world's largest highland–lowland system (see also section 6.2)

4.2.1. A brief look at the longer-term geological history

The Bengal Basin is situated in a critical geographical position, namely at the junction of three interacting plates: the greater Indian, Burma and Tibetan (Eurasian) plates. The basin lies within a region of Tertiary to Holocene compression associated with the eastern Himalayan and Indo-Burman orogenic belts with an area of about 200,000 km^2. The Bengal Basin has more than 20 km of Tertiary–Holocene sedimentary fill, which consists predominantly of the orogenic sediments derived from both the eastern Himalaya to the north and the Indo-Burman ranges to the east. Accordingly, the geological information hidden within the Tertiary and Quaternary sedimentary succession of the Bengal Basin has considerable significance for understanding the geological history of the Greater Himalayan–Indo-Burman ranges (Alam and Curray 2003). More precisely, with continuing collision events between the plates and uplift in the Himalayas and Indo-Burman ranges by the middle Miocene, there was a huge influx of clastic sediments into the basin from the north-east and east. Throughout the Miocene, the depositional settings varied from deep marine conditions in the basin to shallow and coastal marine conditions at the margins of the basin. From the Pliocene onwards, large amounts of sediment filled the Bengal Basin from the west and north-west. The present basin configuration, with the Ganga–Brahmaputra Delta System to the north and the Bengal Deep Sea Fan to the south, was established during the later part of the Pliocene and Pleistocene. Since then, delta progradation has been strongly affected by orogeny in the eastern Himalaya (Alam et al. 2003). As a result of geological activities by both local and international hydrocarbon exploration agencies over the past few decades in different parts of Bangladesh, a considerable amount of subsurface data has been accumulated. However, most of the data recently acquired by foreign oil companies are not yet accessible. This short summary may show that the basin draws broad international interest because of its relation to three spectacular geological systems:

Box 4.2 Forest history in the Himalayas: The need for a differentiated discussion

Forest use and degradation in the Himalayas and its adjacent lowlands are not confined to recent decades or even to the twentieth century. These processes have been going on for hundreds of years. It was on the Ganga Plain that land use first expanded intensively over wide areas at the expense of forests. The first period of massive deforestation in the Himalayas occurred during the 1850s and 1860s as a result of the establishment of British control in the upper Ganga and Indus plains and the penetration of that region by railways (Richards et al. 1985; Tucker 1987; Griffin et al. 1988).

An examination of detailed studies on forest cover change (Everest region: Opitz 1968; Limberg 1982; Zimmermann et al. 1986; Byers 1987; Tinau watershed in Nepal: Strebel 1985; Hengduan mountains in China: Ives and Messerli 1989; Upper Beas Valley in India: Kuster 1993; Nepal and Himalaya: Ives 2004; Himalaya and South-East Asia: Bruijnzeel 2004) clearly reveals how varied the situation is. In some areas, the forest cover might indeed be decreasing; in other areas, however, it is increasing. Change in land cover is undoubtedly most apparent in the plains of the Terai, where settlement has been expanding since the successful fight against malaria. In the period 1964–1977 alone, 2,500 km^2 or 10.2 per cent of the forest cover was cleared (HMG 1983).

A very important element in the forest history in the Indian and Nepali Himalayas is the development of community forestry programmes since 1970. Recognizing the dependency of the local population on forest resources, more and more forest lands are being handed over to the communities to develop their own management plans. Particularly in Nepal, the community forestry programme has been very successful and in many areas has reversed the process of declining forest cover and forest quality.

The traditional perception of the ecological role of forests needs differentiation (Hamilton 1987). A mountain forest does not necessarily guarantee soil and water conservation: a forest without any canopy layers or litter cover may be much worse in terms of erosion than well-maintained sloping agricultural terraces or grazing lands; big raindrops might be formed in the crowns of the trees and cause significant splash erosion on the unprotected soil. It is therefore not the forest cover as such but the forest quality that is decisive for the protective role of a mountain forest.

Box 4.2 (cont.)

From this discussion we may conclude that

- change in the forest cover of the Himalayas is a temporally and spatially differentiated process of recent centuries, not just of recent decades;
- information on forest quality is much more important than information on forest area;
- there are a number of very positive programmes and initiatives ongoing in the Himalayas that are leading to an increase in forest cover and an improvement of forest quality; and
- statements attributing floods in the lowlands to forest removal in the highlands are very questionable.

Generalizing statements must give way to more differentiated discussions regarding forestry in the Himalayas. It is harmful to provide political authorities and decision makers in any position with non-reviewed reports because they might be misleading, result in wrong decisions or distract attention from really critical areas.

For further references to forest history and forest management in the Himalayas, see Tucker (1983), Gurung (1984), Singh et al. (1984), Sargent (1985), Myers (1986), Tucker (1987), Applegate and Gilmour (1987), Westoby (1989: Ch. 17), Ives and Messerli (1989: Ch. 3), Denholm (1990), Verghese (1990: Ch. 8), Anwar (1993), Hobley et al. (1996).

the world's largest orogenic system, the Himalayan range; the world's largest fluvio-deltaic system with the Ganga and Brahmaputra rivers; and the world's largest submarine fan system, extending as far south as 7° S latitude or extending 3,000 km from the delta platform to the lower fan (Alam et al. 2003; Weber et al. 2003). Alam and Curray (2003: 175) state: "The curtain goes up on a sedimentary basin in south-central Asia: unveiling the sedimentary geology of the Bengal Basin of Bangladesh." In our context we may say that, within this long and impressive highland–lowland history of erosion and sedimentation processes, human intervention represents a very short and quite negligible moment.

4.2.2. The last 20,000 years

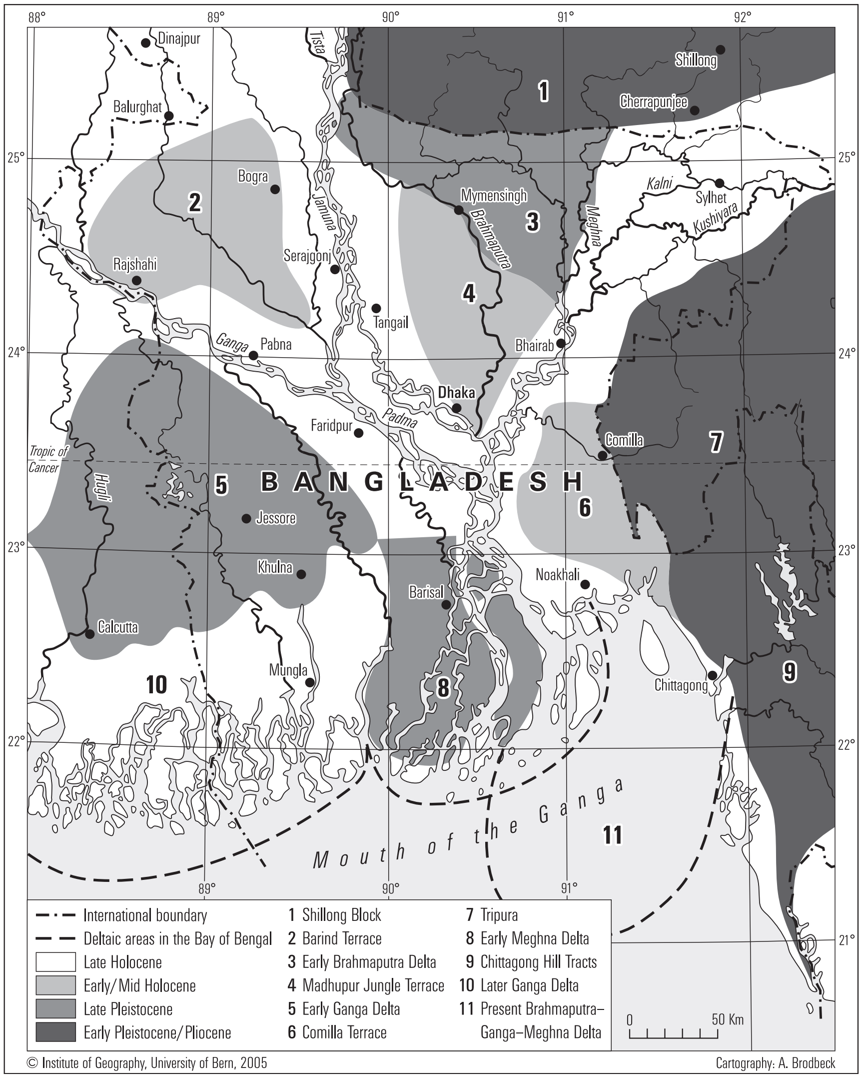
Some findings have already been documented in the following publications: Umitsu (1987), Grosjean et al. (1995, 1996), Hofer (1998b). Two very interesting episodes during the fieldwork in autumn 1994 (see section 1.3 and Figure 1.3) were key to the reflections of this section:

- Several interview partners in the test area of Nagarbari in the confluence area of the Ganga and Brahmaputra (Figure 1.2) informed us about the time when an engineering company constructed the electricity line from east to west across the Brahmaputra with several pillars in the river and with foundations going down to a depth of 103 metres. They told us about their excitement when ‘‘stones’’ were discovered at a certain depth in the sediments during the drilling process. ‘‘Stones’’ to Bangladeshi people in this area mean rough sands – real stones are unknown in today’s depositions of the rivers.
- In the office of the electricity authority in that particular area we were allowed to look at the material of the stratigraphic profiles. They were indeed very informative since they documented different grain sizes (including the ‘‘stone layer’’) and the various colours of the sediments at different depths of the profiles. This gave us a first hint of the significant fluctuations in the sedimentation processes in the Bay of Bengal during different geological time periods.

A number of good profiles are available since all major civil engineering works in this unstable delta region need to have deep foundations. The knowledge base for the uppermost and youngest geological layer of the Bangladesh delta is therefore quite good, even if we do not yet know the thickness of the Quaternary sediments (approximately 4 km according to Verghese 1990).

The general evolution of the delta complex during Quaternary times is shown in Figure 4.1. However, new drillings and absolute age determinations improve the understanding of these complex processes, especially for the late glacial and Holocene time period. With Figure 4.2, an even more specific discussion of the geomorphic history of the last 20,000 years in the Bengal delta is possible. The figure includes a geological section from north to south through the Bengal lowland. A wood fragment aged 28,320 ^{14}C yr BP at a sediment depth of 112 metres at Serajgonj suggests that the deposition of the gravel layer underneath the hard clay occurred before the Last Glacial Maximum (LGM). Umitsu (1987: 171) concluded that, based on a series of ^{14}C data, the ‘‘Basal Gravel’’ in Figure 4.2 above the clay was the surface of the river bed during the LGM. The steep southward slope of the Basal Gravel suggests stronger topographical gradients. The river beds were much lower than today, most probably incised into the older delta compartments.

Figure 4.2 also reflects the elevation changes in the erosion baseline, which in turn controls the general sediment accumulation and erosion pattern in the floodplain. Gravel deposits in channels and a generally erosive milieu are typical of the period of transition to low sea levels during the LGM, when the river beds were cut into the delta. The silt and clay deposits are very different and reflect periods of high sea levels since



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Cartography: A. Brodbeck

Figure 4.1 Quaternary deltaic arcs in Bangladesh, schematic.
Sources: MPO (1985) and ISPAN (1993).

the middle Holocene period, with backwater effects in the rivers, most probably extensive flooding processes and sediment accumulation in the delta.

The gradient of the gravel bed (Figure 4.2) is steeper than the surface of the recent floodplain. Because this layer is below −70 metres in the

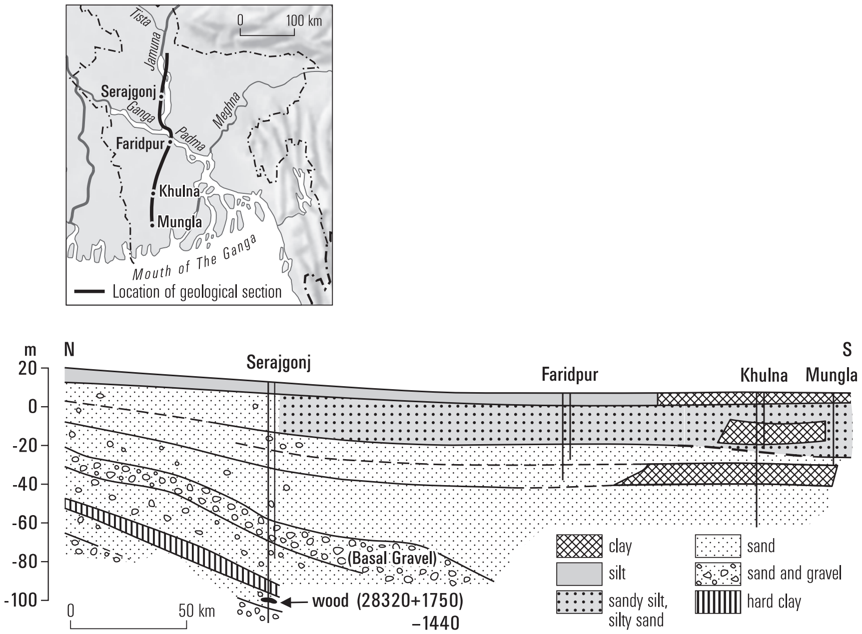


Figure 4.2 Geological section of the Bengal lowland from north to south; locations of the cross-section are shown in a small figure above.
Source: Umitsu (1987: 168).

north between Serajgonj and Nagarbari, the sea level must have been −100 metres or maybe even −120 metres, considering the altitude and the gradient of the sediments (Umitsu 1987). When the sea level rose during the late Glacial and early Holocene periods, it is assumed that most of Bangladesh was under water and the coastline was at the Rajmahal Hills in Assam Province (Rana 1993). Because of the enormous amount of accommodation space available in the tectonically active Bengal Basin, the early (more than 5,000 calibrated years BP) deltas of the Brahmaputra, and possibly the Ganga, were far inland of the present shoreline. Radiocarbon dates, clay mineralogy and elemental evidence from the lower delta plain sediment records suggest that, after the maximum transgression, the shoreline progradation associated with the two rivers was relatively separate after 5,000 calibrated years BP. The bulk of the Brahmaputra delta plain formation took place inland, east and west of the Pleistocene Madhupur terrace (see Figure 4.1). The Brahmaputra was flowing much more to the east than at the present time (see Figure 4.5). Consequently, there was enough space for the Ganga to expand step by step towards the east. This happened in three main phases, with each progradation taking place over a wide front that encompassed several active island-shoal complexes. The eastern, Sylhet Basin loci of the Brahmaputra delta plain formation funnelled southward into the Meghna estuary following the course of the Meghna River, while the western route was probably similar to the present combined Ganga–Brahmaputra course to the Meghna estuary. Progradation into the Meghna estuary was probably relatively limited until the merger of the two rivers' discharges in historical times (Allison et al. 2003).

Of special interest for future process studies are the first results from a paleoclimatic interpretation of the sediments. By comparing the radiocarbon dates from Bangladesh with the results from the Greenland ice cores, Weber et al. (2003: 377) come to the following conclusions: "Cooler temperatures over Greenland can be associated with coarser grain sizes, greater transport energy, and increased sediment supply from the Ganga–Brahmaputra river systems during cool climate, an interpretation that is corroborated by the observation that the last cooling event, the Younger Dryas, also yielded increased fan activity and sediment supply to the continental slope." This higher transport energy may be explained by lower sea levels, different soil and vegetation cover, and probably more weathered material, but certainly not by increased precipitation during cool or cold periods. Although these results are very interesting, we should not forget that today's global climate model simulations in connection with higher atmospheric and sea surface temperatures indicate greater risks of extreme summer precipitation events in Monsoon Asia, with certain implications for flooding in Bangladesh (Palmer and Räisänen 2002).

All the observations made so far are very important in the context of the flood history in Bangladesh: the interaction between global climate and sea-level changes, regional tectonic movement and local topography dominates the pattern of sediment accumulation in the floodplain over time. Figure 4.2 illustrates that, over the last 20,000 years, more than 100 metres of sediments were deposited in Bangladesh in different layers. This means an average of a few mm per year, a reasonable order of magnitude in comparison with recent observations and measurements (Goodbred and Kuehl 1998). However, bearing in mind that the distribution and magnitude of accumulation are episodic and unpredictable, massive floods must have occurred regularly long before humans' impact in the large watersheds of the big rivers started. Remembering that the Himalayas were covered with forests from the late glacial period or, in the lower parts, even during the late glacial period, we must realize that erosion, sediment transport, accumulation and floods were permanent natural processes in a highland–lowland system before any human intervention. Without the occurrence of big floods it is not possible to explain the enormous thickness of the sediments occurring in the lower Ganga–Brahmaputra region. In support of this finding, Verghese (1990: 122) writes: ‘‘Bangladesh is prone to severe flooding because 80 per cent of its total land surface falls within the flood plain of the Ganga-Brahmaputra-Meghna which has been built up over the millennia through the flood deposits of this enormous river system.... The best that the co-riparians can do can only partially mitigate the flood of which Bangladesh is a child,’’

4.3. The eighteenth and nineteenth centuries

In this third time frame, we investigate how far back floods can be traced in the Ganga and Brahmaputra catchments, and especially within current-day Bangladesh. Dutt (1995), a member of our project team, has made considerable efforts and progress in this subject. The investigation focuses on the period 1740–1890, for which written and descriptive sources were accessible.

4.3.1. Historical floods in the Ganga and Brahmaputra catchments

Figure 4.3 lists historical floods (black bars) that occurred between 1740 and 1890 in the Ganga and the Brahmaputra basins. The selected years are based on references to large floods in the *Imperial Gazetteer of India* (1908) and other government reports. It is impossible to estimate the magnitude of these historical floods or to find out why and how the events got enough attention to be included in this list. Nevertheless, the list provides very useful information and insights into the flooding conditions of the past:

- Big floods are not a new phenomenon of the twentieth century. Quite a few major events were recorded in the eighteenth and nineteenth centuries. Interestingly, there is a marked difference between the Ganga and the Brahmaputra catchments in terms of flood frequency and also in terms of the years in which the floods occurred. Hydrological factors may be one reason behind this. However, the difference could just as well be explained by the greater attention paid to the Ganga catchment by the central government in Delhi than to the ‘‘marginal’’ and ‘‘remote’’ Brahmaputra system.
- There were two distinct periods of high flood frequency: 1770–1790 and 1860–1890. These decades were preceded by phases of low flood occurrence. This is evidence that, in the eighteenth and nineteenth centuries, flood years cumulated in certain periods, but such phases were of limited duration. With very good reasons, an increasing trend of flood occurrence could have been postulated for instance in 1790.

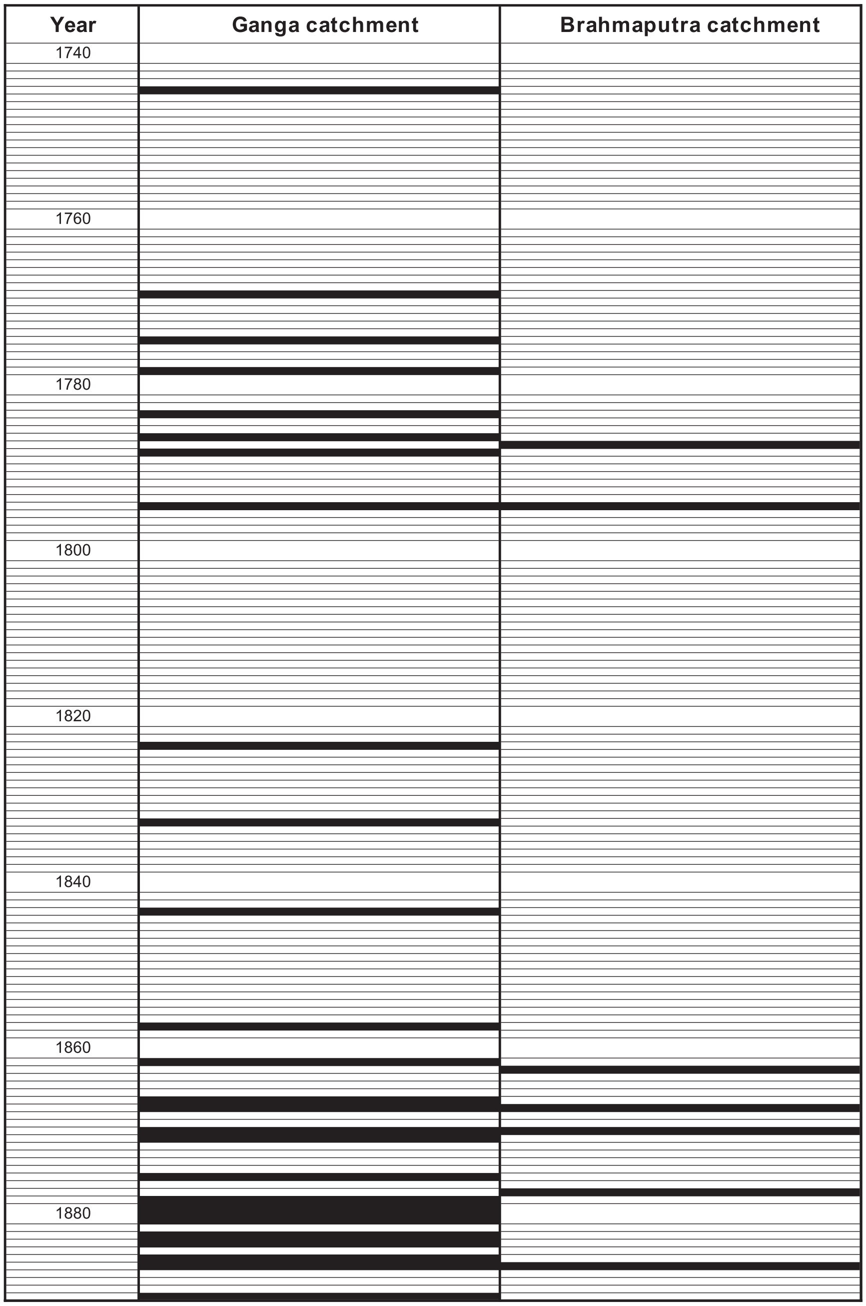


Figure 4.3 List of historical floods, 1740–1890, in the Ganga and Brahmaputra basins.
Source: Khale (1998).

However, the future showed that the reality was different. The cyclical occurrence of big floods is obviously the result of fluctuations in monsoonal rainfall. Khale (1998: 235) writes: "the clustering of large flood events in the last few decades of the 19th century appears to be linked to secular changes in the monsoon rainfall over the subcontinent and seems to be related to long-term climatic variability on the global scale" (see also Parthasarathy et al. 1987; Chowdhury and Mhasawade 1991).

4.3.2. Specific flood events in Bengal in the eighteenth and nineteenth centuries

The following discussion is based on thorough investigations by Dutt (1995), for which, among other descriptions, the *District Gazetteers* (DG) were the most important sources. The Gazetteers were written between 1905 and 1925, with new editions appearing between 1970 and 1980. They include important district-specific information on geography and economy. Under the heading "natural calamities", important information on floods and other natural disasters is available. Summaries of floods, cyclones, droughts, etc. are listed, followed by more detailed descriptions of the major events. One of the main sources for the Gazetteers was W. W. Hunters' oeuvre (eight volumes), edited between 1875 and 1877 (H. E. Rashid 1991). The sections in the Gazetteers discussing floods are based on a compilation of historical records, and they do not necessarily provide a complete picture of all flood events and their geographical extent (Figure 4.4). In addition, a large amount of information documented in the Gazetteers seems to be based on oral communication and therefore the statements are often very general. Another very important source for the last three decades of the nineteenth century is the study by Mahalanobis (1927).

The earliest flood events in Bengal documented by several authors happened in the second half of the eighteenth century (1769 and 1787). Information about these two events is scarce and refers only to particular aspects. The nineteenth century is much better documented, the floods in 1871 and 1885 having been particularly severe. We shall briefly discuss the two major floods in each century. In Figure 4.4 they are mapped in terms of the districts affected. The documentation of the 1769 flood is tentative owing to the unreliable sources of information.

- 1769: The flood-affected districts were concentrated in the Ganga catchment. There is no information available about the timing of the flood. In the *District Gazetteer* (DG) for Darbhanga (1907: 70) a famine is reported that affected major parts of Bengal and Bihar and led to the death of one-third of the population of Bengal. However, the sources do not give any clear indication of whether the famine was actually caused by the flood or if there were other reasons for it.

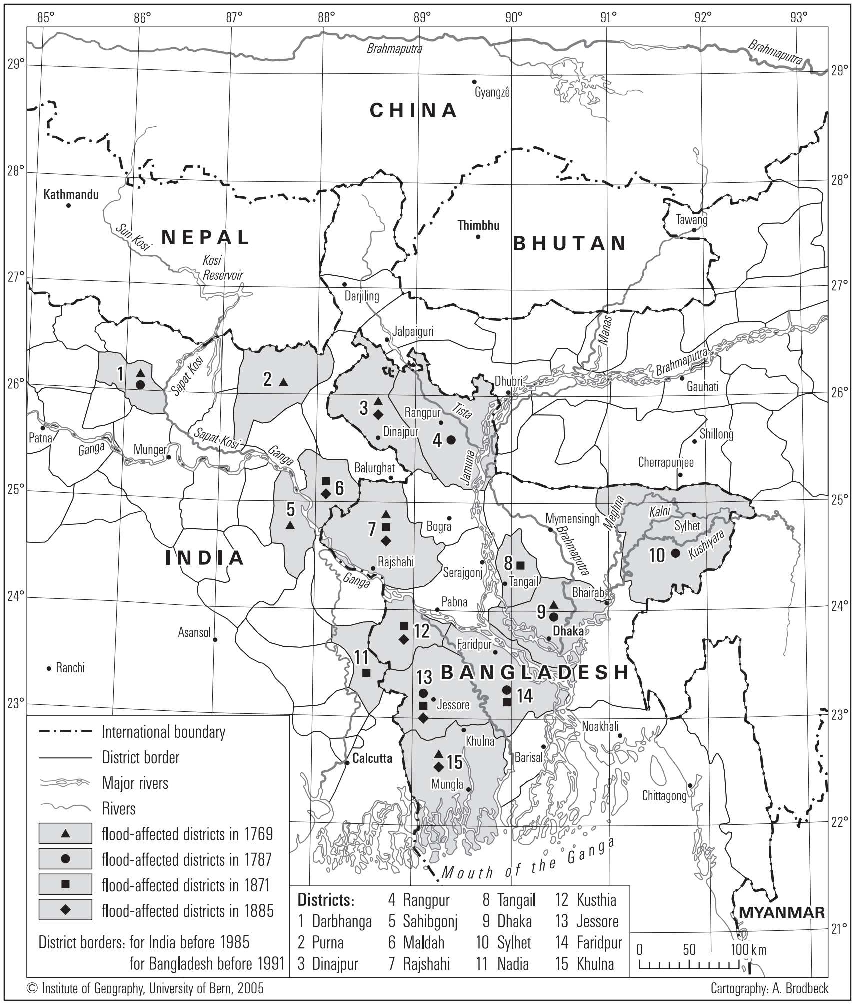
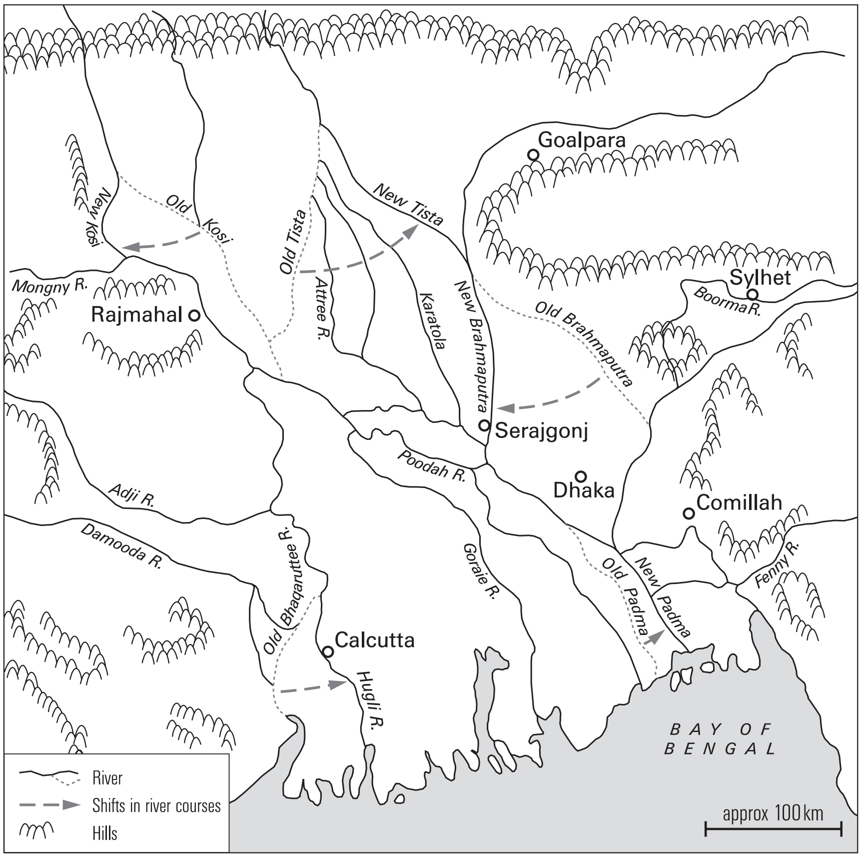


Figure 4.4 The flood-affected districts in Bengal in 1769, 1787, 1871 and 1885. *Sources*: based on *District Gazetteer* (various years) and H. E. Rashid (1991).

- 1787: This flood was probably the most severe and spectacular event of the eighteenth and nineteenth centuries. In addition to the districts mapped in Figure 4.4, most probably additional areas in the north of Bengal were affected by the catastrophe. The flood and the subsequent drought caused the death of one-sixth of the population of the Rangpur district (DG Rangpur 1977). Even Dhaka was submerged by the flood water. A scarcity of food caused an increase in market prices of 300–

400 per cent, which resulted in a severe famine. According to estimates, the event claimed many victims in Dhaka City and caused large movements of refugees. Apart from these features, the extraordinary flood of 1787 also caused major changes to the river systems in Bangladesh: according to several sources (DG Rangpur 1977: 74–75; H. E. Rashid 1991: 46; Rahman et al. 1990: 98) the Tista River, originally a tributary of the Ganga, changed its course during the inundation of 1787 and joined the Brahmaputra near Bahadurabad through an old, abandoned course (Figure 4.5). The processes leading to this major fluvial geomorphic event are described as follows: a long rainy period from the end of March to mid-July flooded all low-lying areas. After a 10–12 day break,



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Cartography: A. Hermann

Figure 4.5 Historical map: Shifts in the courses of the Kosi, Tista, Padma and Brahmaputra rivers since the mid-eighteenth century.
Source: Adapted from Ferguson (1863) and Rennell (1789).

in early August heavy rains started again and, on August 27, huge amounts of sand carried by the Tista River blocked the Attree River and the Tista had to find a new course. As a result, almost the entire district of Rangpur was inundated. Another change of similar magnitude and effect, which started in 1787, was the shift of the Brahmaputra River course: before 1787, the Brahmaputra (“Old Brahmaputra”) was a tributary of the Meghna; after 1787, the river (“New Brahmaputra” or “Jamuna”) took a totally new course southwards and joined the Ganga–Padma system (Figure 4.5). Whether this river course shift was the result of a single flood event or continued over a longer period is disputed. There is also evidence that earthquakes may have been a major factor in initiating the shifting process of the rivers and for aggravating the extraordinary flood event. These major shifts in the river courses are also discussed in section 6.4.

- 1871: As in 1769, most of the affected districts were located in the catchment area of the Ganga (Figure 4.4). The flood reached its maximum height in August. The *District Gazetteers* for Jessore (1979) and Nadia (1910) emphasize the pre-monsoon rains as the most important cause of the flood. In Nadia, half of the rice crop was destroyed. The Rajshahi district was affected by one of the worst floods that had ever occurred in the region (DG Rajshahi 1976: 23), which covered the land continuously from mid-August to the second week of October. The *District Gazetteers* for Tangail (1983: 15), Maldah (1969: 97) and Faridpur (1977: 26) comment on the flood of 1871 as a rare event.
- 1885: According to Mahalanobis (1927: 56), in North Bengal the districts of Rajshahi, Maldah and the southern part of Dinajpur (Figure 4.4) were affected in September. The combination of heavy rainfall and a high water level of the Ganga River was the main reason for the flooding. Regarding southern Bangladesh, an interesting statement was made in the *District Gazetteer* for Jessore (1979: 19–20): “There were simultaneous freshets (sudden rises in the water level) in both the Ganga and the Brahmaputra, and the water of the former, backed up by the latter, was forced to find an outlet to the sea through the rivers of the Kusthia district [Figure 4.4], which had been silting up for two centuries and which were quite inadequate to carry such an immense volume of water as the Ganges was bringing down.”

A brief comparison of the four floods discussed above, combined with a glimpse ahead to the twentieth century, is interesting. In all of the four documented events, mainly the western districts of Bengal were affected, particularly those in the lower Ganga catchment. This is in contrast to the situation in the twentieth century (see Chapter 5 and its appendices). This statement is supported by quotations in specific *District Gazetteers*: “The district was formerly subject to destructive floods, but inundations are now rare owing to fluvial changes. Within the 19th century nearly all the rivers have degenerated into drainage channels which carry off the surplus local rainfall and no longer convey the water of the Ganga to the sea'' (DG Jessore 1979: 18–19). ''The northern portion of the district is liable to occasional floods, but the severity of such inundation is far less than it used to be about a century ago, when a large portion of the volume of the Ganga water poured down to the sea through the district. The Ganga now discharges its waters further to the east, and floods are consequently less frequent and less severe'' (DG Khulna 1908: 106). Chowdhury (1964) rejects the hypothesis about the Ganga having shifted gradually from west to east (from what is called today the Hugli river bed to the Padma). According to Chowdhury, this hypothesis was based on the over-proportional growth of the western part of the delta.

4.3.3. Reflections on the findings

As already concluded in section 4.2.2, floods have always occurred. There were some major events in the eighteenth and nineteenth centuries, when the intensity of humans' activities in the watersheds was much lower than in the twentieth century. There are some very interesting features to be highlighted:

- As a result of fluctuations in the monsoonal rainfall, periods of high flood frequency interchange with periods of rare flood occurrence.
- Floods in the western part of modern Bangladesh, in the Ganga catchment, seem to have been much more intensive in the eighteenth and nineteenth centuries as compared with the twentieth century.
- Catastrophic floods, major river changes and earthquakes have played major, often combined roles, as documented for 1787.

But where is the human impact in this context? In light of such major natural processes must we not assume that the anthropogenic effects could have been only small, if not negligible? One point is very clear: an event such as the one in 1787 (with floods, major changes of river courses and even earthquakes) in today's Bangladesh would cause a disaster with far greater consequences than the floods of 1988 and 1998 did.

4.4. The twentieth century

The amount of information on flooding in the lowlands of the Ganga, Brahmaputra and Meghna rivers increased during the twentieth century owing to the rapid development of communication facilities. Quantitative statistical records are added to qualitative, descriptive information. It is possible, therefore, to be more specific about interpretation and to take a closer look at the trends: did floods in Bangladesh increase in terms of frequency or extent during the twentieth century? If they did, were there similar trends in rainfall and discharge characteristics? Another aspect is the rapid increase of population, urban centres, roads, embankments, etc., which led to a gradual increase in vulnerability to inundation. Accordingly, a clear distinction has to be made between ‘‘natural’’ trends in flooding resulting from meteorological and hydrological factors, and trends in the impacts of flooding in terms of population affected, crops damaged or houses destroyed. The following sections approach these topics step by step from different perspectives.

4.4.1. Floods in Bangladesh, 1890–2004

Figure 4.6 covers the period from 1890 to 2004 and we acknowledge the valuable efforts made by Dutt (1995) and Guntersweiler (1995) to reconstruct the flood history from 1890 to 1950. The graph is principally based on a number of descriptive, qualitative sources and highlights major flood years in Bangladesh. The selection itself was a rather difficult exercise because the lists of major flood years are slightly different in each source consulted. The graph includes those years that are mentioned in several sources and in which the floods are described as severe or widespread. For the years after 1950, beginning with the flood in 1954, the statistics on flood-affected areas (Table 4.1 and Figure 4.7) were also taken into

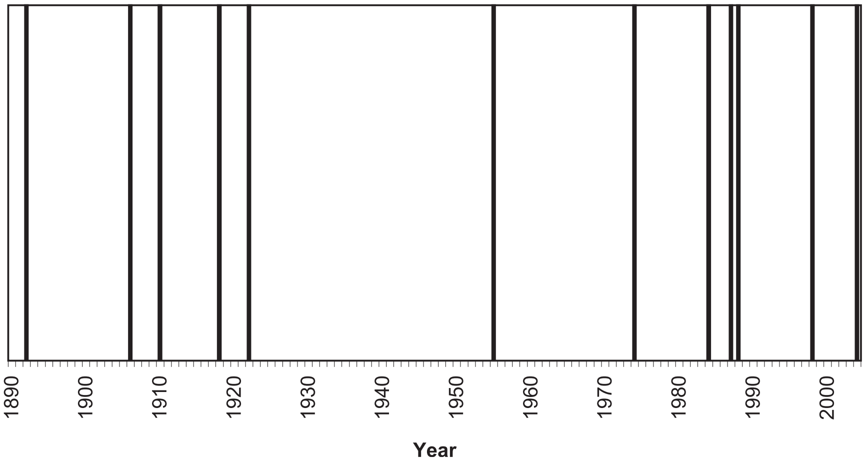


Figure 4.6 Major floods in Bangladesh, 1890–2004.
Sources: Mahalanobis (1927), DGs: Bogra 1979; Jalpaiguri 1981; Maldah 1969; Sylhet 1974; Rasid and Paul (1987), Miah (1988), Ahmad (1989), Huda (1989), Rahman (1989b), USAID (1990), BWDB (1991a, n.d.[a]), Islam (1995).

Table 4.1 Flood-affected areas in Bangladesh, 1954–2004

Year	Area (km^2)	As % of total area of country	Rank
1954	36,800	25.77	12
1955	50,500	35.37	6
1956	35,400	24.79	14
1957	n.a.		
1958	n.a.		
1959	n.a.		
1960	28,400	19.89	24
1961	28,800	20.17	23
1962	37,200	26.05	10
1963	43,100	30.19	7
1964	31,000	21.71	20
1965	28,400	19.89	25
1966	33,400	23.39	17
1967	25,700	18.00	30
1968	37,200	26.05	11
1969	41,400	29.00	9
1970	42,400	29.70	8
1971	36,300	25.42	13
1972	20,800	14.57	32
1973	29,800	20.87	22
1974	**52,600**	**36.84**	**5**
1975	16,600	11.63	33
1976	28,300	19.82	26
1977	12,500	8.75	35
1978	10,800	7.56	38
1979	n.a.		
1980	33,000	23.11	18
1981	n.a.		
1982	**3,140**	**2.20**	**43**
1983	11,100	7.77	37
1984	28,200	19.75	27
1985	11,400	7.98	36
1986	4,600	3.22	40
1987	**57,300**	**40.13**	**3**
1988	**89,970**	**63.01**	**2**
1989	6,100	4.27	39
1990	**3,500**	**2.45**	**42**
1991	28,600	19.38	29
1992	**2,000**	**1.36**	**44**
1993	28,742	19.48	28
1994	**419**	**0.28**	**45**
1995	32,000	21.68	21
1996	35,800	24.26	15
1997	n.a.		
1998	**100,250**	**67.93**	**1**
1999	32,850	22.26	19
2000	35,700	24.19	16

Table 4.1 (cont.)

Year	Area (km^2)	As % of total area of country	Rank
2001	**4,000**	**2.71**	**41**
2002	15,000	10.16	34
2003	21,500	14.57	31
2004	**55,000**	**37.27**	**4**
Average	29,946	20.78	

Sources: BWDB (1991a, 1998a, n.d.[a]).
Notes: n.a. = no information available; figures in bold represent the first five and the last five ranks.

consideration: in almost all the highlighted years the flood-affected area was more than 30 per cent of the country's territory. An exception is 1984, which received a great deal of attention in the descriptive sources in spite of evidence in the statistics of only average flooding conditions.

Over the 115 years covered by Figure 4.6, Bangladesh was affected by 12 major floods, one per decade on average. However, as already pointed

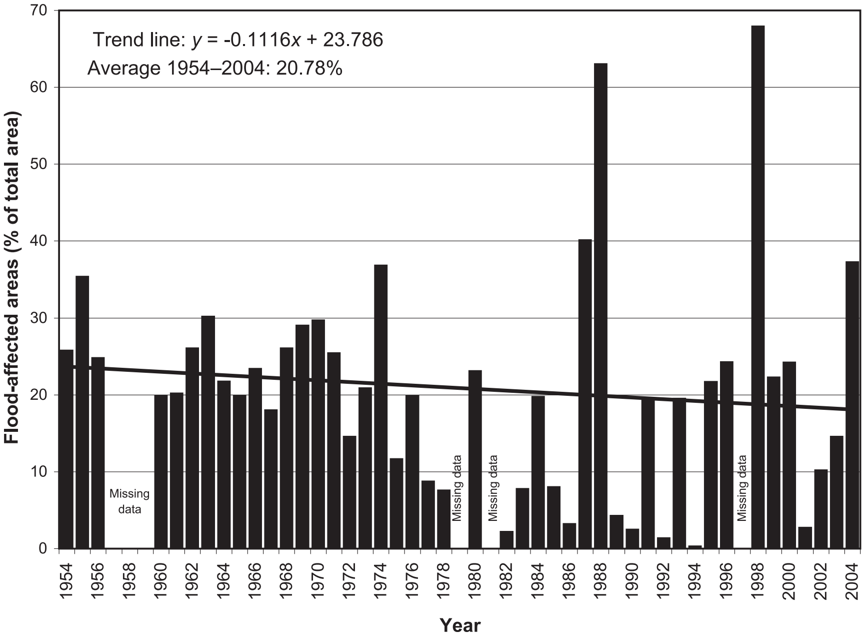


Figure 4.7 Extent of flood-affected areas in Bangladesh, 1954–2004.
Sources: BWDB (1991a, 1998a, n.d.[a]).

out in the discussion of the floods in the eighteenth and nineteenth centuries, these events did not occur at regular intervals: two phases of fairly frequent flooding (1892–1922; 1974–2004) are interrupted by a long phase (1923–1973) with only one widespread inundation. Certainly the large floods in the consecutive years 1987 and 1988 were an exceptional situation. The 30-year period from 1923 to 1954, when there was a complete absence of major flood events, is particularly striking. Whether this situation can be explained by rainfall fluctuations or whether it is the result of less communication and recording towards the end of the British period cannot be determined conclusively at this point. However, based on the listing of major floods in the twentieth century in Khale (1998), this scarcity of big floods from 1920 to 1950 seems to be a phenomenon of the entire Ganga and Brahmaputra catchments. Further confirmation for this is found in Parthasarathy et al. (1987: 57): "The percentage area of India which suffered from drought and flood was low during the continuous three decades 1921–1930, 1931–1940, and 1941–1950." It is clear that, after the unspectacular period from 1920 to 1950, the frequency of major flooding seems to have increased from 1950 to 2004. However, if the years from 1890 to 1922 are also taken into consideration, then this interpretation must be replaced by another conclusion: big floods seem to occur in cycles of higher and lower frequency.

Figure 4.7 covers a 50-year period (1954–2004) during which, with only a few exceptions, annual statistics on the flood-affected areas in Bangladesh are available (for data and ranking of the flood events see Table 4.1). These statistics were compiled by the head office of the Bangladesh Water Development Board on the basis of incoming information on flood-affected areas from the regional offices (section 2.3.3). The figure clearly shows that floods occur annually in Bangladesh, forming an intrinsic element of the seasonal cycle. The extent of flooding, however, varies significantly from year to year. The trend line in Figure 4.7 has a slightly negative slope, which would indicate that in the longer term the areal extent of flooding in Bangladesh is gradually decreasing. However, statistically this trend is far from being significant. It would be too simplistic to stop the discussion at this point and a more thorough analysis of the situation is necessary. Figure 4.7 provides clear evidence that the interannual variability of the flood-affected areas has significantly increased since 1975: years with a low flood extent have become more frequent. In the ranking of Table 4.1, the five years with the lowest flood-affected areas over the 50-year period all occurred after 1980 (1982, 1990, 1992, 1994, 2001). On the other hand, all four of the most extensive floods in the period 1954–2004 occurred after 1986 (1987, 1988, 1998, 2004) and it is striking that two record floods (1988 and 1998) that, according to the World Bank (1989), have a return period of 100 years or more (see Table

Table 4.2 Return period of different flood dimensions in Bangladesh

Return period (years)	Affected area (% of the country)
2	20
5	30
10	37
20	43
50	52
100	around 60
500	around 70

Return period of 1998 flood: around 400 years
Return period of 1988 flood: around 100 years
Return period of 1987 flood: 20 years
Return period of 1974 flood: 10 years

Source: World Bank (1989).

4.2) occurred twice within a short period of time. In addition, the extent of big floods seems to have gradually increased (see flood-affected areas 1955, 1974, 1987, 1988, 1998).

A number of elements can be considered in interpreting these observed tendencies. Sections 4.4.3 and 4.4.4 will focus on investigating rainfall and discharge data series and their eventual relations with the changing flooding conditions. The following paragraphs look more into the human dimension of this question. The first argument that may come to mind is of course the possible impacts that land-use changes, e.g. deforestation, in the Himalayas may have on the extent of flooding. However, it is striking that, whereas the extent of the big floods in Bangladesh seems to be increasing, the forest situation at least in parts of the Himalayas is improving (see Box 4.2). A second interesting observation is that the changes in the flooding patterns after 1974 fall into the same period as the implementation of the Master Plan (1965–1985, see also section 7.6.1), which to some extent included the construction of lateral embankments along the major rivers in Bangladesh. In terms of the potential impact of embankments on the extent of flooding (a reduction in normal floods, but an increase in abnormal floods after embankments are breached), Hughes et al. (1994: 21) state: ''Ironically, embankments serve to prevent 'normal floods' whilst failing to prevent 'abnormal floods', thus reducing the beneficial functions of normal flooding.'' In a personal oral communication (20 July 1997), Hugh Brammer strongly opposes such an interpretation. He argues that the design of the lateral river embankments ''provides 'flushing sluices' which can be operated to let water onto or off the floodplain when local people demand it (and when external water levels allow this)". In addition he argues that "the hated embankments do not hold an umbrella over the land: rainwater flooding is not prevented. It is particularly the Brahmaputra Right Embankment which has breached; embankments on both banks of the Ganga and, with one exception, the Tista have not breached, even in the record high floods of 1987 and 1988. Lay antagonists generalise from the rather special case of the Brahmaputra Right Embankment."

Another reason for the increasing area affected during very big flood events, such as in 1988 and 1998, could be the loss of beels (seasonal or perennial lakes) and swamps in the floodplains, which served as natural storage for excess water. Such areas have been disappearing more and more, not only in Bangladesh but also higher up in the catchment, for example in Assam, owing to the expansion of agriculture, the construction of roads, the cutting of small feeder channels, and the construction of embankments. As a consequence, the potential for storage of surplus water throughout the watershed is diminishing, which might lead to higher peaks in the rivers and larger areas affected by floods further downstream. Concerns along these lines were raised particularly in the Technical Faculty of the University in Gauhati (Assam) and were widely discussed in the context of the 1998 flood on the Yangtze, the 1993 flood on the Mississippi and the 1993 and 1995 floods on the Rhine. However, participants in a seminar in Dhaka in January 1998 stated that the beels and swamps in Bangladesh had already been occupied a long time ago and that their disappearance was not a valid explanation of increasing flood extent over recent decades.

Reference to this important issue is made in Chowdhury (1998: 215–217):

> To illustrate the hydraulic impacts of floodplain interventions, some examples from NW, NE and SW regions can be discussed here. Several polders were built in the lower part of the Atrai River basin in the NW region in the eighties to prevent flooding by river spill. Beels are important hydraulic elements in this area. These beels act as natural storage areas for flood water. Beels were empoldered under the flood control projects. With the construction of polders one after another, the flood flow of the Atrai River became more and more confined causing gradual increase in flood level. A mathematical model study indicates that the flood storage capacity decreased by 44 percent due to construction of seven polders. Hydraulic effects of embankment to prevent the overbank spill in the NE region have been studied under FAP [Flood Action Plan]. There are several Haors (big lakes) in this region. These Haors retard the flood flow by acting as storage area. The study shows that the water levels and discharges have increased in several rivers as a result of reduction of floodplain storage due to the confinement effect of embankment. Extensive floodplain is an important element in the hydraulics of flood flow in Bangladesh. The extreme water level during infrequent

> flood events such as 100-year flood is not much higher than that of more frequent events such as 20-year floods. This is because the flood water spreads into the floodplain. The flood risks have changed and the country is more vulnerable to losses as a result of floodplain interventions. The hydrologic impacts of floodplain interventions should be given due attention at the planning stage of flood management programmes.

At this point we do not want to go further into these controversial discussions. We intended only to present some facts related to flood statistics and to highlight the diversity of interpretations. To conclude the interpretation of Figure 4.7, we once again emphasize that, hydrologically, the frequency of major flood events does not seem to have increased since the middle of the twentieth century, but that there is quite strong evidence of an increase in the areal extent of major flood events.

Table 4.3, which consists of a simple comparison between the statistical records and one descriptive source, adds additional elements to the interpretation of the flood history since 1954. USAID (1990), from which the descriptive information was collected, gives accounts of all reported disasters in the world. Many more flood events are listed and discussed in the 1980s and 1990s than in the 1950s and accordingly this source seems to indicate that the flood frequency has increased. However, this clearly results from the fact that awareness about natural disasters has increased and international communication has improved since 1950. Today, floods may be recorded and data transmitted that would not have received any particular attention in previous decades. Population increase and the resulting higher vulnerability of rural and urban areas have attracted the interest of national and international media (see section 4.4.5).

The statistical and the descriptive sources in Table 4.3 do not necessarily draw attention to the same flood years:

- In 1955 the situation was quite extraordinary in terms of the flood-affected area (rank 6 in the period 1954–2004; see also Table 4.1), yet this flood is not reported in USAID (1990).
- In 1982, 1986, 1989, 1990 and 1994, the areal extent of flooding was very small. However, for all these years, there are entries in the records of USAID about floods in specific areas of Bangladesh.
- In 1984, 1993 and 1995, USAID discusses widespread inundations despite only average extents of flooding according to the statistics (see also Figure 4.7).

These observations are evidence that statistical information alone is not sufficient for the discussion of flood problems. A monsoon season that inundates large areas but produces almost no damage to crops (e.g. because the water is shallow) may be striking in terms of the extent of flooding, but may not be mentioned in accounts of flood problems. On

Table 4.3 Flooding conditions in Bangladesh, 1954–1998: A comparison of sources

Year	Statistical records	Descriptive records
1954		
1955	XX	
1956		
1957		
1958		
1959		
1960		
1961		
1962		
1963	X	
1964		F
1965		
1966		F
1967		
1968		FF
1969		
1970		FF
1971		
1972		F
1973		
1974	XXX	FFD
1975		
1976		F
1977		F
1978		F
1979		
1980		F
1981		
1982	xxxx	F
1983		FD
1984		FF
1985		F
1986	xx	F
1987	XXXX	FF
1988	XXXXX	FF
1989	x	FD
1990	xxx	F
1991		F
1992	xxxxx	
1993		FF
1994	xxxxxx	F
1995		FF
1996		n.a.
1997		n.a.
1998	XXXXXX	n.a.

Notes: Statistical records – XXXXXX–X = the six highest ranks of flood-affected areas; xxxxxx–x = the six lowest ranks of flood-affected areas. Descriptive records – FF = nationwide floods; F = flood in specific regions; D = drought; n.a. = missing information.

Sources: Statistical records – BWDB (1991a, n.d.[a]); descriptive records – USAID (1990).

the other hand, a severe flood of limited geographical extent may cause damage and receive considerable attention in reports (especially if an important centre is affected), but in terms of the area affected the event is not extraordinary. Of course, truly outstanding events such as the floods in 1974, 1987 and 1988 are reflected in both types of sources.

4.4.2. Flood history in the lowlands of the Ganga and Brahmaputra, 1954–1994

It is helpful to complement this discussion of the flood history with a comparison between the data of Bangladesh and those of the Indian plains (Uttar Pradesh, Bihar, West Bengal and Assam; see Figure 4.8). The statistics listed in Table 4.4 are compiled from different sources. The investigation ends with the year 1994, because from 1995 onwards no information is available for the Indian states. For Uttar Pradesh, Bihar and West Bengal, the three Indian states of the Ganga Plain, the statistics are missing from 1985 to 1989, which is particularly unfortunate for the years 1987 and 1988 in which the extent of flooding was very high in Assam and Bangladesh.

The graphs of Figure 4.9 display the flood-affected areas as a percentage of the total area of each state, as well as showing the trend line. In all the graphs, the flood history is characterized by a high inter-annual variability. The range between the lowest and highest extent of flood-affected areas is remarkable. For none of the areas, however, is there any reason to assume an increasing trend in the extent of flooding: the trend lines of the Indian states are almost horizontal. Moreover, the frequency of high flood peaks does not follow any rising trend. The situation in Bangladesh, in particular the considerably higher variability of flood-affected areas after 1973, has already been discussed in the previous section.

Based on Figure 4.9, the flood history in the lowlands of the Ganga–Brahmaputra–Meghna systems is obviously characterized by a significant regional differentiation, a fact that was emphasized in Messerli et al. (1988). In order to further verify this important statement, the statistics on flood-affected areas for each state listed in Table 4.4 were correlated with each other (see Table 4.5). Figure 4.9 and Table 4.5 document the following findings:

- No outstanding floods of similar magnitude and intensity are recorded in the entire Ganga–Brahmaputra–Meghna system in the same year. Except for 1971 and 1978, it is even hard to identify years in which floods reached a similar size in all three Indian states within the Ganga system (Uttar Pradesh, Bihar and West Bengal).
- The Ganga and the Brahmaputra systems almost never correspond with regard to their flood magnitude; the flood history of Uttar Pradesh

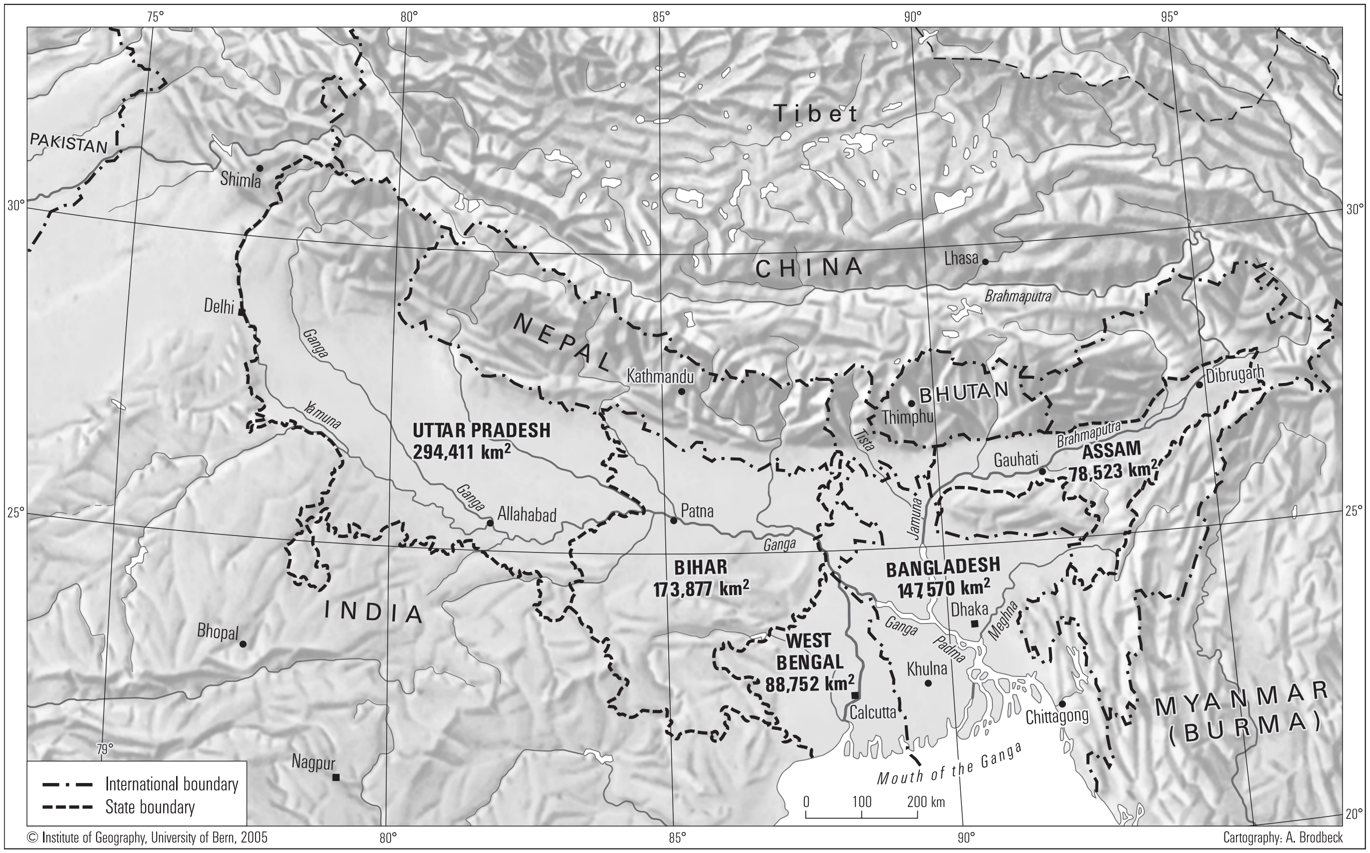


Figure 4.8 Location and geographical area of Uttar Pradesh, Bihar, West Bengal, Assam and Bangladesh.
Sources: Mutiah (1987), Bangladesh Bureau of Statistics (1993).

Table 4.4 Flood-affected areas in Uttar Pradesh, Bihar, West Bengal, Assam and Bangladesh, 1954–1994

	Uttar Pradesh		Bihar		West Bengal		Assam		Bangladesh	
	km^2	% of total area	km^2	% of total area	km^2	% of total area	km^2	% of total area	km^2	% of total area
Average	22,705	7.71	13,467	7.74	8,211	9.25	9,479	12.68	28,208	19.73
1954	13,500	4.59	25,000	14.38	4,200	4.73	31,500	40.12	36,800	25.77
1955	41,300	14.03	17,700	10.18	3,500	3.94	14,100	17.96	50,500	35.37
1956	25,000	8.49	13,200	7.59	26,500	29.86	6,000	7.64	35,400	24.79
1957	17,000	5.77	7,900	4.54	11,600	13.07	4,000	5.09	n.a.	n.a.
1958	21,800	7.40	7,100	4.08	4,500	5.07	12,500	15.92	n.a.	n.a.
1959	700	0.24	2,100	1.21	11,200	12.62	10,400	13.24	n.a.	n.a.
1960	32,500	11.04	13,200	7.59	1,900	2.14	4,700	5.99	28,400	19.89
1961	22,900	7.78	12,700	7.30	2,000	2.25	1,900	2.42	28,800	20.17
1962	10,600	3.60	11,100	6.38	1,600	1.80	16,200	20.63	37,200	26.05
1963	12,600	4.28	2,700	1.55	900	1.01	5,800	7.39	43,100	30.19
1964	10,600	3.60	11,200	6.44	1,000	1.13	7,600	9.68	31,000	21.71
1965	800	0.27	4,300	2.47	1,200	1.35	6,000	7.64	28,400	19.89
1966	5,200	1.77	15,300	8.80	1,300	1.46	17,800	22.67	33,400	23.39
1967	34,300	11.65	12,500	7.19	9,400	10.59	2,600	3.31	25,700	18.00
1968	8,000	2.72	7,300	4.20	21,700	24.45	4,100	5.22	37,200	26.05
1969	24,000	8.15	9,700	5.58	5,300	5.97	8,100	10.32	41,400	29.00
1970	29,100	9.88	9,300	5.35	20,100	22.65	7,200	9.17	42,400	29.70
1971	52,600	17.87	42,600	24.50	20,600	23.21	3,600	4.58	36,300	25.42
1972	3,100	1.05	2,200	1.27	4,400	4.96	11,000	14.01	20,800	14.57
1973	26,300	8.93	7,300	4.20	8,700	9.80	27,500	35.02	29,800	20.87
1974	13,500	4.59	31,400	18.06	3,800	4.28	11,200	14.26	52,600	36.84
1975	21,800	7.40	23,100	13.29	2,000	2.25	100	0.13	16,600	11.63
1976	36,300	12.33	29,900	17.20	13,000	14.65	5,700	7.26	28,300	19.82
1977	13,000	4.42	11,500	6.61	15,500	17.46	11,000	14.01	12,500	8.75
1978	73,400	24.93	23,700	13.63	30,800	34.70	3,100	3.95	10,800	7.56

1979	7,000	2.38	8,100	4.66	200	0.23	6,700	8.53	n.a.	n.a.
1980	58,600	19.90	19,200	11.04	3,800	4.28	11,600	14.77	33,000	23.11
1981	29,900	10.16	12,600	7.25	3,800	4.28	4,600	5.86	n.a.	n.a.
1982	55,000	18.68	9,300	5.35	2,100	2.37	6,100	7.77	3,140	2.20
1983	38,600	13.11	14,700	8.45	3,800	4.28	7,300	9.30	11,100	7.77
1984	16,900	5.74	26,400	15.18	17,300	19.49	15,200	19.36	28,200	19.75
1985	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6,500	8.28	11,400	7.98
1986	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	4,300	5.48	4,600	3.22
1987	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	15,300	39.22	57,300	40.13
1988	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	38,200	53.74	89,970	63.01
1989	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	6,900	8.79	6,100	4.27
1990	22,080	7.50	8,700	5.00	22,680	25.55	4,880	6.21	3,500	2.45
1991	8,110	2.75	9,800	5.64	6,790	7.65	9,970	12.70	28,600	19.38
1992	7,000	2.38	800	0.46	100	0.11	2,130	2.71	2,000	1.36
1993	14,400	4.89	15,200	8.74	100	0.11	13,480	17.17	28,742	20.00
1994	9,900	3.36	6,000	3.45	n.a.	n.a.	1,770	2.25	419	0.28

Sources: Chaphekar and Mhatre (1986), Agarwal and Narain (1991), BWDB (1991a, n.d.[a]), Eriksen et al. (1993), CWC (n.d.), Goswami (1998).

Note: n.a. – no information available.

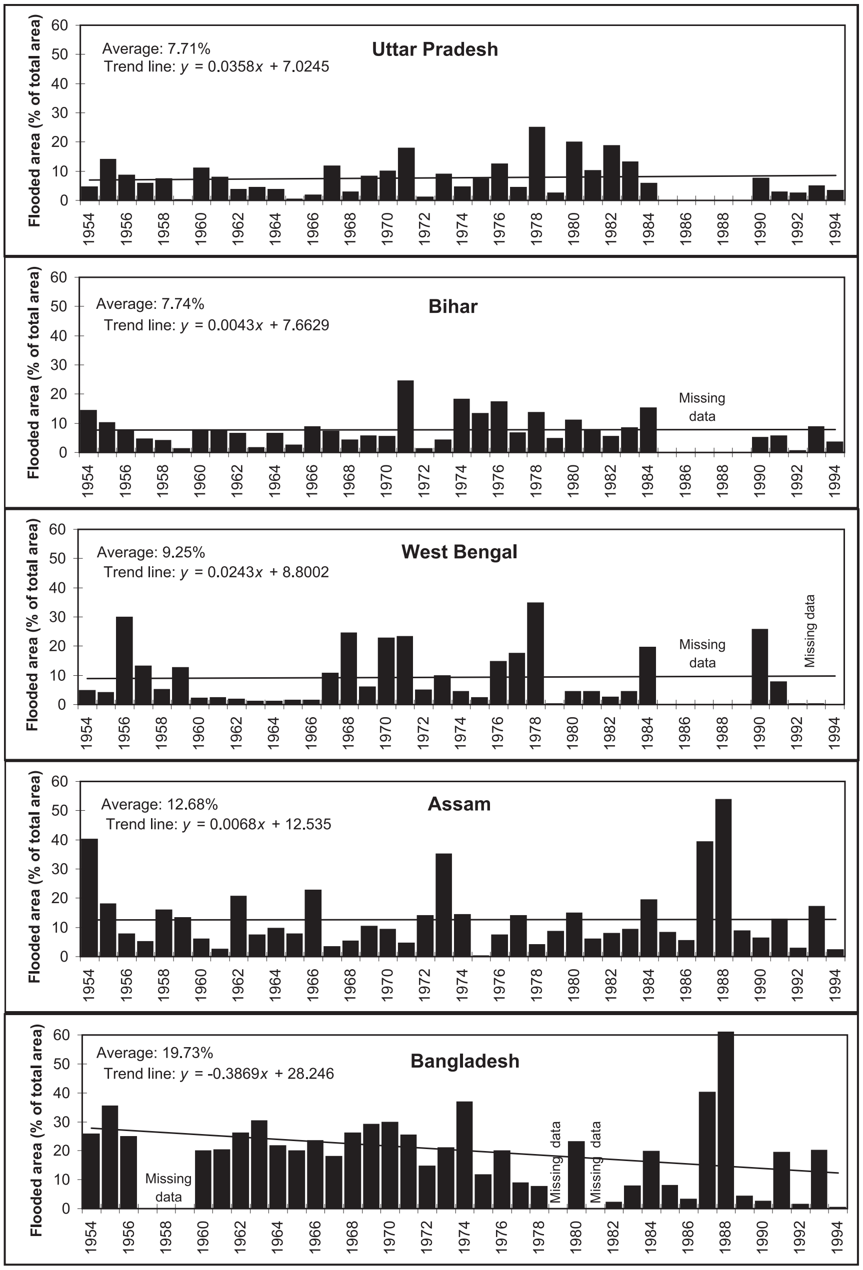


Figure 4.9 Extent of flood-affected areas in Uttar Pradesh, Bihar, West Bengal, Assam and Bangladesh, 1954–1994.
Sources: Chaphekar and Mhatre (1986), Agarwal and Narain (1991), BWDB (1991a, n.d.[a]), Eriksen et al. (1993), CWC (n.d.), Goswami (1998).

Table 4.5 Correlation of flood-affected areas of Uttar Pradesh, Bihar, West Bengal, Assam and Bangladesh, 1954–1994

Correlations	Correlation coefficient
Uttar Pradesh/Bihar	0.49
Uttar Pradesh/West Bengal	0.34
Uttar Pradesh/Assam	–0.18
Uttar Pradesh/Bangladesh	–0.10
Bihar/West Bengal	0.26
Bihar/Assam	0.10
Bihar/Bangladesh	0.29
West Bengal/Assam	–0.18
West Bengal/Bangladesh	–0.10
Assam/Bangladesh	0.65

Sources: Chaphekar and Mhatre (1986), Agarwal and Narain (1991), BWDB (1991a, n.d.[a]), Eriksen et al. (1993), CWC (n.d.), Goswami (1998).

and West Bengal is even negatively correlated to the flood history of Assam. Large flood-affected areas occurred either in the Indian Ganga system (very prominent in 1971 and 1978) or in the Indian Brahmaputra system (very prominent in 1966 and 1973). The marked difference in flooding conditions between the east and the west can be tentatively attributed to typical circulation patterns that each year result in different characteristics of the monsoon, concentrating either in the west or in the east of the study area (see also Chapter 5, particularly section 5.15).

- The flood history of Bangladesh in the period 1954–1994 correlates well with the flood history of the Indian Brahmaputra plain (Assam) and is negatively correlated with the flood history of at least parts of the Indian Ganga Plain (Uttar Pradesh, West Bengal). Years with severe floods in the Indian Ganga system (e.g. 1978) do not tend to be flood years in Bangladesh. Years with widespread flooding in Assam are often flood years in Bangladesh (e.g. 1987 and 1988).
- There is no year in which the extent of flooding increased from Uttar Pradesh down to Bangladesh within the Ganga catchment. Floods formed higher up in the plains, even in the Himalayan foothills, do not seem to move downstream with increasing dimensions. This is reflected by rather low and decreasing correlation coefficients within the Ganga Plain. The most striking year in this respect is 1982: the remarkable extent of flooding in Uttar Pradesh loses importance downstream. In Bangladesh, the flood-affected area was one of the smallest in the period 1954–1994. This conclusion will receive further attention in Chapter 5.

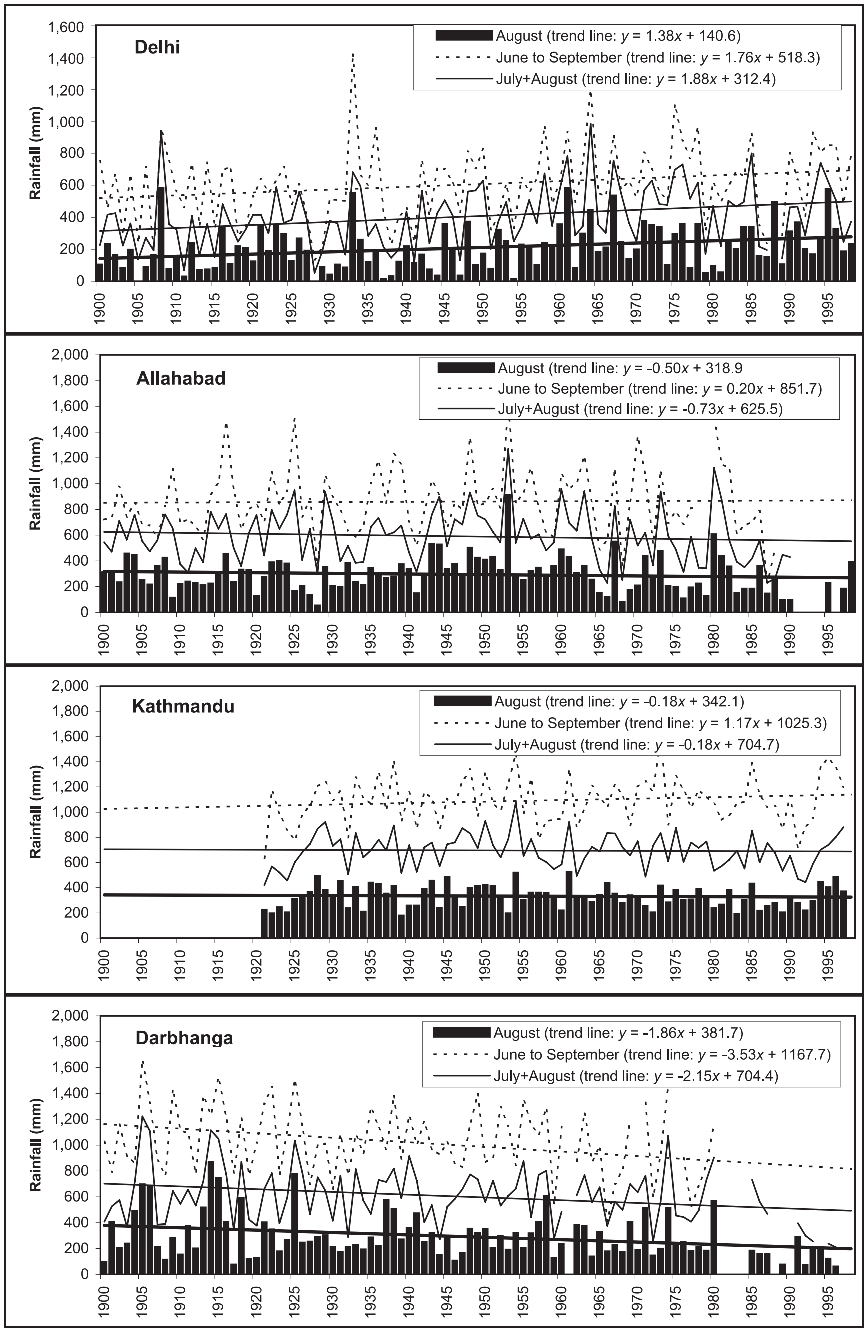


Figure 4.10 August rainfall, combined July and August precipitation, monsoon totals (June to September) and trend lines for selected stations in India and Bangladesh, 1900–1998.

Notes: For the location of stations, see Figure 3.1.

Sources: For data sources, see Table 3.2.

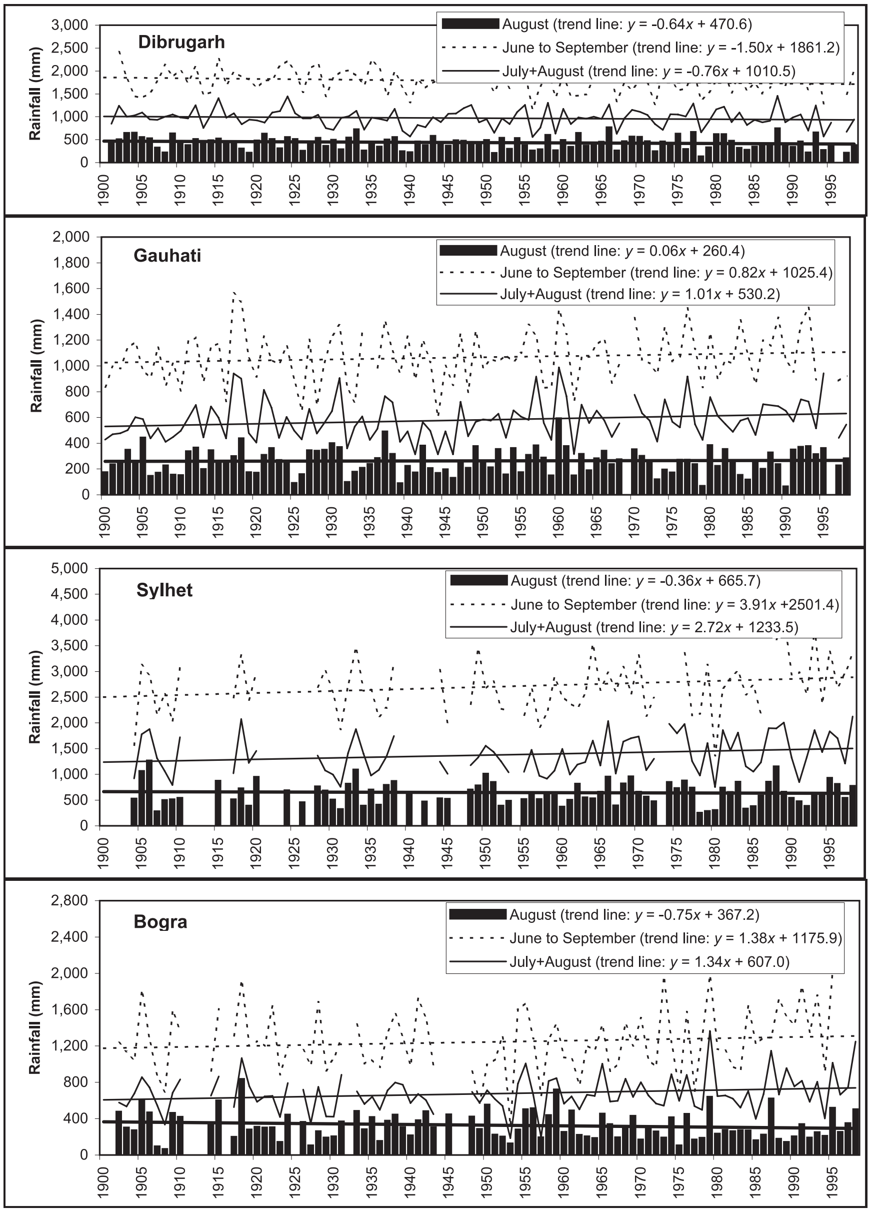


Figure 4.10 (cont.)

Figure 4.9 confirms the key finding of the previous sections: there is no general trend towards increasing frequency and extent of floods in the lowlands of the Brahmaputra and Ganga rivers. The only tendency is an increasing inter-annual variability of the flood-affected areas and an increasing range between the lowest and the highest annual figures of the extent of flooding. Figure 4.9 also documents the regional differentiation of the flood history in the Ganga–Brahmaputra–Meghna basin. With such findings it is no longer admissible to blame the Himalayan inhabitants for the flooding processes in the lowlands.

4.4.3. Rainfall trends in the Ganga–Brahmaputra–Meghna basin in the twentieth century

Taking the findings of the previous sections into consideration, trends in monsoon rainfall and in inter-annual rainfall variability are of particular interest. Eight climatological stations were selected for which the data series are fairly complete and which are reasonably well spread over the Ganga–Brahmaputra–Meghna basin: Delhi, Allahabad, Kathmandu, Darbhanga, Dibrugarh, Gauhati, Sylhet and Bogra (see Figure 3.1). The investigation covers a period of almost 100 years (1900–1998) and is based on monthly data sets. The analysis was implemented in three steps and was kept very simple: the aim was not to carry out a detailed trend analysis of time series with highly sophisticated statistical methods, but rather to identify overall tendencies that might be visible in the rainfall data series.

Step 1

In each graph of Figure 4.10, the August rainfall, the combined July and August precipitation, the monsoon totals (June to September) as well as the trend lines with their equations are depicted for each year over the period 1900–1998. Each trend line was tested for its statistical significance (Table 4.6). As the scale of the *y*-axis is not standardized, a direct quantitative comparison of the graphs is not possible. For Darbhanga the data situation after 1980 is problematic.

Very high inter-annual rainfall variability is a general feature for all the stations. However, the trends of the three variables, which reach statistical significance at only two stations in the Ganga catchment (Delhi with positive trends, Darbhanga with negative trends), can be differentiated:

- In six out of eight stations, the August rainfall is decreasing. Only in Delhi is the trend clearly positive; in Gauhati the trend line is almost horizontal.
- The negative and positive trends of the July+August precipitation are

Table 4.6 Rainfall trends of selected stations in India and Bangladesh, 1900–1998: Analysis of statistical significance

Station	Data set	Correlation coefficient	Degrees of freedom	Critical value (approx)
Delhi	Monsoon	**.2169**	97	0.198
	July+August	**.2814**	97	0.198
	August	**.2870**	98	0.197
Allahabad	Monsoon	.0196	88	0.2075
	July+August	−.0974	92	−0.203
	August	−.1007	94	−0.210
Kathmandu	Monsoon	.1414	76	0.223
	July+August	−.0301	76	−0.223
	August	−.0455	76	−0.223
Darbhanga	Monsoon	**−.3314**	82	−0.215
	July+August	**−.2673**	88	−0.207
	August	**−.2984**	89	−0.206
Dibrugarh	Monsoon	−.1538	94	−0.210
	July+August	−.1114	96	−0.199
	August	−.1301	96	−0.199
Gauhati	Monsoon	.1169	94	0.210
	July+August	.1924	96	0.199
	August	.0183	96	0.199
Sylhet	Monsoon	.2051	75	0.225
	July+August	.2052	77	0.222
	August	−.0445	77	−0.222
Bogra	Monsoon	.1119	85	0.211
	July+August	.1883	87	0.209
	August	−.1400	87	−0.209

Notes: Correlation coefficients in bold are statistically significant. For the location of the stations, see Figure 3.1.
Data sources: see Table 3.2; statistical method after Bahrenberg et al. (1990).

almost balanced: in four stations the trend is decreasing, in four stations increasing. Three out of four positive trends are located in the Brahmaputra and Meghna catchments (Gauhati, Sylhet, Bogra), three out of four negative trends in the Ganga catchment (Allahabad, Kathmandu, Darbhanga).

- The monsoon totals (June to September) follow a generally rising trend: at six out of eight stations the slope of the trend line is positive. For the two stations located in Bangladesh (Sylhet and Bogra) as well as for Delhi the trend is quite remarkable.

Within this general picture, regional differentiation is, to some extent, documented; for example, in the comparisons of Delhi/Allahabad and of Dibrugarh/Gauhati, the trends are almost completely opposite to each other.

The generally increasing trend in monsoon rainfall, particularly in Bangladesh, is confirmed in Moudud et al. (1989: 86–87): ‘‘During the eighties there has been an observed increase in rainfall in Bangladesh, particularly during the peak of the monsoon. In 1987 and 1988 there has been a sharp increase in rainfall’’ (both 1987 and 1988 were heavy flood years in Bangladesh – see Figure 4.7). An interesting finding regarding the trends in annual rainfall in Bangladesh is discussed in ADB (1994). According to this source, the trend in annual rainfall is not the same in all the regions of Bangladesh: whereas the north-west and north-east very clearly show an upwards trend, rainfall in the south-east is decreasing. In the south-west there is no dominant trend.

Step 2

In order to be able to make a temporal differentiation of the trends and to filter inter-annual variabilities, averages of monsoonal rainfall (June to September) were calculated over 21-year periods, each period overlapping the next by 10 years. The results of these calculations are documented in Figure 4.11. There seems to be a clear difference between the four stations located in the Ganga system (left side of the graph) and the four stations located in the Brahmaputra–Meghna system (right side of the graph):

- In the Brahmaputra–Meghna system, a cycle is documented, with comparatively high average monsoon rainfall in the first part of the twentieth century, followed by decreasing values towards the middle part of the century and again gradually rising average monsoonal rainfall in the last decades of the century. Interestingly, this fluctuation is well reflected in the flooding conditions in Bangladesh (see Figures 4.6 and 4.7): a high frequency of major floods in the first decades of the twentieth century, an unspectacular period between 1923 and 1973, followed by several major floods and indications of an increase in the areal extent of flooding in the last decades of the century. These long-term natural fluctuations in monsoonal rainfall leading to a cyclicality of flood occurrence have already been discussed in section 4.3 and are confirmed in Khale (1998).
- The situation in the Ganga catchment does not provide a clear and homogeneous picture. In general, the average monsoonal rainfall seems to have decreased in the second half of the twentieth century.

Step 3

In the third step, possible trends in the inter-annual variability of monsoonal rainfall were analysed, based on the standard deviations of 21-year series (see step 2), again overlapping each other by 10 years (Figure 4.12). The standard deviation of the monsoonal rainfall seems to get

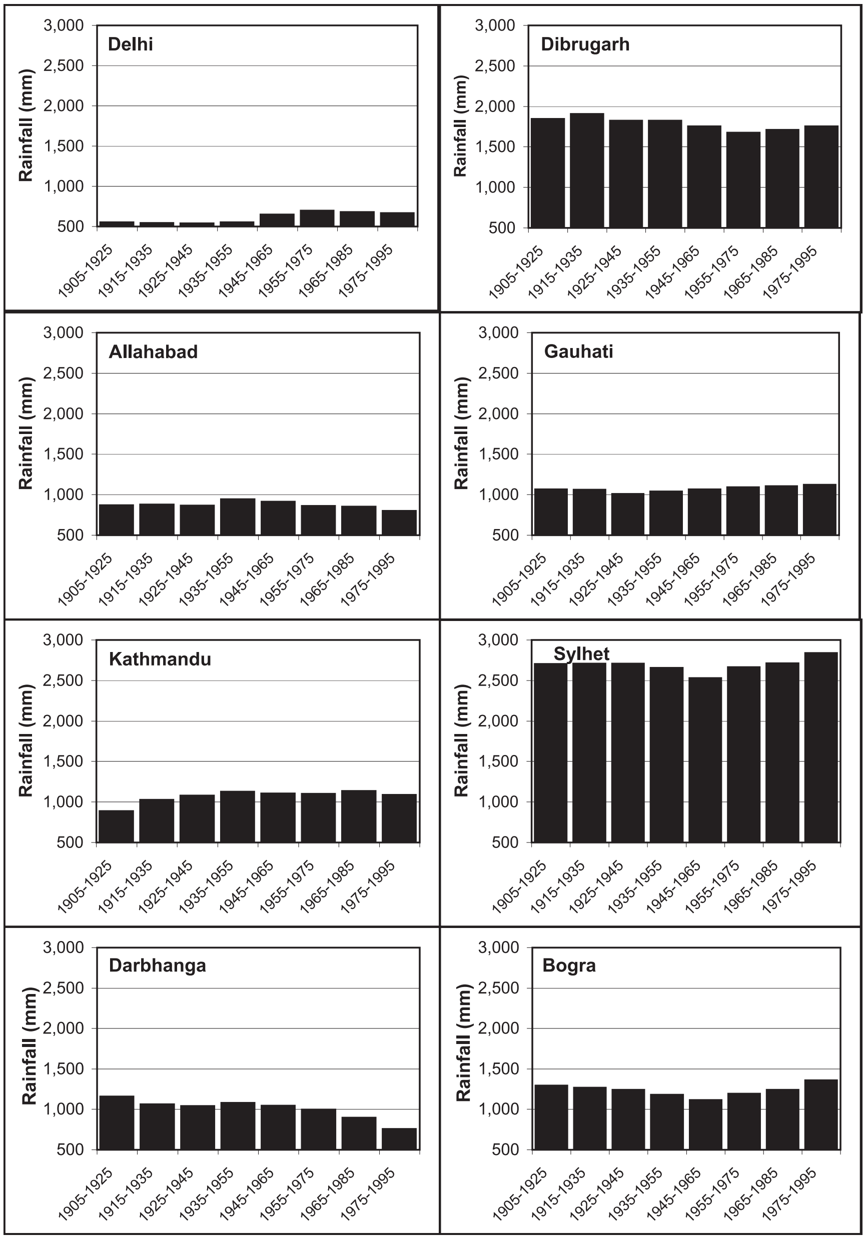


Figure 4.11 Monsoonal rainfall (June to September) for selected stations in India and Bangladesh, 1900–1995, 21-year averages.
Notes: For the location of stations, see Figure 3.1.
Sources: For data sources, see Table 3.2.

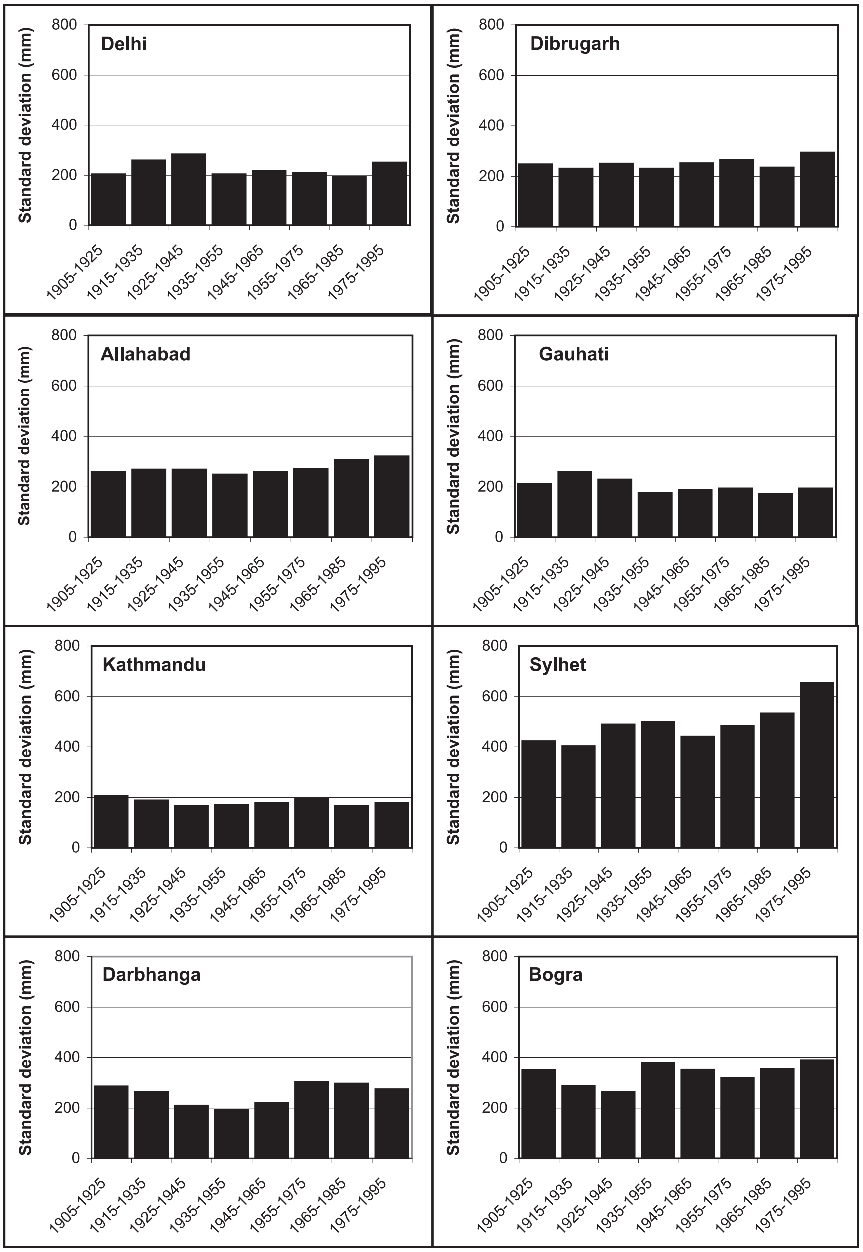


Figure 4.12 Standard deviation of monsoonal rainfall (June to September) for selected stations in India and Bangladesh, 21-year series 1900–1995.
Notes: For the location of stations, see Figure 3.1.
Sources: For data sources, see Table 3.2.

higher with decreasing rainfall averages (compare with Figure 4.11). This finding was to be expected. However, this rule does not apply to recent decades in the Brahmaputra–Meghna systems: the standard deviation rises in parallel with the increasing monsoonal rainfall. This trend is particularly striking in Sylhet. In Dibrugarh, Sylhet, Bogra and Allahabad, the standard deviation is highest in the period 1975–1995. This finding is confirmed by Warrick et al. (1994: 17): "What is striking is the natural year-to-year variation in rainfall, which is quite large. There has also been an apparent increase in rainfall variability during recent decades."

Discussion of the results

Based on the results from Figures 4.10 and 4.11 and the literature statements, a gradual increase in monsoonal rainfall can be observed since the middle of the twentieth century, particularly in the Brahmaputra–Meghna system and to some extent also in parts of the Ganga catchment. Accordingly, an intensification of flooding processes in Bangladesh can be expected. This tendency of increasing monsoonal rainfall towards the end of the twentieth century can be related to the long-term fluctuations in the monsoonal rainfall: a similar situation prevailed in the first part of the twentieth century, when the incidence of severe flooding was rather high too. On the other hand, the trend could be looked at in the context of the climate change scenario for Bangladesh. According to the ADB (1994), the most significant impact on climate for Bangladesh will be during the monsoon season. There are good reasons to believe that an increased temperature gradient between the sea and the Indian subcontinent will produce a higher monsoon rainfall in terms of a longer duration of the monsoon season (i.e. early start and late departure) or in an intensification of the daily rainfall. Another interesting result is the increasing trend both in the inter-annual variability of flood-affected areas, depicted in Figure 4.7, and in the monsoon rainfall, depicted in Figure 4.12. All these findings are much more evident in the Brahmaputra–Meghna system than they are in the Ganga catchment.

Overall, the investigations of rainfall trends discussed in this section seem to indicate that the tendency towards an increasing areal extent of major floods in Bangladesh might be the result more of long-term rainfall fluctuations or even of climate change rather than of human impacts on the Himalayan natural and human-made ecosystems.

4.4.4. Discharge trends in the Ganga–Brahmaputra–Meghna basin in the twentieth century

A second issue of interest related to the findings on flood history (sections 4.4.1 and 4.4.2) is the flow characteristics of the rivers in the

Ganga–Brahmaputra–Meghna basin over time. Trends in monsoon discharge, in peak flows and in inter-annual variability of discharge are particularly worth looking at in this context. For the purposes of this section, hydrological stations were selected for which sufficiently long records are available (see Figure 3.2 and Table 3.3):

- stations in the Himalayan foothills or forelands: Chispani (Karnali River), Narayangarh (Narayani River), Kaunia (Tista River);
- a station in the piedmont area of the north-eastern hills: Sheola (Kushiyara River); and
- stations on the big rivers: Hardinge Bridge (Ganga River), Bahadurabad (Brahmaputra River), Bhairab Bazar (Meghna River).

In general, the investigation covers the period 1955–1995. For the Ganga, the analysis is possible over a 60-year period because the available records go back as far as in 1934. However, it has to be kept in mind that the Farakka Barrage was inaugurated in 1975, which certainly modified the flow of the Ganga. As in the previous sections, the aim here was not to carry out a detailed trend analysis of time series with highly sophisticated statistical methods, but to identify overall tendencies that might be visible in the discharge data series.

The investigation is based on Figure 4.13, which depicts monsoon and August discharge, on Figure 4.14, which illustrates the highest daily flows per year, and on Table 4.7, which provides the results of the statistical trend analysis. In both figures, the stations are clustered into two groups: stations located on the tributaries near the foothills of the mountains (Karnali, Narayani, Tista, Kushiyara) and stations located on the main rivers in Bangladesh (Ganga, Brahmaputra, Meghna). Except for the Ganga, the time axis (*x*-axis) is standardized and covers the period 1955–1995. Accordingly, the graphs can be directly compared. Each river has a different average flow and range of discharge (*y*-axis). In order to achieve comparability of the graphs and interpretations, particularly of the trend lines, the range of the *y*-axis was standardized as follows:

- Graphs of monsoon and August discharge (Figure 4.13): the range of the *y*-axis in each graph represents 20–180 per cent of the average monsoon discharge of that particular station (the average taken as 100 per cent).
- Graphs of maximum daily discharge/year (Figure 4.14): the range of the *x*-axis in each graph represents 20–180 per cent of the average (the average taken as 100 per cent).

The trend analysis in the case of data series with a wide range of variability has to be carried out cautiously. The results can vary significantly depending on which part of the data series is considered, and the trends may even go in opposite directions (e.g. the Narayani River in Figure

4.14: positive trend 1963–1977; negative trend 1975–1985). Except for the Ganga (see the bottom panel of Table 4.7), we therefore refrained from subdividing the data series into different phases and the analysis was carried out for the longest period for which data are available.

General findings

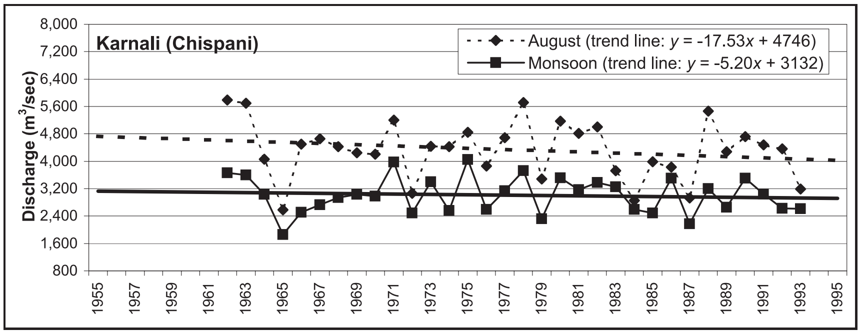
In the graphs documenting the average monsoon and August discharge (Figure 4.13), the range of inter-annual variability is much smaller than in the graphs depicting the highest daily flows per year (Figure 4.14). This is to be expected since short-term hydrological effects are levelled out through the calculation of average monthly figures and the resulting graphs are smoother. Interestingly, very high/low values of daily maximum flows do not necessarily occur in years with high/low August or monsoon discharge. With the exception of the Karnali River, all the discharge trends are positive. However, very few of these trends are statistically significant (see Table 4.7). The following sections present and discuss a regional differentiation of the trend analysis, based on Figures 4.13 and 4.14.

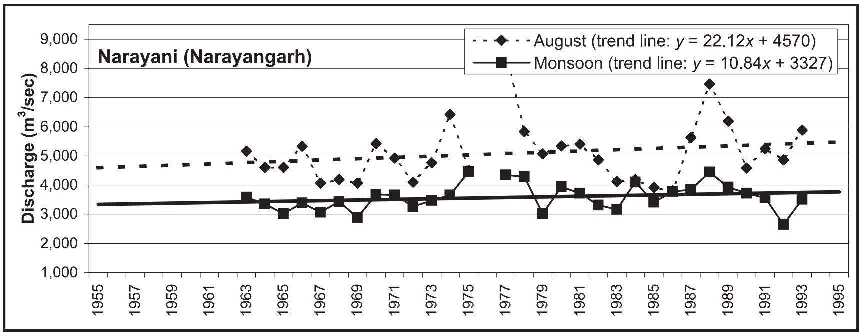
Himalayan foothills (Karnali, Narayani, Tista)

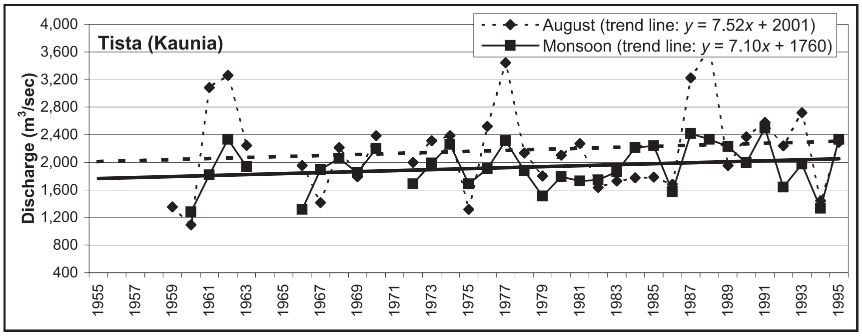
In the Karnali River the trend is negative for all the three variables (August discharge, monsoon discharge, maximum daily discharge per year), but the trends do not reach statistical significance. In the case of the monsoon discharge, the trend is only very weak. For the Narayani and the Tista, a rising trend in all three variables is documented, which is particularly evident for the maximum daily discharge per year. The positive trend in the maximum daily discharge per year on the Narayani River is statistically significant (Table 4.7); the other trends do not reach statistical significance, particularly also in view of the high inter-annual variability. This result is supported by a previous study that looked at hydrological changes in the Western Himalayan catchments of the Indus tributaries Sutlej, Chenab, Beas and Jhelum (Hofer 1993). Analysis of the accessible data series from the 1960s, 1970s and 1980s indicates that there are no statistically significant trends over this period on these rivers.

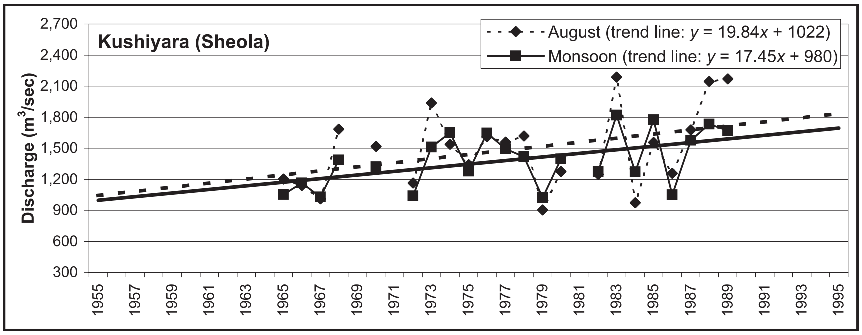
Piedmont zones of the Meghalaya and other north-eastern hills (Kushiyara)

The positive trends in the Kushiyara River flow are striking, being statistically significant in the case of the monsoon discharge as well as the maximum daily discharge per year (Table 4.7). Interestingly, the values in


Karnali (Chispani)
August (trend line: y = -17.53x + 4746)
Monsoon (trend line: y = -5.20x + 3132)
Discharge (m³/sec)
8,000
7,200
6,400
5,600
4,800
4,000
3,200
2,400
1,600
800
1955 1957 1959 1961 1963 1965 1967 1969 1971 1973 1975 1977 1979 1981 1983 1985 1987 1989 1991 1993 1995


Narayani (Narayangarh)
August (trend line: y = 22.12x + 4570)
Monsoon (trend line: y = 10.84x + 3327)
Discharge (m³/sec)
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
1955 1957 1959 1961 1963 1965 1967 1969 1971 1973 1975 1977 1979 1981 1983 1985 1987 1989 1991 1993 1995


Tista (Kaunia)
August (trend line: y = 7.52x + 2001)
Monsoon (trend line: y = 7.10x + 1760)
Discharge (m³/sec)
4,000
3,600
3,200
2,800
2,400
2,000
1,600
1,200
800
400
1955 1957 1959 1961 1963 1965 1967 1969 1971 1973 1975 1977 1979 1981 1983 1985 1987 1989 1991 1993 1995


Kushiyara (Sheola)
August (trend line: y = 19.84x + 1022)
Monsoon (trend line: y = 17.45x + 980)
Discharge (m³/sec)
2,700
2,400
2,100
1,800
1,500
1,200
900
600
300
1955 1957 1959 1961 1963 1965 1967 1969 1971 1973 1975 1977 1979 1981 1983 1985 1987 1989 1991 1993 1995

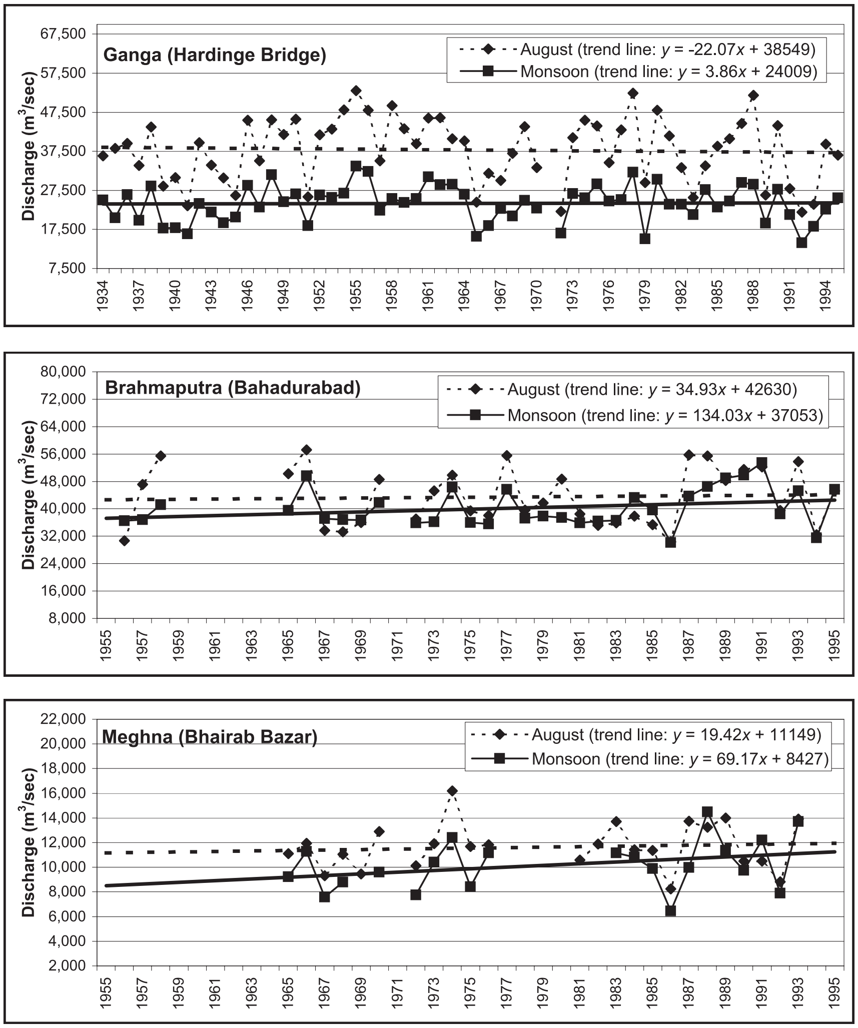


Figure 4.13 August and monsoon discharge of selected rivers in the Ganga–Brahmaputra–Meghna basin.
Notes: For the location of stations, see Figure 3.2.
Sources: For data sources, see Table 3.4.

years with both high August and monsoon discharge gradually increase, whereas the values in years with both low August and low monsoon flows remain more or less constant. This is an indication of an increase in the inter-annual variability of both August and monsoon season flow. In terms of the maximum daily discharge per year, the rising trend is

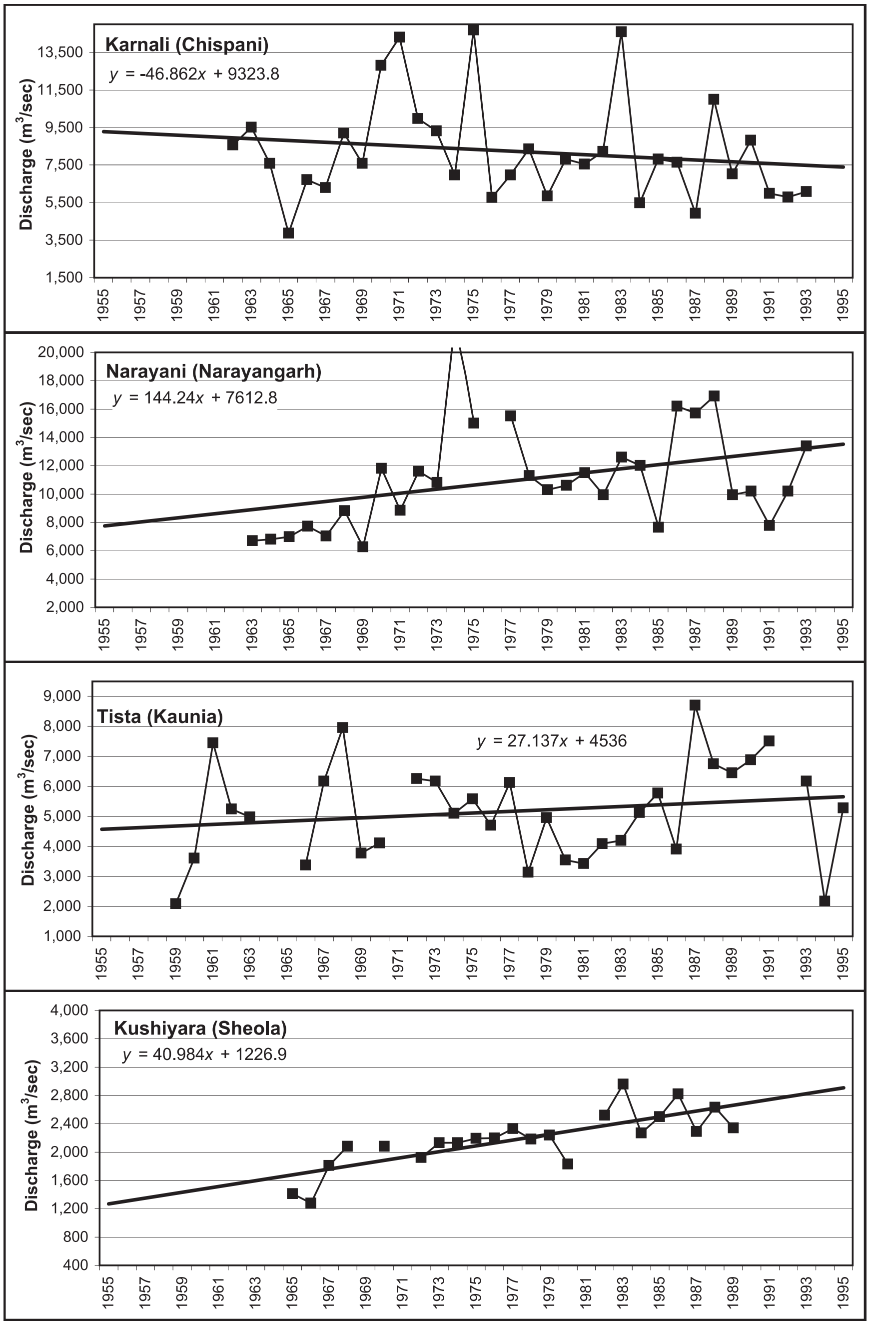


Figure 4.14 Maximum daily discharge per year of selected rivers in the Ganga–Brahmaputra–Meghna basin.
Notes: For the location of stations, see Figure 3.2.
Sources: For data sources, see Table 3.4.

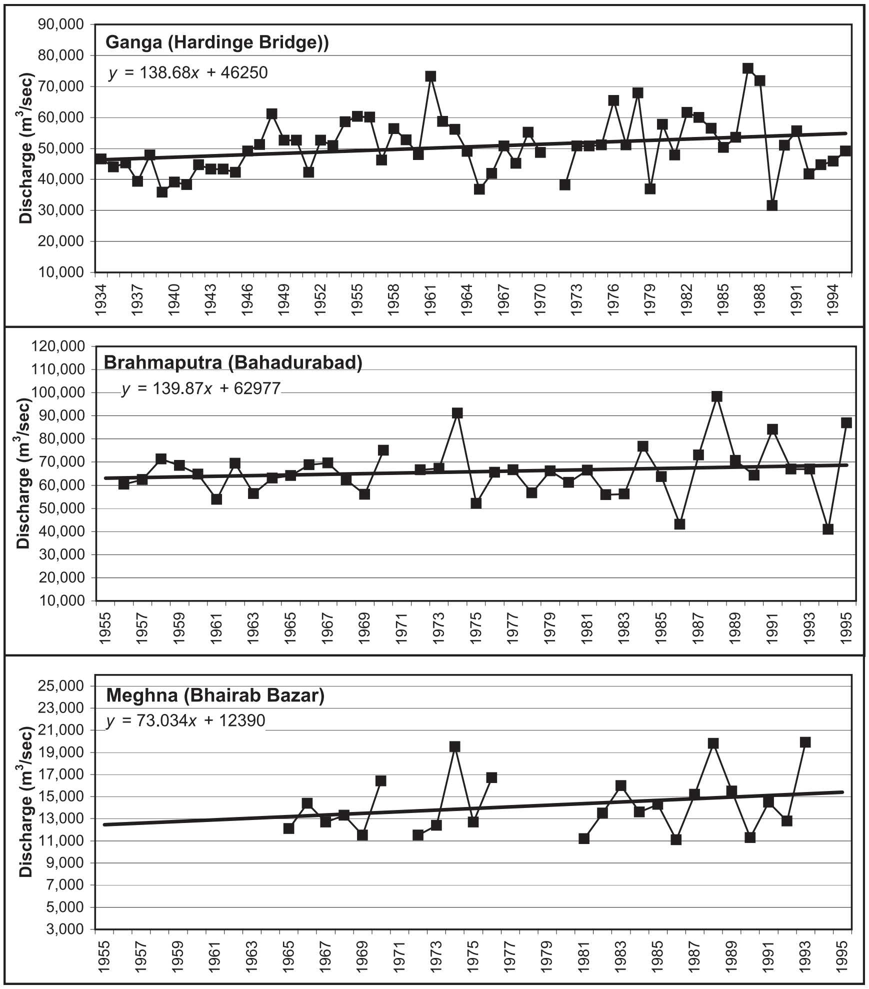


Figure 4.14 (cont.)

constant: the average maximum daily flow is 1,345 m^3/second in 1965–1966, 2,093 m^3/sec in 1967–1980 and 2,541 m^3/sec in 1982–1989. Interestingly, the inter-annual variability is rather small. Based on this investigation it has to be assumed that, as a general tendency, more and more water is contributed each monsoon season from the north-eastern hills to the Meghna River flow. However, it has to be considered that this result is based on the analysis of only one tributary to the Meghna.

Table 4.7 Discharge trends of selected rivers in the Ganga–Brahmaputra–Meghna basin: Analysis of statistical significance

River	Data set	Correlation coefficient	Degrees of freedom	Critical value
Karnali	August	−.1953	31	approx. 0.345
	Monsoon	−.0914	31	approx. 0.345
	Daily max/year	−.1605	31	approx. 0.345
Narayani	August	.1938	29	0.355
	Monsoon	.2195	29	0.355
	Daily max/year	**.3591**	29	0.355
Tista	August	.1301	33	approx. 0.335
	Monsoon	.2256	32	approx. 0.340
	Daily max/year	.1776	32	approx. 0.340
Kushiyara	August	.3915	21	0.4132
	Monsoon	**.5003**	21	0.4132
	Daily max/year	**.7790**	21	0.4132
Ganga	August	−.0490	60	0.250
	Monsoon	.0152	60	0.250
	Daily max/year	**.2720**	60	0.250
Brahmaputra	August	.0455	32	approx. 0.340
	Monsoon	.2637	32	approx. 0.340
	Daily max/year	.1462	38	approx. 0.315
Meghna	August	.0954	23	0.3961
	Monsoon	.3245	20	0.4227
	Daily max/year	.2504	23	0.3961

Ganga 1934–1964 (daily max/year)		Ganga 1965–1995 (daily max/year)	
Regression	$y = 596.17x + 40184$	Regression	$y = 172.97x + 48694$
Correlation coefficient	**.6598**	Correlation coefficient	.1526
Degrees of freedom	30	Degrees of freedom	29
Critical value	0.3494	Critical value	0.355

Notes: Correlation coefficients in bold are statistically significant. For the location of the stations, see Figure 3.2.
Data sources: see Table 3.4.

The big rivers (Ganga, Brahmaputra, Meghna)

For all three rivers, the trend lines of the August discharge are almost horizontal. The monsoon flow is slightly increasing, most prominently for the Meghna River. For the Ganga, this trend is almost negligible for the 60-year period. The maximum daily discharge per year of all three rivers is increasing and reaches statistical significance for the Ganga. This clearly positive trend of the Ganga is the result of the period 1934–1964 rather than the period 1965–1995 (see the differentiated regression analysis presented in the bottom panel of Table 4.7). For all stations, the inter-annual variability of the maximum daily discharge per year rises as a result of both the increase in the high values and the decrease in the low values. Interestingly, the hydrographs of the Ganga do not show any abrupt change in river flow as a result of the construction of the Farakka Barrage, which was inaugurated in 1975 (see Box 4.3). This contradicts Shailo (1988: 7), who states that the flow into the Hugli River (Figure 2.1) is controlled as a result of the Farakka Barrage and that more flood water is diverted through the Ganga to Bangladesh, causing an increase in flood levels. However, as discussed in Liechti (1995), the effect of the Farakka Barrage is very strong in the dry season and is evidenced by a significant decrease of the Ganga flow in Bangladesh.

In the literature there are some interesting references regarding the trends in the Brahmaputra flow in Assam. The 1950 earthquake had a significant impact on the fluvio-sedimentary regime of the Brahmaputra and its tributaries. As a result of this major tectonic event, the lowest water level of the Brahmaputra at Dibrugarh (upper Assam) rose by about 3 metres (Goswami 1998). Panchang (1964) attributes the different phases of rising and falling low-water level of the Brahmaputra at Dibrugarh between 1910 and 1962 to aggradation and scouring of the Brahmaputra river bed. The impact of the 1950 earthquake and of the geomorphological changes in the Brahmaputra river bed at the high-water level is rather difficult to identify: Khale (1998) documents a generally rising trend in the high-water level of the Brahmaputra at Dibrugarh from 1913 to approximately 1967. Information is missing for 1968–1986. The data after 1986 follow a slightly negative trend.

Discussion of the results

With some exceptions, the trends in the flow of the investigated rivers (August discharge, monsoon discharge, maximum daily discharge per year) are generally positive. These trends are most prominent in the Meghna system, with the exceptions mainly relating to the Ganga system. The inter-annual variability of the maximum daily discharge per year of the big rivers is increasing. All these key findings correspond to the positive trends in monsoon rainfall, its regional differentiation and its increasing inter-annual variation identified in the previous section. Furthermore, the findings provide important pieces of the puzzle to explain the tendency towards a larger areal extent of big floods in Bangladesh.

4.4.5. Increasing vulnerability: The socio-economic dimension

Floods are elements of the annual cycle in Bangladesh and are a part of the Bangladeshi's daily life. However, it is obvious that vulnerability to floods and the socio-economic effects of inundations must have increased as a result of population growth, of agricultural intensification and expan-

Box 4.3 The Farakka Barrage: A matter of political tensions

The Farakka Barrage is located on the Ganga River in India, 18 km upstream of the Bangladesh border. The barrage was inaugurated in 1975. The purpose of the structure is to divert the Ganga water into the Hugli system (see Figure 2.1) in order to clear the silt and to improve the navigability of the Hugli River and Calcutta Port. The Farakka Barrage, and in particular the sharing of the dry season flow, has been a subject of conflict between India and Bangladesh for years; in 1976 the case was even taken to the United Nations. Only at the end of 1996 did India and Bangladesh manage to agree on a comprehensive contract for the sharing of the Ganga water.

It is not only the water sharing as such but also the consequences of the reduced Ganga flow for Bangladesh owing to the Farakka Barrage that have been the reason for controversial political, scientific and economic discussions. The following hydrological trends in Bangladesh are generally attributed to the Farakka Barrage (see: Choudhury and Tauhidul 1983; Khan and Miah 1983; MPWRFC 1983; Shahjahan 1983; Zaman 1983; Crow 1985; Rahman 1986):

- *Salt water intrusion*: before the barrage, salt water normally intruded 274 km inland; it now intrudes 434 km.
- *Degeneration of freshwater plant life throughout the delta*: the Forest Department estimates that Bangladesh has lost some 1.44 million m^3 of Sundari alone (the most important tree species in the coastal zone) since 1976 with a value of US$100 million.
- *Impacts on power production*: because of high water salinity, the largest power plant in the western grid of Bangladesh is forced to run its boiler on water imported from 30 miles upstream, thus increasing production and operating costs. In 1981, electricity production had to be stopped for several months in order to replace corroded condenser tubes. This caused production losses in the industrial belt of Khulna and Jessore.
- *Impact on groundwater*: the groundwater table in the basin area has fallen. This has affected the use of low-lift pumps for irrigation. Bangladesh lost more than US$1,000 million worth of crops in the seven years after the Farakka Barrage was commissioned.
- *Effects of reduced flow*: the reduced flow of the Ganga is no longer able to flush away the rotting vegetation, insecticides and industrial wastes that are dumped in the river. Water temperatures have increased, resulting in a shortage of oxygen. The population of over 200 species of freshwater fish and 18 species of prawns, both very important in the economy of Bangladesh, has been seriously affected.

Box 4.3 (cont.)

- *Impacts on traffic*: the inland waterway traffic in south-west Bangladesh was reduced by 11 million tons in 1975/76 and 1976/77. Throughout the country, the total length of waterways suitable for mechanically propelled vessels such as motorized launches, steamers and coasters has shrunk from 24,000 km to 4,800 km.

It is not intended to discuss these issues further. It is obvious, though, that the Farakka Barrage has had an impact on the hydrology further downstream. Therefore the barrage has to be taken into consideration in the analysis of discharge trends of the Ganga and in the discussion of flood history in Bangladesh.

For further references to the political aspects of Himalayan water resources management and to the Farakka Barrage, see Begum (1987), Abrar (1994), Bandyopadhyay and Gyawali (1994a,b), Dixit and Gyawali (1994), Gyawali and Schwank (1994), Hofer (1994).

sion, of the elimination of water storage areas (beels, swamps) and finally of increased construction (settlements, roads, embankments, etc.). Using a few data sets for Bangladesh and Assam, we attempt to look into these issues and to document these trends. A number of variables are linked to these issues, but they have hardly any relevance for the interpretation in this section. Generalized demographic and agronomic statistics provide only indirect reference to vulnerability issues. Statistics about monetary losses from floods are not appropriate owing to inflation or currency devaluation trends over time. Statistics on crop damage are useful but are not available on a regular basis. Therefore data sets on flood-affected people, which are fairly complete, were the principal information used for this investigation. However, interpretation of these data sets is difficult: depending on the regional pattern of the floods, the number of people affected in different years may vary considerably even when the depth of the flood water and duration of the inundation are comparable. The definition of ‘‘flood affected’’ is another grey area in terms of these statistics. In view of these difficulties and uncertainties it would be inappropriate to use the data sets for detailed comments or even final conclusions. The following discussion provides a few thoughts and ideas about flood-induced vulnerability.

Demographic trends in Bangladesh

As is generally the case in developing countries, Bangladesh has faced a huge increase in population since 1872 (see Figure 4.15): the number of

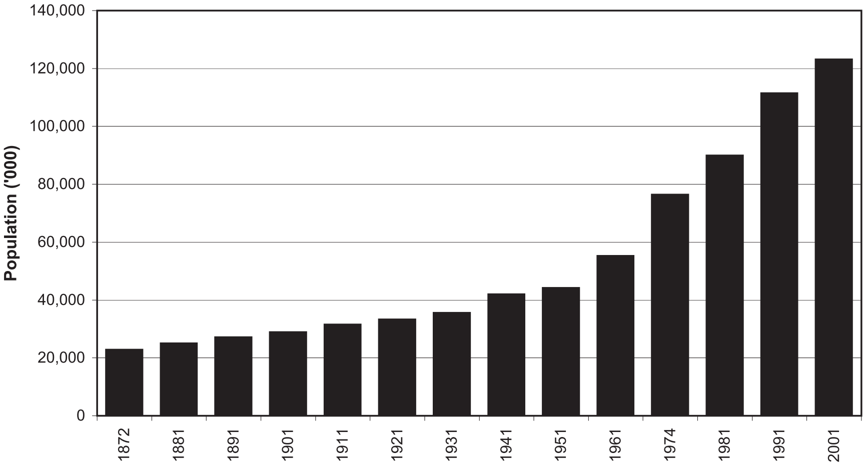


Figure 4.15 Population development in Bangladesh, 1872–2001.
Sources: Bangladesh Bureau of Statistics (1993, 2005), Rahman et al. (1994).

people in 2001 was almost six times higher than the number in 1872. Between 1872 and 1951 the increase was gradual and constant, leading to a doubling of the population over a period of 80 years. From 1951 to 2001 the increase was drastic and resulted in a tripling of the population in only 40 years.

It would be wrong to assume that along with this population increase there was a gradual encroachment on originally ‘‘empty’’ floodplains by settlements and agriculture. This may be true for areas of beels and swamps that served as natural storage areas for flood water, but not for the floodplains themselves. Based on the interpretation of maps from the British period dating back to the beginning of the twentieth century (Zumstein 1995) and according to information provided by old people in Bangladesh, the floodplains have always been preferred areas for settlements and agricultural activities owing to their high soil fertility. The reality therefore seems to be that the increase in population, particularly during the second part of the twentieth century, has led to a significant increase in the population density in the floodplains of Bangladesh and a decrease in the size of land holdings per family (see Table 4.8). It is obvious, therefore, that the vulnerability of the people to floods must have significantly increased. There is diminishing flexibility to cope with flood hazards and to apply traditional strategies of flood management. Owing to the smaller size of land holdings, the probability increases that a flood event will damage the entire crop of one family and force farmers to sell their land in order to survive. In view of such considerations, the effects

Table 4.8 Per capita land holdings in Bangladesh, 1950–1985 (hectares)

Year	Per capita land holdings
1950	0.400
1960	0.325
1970	0.230
1985	0.159

Note: based on a study of six villages.
Source: Ali (1992).

of floods and the attention given to inundation processes must increase even without hydrologically significant positive trends.

Flood-affected people in Bangladesh

Figure 4.16 includes both variables: the flood-affected areas and the flood-affected population. Information for the latter was mainly extracted from the USAID (1990) database, which lists all the major disasters worldwide on an annual basis. The gaps in the data set show that Bangladesh obviously does not provide information on a regular basis, although it is certain that people are affected by floods every year. It is unfortunate that the data are missing after 1995 since the flood in 1998 was particularly severe.

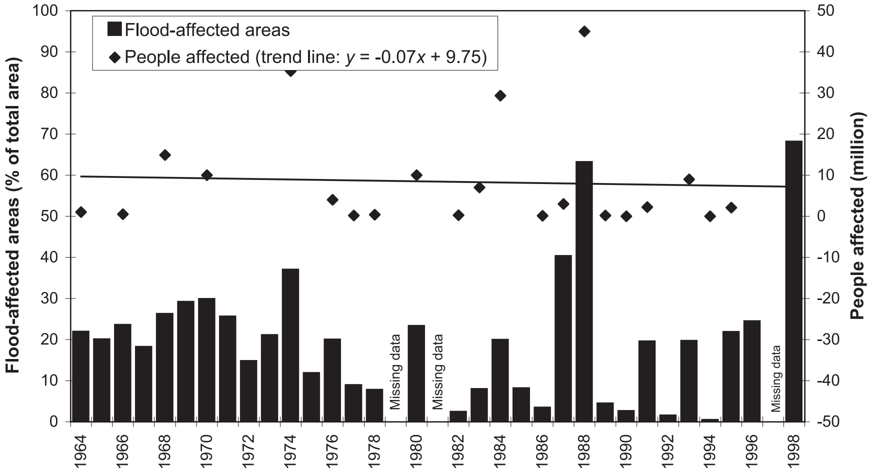


Figure 4.16 Flood-affected areas and people affected by floods in Bangladesh, 1964–1998.
Sources: BWDB (1991a, n.d.[a]), USAID (1990).

The number of people affected by inundations is primarily a function not of the total areal extent but, more importantly, of the regional pattern, duration and depth of the inundation. This finding results from the following observations. In relative terms, the figures for flood-affected areas and people affected by floods seem to be related: if the flood-affected area in a specific year is comparatively high, then the number of people affected by floods tends to be high as well, and vice versa. In absolute terms, however, this relationship does not really exist:

- 1984: a large number of people were affected in spite of only average flooding;
- 1987: a large area was affected by floods but the number of affected people was average;
- 1964, 1980, 1984, 1991, 1993: the flood dimension was comparable, but there was a big difference in the number of people affected.

The trend line for the number of flood-affected people in Figure 4.16 is almost horizontal, which differs from the expected rising trend of this line. Why is there a mismatch between expectations and reality? Is the assumption that population increase leads to higher vulnerability incorrect? Are people becoming better prepared as a result of improved early warning systems? Do they get greater flood protection from lateral river embankments? Or is this mismatch simply a question of an inconsistent definition of ‘‘affected people’’, of changing procedures for data recording and reporting? At this stage we are not in a position to give a clear interpretation. Nevertheless, there does not seem to be any reason to assume that the number of people affected by flooding in Bangladesh is gradually increasing.

Flood-affected people in Assam

Owing to the existence of a complete data set over 40 years, a short glance over the Bangladeshi border to the Brahmaputra Valley in Assam (India) is worthwhile (Figure 4.17). Again, both the flood-affected areas and the number of people affected by floods are depicted. Similarly to the findings for Bangladesh, the two variables are related in relative, but not in absolute, terms (compare 1987 and 1988). Whereas the trend line of the flood-affected areas is almost horizontal, the number of people affected by floods is gradually increasing. With a correlation coefficient of .4559, this trend is statistically significant. In Assam, the expected increase in the number of flood-affected people is indeed documented.

Reflection on the findings

Based on the demographic statistics and on land-holding figures, it is obvious that the vulnerability of the Bangladeshi population to floods and

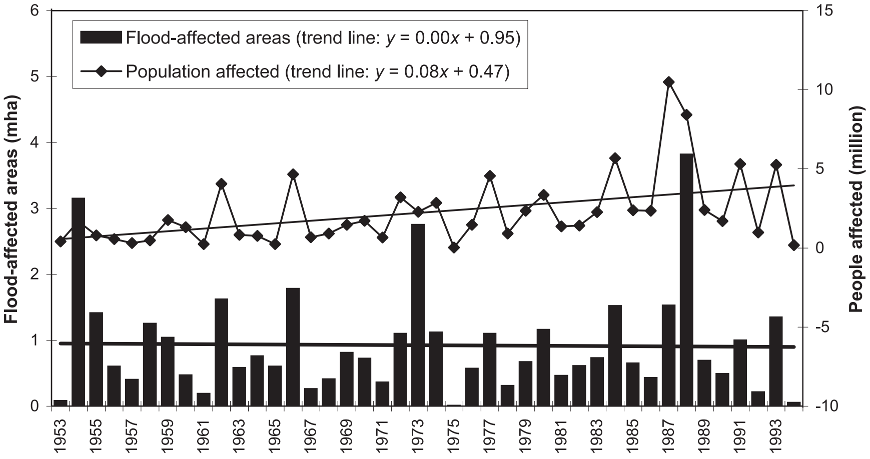


Figure 4.17 Flood-affected areas and people affected by floods in Assam, 1963–1994.
Source: Goswami (1998).

the attention given to these phenomena must have increased. “The increasing intensity of land use in flood prone areas may account for the progressive increase in the economic damage” (Hughes et al. 1994: 21). However, these trends are very difficult to document with data series representing the number of flood-affected people.

The following quotation (Verghese 1990: 132–133) supports most of the findings of this section and puts them into an even larger context:

> To deduce that floods have really increased would be misleading. More accurately, the effects of flooding are greater as is the trend in the U.S., Japan and elsewhere. With development and population increase and the sense of security that goes with flood protection, drainage has deteriorated and the flood plain has been increasingly invaded for agriculture, settlement and other development purposes. Even char lands, which belong to the river, or the floodways between embankments and the beds of drains have been cultivated. Wetlands and spill channels have been reclaimed or allowed to choke with silt and hyacinth. A population of two million has been settled in the Trans-Yamuna area of Delhi within the active flood plain of the river. Salt Lake in Calcutta has been reclaimed. Yet the same volume of rainfall and discharge, sometimes with extraordinary cloudbursts, must pass through even more restricted channels without the benefit of “bank storage”. It is something like traffic jams on the roads with pavement dwellers and stalls crowding the sidewalks, forcing pedestrians on to the highway along which cars are parked with abandon.

On the vulnerability issue, Aminul Islam made a very important statement during our seminar in October 1994 in Dhaka: ''Flood problems become particularly acute in Bangladesh because of under-development, over-population, under-employment and poverty. If there were large landmass and the people had alternative livelihoods, nobody would have bothered to go to the fringe areas to suffer from floods.''

4.5. The main findings

From the Tertiary to the present time, and more precisely defined and dated in the last 20,000 years, the large depositions in the Bangladesh delta indicate that massive floods must have occurred regularly long before humans' impact on the large watersheds of the big rivers began.

In the eighteenth and nineteenth centuries a number of major floods were recorded. Fluctuations in flood frequency correspond to fluctuations in the monsoon rainfall. The catastrophic flood of 1787 was associated with an earthquake and resulted in major river course changes in the territory of modern Bangladesh.

The flood history in the lowlands of the Ganga and Brahmaputra shows considerable regional differentiation. There is no statistical evidence that the frequency of major floods in Bangladesh has increased from 1890 to the present. There is some evidence, however, that the inter-annual variation in the extent of flooding and the areal extent of big events has been increasing since 1950, in spite of the general improvement in the forest situation in at least parts of the Himalayas over recent decades.

There is a generally increasing trend of monsoonal rainfall and of its inter-annual variability, particularly in the Brahmaputra–Meghna system.

With a few exceptions, there are generally positive discharge trends for the investigated rivers during the monsoon period. They are most prominent in the Meghna system. Only a few of these trends are statistically significant. Furthermore, the inter-annual variability of the maximum daily discharge per year of the big rivers is increasing. Natural events (e.g. earthquakes) play a very important role in shaping the discharge behaviour of the rivers over time.

The trend towards higher inter-annual variation in the extent of flooding and the tendency towards a larger extent of the big events can be related to similar trends in rainfall and discharge patterns, and thus to natural processes. However, human-made influences on the extent of flooding, such as encroachment on the natural storage areas for flood water or the construction of embankments, must also be taken into consideration, even if these impacts are very difficult to quantify.

Based on demographic statistics and on land-holding figures, it is obvious that the vulnerability of the Bangladeshi population to floods must have increased. Such trends, however, are very difficult to document.

There is no reason to assume that anthropogenic activities in the Himalayas have had any significant impact on flooding conditions in Bangladesh. Accordingly, the statements in the newspaper article quoted in the introduction to this chapter cannot be confirmed by this investigation.

5

Understanding Bangladesh floods in the context of highland–lowland linkages

5.1. Introduction

“Bangladesh in grave danger: deforestation in Himalayas aggravating floods” (*Bangladesh Observer*, 2 June 1990).

As already highlighted in section 4.1, the author of this headline, like many others, makes a direct and causative link between human activities in the Himalayas and the flood processes in the plains. The considerable doubts that have been raised within the scientific community regarding the accuracy of this simplified perception have already been presented in Chapter 1.

The discussions in this chapter focus on understanding the flood processes in Bangladesh in the context of highland–lowland linkages. This aspect constituted the most important core theme of the project (see Figure 1.1). Accordingly, this chapter, together with 11 appendices, forms the most prominent part of this book in terms of length, content and innovative approaches. The complexity of the factors leading to inundations also receives attention here. The question of whether the triggers for the floods in Bangladesh are located in the Himalayas is the guiding theme. Within this overall context, the following specific questions need to be answered:

1. What is the contribution from the different areas in the highlands and lowlands of the Ganga–Brahmaputra–Meghna basin to the hydrologi-

cal system and what is the relevance of these areas and their hydrological contribution to the flood processes in Bangladesh?
2. What are the spatial patterns of the hydro-meteorological conditions in the Ganga–Brahmaputra–Meghna basin in specific years and where are the most important hydro-meteorological anomalies, compared with the long-term average?
3. What are the combined effects of different physical factors such as rainfall, river discharge, groundwater level and tidal movements on flood processes in Bangladesh and is it possible to prioritize specific parameters?
4. Is it possible, through the investigation of specific years, to identify a pattern of repeating or recurring combinations of factors or is each flood event an individual combination of factors?

Information related to these questions is very scanty and limited in the existing literature, as can be seen in Box 5.1. There are discussions of specific flood events in some of the references. However, as already pointed out in section 1.3, no attempt has been made so far to analyse flood events systematically by applying consistent and standardized methodologies and by comparing the findings. In addition, the existing reports usually are restricted to the discussion of the flood processes in the affected areas themselves without taking a broader view of the hydro-meteorological patterns in the entire Ganga–Brahmaputra–Meghna basin.

It was decided to approach the complex questions listed above by analysing and discussing the flooding conditions and processes in specific years, subsequently referred to as "case studies". Altogether, 11 case studies, selected from the period 1900–2000, will be presented and compared in this chapter as well as in the 11 appendices (for more details about how the presentation of the case studies is structured, see section 5.3). Eight of these case studies deal with years characterized by above-average or even extraordinary flooding conditions within Bangladesh. In order to identify important differences between contrasting situations and in order to sharpen understanding of the specific processes leading to widespread flooding, we added to the list of case studies two years in which the extent of flooding in Bangladesh was particularly low and one year with more or less average flooding conditions. The flood dimension within Bangladesh was the main selection criterion for the case studies. We based the identification of case studies before 1950 on descriptive, qualitative sources (see also section 4.4.1), and the selection of the case studies after 1950 on the flood statistics of Table 4.1 by using the following clusters: "flood years" (>30 per cent flood-affected areas), "dry years" (<10 per cent flood-affected areas), and "average years"

Box 5.1 Literature statements on flooding in Bangladesh related to highland–lowland linkages

The literature does not provide a clear answer to whether floods in Bangladesh are primarily the result of events in Bangladesh itself or strongly influenced by processes outside the country. For some authors the external input is the dominant factor; for a number of others heavy rainfall within Bangladesh is important; and, finally, a number of authors are of the opinion that the combination of internal and external factors is the cause of severe floods. There are even some statements that place more importance on rainwater than on river water for the generation of floods in Bangladesh.

- ‘‘One of the main causes of flood in Bangladesh is heavy intense rainfall over the vast catchment area of the rivers of Bangladesh, most of which (93%) lies outside the country. Local rainfall also sometimes causes floods in different times.’’ (BWDB 1975: 39)
- ‘‘A most significant contribution to flooding is the inflow of the main rivers from India, and rainfall in Bangladesh is not necessarily an indicator of conditions elsewhere over the catchments.’’ (BWDB 1991a: 48)
- ‘‘The main influx of flood water comes from outside Bangladesh.’’ (Hossain et al. 1987: 7)
- ‘‘Snowmelt and rainfall produce a large water flow from the Himalayas.’’ (Hossain et al. 1987: 8)
- ‘‘Due to urbanisation and agricultural development in India and Nepal, the problems of flooding and sedimentation are worsening.’’ (Huda 1989: 119)
- Even without river water in the flat topography huge areas would be inundated only by rainwater. (Rasid and Paul 1987: 159)
- ‘‘On the monthly basis it was found that a significant correlation exists between Brahmaputra and Meghna flows and rainfall over Bangladesh.’’ (GOB 1992a: 6–8)
- ‘‘The rapid leaching of most flood-plain topsoils confirms field observations that most river and estuarine flood-plains are not flooded by river water. They are flooded with rainwater or the risen groundwater table derived from the heavy monsoon rainfall which is ponded on the land by high monsoon season river levels.’’ (Hossain et al. 1987: 54)
- The correlation between the mean annual rainfall in the catchment area of the Ganga and the discharge at Hardinge Bridge is not evident. (GOB 1992a: 6–8)

Box 5.1 (cont.)

- “Under the existing geophysical conditions in the country the amount of runoff generated by rainfall within the country may not be sufficient to cause flooding in Bangladesh. But it is a critical factor aggravating the hydrological situation in the country.” (Ahmad 1989: 24)
- The external contribution is not the same throughout the monsoon season. As the monsoon season in Bangladesh is longer than in north-western India, the contribution to the floods from the country is significant in the beginning and the end of the monsoon season. In the middle of the rainy season the external contribution is important. (GOB 1992a)
- “Though there may not be much rainfall locally, there may be heavy rainfall in the catchment area causing flood. Of course, if there is rainfall in Bangladesh as well, flood will worsen.” (Choudhury 1989: 235)

(10–30 per cent flood-affected areas). The selection process resulted in the following 11 years (monsoon seasons) that were analysed as case studies and that will be presented in this chapter as well as in the appendices:

- “flood years”: 1906, 1910, 1922, 1955, 1974, 1987, 1988, 1998
- “dry years”: 1923, 1978
- “average flood year”: 1993

Question 1 formulated for this chapter is obviously the most important, the most difficult and the least explored one. It requires a regionalization of the river basin into different subcatchments. In view of the limited experience related to the analysis of Bangladesh floods in the context of large-scale highland–lowland linkages and especially also the difficult data situation (see Chapter 3, Tables 3.1 and 3.3 in particular), it is not possible to approach this challenging question with the usual procedures of hydro-meteorological regionalization and analysis of rainfall–discharge relationships. Therefore, new and innovative procedures had to be developed to use the existing information, particularly the precipitation data, in order to estimate the potential runoff from subcatchments as well as to assess the relevance of these contributions to the flood processes in Bangladesh. In section 5.2, we discuss the methodology that was developed to approach these questions step by step, before embarking on the presentation of the case studies.

5.2. Methodology

5.2.1. Delimitation of subcatchments (step 1)

The task of the first step in the development of this methodology was to structure the Ganga–Brahmaputra–Meghna basin into different subcatchments. In the literature, several attempts to regionalize the Indian subcontinent are available (Kulkarni et al. 1992; Gadgil et al. 1993; Iyengar and Basak 1994). For the following reasons these regionalizations did not fulfil the requirements of the project:

- The regionalizations are based on precipitation patterns only and do not include other parameters such as the catchment boundaries of rivers, highlands and lowlands, etc.
- The regionalizations usually are made for the whole of India, which goes far beyond the Ganga–Brahmaputra–Meghna basin, but they do not include Bangladesh.

Therefore a new regionalization of the Ganga–Brahmaputra–Meghna basin was developed that resulted in the delimitation of 13 areas, referred to throughout the book as ‘‘subcatchments’’ (Figure 5.1). For the delimitation of these subcatchments, criteria were used that are important for the analysis of the flood processes in the highland–lowland context: watershed boundaries; political boundaries (owing to their implications for the data sets); topographical boundaries (mountains, hills and plains); available information and documents (such as rainfall distribution maps). Tibet, the eastern Himalaya and the headwaters of the Meghna system have been excluded owing to a complete lack of data.

Some specific comments are necessary to clarify the delimitation of some subcatchments (SCs):

- SC1, SC2: the areas located beyond the highest Himalayan peaks are excluded (dry conditions). For SC2, the southern border of the subcatchment corresponds to the political boundary between India and Nepal.
- SC4, SC5: these two subcatchments, which include primarily the Indian Ganga Plain, are huge because the catchment of the Ganga extends far south into the Indian peninsula.
- SC6, SC13: the southern border basically corresponds to the mainland of the delta, excluding the vast areas where land and ocean interact (islands, swamps, ocean channels).
- SC9: the southern and western borders correspond to the political boundaries between India and Bangladesh. The northern and eastern delimitation includes the areas of very high precipitation of the Meghalaya Hills. Although most of SC9 belongs to the Meghna catchment, the northern strip discharges into the Brahmaputra system.

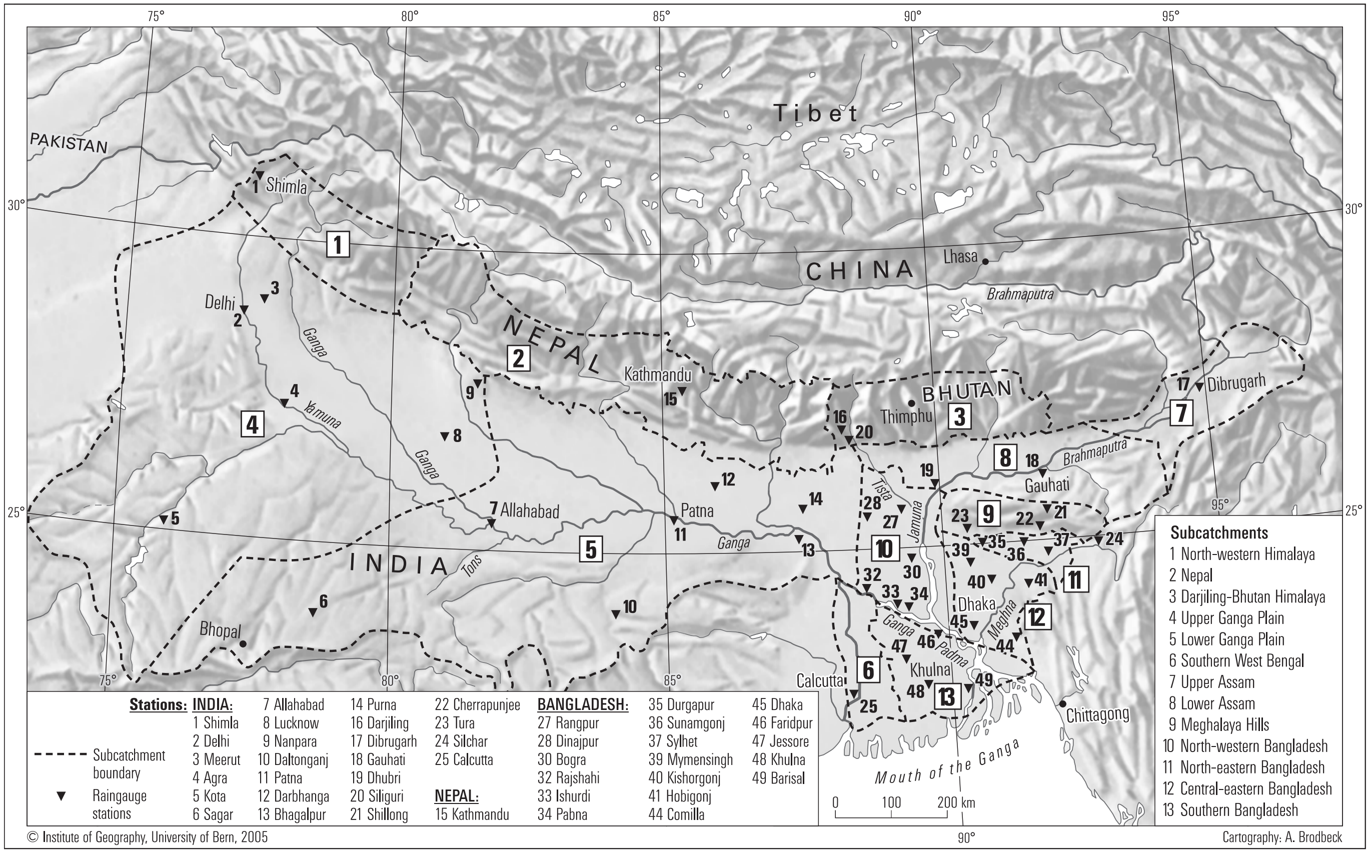


Figure 5.1 The 13 subcatchments as defined for the project.

Notes: The raingauge stations on the map are those that were used for the development of the methodology and the resulting data sets (for the full set of raingauge stations available for the project, see Figure 3.1).

Table 5.1 lists the 13 subcatchments with their specifications. Precipitation is very important in the discussion of this chapter (see section 5.2.3) and therefore the raingauge stations located in each subcatchment that were used for the development of the methodology and the resulting data sets are listed in Table 5.1 as well. The number of stations per subcatchment varies significantly. This is because the density of raingauge stations for which data were accessible is higher in Bangladesh than in India or Nepal. Indeed, some areas, e.g. the three Himalayan subcatchments SC1, SC2 and SC3, are represented by only one station each in the analysis of the case studies after 1950. Although there are currently more climatological stations, particularly in Nepal, most of these stations were established only in the 1970s and do not provide sufficiently long data series for our purposes (less than 50 years). It is evident from Table 3.1 that the list of meteorological stations for which precipitation data were available is not identical before and after 1950. This situation is specified in the notes to Table 5.1.

5.2.2. Definition of inner-annual time periods (step 2)

Floods in Bangladesh usually occur during the monsoon season, from June to September. Therefore the investigations must focus on these four months. However, in specific years the hydro-meteorological conditions before the monsoon season must be taken into consideration as well:

- If in April or May heavy pre-monsoon rains occur in Bangladesh, as was the case in 1974 in the southern parts (see Appendix 5.5) and in 1988 in all parts of the country (see Appendix 5.7), then the humidity of the soils might be above average and the groundwater table higher than normal at the onset of the monsoon and consequently the absorption capacity for rainwater might be reduced. In such a situation the probability of widespread flooding is potentially higher than after a dry pre-monsoon period.
- If the period January–March has been comparatively humid, as was again the case in 1974 in the southern parts and in 1988 in all parts of Bangladesh, then the groundwater level in Bangladesh might not drop as usual during the winter. In the subsequent monsoon season the groundwater table might reach the surface much faster than after a dry winter season.
- After a humid winter or pre-monsoon period, the water levels in the rivers might already be higher than usual at the onset of the monsoon. The probability of river overflow might be higher than after dry conditions from January to May.

Based on such considerations, six time periods in the year were defined for the investigations: January–March (winter); April–May (pre-

Table 5.1 The 13 subcatchments, their size and the raingauge stations that were used for the development of the methodology and the resulting data sets

Subcatchment	Region	Area (km^2)	Raingauge station	No.	Used for[a]
SC1	North-western Himalaya	51,765	Shimla	1	A
SC2	Nepal	123,336	Kathmandu	15	C
SC3	Darjiling–Bhutan Himalayas	41,925	Darjiling	16	A
			Siliguri	20	B
SC4	Upper Ganga Plain	350,907	Delhi	2	C
			Meerut	3	B
			Agra	4	C
			Kota	5	C
			Lucknow	8	B
SC5	Lower Ganga Plain	340,349	Sagar	6	C
			Allahabad	7	A
			Nanpara	9	B
			Daltonganj	10	C
			Patna	11	A
			Darbhanga	12	C
			Bhagalpur	13	B
			Purna	14	B
SC6	Southern West Bengal	21,766	Calcutta	25	C
SC7	Upper Assam	38,021	Dibrugarh	17	A
SC8	Lower Assam	59,999	Gauhati	18	A
			Dhubri	19	B
SC9	Meghalaya Hills	20,845	Shillong	21	C
			Cherrapunjee	22	A
			Tura	23	B
SC10	North-western Bangladesh	39,168	Rangpur	27	A
			Dinajpur	28	C
			Bogra	30	A
			Rajshahi	32	C
			Ishurdi	33	C
			Pabna	34	B
SC11	North-eastern Bangladesh	8,987	Durgapur	35	C
			Sunamgonj	36	C
			Sylhet	37	A
SC12	Central–Eastern Bangladesh	27,413	Mymensingh	39	A
			Kishorgonj	40	C
			Hobigonj	41	C
			Comilla	44	C
			Dhaka	45	A
SC13	Southern Bangladesh	33,494	Faridpur	46	C
			Jessore	47	C
			Khulna	48	A
			Barisal	49	C

Notes: For the location of the subcatchments, see Figure 5.1.

[a] A = stations used for all case studies; B = stations used for case studies before 1950 only; C = stations used for case studies after 1950 only.

monsoon); and June, July, August and September (monsoon). The post-monsoon period from October to December obviously has no relevance for the questions dealt with here and was therefore excluded.

5.2.3. Calculation of areal precipitation and precipitation volume for the 13 subcatchments (step 3)

A principal aim of the investigations was to estimate the hydrological contribution of the 13 subcatchments to the overall river system in the six defined time periods, on average and in specific years. In order to achieve this, a database on areal and volumetric precipitation had to be established. As is evident from Table 3.1 and Table 5.1, two data sets had to be created based on slightly different lists of stations:

- for the case studies before 1950, the stations in categories A and B were used, and the reference period for the calculation of the average figures is 1891–1950;
- for the case studies after 1950, the stations in categories A and C were used, and the reference period for the calculation of the average figures is 1900–1990.

Table 5.2 provides an example of the data sheet for areal precipitation and precipitation volume that was used for the case studies after 1950.

Areal precipitation

Areal precipitation is the average height of precipitation (mm) occurring over the area of a subcatchment in a defined unit of time. In principle, areal precipitation was calculated as the average of all the stations represented in the relevant subcatchment. However, because the number of stations per subcatchment differs considerably (Table 5.1 and Figure 5.1), a subcatchment-specific discussion of the methods used for the calculations is required.

Areal precipitation in SC4, SC5, SC10, SC11, SC12 and SC13

Each of these subcatchments is represented by several raingauge stations. Calculations have shown that the precipitation patterns recorded at the different stations within each subcatchment are, in general, well correlated with each other. This indicates that the records of each station, as well as the resulting areal precipitation data, are representative of the precipitation conditions in the relevant subcatchment.

Areal precipitation in SC9

This subcatchment is represented by two stations – Cherrapunjee and Shillong (Tura for the case studies before 1950). The amount of precipitation recorded at these stations usually differs considerably, with Cherrapunjee reaching among the highest values in the world. Assuming that:

- the entire southern slope of the Meghalaya Hills is characterized by conditions similar to those in Cherrapunjee and represents approximately one-third of SC9, and
- the remaining two-thirds of SC9 receives less precipitation compared with the records for Shillong (Tura),

the areal precipitation of SC9 was calculated as twice the precipitation of Shillong (Tura) plus once the precipitation of Cherrapunjee, and the resulting total was divided by three. In this calculation, Shillong (Tura) is given double the importance of Cherrapunjee. Although this approach is an approximation, the resulting areal precipitation figures for SC9 are certainly more accurate than if Cherrapunjee and Shillong (Tura) had been given equal weight.

Areal precipitation in SC1, SC2 and SC3

According to Figure 5.1 and Table 5.1, the three Himalayan subcatchments are represented by only one station each (although SC3 was represented by two stations before 1950). Whereas Shimla and Darjiling are hill stations located on the first Himalayan ridges, Kathmandu is situated in a basin within the Middle Hills of Nepal. It is obvious that the approach of using only one station for the calculation of areal precipitation is risky and that the considerable regional variability of precipitation in the Himalayas is ignored. Unfortunately the data situation does not leave us with any other option. However, according to Question 2 above, the precipitation anomalies or variations from the average will be more important for the analysis of the case studies than the amount of precipitation per se. In this perspective, the one-station approach is acceptable: the key question must be whether the precipitation data for the three stations represent, more or less, the general precipitation patterns of their relevant subcatchments in terms of variations from the long-term average. To check the appropriateness of this procedure, additional raingauge stations were included for which only short-term records exist, but which provide sufficient information over a certain time period:

for SC1: Chakrata and Mussoorie (both located to the east of Shimla);
for SC2: Butwal, Pokhara and Chispani (located to the south-west and west of Kathmandu), Okhaldunga (located to the east of Kathmandu); and
for SC3: Bathpalithang (located to the east of Darjiling in Bhutan).

Subsequently, the correlations of the monthly precipitation variations among the stations within the three subcatchments were calculated and all the correlations gave statistically significant results. This indicates that Shimla, Kathmandu and Darjiling can be considered representative

Table 5.2 Areal precipitation (P(areal)) and precipitation volume (P(vol)) for subcatchment 12: Example of a data set used for the case studies after 1950

	Jan–Mar		Apr–May		Jun		Jul		Aug		Sep	
Year	P(areal) mm	P(vol) 10^6 m^3	P(areal) mm	P(vol) 10^6 m^3	P(areal) mm	P(vol) 10^6 m^3	P(areal) mm	P(vol) 10^6 m^3	P(areal) mm	P(vol) 10^6 m^3	P(areal) mm	P(vol) 10^6 m^3
Av. 1900–1990	*86*	*2,358*	*481*	*13,186*	*439*	*12,034*	*403*	*11,047*	*383*	*10,499*	*301*	*8,251*
1950	71	1,948	282	7,732	495	13,571	168	4,617	515	14,107	124	3,405
1951	36	985	325	8,907	531	14,562	492	13,480	409	11,208	238	6,518
1952	56	1,523	587	16,086	421	11,529	447	12,267	315	8,630	392	10,736
1953	103	2,832	438	12,008	538	14,745	415	11,367	356	9,749	528	14,469
1954	76	2,083	338	9,252	719	19,701	337	9,229	301	8,242	255	6,977
1955	51	1,398	256	7,027	369	10,115	567	15,543	426	11,678	256	7,027
1956	121	3,326	367	10,051	618	16,941	515	14,127	534	14,648	339	9,293
1957	156	4,276	166	4,560	480	13,158	341	9,348	413	11,331	281	7,712
1958	111	3,034	329	9,019	275	7,548	235	6,451	520	14,264	175	4,788
1959	176	4,834	376	10,298	509	13,962	273	7,493	642	17,590	277	7,603
1960	45	1,234	327	8,973	347	9,503	543	14,885	293	8,023	421	11,550
1961	22	612	402	11,009	575	15,759	293	8,025	320	8,763	167	4,580
1962	30	828	488	13,389	376	10,303	305	8,368	356	9,747	167	4,577
1963	49	1,337	374	10,264	596	16,345	408	11,188	221	6,056	262	7,169
1964	70	1,920	503	13,788	483	13,251	660	18,082	289	7,922	381	10,455
1965	52	1,434	269	7,381	540	14,812	403	11,046	575	15,767	291	7,984
1966	50	1,379	280	7,665	405	11,104	334	9,162	455	12,467	324	8,881
1967	123	3,385	353	9,682	226	6,199	388	10,631	381	10,432	354	9,700
1968	53	1,446	439	12,030	477	13,089	442	12,121	268	7,356	209	5,739
1969	116	3,182	328	8,994	553	15,160	322	8,814	583	15,976	251	6,871
1970	64	1,751	306	8,387	456	12,501	538	14,741	295	8,099	194	5,324
1971	93	2,536	926	25,383	476	13,040	513	14,072	557	15,282	420	11,511

1972	99	2,704	370	10,135	481	13,182	330	9,058	281	7,696	158	4,338
1973	101	2,780	744	20,386	495	13,568	371	10,157	288	7,889	373	10,228
1974	72	1,987	661	18,114	443	12,142	708	19,410	193	5,284	363	9,958
1975	37	1,005	499	13,670	248	6,806	519	14,226	308	8,435	295	8,088
1976	53	1,455	462	12,674	684	18,741	434	11,888	376	10,302	132	3,611
1977	116	3,166	845	23,175	538	14,758	325	8,911	160	4,391	130	3,558
1978	37	1,024	688	18,855	454	12,450	351	9,608	264	7,238	194	5,326
1979	47	1,290	164	4,503	350	9,584	351	9,615	361	9,898	319	8,749
1980	53	1,441	705	19,329	298	8,163	359	9,845	363	9,958	223	6,106
1981	135	3,691	717	19,653	150	4,125	486	13,328	315	8,638	214	5,858
1982	62	1,691	377	10,329	597	16,359	282	7,739	446	12,223	226	6,195
1983	160	4,379	521	14,283	243	6,664	328	8,995	695	19,053	349	9,561
1984	26	699	762	20,889	484	13,257	525	14,396	308	8,445	476	13,038
1985	131	3,588	449	12,314	377	10,333	204	5,591	282	7,738	333	9,130
1986	15	412	561	15,366	253	6,940	416	11,399	268	7,339	489	13,415
1987	48	1,324	395	10,837	332	9,099	471	12,920	452	12,387	357	9,795
1988	123	3,376	788	21,595	515	14,120	481	13,177	413	11,333	291	7,974
1989	31	840	349	9,567	362	9,934	497	13,612	211	5,796	324	8,870
1990	162	4,445	514	14,100	364	9,978	457	12,517	287	7,870	338	9,264

Notes: Subcatchment 12 = Central–Eastern Bangladesh; area of subcatchment: 27,413 km^2; stations used (A + C stations): Mymensingh, Kishorgonj, Hobigonj, Comilla, Dhaka.

of the precipitation patterns of their respective subcatchment, at least in terms of the precipitation variations from the average.

Areal precipitation in SC6, SC7 and SC8

Similar to the Himalayan subcatchments, only one station with sufficiently long records is available for each of these areas. Because these subcatchments are located on the plains (Assam and Southern West Bengal), we assume that the monthly precipitation variations measured at Calcutta, Dibrugarh and Gauhati are representative of their respective subcatchments.

Precipitation volume

As discussed above, areal precipitation represents the height of precipitation per surface unit, in our case per subcatchment, in a given time period. The multiplication of this precipitation by the area of the respective subcatchment results in the total volume of rainwater accumulated in a subcatchment during a specific time period (see Table 5.2). The area of each subcatchment listed in Table 5.1 was measured with a ‘‘Numonics Electronic Graphics Calculator’’, based on a 1:4,000,000 scale map (Nelles Map n.d.). As is evident in Figure 5.1, the subcatchments differ significantly in size, with the two subcatchments in the Ganga lowlands, SC4 and SC5, being the largest. Assuming an areal precipitation of 1,000 mm or 1 metre in a subcatchment of 1,000 km^2, the calculation of precipitation volume is as follows:

$$1 \text{ m} \times 1{,}000{,}000{,}000 \text{ m}^2 = 1{,}000{,}000{,}000 \text{ m}^3 = 1{,}000 \times 10^6 \text{ m}^3$$

Average areal precipitation and precipitation volume: A brief discussion

The calculation of areal precipitation and precipitation volume provides very interesting spatial and volumetric information for the different subcatchments (see Figure 5.2). The increase in areal precipitation from west to east, from the Ganga across the Brahmaputra to the Meghna basins, is very striking: precipitation is lowest in the Upper Ganga Plain (SC4) and highest in the Meghalaya Hills (SC9) as well as in North-eastern Bangladesh (SC11). In terms of precipitation volume, the subcatchments of the Ganga lowland (SC4, SC5) clearly dominate the picture owing to their huge area. Within this generalized picture some interesting specifications should be made:

- In spring, the precipitation volume in SC12 is higher than in SC4, although SC4 is 13 times the size of SC12.
- The situation in the Meghalaya Hills (SC9) is outstanding: the precipi-

tation volume of all time periods is almost comparable to Nepal (SC2), although SC9 is only one-sixth the size of SC2. This fact highlights the concentration of rainwater in the Meghalaya Hills and the particular attention that needs to be given to this area in the analysis of flood events.

With this third methodological step, a clear differentiation of the precipitation patterns in the basin was elaborated. However, it is not yet possible to quantify the contribution of water from different subcatchments to the hydrological system, or to estimate the relevance of this contribution to the flooding processes in Bangladesh. We do not know how much of the precipitation volume accumulated in a specific subcatchment over a specific period of time is actually discharged, enters the river system and sooner or later reaches Bangladesh. Such questions are considered in the next methodological step.

5.2.4. Potential runoff (step 4)

In this step a methodology was developed to assess the water volume potentially discharged from a specific subcatchment in a given period of time. In order to achieve this, the potential runoff (R(pot)) was introduced as a new variable. R(pot) is based on the following premise: the proportion of precipitation that is discharged through surface runoff into the river system is expressed as a discharge factor. The discharge factor ranges from 0 to 1 and is a function of topography, temperature, air humidity, vegetation cover, soil moisture content, groundwater level, etc. A discharge factor of 0.1 indicates that 10 per cent of the precipitation is transformed into surface runoff, thus directly contributing to the river discharge, and 90 per cent either evaporates or is infiltrated. The closer the discharge factor is to 1, the higher is the direct contribution of precipitation to the river system. Based on these considerations, it is possible to assess the amount of water that is potentially discharged from a specific subcatchment in a given time period by multiplying the precipitation volume with a discharge factor:

$$R_{ij}(\text{pot}) = P_{ij}(\text{vol}) * \alpha_{ij},$$

where $R_{ij}(\text{pot})$ = potential runoff from subcatchment i in time period j,
$P_{ij}(\text{vol})$ = the precipitation volume of subcatchment i in time period j (see methodological step 3 above),
α_{ij} = the discharge factor of subcatchment i in time period j.

For the subcatchments, see section 5.2.1; for the time periods, see section 5.2.2. The discharge factor α is the focus of the following discussions.

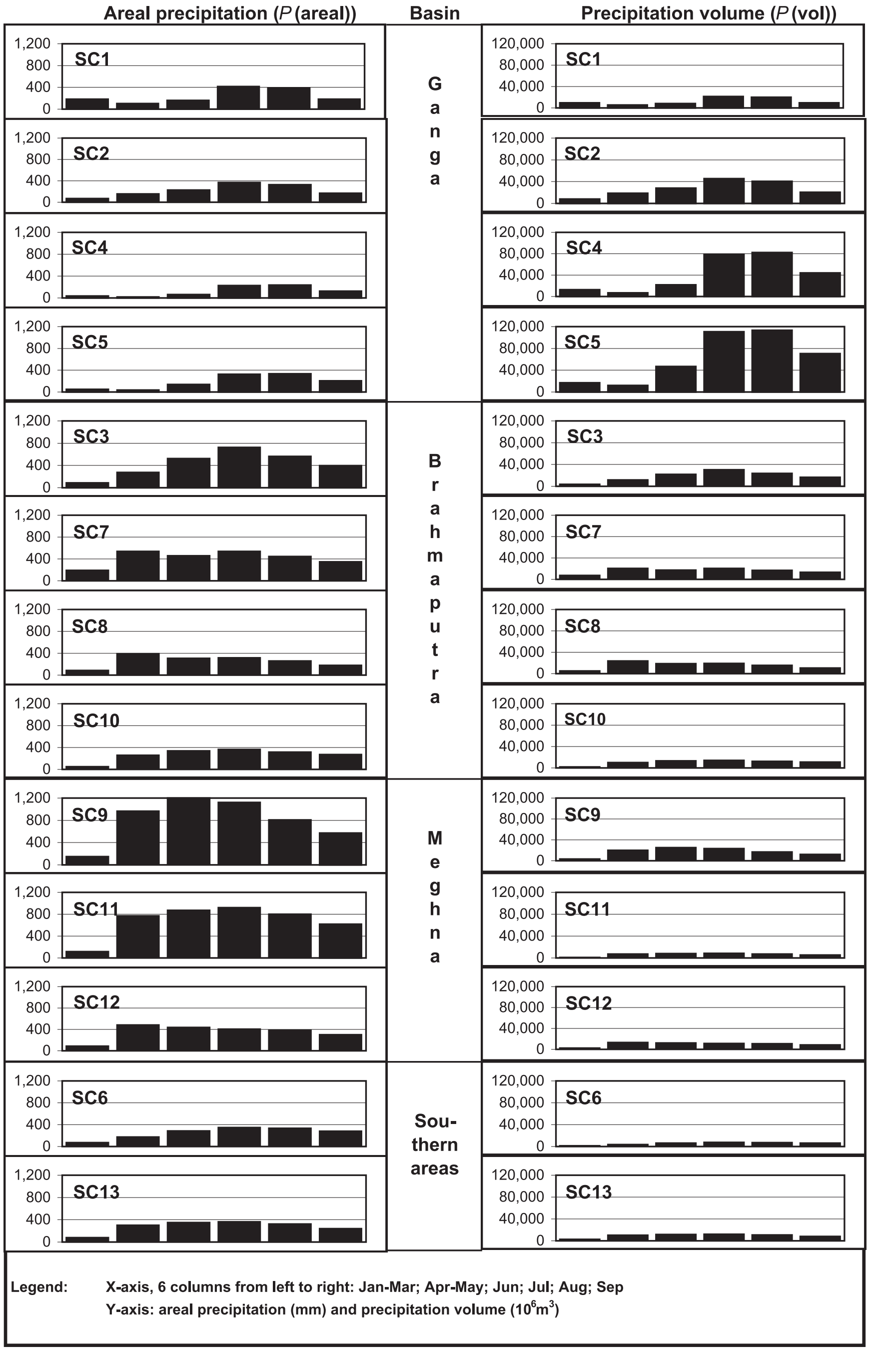


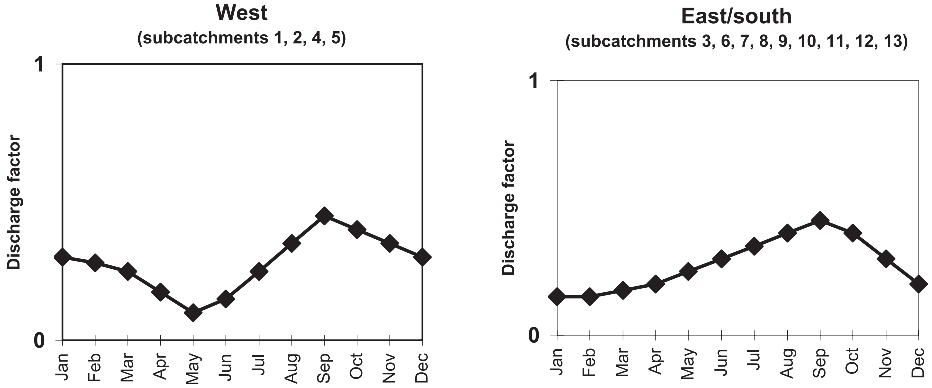
Figure 5.2 Average patterns (1900–1990) of areal precipitation and precipitation volume in the 13 subcatchments and 6 time periods.

Notes: For the location of the subcatchments, see Figure 5.1; for data sources see Table 3.2.

Theoretical background

As noted above, the discharge factor is influenced and determined by a number of parameters. In addition, the climatological patterns in the Ganga–Brahmaputra–Meghna basin are significantly differentiated in space and time (see also section 2.2.4 and Figure 2.4): generally humid conditions in summer and dry conditions in winter; less humid conditions in the west than in the east; later onset and earlier ending of the monsoon in the west than in the east; lower winter temperatures in the west than in the east. As a consequence, the discharge factor certainly varies in the 13 subcatchments and 6 time periods. A differentiation in time, geographical longitude (west–east) and elevation (highland–lowland) needs to be made. For the discussion of these differentiated conditions, two theoretical curves for the discharge factor (α) were developed, one for the west and one for the east/south (Figure 5.3):

- West: from January to March the climate is dry and cool with moderate evaporation. As a result the discharge factors reach average levels. From April to mid-June, temperatures as well as evaporation rates are very high. Most of the scarce precipitation either evaporates, is infiltrated or is used for irrigation. The soil moisture content is very low. Accordingly, the discharge factor is significantly reduced. From mid-June to September, air humidity is generally high, irrigation is less important, the soil becomes increasingly humid as a result of frequent precipitation, and the groundwater table rises. The proportion of precipitation that is directly discharged is much higher, and accordingly the discharge factor gradually increases. With the ending of the monsoon in October, the rains stop and air humidity and soil moisture content reduce. The discharge factor gradually decreases.
- East/south: from January to March the climate is dry, the temperatures are higher than in the west and evaporation is significant. As a result, the discharge factor is low. From April to May the climate gets more humid and the pre-monsoon rains start; these are followed by the onset of the monsoon in early June. The discharge factor starts rising much earlier than in the west. From July to December the discharge factors are comparable to those in the west, with the exception that the decrease in the discharge factor is delayed in the east owing to the later ending of the monsoon.
- The differentiation of the discharge factors according to elevation is important, but not taken into account in Figure 5.3: in the mountains, steep slopes and cool temperatures in the winter and pre-monsoon periods promote surface runoff; in the lowlands, the flat topography enables the rainwater to infiltrate the soil and the evaporation rate is higher owing to warmer temperatures. As a result, the discharge factor


West
(subcatchments 1, 2, 4, 5)

East/south
(subcatchments 3, 6, 7, 8, 9, 10, 11, 12, 13)

Figure 5.3 Theoretical discharge factors for the west and east/south.

is higher in the mountains than in the plains. During the monsoon period, the difference between the discharge factor for the highlands and that for the lowlands gets smaller.

In order to verify this theoretical background, the average climatic parameters of selected stations have been taken into consideration: Shimla and Delhi for the western part, Darjiling and Gauhati for the eastern part and Mymensingh for the southern part of the basin (see Figure 5.1). The following observations clearly confirm the theoretical considerations:

- *Temperature west–east/south (Figure 5.4)*: the graphs of average monthly temperature in Gauhati and Mymensingh are similar. In Delhi, the winter temperature is lower but rises high above the values of Gauhati and Mymensingh from April to June. From August to December all the graphs are comparable.
- *Evapotranspiration and precipitation west–east/south (Figure 5.5)*: in Delhi and Shimla, the evapotranspiration rate starts rising from rather low values in winter. The spring months (April, May and part of June) are characterized by arid conditions; evapotranspiration is considerably higher than precipitation. From June onwards, precipitation rises, with the highest values being reached in July or August, and evapotranspiration gradually decreases. The main difference in the east/south (Darjiling, Gauhati and Mymensingh) compared with the situation in the west is evidenced in the pre-monsoon period, during which precipitation starts to increase and soon exceeds the evapotranspiration figures. From July to December the graphs are comparable to those in the west in qualitative but not in quantitative terms.
- *Evapotranspiration and precipitation highland–lowland (Figure 5.5)*:

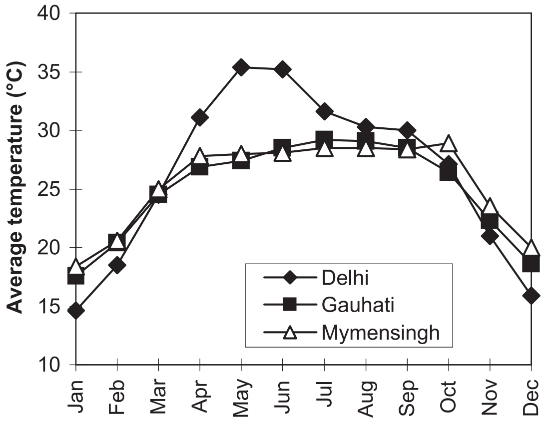


Figure 5.4 Average monthly temperature in Delhi (west), Gauhati (east) and Mymensingh (south).
Source: FAO (1987).

evapotranspiration at the hill stations of Shimla (2,206 metres above sea level) and Darjiling (2,134 metres above sea level) almost never exceeds precipitation.

As an immediate follow-up to these theoretical reflections, a list of estimated, but reasonable, discharge factors for the 13 subcatchments and 6 time periods needed to be developed. At this stage of the methodological considerations, a unique opportunity appeared: the discharge station at Farakka is located exactly at the outflow of the combined SC1, SC2, SC4 and SC5 in the Ganga basin (Figures 3.2 and 5.1). This situation allows for a calibration of estimated discharge factors by comparing the total potential runoff for SC1, SC2, SC4 and SC5 (calculated according to the equation above for a specific time period) with the actually measured discharge of the Ganga at Farakka (inflow into the reservoir) for the same period of time. The procedure is presented in the following sections.

Estimation of the discharge factors in the Ganga basin (SC1, SC2, SC4 and SC5)

A first set of estimated discharge factors for SC1, SC2, SC4 and SC5 was elaborated, based primarily on the theoretical background discussed above (see the table at the top left of Table 5.3). Experiences from different highland and lowland catchments in Switzerland were also taken into consideration (Näf et al. 1985). Subsequently, the average potential runoff (*R*(pot)) for the reference period 1950–1980 was calculated for SC1,

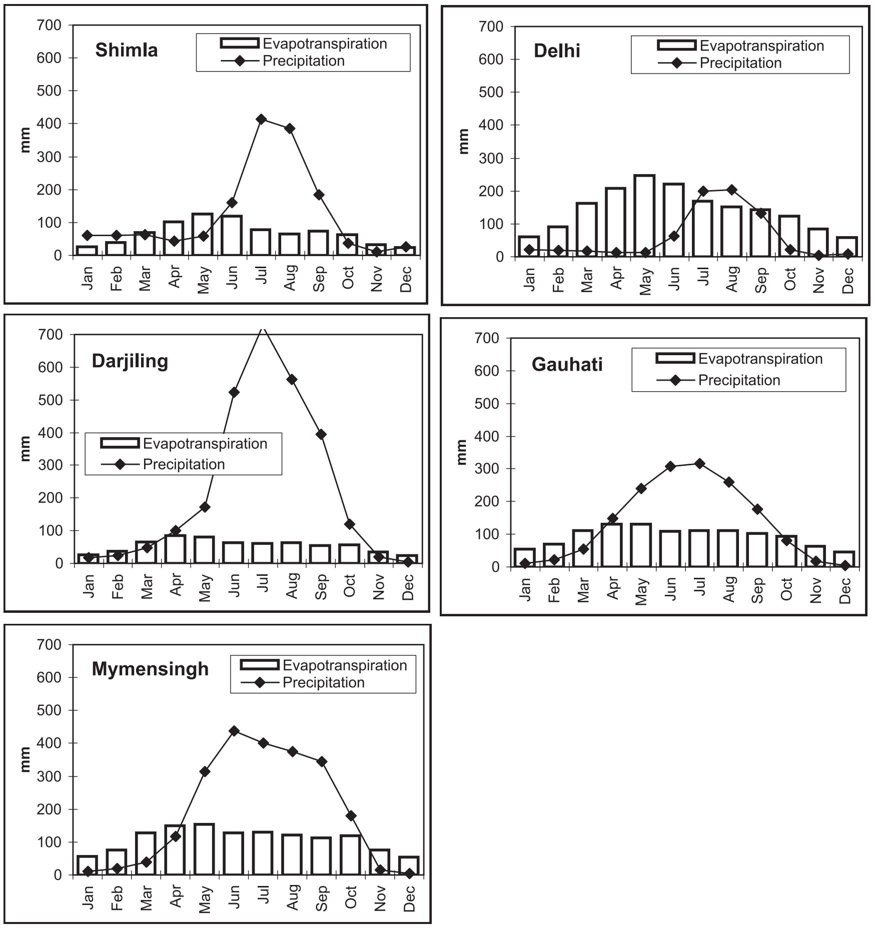


Figure 5.5 Average evapotranspiration and precipitation at selected stations showing the west–east/south and the highland–lowland differentiation.
Sources: Evapotranspiration data – FAO (1987); rainfall data – Table 3.2.

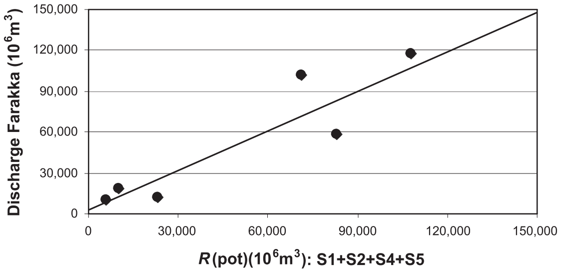
SC2, SC4 and SC5 and for six time periods, based on the multiplication of the average precipitation volume (P(vol)) by the relevant estimated discharge factor α. The list at the bottom of Table 5.3 presents the results of these calculations. After that, the average discharge (1950–1980) of the Ganga at Farakka was extracted from the relevant data set and the average total inflow of the Ganga into the Farakka Reservoir for each of the six time periods was calculated. These numbers were added to the list

Table 5.3 Estimated discharge factors and their application for subcatchments 1, 2, 4 and 5

Estimated discharge factors for subcatchments 1, 2, 4 and 5: Ganga basin; reference period 1950–1980

	Discharge factor (α)					
SC	Jan–Mar	Apr–May	Jun	Jul	Aug	Sep
1	0.30	0.20	0.25	0.35	0.45	0.55
2	0.30	0.20	0.25	0.35	0.45	0.55
4	0.20	0.10	0.20	0.30	0.40	0.50
5	0.20	0.10	0.20	0.30	0.40	0.50

X–Y diagram



Calculation of potential runoff (*R*(pot)) with the estimated discharge factors

	January–March			April–May			June			July			August			September		
SC	*P*(vol) 10^6 m^3	α	*R*(pot) 10^6 m^3	*P*(vol) 10^6 m^3	α	*R*(pot) 10^6 m^3	*P*(vol) 10^6 m^3	α	*R*(pot) 10^6 m^3	*P*(vol) 10^6 m^3	α	*R*(pot) 10^6 m^3	*P*(vol) 10^6 m^3	α	*R*(pot) 10^6 m^3	*P*(vol) 10^6 m^3	α	*R*(pot) 10^6 m^3
1	8,429	0.30	2,529	4,942	0.20	988	9,541	0.25	2,385	21,453	0.35	7,508	17,228	0.45	7,753	9,911	0.55	5,451
2	7,974	0.30	2,392	16,853	0.20	3,371	31,279	0.25	7,820	46,702	0.35	16,346	41,503	0.45	18,676	18,991	0.55	10,445
4	11,568	0.20	2,314	5,464	0.10	546	20,873	0.20	4,175	86,537	0.30	25,961	91,972	0.40	36,789	41,637	0.50	20,818
5	14,951	0.20	2,990	11,411	0.10	1,141	44,944	0.20	8,989	110,745	0.30	33,224	111,579	0.40	44,632	68,844	0.50	34,422
Total			10,225			6,046			23,368			83,039			107,850			71,136
Ganga discharge Farakka			18,647			10,109			12,300			58,547			117,532			101,644

Notes: *P*(vol) = precipitation volume; α = discharge factor; *R*(pot) = potential runoff.

in Table 5.3 as well. In order to compare our estimates (potential runoff) against the facts (discharge), the sum of the average potential runoff of subcatchments 1, 2, 4 and 5, calculated with the estimated discharge factors, was plotted against the discharge at Farakka in an *X–Y* diagram (see the top right of Table 5.3), each dot representing one of the six time periods. The figures show in an impressive way that even the first attempt to calculate potential runoff with a set of estimated discharge factors was a significant success: the summed average potential runoff for the four Ganga subcatchments is of the same order of magnitude as the actually measured average discharge of the Ganga at Farakka. This positive result motivated us to reflect on the discrepancies between *R*(pot) and discharge that are visible in the numbers as well as in the *X–Y* diagram of Table 5.3 and to fine-tune the results:

- In winter (January–March), in the pre-monsoon period (April–May), in August and in September, the calculated average potential runoff for the Ganga basin (SC1+SC2+SC4+SC5) is lower than the average measured discharge of the Ganga at Farakka. Obviously the proportion of precipitation that is directly discharged was undervalued in the estimated discharge factors.
- In June and July, the potential runoff is too high. The proportion of precipitation that is directly discharged was overestimated.

Calibration of the discharge factors for the Ganga basin (SC1, SC2, SC4 and SC5)

Based on these experiences, the estimated discharge factors were modified, corrected and optimized. An attempt was made to bring the average potential runoff for the four Ganga subcatchments as close as possible to the average discharge of the Ganga at Farakka, in other words to bring the dots in the *X–Y* diagram (top right of Table 5.3) as close as possible to the diagonal line. The arguments for this fine-tuning, which had of course to remain in line with the theoretical background discussed at the beginning of this section, were the following:

- In the winter (January–March), evapotranspiration is less important than expected. We therefore raised the discharge factors considerably – more for the lowland subcatchments SC4 and SC5 than for the highland subcatchments SC1 and SC2.
- Considering the high temperature and evapotranspiration (see Delhi station in Figures 5.4 and 5.5) and the intensity of irrigated agriculture during the pre-monsoon (April–May) period, the discharge factor in the plains is certainly very low. We therefore modified the discharge factor only for the two Himalayan subcatchments SC1 and SC2, for which it is reasonable slightly to raise the discharge factor in spite of

the rather significant evaporation rate. The vegetation cover is certainly less dense than in subsequent months, and, together with the rough topography, this leads to significant surface runoff.

- The rains in the first two monsoon months (June and July) and their effect on the discharge factors were obviously overestimated. After the onset of the monsoon it seems to take more time than expected for the discharge factor to rise as a result of a higher soil moisture content, a lower evapotranspiration rate and reduced extraction of irrigation water. Accordingly, we reduced the estimated discharge factors – slightly more for the lowland subcatchments SC4 and SC5 than for the highland subcatchments SC1 and SC2.
- For August and September two elements were underestimated: the gradual accumulation of water during the monsoon season, which raises the proportion of precipitation directly discharging into the river system, and the probability and occurrence of heavy short-term precipitation events, which generally produce a very high surface runoff. Accordingly, we raised the estimated discharge factors significantly.

This fine-tuning exercise resulted in a revised set of discharge factors, listed at the top left of Table 5.4. The calculations and the X–Y diagram in Table 5.4 show that this calibration of the discharge factors was successful: for each time period, the difference between the average potential runoff (R(pot)) of the Ganga basin (SC1+SC2+SC4+SC5) and the average discharge of the Ganga into the Farakka Reservoir is much reduced; the six dots in the X–Y diagram are positioned on or very close to the diagonal line. At least on an average basis, this calibrated final list of discharge factors seems to be a reliable tool for the calculation of potential runoff from the four Ganga subcatchments in different time periods.

Testing the discharge factors (Ganga basin)

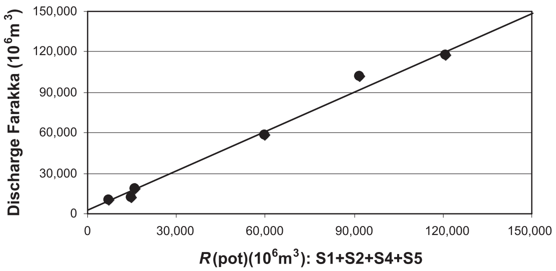
The discharge factors established for the calculation of potential runoff in the four subcatchments of the Ganga basin have so far been tested and discussed only for the average situation of the period 1950–1980. In the following, we test the validity of the defined discharge factors for the calculation of the potential runoff in specific years. For each year with available data from 1950 to 1980 and for the six time periods (January–March, April–May, June, July, August and September), the total potential runoff of the four Ganga subcatchments and the discharge of the Ganga at Farakka are listed in Table 5.5 and plotted in the X–Y diagrams of Figure 5.6. The difference between R(pot) and the Ganga discharge is added as a third column for each time period in Table 5.5. Subsequently, the data series of potential runoff and discharge

Table 5.4 Calibrated discharge factors and their application for subcatchments 1, 2, 4 and 5

Calibrated discharge factors for subcatchments 1, 2, 4 and 5: Ganga basin; reference period 1950–1980

	Discharge factor (α)					
SC	Jan–Mar	Apr–May	Jun	Jul	Aug	Sep
1	0.40	0.25	0.20	0.30	0.50	0.70
2	0.40	0.25	0.20	0.30	0.50	0.70
4	0.35	0.10	0.10	0.20	0.45	0.65
5	0.35	0.10	0.10	0.20	0.45	0.65

X–Y diagram



Calculation of potential runoff (R(pot)) with the calibrated discharge factors

	January–March			April–May			June			July			August			September		
SC	P(vol) 10^6 m^3	α	R(pot) 10^6 m^3	P(vol) 10^6 m^3	α	R(pot) 10^6 m^3	P(vol) 10^6 m^3	α	R(pot) 10^6 m^3	P(vol) 10^6 m^3	α	R(pot) 10^6 m^3	P(vol) 10^6 m^3	α	R(pot) 10^6 m^3	P(vol) 10^6 m^3	α	R(pot) 10^6 m^3
1	8,429	0.40	3,371	4,942	0.25	1,235	9,541	0.20	1,908	21,453	0.30	6,436	17,228	0.50	8,614	9,911	0.70	6,938
2	7,974	0.40	3,190	16,853	0.25	4,213	31,279	0.20	6,256	46,702	0.30	14,011	41,503	0.50	20,751	18,991	0.70	13,293
4	11,568	0.35	4,049	5,464	0.10	546	20,873	0.10	2,087	86,537	0.20	17,307	91,972	0.45	41,388	41,637	0.65	27,064
5	14,951	0.35	5,233	11,411	0.10	1,141	44,944	0.10	4,494	110,745	0.20	22,149	111,579	0.45	50,211	68,844	0.65	44,749
Total			15,843			7,136			14,746			59,903			120,964			92,044
Ganga discharge Farakka			18,647			10,109			12,300			58,547			117,532			101,644

Notes: P(vol) = precipitation volume; α = discharge factor; R(pot) = potential runoff.

were correlated with each other for each time period. The correlation coefficients are given in the bottom left panel of Table 5.5. In spring (April–May), July and August, the correlation coefficients are not very high, and in July they are statistically insignificant (significance level 95 per cent).

In order to verify whether this rather poor correlation is systematic or results from single, extreme records, the two highest positive and negative differences between both variables were identified for each time period (bold figures in Table 5.5) and the correlation was recalculated excluding these highest values (see the bottom right panel of Table 5.5). The result of this exercise is very promising: except for June, the correlation coefficients are much higher and all of them are statistically significant. Accordingly, we can say with good confidence that, except for some extreme cases, the newly introduced variable *R*(pot) is a very sound tool for estimating the contribution of defined subcatchments to the hydrological system over defined time periods.

An even better match between the calculated potential runoff for the four Ganga subcatchments and the measured Ganga discharge could not have been expected owing to a number of important unknown parameters:

- The contribution of water from snowmelt and glacial melt is not considered in the calculations of potential runoff, but it is of course included in the flow of the Ganga measured at Farakka. Particularly in the premonsoon period (April–May), low precipitation and high snow and glacial melt could lead to lower *R*(pot) values for the four subcatchments in the Ganga basin compared with the discharge measured at Farakka (see also Figure 5.6).
- The highest parts of the headwaters of the Ganga and of its principal tributaries are located outside the delineated subcatchments (see Figure 5.1) and are therefore not included in the calculations of potential runoff.
- As pointed out several times, monthly records were used for the calculations of *R*(pot). In the Ganga catchment, the monsoon starts on average in the second half of June. Accordingly, the June figures for potential runoff may include the first monsoon rains, whereas the discharge of the Ganga may document this input only in July because of the lead time. This is most probably the main reason for a generally higher potential runoff figure for the Ganga catchment in June compared with the Ganga discharge at Farakka (Figure 5.6).
- Localized and heavy precipitation significantly contributes to the river discharge. Owing to the low density of raingauge stations, such events may not have been recorded by the available stations and are therefore not reflected in the calculations of precipitation volume and potential

Table 5.5 Potential runoff for the Ganga catchment (sum of subcatchments 1, 2, 4 and 5) and discharge of the Ganga at Farakka, 1950–1980: A comparison

	January–March			April–May			June			July			August			September		
Year	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
1950	17,684	21,971	4,286	6,124	10,565	4,441	17,743	17,283	–460	70,959	71,409	450	136,591	137,450	859	77,936	95,736	17,799
1951	17,977	19,682	1,706	4,762	10,003	5,241	11,262	11,635	373	49,157	57,039	7,882	103,978	83,887	–20,090	80,490	78,074	–2,417
1952	16,649	14,187	–2,463	7,772	7,687	–85	23,482	10,197	–13,286	47,251	66,438	19,187	137,674	109,239	–28,436	65,509	86,355	20,846
1953	15,551	15,063	–488	4,484	6,794	2,310	13,077	7,623	–5,454	67,302	65,779	–1,523	122,411	132,286	9,875	91,113	95,816	4,703
1954	22,645	20,294	–2,351	4,444	10,321	5,877	11,965	14,756	2,791	63,135	61,938	–1,197	108,465	167,847	**59,383**	95,572	107,324	11,752
1955	15,744	19,347	3,603	5,036	8,436	3,400	13,188	10,083	–3,106	59,935	90,819	**30,885**	142,360	164,285	21,925	119,382	135,041	15,659
1956	17,011	22,358	5,347	11,219	12,473	1,254	19,286	26,425	7,140	72,360	62,867	–9,493	125,422	127,444	2,022	107,281	112,482	5,202
1957	29,908	26,823	–3,086	5,404	10,786	5,382	8,979	6,436	–2,543	65,014	47,804	–17,210	101,151	106,464	5,313	85,663	95,920	10,257
1958	10,873	16,715	5,843	4,955	9,512	4,557	7,488	6,278	–1,210	71,243	38,419	**–32,824**	123,575	142,992	19,416	134,645	103,242	–31,403
1959	18,197	21,627	3,430	7,629	9,823	2,194	9,549	10,314	765	52,130	38,151	–13,979	112,104	117,043	4,940	89,173	83,149	–6,024
1960	16,809	17,715	905	6,295	8,479	2,184	10,632	8,261	–2,372	61,692	52,068	–9,624	152,365	109,616	–42,749	78,479	101,085	22,607
1961	23,545	21,439	–2,106	3,755	10,061	6,306	16,108	14,777	–1,331	52,528	51,527	–1,001	200,222	121,937	**–78,285**	78,073	126,500	**48,427**
1962	24,055	26,560	2,505	7,617	13,941	**6,324**	12,962	15,345	2,383	50,193	46,382	–3,811	122,930	121,452	–1,478	128,230	119,426	–8,804
1963	13,753	17,634	3,881	7,644	11,351	3,707	12,335	14,707	2,372	49,973	51,302	1,329	130,769	98,059	–32,710	144,084	105,912	**–38,173**
1964	4,601	20,793	**16,191**	8,612	10,919	2,308	13,416	7,810	–5,607	68,830	59,035	–9,795	124,013	100,119	–23,895	113,845	139,149	25,304
1965	8,577	19,854	**11,277**	6,512	10,904	4,392	10,986	9,059	–1,927	n.a.	n.a.	n.a.	73,980	74,476	495	87,973	72,117	–15,855
1966	10,191	18,290	8,100	6,345	7,456	1,111	16,904	7,162	–9,742	39,097	39,367	270	102,260	95,324	–6,936	24,437	68,151	43,714
1967	15,562	15,489	–73	3,379	8,262	4,883	11,315	8,302	–3,012	60,660	50,809	–9,851	166,347	92,014	**–74,333**	94,042	119,110	25,068
1968	17,835	19,027	1,192	5,833	8,168	2,334	15,939	10,977	–4,961	64,632	62,747	–1,885	89,041	99,334	10,293	24,992	50,085	25,094
1969	9,529	14,351	4,822	6,338	8,376	2,038	7,960	10,658	2,698	70,904	45,570	–25,333	128,158	123,980	–4,178	83,512	91,026	7,514
1970	26,319	17,428	**–8,891**	7,147	9,766	2,619	17,963	12,833	–5,130	54,615	59,918	5,304	118,564	91,296	–27,268	140,637	101,127	**–39,510**
1971	10,669	16,258	5,589	17,300	12,048	**–5,253**	39,228	29,059	**–10,169**	58,441	104,024	**45,583**	143,319	174,391	31,071	91,802	128,530	36,728
1972	16,881	21,721	4,840	5,413	10,566	5,153	8,960	9,966	1,006	43,325	37,889	–5,437	110,715	50,761	–59,954	86,633	65,064	–21,569
1973	16,407	15,537	–869	5,809	9,905	4,096	18,503	17,600	–903	61,812	47,523	–14,289	138,963	101,806	–37,157	112,248	114,183	1,935
1974	5,205	15,338	10,132	7,033	9,913	2,880	8,173	8,046	–127	80,216	41,729	**–38,487**	102,567	127,071	24,505	47,615	85,101	37,485
1975	13,595	15,305	1,709	5,966	8,855	2,889	12,014	11,682	–332	63,221	85,439	22,218	108,565	129,803	21,239	144,553	123,763	–20,790

1976	9,017	17,333	8,316	11,529	11,314	−215	18,333	14,342	−3,991	49,678	45,198	−4,480	106,660	113,145	6,484	132,217	125,874	−6,343
1977	8,692	15,606	6,914	14,230	10,002	**−4,228**	15,655	9,943	−5,712	81,708	65,792	−15,915	99,029	126,755	27,726	89,590	98,225	8,635
1978	29,181	19,979	**−9,201**	8,264	15,362	**7,098**	22,638	18,684	−3,954	50,394	79,723	29,329	145,847	157,051	11,203	113,847	133,064	19,216
1979	19,042	21,671	2,629	7,250	13,288	6,038	13,217	7,193	−6,024	59,702	45,968	−13,734	61,996	85,959	23,963	28,936	42,096	13,159
1980	9,419	12,654	3,235	7,123	8,035	912	17,854	13,878	−3,975	63,159	83,734	20,575	109,843	160,207	**50,364**	60,848	148,233	**87,385**

Correlation coefficients using all the data	
January–March	.5680
April–May	.3991
June	.7410
July	.1430
August	.2986
Sep	.6094

Correlation coefficients excluding the two highest positive and negative differences per time period (in bold above)	
January–March	.7795
April–May	.4478
June	.6773
July	.3924
August	.5473
Sep	.8049

Notes: For the sources of the data, see Tables 3.2 and 3.4. Column 1 = *R*(pot) SC1+SC2+SC4+SC5 (10^6 m^3); column 2 = discharge of the Ganga at Farakka (10^6 m^3); column 3 = column 2 minus column 1 (10^6 m^3). Figures in bold are the two highest positive and negative differences (column 2 minus column 1) per time period. n.a. = data not available.

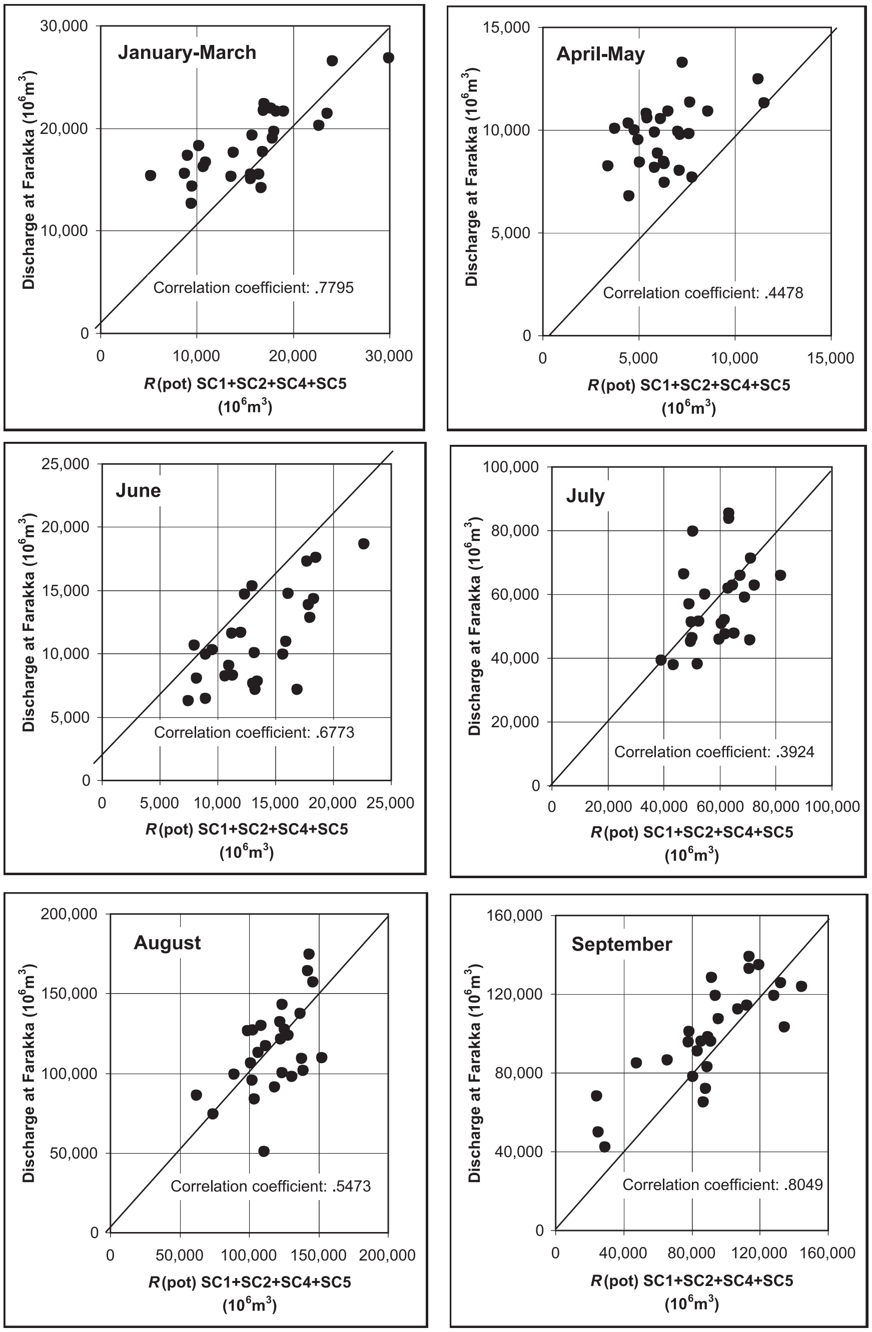


Figure 5.6 *X–Y* diagrams of potential runoff (*R*(pot)) for the Ganga catchment (SC1+SC2+SC4+SC5) and the discharge of the Ganga at Farakka, 1950–1980.
Note: For the sources of the data, see Tables 3.2 and 3.4.

runoff. In such situations, the potential runoff may be considerably lower than the measured discharge.

Determining the discharge factors for subcatchments 3, 6, 7, 8, 9, 10, 11, 12 and 13

Unfortunately, a calibration of discharge factors such as the one implemented for the Ganga basin was not possible for the Brahmaputra and the Meghna basins: there are no discharge gauging stations located at the outflow of a subcatchment or of a combination of several subcatchments. The determination of the discharge factors for the subcatchments located in the Brahmaputra and Meghna basins including Bangladesh (subcatchments 3, 6, 7, 8, 9, 10, 11, 12 and 13) was therefore implemented mainly by modifying the factors established for the four Ganga subcatchments and by considering the arguments put forward in the theoretical background, in particular the differentiation between west and east/south (Figure 5.3). Field observations in the Meghalaya Hills and in Bangladesh were additional important components. Compared with the west,

- the discharge factors in the east/south are lower in winter owing to less precipitation and higher temperatures; and
- the discharge factors in the east/south are higher from the pre-monsoon period through August, in particular in June and July, owing to the earlier onset of the monsoon in the east and south. Towards September, the differences are gradually reduced.

Table 5.6 lists the discharge factors for all 13 subcatchments and 6 time

Table 5.6 The discharge factors for the 13 subcatchments and 6 time periods

		Discharge factor (α)					
Basin	Sub-catchment	Jan–Mar	Apr–May	Jun	Jul	Aug	Sep
Ganga	1	0.40	0.25	0.20	0.30	0.50	0.70
	2	0.40	0.25	0.20	0.30	0.50	0.70
	4	0.35	0.10	0.10	0.20	0.45	0.65
	5	0.35	0.10	0.10	0.20	0.45	0.65
Brahmaputra	3	0.30	0.35	0.40	0.50	0.60	0.70
	7	0.20	0.25	0.35	0.45	0.55	0.65
	8	0.20	0.25	0.35	0.45	0.55	0.65
	10	0.20	0.25	0.35	0.45	0.55	0.65
Meghna	9	0.50	0.55	0.60	0.70	0.75	0.80
	11	0.30	0.50	0.70	0.80	0.90	0.90
	12	0.20	0.25	0.35	0.45	0.55	0.65
Southern areas	6	0.20	0.25	0.35	0.45	0.55	0.65
	13	0.20	0.25	0.35	0.45	0.55	0.65

periods, grouped according to the main river basins (Ganga, Brahmaputra, Meghna) and the southern areas. There are a few additional comments to be made regarding Table 5.6:

- All the discharge factors reach their maximum in September. This indicates that heavy precipitation in this last monsoon month can be particularly important to the occurrence of floods.
- The eastern border of SC2 and SC5 (Figure 5.1) was taken as the boundary between the west and the east/south for the determination of the discharge factors. Accordingly, the discharge factors make an unnatural jump from one neighbouring subcatchment to the other instead of following a gradual change from west to east. However, with the data available, a more gradual geographical differentiation of discharge factors was not possible.
- In the Meghalaya Hills (SC9), field observations revealed shallow soils and high surface runoff. In order to take this situation into consideration, comparatively high discharge factors were determined for this area.
- North-eastern Bangladesh (SC11) is characterized by extensive depressions in which large standing water bodies are formed from June to September. The rise of the discharge factor early in the monsoon period and a constantly high level during the entire rainy season reflect the particular situation in this area.

Discussion

Based on Table 5.6, the calculation of potential runoff was carried out systematically for each subcatchment, time period and year from 1891 to 1990 by multiplying the precipitation volume (P(vol)) by the relevant discharge factor α. In the process of developing and introducing potential runoff (R(pot)) as a new variable, in which the discharge factor plays a critical role, it gradually became clear what R(pot) actually represents. Based on precipitation data, the potential runoff is an indicator of the discharge characteristics of specific areas. This indicator makes it possible to compare different subcatchments in the Ganga–Brahmaputra–Meghna basin with regard to their discharge characteristics and to estimate their hydrological contribution to the whole system, in different periods of time and in specific years, by using a common, standardized methodology. Thus, the introduction of R(pot) was a very important step towards achieving the overall goals laid out in this chapter. Until now no better data or methods have been available. It is hoped that in future the approach for calculating the potential runoff and for calibrating the discharge factors can be further tested, improved and refined with better input data. However, we are convinced that, for the time being and for our purposes, the potential runoff provides an important and valuable tool for understanding the processes in and between different subcatchments of the basin and in the floodplains of Bangladesh.

5.2.5. The relevance of the potential runoff for Bangladesh (step 5)

In this step, a methodology was developed that allows the estimation of the relevance of the potential runoff (R(relev)) produced in a specific subcatchment for the flood processes in Bangladesh. R(relev) was introduced as a new variable. It is based on the following premise: the relevance of the potential runoff contributed by a specific subcatchment in a given year and time period for the flood-triggering hydrological processes in Bangladesh is a function of distance. The further away the subcatchment is located, the less important is the potential runoff. Accordingly it should be possible to assess the relevance of the potential runoff by multiplying R(pot) by a distance factor.

$$R_{ij}(\mathrm{relev}) = R_{ij}(\mathrm{pot}) * dist_i,$$

where R_{ij}(relev) is an indicator for the relevance of the potential runoff in subcatchment i in time period j for flooding in Bangladesh; $dist_i$ is the weighted distance from the reference point in subcatchment i to the reference point in Bangladesh; i.e.

$$dist_i = \frac{1/d_i^2}{\sum_{i=1}^{n}(1/d_i^2)};$$

where d_i is the absolute distance from the reference point in subcatchment i to the reference point in Bangladesh.

This distance factor is the focus of the following discussions.

Theoretical background

Our calculations of potential runoff are based on monthly precipitation records. However, we should bear in mind that precipitation in the Ganga–Brahmaputra–Meghna basin in reality does not fall continuously throughout a month with regular intensity, but rather falls in single high-intensity events of short duration. The resulting potential runoff, which is expressed in our calculations in seasonal or monthly totals, is contributed to the river system in single, sometimes big portions over short periods of time, eventually producing a sharp rise in the water levels and overflow of the river channel in those areas where the precipitation occurred. Further downstream, with increasing distance from the rainfall event, the short-term discharge peaks level off and lose their flood-triggering poten-

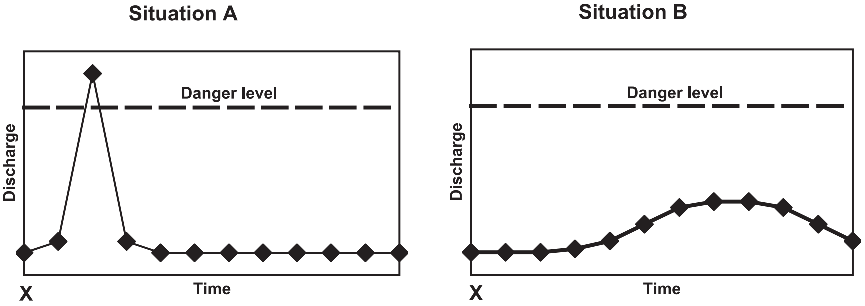
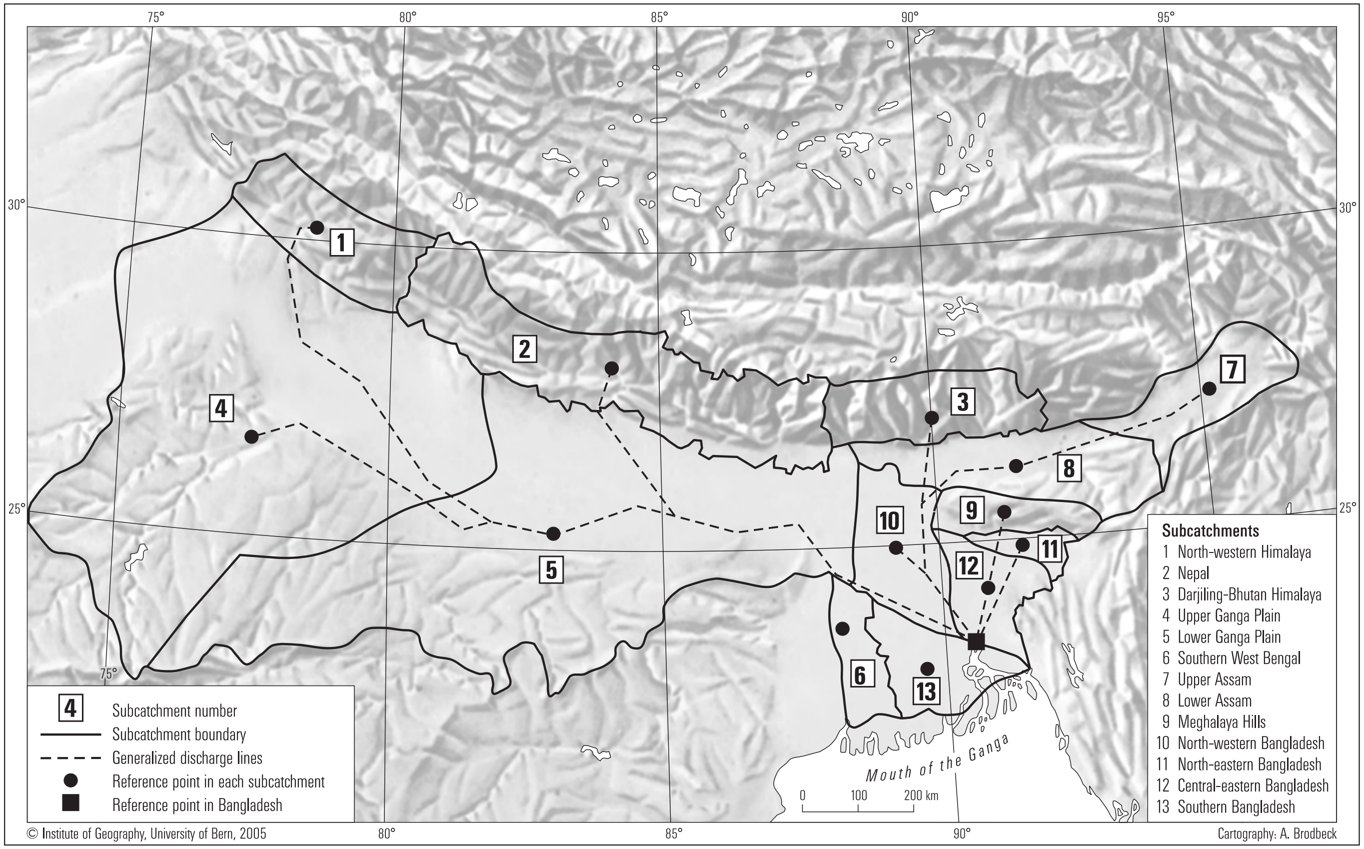


Figure 5.7 Theoretical discharge curves at a gauging site in Bangladesh.
Notes: Situation A: at time *X*, a heavy precipitation event in the vicinity of the measuring site produces a short, but massive, discharge peak. The river crosses the danger level and is liable to overflow its banks and to inundate the adjacent areas. Situation B: at time *X*, a similarly heavy precipitation event with the same amount of water discharged into the river system occurs higher up in the catchment, far away from the gauging site. Compared with situation A, the reaction to this event at the gauging site is delayed and of longer duration, and the discharge curve is flat and smooth. There is no danger of river overflow or flood spills.

tial. With the theoretical curves in Figure 5.7, which represent two discharge situations of a river at a specific gauging site in Bangladesh, we attempt to illustrate these circumstances: the relevance of specific precipitation events and of the resulting potential runoff for the hydrological processes at a particular location in Bangladesh decreases the further away from Bangladesh the inputs occur. This indicates that, even with identical potential runoff, each subcatchment has differing relevance to the flood-triggering hydrological processes at a specific reference point. That this theoretical background matches reality is documented, for example, in the case study of 1993 (see section 5.14 and Appendix 5.11): two days of extraordinary precipitation in specific areas of Nepal produced outstanding discharge peaks in the rivers as well as large floods and devastation in the Nepalese Middle Mountains and the nearby forelands (Terai). However, the Ganga flow at Hardinge Bridge in Bangladesh did not react to this event. It would appear that the discharge peaks of the Nepali tributaries levelled off and even disappeared below the confluence with the Ganga.

Absolute distance from each subcatchment to the reference point in Bangladesh (d_i)

The discussions in this section are depicted in Figure 5.8. A reference point needed to be defined within Bangladesh to which all the calcula-



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Cartography: A. Brodbeck

Figure 5.8 Generalized discharge lines from the reference point in each subcatchment to the reference point in Bangladesh for the calculation of *R*(relev).

Table 5.7 Absolute distances and weighted distances from the reference point of each subcatchment to the reference point in Bangladesh

Subcatchment	Absolute distance (d_i) in km	Weighted distance ($dist_i$)
1	1,708	0.0020563
2	952	0.0066190
3	464	0.0278630
4	1,460	0.0028142
5	852	0.0082639
7	868	0.0079621
8	484	0.0256079
9	244	0.1007592
10	224	0.1195552
11	204	0.1441465
12	104	0.5546228

Notes: For the location of the reference points, see Figure 5.8.

tions of the relevance factor (R(relev)) refer. This point was positioned at the confluence of the Meghna with the joint Ganga–Brahmaputra system in order to include all three main river basins. Then a reference point was defined within each subcatchment. These reference points were positioned more or less in the centre of each subcatchment. From there, generalized discharge lines to the reference point in Bangladesh were drawn that schematically follow the major river courses, and the distances were measured along these lines (see Table 5.7 and Figure 5.8). The two southern subcatchments (SC6, SC13) do not discharge through the reference point in Bangladesh and therefore had to be excluded from this investigation.

Weighted distance from each subcatchment to the reference point in Bangladesh ($dist_i$)

As shown in the formula above, the relevance variable R(relev) results from the multiplication of the potential runoff not by the absolute distance (d_i) but by the weighted distance ($dist_i$) from the reference point of a specific subcatchment to the reference point in Bangladesh. The weighted distance for each subcatchment is listed in Table 5.7. The following explanations are necessary to understand the justification for and the calculation of the weighted distances:

- As discussed, the relevance of the potential runoff of a specific subcatchment for the hydrological processes in Bangladesh decreases with the increasing distance of this particular subcatchment from Bangladesh. This means that, according to the formula given above, the weighted distance ($dist_i$) needs to get smaller with the increasing distance of the particular subcatchment. Therefore the distance (d_i) had to be entered reciprocally into the formula.

- Based on general practice in hydrology, the squared distance has been used for the calculation of the weighted distance (Sevruk 1985). With this approach it is stressed that the relevance of a hydrological input to a reference point does not decrease linearly with increasing distance, but rather is squared.
- The weighted distance of a subcatchment is not an independent figure, but is related to the distances of all the other subcatchments. The reciprocal and squared distance of a subcatchment is divided by the sum of the reciprocal and squared distances of all 11 subcatchments. Accordingly, the distance of one subcatchment is expressed as a proportion of the summed distances of all 11 subcatchments that enter into the calculation.
- The weighted distance ranges between 0 and 1. The sum of the weighted distances of all 11 subcatchments is equal to 1.

Discussion

Based on the formula above and the weighted distances listed in Table 5.7, the relevance variable R(relev) was calculated systematically for each subcatchment (with the exception of SC6 and SC13), each time period and each year from 1891 to 1990. Again, it is important to discuss what the relevance variable actually represents: R(relev) is not a tool to forecast peak flows at the reference point in Bangladesh. Similarly to R(pot), which was described as an indicator for the discharge characteristics of specific subcatchments, R(relev) is an indicator for the relevance of this potential runoff from specific subcatchments for the hydrological characteristics in Bangladesh, more precisely at the defined reference point within the country. It is again a methodology that can be applied comparatively for the different subcatchments. Because R(relev) results from the multiplication of R(pot), which is a volumetric variable, by a distance factor ($dist_i$), which is a linear variable, R(relev) is a weighted variable without any measuring unit (see also Table 5.8).

With the introduction of the two new variables, R(pot) and R(relev), and the resulting data sets for the period 1891–1990, we were now in a position to approach Questions 1 and 2 of this chapter: to estimate the hydrological contribution from different subcatchments in the Ganga–Brahmaputra–Meghna basin in different periods and in specific years; to assess the relevance of this contribution to the hydrological (mainly flood-generating) characteristics at a reference point in Bangladesh; to discuss the spatial patterns of hydro-meteorological conditions in the Ganga–Brahmaputra–Meghna basin; and to spot the most important hydro-meteorological anomalies.

Table 5.8 Average potential runoff (R(pot)) and relevance (R(relev)), 1900–1990 (absolute figures and percentages)

Sub-catchment	Area	January–March				April–May				June				July				August				September			
		R(pot)		*R*(relev)		*R*(pot)		*R*(relev)		*R*(pot)		*R*(relev)		*R*(pot)		*R*(relev)		*R*(pot)		*R*(relev)		*R*(pot)		*R*(relev)	
	%	10^6 m^3	%	Abs	%	10^6 m^3	%	Abs	%	10^6 m^3	%	Abs	%	10^6 m^3	%	Abs	%	10^6 m^3	%	Abs	%	10^6 m^3	%	Abs	%
Ganga basin																									
SC1	4.5	3,810	15.5	8	1.2	1,333	2.9	3	0.1	1,656	2.3	3	0.1	6,414	4.8	13	0.2	9,991	5.2	21	0.3	6,667	4.2	14	0.2
SC2	10.7	3,256	13.2	22	3.2	4,718	10.1	31	0.8	5,624	7.9	37	0.6	13,616	10.2	90	1.3	20,289	10.6	134	1.8	14,418	9.1	95	1.4
SC4	30.3	4,421	18.0	12	1.9	667	1.4	2	0.0	2,176	3.1	6	0.1	15,791	11.8	44	0.6	36,951	19.3	104	1.4	28,739	18.1	81	1.2
SC5	29.4	5,956	24.2	49	7.4	1,191	2.6	10	0.2	4,663	6.6	39	0.7	22,123	16.5	183	2.5	51,001	26.6	421	5.6	45,794	28.8	378	5.7
Brahmaputra basin																									
SC3	3.6	1,107	4.5	31	4.6	4,006	8.6	112	2.7	8,771	12.3	244	4.3	15,219	11.4	424	5.9	14,137	7.4	394	5.2	11,592	7.3	323	4.9
SC7	3.3	1,460	5.9	12	1.7	5,114	11.0	41	1.0	6,108	8.6	49	0.8	9,205	6.9	73	1.0	9,285	4.8	74	1.0	8,600	5.4	68	1.0
SC8	5.2	1,032	4.2	26	3.9	5,880	12.6	151	3.7	6,468	9.1	166	2.9	8,532	6.4	218	3.0	8,547	4.5	219	2.9	6,903	4.3	177	2.7
SC10	3.4	392	1.6	47	7.0	2,507	5.4	300	7.3	4,647	6.5	556	9.7	6,416	4.8	767	10.7	6,807	3.5	814	10.7	6,950	4.4	831	12.6
Meghna basin																									
SC9	1.8	1,553	6.3	156	23.4	11,041	23.7	1,112	27.2	15,033	21.1	1,515	26.4	16,357	12.2	1,648	23.0	12,616	6.6	1,271	16.8	9,522	6.0	959	14.5
SC11	0.8	307	1.2	44	6.6	3,451	7.4	497	12.2	5,486	7.7	791	13.8	6,607	4.9	952	13.3	6,471	3.4	933	12.3	4,982	3.1	718	10.8
SC12	2.4	472	1.9	262	39.1	3,296	7.1	1,828	44.7	4,212	5.9	2,336	40.7	4,971	3.7	2,757	38.4	5,775	3.0	3,203	42.2	5,363	3.4	2,975	44.9
Southern areas																									
SC6	1.9	305	1.2			941	2.0			2,179	3.1			3,379	2.5			3,974	2.1			3,990	2.5		
SC13	2.9	536	2.2			2,537	5.4			4,091	5.8			5,441	4.1			5,950	3.1			5,225	3.3		
Total	**100.0**	**24,606**	**100.0**	**669**	**100.0**	**46,681**	**100.0**	**4,086**	**100.0**	**71,114**	**100.0**	**5,741**	**100.0**	**134,071**	**100.0**	**7,171**	**100.0**	**191,794**	**100.0**	**7,587**	**100.0**	**158,747**	**100.0**	**6,620**	**100.0**

Notes: For the location of the subcatchments, see Figure 5.1; for the sources of the data, see Table 3.2. R(pot) = potential runoff; R(relev) = relevance for Bangladesh; Total = the sum of 13 subcatchments; Abs = absolute figures for R(relev) – being a weighted variable, R(relev) has no measuring unit.

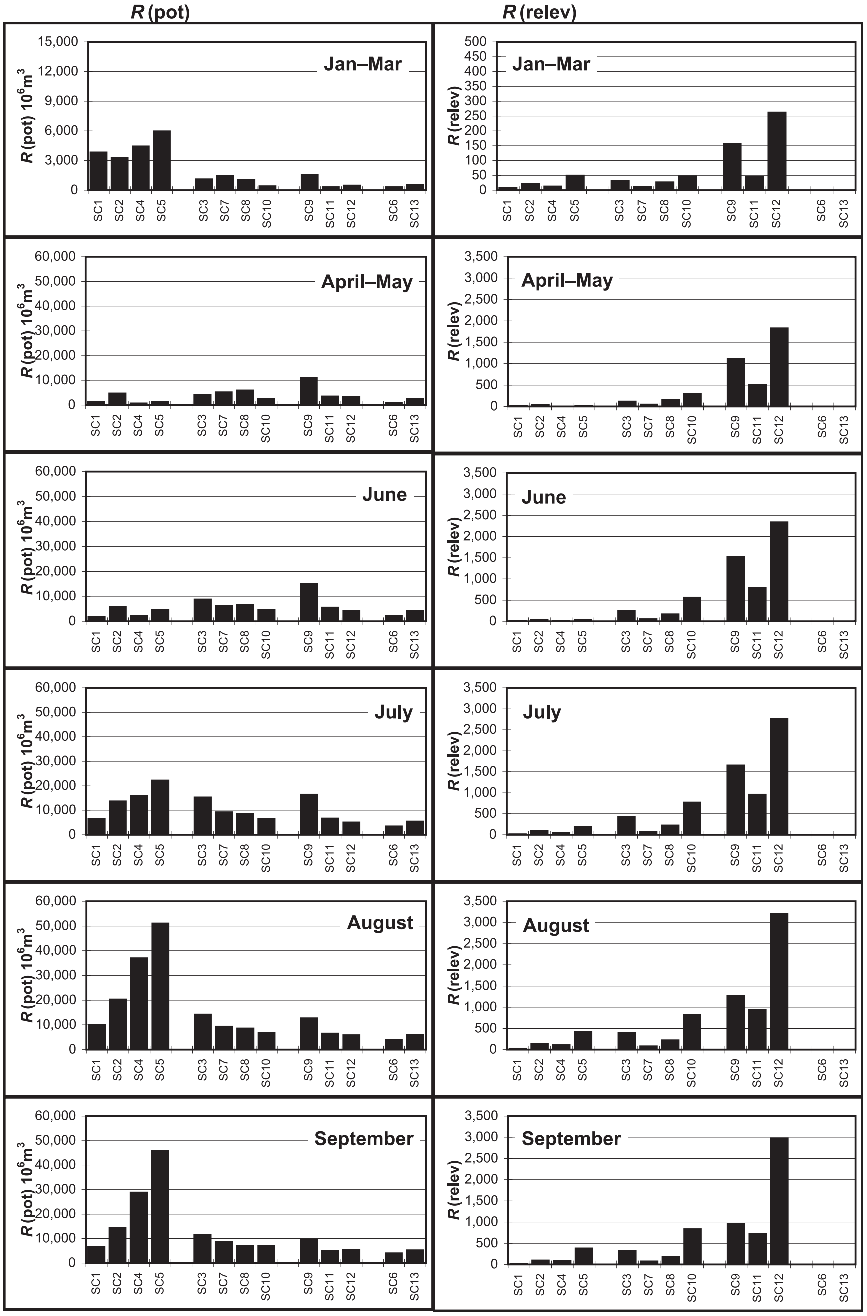
5.2.6. Gaining experience with the newly introduced variables – average patterns of R(pot) and R(relev) in the Ganga–Brahmaputra–Meghna basin

Before applying the newly introduced variables to the analysis of the case studies, it was appropriate to test them first and to become experienced in their interpretation. This was done with the investigation of the 90-year average figures for *R*(pot) and *R*(relev) for the 13 subcatchments (11 in the case of *R*(relev)) and 6 time periods. The data used for this investigation are listed in Table 5.8. The figures for each subcatchment are given in absolute as well as percentage terms. Table 5.8 has been visualized in two ways:

- In Figure 5.9, the average patterns of *R*(pot) and *R*(relev) for each time period are compared with each other. In each graph, the subcatchments are grouped along the *x*-axis from left to right according to the structure in Table 5.8 (Ganga subcatchments, Brahmaputra subcatchments, Meghna subcatchments, southern areas). It should be noted that the graphs for January–March do not have the same scale on the *y*-axis as the graphs for the other time periods.
- In Figure 5.10, *R*(pot) and *R*(relev) are plotted against the area of each subcatchment, all expressed in percentage terms. The structure of the graphs is identical to that of Figure 5.9.

The figures highlight the following principal findings:

- In winter, July, August and September, *R*(pot) is high in the Ganga system, particularly in the two lowland subcatchments SC4 and SC5. In marked contrast to this, the highest values of *R*(relev) are found in the subcatchments located within Bangladesh (SC10, SC11, SC12) as well as in the Meghalaya Hills (SC9). SC1, SC2 and SC4 in the Ganga system and SC7 and SC8 in the Brahmaputra system can almost be neglected in terms of *R*(relev). The interpretation of this contrasting situation illustrates the very nature of the two variables *R*(pot) and *R*(relev). The dominance of *R*(pot) in winter and from July to September in the Ganga system is a function of the catchment size. In very large subcatchments such as SC4 and SC5, a significant accumulation of water takes place, resulting in high figures for *R*(pot). *R*(relev) is a function of the distance from a specific subcatchment to the reference point in Bangladesh. Subcatchments located within or near Bangladesh receive a high relevance even if their size is comparatively small.
- The contribution of *R*(pot) from the Ganga Plain (SC4, SC5) is very high in absolute terms. In percentage terms, however, this contribution is lower than might be expected considering the large size of SC4 and SC5, which together account for 60 per cent of the total area of the 13 subcatchments. This is the case in all six time periods. In contrast to


R (pot)
R (relev)
R (pot) 10^6m^3
R (relev)
Jan–Mar
April–May
June
July
August
September
0
3,000
6,000
9,000
12,000
15,000
10,000
20,000
30,000
40,000
50,000
60,000
50
100
150
200
250
300
350
400
450
500
500
1,000
1,500
2,000
2,500
3,000
3,500
SC1
SC2
SC4
SC5
SC3
SC7
SC8
SC10
SC9
SC11
SC12
SC6
SC13

this, the percentage contribution of R(pot) from almost all subcatchments in the Brahmaputra and Meghna systems as well as in the southern areas is consistently higher than might be expected considering the size of these subcatchments and their percentage share of the total study area. If R(relev) is taken into account, then the differences are even clearer. This result matches the findings in section 5.2.3: areal precipitation is much higher in the east than in the west. This means that the total contribution of R(pot) from western subcatchments might be remarkable, but the hydrological output per surface unit is much higher in eastern subcatchments, which might be a crucial factor in the generation of floods.

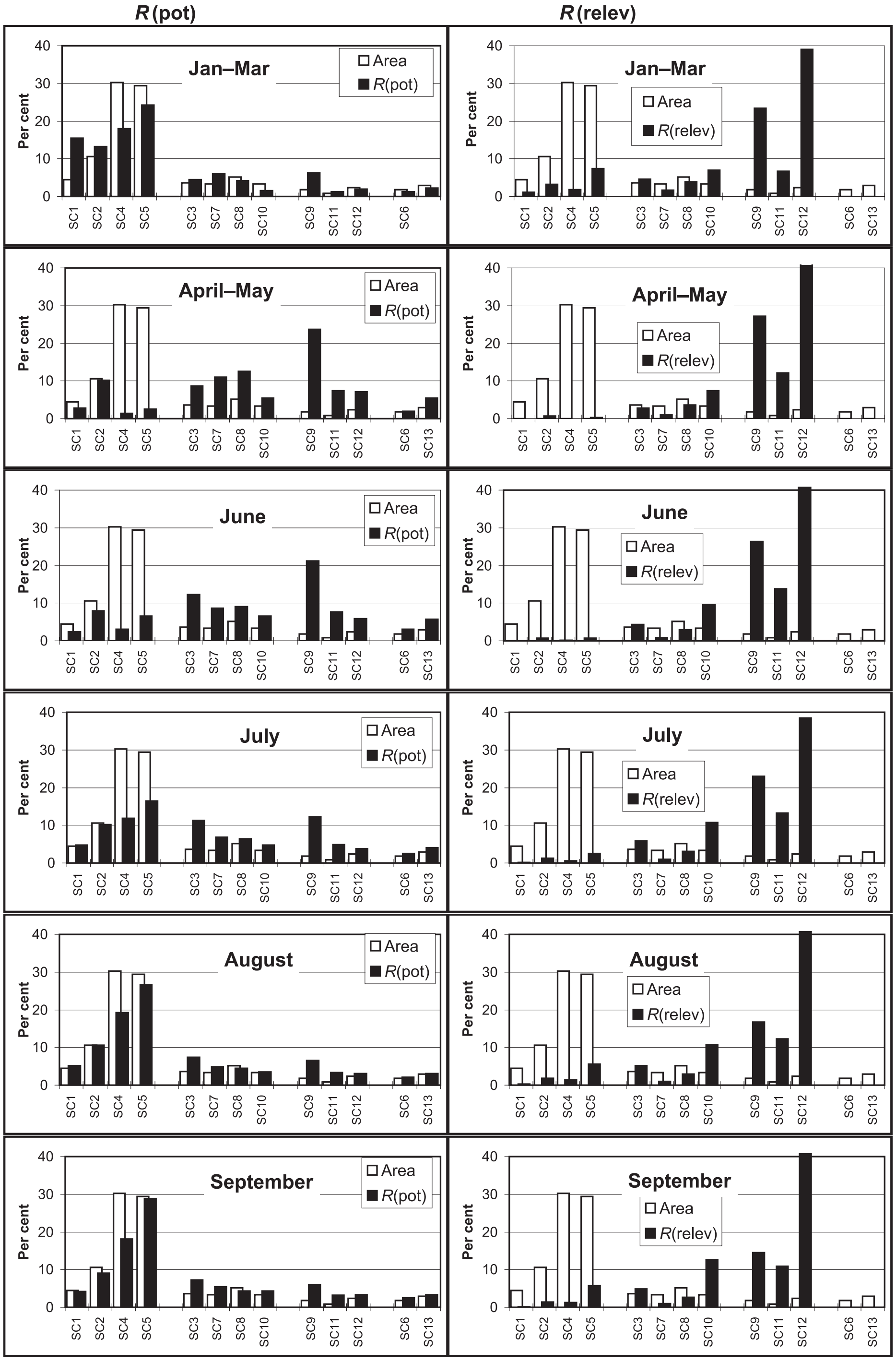
- In spite of their fairly important contributions of R(pot), the two Himalayan subcatchments in the Ganga system (SC1, SC2) are very low in the R(relev) ranking: these areas are too far away from Bangladesh to have a significant effect on flood-related discharge characteristics at the reference point. It is notable, though, that the Darjiling/Bhutan Himalayas acquire a higher relevance than the Indian Ganga and Brahmaputra plains during the monsoon months (except for SC5 in August and September).
- The Meghalaya Hills (SC9) merit special attention. In the pre-monsoon period (April–May) as well as in June, R(pot) is the highest of all subcatchments, even higher than in the two large subcatchments in the Ganga basin (SC4 and SC5). Of the total R(pot) from all 13 subcatchments, SC9 on average contributes 24 per cent in April–May and 21 per cent in June, although in terms of area the Meghalaya Hills account for only 2 per cent of the total surface of the 13 subcatchments. From July to September, R(pot) from the Meghalaya Hills continues to be very important, ranking second in July. In terms of R(relev), SC9 holds second position in all six time periods. The high R(pot) and R(relev) resulting from such a small area as SC9 reflect the extraordinary precipitation per surface unit, the relative vicinity of this subcatchment to the Bangladesh floodplains and consequently its considerable importance for flood generation.

Our first experiences in applying the two variables R(pot) and R(relev)

◄

Figure 5.9 Average R(pot) and R(relev), 1900–1990, for each subcatchment and six time periods.

Notes: For the location of the subcatchments, see Figure 5.1; for the sources of the data, see Table 3.2. The graphs for January–March do not have the same scale on the y-axis as the graphs for the other time periods. The difference in the average patterns of R(pot) and R(relev) is impressive – a concentration of R(pot) in the Ganga basin and a concentration of R(relev) in the Meghna basin.


R (pot)
R (relev)
Jan–Mar
April–May
June
July
August
September
Area
R(pot)
R(relev)
Per cent
0
10
20
30
40
SC1
SC2
SC4
SC5
SC3
SC7
SC8
SC10
SC9
SC11
SC12
SC6
SC13

have been very successful. The variables have proved to be the appropriate tools to compare the different subcatchments with regard to their potential hydrological contribution and to weigh this output in terms of its relevance for the flood-related hydrological processes in Bangladesh. Our discussion of the average patterns has revealed that the hydrological contribution from the subcatchments located outside Bangladesh can be important, but that the subcatchments in Bangladesh as well as in the Meghalaya Hills have the greatest relevance for the hydrological processes in Bangladesh. This interpretation can be further developed into a very important hypothesis: although the "base flow" of the big rivers in Bangladesh is significantly fed by the areas outside the country, short-term variations, which are very important for the generation of floods, are significantly influenced by the hydro-meteorological processes within Bangladesh or in nearby areas.

5.3. Introduction to the case studies

From the methodological section 5.2, we are now prepared to dive into the chapter's complex questions and systematically to discuss the flooding conditions and processes in 11 selected years, referred to as "case studies" in section 5.1. As far as possible, the same procedures were followed in the investigation of the case studies in order to achieve maximum comparability as well as to facilitate the synthesis and identification of key results. Accordingly, the presentation of the case studies will follow a more or less standardized structure. However, some flexibility will be required owing to differences in the data situation, particularly before and after 1950 (see Chapter 3), and to interesting specificities of each case study. Table 5.9 summarizes the basic data availability for the investigation of the 11 case studies. Some specific additional information is available for single years.

In the original manuscript for this book, sections 5.4–5.14 consisted of detailed presentations and discussions of the 11 case studies. In the course of the review process of the manuscript, it was rightly pointed out that

Figure 5.10 Average percentage R(pot) and R(relev), 1900–1990, for each subcatchment and the six time periods compared with the percentage area of all 13 subcatchments.

Notes: For the location of the subcatchments, see Figure 5.1; for the sources of the data, see Table 3.2. The figure illustrates the fact that the hydrological output per surface unit is much smaller in subcatchments of the Ganga basin than it is in subcatchments of the Brahmaputra or Meghna basins.

Table 5.9 Data situation for the analysis of the case studies

	Flood years								Dry years		Average flood year
	1906	1910	1922	1955	1974	1987	1988	1998	1923	1978	1993
Map: flood-affected area	X	X	X	X	X	X	X	X			
R(pot)	X	X	X	X	X	X	X		X	X	
R(relev)	X	X	X	X	X	X	X		X	X	
Monthly discharge				X	X	X	X	X		X	
Daily rainfall	X	X	X	X	X	X	X	X	X	X	X
Daily discharge					X	X	X			X	
Daily water level	X	X	X	X				X	X		X
Groundwater					X	X	X			X	
Tidal information						X	X				

Note: X indicates availability of data.

the wealth of information presented in the case studies was invaluable, but that it was difficult for the reader to get through the case studies without losing the bigger picture and the key messages. Accordingly it was decided to move the detailed discussions of the case studies to appendices (Appendices 5.1 to 5.11) and to present a summary of each case study in sections 5.4–5.14 instead. These summaries consist of a narrative that discusses the flooding situation in the particular year, in many cases illustrated with a map, and presents a synthesis of the main findings and conclusions from the in-depth investigations of that particular year. This narrative is complemented and enriched with a box that includes important, illustrative and striking main points extracted from the detailed investigations. These main points are structured into different thematic blocks, and for each of these blocks reference is made to figure(s) in the relevant appendix from where the main points originate.

The detailed presentation of the case studies in Appendices 5.1–5.11 is structured in principle as follows:

- The discussion of existing knowledge summarizes the known facts about the flood conditions in a specific year, provides an understanding of the extent, location and chronology of floods within and, as much as possible, also outside the present territory of Bangladesh, and finally lists some causes of the floods as perceived by the authors of the available literature.
- The investigations of the processes in the entire basin focus on Questions 1 and 2 and are based on monthly information. The identification of hydro-meteorological anomalies, the regionalization of relevant hydro-meteorological inputs and the estimation of the relevance of these inputs to the floods in Bangladesh lead to an understanding of both the large-scale highland–lowland linkages and the overall physical conditions in the basin contributing to the development of the flood processes. The calculations of potential runoff (*R*(pot)) and of the relevance factor (*R*(relev)) provide the data for these discussions. The monthly variations in discharge of selected rivers in Bangladesh are additional data sets used in this part of the detailed investigation.
- The large-scale analyses are followed by more specific investigations based on data series of a higher, ideally daily, temporal resolution. This investigation aims at a more detailed understanding of the flood processes in terms of highland–lowland linkages. In addition, it focuses on Question 3 concerning the combined effects of different physical factors such as rainfall, river discharge/water level, groundwater level and tidal movements on flood processes in Bangladesh as well as their prioritization. For case studies after 1950, these investigations necessarily have to focus on Bangladesh in view of the data situation (see Tables 3.1 and 3.3).

- The summary at the end of each case study in the appendices highlights the key results of the investigations and provides a list of the most important driving forces in the generation of the floods in the particular year.

Some case studies in the appendices also include short methodological explanations about the graphical presentation of meteorological and hydrological variables as well as their interpretation (see also Table 5.9). In particular, this concerns

- case study 1906 (Appendix 5.1): potential runoff (R(pot)), relevance factor (R(relev)), daily rainfall, daily water level;
- case study 1955 (Appendix 5.4): monthly discharge;
- case study 1974 (Appendix 5.5): daily discharge, groundwater;
- case study 1988 (Appendix 5.7): tidal movements.

The approach of presenting a summary of the case studies in the main text and a detailed account in the appendices allows the reader to follow the big lines of the investigations and argumentation while at the same time delving more deeply into the findings according to individual interests and needs.

5.4. 1906: A "flood year"

This case study is based on investigations made by project team member Robeen Dutt (Dutt 1995). The detailed analysis of the 1906 floods is presented and discussed in Appendix 5.1 (pp. 222–236).

The flood of 1906 was the most catastrophic event in the period 1890–1909, even though the territory of modern Bangladesh was only slightly or moderately affected by the floods (Figure 5.11). The map in Figure 5.11, which is based on administrative boundaries, depicts not the actually flood-affected areas but those districts that were affected to varying degrees by the floods. These districts are obviously not identical with the subcatchments according to which the data on R(pot) and R(relev) have been calculated (see Figure 5.1). The same note applies to the 1910 (section 5.5) and 1922 (section 5.6) case studies. Based on Figure 5.11, three areally distinct flooding patterns can be identified: (a) floods, some of them categorized as severe or even catastrophic, in or directly to the south of the Himalayan ranges (districts 1, 2, 3, 4, 7, 8, 9, 10, 11, 12, which represent parts of SCs 4, 5, 3, 8 and 10); (b) floods along the Ganga in India and in the confluence region of the Ganga and Brahmaputra in the territory of modern Bangladesh (districts 5, 6, 13, 14, 15, 16, 17, 21, 22, which represent parts of SCs 5, 10, 6 and 13); (c) floods in central and eastern Bangladesh (districts 18, 19, 20, which represent parts of SCs 11 and 12). It is interesting to note that there was no continuous flood from

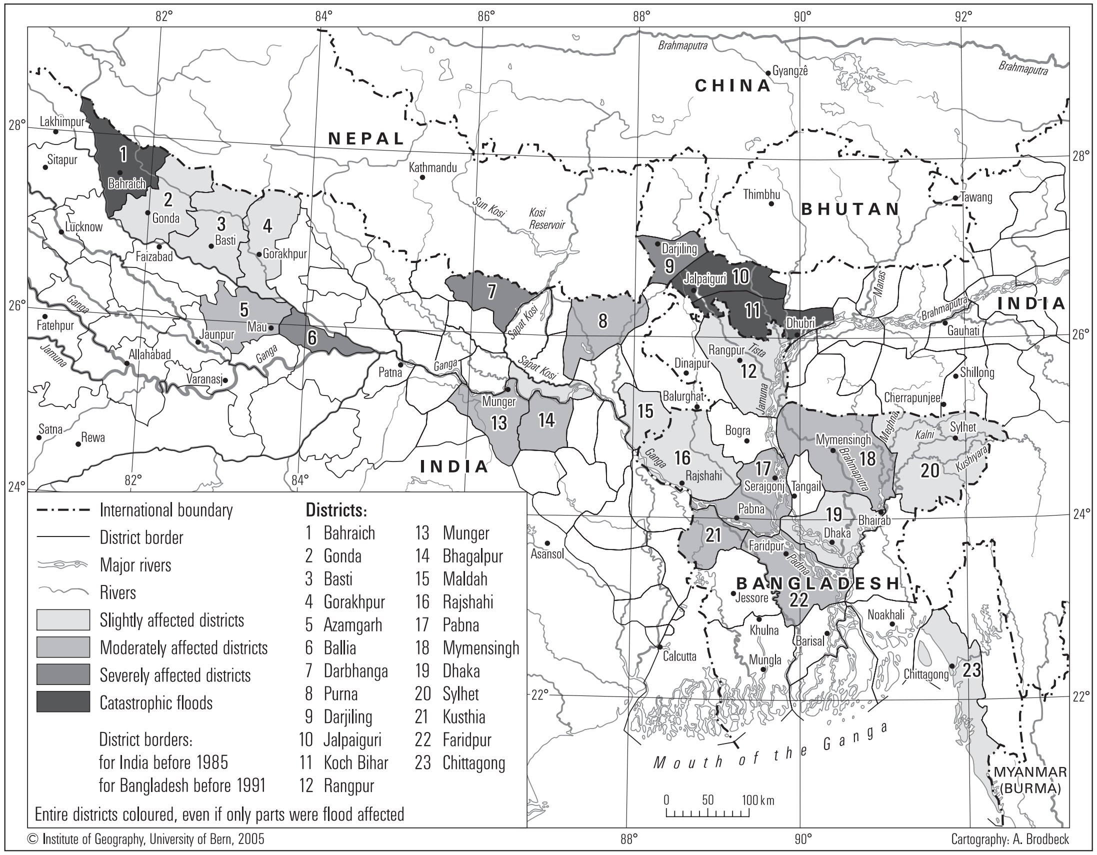


Figure 5.11 Flood-affected areas and flood intensities: 1906.

the Himalayan foothills down to Bangladesh; rather, the floods occurred in isolated patches.

Based on the available literature sources,[1] it is difficult to identify the precise timing of the floods. Generally speaking, the flood period extended from early August to early September. The floods were most widespread during the second half of August, and lasted longest in the area of modern Bangladesh. Flooding in districts 9, 10, 11 and 12 had already occurred in early August and must therefore be considered a separate event.

The available literature lists the following causes of the flooding in the different areas: Himalayan rivers; simultaneously high levels of the Kosi (an important tributary of the Ganga, see Figure 3.2) and the Ganga; the high level of the Brahmaputra; simultaneous peaks of the Ganga and the Brahmaputra in the areas near their confluence; heavy local rainfall in Pabna and Mymensingh districts (17 and 18).

Box 5.2 provides a few of the main points extracted from the detailed investigations of the 1906 floods in Appendix 5.1. To summarize and generalize the findings of the in-depth analysis, floods were widespread in the areas located immediately to the south of the Himalayan ranges, particularly in the forelands of the Darjiling and western Bhutan Himalayas, as well as in the territory of modern Bangladesh. Heavy and continuous rainfall in most parts of the basin, resulting in widespread above-average potential runoff (R(pot)), can be seen as the basic cause of the flood events. The Himalayan ranges are important as an orographic barrier that triggers rainfall. The comparison of the rainfall figures for Darjiling (a highland station in district 9) and Siliguri (a lowland station in the far western corner of district 10) has shown that it is mainly the foothills and the first ranges that are responsible for this effect. Higher up and further into the Himalayas, rainfall seems to decrease. In addition to the contribution from the foothills and the first Himalayan ranges, it seems that the rains over the flood-affected areas in the forelands themselves were equally or even more decisive for the flood processes.

The flood waves occurring to the south of the Himalayan ranges obviously did not rush downstream with increasing intensity: they were not linked to the flood processes in Bangladesh either geographically or, in the case of the floods in the forelands of the Darjiling and Bhutan Himalayas, even temporally. These findings imply that the highland–lowland interaction between the Himalayas and Bangladesh was of only an indirect nature: the likely flood flows of the tributaries, which discharged the flood-affected areas in the Himalayan forelands, were incorporated into the base flow of the Ganga and Brahmaputra. These two rivers then reached their highest flow of the year simultaneously while flowing through Bangladesh. Together with other factors such as heavy rainfall

Box 5.2 Investigation of the 1906 flood: Main points extracted from the detailed analysis presented in Appendix 5.1

Flood damage (for the location of the districts, see Figure 5.11)

- Disruption of railway lines in districts 7, 9, 20, 22.
- Bridge collapse in district 7.
- Loss of human life and cattle in district 1.
- Crop damage in districts 5, 6, 15, 16, 17, 18, 21, 22.

Monthly potential runoff (*R*(pot)) and relevance (*R*(relev)) (see Figure 5A.2 in Appendix 5.1; for the location of the subcatchments, see Figure 5.1)

- In August, the main flooding period, *R*(pot) was above average in 9 of 11 documented subcatchments.
- The anomalies in *R*(pot) in the Himalayan subcatchments SC1 and SC3 in August are particularly high and were certainly very relevant for the flood processes that occurred directly to the south of the Himalayan ranges, most obviously in the case of districts 10 and 11. However, in terms of relevance to the floods in Bangladesh, only the anomaly in SC3 is of some importance.
- In the Meghalaya Hills (SC9) the anomalies in *R*(pot) and particularly in *R*(relev) were positive throughout July, August and September.
- Compared with the other subcatchments, the situation was unspectacular on both the Upper and Lower Ganga Plains (SC4, SC5) in August.

Daily rainfall (see Figure 5A.3 in Appendix 5.1; for the location of the stations, see Figure 3.1)

- Main periods of widespread rainfall: 9–16 July (no flooding, but most likely increase in soil moisture), 27 July–20 August (before the floods reached their maximum extent).
- Daily rainfall recorded in Darjiling (a highland station) was lower than in Siliguri (a lowland station south of the Darjiling Himalayas).
- In Cherrapunjee (Meghalaya Hills, SC9) rain fell on roughly 75 per cent of the days from June to September. Total rainfall in July and August amounted to 7,449 mm compared with an average of 4,424 mm for these two months.

Daily water level (see Figure 5A.4 in Appendix 5.1)

- The graphs of the daily water level can be directly related to the flood and the most important rainfall periods.
- As a result of the second rainfall period (27 July–20 August), the water levels reached unusual and even record values.
- The highest water levels of the three rivers temporally coincided with the period of widespread flooding in the second half of August.

in Bangladesh itself and extraordinary input from the Meghalaya Hills (where the highland–lowland linkages are direct), this led to a gradual spreading out of flood waters in Bangladesh. This finding is supported by an interesting statement by Mahalanobis (1927: 74): "it is again important to notice that the extremely severe flood [see Figure 5.11] in the districts of Darjiling [district 9], Jalpaiguri [district 10], Cooch Behar [district 11] and portions of Rangpur [district 12] did not apparently cause any appreciable flooding in the districts lying immediately to the south."

This is the first case study for which the two newly introduced parameters, *R*(pot) and *R*(relev), have been used. The experiences are positive: applied to a specific case study, the two variables are useful tools for quantifying the hydrological contribution from different subcatchments, for identifying areas of important anomalies, and for obtaining indications of the areas most relevant to the flood processes in Bangladesh.

Factors that were important for the floods to the south of the Himalayan ranges (particularly the forelands of the Darjiling and western Bhutan Himalayas):
- heavy rainfall in the first Himalayan ranges;
- high water levels of the Himalayan rivers;
- heavy rainfall over the flood-affected areas themselves in August;
- early monsoon rains in July leading to rising soil humidity and groundwater level.

Factors that were important for the floods in Bangladesh:
- temporal sychronization of the highest flow of the Ganga and the Brahmaputra in 1906;
- widespread rainfall in August in the basin, particularly over Bangladesh and the Meghalaya Hills;
- early monsoon rains in July.

Factors that were not important for the floods in Bangladesh:
- input originating in the Ganga lowlands;
- input originating in Upper Assam;
- the pre-monsoon period.

5.5. 1910: A "flood year"

This case study is based on investigations made by project team member Roland Guntersweiler (Guntersweiler 1995). The detailed analysis of the 1910 flood is presented and discussed in Appendix 5.2 (pp. 236–245).

The flood of 1910 was not an extraordinary event, but again proved to be a very interesting case in the context of highland–lowland linkages. As is shown in Figure 5.12, there were basically four distinct flood-affected areas: (a) the lower part of the Indian Ganga Plain (districts 4, 5 and 6,

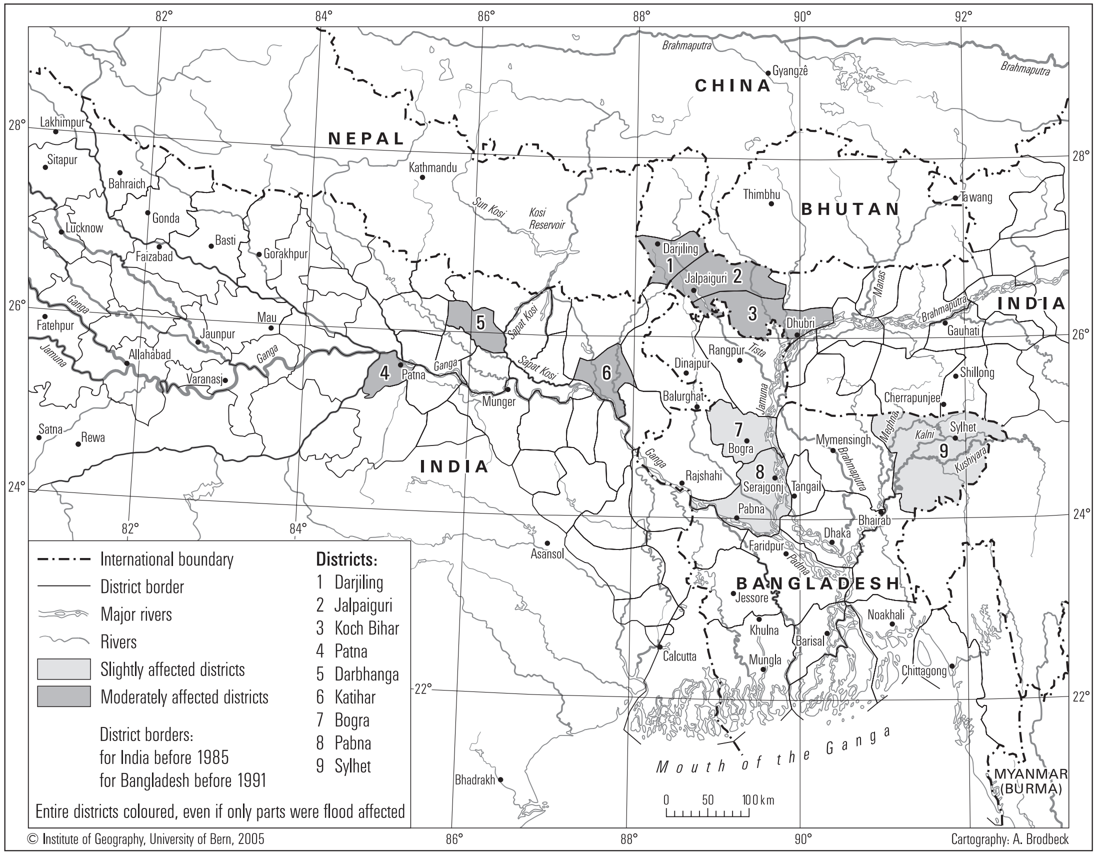


Figure 5.12 Flood-affected areas and flood intensities: 1910.

which represent parts of SC5); (b) areas located directly to the south of the Himalayan ranges (districts 1, 2 and 3, which represent parts of SC3 and SC8); (c) the north-western part of modern Bangladesh (districts 7 and 8, which represent parts of SC10); (d) the north-eastern part of modern Bangladesh (district 9, which in part is located in SC11, in part in SC12). Similarly to the situation in 1906, there was no continuous flooding from the Himalayan foothills or from the Indian floodplains down to Bangladesh; rather, the floods occurred in isolated patches. The available sources do not provide a clear and differentiated picture of the flood chronology. The floods in districts 4 and 5 seem to have occurred throughout July and well into August. The inundations in districts 1, 2 and 3 developed in July and reached their maximum extent most probably around the middle of the same month. Finally, the floods within modern Bangladesh in districts 7, 8 and 9 occurred towards the end of July and extended into August. Based on these very rough indications it seems that the floods were most widespread in the last part of July. In the available literature only a few causes of the floods are mentioned, namely heavy local rainfall for all affected areas except those in North-eastern Bangladesh, discharge from the Himalayas in the case of the floods in districts 2 and 3, and an abnormally high level of the Brahmaputra in the case of the floods in districts 7 and 8.[2]

Box 5.3 provides a few of the main points extracted from the detailed investigations of the 1910 floods in Appendix 5.2. To summarize and generalize the findings of the in-depth analysis, it can be confirmed that the flood of 1910 was certainly not an extraordinary event, at least compared with the other case studies. In terms of highland–lowland linkages it has some similarities to the flood in 1906. A very important factor seems to have been the above-average potential runoff during June and July in a large and connected area including the subcatchments of the Darjiling–Bhutan Himalayas, Lower Assam, the eastern part of the Lower Ganga Plain, North-western Bangladesh, North-eastern Bangladesh and the Meghalaya Hills. Most probably this situation led to a gradual accumulation of water in the soils as well as to rising groundwater levels. High-intensity rains over the flood-affected areas themselves are another important element for understanding the particular flooding patterns in 1910. In terms of highland–lowland linkages, significantly above-average rainfall in the Meghalaya Hills was probably very important for the flooding in the directly adjacent lowlands of north-eastern Bangladesh (district 9). Also, there is no doubt that the rains in the first Himalayan ranges in the Siliguri–Darjiling area contributed to the development of the floods in the lowlands immediately to the south (districts 1, 2 and 3). However, the local rains over the flood-affected areas seem to have been equally or even more important than the input from the Himalayas. The fact that, as

Box 5.3 Investigation of the 1910 flood: Main points extracted from the detailed analysis presented in Appendix 5.2

Flood damage (for the location of the districts, see Figure 5.12)

- Devastation of paddy crops, disruption of numerous railway lines in districts 4, 5 and 6.
- Disruption of railway lines between Calcutta and Gauhati, loss of some lives, damage to tea estates and to jute crops in districts 1, 2 and 3.
- Several bridges of the Eastern Bengal State Railway affected near the station of Bogra, destruction of houses in districts 7 and 8.
- No damage reported from the floods in district 9.

Monthly potential runoff (R(pot)) and relevance (R(relev)) (see Figure 5A.6 in Appendix 5.2; for the location of the subcatchments, see Figure 5.1)

- In subcatchments 3, 8, 9, 10, 11 and 12, R(pot) was above average in June as well as in July. In July, these variations resulted in some significant anomalies in R(relev). The floods in these areas occurred in July and early August.
- The most outstanding anomaly in R(pot) in July was recorded in the Meghalaya Hills (SC9) and accordingly this area achieved a very high R(relev) for the hydrological processes in Bangladesh.
- Throughout the monsoon season, significantly negative anomalies in R(pot) dominated the Ganga Plain (SC4 and SC5).

Daily rainfall (see Figure 5A.7 in Appendix 5.2; for the location of the stations, see Figure 3.1)

- Main periods of widespread rainfall (except for the Ganga Plain): 9–23 June (no flooding, but most likely water accumulation in the soils and rising groundwater table), 10–29 July (coincidence with the period of most widespread flooding), 12–19 August.
- As in 1906, daily rainfall recorded in Darjiling (a highland station) was lower than in Siliguri (a lowland station south of the Darjiling Himalayas).
- During the critical flood period in districts 1, 2 and 3, rainfall over the flood-affected areas themselves was massive, in terms of both intensity and amount.
- In Cherrapunjee (Meghalaya Hills, SC9), rainfall was recorded on almost 80 per cent of the days, and some daily rainfall totals were extremely high (close to 1,000 mm of rainfall on 12 July).

Box 5.3 (cont.)

Daily water level (see Figure 5A.8 in Appendix 5.2)

- The Brahmaputra at Gauhati in Assam and the Padma at Goalundo, located below the confluence of the Brahmaputra and the Ganga, reached their highest water level during the main flood phase at the end of July and in early August, respectively.
- The water level of the Brahmaputra at Gauhati on 30 July was the highest for the period 1891–1930. This confirms the literature statement that the floods in Serajganj area (districts 7 and 8) were in part related to the abnormally high water level of the Brahmaputra.
- The hydrograph of the Ganga at Varanasi (see Figure 5.12) is difficult to relate to the prevailing rainfall conditions. The water level remained rather low during July and the first part of August, which is when the most extended rains and floods occurred. The highest water level of the Ganga was reached around mid September.

in 1906, there was no continuous flood further downstream indicates that there were no direct and large-scale highland–lowland linkages to trigger flood processes in Bangladesh. In spite of the constantly above-average rainfall over the North-western Himalayas, the hydrological contribution from the Ganga system into Bangladesh was unimportant. Based on the different puzzle pieces of the investigation, it has to be assumed that the floods in the Ganga system (districts 4, 5 and 6) as well as their triggers were rather localized in nature. It is very unfortunate that owing to missing data it was not possible to calculate the potential runoff (*R*(pot)) and the relevance factor (*R*(relev)) for the Nepal Himalayas (SC2).

Factors that were important for the floods to the south of the Himalayan ranges, particularly the forelands of the Darjiling and western Bhutan Himalayas (districts 1, 2 and 3):

- early monsoon rainfall in June;
- heavy rainfall in July over the flood-affected areas themselves;
- rainfall in the lower part of the Himalayas;
- probable high water levels of the Himalayan rivers at the entry points to the plains.

Factors that were important for the floods in Bangladesh:

- early monsoon rainfall in June;
- widespread rainfall in July during the flood period;
- heavy local rainfall over the flood-affected areas themselves;
- the high water level of the Brahmaputra in the case of the floods in north-western Bangladesh (districts 7 and 8);

- heavy rainfall in the Meghalaya Hills in the case of the floods in north-eastern Bangladesh (district 9).

Factors that were not important for the floods in Bangladesh:

- input originating in the Ganga lowlands.

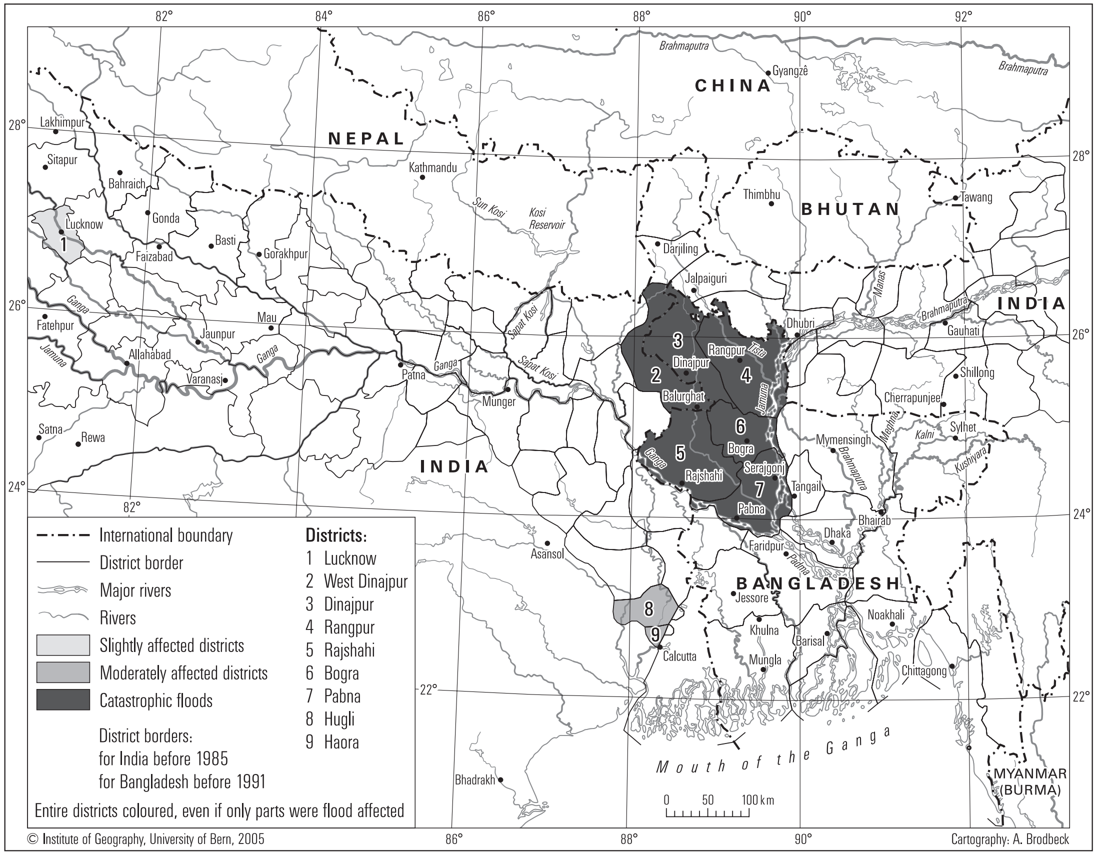
5.6. 1922: A ‘‘flood year’’

This case study is based on investigations made by project team member Roland Guntersweiler (Guntersweiler 1995). The detailed analysis of the 1922 flood is presented and discussed in Appendix 5.3 (pp. 245–254).

The worst flooding in the period 1910–1930 occurred in 1922. However, it was limited in terms of geographical extent (see Figure 5.13): covering districts 2, 3, 4, 5, 6 and 7, the flooding affected more or less the entire north-western part of modern Bangladesh, which largely corresponds to SC10 and a small part of SC5 (see also Figure 5.1). The flood in these areas was rated as very severe and extensive. In addition to this main area of flooding, moderate inundations were reported from districts 8 and 9 located to the west of Calcutta (partly in SC6) as well as slight flooding in the area of Lucknow in the Indian Ganga Plain (district 1, located in SC4). The severe floods in districts 2–7 occurred very late in the monsoon season, in the last part of September. Whereas the timing of the moderate floods to the west of Calcutta is not known, reports of the slight inundations in the area of Lucknow date from the first week of September. According to the available literature, the floods in districts 2–7 were caused by heavy rains linked to a storm that lasted for three days and moved from the south to the north.[3] The severe damage caused in Rajshahi was related to the high water level of the Ganga. Heavy rainfall was also given as the main reason for the moderate floods to the west of Calcutta. The overflow of the Ganga is perceived as the main reason for the light floods in the area of Lucknow.

In contrast to these accounts of floods, the available sources report a severe drought in the entire catchment of the Meghna: throughout the monsoon season complaints and reports about scanty rain and terrible heat were published.

Box 5.4 provides a few of the main points extracted from the detailed investigations of the 1922 floods in Appendix 5.3. To summarize and generalize the findings of the in-depth analysis, 1922 was the heaviest flood year in the period 1910–1930, not in terms of the geographical extent of the flood, but in terms of the severity of the flooding within North-western Bangladesh (mainly SC10). This event seems to be an interesting example of a severe flood that had a limited areal extent and that was caused almost exclusively by heavy rainfall over the flood-affected areas



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Cartography: A. Brodbeck

Figure 5.13 Flood-affected areas and flood intensities: 1922.

Box 5.4 Investigation of the 1922 flood: Main points extracted from the detailed analysis presented in Appendix 5.3

Flood damage (for the location of the districts, see Figure 5.13)

- The severest damage was reported from the area of Rajshahi in district 5.
- 25–75 per cent of the broadcast winter rice was destroyed, many animals were killed and people were rendered homeless owing to the collapse of their houses in districts 1–7.
- Diseases broke out because of problems with the drinking water supply.
- A number of railway embankments were breached and the important line to Darjiling was disrupted.
- Owing to the (moderate) floods to the west of Calcutta in districts 8 and 9, many people had to flee to railway embankments and trees.
- Some damage to embankments and crops is reported from the slightly flood-affected areas of Lucknow (district 1).

Monthly potential runoff (*R*(pot)) and relevance (*R*(relev)) (see Figure 5A.10 in Appendix 5.3; for the location of the subcatchments, see Figure 5.1)

- *R*(pot) in SC10 (North-western Bangladesh), where the severe flooding took place in the last part of September, reached twice the normal volume for that month. Even more outstanding was the anomaly in *R*(relev), which ranked second of all subcatchments.
- In the Ganga system the anomalies in *R*(pot) were significantly positive throughout the four monsoon months and in all subcatchments for which data were available, with the exception of SC4 (Upper Ganga Plain).
- Negative anomalies in *R*(pot) dominated in parts of the Meghna catchment, namely the Meghalaya Hills (SC9) and North-eastern Bangladesh (SC11) from July to September.
- In June, August and particularly September, *R*(pot) in the Darjiling–Bhutan Himalayas (SC3) was below average.

Daily rainfall (see Figure 5A.11 in Appendix 5.3; for the location of the stations, see Figure 3.1)

- Main periods of widespread rainfall: 14 June–1 July (exception: stations in the Ganga lowlands), 5–9 August, 25 August–6 September (not continuous, but frequent rains), 22–27 September (rains recorded at a limited number of stations, but with very high values at some sites such as Bogra, Pabna and Rangpur in SC10).

Box 5.4 (cont.)

- The rainfall period 22–27 September, during which the severe flooding in north-western Bangladesh occurred, was exceptional: the heavy rains were recorded mainly at the stations located within the flood-affected area.

Daily water level (see Figure 5A.12 in Appendix 5.3; for the location of the stations, see Figure 3.2)

- Hydrological information is very limited for 1922. Information is completely missing for the Ganga, and the records for the Brahmaputra and the Padma are available only until 20 September.
- The water level at Gauhati did not reach anything like the levels recorded in 1910. More importantly, the water level was already very low on 20 September, before the heavy flooding in SC10 even started.

themselves. Based on the water level data measured at Gauhati in Assam, it seems that the flow of the Brahmaputra was already low towards the end of September and consequently cannot be considered an important factor in the triggering of the floods. However, the high water level of the Ganga at Rajshahi, which is reported in the literature sources, might have contributed to the flooding processes in the southernmost part of SC10. The contrast between the heavy monsoon rains in the Ganga system and the drought conditions particularly in the Meghna system was strongly articulated in 1922. Should the below-average monsoon in the Brahmaputra and Meghna catchments be considered one reason for the fact that the floods in Bangladesh did not reach nationwide dimensions in spite of the high inflow from the Ganga system? Does this indicate that the monsoon characteristics in the Meghna and Brahmaputra basin, and not those in the Ganga catchment, ultimately exert the decisive influence on flood dimensions in Bangladesh? These interesting and pertinent questions will be addressed again in the further discussion of the case studies in subsequent sections.

From the written sources it is evident that in the 1920s the discussion about the positive and negative aspects of road and railway embankments was already intense and controversial. In relation to the 1922 floods it is stated that, on the one hand, embankments provided shelter for homeless people; on the other hand, dams obstructed the timely discharge of excessive flood water. In particular, it was perceived that, owing to bad planning, the railway embankment in the region of Bogra (district 6) did not have a sufficient number of drainage outlets. The Bengal

Flood Committee, which was charged with an investigation of floods, concluded in 1923 that the following measures had to be taken (*The Statesman*, 20 September 1923): "On the transversal embankments more openings should exist for an improved water flow. More artificial reservoirs should be built for better storage capacity in addition to the natural beels. Better maintenance of the drainage and irrigation canals was also recommended. In terms of the benefits of embankments, the committee discussed whether the effects of normal and abnormal flood events would have been the same with or without embankments, but a final conclusion was not drawn."

Factors that were important for the floods in Bangladesh:

- heavy rainfall directly over the flood-affected areas at the end of September;
- the high water level of the Ganga, possibly causing backwater effects in the southern part of the flood-affected areas.

Factors that were unimportant for the floods in Bangladesh:

- rainfall in the pre-monsoon period as well as during the monsoon months until 20 September;
- hydro-meteorological conditions in the Meghna catchment, especially in the Meghalaya Hills;
- the contribution from the Darjiling–Bhutan Himalayas.

5.7. 1955: A "flood year" for Bangladesh

The data and information available for the case studies after 1950 differ quite significantly from those before 1950 (see Chapter 3). First, the available flood maps cover only the territory of Bangladesh. They do not depict the flood-affected districts as in 1906, 1910 and 1922, but give a composite picture of the actually flood-affected areas during the particular monsoon season. Secondly, systematic records of daily rainfall are available only for measuring sites within Bangladesh, whereas monthly information on precipitation continues to be accessible for more or less the whole study region. Finally, the availability of regular and continuous hydrological data series for Bangladesh, after 1965 on a daily basis, provides new opportunities for the investigations.

The detailed analysis of the 1955 floods is presented and discussed in Appendix 5.4 (pp. 254–263). The map in Figure 5.14 provides a very rough idea of the geographical extent of the floods in 1955. According to this map, significant parts of the Meghna and Brahmaputra catchments, the confluence area of the three major rivers, and regions towards the south were affected. Interestingly, the coastal areas south of Khulna, Barisal and Noakhali seem to have been flood free. There is no information

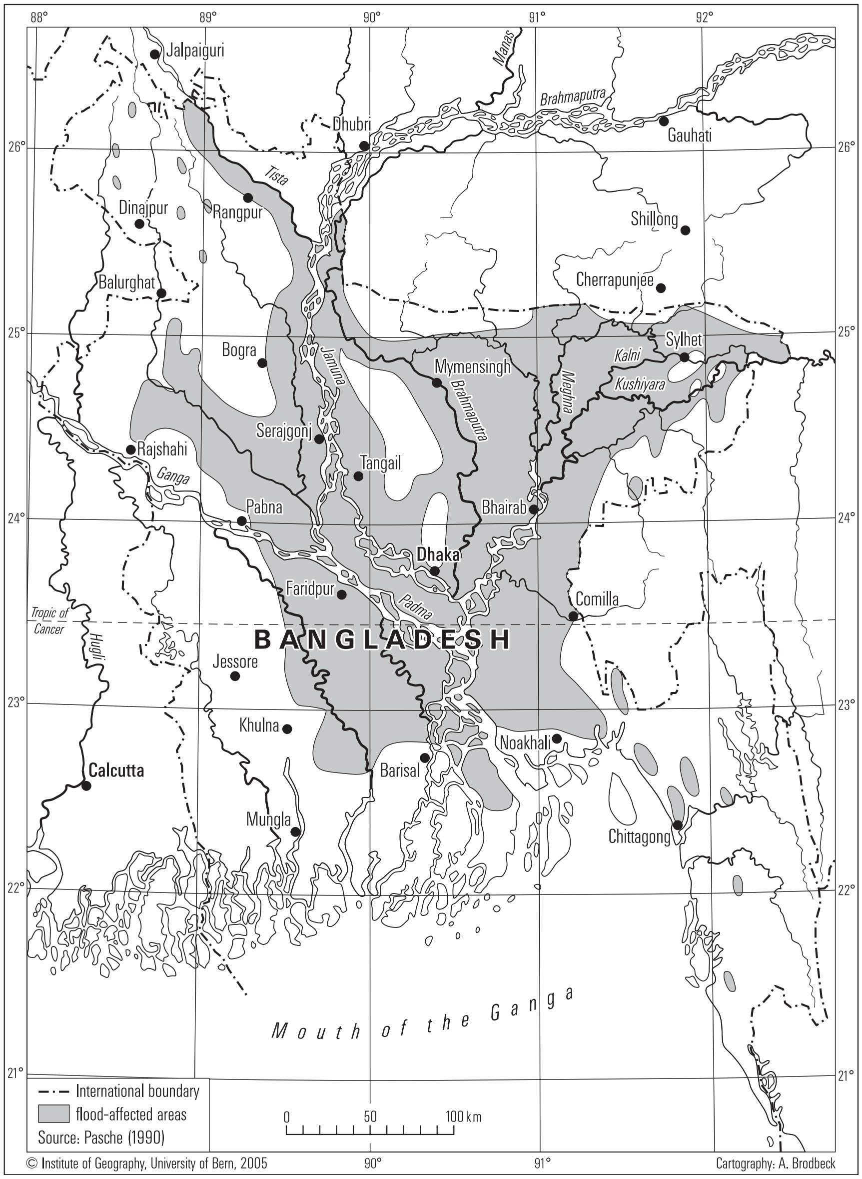


Figure 5.14 Flood-affected areas, synthesized for the entire monsoon season: 1955.

about the timing of the floods but, based on the hydrological records (see Figure 5A.17 in Appendix 5.4), the inundations most likely occurred in August. According to the literature, flooding was also reported in Assam (Brahmaputra lowland in India) and, in early October, in Uttar Pradesh (Upper Ganga Plain).[4] The few available references mention excessive, high-intensity precipitation as one of the main causes of the generation of the floods.

Box 5.5 provides a few of the main points extracted from the detailed investigations of the 1955 floods in Appendix 5.4. To summarize and generalize the findings of the in-depth analysis, it needs first of all to be emphasized that, in general, the data situation for the analysis of the 1955 floods was very limited. Most probably a combination of three main factors resulted in the widespread flooding in Bangladesh: rainfall within Bangladesh; significant hydrological inflow from the Indian Ganga and Brahmaputra Plains as well as from Meghalaya; and the synchronized flow above danger levels of the Ganga, Brahmaputra and Meghna over three weeks. As the timing is not specified in the literature sources, it cannot be verified whether the floods in Bangladesh and those in Assam occurred at the same time. Interestingly, and in spite of the long period that the flow was above danger level, the Ganga did not trigger any flooding in Bangladesh upstream of its confluence with the Brahmaputra. The hydrological processes and the flood situation in 1955 seem to document that local triggers (mainly precipitation within Bangladesh) for widespread flooding do not need to be very strong if the hydrological inflow into Bangladesh through the major rivers is high.

Factors that were important for the floods in Bangladesh in August:

- widespread rainfall during July, leading to an increase in river flow, and presumably also contributing to a rising groundwater table and soil saturation;
- fairly constant but moderate rainfall in the first part of August within Bangladesh;
- above-average inflow from the Indian Ganga and Brahmaputra Plains as well as from Meghalaya;
- synchronization of above-danger-level flow of the Meghna, the Brahmaputra and the Ganga for three weeks in August.

Factors that were not important for the floods in Bangladesh:

- the contribution from the Himalayas (this statement is based on calculations of R(pot)).

5.8. 1974: A "flood year" for Bangladesh

The detailed analysis of the 1974 floods is presented and discussed in Appendix 5.5 (pp. 263–276). As indicated in the caption, the map in

Box 5.5 Investigation of the 1955 flood: Main points extracted from the detailed analysis presented in Appendix 5.4

Flood dimension

- At 50,500 km^2 (35.37 per cent of the country), ranks sixth for the period 1954–2004 (see Table 4.1).
- Maximum flood extent: most likely in August.

Monthly potential runoff (*R*(pot)) and relevance (*R*(relev)) (see Figure 5A.14 in Appendix 5.4; for the location of the subcatchments, see Figure 5.1)

- During July, positive anomalies in *R*(pot) were widespread, particularly in Bangladesh (SC10, SC12, SC13), Assam (SC7 and SC8) and Meghalaya (SC9). In Bangladesh and Meghalaya, *R*(relev) was significantly above average as a result of the positive variations in *R*(pot).
- In Bangladesh, the positive variations in *R*(pot) and *R*(relev) continued into August.
- In August and September, positive anomalies in *R*(pot) dominated in the lowland subcatchments of the Ganga system (SC4 and SC5).
- The figures for *R*(pot) and *R*(relev) calculated for the three Himalayan subcatchments (SC1, SC2 and SC3) do not deviate significantly from the average.

Monthly discharge (see Figure 5A.15 in Appendix 5.4; for the location of the stations, see Figure 3.2)

- Information is available for three stations only: Ganga (Hardinge Bridge), Brahmaputra (Pandu), Sapt Kosi (Barakshetra – a major tributary to the Ganga from Nepal).
- The flow of the Ganga and the Brahmaputra was significantly above normal during July and August.
- The discharge of the Sapt Kosi was constantly below average from April to November.

Daily rainfall (see Figure 5A.16 in Appendix 5.4)

- Unfortunately, daily rainfall data were available only for a few stations in Bangladesh.
- Main periods of widespread rainfall: 10 July to 20 August (in the second half most likely coinciding with the flooding period), 10–18 September.

Daily water level (see Figure 5A.17 in Appendix 5.4)

- The Ganga, Brahmaputra and Meghna crossed the danger level almost simultaneously between 25 July and 30 July.

Box 5.5 (cont.)

- The duration of flow above danger levels is quite significant: 22 days for the Brahmaputra, 71 days for the Ganga and 52 days for the Meghna (synchronized in all three rivers for about three weeks from the beginning of August).
- The dominant characteristics of the hydrographs can be related to the rainfall patterns in Bangladesh.

Figure 5.15 is a composite of various distinct flood periods and affected areas during 1974, and thus does not necessarily represent the maximum flood extent at a given time. However, the delineation of the floods in this figure most probably comes close to representing the flood situation in early August (see below). The 1974 flood was widespread, but mainly occurred in the Meghna and Brahmaputra basins. It did not affect the western, south-western and southernmost parts of the country. The floods occurred in three phases. The floods in late June mainly affected districts of north-western Bangladesh (SC10, see Figure 5.1), north-eastern Bangladesh (SC11) and central–eastern Bangladesh (SC12). Floods in the first part of August reached nationwide dimensions and affected all districts, with the exception of the western and southernmost parts of the country. The third flood wave was regionally limited to areas in Rangpur district in north-western Bangladesh. Floods did not occur only in Bangladesh: Assam (Brahmaputra lowland in India) experienced a devastating flood that occurred in five successive waves. Its impact was particularly severe in the districts of Goalpara and Kamrup, which are located downstream of Gauhati. For the Indian part of the Ganga system there is no evidence of flood problems. The available literature discusses a number of causes of the 1974 floods: heavy, intense precipitation over the catchment areas of the rivers outside and within Bangladesh, but particularly outstanding in Cherrapunjee; high upland discharge with a huge onrush of water down the Brahmaputra from the hill areas of Assam; high water levels and high tides; simultaneous flow above danger levels of the three major rivers from early August to mid August and again for a week during early September.[5]

Box 5.6 provides a few of the main points extracted from the detailed investigations of the 1974 floods in Appendix 5.5. First of all it needs to be emphasized that, as a new feature for the 1974 case study, groundwater data series became available on a weekly basis. For the investigations, nine stations were selected (see Figure 3.3) that are more or less equally distributed over the floodplain of Bangladesh. The following

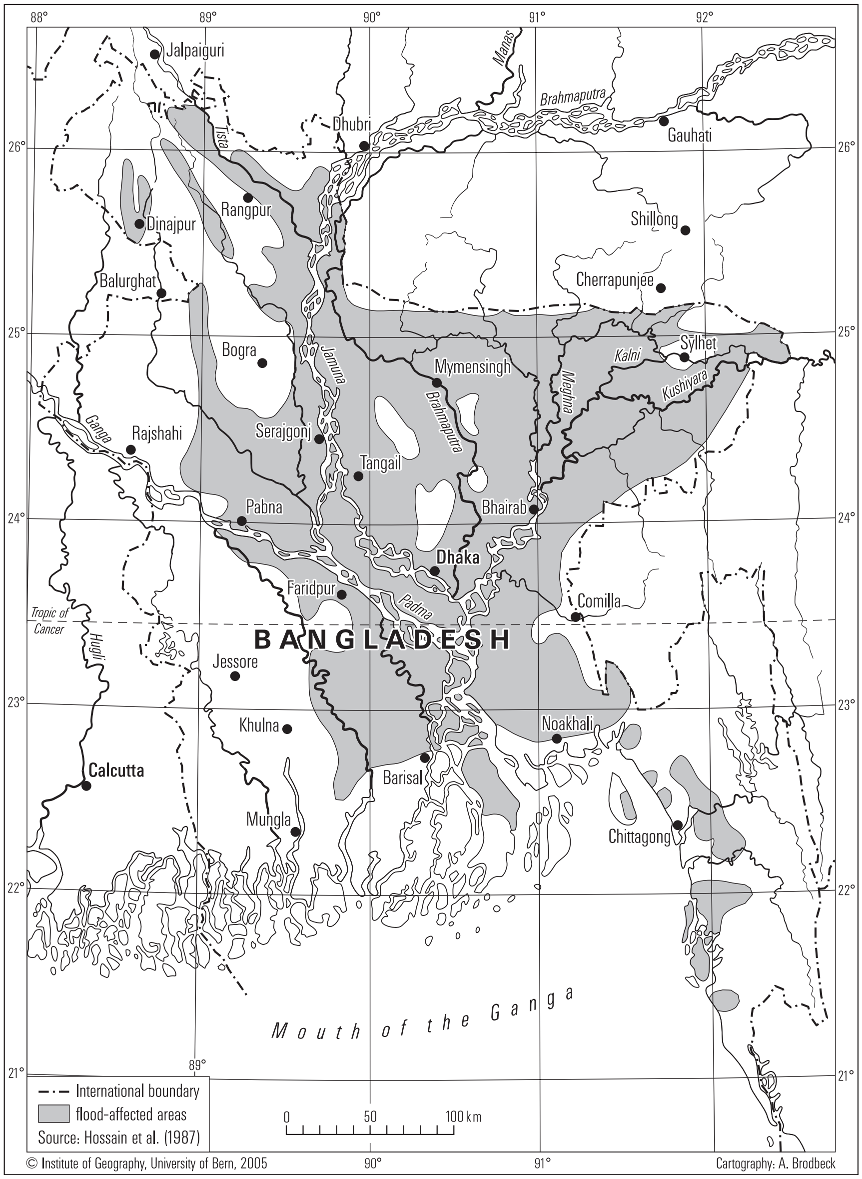


Figure 5.15 Flood affected areas, synthesized for the entire monsoon season: 1974.

Box 5.6 Investigation of the 1974 flood: Main points extracted from the detailed analysis presented in Appendix 5.5

Flood dimension

- At 52,600 km^2 (36.84 per cent of the country), ranks fifth for the period 1954–2004 (see Table 4.1).
- Maximum flood extent: first part of August.

Monthly potential runoff (*R*(pot)) and relevance (*R*(relev)) (see Figure 5A.19 in Appendix 5.5; for the location of the subcatchments, see Figure 5.1)

- In July, positive variations in *R*(pot) were recorded in all subcatchments except Nepal (SC2). In terms of *R*(relev) this anomaly was particularly important for the Meghna system.
- In August, when the floods reached their maximum dimension, *R*(pot) and *R*(relev) were below average in most subcatchments.
- In major parts of the Meghna catchment, but particularly striking in the Meghalaya Hills (SC9), positive anomalies in *R*(pot) and *R*(relev) were recorded throughout the monsoon period. At a total of 23,663 mm, the annual precipitation in Cherrapunjee was outstanding and reached the highest values since the beginning of measurements in 1851.
- With the exception of July, *R*(pot) and *R*(relev) in the Ganga system were generally below average.
- The calculations of *R*(pot) and *R*(relev) for the three Himalayan subcatchments (SC1, SC2 and SC3) do not result in any outstanding figures.

Monthly discharge (see Figure 5A.20 in Appendix 5.5)

- In July, all the rivers in the Meghna and Brahmaputra systems recorded above-average flows.
- Considering the whole year, the most important positive variations in monthly flow were measured in the Meghna catchment.
- The flow of the Ganga was only average or even below average during the monsoon season.
- The flow of the Brahmaputra was above average from July to September.
- In terms of the Himalayan tributaries, the flow was above average for the Tista (tributary to the Brahmaputra) throughout the year. Towards the west, the anomalies became smaller and turned into negative variations in western Nepal.

Box 5.6 (cont.)

Daily rainfall (see Figure 5A.21 in Appendix 5.5)

- Important rainfall periods: 1–8 June, 16–24 June, 30 June–7 July, 13–30 July, 26 August–1 September, 12–15 September.
- The nationwide flood in the first part of August started at the end of a long rainy phase and significantly extended into the subsequent dry period.

Daily discharge (see Figure 5A.22 in Appendix 5.5)

- The flow of the Brahmaputra and the Meghna was exceptional and significantly exceeded the maximum values that are on average recorded during the monsoon season. The highest flow of the Ganga never reached the maximum values that are on average recorded during the monsoon season.
- The Brahmaputra and the Meghna reached their highest flow of the year almost simultaneously between 5 August and 10 August.
- The three major rivers were flowing above danger levels from 1 August to 14 August, the period of the nationwide flooding.
- The dimension and to some extent the timing of the maximum flows of the Brahmaputra in early August and in early September cannot be fully understood by considering the rainfall patterns only in Bangladesh; considerable external input from Assam and Meghalaya has to be assumed and a connection to the flood processes in Lower Assam seems to be obvious.
- The flood periods are much less clearly reflected in the hydrographs of the Tista (tributary to the Brahmaputra) and the Kushiyara (tributary to the Meghna) compared with those of the main rivers.

Groundwater (see Figure 5A.23 in Appendix 5.5)

- In general, groundwater levels were above average during the monsoon period.
- Groundwater reached the surface in the area of confluence of the Brahmaputra and the Ganga, in the Meghna region south of Bhairab Bazar and in the coastal areas, in most cases precisely in the period of the most extensive flooding in early August.
- At most stations the level of the groundwater table was higher than normal at the onset of the monsoon season, which indicates that the absorption capacity of the ground was already reduced when the rainy season started.

summary of the findings of the in-depth analysis of the 1974 case study concentrates on the nationwide flooding in the first part of August in Bangladesh: high rainfall inside and outside Bangladesh, flood peaks that originate from within Bangladesh and flood peaks that are imported from outside the country, a synchronization of flood flows of the major rivers, and high groundwater tables are all important elements for understanding the widespread flooding in 1974. This statement is clearly supported by the list of flood-causing factors mentioned in the literature. The Meghna catchment was of particular importance, followed by the Brahmaputra basin. The Ganga was important not on its own but in combination with the other major river systems. Whereas the Himalayas have to be considered very marginal in their contribution to the inundations in Bangladesh, the amount of water pouring down from the Meghalaya Hills into the floodplains of the Meghna system was outstanding. The total amount of precipitation recorded in Cherrapunjee from June to September reached 18,876 mm (the long-term average for these four months was 8,191 mm). We can therefore assume that the high flow of the Meghna River backed up the combined Ganga–Brahmaputra flow at the confluence, which in turn aggravated the flooding situation further upstream. The calculations of both potential runoff (R(pot)) and daily rainfall indicate that the maximum extent of flooding in the first part of August was reached with some lag on the precipitation phases. Considerable inflow from outside Bangladesh, and thus a direct connection between the Assam and Bangladesh floods, seems to be a fact. Finally, the direct link between the level of the groundwater table and the flooding processes was particularly obvious in the area of confluence of the Ganga and the Brahmaputra.

Factors that were important for the nationwide flooding in Bangladesh in early August:

- pre-monsoon rains;
- widespread above-average rainfall in July, inside as well as outside Bangladesh, particularly in the second part of the month;
- the Meghna catchment, and the Meghalaya Hills in particular;
- synchronization of above-danger-level flows of the three main rivers and of the annual maximum flows of the Brahmaputra and the Meghna;
- an imported flood wave through the Brahmaputra from Lower Assam;
- a high level of the groundwater table in specific areas.

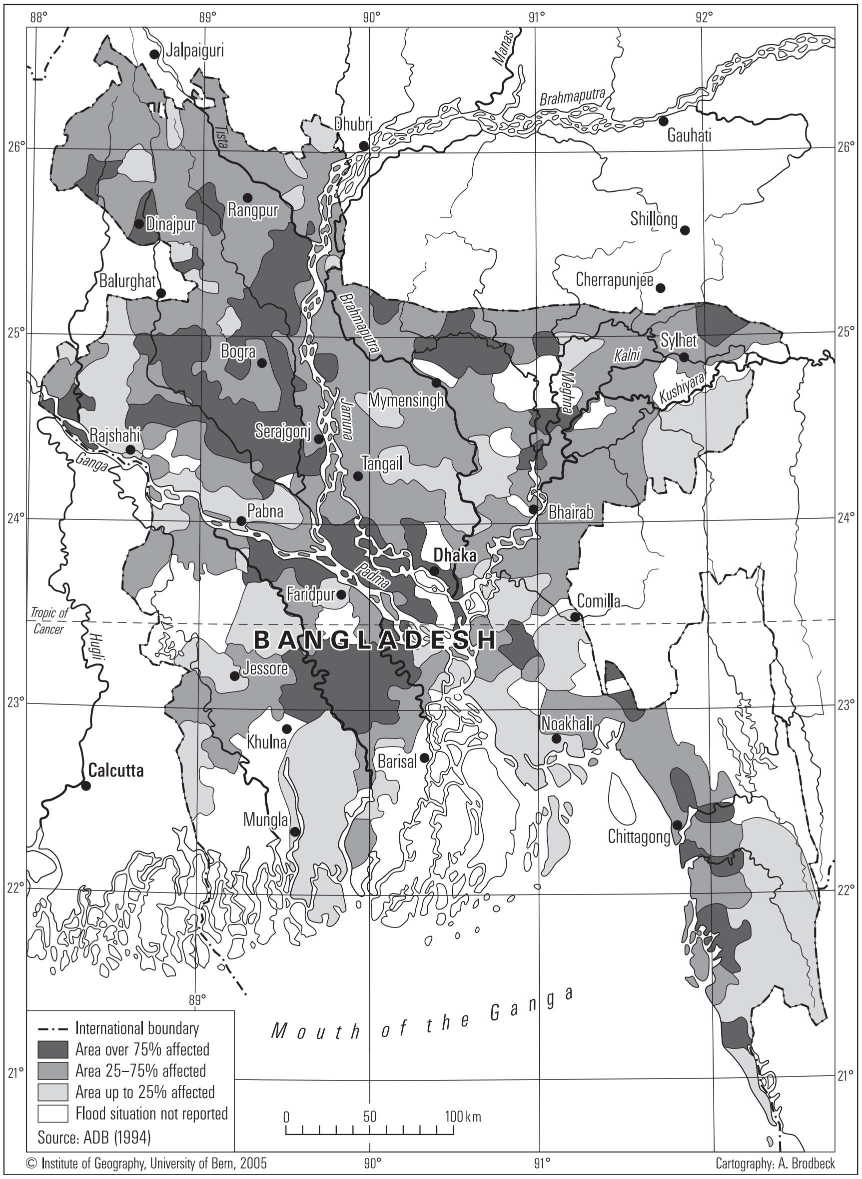
Factors that were unimportant for the nationwide flooding in Bangladesh in early August:

- the Ganga (it is important only in combination with the other big rivers);
- the Himalayas (this statement is based on calculations of R(pot) and on the discharge characteristics of the Tista).

5.9. 1987: A "flood year" for Bangladesh

The detailed analysis of the 1987 floods is presented and discussed in Appendix 5.6 (pp. 277–294). The flood of 1987 "was the worst over the last 40 years that hit Bangladesh, and the country experienced the most deplorable decimation of lives in barely believable digits" (Hussain and Samad 1987: 1). Figure 5.16 maps not only the flood-affected area during 1987, but also the degree to which these areas were affected. As indicated in the caption, the map is a composite of several distinct flood periods and affected areas, and thus does not represent the maximum extent of the flooding at a given time (see also the specification of the flood periods and affected areas in Appendix 5.6, Figure 5A.27). According to Figure 5.16, the most seriously flooded areas were the western bank of the Brahmaputra, the area below the confluence of the Ganga and the Brahmaputra, regions north of Khulna and areas adjacent to the Meghalaya Hills. There were exceptional flood conditions in the north-western districts, which are usually considered flood free. The fact that the southern parts of Bangladesh, namely the areas south of Khulna and Barisal as well as west of Noakhali, were only moderately flooded or even flood free is very striking. The floods started in June with a flash flood in the north-east and they reached their maximum extent in August. In September, additional serious but spatially limited flooding occurred in the Ganga area and again in certain parts in the north-east of Bangladesh. Obviously the duration of flooding was quite extraordinary. All four flood types normally encountered in Bangladesh (flash flood, river flood, rain flood and tidal flood – see Figure 2.7) occurred separately or in combination during the 1987 flood season. In August, flooding was widespread not only in Bangladesh but also in the Indian states of Bihar, West Bengal and Assam (for the location of these states, see Figure 4.8). The floods in Assam were extraordinary, occurring in five waves and reaching their maximum dimension in August. In Bihar, the floods started in August and affected some areas until late October. In West Bengal, floods were reported mainly in August.

The available literature discusses many different causes of the 1987 floods.[6] According to one source (Choudhury 1989: 238), the Bay of Bengal monsoon depressions, which usually travel north-westwards up into western India, changed their course drastically in 1987. All except one or two of the depressions first travelled northwards, causing rainfall in Bangladesh, Assam, West Bengal and Bhutan. Subsequently, these depressions turned westwards and, as a consequence, also affected Bihar and Nepal. The following specific causes of the flooding in Bangladesh are discussed in the literature: above-average rainfall throughout the country, particularly in the north; a combination of flood flow from across the



Source: ADB (1994)

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Cartography: A. Brodbeck

Figure 5.16 Flood-affected areas, synthesized for the entire monsoon season: 1987.

border and high rainfall within the country; synchronized high levels of the Ganga, Brahmaputra and Meghna between 12 and 21 August; spring tides; impeded drainage owing to obstructions such as roads, embankments and bridges with inadequate openings within the Bangladesh floodplains; breaches in the embankments. Of special importance and interest is the observation of Miah (1988: 6), who refers to the significance of localized precipitation (rain flood): "Inland areas have been inundated even before the water level of the river nearby has crossed the danger level. The depth of flooding inland has been more than the river stage would normally suggest … Floods, at least some of them, are due to overland run-off rather than spill over of river-waters."

Box 5.7 provides a few of the main points extracted from the detailed investigation of the 1987 floods in Appendix 5.6. To summarize and generalize the findings of the in-depth analysis, the floods in Bangladesh, Assam, West Bengal and Bihar were interlinked. The rainfall in Bangladesh created the basic conditions for widespread flooding. The imported high water flows, particularly through the Meghna and Brahmaputra–Tista systems, significantly aggravated the flood situation. The literature statements about the combination of high rainfall in the country itself and high flows from across the border as an important factor in the flooding can thus be fully be supported. Again it seems that the Meghna and the Brahmaputra systems were much more important than the Ganga catchment in triggering the widespread inundations in August, particularly in terms of the relevance of these areas as well as the hydrometeorological anomalies in these river systems. The floods along the Ganga within Bangladesh to the south of Pabna documented in Figure 5.16 were spatially limited and occurred not during the main flooding period in August but in September, when the Ganga reached its highest water level of the year. As discussed in the literature, there were indeed floods in August higher up in the Ganga system, in West Bengal and Bihar, but again these floods were spatially limited events. However, the Ganga deserves attention because of the fact that its first period of above-danger-level flow coincided temporally with the annual peak flows of the Brahmaputra and Meghna around mid-August.

In terms of highland–lowland interactions, the flood of 1987 reveals the following interesting situation: the external input into the Meghna system directly originated in the Meghalaya Hills. In the case of the Brahmaputra system, the external input mainly originated in the foothills and the lowlands south of the Himalayas, not in the mountains. Finally, the flood waves recorded in the Himalayan foothills of the Ganga system levelled out once these tributaries reached the Ganga and did not have any flood-triggering effect in Bangladesh (see Figures 5A.28 and 5A.29 in Appendix 5.6).

Box 5.7 Investigation of the 1987 flood: Main points extracted from the detailed analysis presented in Appendix 5.6

Flood dimension

- At 57,300 km^2 (40.13% of the country), ranks third for the period 1954–2004 (see Table 4.1).
- Maximum flood extent: August.

Monthly potential runoff (*R*(pot)) and relevance (*R*(relev)) (see Figure 5A.25 in Appendix 5.6; for the location of the subcatchments, see Figure 5.1)

- *R*(pot)was above average for the whole of Bangladesh from July to September.
- The positive anomalies were particularly important in North-western Bangladesh (SC10).
- Except in September, generally below-average values in the Indian Ganga lowlands (SC4 and SC5). Obviously the (spatially limited) floods in Bihar and West Bengal in August are not reflected in the monthly calculations.
- No significant positive anomalies in the Nepal Himalayas (SC2).

Monthly discharge (see Figure 5A.26 in Appendix 5.6; for the location of the stations, see Figure 3.2)

- The monthly flow of the Brahmaputra at Bahadurabad and of the Tista at Kaunia was permanently above average from July to December. The anomaly in the Brahmaputra partly originated in Assam and partly was caused by the above-average potential runoff in the vicinity of Bahadurabad (SC10) as well as by high inflow from the Tista.
- Except in August and September, below-average discharge was dominant in the Ganga.

Daily rainfall (see Figure 5A.27 in Appendix 5.6)

- Rainfall periods affecting the entire country: 21 July–3 August, 20–28 August, 23–29 September.
- In the north-eastern part of Bangladesh, rainfall occurred almost constantly from mid-June to the end of September.
- During the first and major rainfall period in Bangladesh (21 July–3 August), which corresponds to the first part of the main flood period, precipitation was also high outside Bangladesh, particularly in Meghalaya, Lower Assam and the Himalayan foothills of West Bengal and Bihar. During the second part of the main flooding period (August), rainfall was more important outside (in the Indian lowlands) than inside Bangladesh.

Box 5.7 (cont.)

- Detailed investigations in the Tista catchment (a tributary of the Brahmaputra originating in the Darjiling Himalayas) reveal that, from 10 to 13 August, rainfall at the lowland station of Jalpaiguri significantly exceeded the figure measured at the hill station of Gangtok.

Daily discharge (see Figures 5A.28 and 5A.29 in Appendix 5.6)

- At all stations within Bangladesh the flow exceeded the maximum daily discharge that is on average reached during the monsoon season.
- The most significant anomalies were measured in the Tista in mid-August (the time of the widespread flooding) and in the Ganga in the second part of September (the time of the spatially limited flooding along the Ganga), with the peaks having a return period of approximately 20 years and 40 years respectively.
- All the rivers reacted to the rainfall periods within Bangladesh.
- The really high river flows were reached after the widespread rains in Bangladesh and were imported.
- In the period 12–21 August, the three big rivers recorded flows above danger levels, the Tista reached its extraordinary peak and the floods most probably reached their maximum dimension.
- The flood waves recorded in the Himalayan foothills on three Nepali tributaries of the Ganga system levelled out on their way downstream.

Tidal movements

- The full moon in August coincided with the maximum extent of flooding in Bangladesh.
- The discharge of the accumulated water masses into the Bay of Bengal might have been hampered by the spring tides and might have contributed to the extent of the flooding.

Groundwater (see Figure 5A.30 in Appendix 5.6)

- All stations recorded above-average groundwater levels during the monsoon season.
- The anomalies were highest in the western and north-western part of the country and in most cases the highest groundwater levels were reached during the main flooding period.
- As a result of the intensive and widespread rains before the main flooding period, there was only minimal potential to absorb additional water in the groundwater reservoirs when the imported flood wave reached the country.
- In the confluence area of the Ganga and the Brahmaputra, the groundwater table reached the surface.

The comparison of the hydrographs of the Kushiyara (a tributary of the Meghna with a relatively small catchment) and the Meghna itself (a large catchment) is very interesting (Figure 5A.28 in Appendix 5.6): the Meghna hydrograph is smooth and characterized by long-term discharge fluctuations, whereas the Kushiyara hydrograph includes a large number of short-term discharge fluctuations with sharp gradients. This difference documents the smoothing and levelling of short-term peaks with increasing catchment size and especially also the effects of water storage in the extended beels in the depressions of the Meghna catchment to the west of Sylhet (see also section 2.3.4 and Figure 2.9).

Factors that were important for the flooding in Bangladesh in 1987:

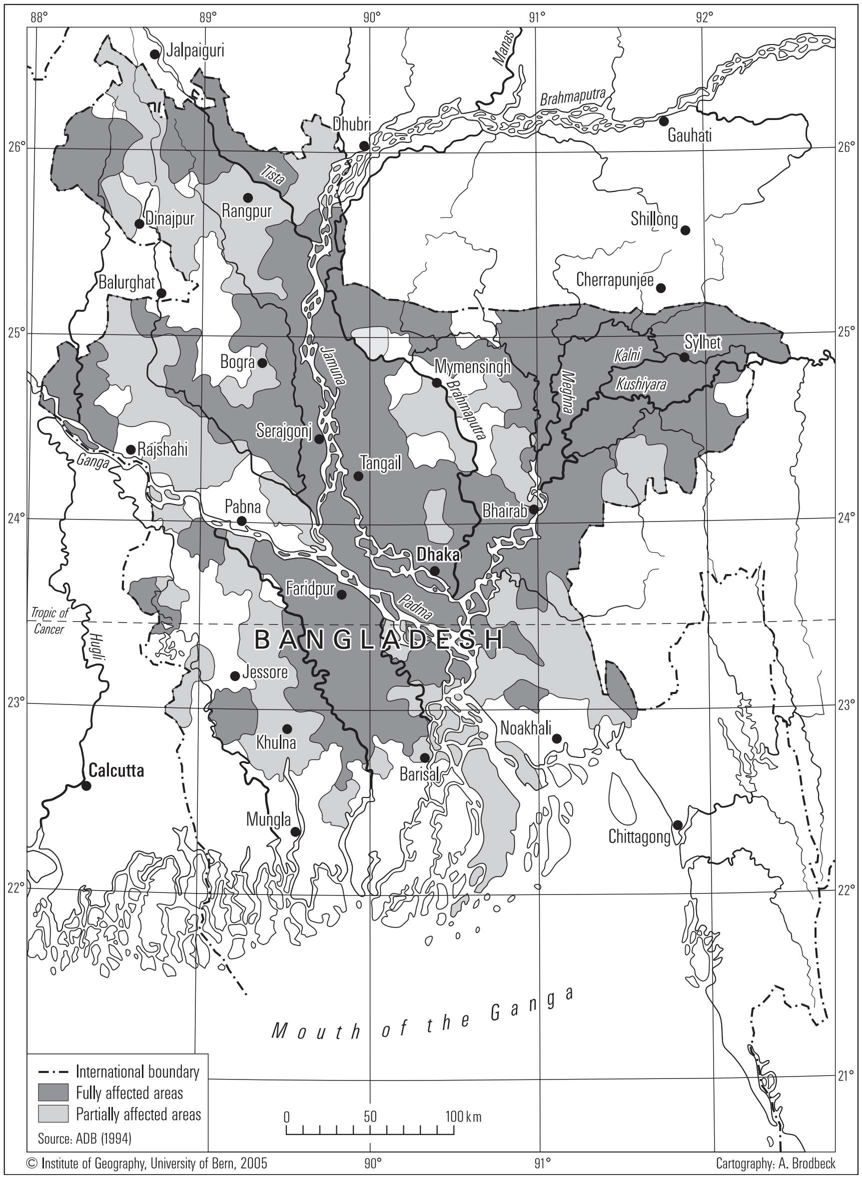
- rainfall in Bangladesh, particularly in the north-western region;
- input from the Meghalaya Hills;
- an imported flood wave from the Tista and the Brahmaputra;
- synchronization of the high flow of the three main rivers from 12 to 21 August;
- a high groundwater table;
- coincidence with a high, even spring, tide after the full moon in August.

Factors that were not important for the flooding in Bangladesh in 1987:

- the pre-monsoon period;
- single daily rainfall events;
- the influence of the Himalayas (this statement is based on calculations of *R*(pot) in the Nepal Himalayas and on detailed investigations in the Tista catchment).

5.10. 1988: A "flood year" for Bangladesh

The detailed analysis of the 1988 floods is presented and discussed in Appendix 5.7 (pp. 294–313). The inundation of 1988 was one of the worst floods in the twentieth century. The source for the map in Figure 5.17 differentiates between areas that were fully affected and areas that were partially affected by the floods. As indicated in the figure caption, the map is a composite of several distinct flood periods and affected areas, and thus does not represent the maximum extent of the flooding at a given time. Areas of the Meghna and the Brahmaputra catchment, including central Bangladesh, suffered most, whereas the southern regions and significant parts of western Bangladesh were only moderately affected or even flood free. This observation is supported by Hossain (1990: 3): "substantial areas in the south-east, south-west, west and north-west of the country did not experience floods at all, while in the north, north-east and the centre of the country the flood lasted long and had been unprecedentedly severe." Islam (1990: 18) adds that, "for the



Source: ADB (1994)

Cartography: A. Brodbeck

Figure 5.17 Flood-affected areas, synthesized for the entire monsoon season: 1988.

first time, the flood almost totally inundated the capital city including the residence of the President of the country and of the foreign ambassadors''.

The flooding processes in 1988 had a very particular chronology. A first flood phase had already occurred from mid-April to mid-May in the eastern and north-eastern parts of the country. In June almost no flooding took place. In early July the Meghna basin experienced severe flooding and the Brahmaputra was also in flood. Before this flood had sufficiently receded, all the major rivers started rising from 10 August onwards and then simultaneously and very rapidly from 20 August, reaching their peaks between 30 August and 2 September. Accordingly, the nationwide flood in Bangladesh occurred roughly between 20 August and 5 September.

Floods were also reported from outside Bangladesh. The flood-affected area in Assam (the Brahmaputra lowland in India) was one of the largest of the twentieth century. These floods occurred in several waves from May to August, the most severe one coinciding with the maximum flood extent in Bangladesh between 20 and 28 August. In the Ganga system, floods were reported in Bihar and West Bengal (see also Figure 4.8) in June, in Nepal in July and in the far western Ganga catchment in late September. Thus, and unlike the events in Assam, the timing of the floods in the Ganga system was different from that in Bangladesh.

A variety of natural as well as anthropogenic flood-causing factors, originating partly inside and partly outside Bangladesh, are discussed in the literature.[7] Most importantly, Popelewski (1988) refers to a swing, during the summer of 1988, towards the positive phase of the Southern Oscillation, which results in heavy rains in monsoon areas (the Southern Oscillation is an alternation in the pressure difference at sea level between the eastern and western Pacific Ocean). As a result of uncertainties in data interpretation or of missing information, some statements in the literature are contradictory. For example, a number of authors emphasize that rainfall within Bangladesh was not particularly high and that most of the flood water must have come across the borders, although the Ganga catchment generally played a minor role. Other authors state that there was heavy rainfall in northern and north-eastern Bangladesh, in Assam and in Meghalaya and that the synchronization of the peak flow of the three major rivers was important. Some additional specific causes of the 1988 floods are listed in the literature: very saturated catchments as a result of rains in July; a delay in the discharge of flood water into the Bay of Bengal owing to a spring tide and southerly winds; deforestation, erosion and river silting within and outside Bangladesh; flood control structures that exacerbated the flood situation.

Box 5.8 provides a few of the main points extracted from the detailed investigation of the 1988 floods in Appendix 5.7. The following summary

Box 5.8 Investigation of the 1988 flood: Main points extracted from the detailed analysis presented in Appendix 5.7

Flood dimension

- At 89,970 km^2 (63.01% of the country), ranks second for the period 1954–2004 (see Table 4.1).
- Maximum flood extent: 20 August–5 September.

Monthly potential runoff (*R*(pot)) and relevance (*R*(relev)) (see Figure 5A.32 in Appendix 5.7; for the location of the subcatchments, see Figure 5.1)

- In August, an important month for floods in both Bangladesh and Assam, positive anomalies in *R*(pot) were calculated for 9 of 11 subcatchments.
- With the exception of the south (SC13), the anomalies in *R*(pot) and *R*(relev) were constantly positive from June to August in Bangladesh.
- In the Meghalaya Hills (SC9), *R*(pot) and *R*(relev) were above average from July to September. The variations were greatest in August, when the values for both variables reached more than double the average.
- In Assam (SC7 and SC8), *R*(pot) and *R*(relev) were above normal in July and August, but the variations were quite small.
- In the subcatchments of the Ganga system, negative variations in both variables dominated from July to September.

Monthly discharge (see Figure 5A.33 in Appendix 5.7)

- The monthly flow of all analysed rivers was above average from July to September, especially for the Meghna.
- The above-average flow of the Ganga, which was really significant only in August, is in contrast to the dominance of negative variations in *R*(pot) and *R*(relev). Was exceptional snow and glacial melt the cause of the above-average Ganga flow?

Daily rainfall (see Figure 5A.34 in Appendix 5.7)

- Rainfall periods affecting the entire country: 12–26 June, 3–12 July, 10 August–13 September (the last period mainly affecting the north-eastern and north-western parts of Bangladesh).
- To some extent, the two flood periods in July and August in Bangladesh can be related to the daily rainfall patterns. However, the rains were not heavy enough to explain the severity and intensity of flooding from 20 August to 5 September.

Box 5.8 (cont.)

- During the two main flood periods in Bangladesh (early July and the last part of August), rainfall was also exceptional in Cherrapunjee (2,697 mm between 3 and 12 July, 2,669 mm between 23 and 29 August) and in Shillong, both of which are located in the Meghalaya Hills (SC9).
- Detailed investigation in the Tista catchment (a tributary of the Brahmaputra originating in the Darjiling Himalayas) reveals that, during the critical periods of flood generation, rainfall at the lowland station of Jalpaiguri significantly exceeded the figure at the hill station of Gangtok (this is similar to the situation in 1987).

Daily discharge (see Figures 5A.35 and 5A.36 in Appendix 5.7)

- The highest flows of the analysed rivers exceeded the maximum discharge that is on average reached during the monsoon season. The maximum flow of the Brahmaputra was particularly outstanding, with a return period of 60 years.
- From 23 August to 6 September, the period of nationwide flooding, all three major rivers recorded flows above the danger level. With a temporal difference of only five days, the annual discharge peaks of the Ganga and the Brahmaputra were almost synchronized.
- Not all the discharge characteristics can be explained by the rainfall situation in Bangladesh alone. Some of the hydrological patterns are a combined result of intensive rainfall in north-western and north-eastern Bangladesh, rainfall in the Himalayan forelands and the northern part of the Meghalaya Hills, and extensive flooding in Assam.
- In view of the rather insignificant rainfall processes in the Ganga basin, the high flow of the Ganga between 25 August and 10 September is surprising.
- In the three Nepali tributaries of the Ganga for which data were available, a remarkable flood flow was recorded in the second part of August, each with a different timing. However, for several reasons it is very unlikely that the discharge peaks of these tributaries significantly contributed to the flow of the Ganga at Hardinge Bridge in Bangladesh.

Groundwater (see Figure 5A.37 in Appendix 5.7)

- At all stations, the recorded groundwater level was above average for most of the monsoon season. The highest groundwater level was reached during the period of nationwide flooding.

Box 5.8 (cont.)

- As in 1974 and 1987, the groundwater level at the measuring station located below the confluence of the Ganga and the Brahmaputra was particularly high.

Tidal movements (see Figure 5A.38 in Appendix 5.7)

- There is a connection between the phases of the moon and the discharge hydrograph of the Meghna, but it is not systematic. However, the spring tide related to the new moon on 11 September could have backed up the Meghna waters during the main flooding period.

of the findings of the in-depth analysis concentrates on the nationwide flooding from 20 August to 5 September in Bangladesh. The flood in 1988 was indeed extraordinary and can be understood only by considering a particular combination of factors. Widespread above-average rainfall in most parts of the basin during August provided important basic conditions for the development of the nationwide flood. We do not agree with the literature that rainfall within Bangladesh was not important: the calculations of potential runoff (R(pot)) show a consistently high input into the hydrological system through precipitation within Bangladesh between June and August. Furthermore, rainfall was exceptional in the northern and north-eastern parts of the country during the main flood periods. We do agree, however, that external input was important as well. First, there was an obvious connection between the floods in Assam and those in Bangladesh. Secondly, there was very high rainfall outside Bangladesh in the Brahmaputra and Meghna catchments during the main flood periods. Similar to the situation in 1987, 1910 and 1906, this external input originated not in the Himalayas but in the foothills and lowlands south of the Himalayas, in Assam and, most importantly, in the Meghalaya Hills, where the anomalies were extraordinary. The Ganga system on its own does not seem to have played a critical role in the development of the large-scale flooding. However, the fact that the timing of the highest flow of the Ganga was almost synchronized with the peak of the Brahmaputra and with a high flow of the Meghna was certainly very important. High levels of the groundwater table within Bangladesh contributed to the extent and intensity of the flooding.

The analysis of tidal information was a particular element in the detailed analysis of the 1988 flood. It can be stated that the impact of spring tides is certainly not a decisive triggering factor for floods in Bangladesh. However, there is no doubt that the discharge of flood water into the Bay of Bengal is hampered by high tides. This means that, at times when rainfall and discharge conditions favour the development of a large inundation, high tides may significantly contribute to the dimension of flooding through backwater effects from the sea. This assumption is supported by literature sources such as Shahjahan (1989).

Factors that were important for the nationwide flooding in Bangladesh from 20 August to 5 September:

- widespread above-average *R*(pot) during August (11 out of 13 subcatchments);
- constantly above-average *R*(pot) in Bangladesh from June to August;
- a combination of local and external input before and during the flood: significant rainfall in northern and north-western Bangladesh, in Meghalaya and in Assam;
- high, at times above-danger-level, flows of all three major rivers in August and September;
- temporal synchronization of the highest flow of the Brahmaputra and the Ganga and of a very high flow of the Meghna;
- a high groundwater table at the onset of the first flood phase and throughout most of the monsoon period;
- backwater effects owing to a spring tide.

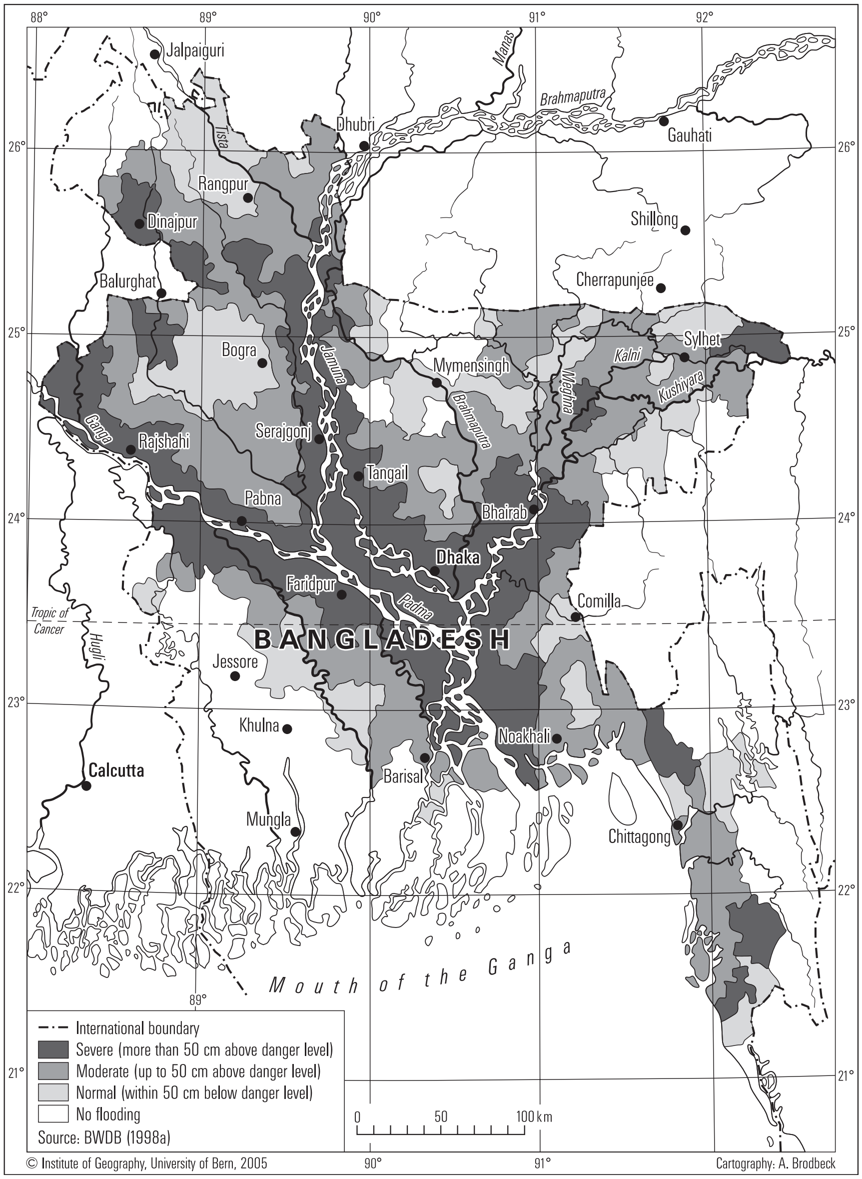
Factors that were not important for the nationwide flooding in Bangladesh from 20 August to 5 September:

- the Ganga on its own (it is of relevance only in combination with the Brahmaputra and the Meghna);
- single daily rainfall events;
- the influence of the Himalayas (this statement is based mainly on calculations of *R*(pot) in the Nepal Himalayas and on detailed investigations of daily rainfall in the Tista catchment).

5.11. 1998: A “flood year” for Bangladesh

The detailed analysis of the 1998 floods is presented and discussed in Appendix 5.8 (pp. 313–330). Because the project activities were officially completed before 1998, the structure of the following summary as well as of the detailed discussion in Appendix 5.8 differs slightly from the case studies presented so far. In particular, it was not possible to calculate potential runoff (*R*(pot)) and relevance (*R*(relev)).

The floods in 1998 were the longest-lasting and most devastating in 100 years. As indicated in the caption of Figure 5.18, the map is a composite of several distinct flood periods and affected areas, and thus does not represent the maximum extent of the flooding at a given time. In total, 53 of the 64 districts of Bangladesh were affected by floods of differing magnitude, and about 50 per cent of the country was under water for periods of



Source: BWDB (1998a)

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Cartography: A. Brodbeck

Figure 5.18 Flood-affected areas and flood intensity, synthesized for the whole monsoon season: 1998.

up to 67 days, at depths of up to 3 metres. The most severe flooding occurred along the main river courses and was particularly serious in a wide stretch in the overall area of confluence of the three rivers, including the capital city of Dhaka. Along the Ganga, the flood seems to have surpassed all previous records. Interestingly, most of the few flood-free zones were located in southern and south-western Bangladesh, a feature that was already in evidence in previous flood years. Flood conditions prevailed continuously from July to mid-September and the situation became critical on three particular dates: 28 July, when 30 per cent of the country was under water, 30 August, when 41 per cent of the country was flooded, and 7 September, when 51 per cent of the country was inundated. The extent of the flooding in Bangladesh on 7 September was probably the greatest of the twentieth century.

Little information is available on flooding outside Bangladesh. The few news reports do not indicate that there were major flood events that came anywhere close to those in Bangladesh in terms of dimension and duration. However, satellite images provide evidence of uninterrupted and fairly wide strips of flooded areas along the Brahmaputra from Assam to Bangladesh as well as along the Ganga from Bihar and West Bengal to Bangladesh (for the location of these Indian states, see Figure 4.8). Finally, some detailed reports of localized and severe flood incidents are available that make reference to flood-triggering hydro-meteorological processes originating in the Himalayas.

The synthesis of the rather general statements made by different authors about the causes of the 1998 floods results in a long list of factors that, in their combined effect, might have been responsible for the magnitude of the event.[8] Among the most important elements are: simultaneous high peaks of the three major rivers between 7 and 11 September; high tides and strong monsoonal currents in the Bay of Bengal; a combination of flash floods, river floods and tidal floods; a monsoon trough that was positioned further north than normal; a La Niña situation that created favourable conditions for a big flood; excessive rainfall in the catchment area; obstructions created by built infrastructures.

Box 5.9 provides a few of the main points extracted from the detailed investigation of the 1998 floods in Appendix 5.8. To summarize and generalize the findings of the in-depth analysis, the floods of 1998 were indeed the most severe of the twentieth century in terms of both duration and extent. Interpretation of the available data sets confirms most of the literature statements about the causes of the floods. Overall, the La Niña situation resulted in very humid monsoon conditions. At a number of hydrological stations the water table reached the highest ever recorded levels. The key to the development of the flood seems to have been the combination of continuous and widespread rains during July and August

Box 5.9 Investigation of the 1998 flood: Main points extracted from the detailed analysis presented in Appendix 5.8

Flood dimension

- At 100,250 km^2 (67.93% of the country), ranks first in the statistics for the period 1954–2004 (see Table 4.1).
- Maximum flood extent: early September (51% of the country flooded on 7 September).

Flood damage

- Colossal damage to life, property, crops and infrastructure.
- Damage to the drinking water system as well as the sewage and storm water drainage system in Dhaka City.
- The spread of waterborne diseases.

Monthly rainfall (see Figure 5A.40 in Appendix 5.8)

- In July and August rainfall was significantly above average in Bangladesh, especially in the central and eastern parts of the country. The rainfall situation outside Bangladesh was much less spectacular.
- The monthly rainfall data for September do not provide elements for understanding the extraordinary extent of the flooding in the first part of the month: at most of the available stations, below-average precipitation was recorded.
- Precipitation in Nepal did not deviate significantly from the average situation. Rainfall in Cherrapunjee (Meghalaya Hills) was above average in July and August.
- Overall, the rainfall situation within Bangladesh was rather homogeneous and distinct during the monsoon season of 1998: a rather dry pre-monsoon and early monsoon period, wet conditions in July and August, and rather dry again in September.

Daily rainfall (see Figure 5A.41 in Appendix 5.8)

- The monsoon rains started on 5 July and lasted until 6 September. Rainfall periods affecting the entire country: 5–23 July, 11–18 August, 31 August–6 September.
- The flood peaks on 28 July and 7 September (see main text) were reached immediately after a rainfall period.
- The periods of scarce precipitation between the main rainfall phases were relatively short.
- Rainfall in Kathmandu (Nepal) was heavy but did not reach outstanding values or coincide particularly with the flooding processes in Bangladesh.

Box 5.9 (cont.)

- The daily rainfall patterns within Bangladesh are clearly linked to the flooding processes and their chronology; however, we cannot fully understand how the flooding reached such exceptional dimensions by investigating only the daily rainfall patterns.

Daily water level (see Figure 5A.42 in Appendix 5.8; for the location of the stations, see Figure 3.2)

- All three major rivers were flowing above danger levels for a significant number of days. Whereas the Brahmaputra and the Meghna had crossed the danger level in July, the Ganga did so only after mid-August.
- All three major rivers responded to the main rainfall periods within Bangladesh.
- The three major rivers reached their annual peak almost simultaneously between 7 and 9 September. ‘‘At one stage, on 7th September, 25 water level stations out of 46 monitoring stations flowed above danger level, which was the worst day of the country’’ (BWDB 1998a).
- The Ganga reached its highest ever recorded water level. However, in terms of the duration of the above-danger-level flow and the dimension of the peak discharge, the flood of 1987 was more important. The Brahmaputra flow broke previous records in both the maximum discharge and the number of days with above-danger-level flow. The hydrological patterns of the Meghna were in all respects less spectacular than in other flood years.
- The number of days and the dimension of above-danger-level flow of the three major rivers increased towards the area of their confluence.
- The hydrograph of the Tista, a tributary of the Brahmaputra originating in the Darjiling Himalayas, never reached danger levels.
- The highest water level of the Karnali, a tributary of the Ganga originating in the Nepal Himalayas, was reached in the first days of August, almost one month before the big rivers in Bangladesh reached their maximum flows.
- The inflow into Bangladesh from Assam through the Brahmaputra and from the Indian Gangetic Plain through the Ganga during August and early September was certainly important. However, it is difficult to assess if and to what extent this inflow was flood triggering or was important only because of the synchronization of the peak flows of the three major rivers.

(particularly in Bangladesh), high inflow into Bangladesh through the main rivers and their almost simultaneous peaking, and backwater effects from the Bay of Bengal owing to high tides. It is unfortunately not possible to quantify these tidal effects and we must trust the statements in the literature sources in this regard. It was as if the water masses accumulating through rainfall within Bangladesh and through significant inflow from the Indian plains were backed up in the larger confluence area of the major rivers, which resulted in the spreading of the flood waters. The Brahmaputra basin in particular, but also the Ganga system, seem to have been more important than the Meghna system. Based on the limited information available it was not possible conclusively to analyse and assess the hydrological contribution by the Himalayas to the exceptional floods in Bangladesh. However, interpretation of the few available data sets does not provide arguments or justification for assigning any particular importance to this contribution.

The analysis of the extraordinary floods in 1998 presented here and in Appendix 5.8 is a first approximation. A much more thorough investigation with more complete data sets is required to fully understand the dimension of the event as well as the complexity and interaction of the contributing factors.

Factors that were important for the nationwide flooding in Bangladesh from mid-July to mid-September:

- the La Niña situation;
- constant and intensive rains, particularly within Bangladesh, during July and August;
- simultaneous and constant above-danger-level flows of the three major rivers;
- backwater effects resulting from the synchronization of the peak flow of the three major rivers between 7 and 9 September and from high tides;
- the river systems, in decreasing order of importance: Brahmaputra, Ganga, Meghna.

Factors that were not important for the nationwide flooding in Bangladesh from mid-July to mid-September:

- rainfall in the pre-monsoon and early monsoon period;
- input from the Himalayas (this statement is based on interpretation of the very few available data sets).

5.12. 1923: A ‘‘dry year’’

As discussed in section 5.1, we added two years in which the extent of flooding in Bangladesh was particularly low (namely, 1923 and 1978) to the list of cases studies. These examples will assist in identifying important differences between contrasting situations and sharpening our understanding of the specific processes leading to widespread flooding. The 1923 case study is based on investigations made by project team member Roland Guntersweiler (Guntersweiler 1995). The detailed analysis of the hydro-meteorological conditions in 1923 is presented and discussed in Appendix 5.9 (pp. 330–336).

Throughout the subcontinent, the onset of the monsoon was late and in general the monsoon is described as having been weak.[9] Favourable conditions for farming were reported from Assam (the Brahmaputra lowland in India) and from Bihar (the Indian Ganga Plain). North Bengal, which basically covers the area of SC10 in the north-western part of modern Bangladesh (see Figure 5.1), was affected by a drought throughout the monsoon season. In July and particularly in August the situation was rated as "severe", and the water levels of the Ganga and Brahmaputra were very low. As a consequence of the drought, sowing of the winter crop was delayed and yields were below average. However, 1923 was not entirely flood free in the Ganga–Brahmaputra–Meghna basin: in the second part of June, a heavy storm caused a localized flash flood in the Sylhet area (SC11). The Patna region in the Lower Ganga Plain in India (SC5) was affected by a flood at the end of August that led to the death of people and animals as well as to the destruction of houses. Some time later, a flood in the area of Lucknow in the Upper Ganga Plain (SC4) caused damage to buildings.

Box 5.10 provides a few of the main points extracted from the detailed investigation of the hydro-meteorological patterns in 1923 in Appendix 5.9. To summarize and generalize the findings, it can be confirmed that 1923 was a dry year in the area of modern Bangladesh. The most obvious differences compared with the situation in the flood years seem to be the dominantly below-average potential runoff (R(pot)) and relevance (R(relev)) in the subcatchments of Bangladesh, in the Meghalaya Hills and in Lower Assam throughout the monsoon season, and more particularly the scarcity of rain in August. Whereas there was less precipitation in the Brahmaputra–Meghna system than in the flood years, there was considerably more in the Ganga lowland: R(pot) on the Upper Ganga Plain was almost constantly above average. Apart from short-term flash floods in June in north-eastern Bangladesh, the Ganga lowland was the only area where major and quite severe flooding occurred. The floods in the Patna area were most probably caused by a combination of local rainfall as well as of high flows of the Ganga and of two of its tributaries (the Son from the south and the Gogra from the north). These flood events in the Indian Ganga Plain evidently levelled out and did not have any impact on hydrological patterns further downstream in Bangladesh.

Box 5.10 Investigation of the year 1923, a dry year for Bangladesh: Main points extracted from the detailed analysis presented in Appendix 5.9

Damage situation (for the location of the subcatchments, see Figure 5.1)

- SC10: sowing of the winter crop delayed and yields were below average as a result of drought conditions.
- SC5: death of 38 people and 1,244 cattle as well as the destruction of 44,000 houses as a result of flooding at the end of August.
- SC4: damage to buildings as a result of flooding at the end of August.

Monthly potential runoff (*R*(pot)) and relevance (*R*(relev)) (see Figure 5A.44 in Appendix 5.9)

- With some exceptions (e.g. SC4), negative anomalies in *R*(pot) and *R*(relev) dominated, particularly in August. In a number of subcatchments (SC5, SC8, SC9, SC10 and SC12), the anomalies were negative over three to four consecutive months.
- In the Upper Ganga Plain (SC4), the hydrological contribution was constantly above normal from July to September.
- The contribution from the Darjiling–Bhutan Himalayas (SC3) was slightly above average in June and significantly above normal in July.

Daily rainfall (see Figure 5A.45 in Appendix 5.9)

- Overall, the number of rainy days was lower and rainfall patterns were temporally and regionally much more differentiated than in the flood years.
- The particularly scarce rainfall throughout August evident at most stations is a very striking difference from the situation in the flood years.
- The flash flood in the Sylhet area in the second part of June resulted from very high-intensity rainfall in the area from 14 June to 17 June. Over these three days, 1,757 mm of rainfall was recorded in Cherrapunjee.

Daily water level (see Figure 5A.46 in Appendix 5.9)

- The available water level data are scanty. For the Ganga, information is too limited to be included in this discussion.
- The water level of the Brahmaputra at Gauhati (see Figure 3.2) never reached levels comparable to the flood years of 1910 and 1922.
- In early August, the water level of the Padma at Goalundo (located below the confluence of the Ganga and the Brahmaputra) reached average values and remained constant during this month.

5.13. 1978: A "dry year" for Bangladesh

The detailed analysis of the hydro-meteorological conditions in 1978 is presented and discussed in Appendix 5.10 (pp. 336–350). This particular year was very interesting in terms of the flood conditions in the Ganga–Brahmaputra–Meghna basin. According to the statistics, only 7.6 per cent of Bangladesh was flooded and thus 1978 has to be rated as a "dry year" for Bangladesh (see also section 5.1). The areal extent of the inundation was one of the smallest in the period 1954–2004 for which statistics are available. Only the western part of Bangladesh encountered minor flooding processes. Interestingly, this area tends to be flood free or only marginally affected in major flood years (see, in particular, case studies 1955, 1974, 1988).

The Indian Ganga system, however, was affected by severe floods in 1978. In Uttar Pradesh and in West Bengal (parts of SC4 and SC5, see also Figure 4.8), the flood-affected area was the largest in the period 1954–1994 for which statistics are available (Figure 4.9). Three flood phases are described in the written sources:[10]

- Continuous heavy rainfall in August over the plains of Bihar, causing severe floods in the Burhi Gandak (a Ganga tributary from Nepal), which was flowing more than 3 metres above danger level.
- Severe floods in the Yamuna and the Ganga in Uttar Pradesh in the first fortnight of September. This flood is perceived as the most severe event of the century.
- Catastrophic floods in Gangetic West Bengal in the last week of September.

Box 5.11 provides a few of the main points extracted from the detailed investigation of the flooding conditions in 1978 in Appendix 5.10. To summarize and generalize the findings of the in-depth analysis, it is first of all important to underline that the monsoon characteristics in the Ganga system were the opposite of those in the Brahmaputra and the Meghna basins. This is particularly obvious in August. The fact that flooding in Bangladesh was far below average was related to the dry conditions in the eastern part of the Ganga–Brahmaputra–Meghna basin rather than to the humid conditions in the western part. As in the "dry year" 1923, the main specific differences compared with the flood years seem to be the below-average potential runoff and relevance during major parts of the monsoon season in Bangladesh itself, in the Meghalaya Hills and to some extent in the Brahmaputra system, and in particular the scarce rainfall during August.

According to Figure 4.9, the flood dimension in the Indian Ganga Plain was outstanding in 1978, ranking first in Uttar Pradesh, fourth in Bihar and again first in West Bengal in the available statistics covering the

Box 5.11 Investigation of the 1978 flooding situation: Main points extracted from the detailed analysis presented in Appendix 5.10

Flood dimension

- Bangladesh: 10,800 km^2 (7.6% of the country), one of the smallest for the period 1954–2004 (Table 4.1).
- Indian Ganga Plain (parts of SC4 and SC5): severe floods in Uttar Pradesh and West Bengal – the largest for the period 1954–1994 (Figure 4.9).

Flood damage (Indian Ganga Plain)

- 6 million hectares of crops were lost and 3 million tons of cereals were destroyed.
- At least 40 million people were affected, and 1,200 people died. 8,000 cattle drowned in the flood waters.

Monthly potential runoff (*R*(pot)) and relevance (*R*(relev)) (see Figure 5A.47 in Appendix 5.10; for the location of the subcatchments, see Figure 5.1)

- Negative anomalies in *R*(pot) and *R*(relev) dominated during July and August, not just in Bangladesh but in the entire basins of the Brahmaputra and Meghna. The negative variations were particularly obvious in the Meghalaya Hills (SC9).
- In the Ganga basin, the positive anomalies in *R*(pot) were remarkable and were particularly strong and widespread in August and September. However, these positive variations did not meaningfully increase the *R*(relev) of the Ganga subcatchments for the hydrological processes in Bangladesh.
- With the exception of July, the hydrological contribution was above average for at least one Himalayan subcatchment in the Ganga system (SC1 or SC2) in each monsoon month.

Monthly discharge (see Figure 5A.48 in Appendix 5.10)

- Unfortunately the data for the Meghna River are missing.
- The discharge of the Ganga was significantly above normal from May to October, with anomalies ranging between +20 per cent and +40 per cent. In contrast, the flow of the Brahmaputra was below average during the monsoon season.
- The positive discharge variations in the Sapt Kosi, an important tributary of the Ganga from the Nepal Himalayas, were remarkable. In contrast, the flow of the Tista, an important tributary of the Brahmaputra from the Darjiling Himalayas, was below average from July to November.

Box 5.11 (cont.)

Daily rainfall (see Figure 5A.49 in Appendix 5.10)

- 20–27 June is the only period during which rainfall was widespread in Bangladesh.
- As in the ‘‘dry year’’ 1923, and in contrast to the situation in most ‘‘flood years’’, very little rainfall was recorded in Bangladesh during most of August and large parts of September, in terms of both the number of rainy days and rainfall intensities.

Daily discharge (see Figure 5A.50 in Appendix 5.10)

- The highest annual flow in 1978 of the Tista and the Brahmaputra remained far below the maximum discharge that is on average reached during the monsoon season.
- The highest annual flow in 1978 of the Ganga, which was reached on 21 August, was significantly above the maximum discharge that is to be expected on average. The value of this peak was estimated to have a return period of 15 years.
- The flow of the Brahmaputra, the Tista and the Kushiyara was highest in June and July and gradually decreased during August and September.
- The high inflow into Bangladesh through the Ganga occurred during August and September, when the flow of the Brahmaputra was already receding.

Groundwater (see Figure 5A.51 in Appendix 5.10)

- The groundwater table was higher than normal at almost all stations at the beginning of July.
- Owing to the scarcity of rainfall from July to September, these positive anomalies gradually disappeared or even turned into negative variations.
- In contrast to the flood years of 1974, 1987 and 1988, the groundwater table at the station located downstream of the confluence of the Ganga and the Brahmaputra reached only average levels and was far from reaching the surface.

period 1954–1994. Interestingly, the floods reported from these three Indian states did not form one big flood event extending simultaneously over the entire Ganga lowland, but represent three distinct flood waves, each with different timing and geographical pattern. The three floods, therefore, were individual events, to a large extent produced by local rainfall and other triggers in the vicinity, such as high inflow from major tributaries.

Kuster (1995) analysed a number of twentieth-century flood events that occurred in the Yamuna basin (an important tributary of the Ganga) from its source in the Himalayas all the way down to Allahabad at the confluence of the Yamuna with the Ganga (see Figure 2.1 and Figure 5A.52 in Appendix 5.10). The case studies include a detailed account of the flood processes in terms of chronology and geographical extent, as well as a discussion of the rainfall patterns before and during the flood events. The severe flood in the Yamuna lowlands in the first fortnight of September 1978 (see above) is one of the case studies analysed by Kuster. His findings are very interesting and provide important insights into several aspects of the highland–lowland linkage: there was a direct link between the heavy rainfall in the first Himalayan ridges and the Siwalik Hills and the flood processes in the adjacent plains north of Delhi. However, the rainfall over these flood-affected areas themselves was at least as important, if not more so. Interestingly, and in spite of their rare magnitude, the floods in the areas to the north of Delhi did not create a flood wave that would have moved through the Ganga Plain all the way down to Bangladesh and would have produced a continuous area of inundation. Indeed, there was flooding downstream of Delhi, but these inundations occurred in isolated patches and levelled off across the Ganga Plain. Local triggers such as heavy rainfall or the high water level of tributaries were as important for the development of these flood patches as the high inflow through the Yamuna River from the flood-affected areas higher up in the catchment.

All these observations very nicely confirm the appropriateness and importance of the relevance factor (R(relev)) introduced in section 5.2.5. The only impact on Bangladesh of the high rainfall and the various flood occurrences in the Ganga system was a high inflow through the Ganga and some areally limited flood processes in western Bangladesh. The low flow of the Brahmaputra, and most probably also of the Meghna, as well as scarce rainfall in Bangladesh in the period of high inflow through the Ganga, were key factors preventing large-scale flooding in Bangladesh. Choudhury (1993) puts this consideration as follows: "There was comparatively less flooding in the Bangladesh part of the Ganga in 1978. This was largely due to the fact that water level was comparatively low in the other two great rivers which flow through Bangladesh namely the Brahmaputra and the Meghna during this time of the year in 1978."

In both "dry years" (1923 and 1978) there was a clear distinction between humid conditions in the Ganga system and dry conditions in the Brahmaputra and Meghna basins. This is in marked contrast to the flood years, when the situation tended to be the opposite. For the interpretation of this finding and for more information, see sections 5.15 and 5.16.

5.14. 1993: An ‘‘average flood year’’ for Bangladesh

The detailed analysis of the hydro-meteorological conditions in 1993 is presented and discussed in Appendix 5.11 (pp. 350–358). We selected 1993 as a case study because Nepal was hit by one of its most severe floods of the twentieth century, whereas for Bangladesh 1993 was an average flood year. Accordingly, the highland–lowland linkages are particularly interesting in 1993. Because of the data situation, the structure of the following summary, as well as of the detailed discussion in Appendix 5.11, differs slightly from that of most of the case studies presented so far. In particular, the calculation of potential runoff (R(pot)) and relevance (R(relev)) was not possible.

On 19 and 20 July, an extraordinary flood with an estimated return period of 50–100 years occurred in eastern and central Nepal, with catastrophic effects (Dhital et al. 1993): several districts were affected by floods and landslides, a number of dams and roads were damaged, and up to 200 people died or were made homeless. A major proportion of the crop in the wheat-growing zone in the Terai was destroyed. Within only three days (19–21 July) the life-span of the Kulekhani Reservoir, which is located to the south of Kathmandu (see Figure 3.2) in the Bagmati watershed, was reduced from 60–70 years to about 10 years owing to very high sedimentation.

In Bangladesh, in contrast, the floods reached only average dimensions. An in-depth and systematic review of three Bangladeshi daily newspapers (Bärtschi et al. 1995) reveals that the floods in Bangladesh occurred between 18 and 25 June and between 10 and 26 July and almost exclusively affected the Meghna and the Brahmaputra/Padma systems.

Box 5.12 provides a few of the main points extracted from the detailed investigation of the flooding conditions in 1993 in Appendix 5.11. To summarize and generalize the findings of the in-depth analysis, it can be stated that floods were recorded simultaneously in the foothills of Nepal, which are part of the Ganga catchment, and in the Meghna/Brahmaputra basin within Bangladesh. The flooding in Nepal was caused by heavy rains in the first Himalayan ranges as well as the Siwalik Hills; the inundations in Bangladesh were the result of widespread and heavy rainfall over Bangladesh itself, particularly in the Meghna catchment. Thus, there is no reason to assume a cause and effect relationship between the floods in Nepal and those in Bangladesh. In accordance with the findings in the 1978 case study (section 5.13), it can be stated that heavy rainfall in the first Himalayan ranges and the foothills can trigger extraordinary floods of rare dimensions in the immediate downstream areas. However, the impact of such an event on the hydrological conditions in Bangladesh, and on the floods in particular, is almost negligible: a flood wave originating

Box 5.12 Investigation of the 1993 flooding situation: Main points extracted from the detailed analysis presented in Appendix 5.11

Flood dimension

- Nepal: catastrophic flood 19–21 July in the eastern and central part of the country.
- Bangladesh: 28,742 km^2 (19.48% of the country), average conditions (Table 4.1).

Monthly rainfall in July (see Figure 5A.53 in Appendix 5.11; for the location of the stations see Figure 3.1)

- Above-average rainfall recorded at all stations available for the Meghna catchment.
- Predominantly above-average rainfall recorded at the stations of the Brahmaputra catchment, except at the Himalayan station of Darjiling.
- Predominantly below-average rainfall recorded at the stations of the Ganga catchment.
- The heavy rains that triggered the severe floods in Nepal must have been geographically limited. In Kathmandu, total precipitation in July was significantly below average.

Daily rainfall (see Figure 5A.54 in Appendix 5.11)

- Intensive and heavy rainfall occurred in the Bagmati watershed in Nepal (the first Himalayan ridges as well as the Himalayan foothills): on average 352 mm of rainfall over an area of 530 km^2 on 19 July; on average 500 mm of rainfall over an area of 500–800 km^2 on 20 July.
- Rainfall periods for Bangladesh: 7–9 June, 17–20 June, 16–24 July, 22–24 August, 26–30 September.
- Both flood phases in Bangladesh were related to rainfall periods. Precipitation in Bangladesh was obviously a very important factor in the development of these inundations.

Daily discharge (see Figures 5A.55 and 5A.56 in Appendix 5.11)

- Based on investigation of the discharge records of three Nepali rivers, it seems that the severe flood on 19 and 20 July in the Bagmati system was of rather limited geographical extent but of very high intensity.
- The impact of the flood in Nepal on the Ganga flow at Hardinge Bridge in Bangladesh (see Figure 3.2) was, if any, very small. The flood flow of the Bagmati in Nepal obviously levelled out once it reached the main river.

Box 5.12 (cont.)

- A rough quantification of the available discharge data from three Nepali tributaries indicates that large amounts of water must disappear before the tributaries join the main Ganga channel, mainly through seepage into the groundwater or through diversion for irrigation.
- The flow of the Meghna was very high: from mid-June to mid-August it was consistently above the maximum discharge that is to be expected on average. The peak flow temporally coincided with the flood period in the Meghna–Brahmaputra basin within Bangladesh.
- The discharge patterns of the Tista and Brahmaputra hardly exceeded average conditions. In both cases the annual peak was reached during the main rainy and flood period in Bangladesh.

in the Himalayan foothills tends to level off and the water tends to be integrated into the base flow of the main river channel further downstream.

An additional very interesting element emerging from the 1993 case study is the observation that the total daily discharge of the three Nepali rivers Karnali, Narayani and Sapt Kosi (see Figure 3.2), measured on 20 July at their transition from the Himalayas to the plains, was very close to the total flow of the Ganga at Hardinge Bridge in Bangladesh five days later. Considering that these rivers are only three of many Ganga tributaries from the Himalayas in the north as well as from the Deccan Plateau in the south (see Figure 2.1), this could indicate that a significant amount of water seeps into the groundwater reservoirs even before the tributaries join the Ganga. This observation additionally supports the statements about the levelling off of flood peaks in Himalayan tributaries on their way downstream towards the main river channel. In this discussion, the effect of the Farakka Barrage in India on the discharge characteristics of the Ganga at Hardinge Bridge in Bangladesh remains an unknown factor (see also Box 4.3).

5.15. The application of remote sensing techniques for the analysis of floods

As shown in sections 5.9 and 5.10, the 1987 and 1988 floods were two of the most outstanding events of the twentieth century. For these case studies, therefore, the analysis was expanded by using images from the

US National Oceanic & Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA-AVHRR). With the interpretation of remote sensing data, the intention was to gain additional insights into the flood processes of 1987 and 1988, to understand the meteorological situation and the rainfall patterns, and finally to analyse further the significance of the Himalayas for the floods in Bangladesh. To a large extent, the following text is based on a master's thesis by project team member Barbara Schneider (Schneider 1996). While reading this section, it is important to refer to the presentation of the respective case studies in sections 5.9 and 5.10 and Appendices 5.6 and 5.7, as well as to the discussion of the mechanisms of monsoon circulation in section 2.2.

The investigations for this particular component of the project included:

- Analyses and interpretation of the weather situation during defined test periods based on weather maps.
- Discussion of the cloud patterns and cloud clusters on 50–70 satellite images with a focus on the following questions: What were the cloud patterns before and during a flood event? Were the clouds during the flood-triggering rains positioned mainly over the mountains (Himalayas, Meghalaya Hills) or mainly over the plains (India, Bangladesh)?
- Rainfall estimates, based on the cloud patterns identified on the satellite images, and subsequent verification of these estimates by looking at rainfall records from specific sites in India and Bangladesh.

Owing to the time-consuming nature of digital processing of satellite data, it was impossible to investigate the entire monsoon period of 1987 and 1988. Therefore, three test periods were selected, one for 1987 and two for 1988, by consulting the respective flood reports (BWDB 1987, 1988).

5.15.1. The database

The satellite images used are NOAA-AVHRR data recorded by NOAA 9. The information consists of Global Area Coverage (GAC) data with a resolution of 4 × 4 km in the subsatellite point. Each scan line consists of 409 pixels and each pixel records information on five channels. Since the study deals with cloud patterns in the tropics, the rather coarse resolution of 4 × 4 km is sufficient.

The satellite images available for Asia are from afternoon flights. The recording starts when the satellite crosses the equator. The satellite flies over Bangladesh between 14:00 and 15:00 local time. Each day, one sequence of images is recorded over Asia, which normally consists of five equator crossings (so-called orbits). Each orbit has a width of about

1,600 km. On each subsequent day, the orbit of the satellite shifts slightly to the west and the exact same area is recorded only every eleventh day. The fact that the area covered by a specific orbit differs from day to day makes working with the satellite images complicated. On some days, Bangladesh may be in the centre of the images; often, however, its position is at the margins, which makes the interpretation difficult owing to the significant distortion of the images. The NOAA-AVHRR data were extracted from the archives at the European Union's Joint Research Centre in Ispra, Italy (see also Figure P.1). Using a program specifically written for this purpose, the compiled 10-bit data had to be converted to 8-bit data. Only after this conversion was it possible to read and process the data on the computer.

The weather maps used in this study were produced at the Indian Meteorological Department in Poona (IMD 1987, 1988). The weather maps represent the situation at 08:30 local time, which is roughly six hours ahead of the NOAA images. These daily bulletins consist of a sea surface pressure map, showing isobars, wind directions and the degree of cloudiness. In addition, a synoptical summary is available that includes information on cloud coverage, wind speed and direction, daily precipitation, etc. Pressure data for the 500 hPa level were extracted from a CD-ROM of the US National Centers for Environmental Prediction (NOAA, National Weather Service).

For verification, daily rainfall data were used from a number of stations in Bangladesh and India, the latter being extracted from the synoptical summary.

5.15.2. Classification of clouds and image-processing

The different types of cloud can be classified into three altitude levels, with the lower border of the clouds as the reference: low, middle and high levels. Several types of cloud extend over more than one level – for example, the Cumulus Congestus over two levels or the Cumulonimbus over all three levels. As regards the formation of clouds, two main types can be distinguished: cumuliform and stratiform. Cumuliform clouds are developed in unstable atmospheric conditions, connected to strong vertical wind shears. Stratiform clouds are developed in more stable conditions with hardly any vertical motion. In the tropics, the development of clouds is dominantly convective and the cumuliform clouds, especially Cumulonimbus, are therefore the most important for understanding rainfall processes.

Cloud size, shape, structure, shades and patterns are important factors in the classification of clouds on satellite images. Without discussing the currently available remote sensing technology, the methodology of cloud classification, the different bands of the electromagnetic spectrum, the relation between radiation and emissions and the interpretation of the images from visible and infrared channels, it can be said that "clouds which are coldest in the infrared and brightest in the visible produce most rain" (Henderson-Sellers 1984: 217). This statement refers especially to the Cumulonimbus type of cloud. Accordingly, the interpretation of satellite images makes it possible roughly to identify areal precipitation patterns but not the amount of rainfall. It is therefore absolutely necessary to cross-check and verify the results against climatological information from weather maps and data from meteorological stations (Riehl 1979; Haberäcker 1989; Albertz 1991; Barrett and Curtis 1992; Houze 1993; Richards 1994; Heinzmann 1995).

The image-processing was based on two standard procedures: a quantitative, computer-based classification and a visual interpretation (Richards 1994). As mentioned above, three altitude levels were differentiated and, after the classification, the images were geocoded, which was a major challenge. The fix point method, the most commonly used procedure to rectify images, failed owing to the high cloud coverage and a resulting lack of adequate fix points. Therefore, the second method, rectification based on the orbiter parameters of the satellite, had to be applied. Holzer (1996) has written a program for geocoding NOAA data, based on the orbiter parameters of the satellite and a Mercator projection as a reference system.

The analysis and interpretation of each image were done in a descriptive way. For each test period (see above) and for 18 defined study areas (see Figure 5.19), a cloud coverage map was produced based on the high and middle-high cloud levels. Classes of cloudiness had to be defined for the estimation of the degree of cloud coverage. For the human eye it is easier to estimate cloud coverage close to 0 per cent and 100 per cent than cloud coverage in the middle of the scale. "This experiment showed that areas with about 5% and 95% cloud coverage can be determined more accurately than areas with about 50% covering. Therefore it is fairly reasonable to choose smaller class widths for mostly open or mostly covered areas and larger class widths for areas with medium cloud cover. This procedure reduces the number of false classifications to a minimum" (Heeb 1983). Accordingly, the following classes were defined:

- Class 1: 0–10 per cent (without clouds)
- Class 2: 10–30 per cent (slightly cloudy)
- Class 3: 30–70 per cent (moderately cloudy)
- Class 4: 70–90 per cent (mostly cloudy)
- Class 5: 90–100 per cent (completely cloudy)

Classes 1 and 2 are of only minor interest. Of particular relevance for the

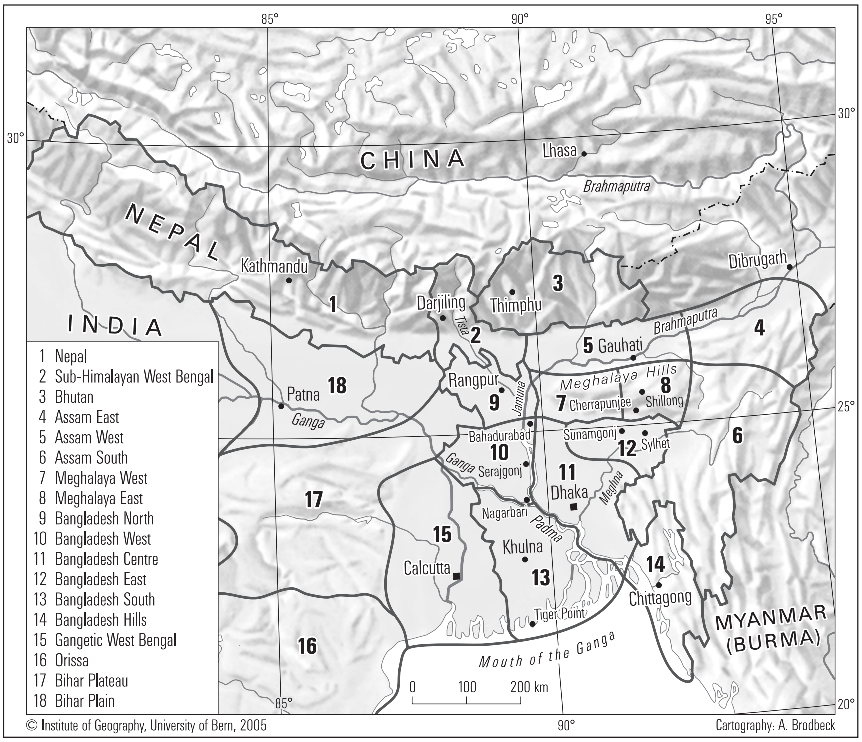

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Figure 5.19 The 18 study areas defined for the analysis of cloud coverage for three test periods during the most extensive flooding in 1987 and 1988.

understanding of flood processes are classes 4 and 5, which make it possible to localize areas with heavy precipitation.

5.15.3. The test period 28 July–20 August 1987 (24 days)

Summary of the floods in 1987, based on section 5.9 and Appendix 5.6

The inundations developed in June as flash floods in north-east Bangladesh and reached their maximum extent in August, particularly affecting the north-western part of the country. In August, flooding was also widespread in Bihar, West Bengal and Assam. Rainfall in Bangladesh, combined with peak flows from across the border, particularly through the Meghna and Brahmaputra–Tista systems, created the basic conditions for widespread flooding. The external input mainly originated in the Meghalaya Hills, in the Himalayan footzones and in the lowlands of the Brahmaputra system.

Interpretation of the weather maps

For the analysis of the meteorological situation it is appropriate to subdivide this test period into four parts (see also Figure 5A.27 in Appendix 5.6):

- 28 July–3 August 1987: because of the position of the monsoon trough in the north and its extension into Bangladesh, convergent processes at the surface prevailed, resulting in heavy rainfall. Precipitation was additionally intensified by a low pressure area moving over Bangladesh on 1 August.
- 4–9 August 1987: strongly divergent processes prevailed in Bangladesh as the currents were deflected towards the monsoon trough. The amount of rainfall was low.
- 10–13 August 1987: because the axis of the monsoon trough was again far in the north, convergent processes prevailed in Bangladesh and in Assam, and the second rainfall period started. Rainfall occurred primarily in the northern parts of Bangladesh, which were under the influence of the monsoon trough.
- 14–20 August 1987: in this period the monsoon trough almost disappeared and there was hardly any rainfall. On 18 August the situation changed. The monsoon trough was intensifying and moving northward. In addition, a low pressure area was moving over Bangladesh on 19 August. This low pressure system was overlapped by low pressure in the middle troposphere, which resulted in heavy rainfall.

Temporal interpretation of satellite images

Satellite images were available for 17 of the 24 days of the test period. As expected from the discussion of the meteorological situation, there was a sequence of days with high cloud coverage and widespread rains alternating with days of few clouds and scattered rain. At the beginning of the test period, Bangladesh was completely covered by high and middle-high clouds. Accordingly, rainfall on 31 July and 1 August reached the highest values for the entire test period and was widespread. With one exception, rainfall was recorded at all the sites documented in Figure 5A.27 in Appendix 5.6. Table 5A.3 in Appendix 5.6 shows high rainfall totals for the last part of July and early August for the Meghalaya Hills (Cherrapunjee, Shillong), Assam (Dibrugarh, Gauhati, Gangtok, Jalpaiguri) and Bihar (Patna) as well. The days after 3 August were characterized by only a few clouds. This situation changed again on 10 and 11 August: the satellite images show dense cloud coverage over Bangladesh, Assam and the Meghalaya Hills. During this period, rainfall was less intensive and occurred mainly in the northern parts of Bangladesh (Figure 5A.27 in Appendix 5.6), in the Meghalaya Hills and Assam (Table

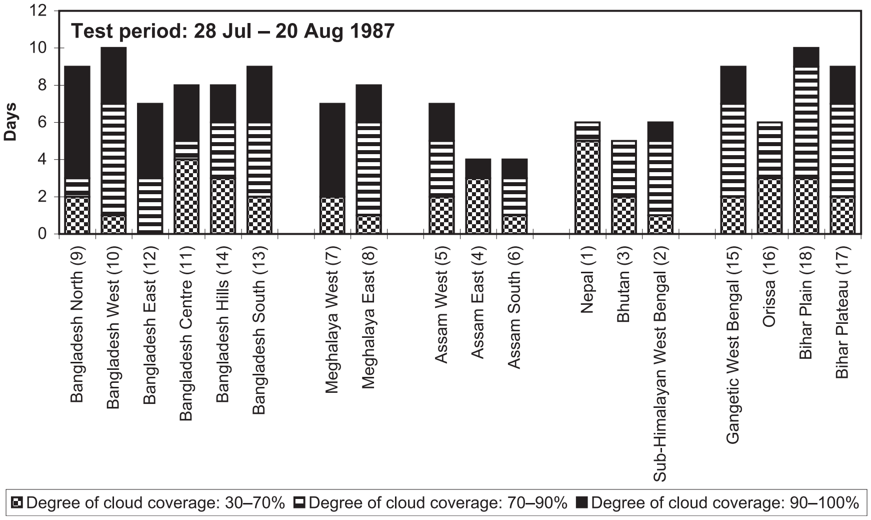


Figure 5.20 Coverage with high and middle-high clouds of the 18 study areas in the period 28 July–20 August 1987.
Note: For the location of the study areas, see Figure 5.19.

5A.3 in Appendix 5.6; see particularly Jalpaiguri). After a subsequent period with few clouds and little rainfall, dense cloud coverage and rainfall again commenced on 18 and 19 August. The results from the analysis of weather maps, from the interpretation of satellite images and from verification with rainfall measurements match very well.

Spatial interpretation of satellite images

Figure 5.19 shows the 18 study areas used in the analysis of the cloud coverage. These areas allow for a differentiation between the mountains and the plains as well as between the Ganga and the Brahmaputra river systems. Figure 5.20 illustrates the cloud coverage of high and middle-high clouds for the period 28 July–20 August 1987, and represents the number of days on which cloud coverage reached classes 3–5 (more than 30 per cent coverage). The following interesting observations can be made:

- The concentration of clouds over the territory of Bangladesh (study areas 9–14) is obvious: on 7–10 days, the cloud coverage was higher than 30 per cent. The number of days with cloud cover of class 5 (90–100 per cent) is particularly striking. As indicated above, high clouds in the tropics consist mainly of Cumulonimbus, middle-high clouds of big Cumuli. It is thus not surprising that heavy rainfall was recorded in all regions of the country on those days with almost complete cloud coverage. Again, we can conclude that the rainfall that contributed most to the floods in Bangladesh originated in the country itself.

- Outside Bangladesh, cloud coverage was similar in Western Assam, Bihar and Gangetic West Bengal, which were all flood-affected lowland regions. Accordingly, similar rainfall patterns can be expected in these areas. Gangetic West Bengal and Bihar were strongly affected by low pressure areas moving across or by the monsoon trough lying over the area.
- Cloud coverage in the Meghalaya Hills was also remarkable, particularly the significant number of days with cloud coverage of 90–100 per cent in the western part. This provides a clear indication of heavy rainfall in these hills.
- In Bhutan and Nepal, and to some extent also in Sub-Himalayan West Bengal, coverage with high and middle-high clouds was comparatively low during the study period. The two Himalayan countries, Nepal and Bhutan, had more than 70 per cent coverage by high to middle-high clouds on only one and three days, respectively. It is very unlikely that there was any significant rainfall in these areas. This finding is a particularly important addition to the findings in section 5.9 because almost no rainfall information was available for the Himalayan areas in the analysis of the 1987 flood case study.

5.15.4. The test period 1–20 July 1988 (20 days)

Summary of the floods in July 1988 based on section 5.10 and Appendix 5.7

The Meghna basin experienced a severe flood in early July, while simultaneously the Brahmaputra was at flood level. In July, serious flooding was also reported from Assam and Nepal. During this flood period there was significant rainfall both within and outside Bangladesh.

Interpretation of the weather maps

To better analyse the meteorological situation it is appropriate to subdivide this test period into three parts (see also Figure 5A.34 in Appendix 5.7):

- 1–7 July 1988: because of the extension of the monsoon trough into Bangladesh, convergent processes on the surface prevailed, resulting in heavy rainfall.
- 8–12 July 1988: because the monsoon trough was still extending into Bangladesh, convergent processes prevailed, which caused rainfall in the country. The intensity of precipitation was significantly less than on previous days. In addition, western Bangladesh was under the influence of a low pressure system, which had its centre over Gangetic West Bengal (Figure 5.21).

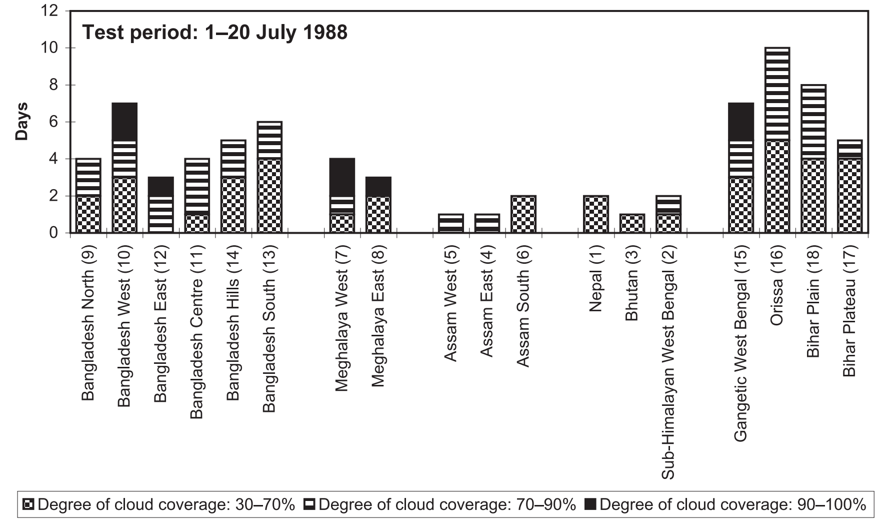


Figure 5.21 Coverage with high and middle-high clouds of the 18 study areas in the period 1–20 July 1988.
Note: For the location of the study areas, see Figure 5.19.

- 13–20 July 1988: the axis of the monsoon trough had moved far south and Bangladesh was no longer under its influence. A divergent flow pattern was established. There was only little rainfall in Bangladesh, concentrated mainly in the southern and eastern parts of the country. On 17 July a monsoon depression developed that, over the following days, moved north-westwards and weakened over the land.

Temporal interpretation of satellite images

The patterns of high and middle-high clouds point directly to the potential rainfall period and areas. On 5 and 6 July, Bangladesh was entirely covered with cloud. Accordingly, and as illustrated in Figure 5A.34 in Appendix 5.7, rainfall was recorded at all sites, with only two exceptions. Table 5A.4 in Appendix 5.7 shows high rainfall totals for the early part of July for the Meghalaya Hills (Cherrapunjee, Shillong) and Assam (Dibrugarh, Gauhati, Gangtok, Jalpaiguri). Unfortunately it was not possible to analyse the situation on 3 and 4 July owing to the lack of satellite images. The days after were characterized by sporadic clouds, out of which rainfall was possible. On 12 and 13 July the situation changed drastically and Bangladesh was mostly cloudless. As confirmed by Figure 5A.34 in Appendix 5.7, the probability of rainfall was very small and mostly orographic in nature. During the formation of the monsoon depression towards the end of the test period, Bangladesh was not under the influence of the monsoon trough and divergent processes dominated. Accordingly, hardly any clouds are visible on the satellite images and rainfall was very scarce.

Spatial interpretation of satellite images

Figure 5.21 illustrates the cloud coverage of high and middle-high clouds for the period 1–20 July 1988. The following interesting observations can be made:

- All the study areas in Bangladesh were covered for three to seven days with clouds relevant for rainfall, concentrated in the first half of the test period. There were very few cases within Bangladesh of 90–100 per cent cloud coverage.
- Cloud coverage was more important for a number of lowland areas outside Bangladesh: the cloud coverage was above 30 per cent in Orissa on 10 days, in Bihar Plain on 8 days and in Gangetic West Bengal on 7 days. The main reason for this situation was the axis of the monsoon trough, which was often situated exactly over this region. In addition, four low pressure systems developed over Gangetic West Bengal during this period.
- The small number of days with cloud coverage above 30 per cent in the Meghalaya Hills and Assam is surprising in view of the significant amount of rainfall that occurred during the first part of the test period in these areas (see Table 5A.4 in Appendix 5.7) and in view of the serious flooding reported for the month of July in Assam. Does this mean that the time of overflight of the satellite between 14:00 and 15:00 does not correspond to the timing of maximum cloud development in the day?
- In the highland areas in Nepal, in Sub-Himalayan West Bengal and in Bhutan there was hardly any cloud coverage over 30 per cent and therefore the probability of heavy rainfall in these Himalayan areas was very low. The flood in Nepal, which according to the literature sources occurred in July, might have been a very localized event or might have developed in the second half of July, which is outside the test period considered here.

5.15.5. The test period 20 August–5 September 1988 (17 days)

Summary of the floods in the second part of August and the early part of September 1988, based on Section 5.10 and Appendix 5.7

Before the July flood had fully receded, heavy rainfall occurred in the northern and north-eastern parts of Bangladesh, with the actual rainfall centres lying outside the country in Assam, the Indian Gangetic Plain and the Meghalaya Hills. As a result, all major rivers started rising gradually and reached their peaks between 30 August and 2 September. The nationwide flood occurred roughly from 20 August to 5 September. In the same period, particularly between 20 and 28 August, there was a severe flood in Assam as well. In both Bangladesh and Assam, the flood was one of the biggest in the twentieth century.

Interpretation of the weather maps

For the analysis of the meteorological situation, it is appropriate to subdivide the test period into two parts (see also Figure 5A.34 in Appendix 5.7):

- 20–29 August 1988: starting from 23 August, the axis of the monsoon trough was positioned far north in India and extended into Assam and Bangladesh. Especially in northern Bangladesh this situation resulted in convergence with abundant precipitation. From 23 to 25 August there was heavy rainfall in the whole of Bangladesh, in Assam and in the Meghalaya Hills; from 26 to 29 August the northern parts of Bangladesh, Assam and the Meghalaya Hills continued to receive high amounts of rainfall, while the southern part of Bangladesh remained more or less dry.
- 30 August–5 September 1988: because of the monsoon trough's shift to the south over central India and its weakening, Bangladesh was not affected. However, on 5 September the monsoon trough became active again. In the early days of September, rainfall was recorded in the eastern and north-eastern parts of Bangladesh in particular, most probably as a result of orographic processes.

Temporal interpretation of satellite images

Choudhury (1989: 237) states: ‘‘If we look at the satellite imageries we notice that from 20 August to 1 September 1988 most of the catchment area of the river Brahmaputra and at times of the Ganga and Meghna as well is covered by Cumulonimbus clouds indicating heavy rainfall. If this sort of cloud occurs at a place for 2–3 days, this is sufficient to cause a moderate flood.’’ The cloud patterns on the satellite images clearly reflect the meteorological processes. For example, the movement of the monsoon trough is recognizable in the distribution of the big meso-scale, convective Cumulonimbus cloud systems. On 23 and 24 August, Bangladesh was entirely covered by high and middle-high clouds, and rainfall was recorded at a large number of stations in Bangladesh (see Figure 5A.34 in Appendix 5.7). Until 28 August Bangladesh continued to be heavily cloud covered, mostly by Cumulonimbus. Rainfall during these days occurred mainly in the northern parts of the country. Based on the statement by Choudhury quoted above, we can assume that six days with widespread Cumulonimbus clouds and the resulting precipitation (23–28

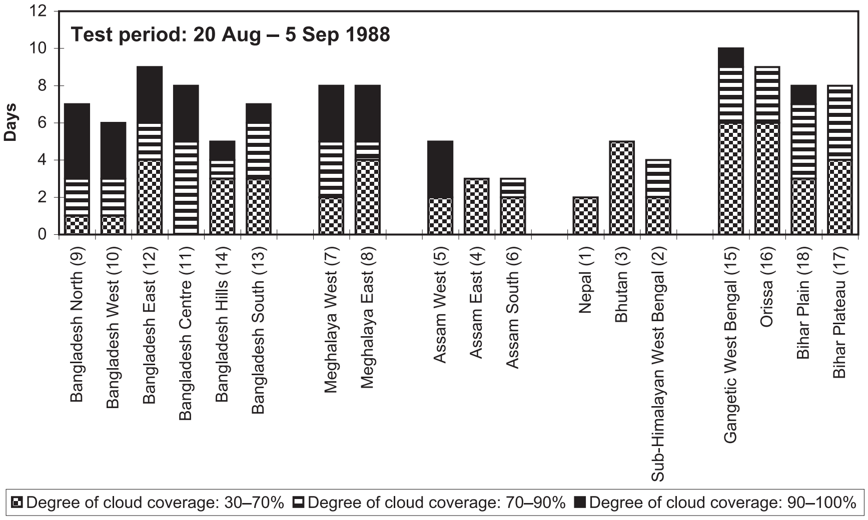


Figure 5.22 Coverage with high and middle-high clouds of the 18 study areas in the period 20 August–5 September 1988.
Note: For the location of the study areas, see Figure 5.19.

August) would be sufficient to cause major flooding, particularly if combined with other factors such as synchronization of peak flows, spring tides and high groundwater tables (see section 5.10). After 29 August the density of clouds temporarily decreased, leaving Bangladesh, Assam and the Meghalaya Hills only slightly cloud covered. Accordingly, there was very little rainfall. On 5 September Bangladesh again came under dense cloud cover, which resulted in widespread rains (Figure 5A.34 in Appendix 5.7).

Spatial interpretation of satellite images

Figure 5.22 illustrates the cloud coverage of high and middle-high clouds for the period 20 August–5 September 1988. The following interesting observations can be made:

- Cloud coverage over Bangladesh, particularly during the first part of the test period, was very high. For between five and nine days, all areas within Bangladesh were more than 30 per cent covered with high and middle-high clouds. The number of days with cloud coverage of 90–100 per cent is remarkable. The degree of cloud coverage was particularly striking for the north, west, east and centre of Bangladesh, where most of the rainfall occurred during this period.
- In the Meghalaya Hills, too, cloud coverage was above 30 per cent on eight days (and above 90 per cent on three of these days) – the connec-

tion with the exceptional rainfall figures listed in Table 5A.4 in Appendix 5.7 (Cherrapunjee, Shillong) is obvious. To some extent, western Assam was heavily cloud covered as well.

- Although cloud coverage over Gangetic West Bengal, Orissa and Bihar was lighter than over Bangladesh (only very few days with 90–100 per cent coverage), the satellite images show cloud coverage above 30 per cent on 4–10 days. This was the result of the monsoon trough, which, throughout the last eight days of August, was positioned over these areas. Significant rainfall and, as a result, a substantial contribution to the Bangladesh floods from at least part of the Ganga catchment could be expected.
- Cloud coverage in Nepal, Sub-Himalayan West Bengal and Bhutan was very low. There was not one single day in Bhutan and Nepal with coverage by high or middle-high clouds of more than 70 per cent. With good reason it can be assumed that, during the period of one of the most widespread floods of the twentieth century in Bangladesh, there was hardly any meaningful rainfall in these Himalayan areas. This is an important finding and it confirms the statement in Box 5.8 that the amount of rainfall at the lowland station of Jalpaiguri significantly exceeded the figure measured at the hill station of Gangtok.

5.15.6. Summary

The overall meteorological situation leading to rainfall and flooding was different in the two consecutive major flood years:

- In 1987, the monsoonal trough, positioned over northern India, was relevant, but rainfall was further intensified by the low pressure areas that formed over the Bay of Bengal and moved northward across Bangladesh. In addition, orographic processes played an important role in the eastern and north-eastern parts of Bangladesh and led to intensified rainfall (see also section 2.2).
- In 1988, the rainfall was mainly the result of the extreme northern position of the monsoonal trough and convergent processes in the trough region.

The satellite images confirm that the relevant rainfall for the development of the Bangladesh floods in 1987 and 1988 primarily originated in the country itself. Precipitation in Assam and the Meghalaya Hills significantly contributed to the high discharge of the rivers flowing into Bangladesh and, accordingly, to the dimension of flooding. In the Meghalaya Hills, orographically induced precipitation played a very important role.

Interestingly, hardly any rain-producing clouds were visible on the satellite images over the Himalayas (Nepal, Sub-Himalayan West Bengal and Bhutan) during the three test periods. This confirms that the hydro-meteorological processes in these Himalayan areas had little to do with the flooding processes in the lowlands. This is a very significant finding for the overall context of this book. In particular, it confirms the assumptions made in sections 5.9 and 5.10, which were based on a limited number of rainfall stations.

The study by Schneider (1996) shows that, in order to understand the flooding in Bangladesh, it is essential to identify how strongly the monsoon trough has developed and where the axis of the trough is positioned:

- If the axis of the monsoon trough is located far north in India (in the foothills of the Himalayas), the northern part of Bangladesh and Assam may receive heavy rainfall. Large parts of India (e.g. the Gangetic Plain), however, remain without precipitation.
- If the axis of the monsoon trough lies more to the south (over central parts of India), rainfall may occur in large parts of India but not in Bangladesh. The monsoon winds from the Bay of Bengal are deflected in a westerly direction towards the low pressure area of the monsoon trough (see also the 1978 case study in section 5.13).

The analysis of the three test periods has clearly demonstrated that satellite images are a very appropriate tool for investigating large flood events in the context of highland–lowland linkages:

- Satellite images serve to analyse cloud coverage in a qualitative (cloud classification) and a quantitative (degree of cloud coverage) way.
- It is possible to see a number of important meteorological phenomena on the satellite image, e.g. the position of the monsoonal trough, which is characterized by meso-scale convective cloud systems, mainly Cumulonimbus.
- Based on the classification of clouds appearing in the satellite images into high, middle-high and low clouds, complemented by verification with records from meteorological stations, it is possible to make rainfall estimations. With a significant degree of confidence the connection can be made between high and middle-high clouds on the satellite images and rainfall areas. This approach is particularly appropriate and useful for rainfall estimations in areas with a very low density of meteorological stations. It may have some limitations in areas where the timing of the satellite overflight and the timing of the maximum cloud coverage and rainfall in the daily cycle do not coincide.

5.16. The 11 case studies: A comparison

Through the analysis and discussion of 11 case studies (eight “flood years”, two “dry years” and one “average year”), considerable insight was gained into the hydro-meteorological processes leading to floods in Bangladesh from the perspectives of highland–lowland linkages, regional patterns and important combinations of factors. The objective of this section is to compare the 11 case studies, to sift out the most important findings and to identify common or repeating hydro-meteorological situations that lead to large-scale flooding. This comparison is carried out at an aggregated and generalized level.

5.16.1. Mid-August – a critical time for the development of large floods

The bars in the left-hand panel of Table 5.10 represent tentative (grey) or confirmed (black) periods of the maximum ‘‘nationwide’’ extent of flooding in Bangladesh. In the right-hand panel of the table, floods are listed that were reported from outside Bangladesh (India or Nepal), with their geographical extent and approximate timing. August seems to be the most important flood month. With the exception of 1922, there was flooding during August in all the selected case studies. However, the floods in 1988 and 1998, which were the two most exceptional events of the twentieth century, reached their maximum extent only at the beginning of September. We may conclude from this that, in the course of the monsoon season, water is gradually accumulated in the rivers, groundwater reservoirs, ponds and other water bodies and the soils become saturated. The capacity to absorb additional and surplus water is increasingly reduced. As a result, the flood situation can be particularly severe if flood-triggering conditions (e.g. heavy rainfall, river peak flows, spring tides) develop after mid-August.

On average, widespread flooding lasts for two to three weeks. As confirmed by all the references consulted, the flood of 1998 was a very striking exception to this: severe flooding occurred more or less continuously from mid-July to mid-September in different parts of the country.

With the exception of 1922, flood years in Bangladesh are also flood years in Assam (SC7 and SC8, see Figure 5.1). Many of these Assam floods were composed of different waves. It is evident that in 1910, 1987, 1988 and 1998, and most probably also in 1974, the Assam and the Bangladesh floods had similar timing. This clearly indicates that an upstream–downstream link exists in terms of flooding conditions within the Brahmaputra lowlands from Assam to Bangladesh.

In the case of the Indian Ganga system (SC3, SC4, SC5), the situation is more complex and different. It is true that floods were also reported in 1906, 1910, 1922, 1987, 1988 and 1998, which were major flood years for Bangladesh. However, in many cases these floods in the Indian Ganga

Table 5.10 Inundations inside and outside Bangladesh in eight major flood years of the twentieth century: A temporal comparison

	Floods inside Bangladesh			
Flood year	July	August	September	**Floods outside Bangladesh**
1906		▨	▨	Parts of SC3, SC8, SC10: 1–7 Aug; parts of SC4, SC5: 16–31 Aug
1910	▨	▨		Parts of SC3, SC5, SC8: July (SC5 into August)
1922			■	Parts of SC4: 1–8 Sep
1955		▨		Assam (SC7, SC8): timing unknown
1974		■		Assam (SC7, SC8): 5 waves
1987	■	■		Assam (SC7, SC8): 5 waves (Aug); Bihar (SC5): Aug–Oct; W. Bengal (SC5, SC6): Aug
1988		■	■	Assam (SC7, SC8): 4 waves (Aug); SC5: June; SC2: July
1998	■	■	■	Assam (SC7, SC8): c. 15 Jul – 15 Aug; SC2: end Aug – early Sep; SC5: timing unknown

Notes: For the location of the subcatchments, see Figure 5.1. Grey shading indicates tentative timing of the flood; black shading indicates confirmed timing of the flood.

system were not widespread and occurred in areas close to Bangladesh and the confluence area of the Ganga with the Brahmaputra (e.g. 1910 and 1987). Furthermore, only in 1906, 1910 and 1987 was the timing of the floods in the Indian Ganga system comparable with the timing of the inundations in Bangladesh. Most interestingly, 1978 was a severe flood year in the Indian Ganga Plain but a ''dry year'' in Bangladesh. The analysis of flood statistics in section 4.4.2 confirms that the flooding patterns in Bangladesh have a much stronger similarity to those in Assam than to those in the Indian Ganga Plain.

5.16.2. The hydro-meteorological patterns in the Ganga–Brahmaputra–Meghna system: A differentiated picture

In this section we discuss a correlation analysis of potential runoff (*R*(pot)) carried out for the period 1950–1990 (all years with available data, in most cases around 40 observations) for the 13 subcatchments and the four monsoon months (Table 5.11). The correlation coefficients listed in Table 5.11 are indicators of the geographical patterns of *R*(pot) anomalies:

- A high positive correlation coefficient between two subcatchments indicates that the two data series of *R*(pot) have a similar pattern. If *R*(pot) in one subcatchment is high/low, the probability exists that *R*(pot) in the other subcatchment is also high/low.
- A low positive correlation coefficient between two subcatchments indicates that the two data series of *R*(pot) do not have much in common. If *R*(pot) in one subcatchment is high/low, the probability is small that *R*(pot) in the other subcatchment is also high/low.
- A negative correlation coefficient between two subcatchments indicates that the two data series of *R*(pot) have opposite patterns. If *R*(pot) in one subcatchment is high/low, the probability exists that *R*(pot) in the other subcatchment is low/high.

The interpretation of Table 5.11 reveals the following findings:

- *Correlation between the Himalayan subcatchments and the adjacent plains*. The patterns of *R*(pot) do not show much similarity. The best correlations are reached in June and September.
- *Correlation among the Himalayan subcatchments*. Except for June, there is not much similarity in the patterns of *R*(pot) in the mountain areas.
- *Correlation among the subcatchments of the Indian plains*. The patterns of *R*(pot) on the Indian Ganga Plain and the Indian Brahmaputra plain (correlations of SC4 and SC5 with SC7 and SC8) are very poorly corre-

Table 5.11 Correlation of R(pot) among different subcatchments in the four monsoon months, 1950–1990

	Correlation coefficients				
Month	Himalayan SCs and adjacent plains	SCs of the Indian plains	SCs of Bangladesh and SCs of the Ganga and Brahmaputra systems outside Bangladesh		SCs of the Meghna system and Assam
	SC1/SC4	*SC4/SC5*	*SC10/SC5*	*SC12/SC5*	*SC12/SC9*
June	0.417**	0.436**	0.147	0.138	0.606**
July	0.273	0.326**	0.059	0.093	0.526**
August	0.075	0.360**	–0.084	0.117	0.285
September	0.667**	0.209	0.023	–0.131	0.531**
	SC2/SC5	*SC4/SC8*	*SC10/SC4*	*SC12/SC4*	*SC9/SC8*
June	0.428**	–0.191	–0.120	–0.236	0.505**
July	–0.017	0.054	–0.302**	–0.136	0.345**
August	0.041	0.244	–0.212	–0.003	0.182
September	0.293	–0.261	–0.139	–0.217	0.389**
	SC3/SC8	*SC4/SC7*	*SC10/SC2*	*SC12/SC2*	*SC9/SC7*
June	0.210	–0.082	0.210	0.296	0.264
July	0.050	–0.016	0.241	–0.022	0.141
August	0.385**	–0.121	–0.048	0.018	0.519**
September	0.567**	–0.142	0.562**	0.376**	0.325**
	Himalayan SCs				SCs in Bangladesh
	SC1/SC2	*SC5/SC8*	*SC10/SC8*	*SC12/SC8*	*SC10/SC12*
June	0.543**	0.163	0.280	0.517**	0.586**
July	–0.025	0.399**	0.335**	0.301**	0.551**
August	0.340	0.279	–0.151	0.051	0.603**
September	–0.111	0.048	0.681**	0.606**	0.623**
	SC1/SC3	*SC5/SC7*	*SC10/SC7*	*SC12/SC7*	*SC10/SC13*
June	0.423**	0.056	0.272	0.168	0.647**
July	0.328	0.228	0.380**	0.228	0.461**
August	0.122	–0.077	0.014	–0.016	0.556**
September	–0.013	–0.217	0.312**	0.333**	0.386**
	SC2/SC3	*SC7/SC8*	*SC10/SC3*	*SC12/SC3*	*SC12/SC13*
June	0.475**	0.015	0.191	0.247	0.489**
July	0.051	0.334**	0.182	0.349**	0.579**
August	0.117	0.289	0.282	0.236	0.572**
September	0.456**	0.378**	0.450**	0.379**	0.397**

Notes: **correlation statistically significant at 5% level; Bahrenberg and Giese (1975: 293).

lated, and there are even a number of negative coefficients. Humid monsoon summers in the east tend to coincide with rather dry monsoon summers in the west, and vice versa.

- *Correlation between the subcatchments of Bangladesh and the subcatchments of the Ganga and Brahmaputra systems outside Bangladesh*. There is not one single positive, statistically significant correlation of SC10 and SC12 (Bangladesh) with SC4 and SC5 (Indian Ganga Plain). Negative correlations dominate, particularly with the Upper Ganga Plain (SC4). In contrast, SC10 and SC12 (Bangladesh) are in most cases positively correlated with SC7 and SC8 (Assam). Particularly in July and September, the coefficients are statistically significant. Overall, these findings confirm that the patterns of *R*(pot) in Bangladesh tend to be similar to those in Assam, and different from or even the inverse of those in the Indian Ganga Plain.
- *Correlation between the subcatchments of the Meghna system and Assam*. The patterns of *R*(pot) in these subcatchments are in most cases well correlated.
- *Correlation among the subcatchments within Bangladesh*. The patterns of *R*(pot) within Bangladesh are very similar. This is illustrated by the statistically significant correlation coefficients in all calculations.

This analysis provides impressive evidence of the marked difference in the hydro-climatological conditions between the east and the west within the Ganga–Brahmaputra–Meghna basin. As already discussed in section 5.15.6, this difference is a result of global circulation patterns, more specifically of the position of the monsoon trough. Indirectly the findings of this correlation analysis once again confirm the results of sections 4.4.2 and 5.16.1 that the flooding conditions in Bangladesh are more related to the hydro-climatological processes in the Brahmaputra and Meghna basins than to those in the Ganga catchment.

The fact that the hydro-meteorological patterns in the Himalayas and those in the adjacent lowlands do not show much similarity has already been discussed in Hofer (1993). The analysis of precipitation series in the period 1953–1981 for the Indian state of West Bengal (for the location, see Figure 4.8) has revealed the fact that rainfall in the plains of West Bengal cannot be correlated with rainfall in the foothills or in the Sub-Himalayan Zone. In the case of the Ganga system, the westward-moving monsoon depressions obviously do not necessarily cover the entire Ganga catchment, but affect either the plains or the first Himalayan ranges. This is supported by Kuster (1995), who identified several examples of monsoon depressions that moved to the west over the Ganga Plain or over the southern end of it, losing their rainfall intensity once they turned north towards the first Himalayan ridges.

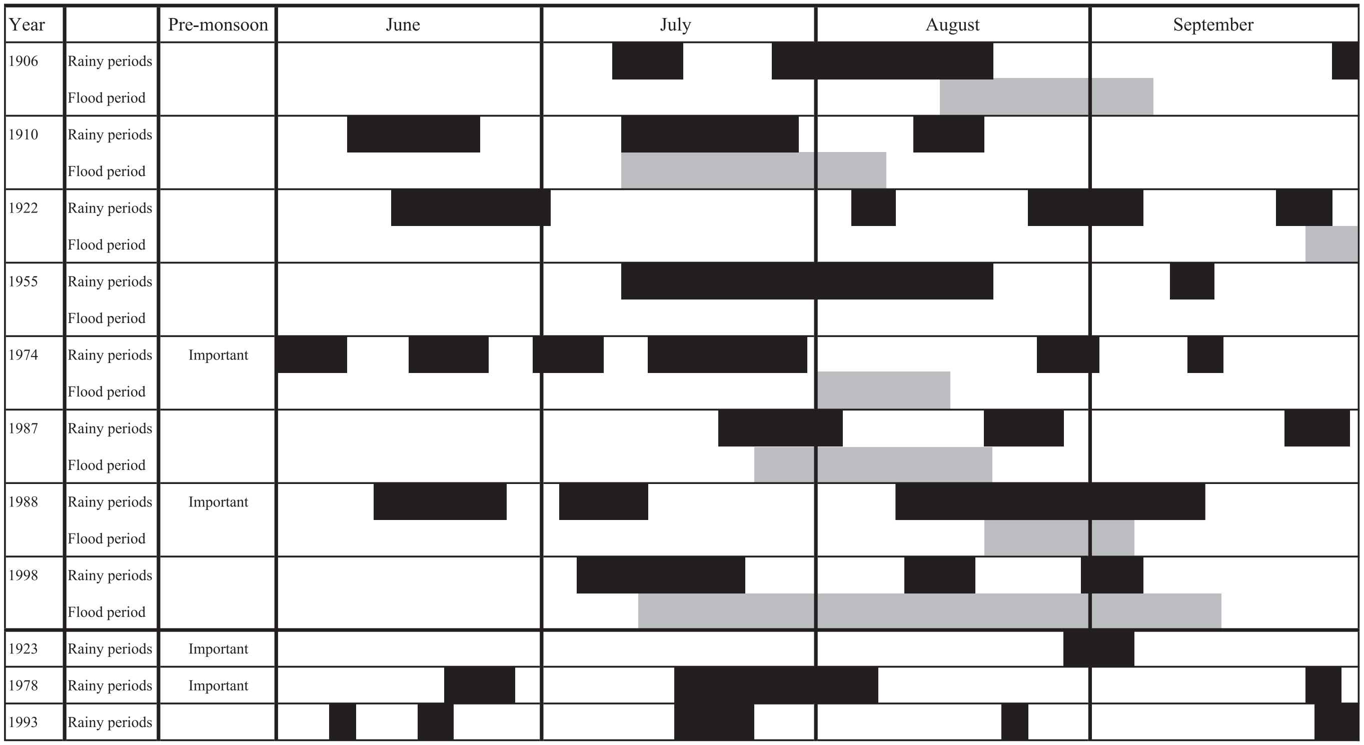
5.16.3. Rainfall within Bangladesh – a key factor in the development of floods

Table 5.12 shows the rainy periods and the main flood period in Bangladesh for each of the 11 case studies. The rainy periods indicate those phases during which rainfall in Bangladesh was widespread. The flood period indicates the timing of the maximum nationwide extent of flooding in Bangladesh (see also Table 5.10). July and August are the months with the highest frequency of widespread rainfall in Bangladesh. The rainy periods in the flood years tend to be more numerous and of longer duration than in the dry years. This is confirmed by a seminar study carried out within the framework of the project that specifically looked into ''active'' and ''break'' phases of the monsoon in different years (Reinhardt 1994). Each flood developed during or (in 1974) immediately following an extended and widespread rainy period and lasted significantly beyond the duration of the precipitation phase. All these arguments clearly indicate that precipitation within Bangladesh is one key factor in the development of large floods. It is often argued that the ''meteorological history'' of a flood, in other words the rainfall patterns immediately preceding a big flood, is critical for the development of large-scale flooding. According to Table 5.12, this is certainly true for the days immediately before the onset of a big flood. In a number of years, such as in 1910, 1922, 1974 and 1988, the ''meteorological history'' of the floods most likely had already begun in June, and important rainfall phases might have resulted in a gradual accumulation of water in the various water bodies. However, the rainfall patterns in the pre-monsoon period (April–May) do not seem to be an important factor in the development of floods: only in the 1974 and 1988 case studies were the pre-monsoon rains above average, which may have resulted in reduced water absorption capacity of the water bodies in Bangladesh at the onset of the widespread monsoon rains. The fact that the same situation was identified for the two dry years (1923 and 1978) as well indicates that pre-monsoon rains are not necessarily a flood-triggering factor.

5.16.4. Synchronization of discharge peaks – a very important trigger for flood generation

The combination of high ''base flow'' and short-term discharge fluctuations with high peaks is important for flood processes in Bangladesh. According to Figure 2.5, which is based on monthly records, the rivers in the Ganga–Brahmaputra–Meghna basin flow at high water levels in the summer months and at low water levels in the winter months. Discharge gradually increases in the pre-monsoon period, reaches a maximum in

Table 5.12 A comparison of rain and flood periods in Bangladesh for eight flood years (1906, 1910, 1922, 1955, 1974, 1987, 1988, 1998), two dry years (1923, 1978) and one average flood year (1993)



July or August, and then gradually decreases again. This "base flow" reflects the overall discharge characteristics of a river in a specific year and is mainly the result of the large-scale hydro-meteorological conditions in the river's catchment. The hydrographs of daily discharge, which were produced for the detailed investigations in the various case studies, show that this general annual pattern of "base flow" is differentiated into a number of short-term fluctuations. The smaller the rivers are, the more accentuated and numerous these fluctuations become. Among these fluctuations, the short-term peaks are of particular interest for the understanding of the flood processes. In some cases these peaks are imported from the Indian Plains of the Ganga and Brahmaputra; in other cases they originate in Bangladesh as a result of heavy rainfall within the country, the synchronization of the peak discharges of the major rivers or even from backwater effects owing to spring tides.

The short-term discharge peaks can be very important, as illustrated by the following example. Over a two-week period, from 25 August to 10 September 1988, the flow of the Brahmaputra at Bahadurabad was very high (Figure 5A.35 in Appendix 5.7) and was continuously above the danger level (the danger level is about 60,000 m^3/sec; see BWDB 1988). Based on a very rough calculation, an attempt was made to quantify the total above-danger-level flow over the two weeks, in other words the discharge that had the potential to overflow the river banks. For each day, the total above-danger-level flow was calculated according to the following formula:

$$\text{discharge record in } m^3/\text{sec} - 60{,}000\ m^3/\text{sec (danger level flow)} \\ * 86{,}400 \text{ (number of seconds in 24 hours).}$$

Over the two-week period, this calculation resulted in a total of $2.498688 * 10^9$ m^3 of above-danger-level flow. Assuming that this amount of water overflowed the river banks and that the soil was 100 per cent saturated, the water would form a lake of 1 metre depth and an area of almost 25,000 km^2, which roughly corresponds to one-sixth of the territory of Bangladesh! It is obvious that the flood-triggering impact of such short-term peaks is much stronger when added to a high base flow close to danger levels (in the middle or end of the monsoon season) than when added to a rather low base flow (in the early monsoon period). The impressive discharge peak of the Brahmaputra in mid-July 1988 (Figure 5A.35 in Appendix 5.7) did not cause any flooding; whereas the peak at the end of August/early September, whose shape was almost identical to the one in July, significantly contributed to one of the most serious nationwide flood events of the twentieth century.

In Table 5.13, the timing of the highest daily discharge records of the

Table 5.13 A temporal comparison of highest daily discharge records in selected years

Year	Main flood period	Ganga	Brahmaputra	Time difference (days)	Brahmaputra	Meghna	Time difference (days)	Ganga	Meghna	Time difference (days)
1955	1–30 Aug	20 Aug	31 Jul	20	31 Jul	19 Aug	19	20 Aug	19 Aug	1
1974	1–15 Aug	2 Sep (15 Aug)	6 Aug	27	6 Aug	7 Aug	1	2 Sep (15 Aug)	7 Aug	26
1987	25 Jul–20 Aug	19 Sep (19 Aug)	15 Aug	35	15 Aug	13 Aug	2	19 Sep (19 Aug)	13 Aug	37
1988	20 Aug–5 Sep	3 Sep	30 Aug	4	30 Aug	11 Jul (1 Sep)	50	3 Sep	11 Jul (1 Sep)	54
1998	12 Jul–15 Sep	9 Sep	8 Sep	1	8 Sep	7 Sep	1	9 Sep	7 Sep	2
1978		21 Aug	29 Jun	53	29 Jun	not available		21 Aug	not available	
1993		22 Sep	23 Jul	61	23 Jul	24 Jul	1	22 Sep	24 Jul	60

Notes: The dates without brackets represent the highest discharge records of that year; the dates in brackets represent the second-highest discharge records.

Ganga, Brahmaputra and Meghna for the five major flood years of 1955, 1974, 1987, 1988 and 1998 is compared and related to the flood periods. The same information for a dry year (1978) and for an average flood year (1993) is also listed. The dates in the table indicate the day on which each river reached its highest flow for that particular year. In some cases, the dates of the second-highest flow are also indicated in brackets. In addition, the time difference between the annual peaks of two of the rivers is listed.

The highest flow of the year of the three major rivers is normally reached during the main flooding period. In some cases (1974 and 1987 for the Ganga, 1988 for the Meghna) it is only the second-highest flow that falls within the flooding period. The temporal synchronization of the highest flow of the major rivers seems to be an important factor in the development of the floods. In 1998, in which the biggest flood of the twentieth century occurred, this synchronization is particularly clear: the annual maximum flow of all three rivers was reached on almost the same day. In the case of 1987 and 1988, the annual peaks of two of the rivers and the second-highest flow of the third river are temporally synchronized. In 1955 and 1974, two of the rivers peaked more or less in the same period. In the two non-flood years, in contrast, the dates of the highest annual flow of the Ganga and Brahmaputra are almost two months apart.

It can be assumed that, in the case of a temporal synchronization of the peak flows of the main rivers, the accumulated water masses in the larger area of confluence significantly exceed the discharge potential into the Bay of Bengal, particularly if combined with high groundwater tables, local rainfall, saturated soils or backwater effects from the sea owing to spring tides (e.g. 1988). As a result, the water gradually spreads out to form large water bodies above and below the ground. This finding is supported by the groundwater hydrographs: at the gauging site FA22, which is located to the south of the confluence of the Ganga and Brahmaputra (see Figure 3.3), the groundwater table reached the surface in all the flood years for which information was available (Figure 5A.23 in Appendix 5.5 for 1974, Figure 5A.30 in Appendix 5.6 for 1987, and Figure 5A.37 in Appendix 5.7 for 1988).

The comparison of the different case studies sheds some additional light on the relative importance of the Ganga, Brahmaputra and Meghna rivers for the generation of the floods in Bangladesh. There is no doubt that the Brahmaputra plays a key role. As is shown in a number of case studies, the Ganga on its own does not seem to be particularly critical for the development of the floods in Bangladesh. However, in combination with the other rivers, the Brahmaputra in particular, the Ganga can significantly contribute to the development of exceptional floods. If the huge Ganga and Brahmaputra rivers have synchronized peaks, then this event clearly dominates the scene in view of the immense water masses that accumulate in the area of confluence. The flow of the Meghna is considerably less in quantitative terms than the flow of the Ganga and Brahmaputra. However, in view of the exceptional areal precipitation in the upper parts of its catchment, the widespread flooding in its lowland areas and its backing-up effect on the joint Ganga and Brahmaputra flow, the Meghna River is very important too.

Notes

1. Literature sources for the 1906 flood: *The Englishman* (1906: 24 Aug, 25 Aug, 4 Sep, 12 Sep); *Pioneer Mail* (1906: 24 Aug); *District Gazetteer*, Purnea 1911; *District Gazetteer*, Dhaka 1912; Mahalanobis (1927).
2. Literature sources for the 1910 flood: *Amrita Bazar Patrika* (1910: 15 Jul, 19 Jul, 31 Jul, 11 Aug); *Eastern Bengal and Assam Era* (1910: 23 Jul, 3 Aug); *The Englishman* (1910: 14 Jul, 26 Jul, 28 Jul, 30 Jul, 1 Aug, 12 Aug); *The Statesman* (1910: 4 Aug); Mahalanobis (1927).
3. Literature sources for the 1922 flood: *The Englishman* (1922: 25 Sep, 28 Sep, 29 Sep, 30 Sep, 2 Oct, 3 Oct, 4 Oct, 5 Oct, 7 Oct, 10 Oct, 11 Oct, 13 Oct, 16 Oct, 19 Oct); *The Statesman* (1922: 15 Jun, 29 Jun, 3 Aug, 17 Aug, 31 Aug, 7 Sep, 21 Sep, 5 Oct, 12 Oct, 19 Oct); *The Statesman* (1923: 20 Sep); Mahalanobis (1927).
4. Literature sources for the 1955 floods: BWDB (1975); Agarwal and Narain (1991); Hughes et al. (1994); Kuster (1995).
5. Literature sources for the 1974 flood: BWDB (1975); Teich (1975); Government of Assam (1979); Ahmad (1989); BWDB (1991a).
6. Literature sources for the 1987 flood: BWDB (1987); Hussain and Samad (1987); IMD (1987); *India Today* (1987); Frisch (1988); Miah (1988); Ministry of Irrigation, Water Development and Flood Control (1988); Venkataramani (1988); Choudhury (1989); Matin and Husain (1989); Brammer (1990a); Pasche (1990); USAID (1990); Agarwal and Narain (1991); GOB (1992b).
7. Literature sources for the 1988 flood: BWDB (1988); Miah (1988); Popelewski (1988); USAID (1988); Abbas (1989); Ahmad (1989); Ahmed (1989); Choudhury (1989); Government of Assam (1989); Khan (1989); Latif (1989); Matin and Husain (1989); Shahjahan (1989); Hossain (1990); Islam (1990); Agarwal and Narain (1991); GOB (1992a, 1992b); Ramasastri (1992).
8. Literature sources for the 1998 flood: BWDB (1998a); Choudhury (1998); FAO/WFP (1998); GOB (1998: 41); IDNDR (1998); ReliefWeb (1998); World Bank (1998); FAO (1999); Jegillos and Mearns (1999); FAO (2000b).
9. Literature sources for the 1923 dry year: *The Englishman* (1923: 9 Jun, 16 Jun, 3 Jul, 4 Aug, 21 Aug, 23 Aug, 29 Aug, 4 Sep, 18 Sep, 22 Sep, 26 Sep); *The Statesman* (1923: 7 Jun, 14 Jun, 21 Jun, 28 Jun, 19 Jul, 9 Aug, 23 Aug, 30 Aug, 6 Sep, 20 Sep, 27 Sep, 4 Oct).
10. Literature sources for the 1978 dry year: Winkelmann (1979); Chattopadhyay (1980); Gosh et al. (1982); Ramaswamy (1987); USAID (1990); Choudhury (1993); Kuster (1995).

5A
Case-study appendices

Appendix 5.1: 1906 – A "flood year"

The contents of this case study are based on investigations made by project team member Robeen Dutt (Dutt 1995). The summary of this case study is presented in section 5.4 (pp. 150–154).

The 1906 flood situation at a glance

Flood dimension and intensity

The flood of 1906 was the most catastrophic event in the period 1890–1909, even though the territory of modern Bangladesh was only slightly or moderately affected by the floods. The map in Figure 5A.1, which is based on administrative (district) boundaries, depicts not the actually flood-affected areas but those districts that were affected to varying degrees by the floods. These districts are obviously not identical with the subcatchments for which the data on R(pot) and R(relev) have been calculated and are discussed in the next section. The relationship between the districts and the subcatchments can be elaborated by comparing Figure 5A.1 with Figure 5.1. The same note applies to the 1910 case study (Appendix 5.2) and the 1922 case study (Appendix 5.3). Based on Figure 5A.1, three distinct flooding patterns can be identified: (a) floods, some of them categorized as severe or even catastrophic, in or directly to the south of the Himalayan ranges (districts 1, 2, 3, 4, 7, 8, 9, 10, 11 and 12, which represent parts of subcatchments 4, 5, 3, 8 and 10); (b) floods along

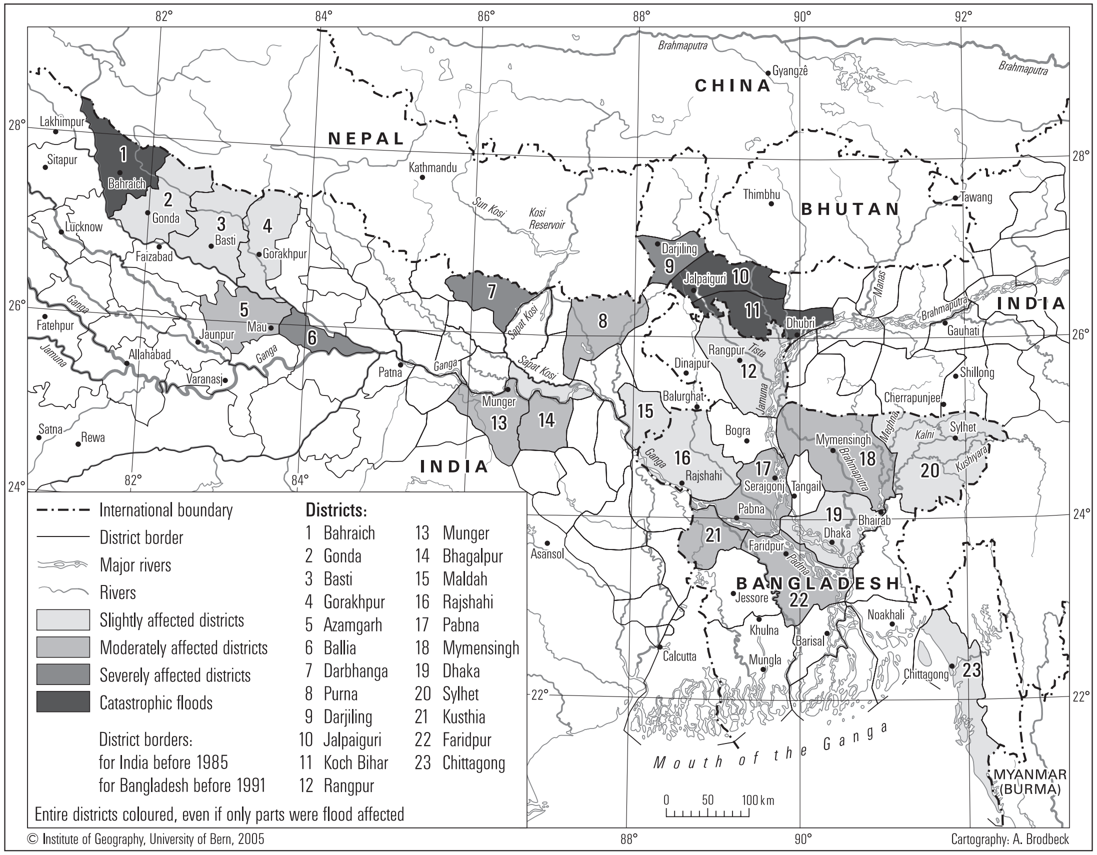


Figure 5A.1 Flood-affected areas and flood intensities: 1906.

the Ganga in India and in the confluence region of the Ganga and Brahmaputra in the territory of modern Bangladesh (districts 5, 6, 13, 14, 15, 16, 17, 21 and 22, which represent parts of subcatchments 5, 10, 6 and 13); (c) floods in central and eastern Bangladesh (districts 18, 19 and 20, which represent parts of subcatchments 11 and 12). It is interesting to note that there was no continuous flood from the Himalayan foothills down to Bangladesh; rather, the floods occurred in isolated patches.

Chronology of the flood (Table 5A.1)

Based on the available literature sources it is difficult to identify the exact timing of the floods, and therefore the chronology of events presented in Table 5A.1 must be considered as an approximation. In general, the floods occurred from early August to early September. They were most widespread during the second half of August, with maximum duration in the area of modern Bangladesh. Flooding in districts 9, 10, 11 and 12 in early August must be considered a separate event.

Reported damage

- disruption of railway lines (districts 7, 9, 20, 22);
- bridge collapse (district 7);
- loss of human life and cattle (district 1);
- crop damage (districts 5, 6, 15, 16, 17, 18, 21, 22).

Causes of the flooding as discussed in the literature

- Himalayan rivers;
- simultaneous high river levels of the Kosi and the Ganga;
- high water level of the Brahmaputra;
- simultaneous peaks of the Ganga and the Brahmaputra in the areas near their confluence and heavy local rainfall in Pabna district;
- heavy rainfall in Mymensingh district.

Literature sources

The Englishman (1906: 24 Aug, 25 Aug, 4 Sep, 12 Sep); *The Pioneer Mail* (1906: 24 Aug); *District Gazetteer* (Purnea 1911, Dhaka 1912); Mahalanobis (1927).

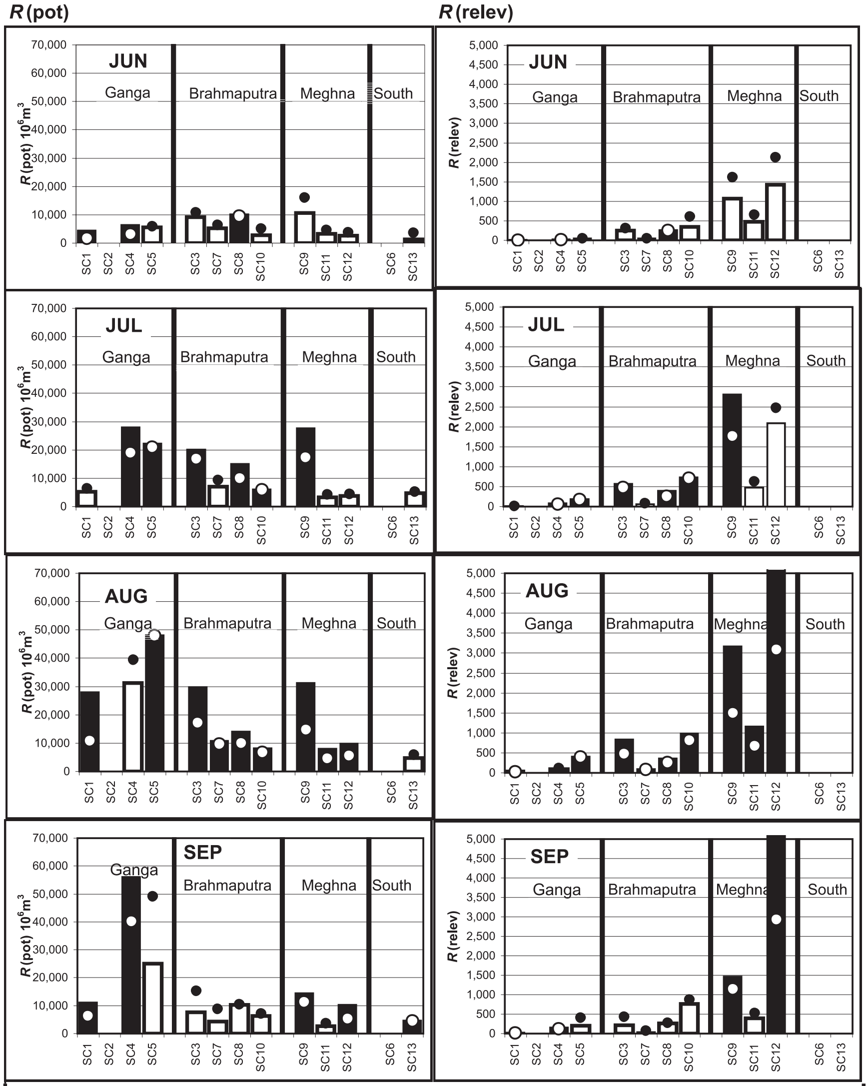
Hydrological contributions from the different subcatchments and their relevance to the flooding conditions in Bangladesh (Figure 5A.2, Figure 5.1)

The raw data for these investigations are the calculations of the potential runoff (R(pot)) and the relevance factor (R(relev)). The definition of these two variables and the methodological background are presented

Table 5A.1 The floods in 1906: Affected districts and chronology

Affected areas	August				September			
Districts 9, 10, 11, northern parts of 12 (areas of SC3, SC8, SC10)	■							
Districts 7, 8, 13, 14 (areas of SC5)			■	■				
Districts 1, 2, 3, 4, 5, 6 (areas of SC4, SC5)			■	■				
Districts 15, 16, 17, 21, 22 (areas of SC13, SC10, SC5)			■	■	■			
Districts 18, 19, 20 (areas of SC12, SC13)			■	■	■			

Notes: shaded area = flood period. For the location of the districts, see Figure 5A.1; for the location of the subcatchments, see Figure 5.1.



LEGEND:

X-axis:	**subcatchments, grouped according to the main river basins and the southern areas**
Dots (black and white):	**average, 1891–1950**
White columns:	**below-average values in 1906**
Black columns:	**above-average values in 1906**
Missing data for:	**SC2, SC6**

Figure 5A.2 Monthly potential runoff (R(pot)) and relevance for Bangladesh (R(relev)) in the 13 subcatchments for the four monsoon months of 1906.

Notes: R(relev) has no measuring unit. For the location of the subcatchments, see Figure 5.1; for the data sources, see Table 3.2.

in section 5.1. The graphs on the left side in Figure 5A.2 illustrate the patterns of *R*(pot) for the four monsoon months June–September; the graphs on the right side show the patterns of *R*(relev) for the same time periods. The data for 1906 are plotted as columns against the respective average values, which are presented as black dots. The data are presented for each subcatchment along the *x*-axis, grouped into the three main river basins (Ganga catchment: SC1, SC2, SC4, SC5; Brahmaputra catchment: SC3, SC7, SC8, SC10; Meghna catchment: SC9, SC11, SC12) and, only for potential runoff, the southern areas (SC6, SC13). The calculations of *R*(pot) and *R*(relev) for winter and for the pre-monsoon period are not illustrated in the graphs, but only commented on in the text. The graphical presentation of the patterns of *R*(pot) and *R*(relev) in Figure 5A.2 will be identical in the case studies for 1910, 1922, 1923, 1955, 1974, 1978, 1987 and 1988. This explanatory text will therefore not be provided in the discussion of these other case studies.

In August, the main flooding period, *R*(pot) was above average in 9 of 11 documented subcatchments, which provides a reasonable overall explanation for the widespread flood processes in the basin. In particular, above-average *R*(pot) in all the subcatchments of Bangladesh (with the exception of Southern Bangladesh, SC13) indicates that hydrometeorological processes within Bangladesh itself contributed significantly to the widespread flooding during August.

To some extent, the August floods were pre-conditioned by the above-average values of *R*(pot) in a number of subcatchments in July. According to the written sources, the effect of these positive anomalies on soil saturation was particularly important in the districts of northern Bengal (parts of SC3, SC8 and SC10), where flooding occurred in early August (see also Table 5A.1).

In the Himalayan subcatchments, the anomalies of *R*(pot) in August are particularly high: the potential runoff reaches almost three times the average values in the North-western Himalayas (SC1), and almost twice the average values in the Darjiling–Bhutan Himalayas (SC3). However, in terms of relevance to the floods in Bangladesh, only the anomaly of SC3 is of some importance. SC1 is a very long way from the floodplains in Bangladesh and accordingly the significant positive anomaly of *R*(pot) does not have any measurable effect on the *R*(relev) of that particular subcatchment. The flooding early August in the districts located immediately to the south of the Himalayan ranges (particularly districts 10 and 11 in Figure 5A.1) can be easily explained by the significantly positive variation of *R*(pot) in SC3 in August and provides an interesting example of a highland–lowland linkage: obviously these floods did not move southwards and thus were not connected with the widespread inundations in Bangladesh, which occurred significantly later in the month

(Table 5A.1). Mahalanobis (1927: 74) states: "it is again important to notice that the extremely severe flood [see Figure 5A.1] in the districts of Darjiling (district 9), Jalpaiguri (district 10), Cooch Behar (district 11) and portions of Rangpur (district 12) did not apparently cause any appreciable flooding in the districts lying immediately to the south."

In the Meghalaya Hills (SC9), the anomalies of *R*(pot) and, very prominently, of *R*(relev) were positive throughout July, August and September. In July and August, *R*(pot) in the Meghalaya Hills and *R*(pot) on the Upper Ganga Plain (SC4) were almost identical, although the area of SC9 is 17 times smaller than that of SC4. This sheds light on the high concentration of precipitation in the Meghalaya Hills and the amount of water that was potentially discharged into the floodplains of the Meghna in Bangladesh. The situation was aggravated by high *R*(pot) and the resulting high *R*(relev) in the floodplains of North-eastern Bangladesh (SC11) and Central–Eastern Bangladesh (SC12). The Meghalaya Hills were obviously a key area contributing to the floods in Bangladesh, at least to the inundations in the eastern part of the country.

Compared with the other subcatchments, the situation was unspectacular on both the Upper and Lower Ganga Plains (SC4, SC5) in August: the almost negligible positive anomaly of *R*(pot) in SC5 is meaningless in terms of *R*(relev). The floods in the Ganga area (districts 6, 13, 14; see Figure 5A.1) cannot be explained using the *R*(pot) records. It must be assumed that the significant hydrological input from the Himalayan areas raised the base flow of the Ganga so that the river overflowed its banks over certain stretches.

According to the relevant calculations, *R*(pot) was below average across most of the subcatchments during the pre-monsoon period (April–May). In winter (January–March), however, *R*(pot) was above average in 9 of 11 subcatchments. In the North-western Himalayas (SC1) the anomaly was particularly high: it must be assumed that a significant portion of this above-average precipitation occurred as snow at higher elevations and that the resulting *R*(pot) was not immediately contributed to the system. Although it is doubtful that the widespread positive anomaly in winter had any direct effect on the flooding processes in August (e.g. through increased soil moisture and higher groundwater tables), there is a strong probability that, at the onset of the monsoon, the rivers were flowing at above-average levels owing to unusually high snow melt in the Himalayas.

This is the first case study for which the two newly introduced parameters, *R*(pot) and *R*(relev), have been used. The experiences are positive: applied to a specific case study, the two variables are useful tools for quantifying the hydrological contribution from different subcatchments, for identifying areas of important anomalies and for obtaining indications of the areas most relevant to the flood processes in Bangladesh. As is to be expected from the definition of the two variables, positive anomalies of *R*(pot) in an area located in or near Bangladesh significantly raise the *R*(relev) of that subcatchment, whereas the effect of a similar positive anomaly of *R*(pot) on *R*(relev) in a subcatchment located far away from Bangladesh can be almost ignored.

Daily rainfall (Figure 5A.3)

The matrix that was developed for the illustration and analysis of the daily rainfall patterns displays on its *x*-axis a daily subdivision of the four monsoon months June to September and on its *y*-axis the stations for which daily rainfall data were available. The matrix provides information about rainfall intensities, grouped into four categories (see the legend). For the classification of rainfall intensities into the different categories, return periods of daily rainfall and potential evapotranspiration (pET) were considered:

- For each station, the threshold values of daily rainfall for a return period of two and five years were calculated (Table 5A.2) by applying the double exponential function after Gumbel (Ginsburg 1971). For each station, the calculation is based on data series of the highest daily rainfall per year. The period of calculation for each threshold value is 40 years: 1891–1930 for the case studies before 1950; 1950–1990 for the case studies after 1950. The years 1931–1949 were excluded from this calculation since there were no major floods in this period (Figure 4.6).
- Days with only a few millimetres of precipitation do not contribute to the hydrological system because the rainwater is potentially evaporated. For each station, average daily pET was calculated based on monthly information published by FAO (1987). These daily pET figures range between 3 mm and 6 mm depending on the location of the stations. Days with rainfall equal to or less than pET were put into the category of rainless days.

The matrix presented in Figure 5A.3 has proved to be a very effective way to illustrate daily rainfall patterns graphically: it not only allows identification of high-intensity rainfall areas, but also the depiction of rainfall periods that affected significant parts of the study area. The horizontal bar at the bottom of the matrix allows a direct link to be established between rainfall and flood periods. The matrix developed for the presentation and discussion of the daily rainfall patterns is in all case studies identical to Figure 5A.3. This explanatory text will therefore not be provided in the discussion of the other case studies.

Three rainfall periods can be identified in Figure 5A.3:

- 9–16 July: rainfall was widespread. In Lucknow, rainfall with a return period of two to five years was measured on two consecutive days. Over these eight days, the rainfall in Cherrapunjee totalled 2,740 mm,

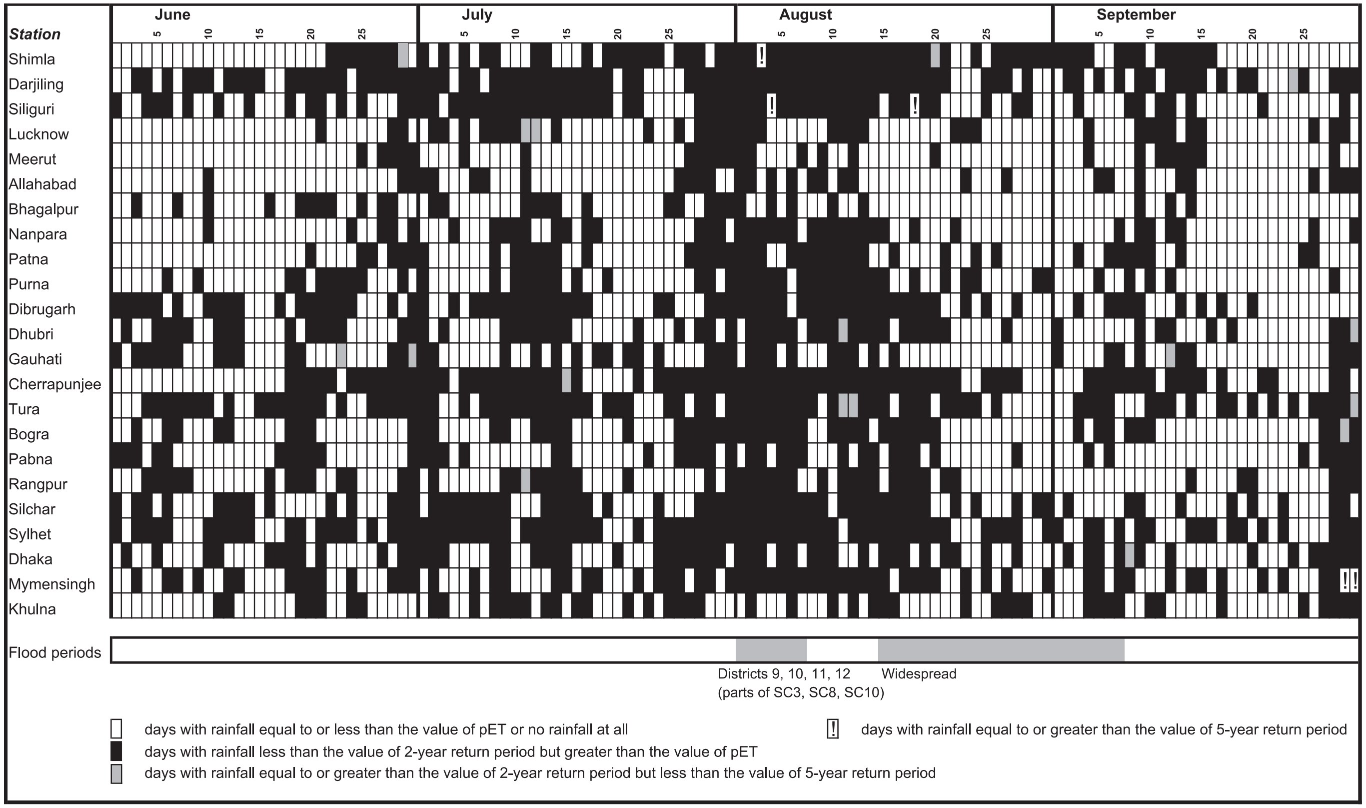


Figure 5A.3 Categories of daily rainfall for the period 1 June–30 September 1906.

Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2; for threshold values for the return periods, see Table 5A.2.

Table 5A.2 Threshold values of daily rainfall for return periods of two and five years at selected stations

	Threshold values (mm)			
	Return period: Two years		Return period: Five years	
Station	Period of calculation, 1891–1930[a]	Period of calculation, 1950–1990[b]	Period of calculation, 1891–1930[a]	Period of calculation, 1950–1990[b]
Shimla	95		141	
Darjiling	165		237	
Siliguri	178		217	
Meerut	102		151	
Lucknow	103		137	
Allahabad	111		169	
Nanpara	123		169	
Patna	123		186	
Bhagalpur	92		132	
Purna	117		165	
Dibrugarh	114		166	
Gauhati	86		110	
Dhubri	164		230	
Cherrapunjee	475		645	
Tura	164		212	
Kaunia		172		228
Rangpur	138	151	192	211
Dinajpur		148		207
Dewanganj		162		238
Bogra	116	122	169	175
Serajgonj		141		206
Rajshahi		121		180
Ishurdi		121		188
Durgapur		195		263
Sunamgonj		247		304
Sylhet	186	212	241	307
Sheola		197		264
Mymensingh	137	145	192	214
Kishorgonj		139		196
Hobigonj		141		183
Srimongal		139		202
Bhairab Bazar		136		191
Comilla		156		256
Dhaka	114	135	166	187
Faridpur		136		201
Jessore		120		180
Khulna	112	128	160	200
Barisal		139		191

Notes:
[a] for case studies before 1950.
[b] for case studies after 1950.

which is more than the average precipitation for the entire month of July at this site. No records on flooding can be found in the literature for this period. It can be assumed, though, that the widespread and in some cases heavy rains increased soil humidity and raised the groundwater table, leading to reduced water absorption and retention capacity of the ground for rainwater occurring in the follow-up to this particular rainfall period.

- 27 July–20 August: throughout this period rainfall was recorded almost constantly at most stations. The rains were particularly intense in the Himalayas and adjacent lowlands, in the Meghalaya Hills and in Bangladesh, and significantly less so in the Ganga Plain. As documented by the stations of Darjiling and Siliguri, the floods in northern Bengal (parts of SC3, SC8 and SC10) in the first week of August coincided with heavy and constant rainfall in the area. However, the maximum dimension of the floods was reached in the second part of August (''widespread'' in Figure 5A.3), when the rains had temporarily stopped at most of the stations.
- 28–30 September: the rainfall during this period was concentrated in Assam, the Meghalaya Hills and Bangladesh. The intensity of rainfall at some stations is remarkable. However, no records of floods have been found in the literature for this period.

The daily rainfall recorded at the two Himalayan stations (Shimla and Darjiling) is remarkable. There were only a few days without precipitation. On some dates the amount of rainfall reached return periods of two to five years, or even more. In line with statements made above, the hydrological contribution from the Himalayas was potentially a key factor in the development of the floods in the areas to the south of the mountain ranges. However, a detailed investigation of the situation in the Darjiling Himalayas (station of Darjiling) and adjacent lowlands (station of Siliguri) reveals some interesting features:

- The total precipitation in the second rainfall period (27 July–20 August) amounted to 1,600 mm in Siliguri (a lowland station) and only 1,181 mm in Darjiling (a highland station).
- On 4 August and on 18 August, 287 mm and 229 mm of rainfall, respectively, were recorded in Siliguri (both events with a return period greater than five years) as compared with only 24 mm and 68 mm, respectively, measured in Darjiling.
- Further to the south, in Tura and Dhubri, very high daily rainfall occurred on some dates as well.

These observations indicate that significantly more rainfall was recorded in the lowlands to the south of the Darjiling Himalayas than in the mountains themselves.

In Cherrapunjee, rain fell on roughly 75 per cent of the days from June to September. The longest non-stop rainfall period began on 24 July and lasted all the way through to 22 August. The total rainfall from July to August amounted to 7,449 mm, compared with an average of 4,424 mm for these two months.

Daily water level (Figure 5A.4)

The graphs of the daily water level in Figure 5A.4 can be directly related to the flood periods (black lines) as well as to the most important rainfall periods (grey bars). The water level at all three stations reacted to some extent to the first rainfall period (9–16 July). As a result of the second rainfall period (27 July–20 August), the water levels rose and reached unusual values, reaching the highest levels for the period 1892–1929 in Gauhati, slightly below the highest level in Munger and the third-highest level in Goalundo. The highest water levels of the three rivers temporally coincided with the period of widespread flooding in the second half of August. Of particular interest is the fact that the highest water levels of the Ganga at Munger and the Brahmaputra at Gauhati were reached more or less on the same day. Assuming a comparable speed of downstream movement, these high flows might have reached the confluence more or less at the same time, which would certainly have contributed significantly to the widespread flooding.

Possibly as a result of the high flow of the Himalayan tributaries as well as the widespread rains, the Ganga reached a secondary peak in the last few days of July and the first few days of August. The sharp rise in the Ganga water level after 10 September is the result of a moderate rainfall period in the Ganga basin from 9 to 15 September (see Figure 5A.3). That this peak reached levels comparable to the main flood period of August is astonishing. This peak of the Ganga in mid-September did not trigger any flood processes in Bangladesh, possibly because the level of the Brahmaputra had already receded significantly by that time.

The characteristics of the graph for the Padma at Goalundo, which is a huge water body located below the confluence of the Ganga and Brahmaputra, are very illustrative: the fluctuations of the Ganga and Brahmaputra are reflected in Goalundo as well, but here they are smoother and their range is smaller. The reaction to rainfall periods is only weak, sluggish and more long term.

Summary

In 1906, floods were widespread in the areas located immediately to the south of the Himalayan ranges, particularly in the forelands of the Darjiling and western Bhutan Himalayas, as well as in the territory of modern

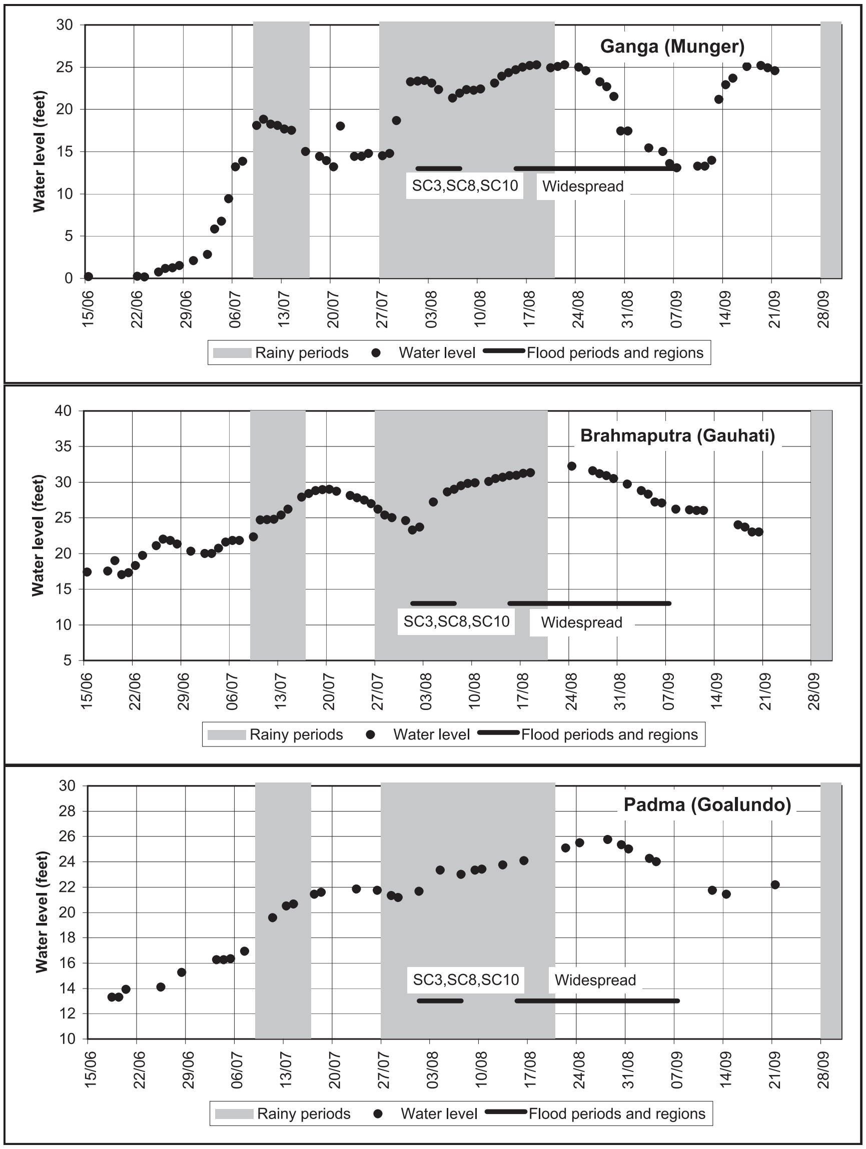


Figure 5A.4 Daily water level of selected rivers for the period 15 June–30 September 1906, compared with flood and rainy periods.

Notes: For the location of the stations, see Figure 5A.1; Goalundo is located immediately after the confluence of the Ganga and the Brahmaputra/Jamuna. The water level data are from *The Englishman* (1906).

Bangladesh. Heavy and continuous rainfall in most parts of the basin resulting in widespread above-average *R*(pot) can be seen as the basic cause of the flood events. The Himalayan ranges are important as an orographic barrier that triggers rainfall. The comparison of the rainfall figures for Darjiling (a highland station) and Siliguri (a lowland statin) has shown that the foothills and the first ranges are mainly responsible for this effect. Higher up and further into the Himalayas, rainfall seems to decrease. This indicates that inappropriate land-use practices or forest cutting in the higher Himalayas or the interior parts of the ranges might have a smaller effect on flooding in the forelands of the Himalayas than similar processes in the foothills and the first Himalayan ranges. In addition to the contribution from the foothills and the first Himalayan ranges, it seems that the rains over the flood-affected areas in the forelands themselves were equally or even more decisive for the flood processes.

The flood waves occurring to the south of the Himalayan ranges obviously did not rush downstream with increasing intensity: they were not linked to the flood processes in Bangladesh geographically or, in the case of the floods in the forelands of the Darjiling and Bhutan Himalayas, even temporally. These findings imply that the highland–lowland interaction between the Himalayas and Bangladesh was of only an indirect nature. The likely flood flows of the tributaries, which drained the flood-affected areas in the Himalayan forelands, were incorporated into the base flow of the Ganga and Brahmaputra. These two rivers then reached their highest flow of the year simultaneously while flowing through Bangladesh. Together with other factors such as heavy rainfall in Bangladesh itself and extraordinary input from the Meghalaya Hills (where the highland–lowland linkages are direct), this led to a gradual spreading out of flood waters in Bangladesh.

Factors that were important for the floods to the south of the Himalayan ranges (particularly the forelands of the Darjiling and western Bhutan Himalayas):

- heavy rainfall in the first Himalayan ranges;
- high water levels of the Himalayan rivers;
- heavy rainfall over the flood-affected areas themselves in August;
- early monsoon rains in July leading to rising soil humidity and groundwater levels.

Factors that were important for the floods in Bangladesh:

- temporal synchronization of the highest flow of the Ganga and the Brahmaputra in 1906;
- widespread rainfall in August in the basin, particularly over Bangladesh and the Meghalaya Hills;
- early monsoon rains in July.

Factors that were not important for the floods in Bangladesh:
- input originating in the Ganga lowlands;
- input originating in Upper Assam;
- the pre-monsoon period.

Appendix 5.2: 1910 – A "flood year"

The contents of this case study are based on investigations made by project team member Roland Guntersweiler (Guntersweiler 1995). The summary of this case study is presented in section 5.5 (pp. 154–159).

The 1910 flood situation at a glance

Flood dimension and intensity (Figure 5A.5)

The flood of 1910 was not an extraordinary event but again proved to be a very interesting case in the context of highland–lowland linkages. There were basically four distinct flood-affected areas:
- districts 4, 5 and 6, located in the lower part of the Ganga Plain in India (part of SC5); reported damage: devastation of paddy crops, disruption of numerous railway lines;
- districts 1, 2 and 3, located directly to the south of the Himalayan ranges (mainly SC3 and SC8); reported damage: disruption of railway lines between Calcutta and Gauhati, some loss of life, damage to tea estates and to jute crops;
- districts 7 and 8, located in the north-western part of modern Bangladesh (mainly SC10); reported damage: several bridges of the Eastern Bengal State Railway near the station of Bogra, destruction of houses;
- district 9, located in the north-eastern part of modern Bangladesh (SC11 and SC12); no damage reported.

Similar to the situation in 1906, there was no continuous flooding from the Himalayan foothills or from the Indian floodplains down to Bangladesh; rather the floods occurred in isolated patches. Another interesting feature is that the floods in north-western Bangladesh are rated only as "slight", whereas those higher up are rated as "moderate" or even "severe".

Chronology of the flood

The available sources do not provide a clear and differentiated picture of the flood chronology. Therefore the following specifications need to be considered as approximations. The floods in districts 4 and 5 seem to have occurred throughout July and well into August. The inundations in districts 1, 2 and 3 developed in July and reached their maximum ex-

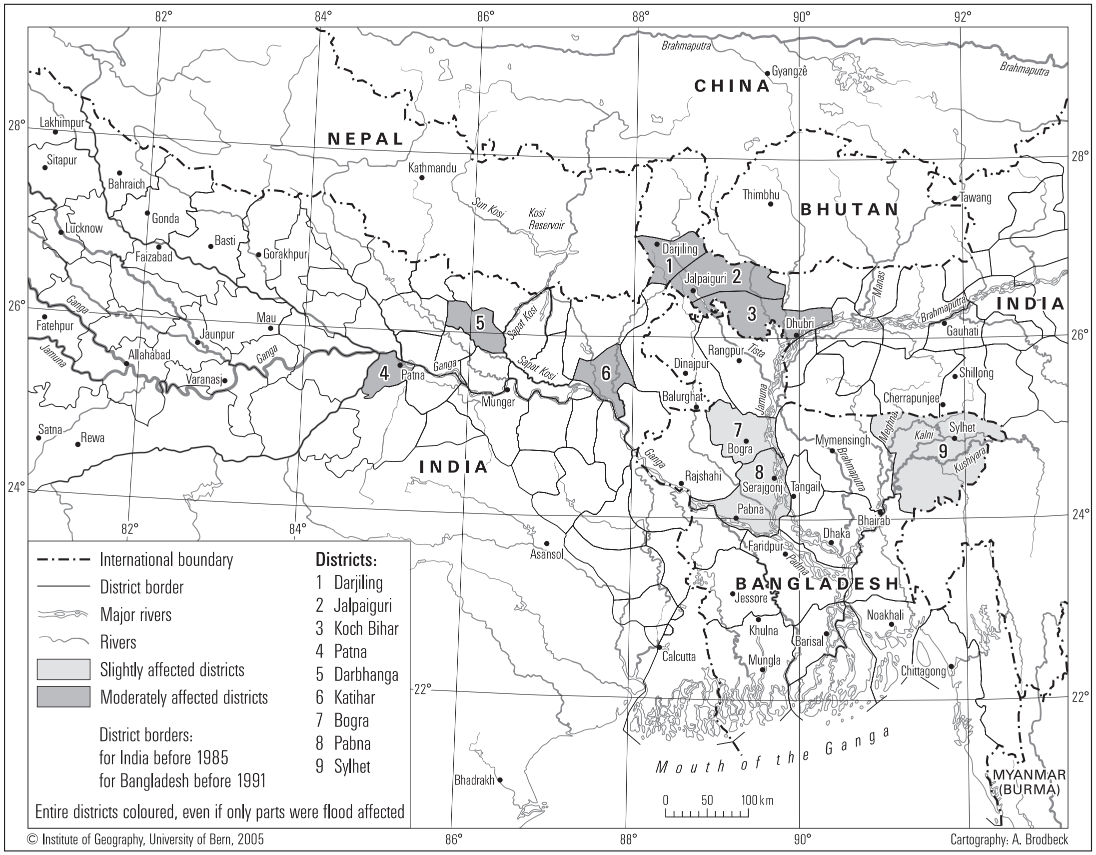
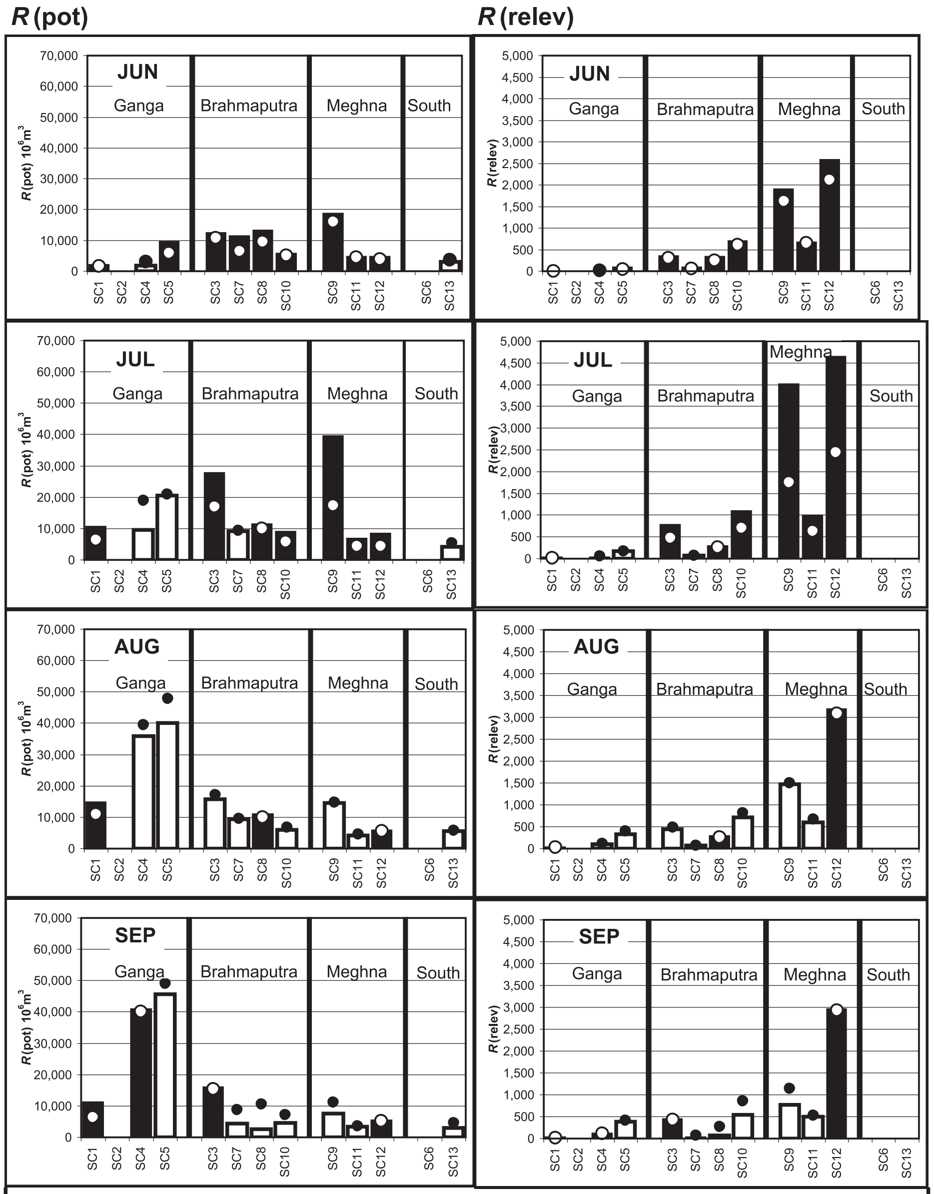


Figure 5A.5 Flood-affected areas and flood intensities: 1910.



LEGEND:	
***X*-axis:**	**subcatchments, grouped according to the main river basins and the southern areas**
Dots (black, white)	**average, 1891–1950**
White columns	**below-average values in 1910**
Black columns	**above-average values in 1910**
Missing data for	**SC2, SC6**

tent most probably around the middle of the same month. The floods within modern Bangladesh (districts 7, 8 and 9) occurred towards the end of July and extended into August. Based on these very rough indications, it seems that the floods were most widespread in the last part of July.

Causes of the floods as discussed in the literature

Heavy local rainfall is explicitly mentioned for all affected areas except north-eastern Bangladesh. Additional important factors include, in the case of the floods in districts 2 and 3, discharge from the Himalayas and, in the case of the floods in districts 7 and 8, an abnormally high level of the Brahmaputra.

Literature sources

Amrita Bazar Patrika (1910: 15 Jul, 19 Jul, 31 Jul, 11 Aug); *Eastern Bengal and Assam Era* (1910: 23 Jul, 3 Aug); *The Englishman* (1910: 14 Jul, 26 Jul, 28 Jul, 30 Jul, 1 Aug, 12 Aug); *The Statesman* (1910: 4 Aug); Mahalanobis (1927).

Hydrological contributions from the different subcatchments and their relevance to the flooding conditions in Bangladesh (Figure 5A.6, Figure 5.1)

In SC3, SC8, SC9, SC10, SC11 and SC12, *R*(pot) was above average in June as well as in July. The flooding in these areas occurred in July as well as in early August. The high input during June was obviously important for the gradual saturation of the soils; the floods, however, were triggered by the rains in July. In July, the above-average *R*(pot) results in some significant anomalies in *R*(relev). The above-average *R*(pot) in the Darjiling–Bhutan Himalayas in July was obviously an important factor in the development of the floods in the Himalayan foothills.

With more than double the volume of *R*(pot) compared with the average, the most outstanding anomaly in July was recorded in the Meghalaya Hills (SC9). The monthly precipitation in Cherrapunjee amounted to 5,547 mm, compared with an average value of 2,628 mm. Accordingly, the Meghalaya Hills have a very high relevance for the hydrological processes in Bangladesh at this time.

Throughout the monsoon season, significantly negative anomalies of

◄

Figure 5A.6 Monthly potential runoff (*R*(pot)) and relevance for Bangladesh (*R*(relev)) in the 13 subcatchments for the four monsoon months of 1910.
Notes: *R*(relev) has no measuring unit. For the location of the subcatchments, see Figure 5.1; for the data sources, see Table 3.2.

R(pot) dominated the Ganga Plain (SC4 and SC5). Thus the hydrological contribution to the flooding does not seem to have been important, at least from the lowlands of the Ganga catchment. Based on these monthly figures, the floods in districts 4, 5 and 6 (see Figure 5A.5) cannot be explained. In part these might have been the result of localized rains, in part the result of an onrush of water from districts in the hilly zones of the Himalayas.

R(pot) in the North-western Himalayas (SC1) was above average throughout the four monsoon months. In terms of relevance to the hydrology in Bangladesh, these positive anomalies are meaningless: SC1 is too far away to have a real impact on flooding in Bangladesh even with significant positive variations of *R*(pot). It is, however, not known whether these positive variations triggered flood processes in the foothills immediately adjacent to the North-western Himalayas.

According to the relevant calculations, *R*(pot) was far above average in a number of subcatchments during the winter (January–March). The anomaly was particularly important in the Meghalaya Hills (SC9). In the pre-monsoon period (April–May), however, most of the anomalies were negative. Thus it is doubtful if the hydro-meteorological processes in the first part of 1910 played any important role in pre-conditioning the flooding during the monsoon season.

Daily rainfall (Figure 5A.7)

Three rainfall periods can be identified during which, except for the Ganga Plain, rainfall was widespread and in certain cases intensive:

- 9–23 June: at a number of stations rainfall was almost constant. In Nanpara, Purna and Dhubri, there was one day of moderate or even high-intensity rainfall. No records on flooding are found in the literature for June. However, it can be assumed that the widespread rains increased soil humidity and raised the groundwater table, leading to reduced water absorption and retention capacity of the ground.
- 10–29 July: this extended rainfall period was recorded across almost the entire study area. A number of rainfall events with a return period of two to five years or above occurred. In Siliguri and Cherrapunjee alone, three medium to very rare events were recorded. As far as can be determined from the literature sources, this second rainfall phase coincided with the period of the most widespread flooding.
- 12–19 August: with only a few exceptions, this third phase is documented at every raingauge station. However, all the values remain below the two-year return period. Since the exact timing of the recession of the flood waters is not known, it is difficult to assess the effect of this third rainfall period on the flood processes.

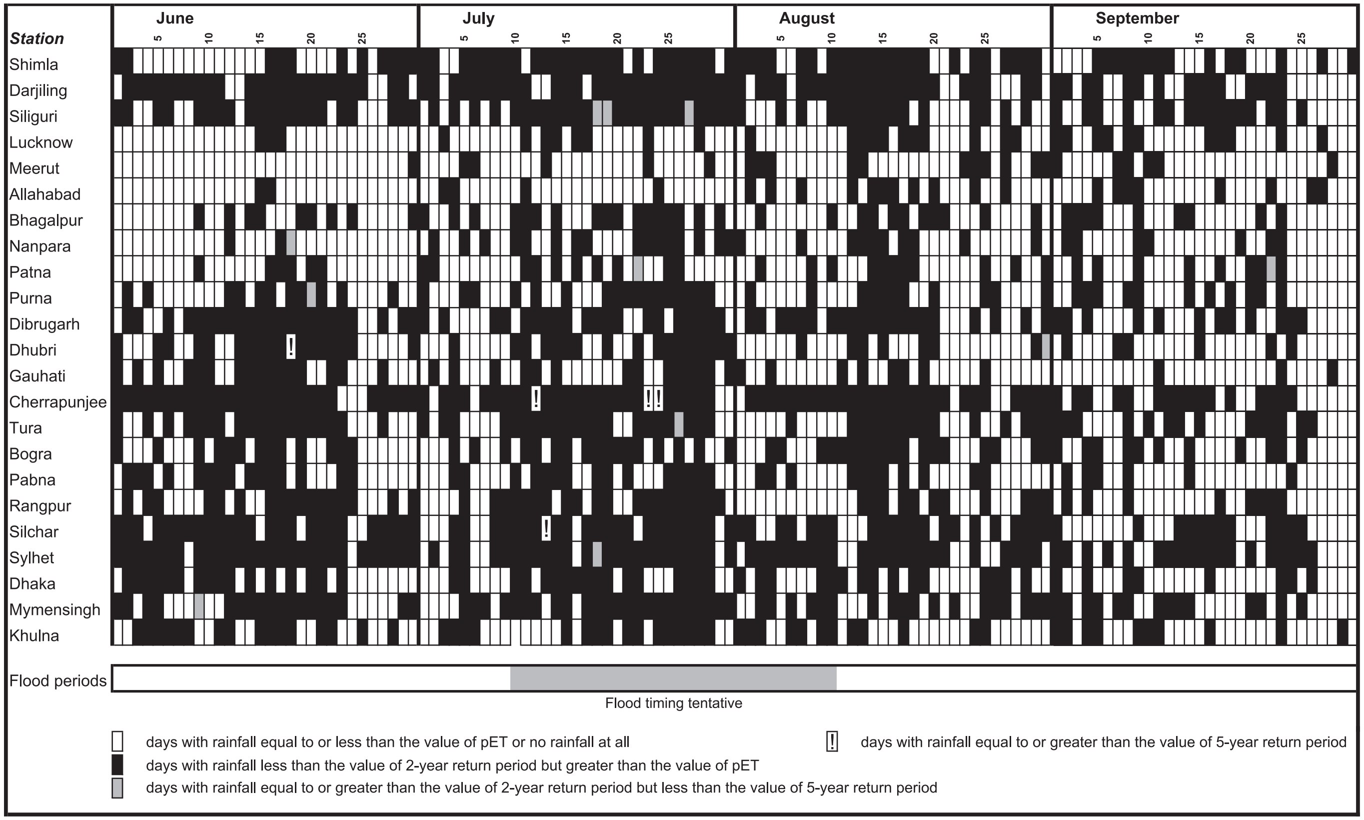


Figure 5A.7 Categories of daily rainfall for the period 1 June–30 September 1910.
Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2; for threshold values for the return periods, see Table 5A.2.

Again, a comparison of the hill station of Darjiling with the lowland station of Siliguri is interesting. It is obvious that the number of rainy days in Darjiling clearly exceeded the number of rainy days in Siliguri. However, as documented in the following examples, the situation looks different in terms of rainfall amount:

- The total rainfall in July amounted to 1,597 mm in Siliguri but only 1,054 mm in Darjiling.
- The rainfall for 18 July and 19 July totalled 372 mm in Siliguri but only 88 mm in Darjiling.
- The rainfall for 26 July and 27 July totalled 346 mm in Siliguri but only 178 mm in Darjiling.

According to the information presented in the first section of this Appendix, July was the main flood period in districts 1, 2 and 3, with a peak around the middle of the month. The rainfall figures above show that, during the critical flood period, the rainfall over the flood-affected areas themselves was massive, in terms of both intensity and amount. There was some precipitation in the Darjiling Himalayas, but this contribution to the flooding in the foothills was certainly much less important than the input from the rains over the floodplains themselves.

The situation in Cherrapunjee warrants special discussion: rainfall was recorded on almost 80 per cent of the days. In July, three daily rainfall records show a return period of five or more years. This is extraordinary for a station where the rainfall intensity is already very high under normal conditions. Close to 1,000 mm of rainfall was recorded on a single day: 12 July. The total precipitation from 20 July to 27 July reached 2,489 mm, which almost corresponds to the monthly average for July. With these figures, the amount of water that must have poured down from the Meghalaya Hills onto the floodplains of north-eastern Bangladesh (SC11) can be imagined.

At some stations in the Ganga Plain (Lucknow, Allahabad and Meerut), there were very few rainy days. In Allahabad, for example, total precipitation over the four monsoon months reached only 606 mm, compared with an average of 855 mm. This finding corresponds to the conclusions drawn from Figure 5A.6.

Daily water level (Figure 5A.8)

The water level graphs of the Brahmaputra at Gauhati in Assam and the Padma at Goalundo, located below the confluence of the Brahmaputra and the Ganga, document a similar structure: both rivers responded to the extended rainfall period in the second half of July, and their highest water level of the year was reached during the main flood phase. The water level temporally receded in mid-August, but for both rivers a

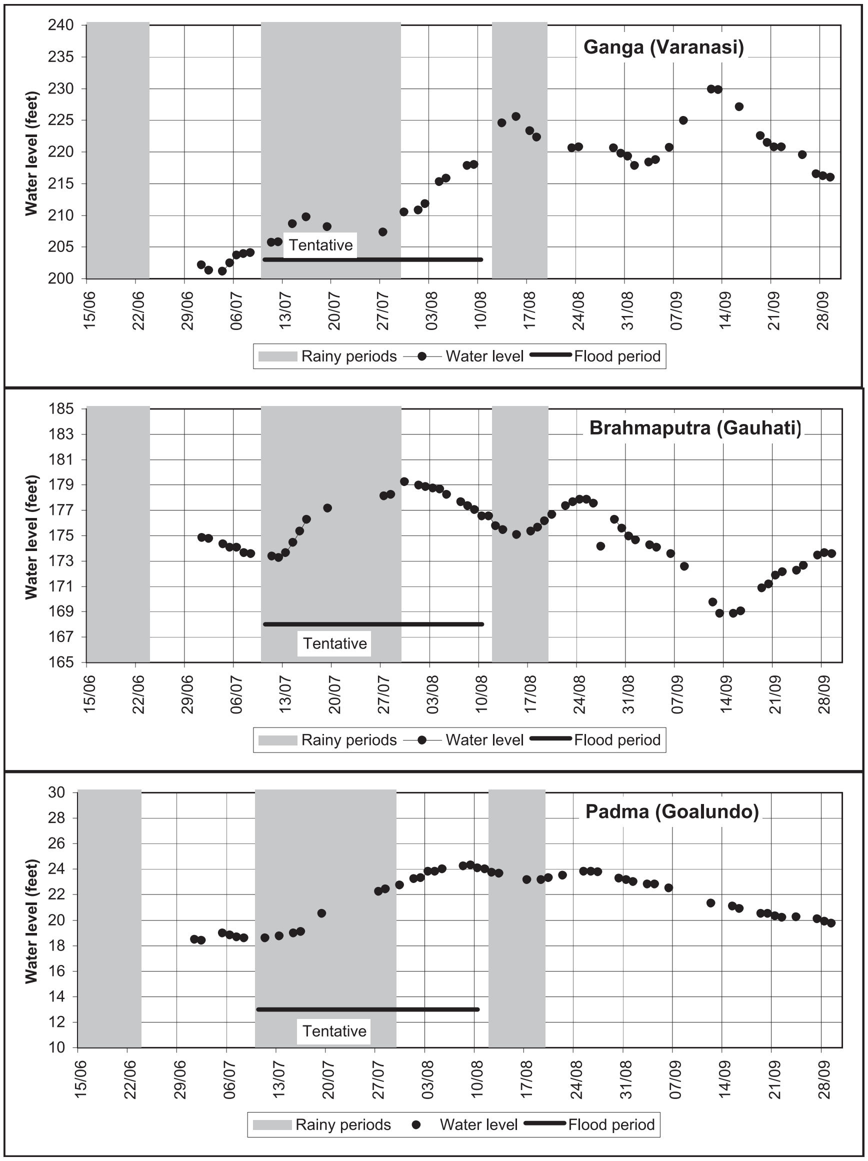


Figure 5A.8 Daily water level of selected rivers for the period 15 June–30 September 1910, compared with flood and rainy periods.
Notes: For the location of the stations, see Figure 5A.5; Varanasi is located between Allahabad and Patna; Goalundo is located immediately after the confluence of the Ganga and the Brahmaputra/Jamuna. The water level data are from *The Englishman* (1910).

second period of high flow was recorded towards the end of the month, which can be interpreted as a delayed reaction to the third rainfall period. Whereas the water level of the Brahmaputra rapidly dropped at the end of August and during the first part of September, the level of the Padma remained high until the end of August and then gradually decreased. According to the written sources, the water level of the Brahmaputra at Gauhati on 30 July was the highest for the period 1891–1930. This confirms the literature statement that the floods in the Serajgonj area were in part related to the abnormally high water level of the Brahmaputra.

The graph of the Ganga at Varanasi has a different structure. The water level remained rather low during both the most extended main rainfall phase in July and the flood period in the different affected areas. It reached a first maximum in mid-August; at that time, most of the flooding was probably already over. Mid-August, however, was the time of the third rainfall period during which, in fact, the rainfall stations in the Ganga lowland recorded the most continuous rains of the entire monsoon season. The highest water level of the year of the Ganga was reached in mid-September, when there was only scarce rain in the entire study area. Overall, the patterns of the hydrograph of the Ganga are difficult to relate to the prevailing rainfall conditions. It can be stated that the inflow from the Ganga into Bangladesh during the main flooding period was certainly below average.

Summary

Compared with the other case studies, the flood of 1910 was certainly not an extraordinary event. It is, however, a very interesting example in terms of highland–lowland linkages and has some similarities to the floods in 1906. A very important factor seems to have been the above-average potential runoff during June and July in a large and connected area comprising the subcatchments of the Darjiling–Bhutan Himalayas, Lower Assam, the eastern part of the Lower Ganga Plain, North-western Bangladesh, North-eastern Bangladesh and the Meghalaya Hills. Most probably this situation led to a gradual accumulation of water in the soil as well as to rising groundwater levels. High-intensity rains over the flood-affected areas themselves are another important element in understanding the particular flooding patterns in 1910. In terms of highland–lowland linkages, rainfall in the Meghalaya Hills was probably very important for the flooding in the directly adjacent lowlands of north-eastern Bangladesh. Moreover, there is no doubt that the rains in the first Himalayan ranges in the Siliguri–Darjiling area contributed to the development of the floods in the lowlands immediately to the south. However, local rains over the flood-affected areas seem to have been equally or even more important than the input from the Himalayas. The fact that, as in 1906, there was no continuous flood further downstream indicates that there were no direct and large-scale highland–lowland linkages to trigger flood processes in Bangladesh. Although the rainfall over the North-western Himalayas was above average throughout the monsoon season, the overall hydrological contribution from the Ganga system was unimportant. Based on the different puzzle pieces of the investigation, it has to be assumed that the floods in the Ganga system, as well as their triggers, were rather localized in nature.

Factors that were important for the floods to the south of the Himalayan ranges (particularly the forelands of the Darjiling and western Bhutan Himalayas):

- early monsoon rainfall in June;
- heavy rainfall in July over the flood-affected areas themselves;
- rainfall in the lower part of the Himalayas;
- probable high water levels of the Himalayan rivers at the entry points to the plains.

Factors that were important for the floods in Bangladesh:

- early monsoon rainfall in June;
- widespread rainfall in July during the flood period;
- heavy local rainfall over the flood-affected areas themselves;
- high water level of the Brahmaputra in the case of the floods in north-western Bangladesh;
- heavy rainfall in the Meghalaya Hills in the case of the floods in north-eastern Bangladesh.

Factors that were not important for the floods in Bangladesh:

- input originating in the Ganga lowlands;
- hydro-meteorological processes in southern Bangladesh;
- the pre-monsoon period.

Appendix 5.3: 1922 – A "flood year"

The contents of this case study are based on investigations made by project team member Roland Guntersweiler (Guntersweiler 1995). The summary of this case study is presented in section 5.6 (pp. 159–163).

The 1922 flood situation at a glance

Flood dimension and intensity (Figure 5A.9)

In the period 1910–1930, 1922 was the worst flood year. However, the event was limited in terms of geographical extent: covering districts 2, 3, 4, 5, 6 and 7, the flood affected more or less the entire north-western part

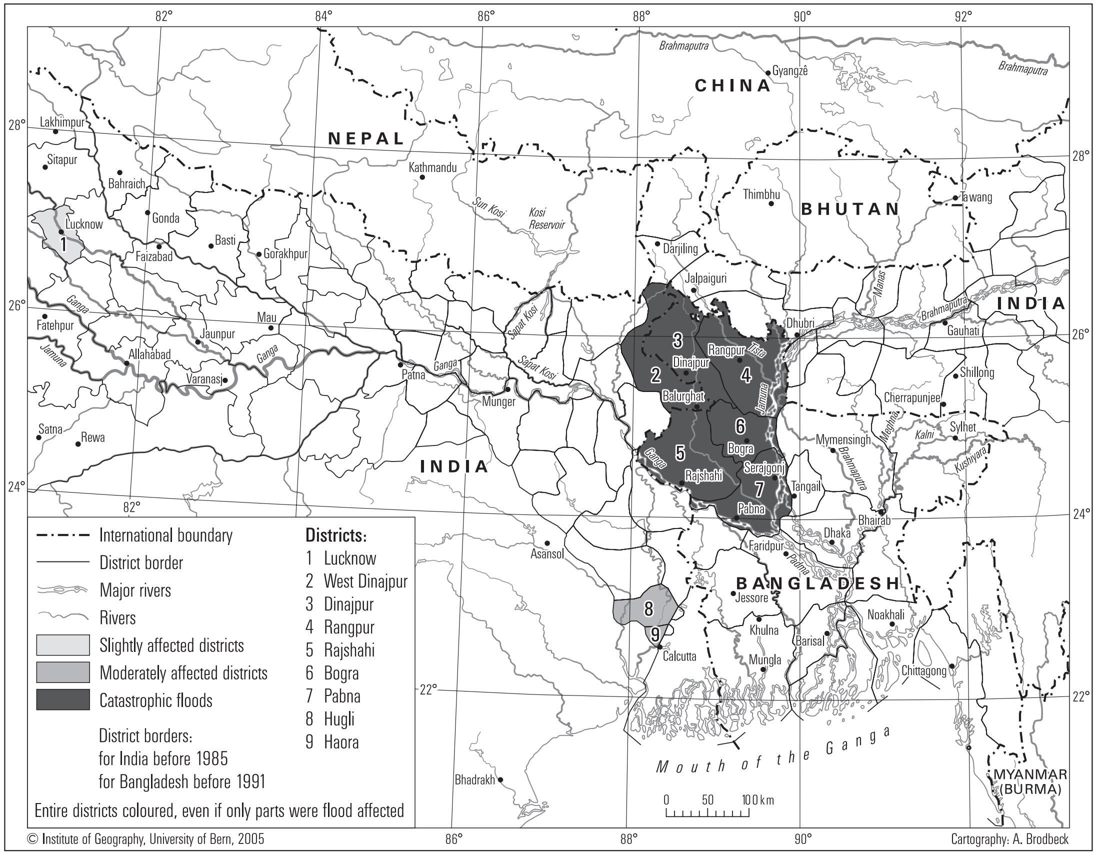


Figure 5A.9 Flood-affected areas and flood intensities: 1922.

of modern Bangladesh, which largely corresponds to SC10 and a small part of SC5 (see also Figure 5.1). The flood in these areas was rated as very severe and extensive. In addition to this main area of flooding, moderate inundations were reported from districts 8 and 9 located to the west of Calcutta (partly in SC6) as well as slight flooding in the area of Lucknow in the Indian Ganga Plain (district 1, located in SC4).

Chronology of the flood

The floods in north-western Bangladesh occurred towards the end of the monsoon season, in the last part of September. Whereas the timing of the moderate floods to the west of Calcutta is not known, reports on the inundations in the area of Lucknow date from the first week in September.

Reported damage

The severest damage occurred in the area of Rajshahi. It is unknown if there were flood victims in north-western Bangladesh. However, it is reported that 25–75 per cent of the broadcast winter rice was destroyed, many animals were killed and people were rendered homeless owing to the collapse of their houses. Diseases broke out because of problems with the drinking water supply. The situation was further aggravated by the lack of boats to carry food for the victims, of fodder for the cattle as well as of support from landlords. A number of railway embankments were breached and the important line to Darjiling was disrupted.

As a result of the moderate floods to the west of Calcutta, which were caused by the breaching of dams and the overflow of rivers, many people had to flee to railway embankments and into trees. Regarding the floods in the area of Lucknow, some damage to embankments and crops is reported.

Causes of flooding as discussed in the literature

The floods in north-western Bangladesh were caused by heavy rains linked to a storm that lasted for three days and moved from the south to the north. Heavy rainfall was also given as the main reason for the floods to the west of Calcutta. The severe damage caused in Rajshahi was related to the high level of the Ganga. Similarly, the overflow of the Ganga was perceived as the main reason for the floods in the area of Lucknow. There was a contradictory discussion on the positive and negative aspects of road and railway embankments: whereas the homeless found shelter on the embankments, the dams obstructed the timely discharge of excessive flood water. In particular it was perceived that, owing to bad planning, the railway embankment in the region of Bogra did not have a sufficient number of drainage outlets.

Drought

The entire catchment of the Meghna River was affected by a severe drought. Throughout the monsoon season complaints and reports about scanty rain and terrible heat were published.

Literature sources

The Englishman (1922: 25 Sep, 28 Sep, 29 Sep, 30 Sep, 2 Oct, 3 Oct, 4 Oct, 5 Oct, 7 Oct, 10 Oct, 11 Oct, 13 Oct, 16 Oct, 19 Oct); *The Statesman* (1922: 15 Jun, 29 Jun, 3 Aug, 17 Aug, 31 Aug, 7 Sep, 21 Sep, 5 Oct, 12 Oct, 19 Oct); *The Statesman* (1923: 20 Sep); Mahalanobis (1927).

Hydrological contributions from the different subcatchments and their relevance to the flooding conditions in Bangladesh (Figure 5A.10, Figure 5.1)

As stated above, severe flooding occurred towards the end of September in North-western Bangladesh (SC10). *R*(pot) in this subcatchment reached twice the normal volume in this last monsoon month. Even more prominent was the anomaly in *R*(relev), which ranked second of all subcatchments. In view of the average or even below-average figures for *R*(pot) and *R*(relev) from June to August, the floods seem to have been produced by the hydro-meteorological conditions during September itself, and, as is shown in Figure 5A.11, even by rains over only a few days.

In contrast to most other case studies, the entire Ganga basin faced a rather strong monsoon season. With the exception of the Upper Ganga Plain (SC4) in June, the anomalies in *R*(pot) were significantly positive throughout the four monsoon months and in all Ganga subcatchments for which data were available. It is very easy to relate the overflowing of the Ganga and the resulting floods in the area of Lucknow, as well as the high water level of the Ganga in the Rajshahi region, to this situation; in fact, even more extensive flooding in the Ganga Plain could have been expected. It is interesting, though, that this above-average input from the Ganga system did not cause widespread and serious floods in Bangladesh. Except for the areas along the Ganga, most parts of SC10 belong to the Brahmaputra system (see Figure 5.1). Accordingly, only the flooding processes in the vicinity of the Ganga, e.g. in the area of Rajshahi, can be related to the humid conditions in the Ganga basin. This could indicate that it is the monsoon characteristics in the Meghna and Brahmaputra basin that ultimately exert the decisive influence on flood dimensions in Bangladesh, and not those in the Ganga catchment. The calculations of *R*(relev) support this statement: in spite of the significant anomalies in *R*(pot) in the subcatchments of the Ganga, these areas have little additional relevance for the hydrological conditions in Bangladesh. This

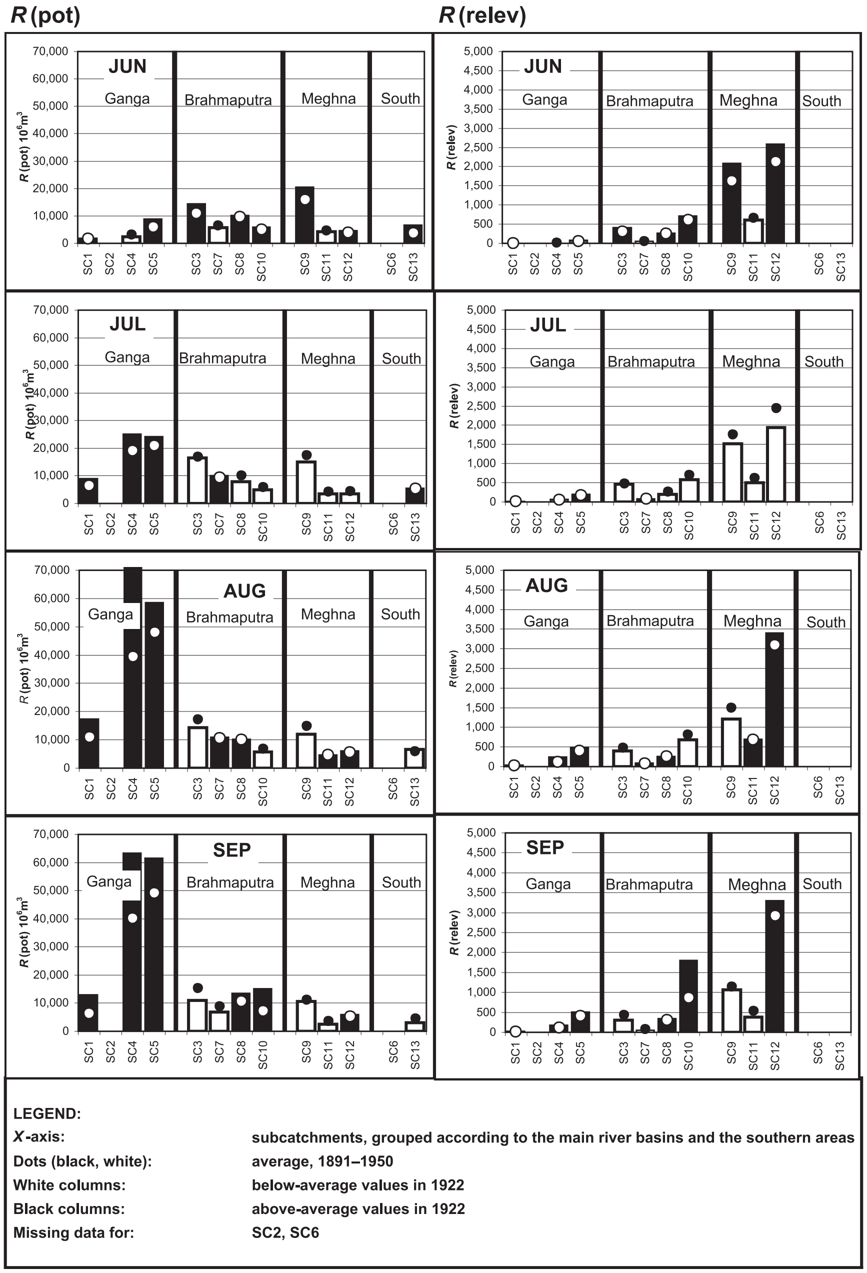


Figure 5A.10 Monthly potential runoff (*R*(pot)) and relevance for Bangladesh (*R*(relev)) in the 13 subcatchments for the four monsoon months of 1922.

Notes: *R*(relev) has no measuring unit. For the location of the subcatchments, see Figure 5.1; for the data sources, see Table 3.2.

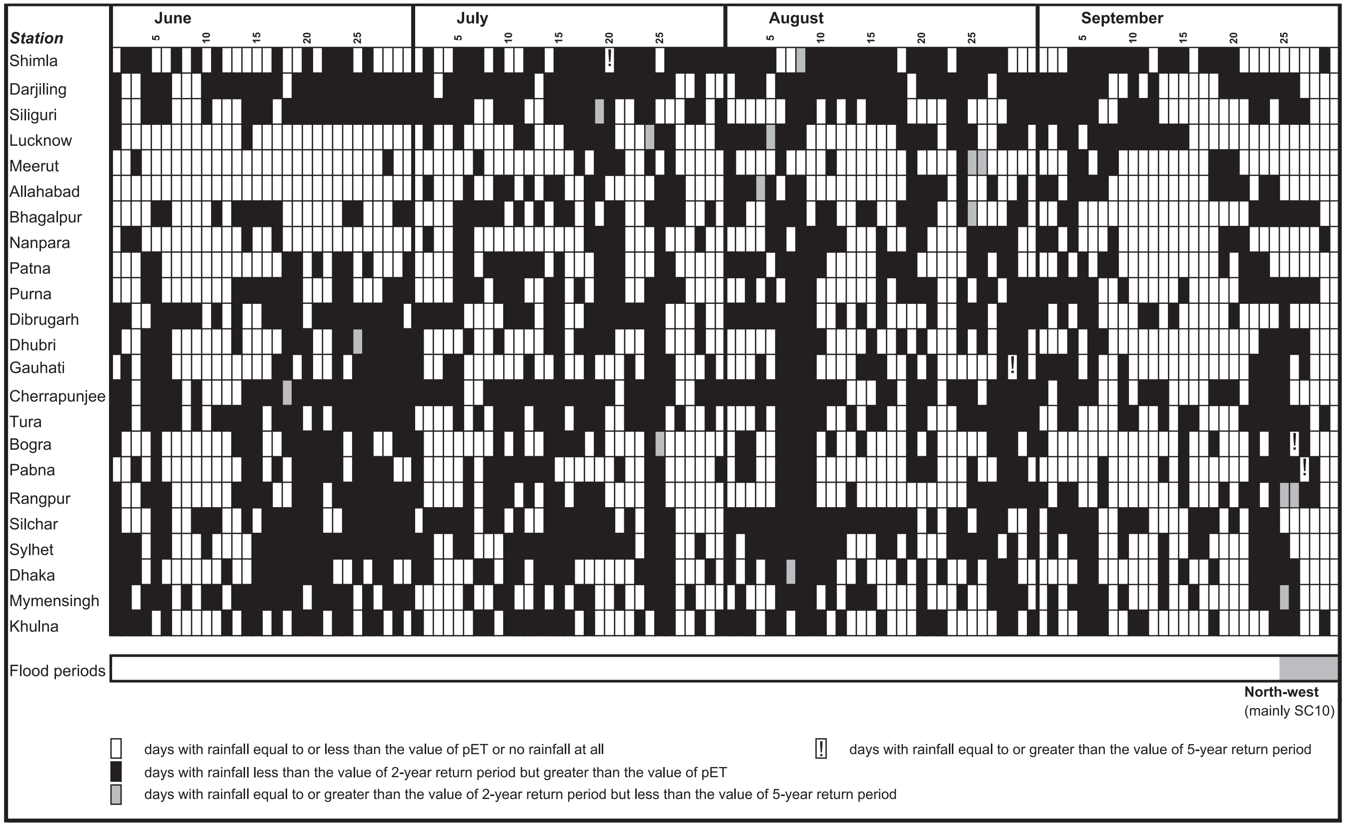


Figure 5A.11 Categories of daily rainfall for the period 1 June–30 September 1922.

Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2; for threshold values for the return periods, see Table 5A.2.

match between reality and the calculations underlines the fact that *R*(pot) and *R*(relev) are very valuable indicators of the regionalization of flood-relevant hydro-meteorological processes.

As expected from the literature sources, negative anomalies in *R*(pot) dominated parts of the Meghna catchment – the Meghalaya Hills (SC9) and North-eastern Bangladesh (SC11). Accordingly, no specific floods were reported in this area.

The severe floods in North-western Bangladesh (SC10) do not seem to have been related to the hydro-meteorological patterns in the relevant Himalayan catchment areas: in June and August, and even more so in September, *R*(pot) in the Darjiling–Bhutan Himalayas (SC3) was below average.

According to the relevant calculations, *R*(pot) was below-average in winter (January–March) and in the pre-monsoon period (April–May) in most subcatchments.

Daily rainfall (Figure 5A.11)

The 1922 monsoon season does not show a clear sequence of rainy periods and phases with low rainfall occurrence. However, some periods with widespread rains can nevertheless be identified:

- 14 June–1 July: rains were constant and widespread at most stations except at those in the Ganga lowlands.
- 5–9 August: continuous rains were recorded at almost all the stations.
- 25 August–6 September: frequent, but not continuous, rains were recorded at most stations.
- 22–27 September: rains were recorded at a limited number of stations, but with high rainfall at some sites in SC10 (see Bogra, Pabna and Rangpur).

Except for the period 22–27 September, none of these phases of precipitation seems to have had rains strong enough to trigger flooding.

Compared with other years, there is in general a relatively large number of daily records with a return period of two to five years or even higher. A significant proportion of these were recorded in the Ganga basin. The positive anomalies in *R*(pot) calculated for the subcatchments in the Ganga basin might therefore be the result of a few strong events rather than of continuous, low-intensity rainfall periods.

The rainfall period 22–27 September, during which the severe flooding in north-western Bangladesh occurred, is very special: first, there were a number of stations, particularly in the Ganga basin, where no rainfall was recorded at all on these days. Secondly, the rainfall period followed a basin-wide dry phase of two weeks. Thirdly, the heavy rains were recorded mainly at stations located within the flood-affected area. It seems,

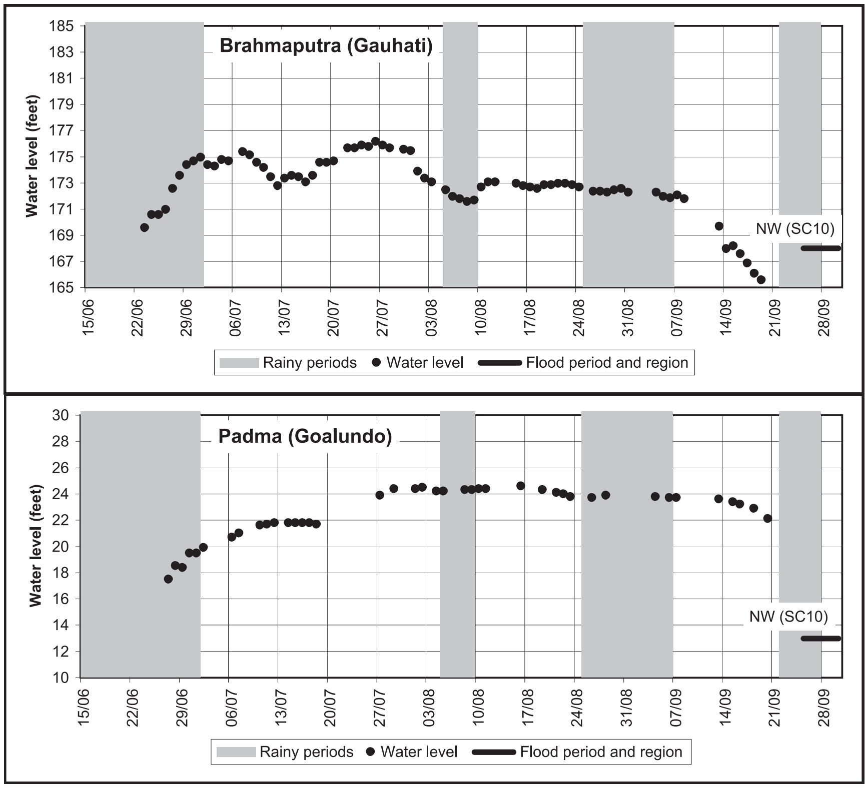


Figure 5A.12 Daily water level of selected rivers for the period 15 June–20 September 1922, compared with flood and rainy periods.
Notes: For the location of the stations, see Figure 3.2. Goalundo is located right after the confluence of the Ganga and the Brahmaputra/Jamuna. The water level data are from *The Englishman* (1922).

therefore, that the severe flooding in SC10 was mainly triggered by heavy rains over the flood-affected areas themselves.

Daily water level (Figure 5A.12)

In terms of hydrological information, the data situation is particularly limited for 1922. Information is completely missing for the Ganga, and the records for the Brahmaputra at Gauhati and the Padma at Goalundo are available only until 20 September, before the floods in north-western Bangladesh even started. The two hydrographs in Figure 5A.12 therefore do not really contribute to understanding the flood processes. It can be stated only that:

- the rainy periods are not reflected in the hydrograph of the Brahmaputra at Gauhati;
- the water level at Gauhati did not even approach the levels recorded in 1910;
- the water level at Gauhati was already very low on 20 September, before the serious flooding in SC10 even started;
- the water level of the Padma at Goalundo remained rather high from the end of July to mid-September, possibly as a result of the large contribution from the Ganga;
- the water level of the Padma reached levels similar to those in 1910, but not similar to those recorded in 1906.

Summary

In the period 1910–1930, 1922 was the most extreme flood year, not in terms of the geographical extent of the flood, but in terms of the severity of the flooding within north-western Bangladesh (SC10). This event seems to be an interesting example of a severe flood that had a limited areal extent and that was caused almost exclusively by heavy rainfall over the flood-affected areas themselves. Based on the water level data measured at Gauhati in Assam, it seems that the flow of the Brahmaputra was already low towards the end of September and consequently cannot be considered an important factor in the triggering of the floods. The high water level of the Ganga at Rajshahi, which is reported in the literature sources, might have contributed to the flooding processes in the southernmost part of SC10. The contrast between the abundant monsoon rains in the Ganga system and the drought conditions particularly in the Meghna system was strongly articulated in 1922. Has the below-average monsoon in the Brahmaputra and Meghna catchments to be considered one of the reasons for the fact that the floods in Bangladesh did not reach nationwide dimensions in spite of the high inflow from the Ganga system?

From the written sources it is evident that already in the 1920s the discussion related to embankments was intensive and controversial. The Bengal Flood Committee, which was charged with an investigation of floods, concluded in 1923 that the following measures had to be taken (*The Statesman*, 20 September 1923): ‘‘On the transversal embankments more openings should exist for an improved water flow. More artificial reservoirs should be built for better storage capacity in addition to the natural beels. Better maintenance of the drainage and irrigation canals was also recommended. In terms of the benefits of embankments, the committee discussed whether the effects of normal and abnormal flood events would have been the same with or without embankments, but a final conclusion was not drawn.’’

Factors that were important for the floods in Bangladesh:

- heavy rainfall directly over the flood-affected areas at the end of September;
- the high water level of the Ganga, possibly causing backwater effects in the southern part of the flood-affected areas.

Factors that were not important for the floods in Bangladesh:

- rainfall in the pre-monsoon period as well as during the monsoon months until 20 September;
- hydro-meteorological conditions in the Meghna catchment, especially in the Meghalaya Hills;
- the contribution from the Darjiling–Bhutan Himalayas;
- hydro-meteorological processes in southern Bangladesh.

Appendix 5.4: 1955 – A "flood year" for Bangladesh

The summary of this case study is presented in section 5.7 (pp. 163–165).

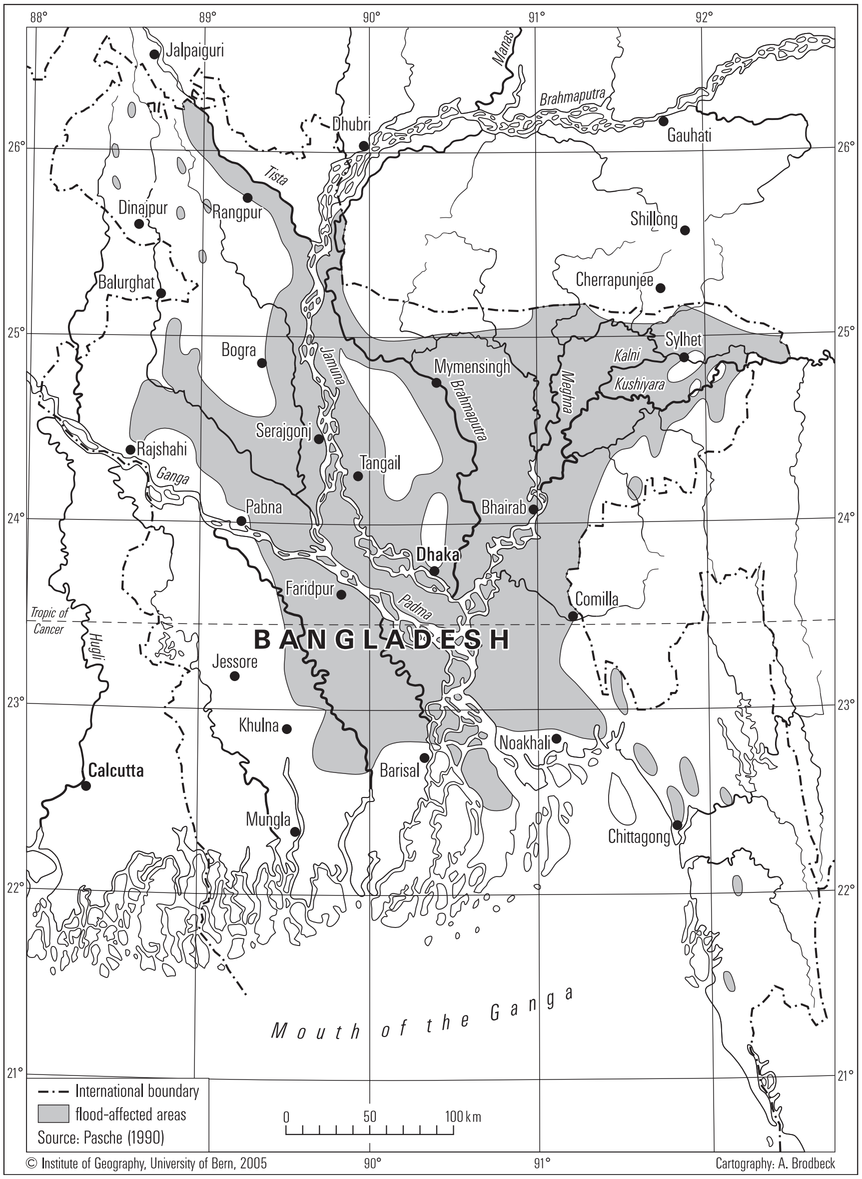
With the creation of West and East Pakistan and of Bangladesh, major political and territorial changes occurred in the Indian subcontinent in the middle and the second part of the twentieth century. Along with these changes there were also modifications in the way information was recorded, structured and stored. This affected our investigations in mainly three ways:

- In the case studies after 1950, flood maps are accessible for the territory of Bangladesh exclusively. Information about flooding processes outside Bangladesh is available only as descriptive texts. Whereas the flood maps for the years 1906, 1910 and 1922 (Figures 5A.1, 5A.5, 5A.9) depict the flood-affected districts, the maps for the case studies after 1950 (e.g. Figure 5A.13) provide a composite picture of the actually flood-affected areas during the particular monsoon season.
- After 1950, systematic information on daily rainfall is available only for Bangladesh (see also Table 3.1). However, monthly precipitation data continue to be accessible for more or less the whole study region.
- The availability of regular and continuous hydrological data series for Bangladesh (even, after 1965, on a daily basis) provides new opportunities for the investigations (see also Table 3.3).

The 1955 flood situation at a glance

Flood dimension in Bangladesh

The flood, which affected 50,500 km^2 (35.37 per cent) of the country, ranks sixth for flood severity in the period 1954–2004 (see Table 4.1).



Source: Pasche (1990)

Cartography: A. Brodbeck

Figure 5A.13 Flood-affected areas, synthesized for the entire monsoon season: 1955.

Most seriously affected areas within Bangladesh (Figure 5A.13)

The map provides only a very rough idea of the geographical extent of the floods. According to this map, large parts of the Meghna and Brahmaputra catchments, the confluence area of the three major rivers and regions towards the south were affected.

Chronology

The timing of the floods in 1955 is unknown. Based on the characteristics of the hydrographs in Figure 5A.17, the inundations most likely occurred in August.

Flooding conditions outside Bangladesh

In Assam, floods occurred in three consecutive years: "The 1954 earthquake is thought to have displaced a sediment 'plug', the progressive movement of which along the Jamuna (Brahmaputra) may have contributed to the severity of the major floods of 1954, 1955, 1956 in Assam" (Hughes et al. 1994: 20, 21). In Uttar Pradesh (Upper Ganga Plain), floods were recorded in early October.

Causes of flooding as discussed in the literature

The floods were caused by excessive, high-intensity precipitation.

Literature sources

BWDB (1975); Agarwal and Narain (1991); Hughes et al. (1994); Kuster (1995).

Hydrological contributions from the different subcatchments and their relevance to the flooding conditions in Bangladesh (Figure 5A.14, Figure 5.1)

Overall, the anomalies in R(pot) and R(relev) were less pronounced in 1955 than in other flood years. During July, positive anomalies in R(pot) were widespread, particularly in Bangladesh (SC10, SC12, SC13), Assam (SC7, SC8) and Meghalaya (SC9). In Bangladesh and Meghalaya, the positive variations in R(pot) resulted in significantly above-average R(relev). In Bangladesh, the positive variations continued into August.

In August and September, the hydrological contribution from the Ganga system was above normal: positive anomalies in R(pot) were recorded in August in the North-western Himalayas (SC1) and the Upper Ganga Plain (SC4), and in September they were recorded in the entire Ganga catchment. However, in terms of relevance to Bangladesh, these

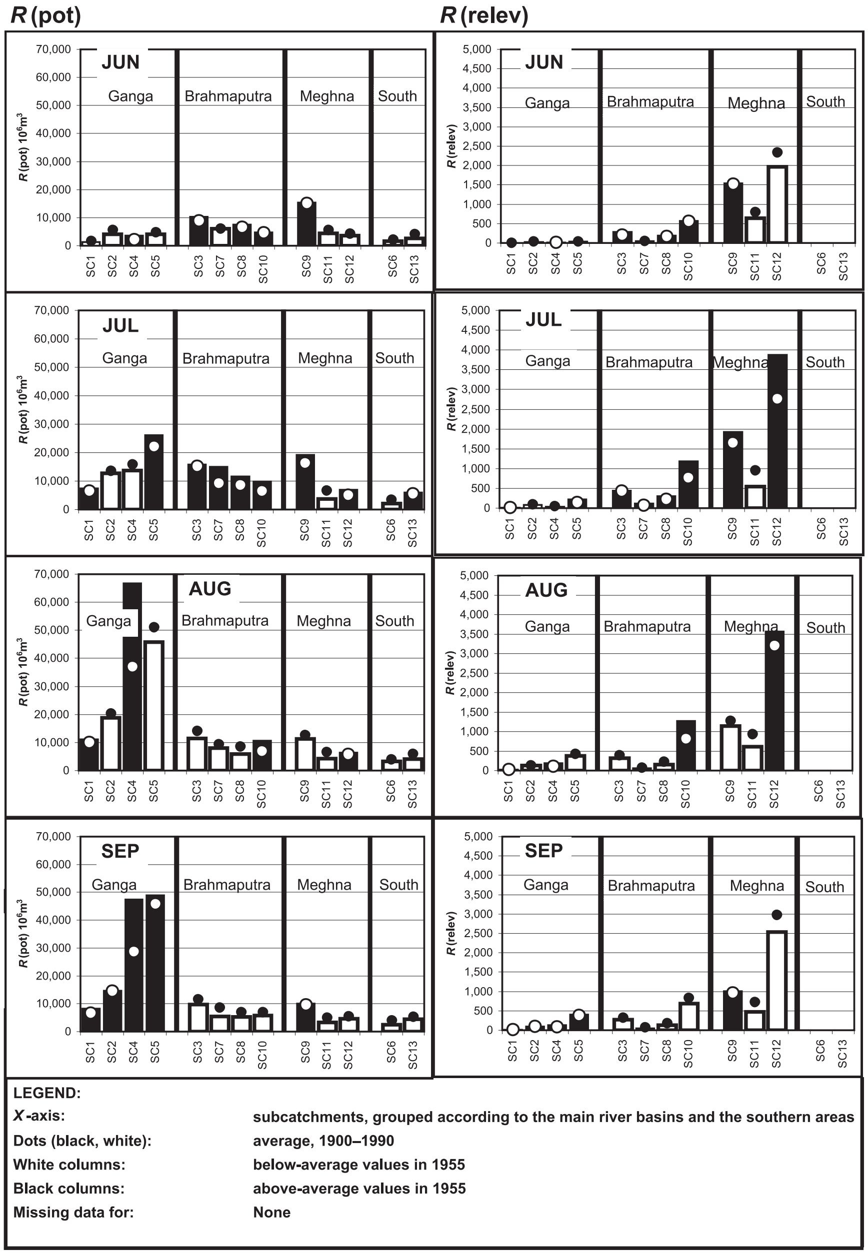


Figure 5A.14 Monthly potential runoff (*R*(pot)) and relevance for Bangladesh (*R*(relev)) in the 13 subcatchments for the four monsoon months of 1955.

Notes: *R*(relev) has no measuring unit. For the location of the subcatchments, see Figure 5.1; for the data sources, see Table 3.2.

anomalies were insignificant and it is interesting to note that almost no flooding occurred in the Ganga area within Bangladesh (Figure 5A.13). This illustrates that, for the development of floods in Bangladesh, important positive variations in *R*(pot) in subcatchments located far away from Bangladesh do not outweigh the relevance of areas located in or nearby Bangladesh.

The hydrological contributions from the Himalayan subcatchments (SC1, SC2, SC3) corresponded very much to the normal situation. The anomalies in *R*(pot), both negative and positive, were very small and, in terms of *R*(relev), negligible.

According to the relevant calculations, *R*(pot) was below average in most subcatchments from April to May. The pre-monsoon period obviously did not pre-condition monsoonal flooding.

Monthly discharge (Figure 5A.15)

The graphs in Figure 5A.15 represent the monthly discharge variations from the average in percentage terms. To calculate the average figures, the entire data set available for each station was used (see also Table 3.3). Although information for only three stations is available, some interesting findings can be drawn from the graphs: throughout the year, but particularly from July onwards, the monthly flow of the Ganga was above normal. Especially in August and September, these anomalies seem to reflect the positive variations in *R*(pot) identified in Figure 5A.14 for parts of the subcatchments in the Ganga basin. The positive flow variations of the Brahmaputra in Assam are much less important and are limited to three monsoon months. Obviously, both the Ganga and the Brahmaputra were flowing significantly above normal during July and August. The discharge of the Sapt Kosi, one of the major Ganga tributaries from Nepal, was constantly below average from April to November. There are good reasons to assume that the input from at least parts of the Himalayas to the hydrological system was not important in 1955.

Daily rainfall (Figure 5A.16)

Unfortunately, daily rainfall data were available for only a few stations in Bangladesh. No information at all was available for the north-eastern part of the country (SC11).

Rainfall was frequent and widespread from 10 July to 20 August. This rainfall period was very important if we assume that the most widespread flooding occurred in August. The rainfall period was long, and the intensities were not very high: only three daily rainfall records exceeded the

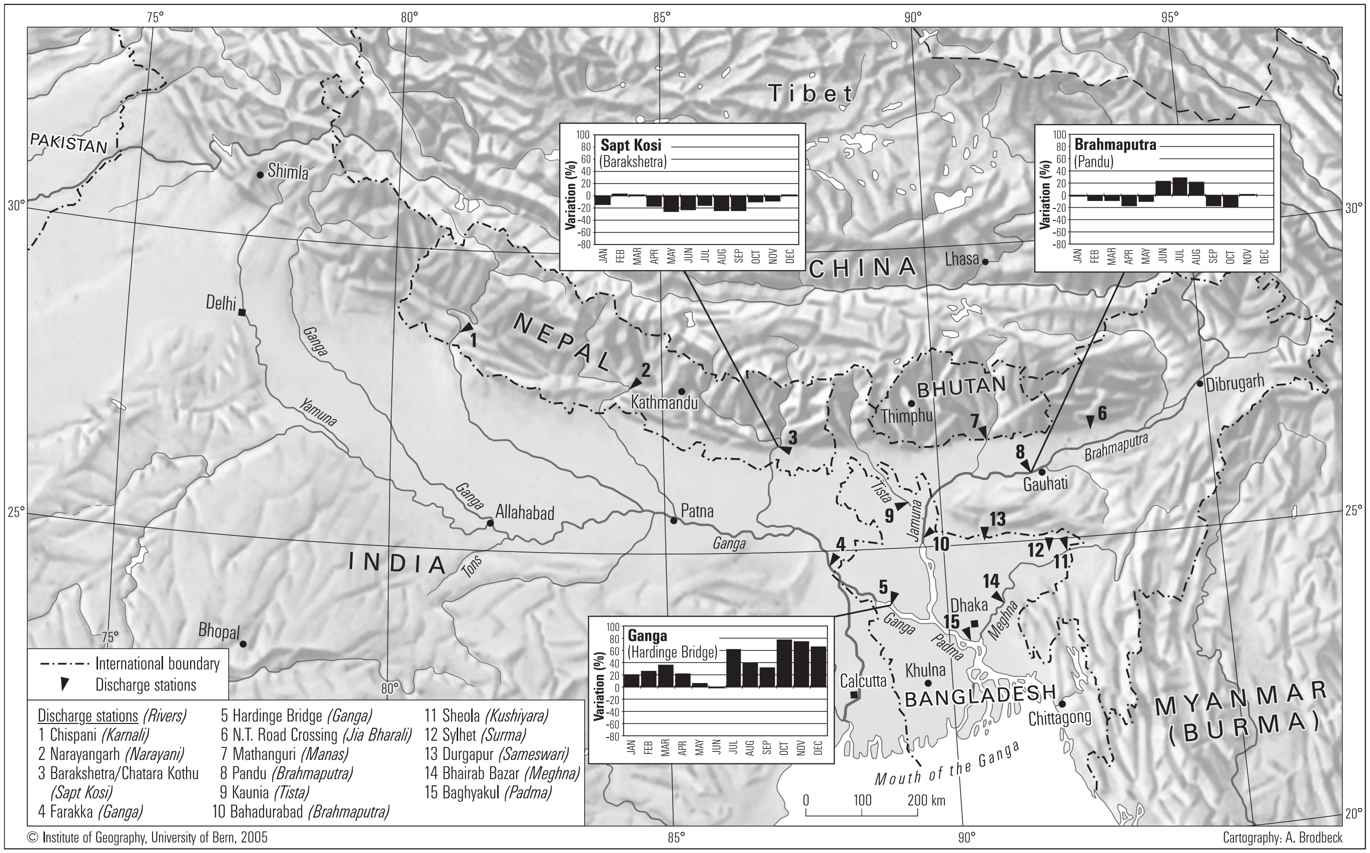


Figure 5A.15 Monthly discharge variations as a percentage of the average for selected rivers in 1955.
Notes: For the data sources, see Table 3.4.

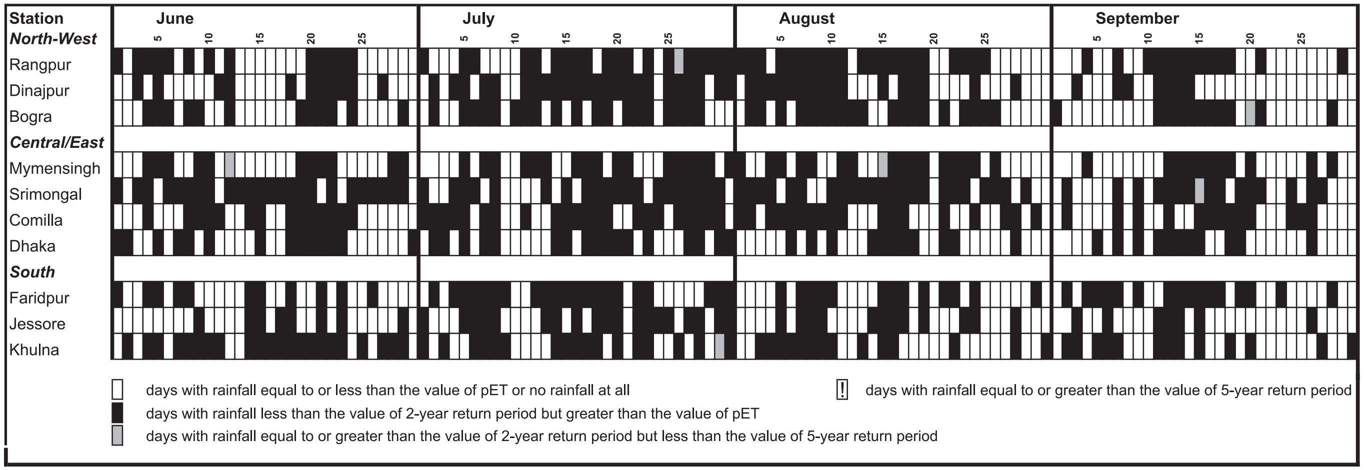


Figure 5A.16 Categories of daily rainfall for the period 1 June–30 September 1955 in Bangladesh.
Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2; for threshold values for the return periods, see Table 5A.2.

return period of two years and none of these reached a return period of more than five years. After 24 August the rains abruptly ceased. Another significant rainfall period followed in mid-September, which obviously did not trigger any important flooding processes.

Daily water level (Figure 5A.17)

For some of the case studies, information on the danger level of river flow was available along with the daily water level data. The danger level is represented by a horizontal line in the three graphs of Figure 5A.17. The danger level is a key parameter in the context of flood forecasting and early warning.

The flow of the three rivers rose above danger level, almost simultaneously, between 25 and 30 July. The duration of above-danger-level flow was significant: 22 days for the Brahmaputra, 71 days for the Ganga and 52 days for the Meghna (BWDB 1975). For about three weeks from the beginning of August, the above-danger-level flow coincided in the three rivers. However, the highest water level of the three rivers had a different timing: the Brahmaputra reached its highest level at the beginning of August, the Ganga towards the end of August and the Meghna around mid-August.

The dominant characteristics of the hydrographs can be related to the rainfall patterns in Bangladesh (Figure 5A.16): a gradual rise of the water level as a result of the rainy period 10 July–20 August; a secondary brief high-flow period of the Brahmaputra and the Meghna in mid-September as a reaction to the precipitation during this period. The high relevance of SC10 throughout June–August as well as of SC12 in July and August (Figure 5A.14) indicates that North-western as well as Central–Eastern Bangladesh had a particular importance. However, the fact that the monthly flows of the Ganga at Hardinge Bridge and the Brahmaputra at Pandu up in Assam were above average in July and August (Figure 5A.15) is clear evidence that the inflow from the Indian plains through the Ganga and Brahmaputra was important as well and certainly contributed to the dimension and duration of the flooding. Interestingly, this is not reflected in the calculations of R(relev) in Figure 5A.14. Finally, the Meghalaya Hills seem to have provided significant external input too, not during the main flooding period but immediately before (see the above-average relevance of SC9 in July in Figure 5A.14).

Summary

Because of the difficult data situation, the analysis of the 1955 flood must remain rather general. Most probably the combination of three main fac-

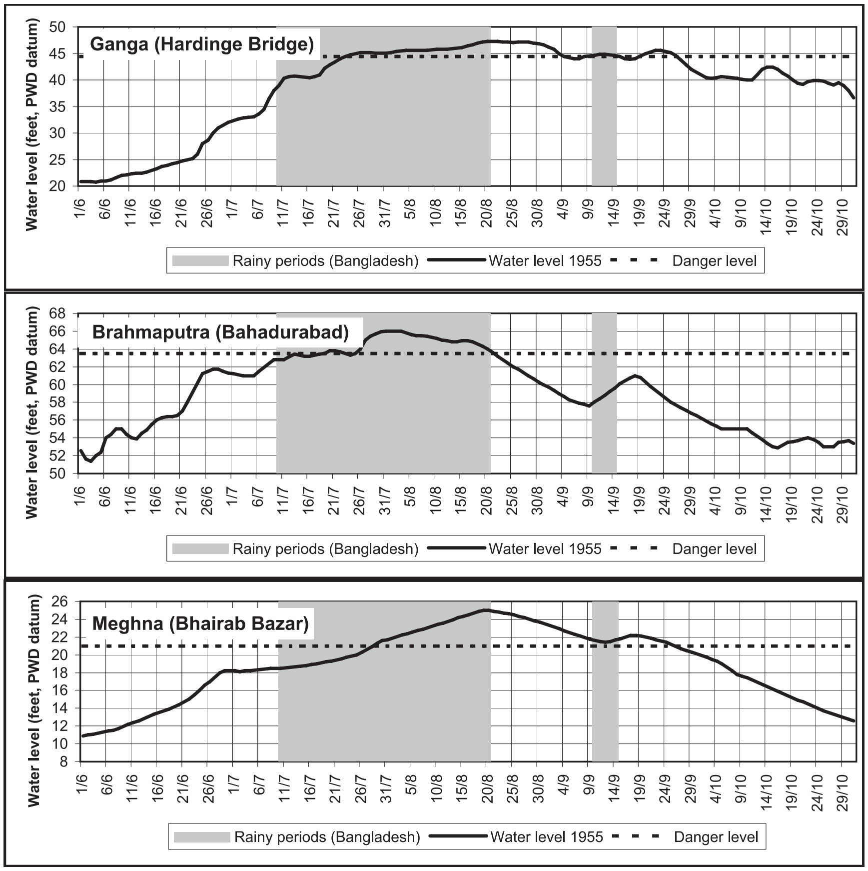


Figure 5A.17 Daily water level of selected rivers in Bangladesh for the period 1 June–31 October 1955, in relation to the danger level and compared with rainy periods.
Notes: For the location of the stations, see Figure 3.2; the data are from BWDB (1975).

tors resulted in the widespread flooding: rainfall within Bangladesh, significant inflow from the Indian Ganga and Brahmaputra Plains as well as from Meghalaya, and the synchronized above-danger-level flow of the Ganga, Brahmaputra and Meghna over three weeks. As the timing is not specified in the literature sources, it cannot be verified whether the floods in Bangladesh and those reported from Assam occurred at the same time. Interestingly, and in spite of the long period of above-danger-level flow, the Ganga did not trigger any flooding in Bangladesh upstream of its confluence with the Brahmaputra. The hydrological processes and the flood situation in 1955 seem to indicate that local triggers of widespread flooding do not need to be very strong if the hydrological import into Bangladesh through the major rivers is high.

Factors that were important for the floods in Bangladesh in August:

- widespread rainfall during July, ahead of the flood period, leading to an increase in river flow, and presumably also contributing to a rising groundwater table and soil saturation;
- fairly constant but moderate rainfall in the first part of August within Bangladesh;
- above-average inflow from the Indian Ganga and Brahmaputra Plains as well as from Meghalaya;
- synchronization of above-danger-level flows of the Meghna, the Brahmaputra and the Ganga for three weeks in August.

Factors that were not important for the floods in Bangladesh in August:

- the contribution from the Himalayas (this statement is based on the calculations of R(pot));
- the pre-monsoon period;
- the southern areas.

Appendix 5.5: 1974 – A "flood year" for Bangladesh

The summary of this case study is presented in section 5.8 (pp. 165–171).

The 1974 flood situation at a glance

Flood dimension in Bangladesh

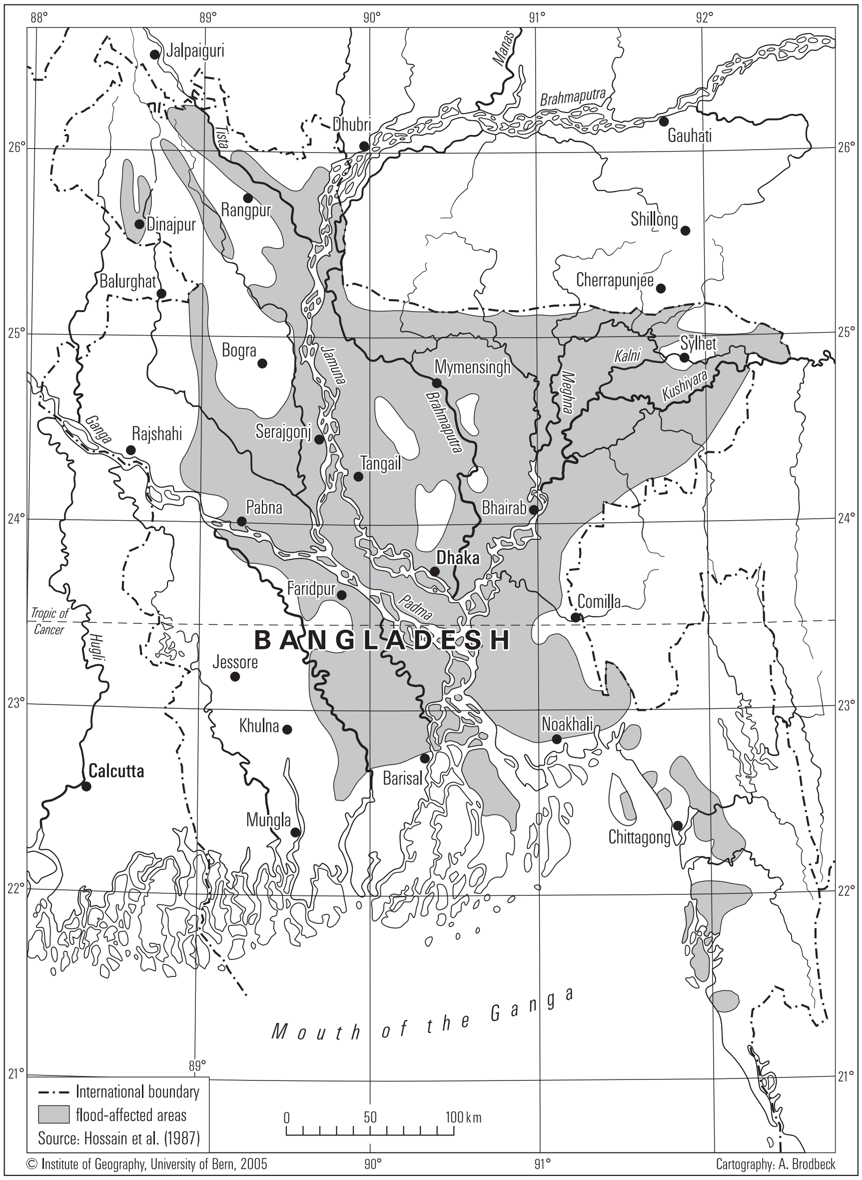
The flood, which affected 52,600 km^2 (36.84 per cent) of the country, ranks fifth for flood severity between 1954 and 2004 (see Table 4.1).

Most seriously affected areas within Bangladesh (Figure 5A.18)

The flood was widespread. However, it occurred mainly in the Meghna and Brahmaputra basins. It did not affect the western, south-western and southernmost parts of the country. In the districts of eastern Bangladesh, more than 60 per cent of the area was flooded; in most districts located in the western or in the southernmost part of Bangladesh, the flood-affected area was less than 25 per cent.

Chronology

The 1974 flood occurred in three phases. The floods in late June mainly affected districts of north-western Bangladesh (Rangpur and Pabna in SC10, Figure 5.1), north-eastern Bangladesh (Sylhet in SC11) and



Source: Hossain et al. (1987)

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Cartography: A. Brodbeck

Figure 5A.18 Flood-affected areas, synthesized for the entire monsoon season: 1974.

central–eastern Bangladesh (Mymensingh and Comilla in SC12). Floods in the early part of August reached nationwide dimensions and affected all districts, with the exception of Patuakhali and Jessore in the south and west of SC13. The third flood wave was regionally limited to areas in Rangpur district in north-western Bangladesh.

Flooding conditions outside Bangladesh

There is no evidence of flood problems in the Ganga system, but Assam experienced a devastating flood, which occurred in five successive waves. Its impact was particularly severe in the districts of Goalpara and Kamrup, which are located downstream of Gauhati.

Causes of the flooding as discussed in the literature

- heavy, intense precipitation over the catchment areas of the rivers outside and within Bangladesh;
- particularly exceptional rainfall in Cherrapunjee;
- high upland discharge with a huge onrush of water down the Brahmaputra from the hill areas of Assam;
- high water levels and high tides;
- simultaneous above-danger-level flow of the three major rivers from early August to mid-August and again for a week during early September (which is unique in the history of floods in Bangladesh).

Literature sources

BWDB (1975); Teich (1975); Government of Assam (1979); Ahmad (1989); BWDB (1991a).

Hydrological contributions from the different subcatchments and their relevance to the flooding conditions in Bangladesh (Figure 5A.19, Figure 5.1)

In July, positive variations in R(pot) and R(relev) were recorded in all subcatchments except SC2 (Nepal). In terms of relevance, this anomaly was particularly important for the Meghna system, less important for the Brahmaputra system and almost negligible for the Ganga system. Assuming 100 per cent as the average, the total R(pot) for the 13 subcatchments reached 160 per cent. At 235 per cent, the anomaly in R(pot) was particularly high for the total of the three subcatchments in the Meghna basin (SC9, SC11, SC12), followed by 147 per cent for the four subcatchments in Bangladesh (SC10, SC11, SC12, SC13). Thus, it is obvious that, in the weeks preceding the nationwide floods in Bangladesh, a considerable amount of water was accumulating in the Ganga–Brahmaputra–Meghna basin. In August, however, when the floods reached their maximum di-

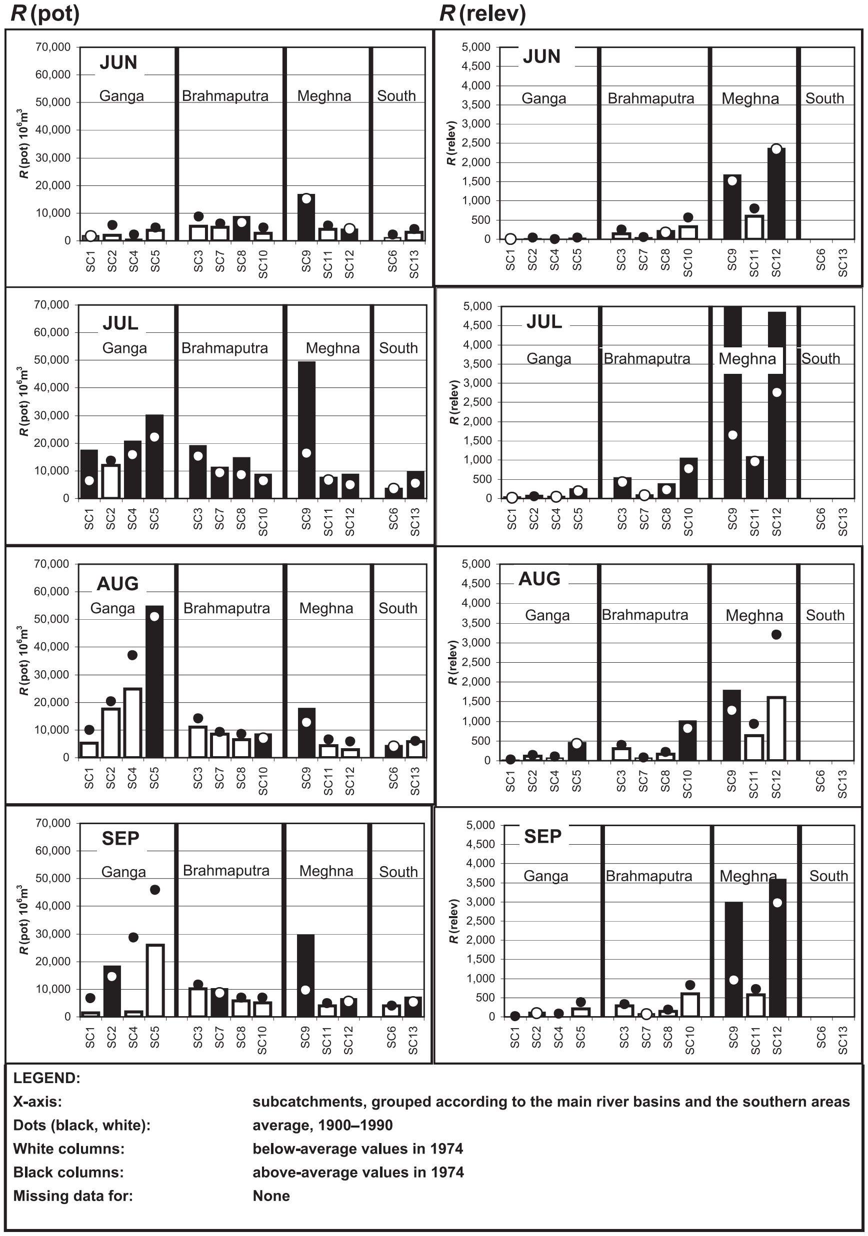


Figure 5A.19 Monthly potential runoff (*R*(pot)) and relevance for Bangladesh (*R*(relev)) in the 13 subcatchments for the four monsoon months of 1974.

Notes: *R*(relev) has no measuring unit. For the location of the subcatchments, see Figure 5.1; for the data sources, see Table 3.2.

mension, *R*(pot) and *R*(relev) were below average in most subcatchments (for further discussion of these findings, see the sections on daily rainfall and daily discharge below).

In major parts of the Meghna catchment, positive anomalies in *R*(pot) and *R*(relev) were recorded throughout the monsoon period. This is particularly the case for the Meghalaya Hills (SC9). The precipitation in Cherrapunjee was outstanding and, according to Teich (1975), was the highest since measurements began in 1851 (the average figures are given in brackets): annual precipitation 23,663 mm (11,117 mm); July 8,247 mm (2,628 mm); August 2,920 mm (1,796 mm); September 4,661 mm (1,126 mm). In July, 23 per cent of the total *R*(pot) of all the 13 subcatchments was contributed by the Meghalaya Hills, a subcatchment that barely amounts to 2 per cent of the study area. *R*(pot) in the Meghalaya Hills in July was more than in the three Himalayan subcatchments together and the relevance of SC9 by far exceeded the values of all the other subcatchments.

In contrast to the Meghna highlands, the hydro-meteorological processes in the Himalayas were not important. The most significant positive anomaly in *R*(pot) was recorded in the North-western Himalayas (SC1) in July, which, however, was negligible in terms of *R*(relev). In the Nepal Himalayas (SC2), *R*(pot) and *R*(relev) were below average from June to August. Finally, only in July were the Darjiling Himalayas (SC3) more relevant than on average, the anomaly being very small.

With the exception of July, *R*(pot) and *R*(relev) in the Ganga system were generally below average.

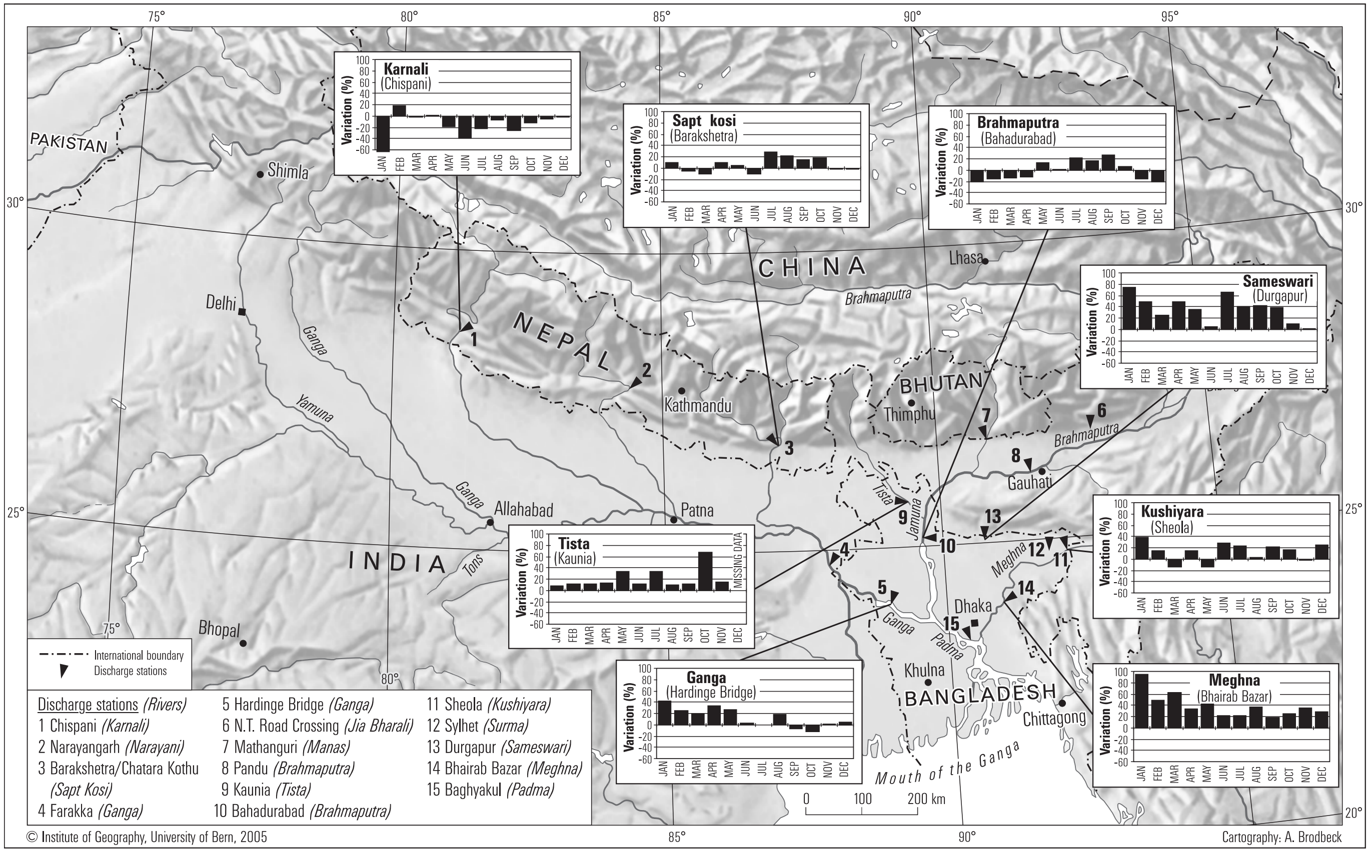
According to the relevant calculations, positive anomalies in *R*(pot) occurred in the southern areas (SC6, SC13) during the winter and the pre-monsoon period. We can assume that the groundwater tables in these regions were already comparatively high at the onset of the monsoon (see the section on groundwater below and Figure 5A.23).

In September, moderate and regionally limited floods were recorded in north-western Bangladesh. In view of the significantly positive anomalies in *R*(pot) and *R*(relev) in the Meghna catchment, much more extensive flooding could have been expected.

Monthly discharge (Figure 5A.20)

In July, all the rivers in the Meghna and Brahmaputra systems recorded above-average flows, which is a clear result of the widespread above-average *R*(pot) during this month. In the Ganga system, above-average flow was measured only on the Sapt Kosi.

The most important positive variations in monthly flow were measured in the Meghna catchment. This situation reflects the outstanding hydro-



Discharge stations *(Rivers)*
1 Chispani *(Karnali)*
2 Narayangarh *(Narayani)*
3 Barakshetra/Chatara Kothu *(Sapt Kosi)*
4 Farakka *(Ganga)*
5 Hardinge Bridge *(Ganga)*
6 N.T. Road Crossing *(Jia Bharali)*
7 Mathanguri *(Manas)*
8 Pandu *(Brahmaputra)*
9 Kaunia *(Tista)*
10 Bahadurabad *(Brahmaputra)*
11 Sheola *(Kushiyara)*
12 Sylhet *(Surma)*
13 Durgapur *(Sameswari)*
14 Bhairab Bazar *(Meghna)*
15 Baghyakul *(Padma)*

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Figure 5A.20 Monthly discharge variations as a percentage of the average for selected rivers in 1974.
Notes: For the data sources, see Table 3.4.

logical input from the Meghalaya Hills in particular. The anomalies are high and, in the case of the Sameswari and the Meghna rivers, positive throughout the whole year. As a consequence, the discharge of the Meghna and of some tributaries was already significantly above the average at the onset of the monsoon.

The flow of the Ganga was above normal during the winter and the pre-monsoon period and, with the exception of August, only average or even below during the monsoon season. This situation is exactly the opposite of the Brahmaputra, which displayed significant positive discharge anomalies from July to September.

In terms of the Himalayan tributaries, the flow was above average on the Tista throughout the year, which is somewhat unexpected in view of the mostly negative variations in R(pot) in SC3 (Figure 5A.19). Towards the west, the anomalies get smaller (Sapt Kosi) and become negative (Karnali).

Daily rainfall (Figure 5A.21)

The 1974 monsoon season was characterized by cycles of rainy and dry periods. This sequence of ‘‘active monsoon’’ and ‘‘break monsoon’’ periods is discussed in Fein and Stephens (1987) as a very typical feature of the summer monsoon climate. Whereas the rainy periods in June and July are reported for more or less the whole of Bangladesh, the rainfall is more region specific after mid-August. The longest rainfall period was recorded in the second part of July and was followed by an extended dry period of roughly two weeks. For the investigations, the following rainfall periods are distinctive in Figure 5A.21: 1–8 June; 16–24 June; 30 June–7 July; 13–30 July; 26 August–1 September; 12–15 September.

Rainfall was important in terms of both the duration and number of rainfall periods, but not in terms of rainfall intensities – very few daily rainfall events had a return period of more than two years.

Flood phases typically occur with some delay after the rainfall periods: the nationwide flood in the first part of August started at the end of a long rainy phase and significantly extended into the subsequent dry period. This indicates that floods need time to develop and to reach their maximum extent: river beds and groundwater reservoirs need to fill up before they overflow and the soil needs to be saturated. It can also be assumed that, for the development of the nationwide flood in the first half of August, external factors, such as exceptional rainfall in the Meghalaya Hills or flood waves in Assam, might have been equally as important as the rainfall within Bangladesh (see also the significant peaks of the Brahmaputra and the Meghna in Figure 5A.22).

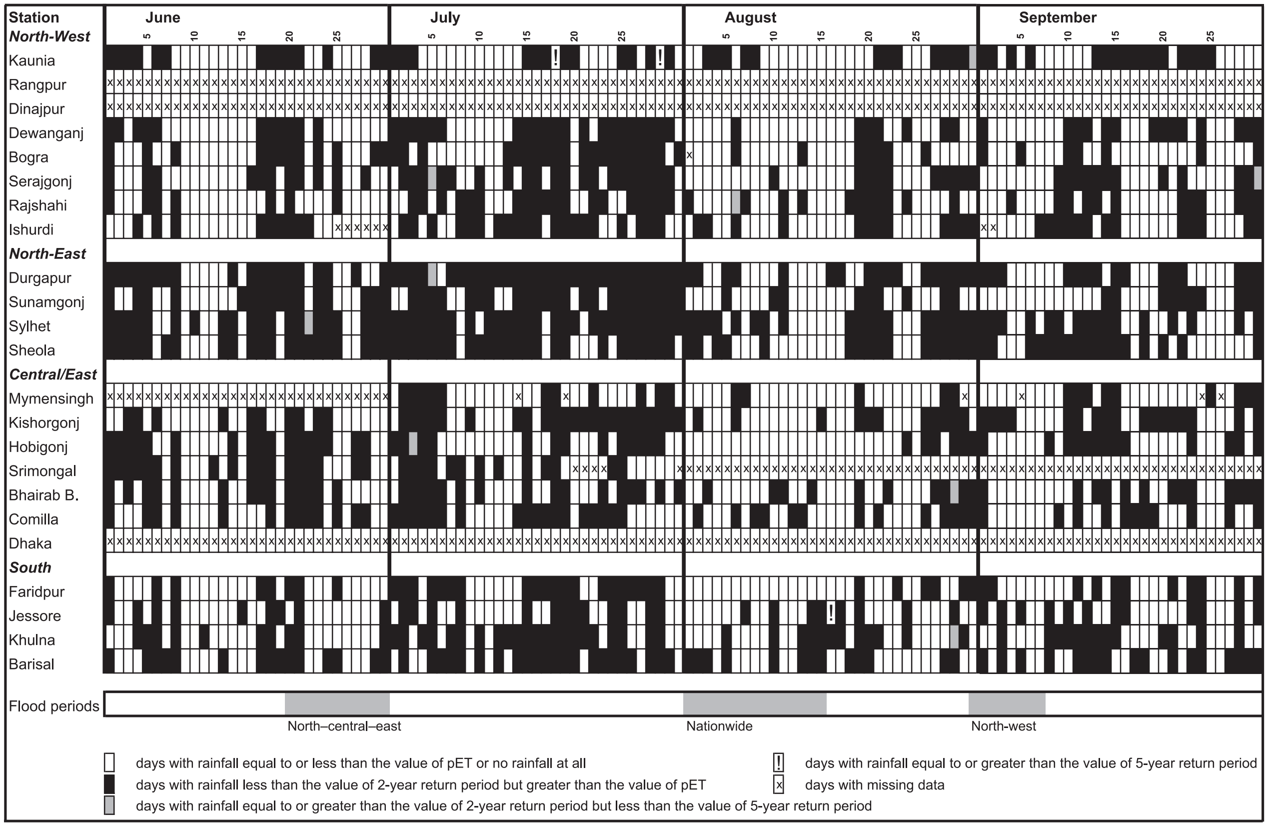


Figure 5A.21 Categories of daily rainfall for the period 1 June–30 September 1974 in Bangladesh.

Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2; for threshold values for the return periods, see Table 5A.2.

Daily discharge (Figure 5A.22)

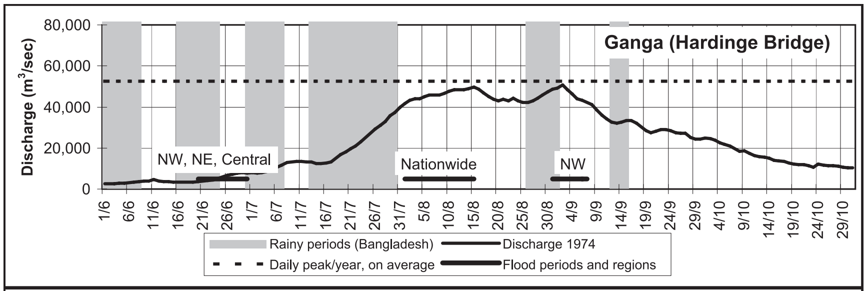
As a new feature, for the 1974 case study daily discharge data from a variety of hydrological measuring sites in Bangladesh became available. The hydrographs for a selection of stations are displayed in Figure 5A.22. The graphs can be directly related to the flood periods (black lines) as well as to the most important rainfall periods (grey bars). The horizontal dotted line helps to identify if the highest discharge measured in a particular year was above or below the average. The value for this dotted line at each station was identified as follows: for each year over the available time period, the highest daily discharge record was extracted from the data set and then the average of all these records was calculated. In all the subsequent case studies for which daily discharge data are available, the structure of the graphs is identical with Figure 5A.22. This explanatory text will therefore not be provided in the discussion of the other case studies.

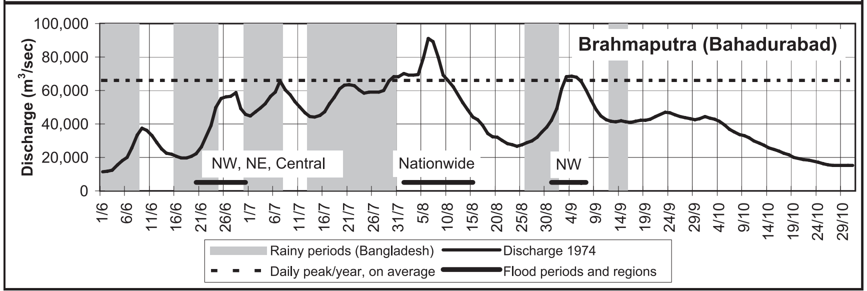
The flow of the Brahmaputra and the Meghna was outstanding: the highest discharge of both rivers significantly exceeded the maximum discharge that is on average reached during the monsoon season. The Brahmaputra flow of 91,100 m^3/sec, measured on 6 August, has a return period of approximately 30 years. The flow was above danger level on a total of 47 days for the Brahmaputra and on 81 days (almost 3 months) for the Meghna (BWDB 1975).

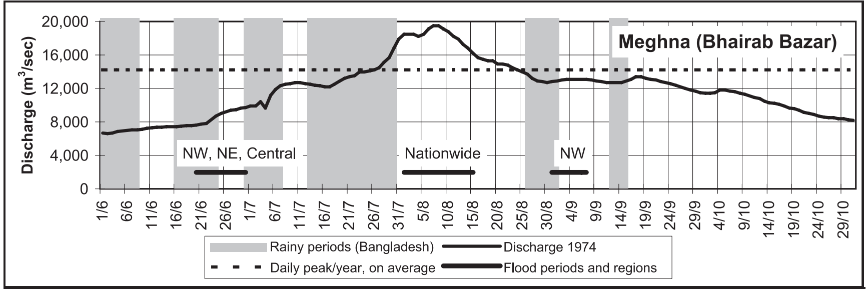
The highest flow of the Ganga never reached the level of the dotted horizontal line. However, above-danger-level flow was recorded on 41 days, which is more than in the extraordinary flood of 1988 (see Appendix 5.7). This overall flow pattern corresponds well with the flood situation, which was most severe in the Meghna catchment, followed by the Brahmaputra catchment. It also matches the rainfall patterns: rainfall was most intensive in the Meghna Basin.

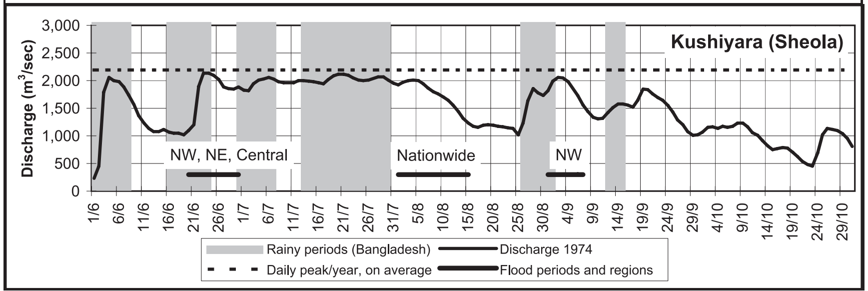
The Brahmaputra and the Meghna reached their highest flow almost simultaneously between 5 and 10 August. Furthermore, all three major rivers were flowing above danger levels from 1 to 14 August (BWDB 1975). Both factors were probably decisive for the development of the floods, which reached their maximum extent in the first two weeks of August. In early September, a second short high-flow period is documented in the graphs for the Brahmaputra and the Ganga, which temporally coincided with the flood in north-western Bangladesh. Finally, only the Brahmaputra reacted to the flood phase in the second part of June.

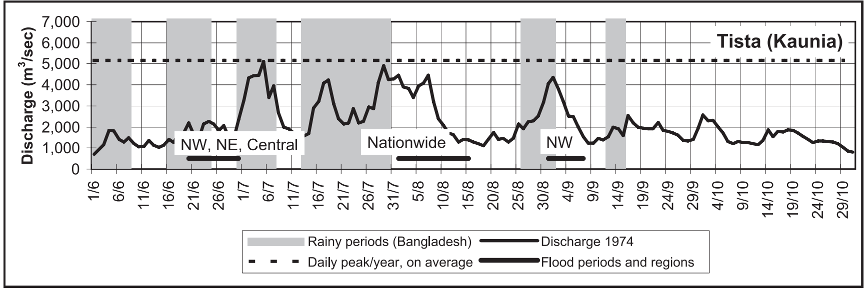
In general, the discharge of the three big rivers increased during the rainfall periods, and this is particularly obvious for the Brahmaputra. The short-term peaks are usually reached just after the relevant rainfall period or even in the following ‘‘break phase’’ of precipitation. However,


Ganga (Hardinge Bridge)
Discharge (m³/sec)
80,000
60,000
40,000
20,000
0
NW, NE, Central
Nationwide
NW
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Rainy periods (Bangladesh)
Discharge 1974
Daily peak/year, on average
Flood periods and regions


Brahmaputra (Bahadurabad)
Discharge (m³/sec)
100,000
80,000
60,000
40,000
20,000
0
NW, NE, Central
Nationwide
NW
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Rainy periods (Bangladesh)
Discharge 1974
Daily peak/year, on average
Flood periods and regions


Meghna (Bhairab Bazar)
Discharge (m³/sec)
20,000
16,000
12,000
8,000
4,000
0
NW, NE, Central
Nationwide
NW
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Rainy periods (Bangladesh)
Discharge 1974
Daily peak/year, on average
Flood periods and regions


Kushiyara (Sheola)
Discharge (m³/sec)
3,000
2,500
2,000
1,500
1,000
500
0
NW, NE, Central
Nationwide
NW
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Rainy periods (Bangladesh)
Discharge 1974
Daily peak/year, on average
Flood periods and regions


Tista (Kaunia)
Discharge (m³/sec)
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
NW, NE, Central
Nationwide
NW
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Rainy periods (Bangladesh)
Discharge 1974
Daily peak/year, on average
Flood periods and regions

the dimension and to some extent the timing of the maximum flows of the Brahmaputra in early August and in early September cannot be fully understood by just considering the rainfall patterns in Bangladesh; as already pointed out in the section on daily rainfall above, a considerable external input from Assam and Meghalaya has to be assumed and a connection to the flood processes in Lower Assam seems clear.

The graphs of the Tista and the Kushiyara are striking not in terms of the maximum flows, which never exceeded the highest discharge reached on average during the monsoon season, but in terms of the duration of high flow (Kushiyara) and the number of high-flow periods (Tista). In terms of timing, the flood periods are much less systematically reflected in the hydrographs of these comparatively smaller rivers than they are in the flow patterns of the big rivers. The large number of short-term discharge variations in the Tista and the Kushiyara documents the much faster reaction to rainfall compared with the big rivers: for example, from 15 to 20 July and on 29 July high rainfall was recorded in Kaunia, which immediately produced short-term discharge peaks on the Tista. Obviously, the flow of the big rivers in Bangladesh responds to regional rainfall with a certain delay, whereas the flow of the smaller rivers reacts almost immediately to local rainfall.

On the Kushiyara, both the highest discharge and the longest duration of high flow occurred in June and July, which demonstrates the constantly high input from the Meghalaya Hills. During the same period, the flow of the Meghna gradually increased, but was not yet very high. There is clearly a significant time lag between the Kushiyara and Meghna peak flows, which is the result of the large water storage potential of the haors and beels in the Sylhet depression downstream of Sheola.

Groundwater (Figure 5A.23)

Again as a new feature, for the 1974 case study groundwater data series became available on a weekly basis. For the investigations, nine stations were selected (see Figure 3.3) that are more or less equally distributed over the floodplains of Bangladesh. The graphs represent the water level

◄

Figure 5A.22 Average daily discharge of selected rivers in Bangladesh for the period 1 June–31 October 1974, compared with flood periods, rainy periods and daily peak/year, on average.
Notes: For the location of the stations, see Figure 3.2; for the data sources, see Table 3.4.

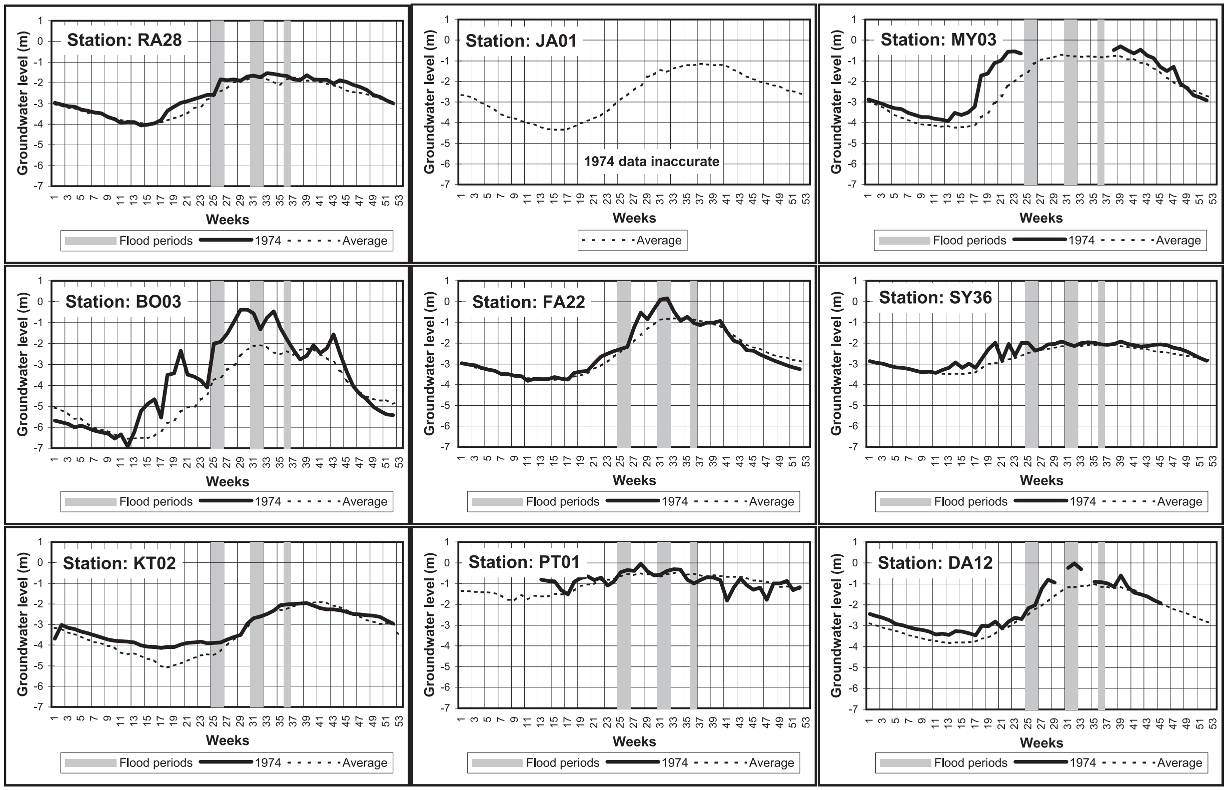


Figure 5A.23 Groundwater levels of selected stations in 1974 compared with flood periods and average groundwater levels over roughly 20 years.

Notes: For the location of the stations, see Figure 3.3. The four monsoon months correspond to the week numbers approximately as follows: June, weeks 23–26; July, weeks 27–30; August, weeks 31–34; September, weeks 35–38.

Source: BWDB (n.d.[b]).

in metres below the surface on a weekly basis for the whole year, with the dotted lines allowing for a comparison with the average situation (over approximately 20 years). If we accept the uncertainties related to the exact location and the specific micro-topography of the measuring sites, the local geological situation and the structure of the sediments, then these groundwater hydrographs make it possible to get a very rough indication about areas of potential waterlogging, about the remaining water storage capacity and indirectly also about soil saturation. We can assume that both rainfall and flooding will raise the groundwater table. Furthermore, a high groundwater table, caused by rainfall, will extend the duration of flooding. In all the subsequent case studies for which groundwater data are available, the structure of the graphs is identical with Figure 5A.23. This explanatory text will therefore not be provided in the discussion of the other case studies.

As a general feature, groundwater levels were above average during the monsoon period. Groundwater reached the surface at the three southernmost stations: at FA22, located near the area of confluence of the Brahmaputra and the Ganga, at DA12 in the Meghna region south of Bhairab Bazar, and at PT01 in the coastal areas. Hydrologically, this situation makes a lot of sense. The probability of the groundwater reservoirs overflowing is highest in the overall area of confluence of the big rivers, where the accumulation of water through the rivers and local rainfall as well as through backwater effects reaches its maximum, and in the southern parts of the Bangladeshi floodplains, where drainage is to some extent hampered by the sea, and by tidal movements in particular. At stations FA22 and DA12, the groundwater level reached the surface precisely in the period of the most extended flooding in early August (weeks 31 and 32). Since the first phase of flooding in late June (week 26) mainly affected districts in north-western Bangladesh, the two hydrographs of stations RA28 and B003, which are located in SC10, revealed the strongest reaction to these flooding processes. Compared with the other stations, the groundwater hydrographs of PT01 and SY36 have very modest inner-annual fluctuations, on average as well as in 1974. For station PT01 this is the result of its proximity to the sea. For SY36 this illustrates the position of the station in or near the depression areas south of Sylhet, which are waterlogged for significant parts of the year.

In the second section of this Appendix it was assumed that, as a result of the positive variations in R(pot) in SC6 and SC13 during the early months of 1974, the groundwater table in the southern areas was potentially above average at the onset of the monsoon. Indeed, at most stations documented in Figure 5A.23, the level of the groundwater table was higher than normal in the pre-monsoon period and even throughout the entire first half of the year. Compared with the average situation, the water absorption capacity of the ground was obviously already reduced at the onset of the monsoon.

Summary

High rainfall inside and outside Bangladesh, local and imported flood peaks, a synchronization of flood flows of the major rivers and high groundwater tables were all important causes of the widespread flooding in 1974. The Meghna catchment was of particular importance, followed by the Brahmaputra basin. The Ganga was important not on its own but in combination with the other major river systems. Whereas the Himalayas have to be considered very marginal in their contribution to the inundations in Bangladesh, the amount of water pouring down from the Meghalaya Hills into the floodplains of the Meghna system was outstanding. We can therefore assume that the high flow of the Meghna River backed up the combined Ganga–Brahmaputra flow at the confluence, which in turn aggravated the flooding situation further upstream. The particular temporal connection between rainfall periods, discharge peaks and flood phases is important for understanding the flood processes. External inflow, and thus a connection between the Assam and Bangladesh floods, is evident. Finally, the direct link between the level of the groundwater table and the flooding processes was particularly obvious in the area of confluence of the Ganga and the Brahmaputra.

Factors that were important for the nationwide flooding in Bangladesh in early August:

- pre-monsoon rains;
- widespread above-average rainfall in July, inside as well as outside Bangladesh, particularly in the second part of the month;
- recurrent rainfall periods in Bangladesh, the most extended of which occurred in the second part of July and led up to the nationwide flood in the first part of August;
- the Meghna catchment, and the Meghalaya Hills in particular;
- synchronization of the above-danger-level flow of the three main rivers and of the annual maximum flows of the Brahmaputra and the Meghna;
- an imported flood wave through the Brahmaputra from Lower Assam;
- the high level of the groundwater table in particular areas.

Factors that were not important for the nationwide flooding in Bangladesh in early August:

- the Ganga (it is important only in combination with the other big rivers);
- single daily rainfall events;
- the Himalayas (this statement is based on calculations of R(pot) and on the discharge characteristics of the Tista).

Appendix 5.6: 1987 – A "flood year" for Bangladesh

The summary of this case study is presented in section 5.9 (pp. 172–177).

The 1987 flood situation at a glance

Flood dimension in Bangladesh

The flood, which affected 57,300 km^2 (40.13 per cent) of the country, ranks third for the period 1954–2004 (see Table 4.1). "It was the worst flood over the last 40 years that hit Bangladesh this year, and the country experienced the most deplorable decimation of lives in barely believable digits" (Hussain and Samad 1987: 1).

Flood-affected areas (Figure 5A.24)

Compared with the 1955 and 1974 case studies, information has again improved. Figure 5A.24 maps not only the flood-affected area during 1987 but also the degree to which these areas were affected. The most seriously flooded areas were: the western bank of the Brahmaputra; the area below the confluence of the Ganga and the Brahmaputra; regions north of Khulna; areas adjacent to the Meghalaya Hills. There were exceptional flood conditions in the north-western districts, which are usually considered flood free. The southern parts of Bangladesh, namely the areas south of Khulna and Barisal as well as west of Noakhali, were only moderately flooded or even flood free, which is rather striking.

Chronology

The floods occurred in different phases and regions. They started in June with a flash flood in the north-east, and they reached their maximum extent in August; in September, additional serious flooding occurred in the Ganga and Kushiyara areas. The duration of flooding was clearly quite extraordinary. All four flood types normally encountered in Bangladesh (flash flood, river flood, rain flood and tidal flood – see Figure 2.1) occurred separately or in combination during the 1987 flood season.

Flooding conditions outside Bangladesh

In August, flooding was widespread not only in Bangladesh but also in the Indian states of Bihar, West Bengal and Assam (for the location of these states, see Figure 4.8). The floods in Assam were extraordinary, occurring in five waves during the period from July to September, and reaching their maximum dimension in August. In Bihar, the floods started in August and affected some areas until late October. In West Bengal, floods were reported mainly in August.

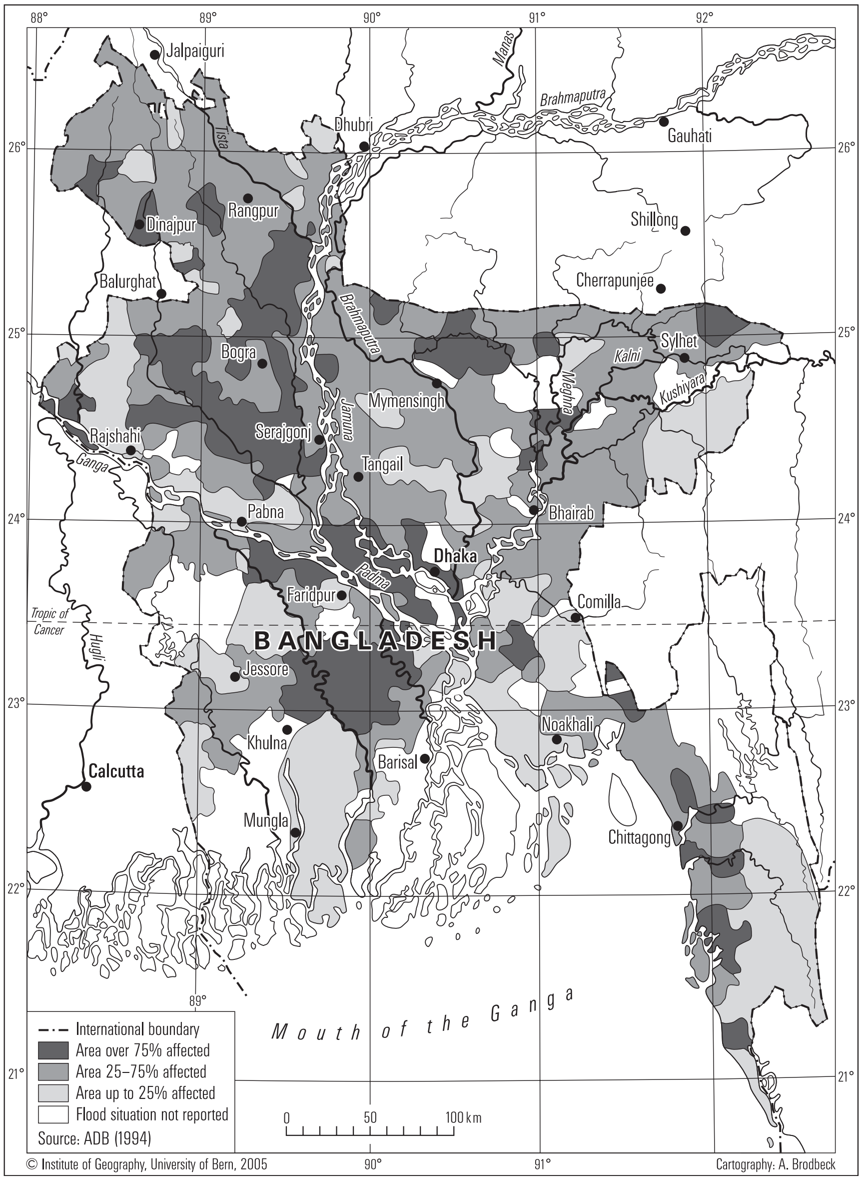


Figure 5A.24 Flood-affected areas, synthesized for the entire monsoon season: 1987.

Causes of flooding as discussed in the literature

> The Bay of Bengal monsoon depressions, which usually travel north westwards extending up into western India, changed their course drastically in 1987. Almost all the depressions with the exception of one or two travelled northwards causing rainfall in Bangladesh, Assam, Bihar, West Bengal, Bhutan and Nepal. Consequently these areas were flooded and Bangladesh, being the lower riparian country, got the most of it. (Choudhury 1989: 238)

References to other specific causes

- above-average rainfall throughout the country, particularly in the north;
- a combination of flood flow from across the border and high rainfall within the country;
- synchronized high levels of the Ganga, Brahmaputra and Meghna;
- spring tides;
- impeded drainage owing to obstructions such as roads, embankments and bridges;
- public cuts and breaches in the embankments.

> Inland areas have been inundated even before the stage [water level] of the river nearby has crossed the danger level. The depth of flooding inland has been more than the river stage would normally suggest ... Floods, at least some of them, are due to overland run-off rather than spill over of river-waters. (Miah 1988: 6)

Literature sources

BWDB (1987); Hussain and Samad (1987); *India Today* (1987); Frisch (1988); Miah (1988); Ministry of Irrigation, Water Development and Flood Control (1988); Venkataramani (1988); Choudhury (1989); Matin and Husain (1989); Brammer (1990a); Pasche (1990); USAID (1990); Agarwal and Narain (1991); GOB (1992b).

Hydrological contributions from the different subcatchments and their relevance to the flooding conditions in Bangladesh (Figure 5A.25, Figure 5.1)

The potential runoff was above average for the whole of Bangladesh from July to September. The positive anomalies were particularly important in North-western Bangladesh (SC10): in July and August, *R*(pot) was double the average, the July figure being the highest recorded between 1950 and 1990 for this month and subcatchment. The fact that, in July, SC10 contributed almost the same amount of *R*(pot) as the Lower Ganga Plain (SC5), which is eight times larger, underlines the importance of this situation. Accordingly, SC10 is placed in the second rank in terms

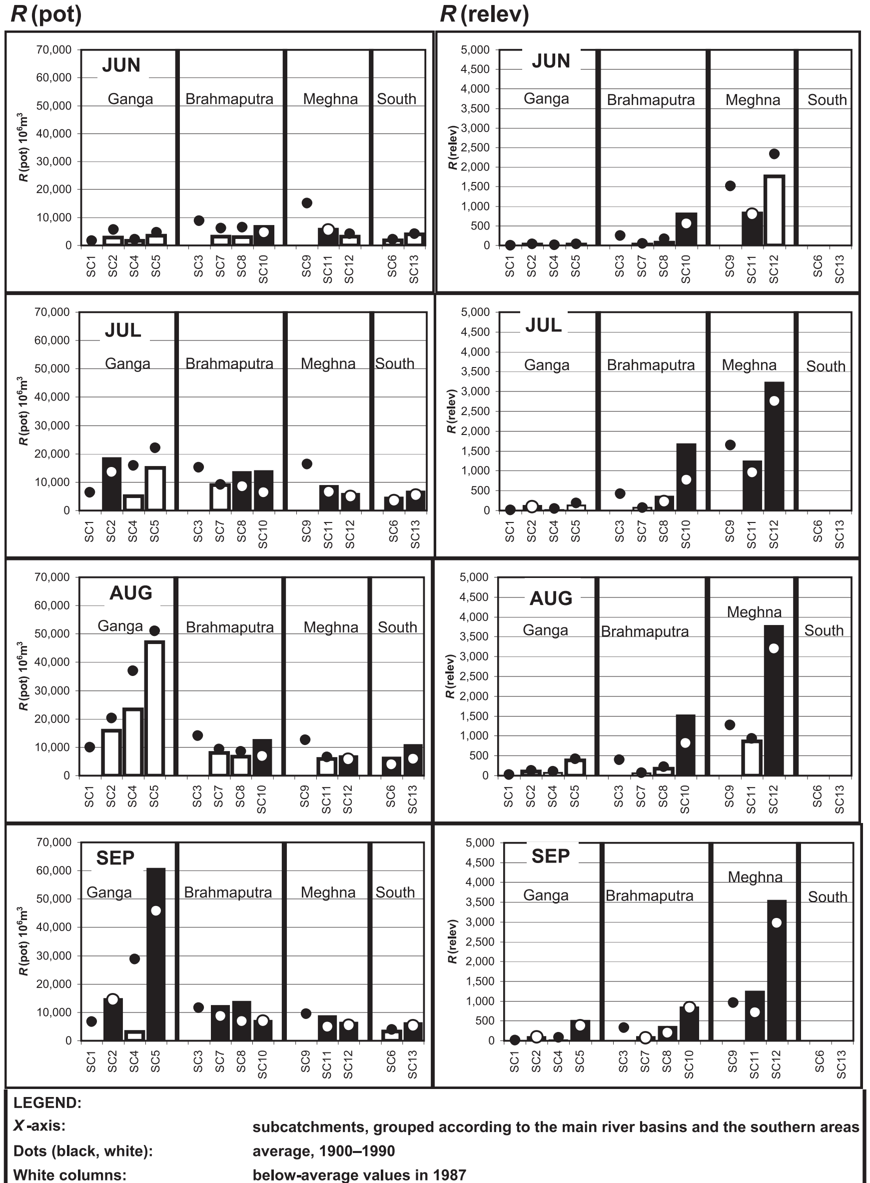


Figure 5A.25 Monthly potential runoff (*R*(pot)) and relevance for Bangladesh (*R*(relev)) in the 13 subcatchments for the four monsoon months of 1987.

Notes: *R*(relev) has no measuring unit. For the location of the subcatchments, see Figure 5.1; for the data sources, see Table 3.2. It is unfortunate that, in terms of highland subcatchments, data are available only for Nepal (SC2).

of *R*(relev), just after Central–Eastern Bangladesh (SC12). SC12 retains the first rank throughout the monsoon season and warrants special attention in terms of above-average relevance. In the south, the positive variations in *R*(pot) from July to September might have hampered the discharge of flood waters into the Bay of Bengal through backwater effects. Based on these observations it is obvious that the hydrological input within the country was an important component in the creation of extended flooding in Bangladesh, particularly in the north-western areas.

The hydrological contribution from the Ganga system was generally below average. Only the positive anomalies in September in the Lower Ganga Plain (SC5) can be related to the flood processes in western Bangladesh in this particular month.

There is no reason to assume that the Nepal Himalayas (SC2) had a significant effect on flooding conditions in Bangladesh. The above-average *R*(pot) in July in SC2 hardly raised the flood relevance even locally.

As discussed in the first section of this Appendix, there were widespread floods in Bihar, West Bengal and Assam in August. It is striking, though, that *R*(pot) in August for the same areas (mainly SC5, SC7 and SC8) was below average. Were these floods triggered by heavy rainfall events of limited duration that are not evidenced in the monthly values of *R*(pot)? Based on the fact that the anomalies in *R*(pot) in August reflect the flooding conditions in Bangladesh (positive variations in potential runoff in SC6, SC10, SC12 and SC13 in August) but not those further upstream in the areas of Bihar, West Bengal and Assam (negative variations in potential runoff in SC5, SC7 and SC8), we propose the following hypotheses for discussion:

- The generation of large-scale flooding in Bangladesh takes time. Flood water is gradually accumulated throughout the monsoon season as a result of long-term hydro-climatological processes. Short-term, heavy rainfall events are not sufficient to trigger extended flooding conditions. Data with monthly resolution are appropriate to get a general understanding of these flooding processes.
- Floods further upstream in the basin, where catchment sizes decrease, develop faster. Short-term, intensive hydro-climatological events are important in their generation. Monthly information is not sufficient to understand these processes: severe flooding might have been triggered by a few days of heavy rainfall within a month of generally low precipitation. The monthly value of *R*(pot) might be below average in spite of serious inundation processes reported from the particular area.

The widespread positive anomalies in *R*(pot) and *R*(relev) in September are remarkable. Considering also the gradual accumulation of water in the Bangladeshi subcatchments throughout the monsoon season, widespread floods, even more severe than the ones in August, could have been expected in September as well. In reality, however, severe flooding was limited to the Ganga and Kushiyara areas.

According to the relevant calculations, the input during the premonsoon period was average or even below in the entire basin. Therefore, the hydro-climatological processes before the onset of the monsoon neither promoted nor contributed to the subsequent flooding conditions.

Monthly discharge (Figure 5A.26)

All the rivers recorded above-average monthly flows during the main flooding period in August and September. This might entail some contradiction of the discussion of Figure 5A.25, particularly in view of the below-average *R*(pot) and *R*(relev) in the Indian Ganga and Brahmaputra lowlands in August. This section provides some ideas to explain the situation.

The smallest positive anomalies in monthly flows in July and August were recorded in the Meghna catchment and were probably related to the above-average *R*(pot) in SC12. Obviously the Meghna basin was less decisive for the generation of the floods in 1987 than in 1974. However, we have to reiterate that no information is available about the situation in the Meghalaya Hills (SC9).

The monthly flow of the Brahmaputra at Bahadurabad and of the Tista at Kaunia was permanently above average from July to December. Considering the five flood waves in Assam from July to September (see the first section of this Appendix), this result is to be expected. However, based on the findings from Figure 5A.25, particularly the below-average *R*(pot) in SC7 and SC8 in August and the constantly above-average *R*(pot) in SC10 from June to September, we can assume that the above-average monthly flows of the Brahmaputra only partially originated in Assam and to a large extent were caused by the above-average *R*(pot) in the vicinity of Bahadurabad (SC10) as well as by high inflow from the Tista.

Except in August and September, below-average discharge was dominant in the Ganga. In September, the positive anomaly in *R*(pot) in SC5, the significantly above-average flow of the Ganga and the regionally limited flood processes in western Bangladesh are certainly all connected. However, the abrupt change from below-average flow in July to above-average flow in August is not explicable with the anomalies in *R*(pot), which were significantly negative for both SC4 and SC5 in July and August. Two uncertainties need to be considered here: snow and glacial melt in the Himalayas and human-made modifications of the Ganga flow in Bangladesh because of the sluices in the Farakka Reservoir.

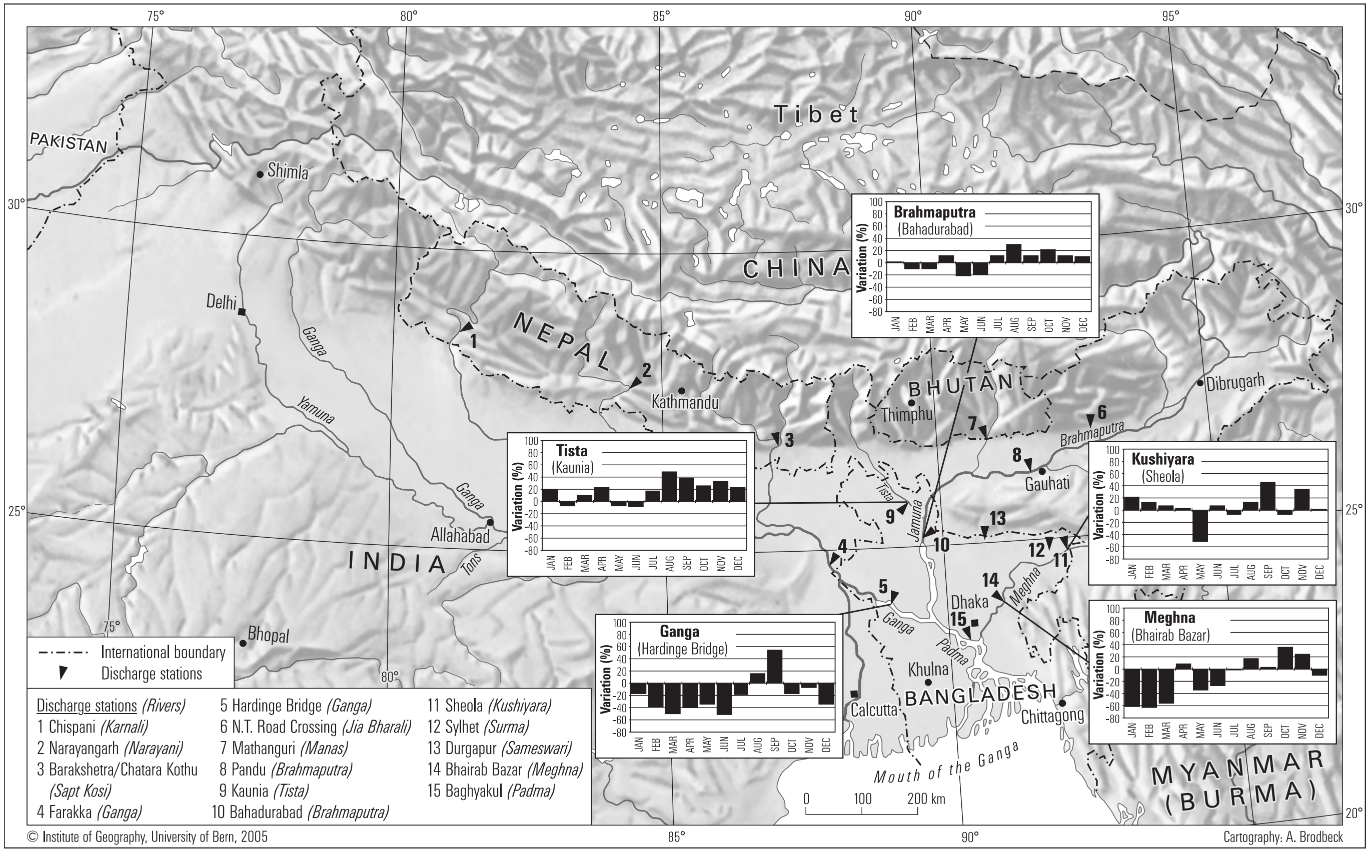


Figure 5A.26 Monthly discharge variations as a percentage of the average for selected rivers in 1987.
Notes: For the data sources, see Table 3.4.

The below-average flow in May and June for all the rivers is in accordance with the discussion in the previous section: the flood processes were not preconditioned or promoted by the hydrological situation in the pre-monsoon period.

Daily rainfall (Figure 5A.27)

In north-eastern Bangladesh, rainfall occurred almost constantly from mid-June to the end of September. However, three distinct rainfall periods can be identified that affected more or less the entire country:

- 21 July–3 August: for almost two weeks, rainfall was recorded constantly throughout Bangladesh, and several rare events occurred, particularly in the north-western part. These heavy and widespread rains coincided with the onset of the nationwide flood in Bangladesh. The climatological situation leading to this long rainfall period is discussed in Schneider (1996) and in section 5.15.
- 20–28 August: this rainfall period, which included a short break, began just after the main flooding period was over. Some unusually high rainfall events were recorded in the south.
- 23–29 September: the rains were most accentuated in north-eastern Bangladesh, where late monsoon floods occurred.

To some extent the spatial and temporal characteristics of the floods are related to the daily rainfall processes in Bangladesh. It is very clear that in north-western Bangladesh, where the floods were very severe, the daily rains were particularly heavy in the last part of July. However, the fact that the flooding reached its maximum extent in the first part of August, which was a rather dry period in terms of rainfall within Bangladesh, provided an interesting case for the discussion of input into the flood-affected areas from outside the borders of Bangladesh. Luckily it was possible to collect daily rainfall data for some Indian stations for selected periods of the 1987 monsoon season (IMD 1987). The most important figures are compiled in Table 5A.3.

During the main rainfall period in Bangladesh (21 July–3 August), which corresponds to the first part of the widespread flooding, precipitation was also high in Meghalaya, Assam and Bihar. At almost 2,300 mm, the rainfall in Cherrapunjee during these 14 days was particularly high. Precipitation in Patna and Shillong significantly exceeded the average July rainfall for these sites. The actual figure for Shillong was probably even higher since there are three days with missing data.

From 10 to 13 August, when the severe flood was still ongoing but the rainfall in Bangladesh was limited to the north-western part of the country, rainfall outside Bangladesh was important and widespread. In this climatological situation we can find a reasonable explanation of the more

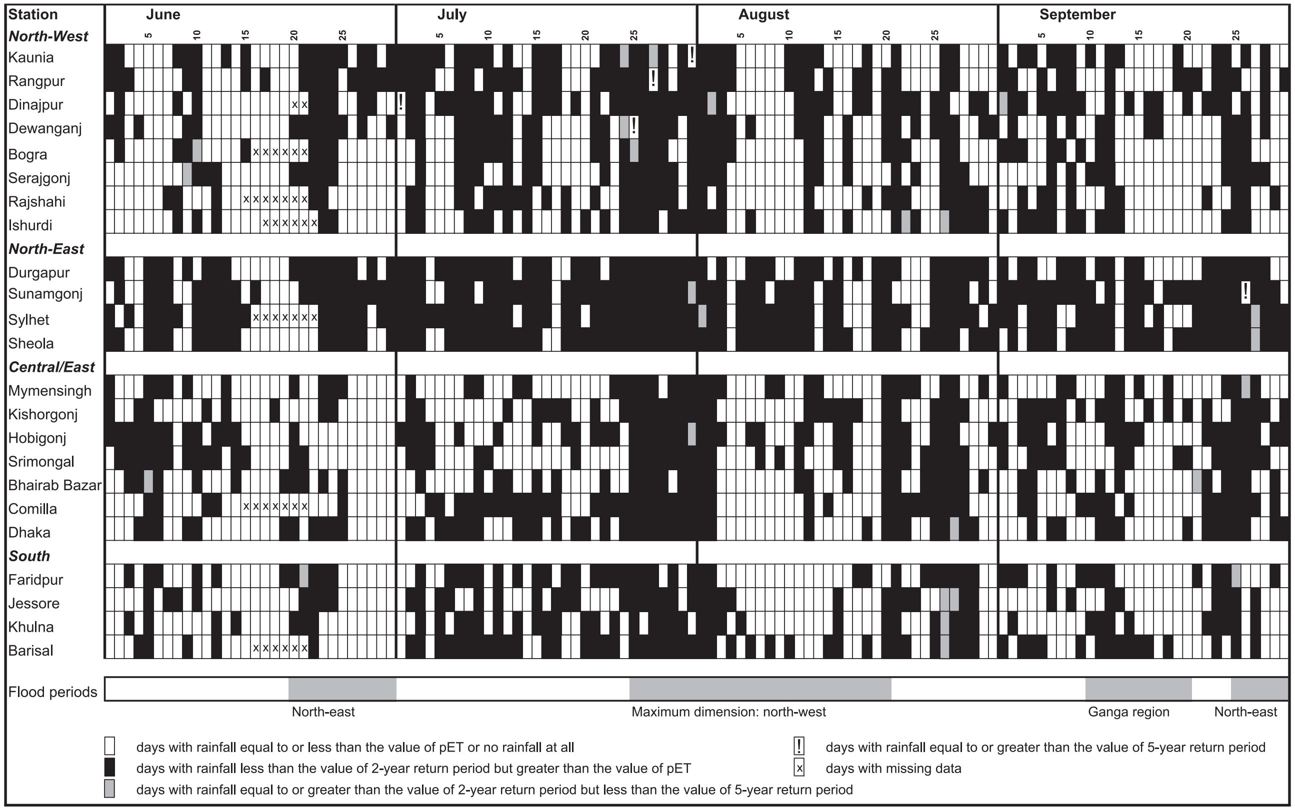


Figure 5A.27 Categories of daily rainfall for the period 1 June–30 September 1987 in Bangladesh.
Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2; for threshold values for the return periods, see Table 5A.2.

Table 5A.3 Rainfall for selected time periods, compared with monthly averages, at selected meteorological stations outside Bangladesh, 1987 (mm)

Station	21 July–3 August	July average	10–13 August	August average
Patna	457[a]	294	273	317
Cherrapunjee	2,266[a]	2,628	660	1,796
Shillong	591[c]	368	184	313
Dibrugarh	315	538	146	444
Gauhati	179[a]	316	83	259
Gangtok	278[a]	n.a.	207	n.a.
Jalpaiguri	359[b]	n.a.	1,062	n.a.

Source: IMD (1987).

Notes: For the location of Gangtok and Jalpaiguri stations, see the text; for the other stations, see Figure 3.1. n.a. = data not available.

[a] 1 record missing.

[b] 2 records missing.

[c] 3 records missing.

or less simultaneous flood processes in Bangladesh, Assam, Bihar and West Bengal, as documented in the first section of this Appendix. The comparison of rainfall in Gangtok and Jalpaiguri is particularly interesting: in Gangtok (Sikkim), located inside the first Himalayan ranges at 1,727 metres above sea level and not too far from Darjiling, total rainfall over the four days was five times less than in Jalpaiguri, which is situated on the Tista River in the floodplains south of the Himalayan foothills roughly 40 km north of the India–Bangladesh border. Rainfall of more than 1,000 mm in Jalpaiguri over only four days is extraordinary. A similar situation has already been identified and discussed in the 1906 (Appendix 5.1) and 1910 (Appendix 5.2) case studies in the sections on daily rainfall.

To summarize these findings, during the first part of the main flood period in Bangladesh, the rainfall was concentrated in Meghalaya, in northern Bangladesh, in Lower Assam and in the Himalayan foothills of West Bengal and Bihar. During the second part there was a strong external input into the flooding in Bangladesh from the Brahmaputra system, not from the Himalayas but from the foothills and the lowlands south of the Himalayas. This interpretation is supported by Schneider (1996), who, from the satellite images of the US National Oceanic & Atmospheric Administration's Advanced Very High Resolution Radiometer (NOAA-AVHRR), identified much higher cloud coverage over the plains and foothills than over Nepal and Bhutan (see also section 5.15).

The flooding at the end of September in north-eastern Bangladesh was produced by rainfall over the area itself as well as by a significant contribution from Meghalaya (1,076 mm between 21 and 28 September in Cherrapunjee). The flooding in mid-September in western Bangladesh cannot be satisfactorily explained with the available data: the event coincided with a high flow of the Ganga (see the next section) but was not related either to daily rainfall in the area or to the precipitation recorded higher up in the Indian Ganga Plain.

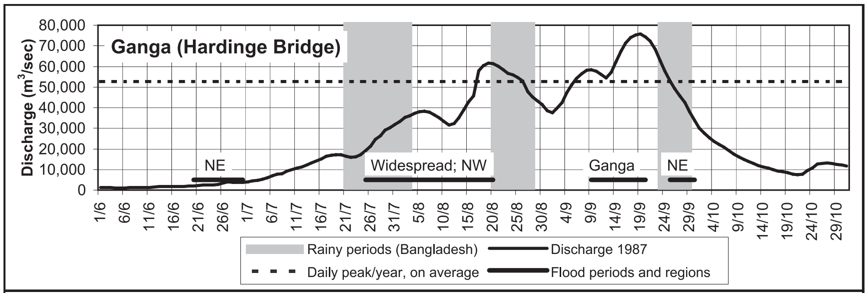
Daily discharge (Figures 5A.28 and 5A.29)

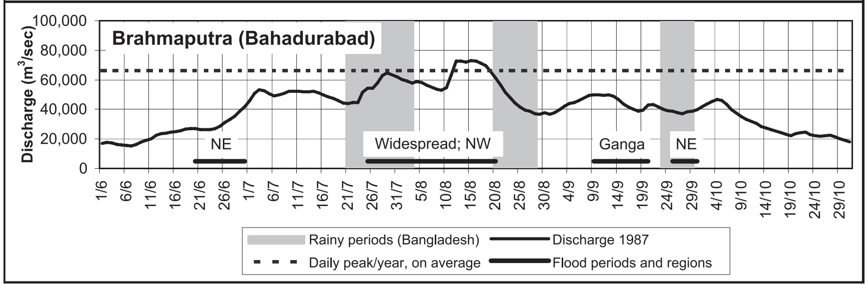
At all stations within Bangladesh (Figure 5A.28) the flow exceeded the maximum discharge that is on average reached during the monsoon season. This observation confirms that 1987 was hydrologically an extraordinary year. The most significant anomalies were measured in the Tista in mid-August and in the Ganga in the second part of September. These peaks have a return period of approximately 20 years and 40 years, respectively. All the rivers reacted to the rainfall periods within Bangladesh, which is most obvious for the Meghna. However, in all the rivers except the Meghna, there are some discharge peaks that do not coincide with rainy periods within the country, for example, the Ganga in mid-September, the Brahmaputra and the Tista in mid-August.

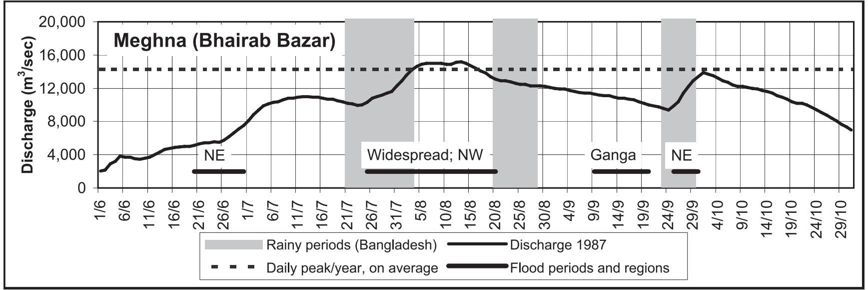
The early flooding at the end of June in north-eastern Bangladesh is not documented in the hydrographs of the Kushiyara and the Meghna. This flood may have been caused by overland flow (flash flooding) rather than by river overflow.

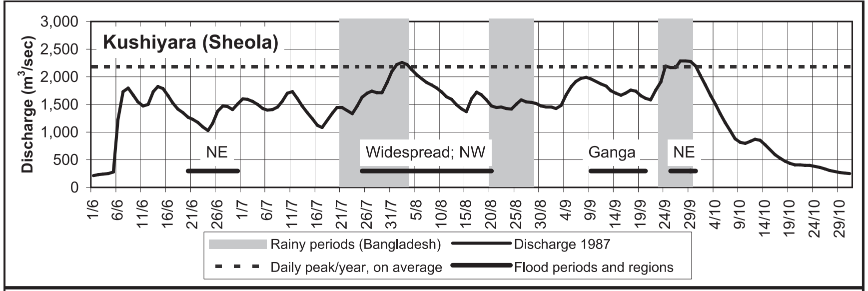
In Figure 5A.28, the first part of the widespread flooding in Bangladesh at the end of July is characterized by increasing discharge of the rivers as a result of the widespread rains within the country. For the development of the flood, the accumulation of rainwater might have been as important as the overflow of the rivers (see also Miah 1988). The really high flows were reached after the widespread rains and were imported: as a result of heavy rains outside the borders of Bangladesh (see the previous section), the three big rivers simultaneously recorded above-danger-level flows in the period from roughly 12 to 21 August (BWDB 1987; Miah 1988), the Tista reached its extraordinary peak, and the floods most probably reached their maximum dimension. This imported flood wave aggravated the existing flood situation through overflowing of the rivers. In summary, the widespread flooding in Bangladesh from 25 July to 21 August was a combination of local rain flood and imported river flood, with origins particularly in the Indian lowland catchments of the Brahmaputra and the Tista and in the Meghalaya Hills.

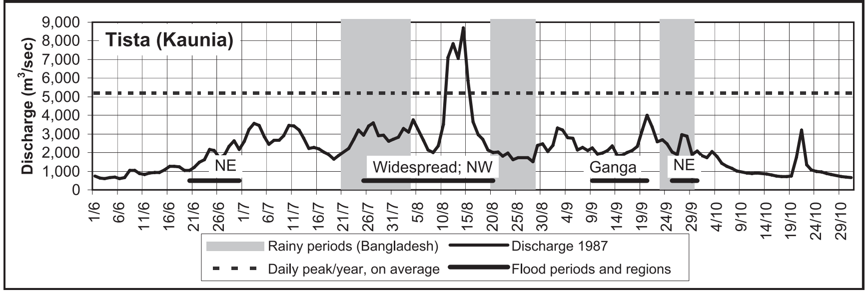
Throughout September the flow of the Ganga was above danger level (BWDB 1987) and the annual maximum flow was reached in the second half of the month. This high flow coincided with the flood phase in west-


Ganga (Hardinge Bridge)
Discharge (m³/sec)
80,000
70,000
60,000
50,000
40,000
30,000
20,000
10,000
0
NE
Widespread; NW
Ganga
NE
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Rainy periods (Bangladesh)
Discharge 1987
Daily peak/year, on average
Flood periods and regions


Brahmaputra (Bahadurabad)
Discharge (m³/sec)
100,000
80,000
60,000
40,000
20,000
0
NE
Widespread; NW
Ganga
NE
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Rainy periods (Bangladesh)
Discharge 1987
Daily peak/year, on average
Flood periods and regions


Meghna (Bhairab Bazar)
Discharge (m³/sec)
20,000
16,000
12,000
8,000
4,000
0
NE
Widespread; NW
Ganga
NE
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Rainy periods (Bangladesh)
Discharge 1987
Daily peak/year, on average
Flood periods and regions


Kushiyara (Sheola)
Discharge (m³/sec)
3,000
2,500
2,000
1,500
1,000
500
0
NE
Widespread; NW
Ganga
NE
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Rainy periods (Bangladesh)
Discharge 1987
Daily peak/year, on average
Flood periods and regions


Tista (Kaunia)
Discharge (m³/sec)
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
NE
Widespread; NW
Ganga
NE
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Rainy periods (Bangladesh)
Discharge 1987
Daily peak/year, on average
Flood periods and regions

ern Bangladesh. However, as discussed in the previous sections, it cannot be explained by the rainfall processes in western Bangladesh or in the Indian Ganga Plain. An important question, then, might be whether water was released from the Farakka Barrage during this period. Or is information missing owing to the low density of the stations? It is interesting, though, that this high flow of the Ganga produced only regional and very limited flooding in Bangladesh.

The late monsoon flood towards the end of September (25–30 September approximately) in north-eastern Bangladesh is well documented in the discharge hydrographs of the Meghna and the Kushiyara in Figure 5A.28 and in the rainfall patterns.

Comparison of the Kushiyara and the Meghna hydrographs is very interesting: the Meghna hydrograph is smooth and is characterized by long-term discharge fluctuations, whereas the Kushiyara hydrograph includes a large number of short-term discharge fluctuations with sharp gradients. This difference documents the smoothing and levelling of short-term peaks with increasing catchment size and especially also the effects of water storage in the extended beels in the depressions of the Meghna catchment to the west of the Sylhet depression.

It was possible to collect daily discharge data for three major Nepali tributaries of the Ganga (Figure 5A.29) for 1987. All three stations are located in the transition zone between the Himalayas and the adjacent plains (see Figure 3.2). The three graphs provide some additional insight into the highland–lowland linkages: the two most important discharge peaks, which occurred towards the end of July and in the period between 10 and 15 August, are reflected in all three graphs. In view of the dimension of these peaks, it is astonishing that there are no indications of flood processes in Nepal in the available records. The two periods of high flow of the three Nepali tributaries (late July and mid-August) fall within the period of maximum flood extent in Bangladesh and very likely also of the floods reported for Bihar and West Bengal (see the first section of this Appendix). We might conclude from this that the hydrological contribution from the Nepal Himalayas to the floods was significant in certain time periods. However, there are a number of arguments and observations that call for a relativization or even rejection of this conclusion, at least in terms of the contribution to the Bangladesh floods:

Figure 5A.28 Average daily discharge of selected rivers in Bangladesh for the period 1 June–31 October 1987, compared with flood periods, rainy periods and daily peak/year, on average.
Notes: For the location of the stations, see Figure 3.2; for the data sources, see Table 3.4.

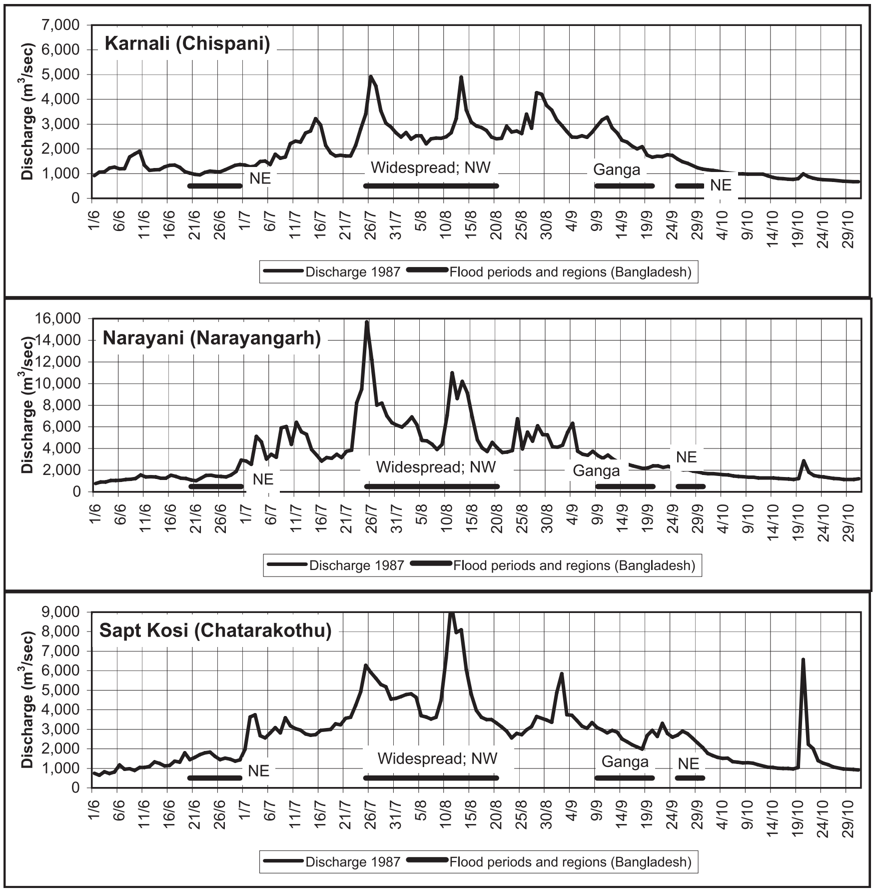


Figure 5A.29 Average daily discharge of three selected rivers in Nepal for the period 1 June–31 October 1987, compared with the flood periods in Bangladesh. *Notes*: For the location of the stations, see Figure 3.2; for the data source, see Table 3.4.

- If we assume a flow velocity of 1.5 m/sec or 130 km/day (see also the section on daily discharge in Appendix 5.11), it might take approximately one week for a flood wave created in the foothills of the Himalayas to reach the floodplains of Bangladesh. Accordingly, there is a significant time difference between the occurrence of a flood wave in the Himalayan foothills and its potential impact on the flood processes in Bangladesh.
- The flow of the Ganga at Hardinge Bridge (Figure 5A.28) does not

react specifically to the marked flood flows of the three Himalayan tributaries. It is therefore very likely that the peaks of the Himalayan tributaries levelled out once they reached the plains (this process will be discussed in detail in the 1993 case study in the section on daily discharge in Appendix 5.11). Again we have to mention here the uncertainty related to the Farakka Reservoir and its particular impact on the Ganga discharge.

- Except for the area of confluence with the other big rivers, there was no major flooding in the Ganga area within Bangladesh during August.

In September, the flow of the three Nepali tributaries gradually decreased. Accordingly, their contribution to the most important period of high flow of the Ganga in mid-September (Figure 5A.28) and, consequently, to the flood processes in western Bangladesh in this period can be ignored.

A closer look at the tidal movements revealed that the full moon in August coincided with the maximum extent of flooding in Bangladesh. There is no question that the discharge of the water masses, accumulated through rainfall and high river discharge, into the Bay of Bengal was influenced by the spring tides. This situation might have contributed to the dimension of the flooding. A more detailed discussion of tidal movements and their effects on flooding is available in the section on tidal effects in Appendix 5.7.

Groundwater (Figure 5A.30)

In general, all the stations recorded above-average groundwater levels during the monsoon season. As is to be expected from the discussion in the previous sections, the anomalies were highest in the western and north-western part of the country (stations RA28, B003, KT02, FA22). Except at station KT02, which recorded a strong reaction to the September floods in western Bangladesh, the highest groundwater levels were reached during the main flooding period (weeks 30–33). The intensive and widespread rains between 20 July and 2 August (weeks 30–31) resulted in a considerable accumulation of groundwater, documented in the sharp rise in the graphs. This indicates that there was only a minimal potential to absorb additional water in the groundwater reservoirs when the imported flood wave reached the country.

At stations MY03 and FA22, the groundwater table reached the surface. However, the data for MY03 do not seem to be reliable: the groundwater level remained at the surface for the rest of the year, which is not realistic. The conditions at station FA22 are similar to those in 1974: the overflowing of the groundwater might be the result of the synchronized high flow of the Ganga and the Brahmaputra.

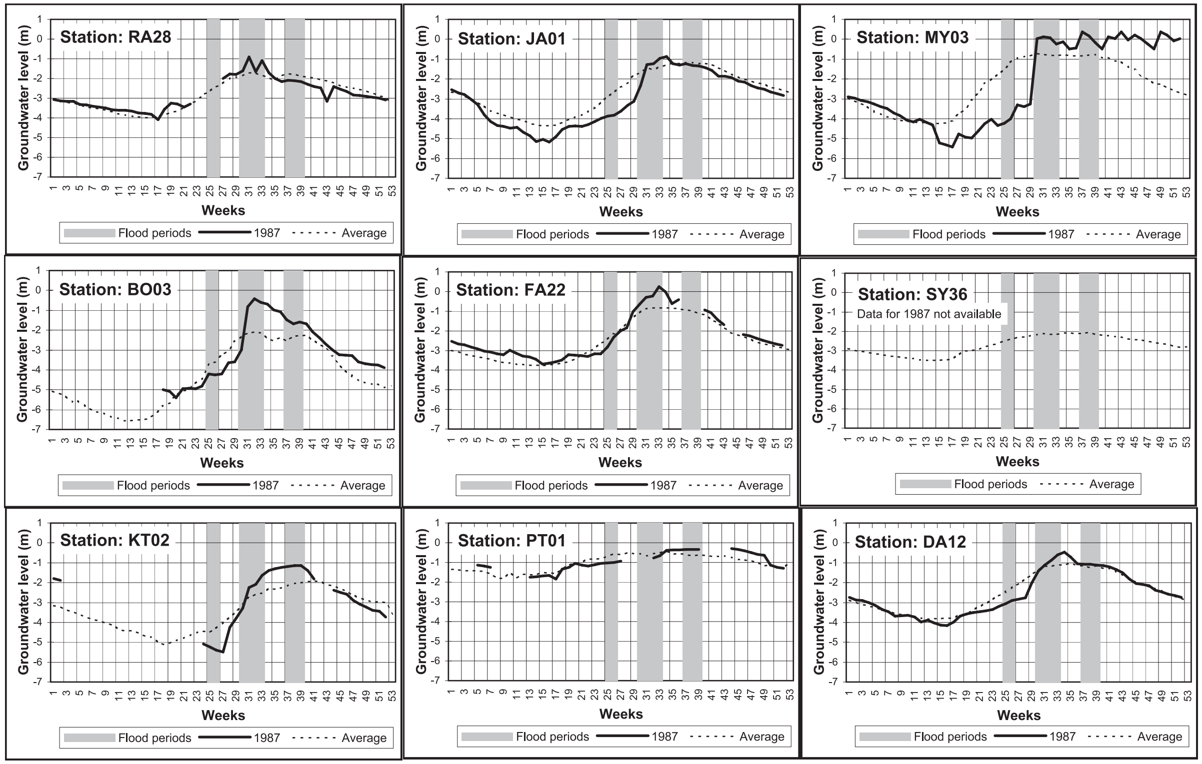


Figure 5A.30 Groundwater levels of selected stations in 1987, compared with flood periods and average groundwater levels over roughly 20 years.

Notes: For the location of the stations, see Figure 3.3. The four monsoon months correspond to the week numbers approximately as follows: June, weeks 23–26; July, weeks 27–30; August, weeks 31–34; September, weeks 35–38.

Source: BWDB (n.d.[b]).

In the pre-monsoon period, the groundwater table was below normal throughout Bangladesh. This finding confirms the statement made in the discussion of R(pot) and monthly discharge: the hydro-meteorological conditions in the pre-monsoon period did not predetermine the floods in 1987 – the inundations were the product of the monsoon period itself.

The September floods in western Bangladesh are well documented in the groundwater records: at station KT02, the groundwater table reached its highest level of the year (weeks 37–39).

Summary

The floods in Bangladesh, Assam, West Bengal and Bihar were interlinked. The rainfall in Bangladesh created the basic conditions for widespread flooding. The imported high water flows, particularly through the Meghna and the Brahmaputra–Tista systems, significantly aggravated the flood situation. The literature statements about the combination of high rainfall in the country itself and high flows from across the border as an important flood-causing factor can fully be supported (see the first section of this Appendix). Again, the Meghna and the Brahmaputra systems were much more important than the Ganga catchment for the triggering of the widespread inundations in August, particularly with regard to the relevance of these areas as well as the hydro-meteorological anomalies in these river systems. The floods along the Ganga within Bangladesh to the south of Pabna documented in Figure 5.16 were spatially limited and occurred not during the main flooding period in August but in September, when the Ganga reached its highest water level of the year. As discussed in the literature, there were indeed floods in August higher up in the Ganga system, in West Bengal and Bihar, but again these floods were spatially limited events. However, the Ganga deserves attention because of the fact that its first period of above-danger-level flow coincided temporally with the annual peak flows of the Brahmaputra and the Meghna around mid-August.

In terms of highland–lowland interactions, the flood of 1987 reveals the following interesting situation. The external input in the Meghna system directly originated in the Meghalaya Hills. In the case of the Brahmaputra system, the external input mainly originated in the foothills and the lowlands south of the Himalayas, not in the mountains. Finally, the flood waves recorded in the Himalayan foothills of the Ganga system levelled out once these tributaries reached the Ganga and did not have any flood-triggering effect in Bangladesh.

Factors that were important for the flooding in Bangladesh in 1987:

- rainfall in Bangladesh, particularly in the north-western region;
- input from the Meghalaya Hills;

- an imported flood wave from the Tista and the Brahmaputra;
- synchronization of the high flow of the three main rivers from 12 to 21 August;
- a high groundwater table;
- coincidence with a high, even spring, tide after the full moon in August.

Factors that were not important for the flooding in Bangladesh in 1987:

- the pre-monsoon period;
- single daily rainfall events;
- the influence of the Himalayas (this statement is based on the calculations of $R(\text{pot})$ in the Nepal Himalayas and on the detailed investigations in the Tista catchment).

Appendix 5.7: 1988 – A "flood year" for Bangladesh

The summary of this case study is presented in section 5.10 (pp. 177–183).

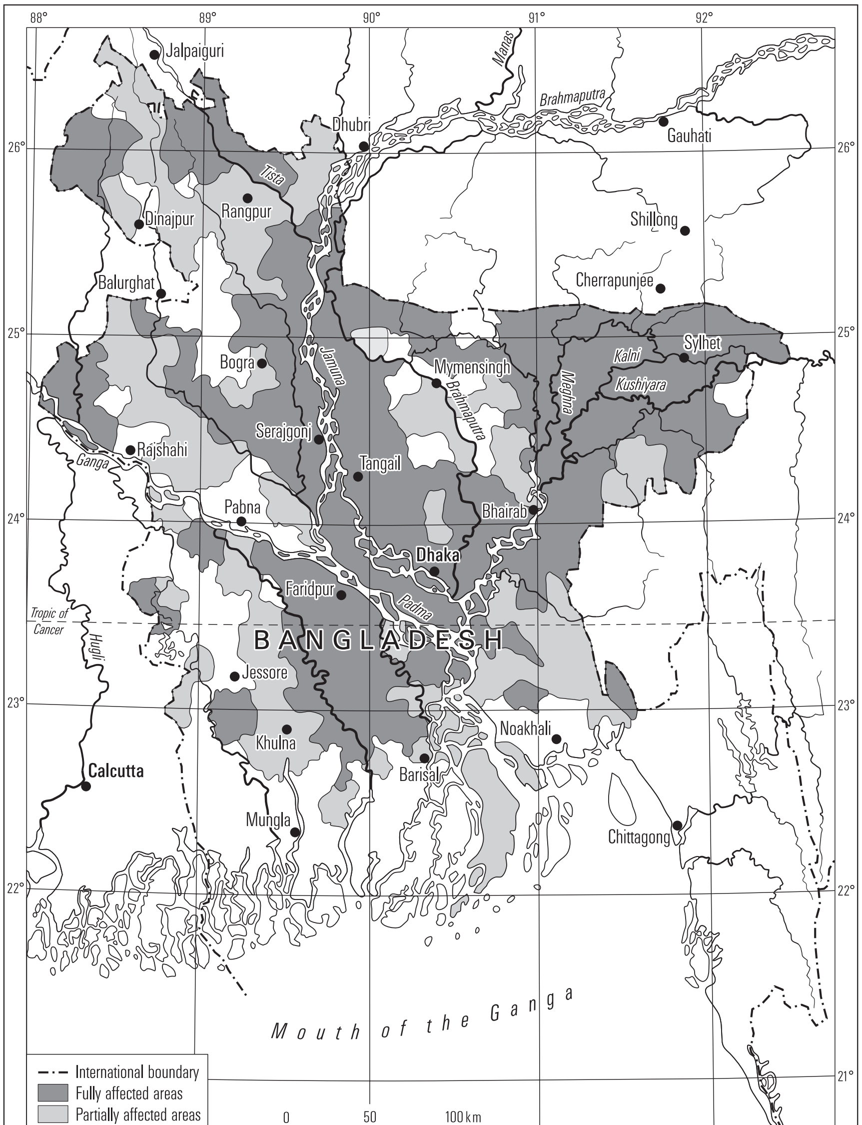
The 1988 flood situation at a glance

Flood dimension in Bangladesh (Figure 5A.31)

With 89,970 km^2 (63.01 per cent) of the country affected, 1988 was one of the worst floods in the twentieth century and ranks second for the period 1954–2004 (see Table 4.1). The available source for the map differentiates only between areas that were fully affected and areas that were partially affected by the floods. Areas of the Meghna and the Brahmaputra catchment, including central Bangladesh, suffered most, whereas the southern regions and significant parts of western Bangladesh were only moderately affected or even flood free. This observation is supported by Hossain (1990: 3): "substantial areas in the south-east, south-west, west and north-west of the country did not experience floods at all, while in the north, north-east and the centre of the country the flood lasted long and had been unprecedentedly severe." Islam (1990: 18) adds that, "for the first time, the flood almost totally inundated the capital city including the residence of the President of the country and of the foreign ambassadors".

Chronology

A first flood phase occurred from mid-April to mid-May in the eastern and north-eastern parts of the country. In June almost no flooding took place. In early July the Meghna basin experienced severe flooding that, in terms of its intensity, exceeded that of 1974 and 1987. During this period the Brahmaputra was also in flood. Before this flood had sufficiently



Source: ADB (1994)

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Cartography: A. Brodbeck

Figure 5A.31 Flood-affected areas, synthesized for the entire monsoon season: 1988.

receded, heavy rainfall occurred in the northern and north-eastern parts of Bangladesh, with the actual rainfall centres lying in Assam, the Indian Gangetic Plain and Meghalaya. As a result, all the major rivers started rising gradually from 10 August and then simultaneously and very rapidly from 20 August, reaching their peaks between 30 August and 2 September. Accordingly, this nationwide flood occurred roughly between 20 August and 5 September.

Flooding conditions outside Bangladesh

As in Bangladesh, the flood-affected area in Assam (the Brahmaputra lowland in India) was one of the largest of the twentieth century. The floods occurred in several waves: May (16 districts, 1.5 million people affected); June (17 districts, 2.4 million people affected); July (4 districts); and August (17 districts, 3.82 million hectares and 8.41 million people affected). The most severe flooding in Assam coincided with the maximum flood extent in Bangladesh between 20 and 28 August. In the Ganga system, floods were reported in Bihar and West Bengal (see Figure 4.8) in June, in Nepal in July and in the far western Ganga catchment in late September. Thus, unlike the events in Assam, the timing of the floods in the Ganga system was different from that in Bangladesh.

Causes of flooding as discussed in the literature

A variety of natural as well as anthropogenic factors, originating partly inside and partly outside Bangladesh, are discussed in the literature. Most importantly, Popelewski (1988) refers to a swing during the summer of 1988 towards the positive phase of the Southern Oscillation, which results in heavy rains in monsoon areas (the Southern Oscillation is an alternation in the pressure difference at sea level between the eastern and western Pacific Ocean). As a result of uncertainties in data interpretation or of missing information, some statements in the literature are contradictory. For example, a number of authors emphasize that rainfall within Bangladesh was not particularly high and that most of the flood water must have come across the borders, although the Ganga catchment generally played a minor role. Other authors state that there was heavy rainfall in northern and north-eastern Bangladesh, in Assam and in Meghalaya and that the synchronization of the peak flow of the three major rivers was important. Some additional specific causes of the 1988 floods are listed in the literature: very saturated catchments as a result of rains in July; a delay in the discharge of flood water into the Bay of Bengal owing to a spring tide and southerly winds; deforestation, erosion and river silting within and outside Bangladesh; flood control structures that exacerbated the flood situation. Interestingly, the loss of natural storage areas such as beels, swamps and old river courses, which is attracting more and more attention in discussions about the causes of the big floods, is not mentioned in the available literature related to the 1988 event.

Literature sources

BWDB (1988); Miah (1988); Popelewski (1988); USAID (1988); Abbas (1989); Ahmad (1989); Ahmed (1989); Choudhury (1989); Government of Assam (1989); Khan (1989); Latif (1989); Matin and Husain (1989); Shahjahan (1989); Hossain (1990); Islam (1990); Agarwal and Narain (1991); GOB (1992a, 1992b); Ramasastri (1992).

Hydrological contributions from the different subcatchments and their relevance to the flooding conditions in Bangladesh (Figure 5A.32, Figure 5.1)

In August, which was a key period for the floods in both Bangladesh and Assam, positive anomalies of *R*(pot) were calculated for 9 of 11 subcatchments. The figures are above average for the whole of Bangladesh as well as for the entire Meghna and Brahmaputra catchments.

With the exception of the south (SC13), the anomalies in *R*(pot) and *R*(relev) were constantly positive from June to August in Bangladesh (SC10, SC11, SC12). This significant local hydrological contribution provides an important element for explaining the floods in July as well as in the end of August/early September. According to the relevant calculations, a significant accumulation of water had already taken place during winter (January–March) and in the pre-monsoon period (April–May): in all the subcatchments of Bangladesh (SC10, SC11, SC12, SC13), variations were positive throughout both time periods. We can assume that, at the onset of the monsoon, the groundwater table and soil moisture levels in Bangladesh were already high.

In the Meghalaya Hills (SC9), *R*(pot) was above average from July to September, resulting in equally important anomalies in *R*(relev). The variations are most accentuated in August, when the values of *R*(pot) and *R*(relev) reached more than double the average; in terms of *R*(pot), SC9 ranks second of all the documented subcatchments, even exceeding the figure for the Lower Ganga Plain, which in terms of area is 17 times larger than the Meghalaya Hills. The amount of water that poured down from the Meghalaya Hills into the Meghna floodplains of Bangladesh during August is almost impossible to imagine.

In Assam, too, *R*(pot) was above normal – in Upper Assam (SC7) from July to September, in Lower Assam (SC8) from June to August. This situation clearly helps in understanding the various flood waves in this area. However, the impact of these positive variations on the flood processes in Bangladesh remains uncertain: the variations in *R*(pot) in

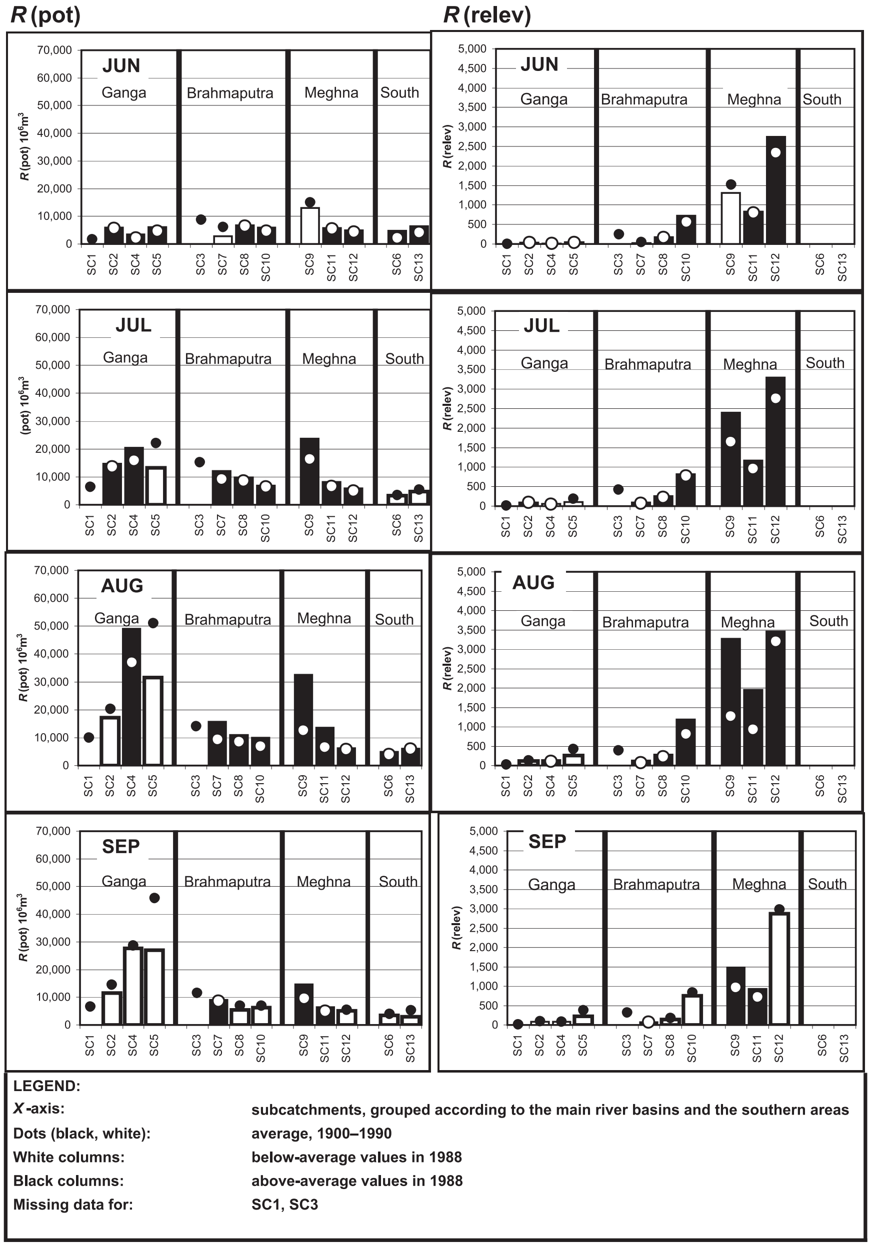


Figure 5A.32 Monthly potential runoff (R(pot)) and relevance for Bangladesh (R(relev)) in the 13 subcatchments for the four monsoon months of 1988.

Notes: R(relev) has no measuring unit. For the location of the subcatchments, see Figure 5.1; for the data sources, see Table 3.2. It is unfortunate that, in terms of highland subcatchments, data are available only for Nepal (SC2).

Upper and Lower Assam are rather small and the corresponding anomalies in *R*(relev) almost negligible. The fact that there was above-average *R*(pot) and that there were flood waves in Assam, but that *R*(relev) of the two subcatchments in Assam (SC7, SC8) for the flood processes in Bangladesh is negligible, is very interesting and again illustrates the nature and significance of the variable *R*(relev): obviously, above-average *R*(pot) and floods in Assam contribute to the high base flow of the Brahmaputra, but they do not necessarily trigger floods in Bangladesh unless a significant hydrological contribution is added in Bangladesh, which certainly was the case in 1988.

In the Ganga catchment as a whole, *R*(pot) was below average from July to September. Negative anomalies are particularly dominant for the Lower Ganga Plain (SC5). The positive anomalies in *R*(pot) recorded in July and August for the Upper Ganga Plain (SC4) were negligible in terms of relevance for Bangladesh. The floods in Bihar and West Bengal in June can be attributed to the slightly positive variations in *R*(pot) in SC2, SC4 and SC5 during this month.

Finally, the monthly information indicates that the Nepal Himalayas (SC2) did not contribute in any substantive way to the floods in Bangladesh: the anomalies in *R*(pot) were negative during the main flooding period.

Monthly discharge (Figure 5A.33)

The monthly flow of all five rivers was above average from July to September. This was to be expected from the calculations of *R*(pot) discussed in the previous section. Apart from this commonality, the monthly discharge characteristics are very specific to each river. In terms of duration and dimension, the positive discharge variations were very pronounced for the Meghna, where the monthly flows were significantly above average continuously from May to October, followed by the Brahmaputra. In marked contrast, the flow of the Ganga was below average for most of the year; out of the three months with positive discharge variations (July to September), only the anomaly in August is really meaningful. Yet, in view of the dominance of negative variations in *R*(pot) and *R*(relev), the positive anomalies from July to September of the Ganga are surprising. Was exceptional snow and glacial melt the cause of above-average Ganga flow? The monthly variations of the tributaries, the Tista and Kushiyara, are much more prominent than those of the three big rivers. The significant above-average flow of the Kushiyara in May reflects the positive anomaly in *R*(pot) calculated for the premonsoon period in Central–Eastern Bangladesh. The anomaly of the Tista in August is remarkable and warrants further consideration in subsequent discussions.

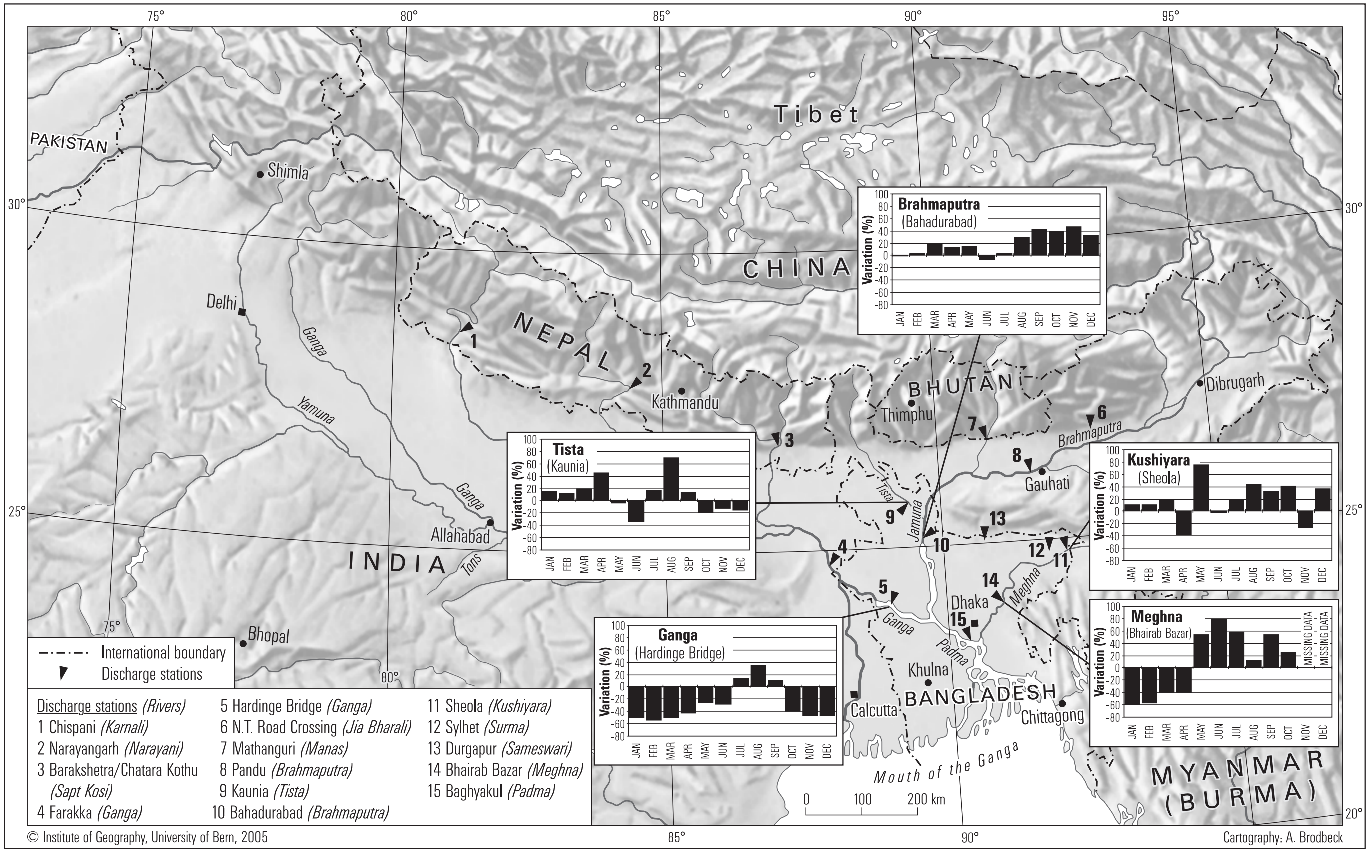


Figure 5A.33 Monthly discharge variations as a percentage of the average for selected rivers in 1988.
Notes: For the data sources, see Table 3.4.

Daily rainfall (Figure 5A.34)

The 1988 monsoon season was characterized by three rainfall periods:

- 12–26 June: rainfall was not only widespread but also heavy – in the last few days of this first period some events with a return period of two or more years occurred. These two weeks were basically flood free. However, significant volumes of water had certainly accumulated in the beels, rivers, soils and groundwater and it must be considered that flooding had already occurred in April and May in the eastern and north-eastern parts of the country.
- 3–12 July: rainfall was recorded continuously at almost all of the 23 stations in Bangladesh. The flood in the first part of July, which mainly affected the Meghna catchment, is related to this second phase: the floods began in the middle of the rainfall period and significantly extended into the subsequent dry period.
- 10 August–13 September: following a comparatively dry period of almost one month, this third rainy phase was particularly evident in the north-eastern and north-western part of the country. In the central and southern parts rainfall was only scattered and not continuous. In general, the rainfall intensities were not very high: there are very few cases of rainfall events with a return period of more than two years. The catastrophic nationwide flood falls more or less in the middle of this rainy period.

To some extent, the spatial and temporal characteristics of the two flood periods in July and August are related to the daily rainfall processes in Bangladesh. This is particularly clear for the inundations in the Meghna catchment in the first part of July, much less so for the severe floods at the end of August and beginning of September. There was undoubtedly a concentration of rainfall in the northern and north-western part of the country, which is confirmed by in Schneider's (1996) investigations of cloud coverage (see also section 5.15). However, the rains were not acute enough to explain the severity and intensity of the flooding during this period. Furthermore, rainfall continued up to mid-September, when the floods were already receding. It is clear, therefore, that important input from beyond the borders of Bangladesh to the flood-affected areas occurred in addition to the high rainfall in parts of Bangladesh. As in 1987, it was possible to collect daily rainfall data for a number of Indian stations and for selected periods (IMD 1988). Unfortunately, there are a number of gaps in the available data sets. The most important rainfall data are compiled in Table 5A.4:

- Similar to the situation in Bangladesh, rainfall in the first part of July and in August, particularly in the last few days of the month, was heavy in Meghalaya (Cherrapunjee and Shillong), in the Assam Valley

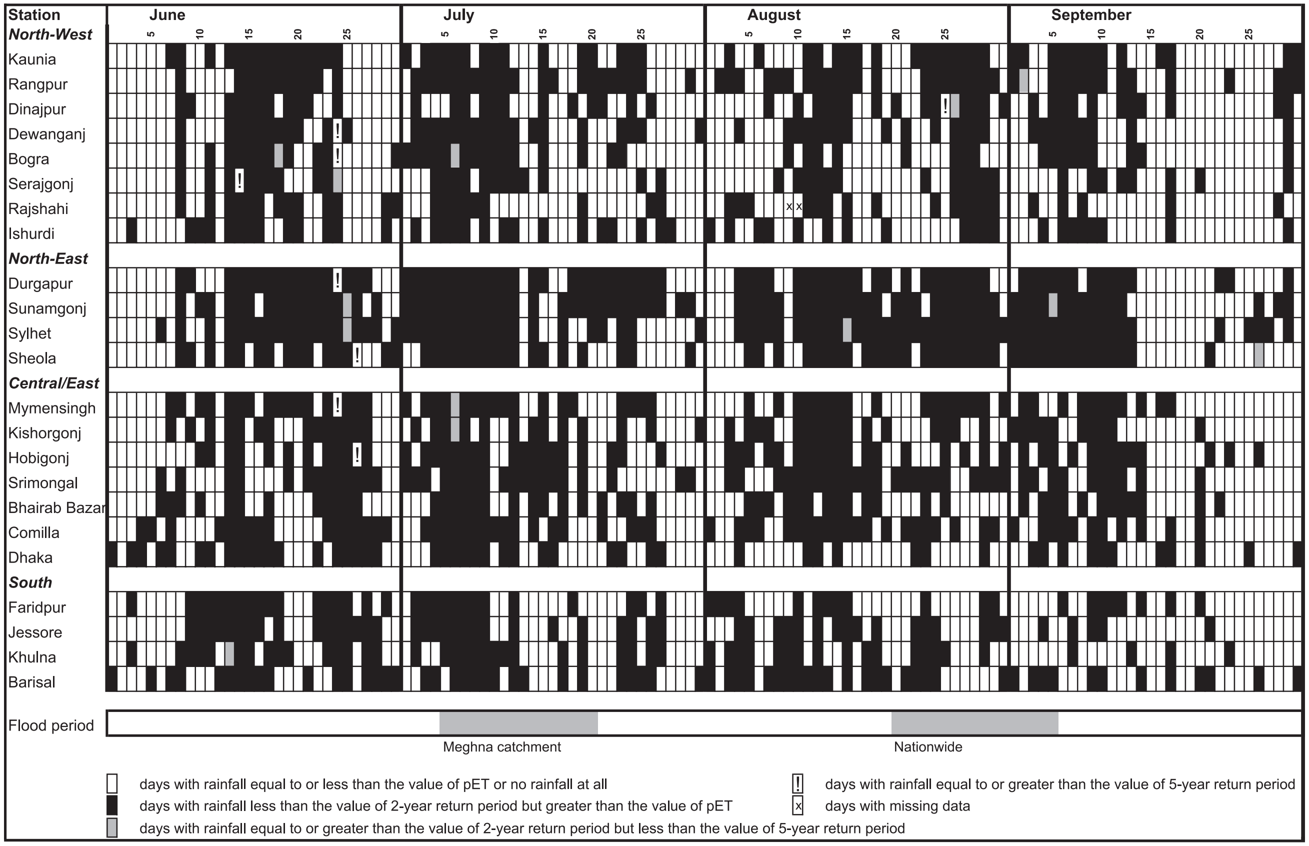


Figure 5A.34 Categories of daily rainfall for the period 1 June–30 September 1988 in Bangladesh.
Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2; for threshold values for the return periods, see Table 5A.2.

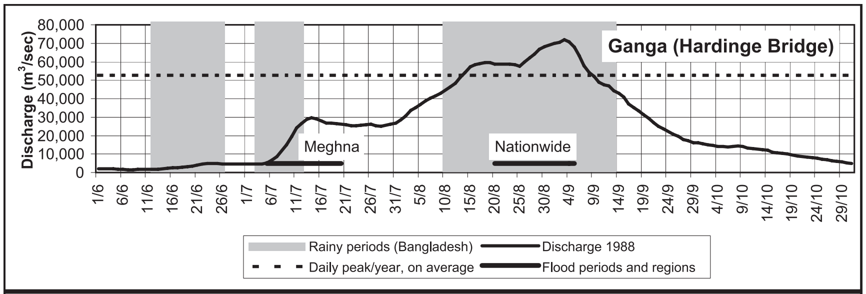
Table 5A.4 Rainfall for selected time periods, compared with monthly averages, at selected meteorological stations outside Bangladesh, 1988 (mm)

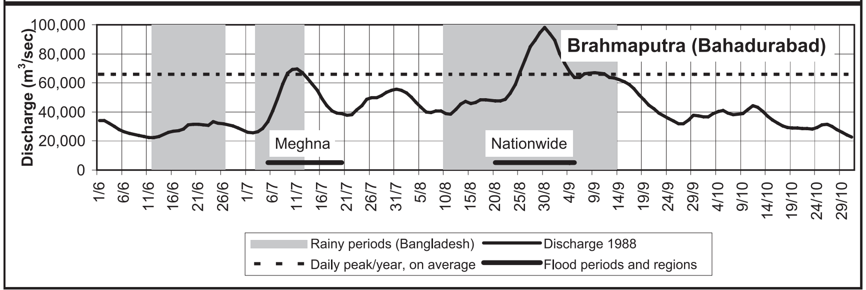
Station	3–12 July	July average	23–29 August	August average
Allahabad	93[b]	295	33[a]	298
Patna	174	294	143	317
Cherrapunjee	2,697	2,628	2,669	1,796
Shillong	562[a]	368	425[b]	313
Dibrugarh	270	538	208	444
Gauhati	202	316	166	259
Gangtok	293	n.a.	120[b]	n.a.
Jalpaiguri	696	n.a.	285[b]	n.a.

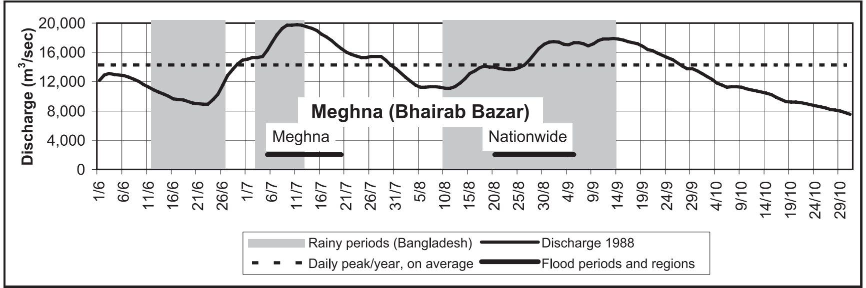
Source: IMD (1988).
Notes: For the location of Gangtok and Jalpaiguri stations, see the text; for the other stations, see Figure 3.1. n.a. = data not available.
[a] 1 record missing.
[b] 2 records missing.

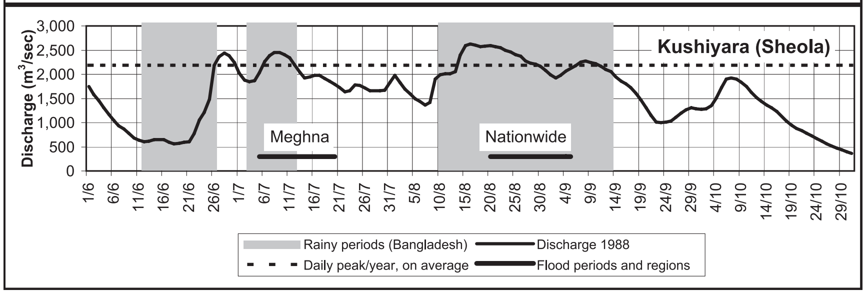
(Dibrugarh, Gauhati) and in parts of West Bengal (particularly Jalpaiguri). This indicates that the external input to the floodplains of Bangladesh was important not only for the nationwide flood at the end of August/early September, but also for the inundation in the first part of July in the Meghna catchment.

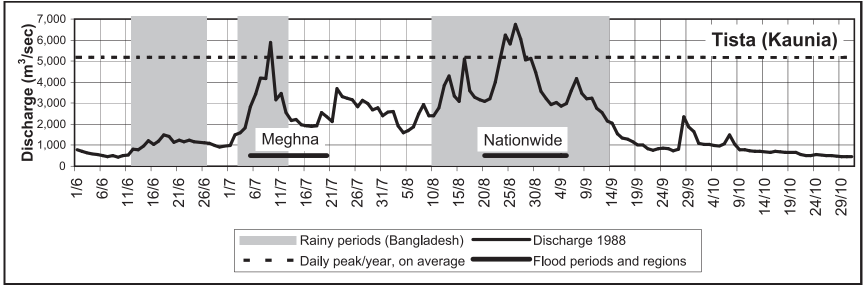
- During the two main flood periods in Bangladesh, rainfall was particularly outstanding in the Meghalaya Hills. Within a period of only seven days, from 23 to 29 August, rainfall in Cherrapunjee significantly exceeded the average figure for the entire month of August. The same situation occurred in Shillong, even with two days of missing information. In the first part of July the situation was similar: within a period of 10 days, the accumulated rainfall significantly exceeded the average July rainfall at both stations.
- As in 1987, comparison of the precipitation in Gangtok and Jalpaiguri is particularly interesting. During July and August, rainfall in Gangtok, which is located inside the first Himalayan range at 1,727 metres above sea level and not too far from Darjiling, was much more constant than in Jalpaiguri, which is situated near the Tista River on the floodplains south of the Himalayan foothills. However, during the flood-triggering rainfall periods (first part of July; end of August), the amount of rainfall at the lowland station of Jalpaiguri significantly exceeded that measured at the hill station of Gangtok. This result is very similar to those discussed for 1987, 1910 and 1906.
- In Assam (Dibrugarh, Gauhati), rainfall was also remarkable in both periods documented in Table 5A.4. Over the 10 and 7 days, respec-


Ganga (Hardinge Bridge)
Discharge (m³/sec)
80,000 70,000 60,000 50,000 40,000 30,000 20,000 10,000 0
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Meghna
Nationwide
Rainy periods (Bangladesh)
Discharge 1988
Daily peak/year, on average
Flood periods and regions


Brahmaputra (Bahadurabad)
Discharge (m³/sec)
100,000 80,000 60,000 40,000 20,000 0
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Meghna
Nationwide
Rainy periods (Bangladesh)
Discharge 1988
Daily peak/year, on average
Flood periods and regions


Meghna (Bhairab Bazar)
Discharge (m³/sec)
20,000 16,000 12,000 8,000 4,000 0
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Meghna
Nationwide
Rainy periods (Bangladesh)
Discharge 1988
Daily peak/year, on average
Flood periods and regions


Kushiyara (Sheola)
Discharge (m³/sec)
3,000 2,500 2,000 1,500 1,000 500 0
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Meghna
Nationwide
Rainy periods (Bangladesh)
Discharge 1988
Daily peak/year, on average
Flood periods and regions


Tista (Kaunia)
Discharge (m³/sec)
7,000 6,000 5,000 4,000 3,000 2,000 1,000 0
1/6 6/6 11/6 16/6 21/6 26/6 1/7 6/7 11/7 16/7 21/7 26/7 31/7 5/8 10/8 15/8 20/8 25/8 30/8 4/9 9/9 14/9 19/9 24/9 29/9 4/10 9/10 14/10 19/10 24/10 29/10
Meghna
Nationwide
Rainy periods (Bangladesh)
Discharge 1988
Daily peak/year, on average
Flood periods and regions

tively, most rainfall totals reached approximately 50 per cent of the relevant monthly averages. Rainfall in the Indian Ganga Plain (Allahabad, Patna), however, was not important.

To summarize, a combination of local rainfall and external input was important for both flood periods in Bangladesh. As far as this can be concluded from the available information, the external input originated primarily in Meghalaya and to some extent in the Assam Valley and in the adjacent Himalayan foothills, but not in the Himalayas and not in the Indian Ganga Plain.

Daily discharge (Figures 5A.35 and 5A.36)

There is no doubt that 1988 was hydrologically an extraordinary year: the highest flows documented in Figure 5A.35 significantly exceeded the maximum discharge that is on average reached during the monsoon season. The maximum flow of the Brahmaputra was particularly outstanding, with a return period of 60 years (compared with 25 years for the Ganga and 5 years for the Tista). According to Table 5A.5, the discharge peaks of the Brahmaputra and Meghna exceeded those in the major flood years 1974 and 1987. However, in terms of the duration of above-danger-level flows, 1974 remains the most outstanding event. The Ganga flow was lower in 1988 than in 1987 and played a minor role: owing to the backwater effects from the Brahmaputra, the Ganga crossed the danger level at Hardinge Bridge earlier than at the upstream station of Rajshahi.

In general, the hydrographs of the stations located inside Bangladesh (Figure 5A.35) are characterized by two periods of high flow that coincided temporally with the two flood phases. As expected, the flow of the Meghna was higher during the first phase than during the second flood phase, whereas for the Brahmaputra the situation was the other way round. The hydrograph of the Ganga does not show any real flood peak in the first part of July. From 23 August to 6 September (the period of most severe flooding), all three major rivers recorded above-danger-level flow. With a temporal difference of only five days, the annual discharge peaks of the Ganga and the Brahmaputra were almost synchronized, which is obviously a key factor for understanding the dimension and severity of the flooding. Based on the characteristics of the Ganga hydro-

◄

Figure 5A.35 Average daily discharge of selected rivers in Bangladesh for the period 1 June–31 October 1988, compared with flood periods, rainy periods and daily peak/year, on average.
Notes: For the location of the stations, see Figure 3.2; for the data sources, see Table 3.4.

Table 5A.5 Above-danger-level flow and maximum daily peak discharge of the Ganga, Brahmaputra and Meghna, 1974, 1987 and 1988

	Above-danger-level flow (days)			Maximum daily peak (m^3/sec)		
River	1974	1987	1988	1974	1987	1988
Ganga (Hardinge Bridge)	41	55	23	50,700	75,800	71,800
Brahmaputra (Bahadurabad)	47	14	27	91,100	73,000	98,300
Meghna (Bhairab Bazar)	81	30	63	19,500	15,200	19,800

Notes: For the location of the stations, see Figure 3.2; for the data source, see Table 3.4.

graph, we can also assume that the sluice gates on the Farakka Reservoir were fully open on these days and that the reservoir did not have any retention capacity for flood water. Between the two flood-flow periods there was a moderate reduction in river discharge. To some extent, the period with only minimal precipitation from mid-July to mid-August might have allowed some of the water masses that had accumulated in the basin in June and early July to drain away. All the same, the first flood phase must be taken into consideration as an important factor in understanding the flood dimension at the end of August and early September.

In general, the river flow reacted to the rainfall phases within Bangladesh. There are some exceptions to this:

- The intensive rains from 12 to 26 June are barely reflected in the river flow. Early monsoon rains may have gradually filled natural storage areas (beels, soil, groundwater reservoirs) without significantly contributing to surface runoff.
- Within only six days, from 24 August to 30 August, the flow of the Brahmaputra almost doubled from roughly 50,000 m^3/sec to 100,000 m^3/sec. A similar trend is documented for the Tista. It is impossible to explain this situation by considering only the rainfall patterns in the area. Based on the previous discussions, it can be concluded that this fast rise in river flow was a combined result of intensive rainfall in north-western and north-eastern Bangladesh, rainfall in the Himalayan foothills and the northern part of the Meghalaya Hills, and extensive flooding in Assam.
- In the first few days of September the discharge of the Brahmaputra dropped rapidly, although the rains in Bangladesh still continued. This supports the statement made in the previous point: if the remarkable discharge peak of the Brahmaputra at the end of August and in early September were caused only by rains in Bangladesh, then the flow of

the Brahmaputra should have continued to be high until the end of the rainy period.

As already discussed for 1974 and 1987, the reaction of the Kushiyara to rainfall periods is faster, and there are many more short-term flow variations than in the Meghna. The annual peak of the Kushiyara was reached in mid-August as a result of heavy rainfall in the region, and not during the main flooding period. Similarly, as documented in the significant number of short-term discharge variations, the reaction of the Tista to single rainfall events is much stronger than that of the Brahmaputra. The two peaks of the Tista coincide perfectly with the intensive rainfall in the nearby catchment and with the flood phases in Bangladesh.

In view of the rather insignificant rainfall processes in the Ganga basin, the high flow of the Ganga from 25 August to 10 September is remarkable. As for 1987, it was possible to collect daily discharge data for three major Nepali tributaries of the Ganga (Figure 5A.36). It again must be noted that the three stations are located in the transition zone between the Himalayas and the adjacent plains (see Figure 3.2). The graphs depict the following features:

- The flow characteristics of the three rivers are quite similar. As is to be expected, there are many more small and short-term flow variations than in the hydrographs of the big rivers.
- In all three rivers, a remarkable flood flow was recorded in the second part of August. Whereas this peak was of short duration in the Karnali and the Narayani, it lasted for several days in the Sapt Kosi. These flood flows have a different timing: the peak was reached on 16 August in western Nepal (Karnali), on 23 August in central Nepal (Narayani) and on 26 August in eastern Nepal (Sapt Kosi).

It is obvious that the tributaries from Nepal reached some remarkable flows in specific, short time periods during the second half of August. In view of the dimension of these peaks, it is surprising that there are no indications in the available literature on flood processes in Nepal during this period. Owing to the lack of daily rainfall data, it is impossible to find out whether the flood peaks were the result of heavy rains in the Himalayas or, similar to the situation in the Tista, the result of storm events in the foothills and forelands. The different timing of the peak flows of these three tributaries may indicate that the marked discharge peaks were caused by individual and geographically limited rainfall events in the catchment areas of the respective rivers rather than by one single and widespread rainfall event.

It is very difficult to assess if, and to what extent, the discharge peaks of the three Himalayan tributaries contributed to the flow of the Ganga at Hardinge Bridge in Bangladesh. The highest discharge of the Ganga was reached one to two weeks after the peaks of the Nepali tributaries.

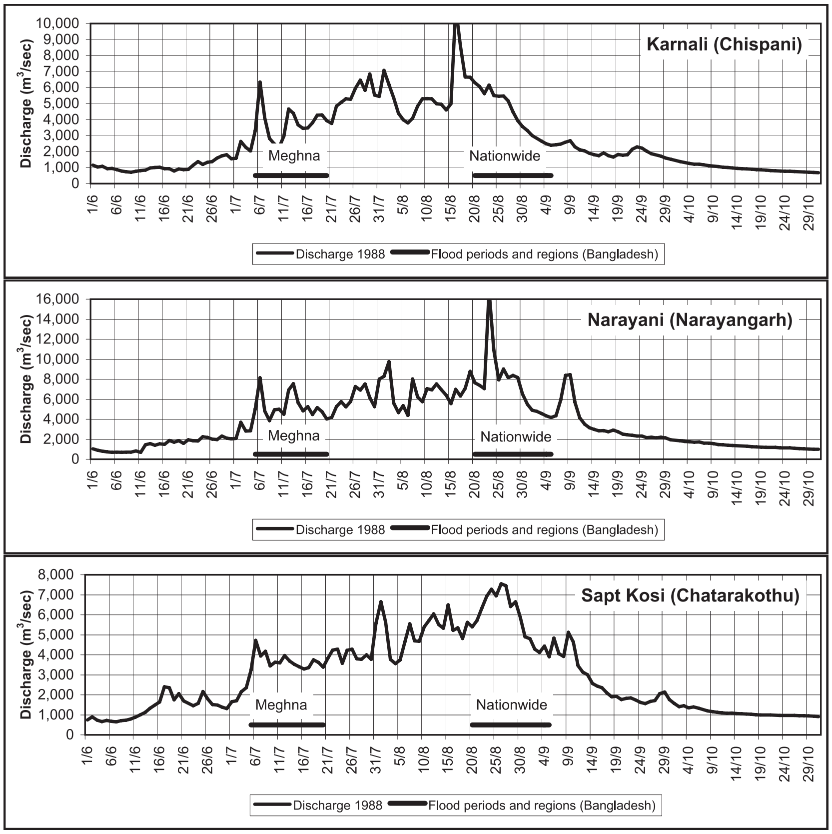


Figure 5A.36 Average daily discharge of three selected rivers in Nepal for the period 1 June–31 October 1988, compared with flood periods in Bangladesh.
Notes: For the location of the stations, see Figure 3.2; for the data source, see Table 3.4.

Again assuming a flow velocity of 130 km/day (see the section on daily discharge in Appendix 5.11), there could have been some connection between these different flood flows. However, in view of the different timing of the peaks in Nepal and of the likely levelling out of the discharge peaks once they reached the plains (see the sections on daily discharge in Appendix 5.6 and Appendix 5.11), this direct connection must be questioned. The release of water from the Farakka Barrage (USAID 1988) or the backing-up of the Ganga as a result of a high Brahmaputra flow (Miah 1988: 94) are both much stronger arguments for the understanding of the flood flow of the Ganga.

Groundwater (Figure 5A.37)

At all stations, the recorded groundwater level was above average for most parts of the monsoon season. The anomalies were particularly impressive at two stations in north-western Bangladesh (RA28 and B003). The highest groundwater level was reached during the period of the nationwide flooding (weeks 34–36). The groundwater table reached the surface at stations FA22, MY03 and DA12. As in 1974 and 1987, the water level at station FA22, which is located below the confluence of the Ganga and the Brahmaputra, was particularly high.

In the second section of this Appendix it was assumed that, as a result of positive R(pot) anomalies in winter and the pre-monsoon period, the groundwater table in Bangladesh was already above normal at the onset of the monsoon (approximately week 22). In reality, the opposite seems to be the case: at a number of stations the groundwater table in the first part of the year was significantly below average. It is however true, as proposed in the section on daily rainfall above, that, owing to the rains from 12 to 26 June (weeks 24–26), significant volumes of water accumulated in the soil and groundwater, causing a sharp rise in the groundwater table during these weeks. As a result, the level of the groundwater table was far above the average during the first flood period (weeks 27–29), which mainly affected the Meghna catchment. During the subsequent dry period (weeks 29–32), the groundwater table remained constant or even dropped and was at more or less average depths at the onset of the nationwide flood. This indicates that, in terms of the groundwater table, the rainy periods in June and July did not necessarily precondition the extent and intensity of the nationwide flood.

Tidal effects (Figure 5A.38)

In several instances, the effects of tidal movements on flood processes in Bangladesh have been mentioned. Field visits to Bhairab Bazar on the Meghna River and a seminar study on tidal movements carried out within the framework of the project (Bucher et al. 1996) have provided some insights into this very complex issue. Since the floods in 1988 were particularly widespread and intensive, it is appropriate to discuss tidal effects briefly.

The mean rise at high water during spring tides in the Bay of Bengal varies from 2 to more than 5 metres (S. Rashid 1991). As a result of the flat topography of Bangladesh, tidal effects reach far inland: at Bhairab Bazar, which is approximately 300 km away from the coast (Figure 3.2), tidal movements produce a reverse flow of the Meghna twice in 24 hours

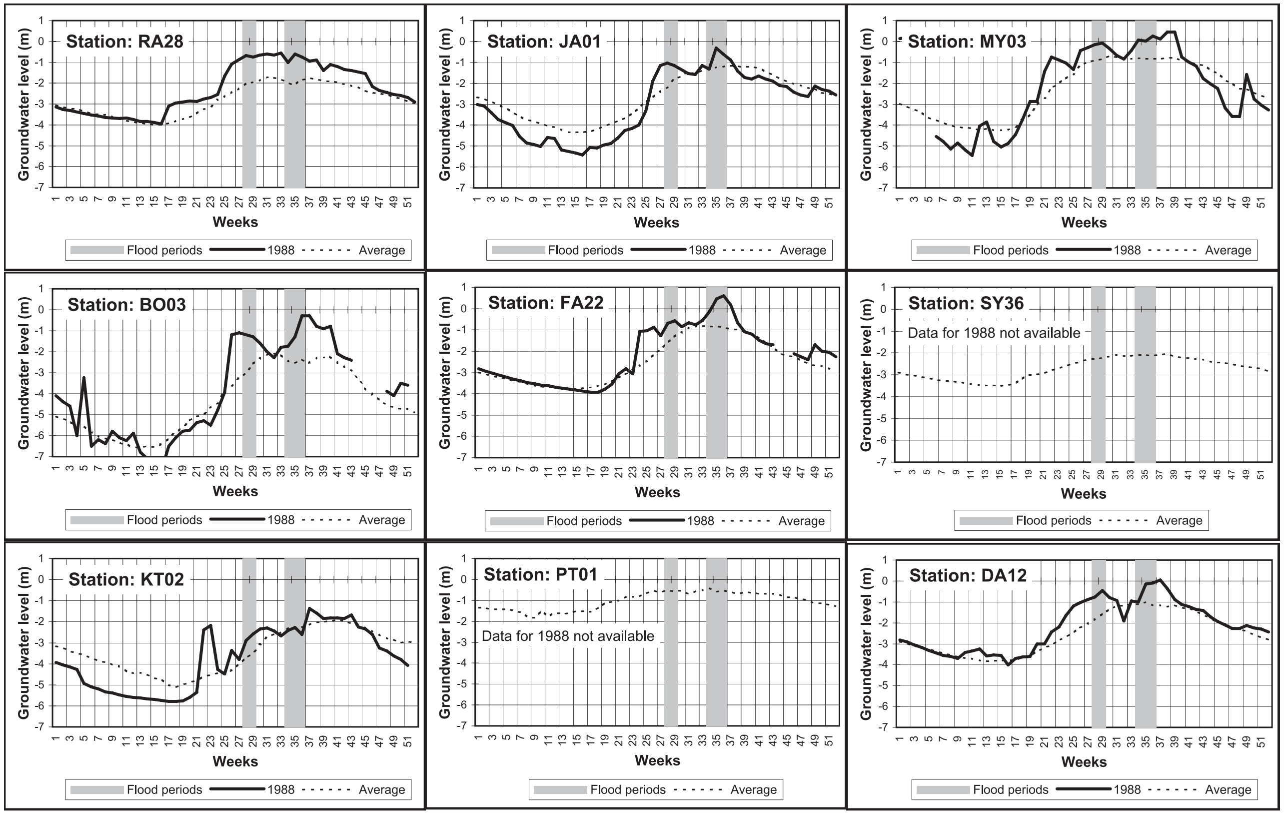


Figure 5A.37 Groundwater levels of selected stations in 1988, compared with flood periods and average groundwater levels over roughly 20 years.

Notes: For the location of the stations, see Figure 3.3. The four monsoon months correspond to the week numbers approximately as follows: June, weeks 23–26; July, weeks 27–30; August, weeks 31–34; September, weeks 35–38.

Source: BWDB (n.d.[b]).

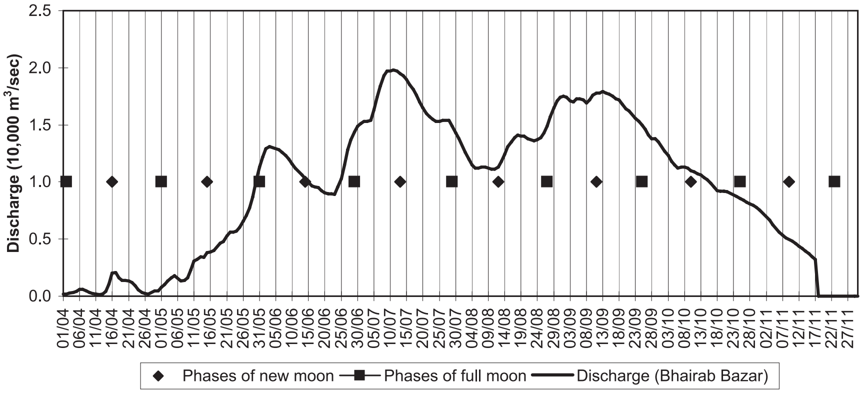


Figure 5A.38 Daily discharge of the Meghna at Bhairab Bazar for the period 1 April–30 November 1988 compared with the moon phases.
Notes: For the location of Bhairab Bazar, see Figure 3.2.
Data sources: BWDB (n.d.[b]); BITWA (1988).

during the dry season, and a reduced flow velocity and a rise in the water level during the monsoon season. The effects of the spring tide reach Bhairab Bazar with approximately a three-day delay after a full or new moon.

For 1988, a connection exists between the moon phases and the discharge hydrograph of the Meghna, but it is not systematic:

- In the pre-monsoon period, discharge fluctuations seem to be related to the moon phases: both short-term peaks in mid-April and early May more or less coincide with a full and new moon, respectively.
- The full moon at the end of May could have affected the discharge peak in early June.
- During the monsoon season there is no systematic connection between the moon phases and discharge peaks: the flood flow in the first part of July reached its peak before the new moon. However, the spring tide, related to the new moon on September 11, could have backed up the Meghna waters during the main flooding period. This finding is supported by literature sources such as Shahjahan (1989).

The impact of spring tides is certainly not a decisive triggering factor for the floods in Bangladesh. However, there is no doubt that the discharge of flood water into the Bay of Bengal is influenced by high tides. If the hydro-meteorological conditions for the development of a large inundation are present, high tides may significantly contribute to the dimension of the flooding.

Summary

The flood in 1988 was extraordinary and its dimension can be understood only by considering a particular combination of factors. Widespread above-average rainfall in most parts of the basin during August provided important basic conditions for the development of the nationwide flood from the end of August to early September. We do not agree with the literature that rainfall within Bangladesh was not important: the calculations of potential runoff *R*(pot) show a constantly high input into the hydrological system through precipitation within Bangladesh from June to August. Furthermore, rainfall was remarkable in the northern and north-eastern parts of the country during the main flooding periods. We do agree, however, that the external input was important as well. First of all there was an obvious connection between the floods in Assam and those in Bangladesh. Secondly, there was very high rainfall outside Bangladesh in the Brahmaputra and Meghna catchments during the main flooding periods. Similar to the situation in 1987, 1910 and 1906, this external input originated not in the Himalayas, but rather in the foothills and the lowlands south of the Himalayas, in Assam and, most importantly, in the Meghalaya Hills, where the anomalies were extraordinary. The Ganga system on its own does not seem to have played a critical role in the development of the large-scale flooding. However, the fact that the timing of the highest flow of the Ganga was almost synchronized with the peak of the Brahmaputra and with high flow of the Meghna was certainly very important. Other factors such as spring tides and high levels of the groundwater table within Bangladesh contributed to the extent and intensity of the flooding.

Factors that were important for the nationwide flooding in Bangladesh from 20 August to 5 September:

- widespread (11 of 13 subcatchments) above-average *R*(pot) during August;
- constantly above-average *R*(pot) in Bangladesh from June to August;
- a flood phase in early July;
- a combination of local and external input before and during the flood: significant rainfall in northern and north-western Bangladesh, in Meghalaya and in Assam;
- two discharge peaks on most rivers;
- high, at times above-danger-level, flow of all three major rivers in August and September;
- temporal synchronization of the highest flow in 1988 of the Brahmaputra and the Ganga and the very high flow of the Meghna;
- a high groundwater table at the onset of the first flood phase and throughout most of the monsoon period;

- backwater effects owing to spring tides.

Factors that were not important for the nationwide flooding in Bangladesh from 20 August to 5 September:

- the Ganga on its own (it is only of relevance in combination with the Brahmaputra and the Meghna);
- single daily rainfall events;
- the influence of the Himalayas (this statement is mainly based on the calculations of R(pot) in the Nepal Himalayas and on detailed investigations of daily rainfall in the Tista catchment).

Appendix 5.8: 1998 – A "flood year" for Bangladesh

The inundation of 1998 was the most severe flood of the twentieth century. Because this was a particularly impressive event and it occurred after the official completion of the project work, the structure of the following discussion differs slightly from the case studies presented so far. In particular, it was not possible to calculate R(pot) and R(relev). The summary of this case study is presented in section 5.11 (pp. 183–188).

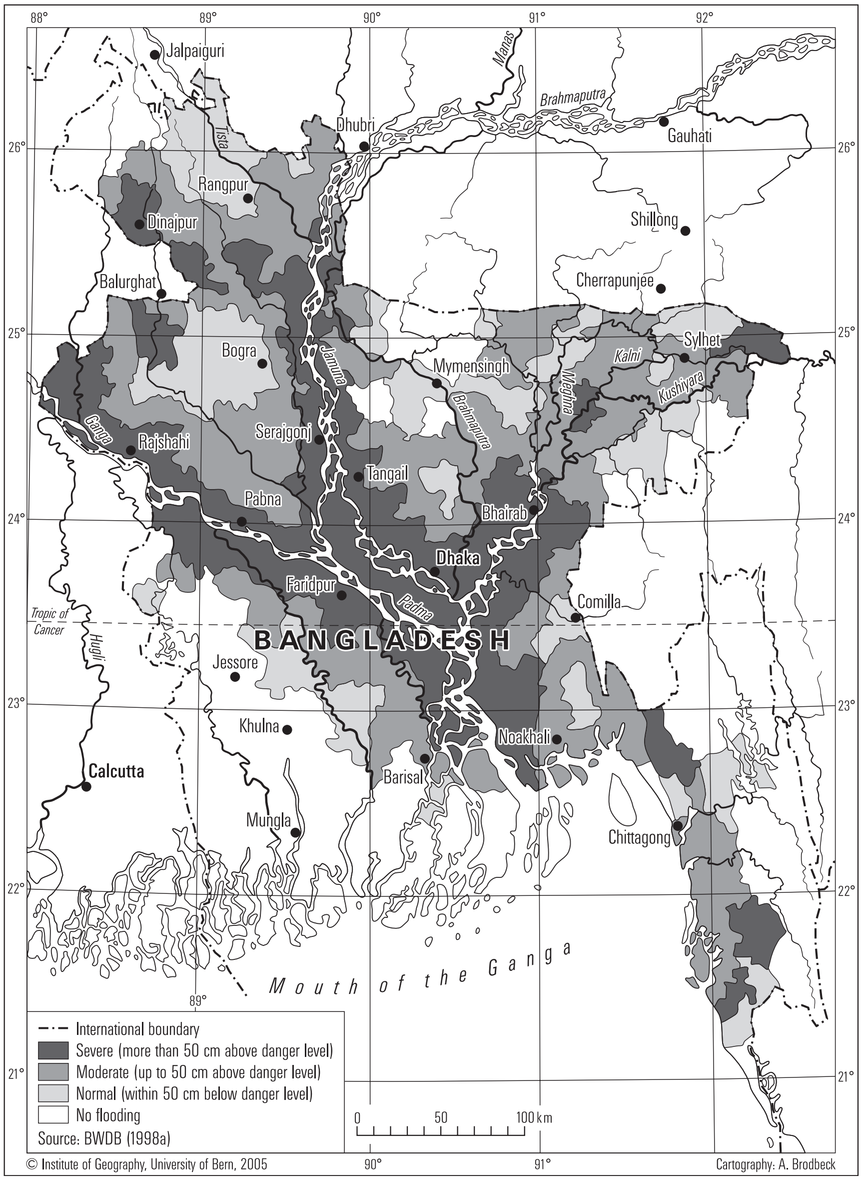
The 1998 flood situation at a glance

Flood dimension in Bangladesh

With 100,250 km^2 (67.93 per cent) of the country affected, the inundation in 1998 ranks first in the statistics for the period 1954–2004 (see Table 4.1). The floods from mid-July to the end of September 1998 were the longest-lasting and most devastating in 100 years, causing colossal damage to life, property, crops and infrastructure. About 50 per cent of the country was under water for periods of up to 67 days, at depths of up to 3 metres. The figure of 67.93 per cent is the total sum of all affected areas during 1998. As is shown in the discussion of the flood chronology below, the maximum extent of simultaneous flooding reached 51 per cent of the country on 7 September.

Most seriously affected areas within Bangladesh (Figure 5A.39)

In total, 53 of the 64 districts were affected by floods of differing magnitude. The most severe flooding occurred along the main river courses and was particularly serious in the overall area of confluence of the three rivers, including the capital city of Dhaka. Most of the few flood-free zones were located in southern and south-western Bangladesh, a feature that was already in evidence in previous years. Along the Ganga, the flood seems to have surpassed all previous records, including those of the 1988 flood.



Source: BWDB (1998a)

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Cartography: A. Brodbeck

Figure 5A.39 Flood-affected areas and flood intensity, synthesized for the entire monsoon season: 1998.

Chronology

> During the month of July, the flood situation became more prominent in the north-eastern and south-eastern part of the country resulting from flash floods. During this time the northern part experienced flood due to the Brahmaputra River. In the month of August, the river Brahmaputra continued to experience flooding conditions while flow from the north-eastern part of the country was added to it. Moreover, the flow from the Ganga aggravated the whole flood situation of the country. During the first part of September the flood situation became severe in the country with an abrupt rise of the Brahmaputra flow along with the continued high flow of the Ganga. During this time, unnatural behaviour of spring tides impeded the whole drainage through the river system and made the flood situation alarming for the whole nation ... The flood situation continued up to middle of September and only gradually improved until the end of September. (BWDB 1998a: 1/A)

The flood of 1998 was characterized by three separate peaks:

- 28 July: the flood situation became critical for the first time – 23 out of 46 monitoring stations recorded above-danger-level flows and 30 per cent of the country was flooded.
- 30 August: the flood situation became critical for the second time – 24 out of 46 monitoring stations recorded above-danger-level flows and 41 per cent of the country was flooded.
- 7 September: the flood situation became critical for the third time – 25 out of 46 monitoring stations recorded above-danger-level flows and 51 per cent of the country was flooded. This was probably the greatest extent of simultaneous flooding of the twentieth century and maybe even since records began.

Damage caused by the floods

The extent of damage was huge: the flood disrupted the economy and reduced potential GDP. The floods damaged livestock, fishponds, homesteads, roads and bridges. Many of the detailed figures describing the effects of the flood are, of course, estimates and they vary in different sources. Table 5A.6 lists some figures that may provide a sense of the order of magnitude and highlight the effects of the 1998 floods. Dhaka city was significantly affected, the floods seriously damaging the drinking water system as well as the sewage and storm water drainage system; waterborne diseases spread fast through some areas of the city, which has a population of 9 million.

Flooding conditions outside Bangladesh

Information on flooding outside Bangladesh was very scarce. The few available pieces of news do not indicate that there were major flood

Table 5A.6 Estimated effects of the 1998 flood

Item	Damage
No. of districts affected	53 (out of 64)
No. of people affected (different sources)	30,000,000; 31,648,746
No. of human deaths from flood-related causes (different sources)	783; 1,050; 1,414; >1,500
No. of people facing malnutrition and disease	25 million
Estimated damage in the agricultural sector:	
• Rice production losses	• 2.2 million tonnes
• Damage to cultivated area	• 1,565,390 hectares
• Crops washed away	• on 100,000 hectares
Estimated losses in the forestry sector (including village tree resources):	US$52 million
Estimated total losses in the fisheries sector	US$73.9 billion
Estimated total losses in the livestock sector	US$500 million
• Cattle/buffaloes	• 7.8 million affected/5,326 dead
• Goats/sheep	• 4.2 million affected/9,297 dead
• Poultry/ducks	• 352 million affected/46,847 dead
Roads and highways partially or completely damaged	15,000 km
Embankments partially or completely damaged (different sources)	4,451 km; 4,528 km
No. of bridges and culverts damaged	20,500
No. of villages damaged	30,000
No. of houses damaged (different sources)	550,000; 894,015
No. of educational institutions damaged	24,000
No. of industrial units damaged	11,000
No. of tube wells damaged	300,000

Sources: BWDB (1998a); Choudhury (1998); FAO/WFP (1998); IDNDR (1998); ReliefWeb (1998); World Bank (1998); FAO (1999, 2000b); Jegillos and Mearns (1999).

events that came anywhere close to those in Bangladesh in terms of dimension and duration. However, a map of the flood-affected areas, prepared by the Bangladesh Space Research and Remote Sensing Organization (SPARRSO) based on a number of satellite images, reveals uninterrupted and fairly wide strips of flooded areas along the Brahmaputra from Assam to Bangladesh as well as along the Ganga from Bihar and West Bengal to Bangladesh (for the location of these Indian states, see Figure 4.8). In addition, some detailed reports of localized and severe flood incidences were available that make reference to flood-triggering hydro-meteorological processes originating in the Himalayas:

- "At least 16 persons have been killed while 13 are reported missing in flash floods and landslides triggered by incessant rains that lashed

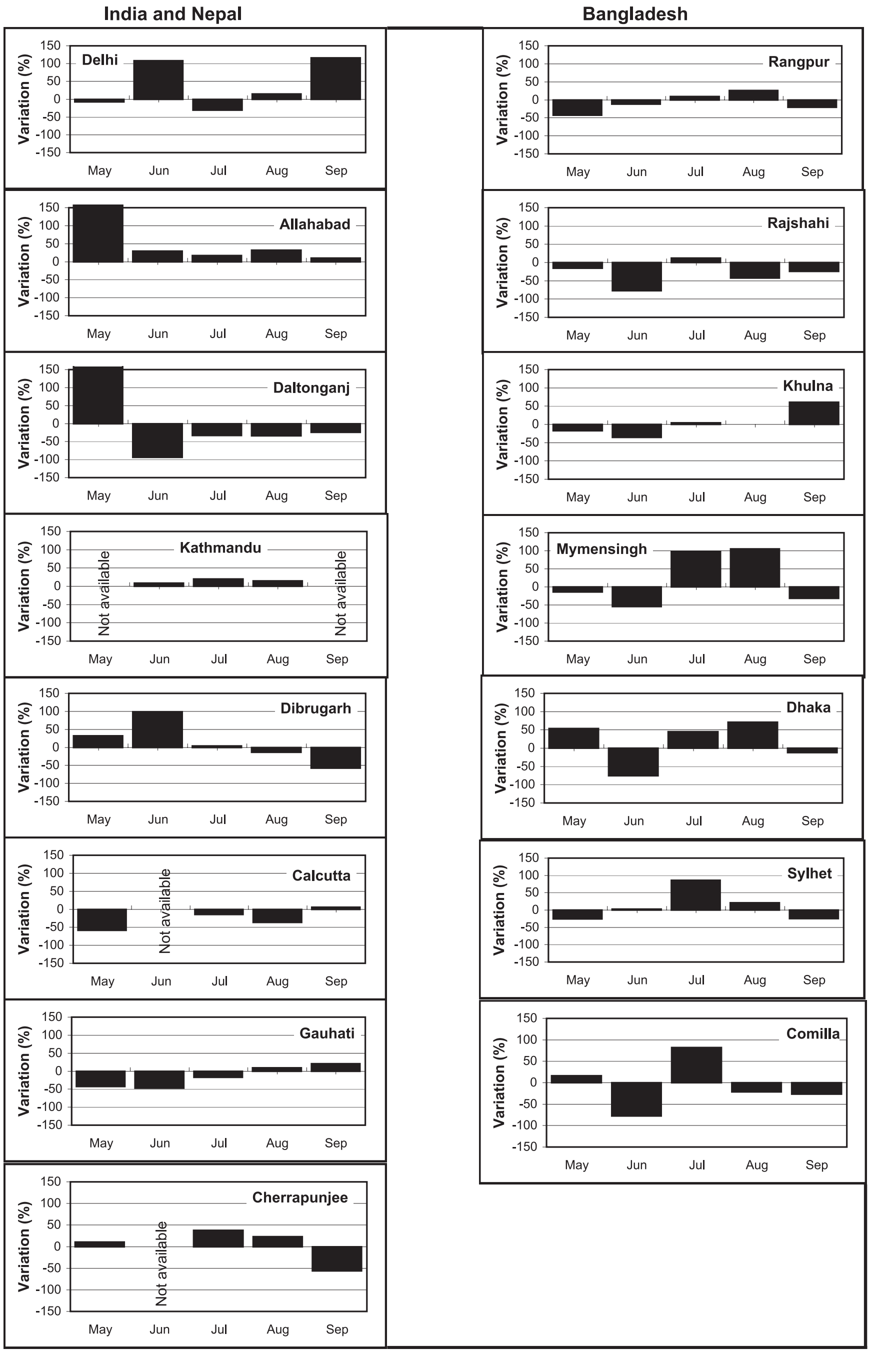
Syangja district to the west of Nepal since Sunday evening. Two bridges built over the Aroundi river and Bath river were also damaged." (*Kathmandu Post*, Kathmandu, Nepal, 31 August 1998).

- "The Koshi barrage in Nepal on a high alert after incessant rains in the eastern hills and plains flooded the Sapta Koshi tributaries.... Sapta Koshi river, fed by seven rivers, is the biggest river system of Nepal." (*The Kantipur*, Kathmandu, 4 September 1998)
- "The monsoon, which has arrived rather late this year, has flooded major parts of the Assam Valley over the last month. Now the rains have also reached the mountain valleys of Nepal and India in their advance along the Himalayan chains." (*Der Bund*, Bern, Switzerland, 20 August 1998)
- "The floods ravaging Bengal, Assam and Bihar have been caused by heavy rain in the upper reaches of the Himalayas and in Tibet. The Brahmaputra, with its origin in Tibet, has been in spate in Assam and Bangladesh where it pours into the Padma." (*The Telegraph*, Calcutta, India, 11 September 1998)
- "Torrential rains trigger landslides in Uttar Pradesh hills, killing, among others, pilgrims to Mansarovar in July." (*The Telegraph*, Calcutta, 11 September 1998)

Causes of the 1998 floods as discussed in the literature

The synthesis of the rather general statements made by different authors in the available sources (see below) results in a long list of factors that, in their combined effect, might have been responsible for the magnitude of the event:

- The three major rivers reached very high peaks simultaneously between 7 and 11 September.
- High tidal levels and strong monsoonal currents prevailed in the Bay of Bengal (particularly affecting the mouth of the Meghna estuary). The effect of the spring tide at high water level observed at Chandpur (located below the confluence of the Meghna with the Padma, see Figure 5.1) was the highest ever recorded. The high tide seems to have been further exacerbated by a submarine earthquake. This general situation inhibited drainage from the delta. These statements seem to contradict the fact that the southern districts and delta areas were not affected by the floods (Figure 5A.39).
- There was a combination of flash floods, river floods and tidal floods.
- 1997 and 1998 were El Niño/La Niña years: from May 1998 onwards, the Southern Oscillation Index (SOI) started shooting up, creating a La Niña situation that produced favourable conditions for a big flood in Bangladesh.
- The monsoon trough was further north in 1998 than normal.


India and Nepal
Bangladesh
Variation (%)
150
100
50
0
-50
-100
-150
May
Jun
Jul
Aug
Sep
Delhi
Allahabad
Daltonganj
Kathmandu
Not available
Not available
Dibrugarh
Calcutta
Not available
Gauhati
Cherrapunjee
Not available
Rangpur
Rajshahi
Khulna
Mymensingh
Dhaka
Sylhet
Comilla

- In terms of magnitude, the Ganga River played a vital role and the river Brahmaputra, along with the rivers of the Meghna basin, caused a prolonging of the flood situation. The Ganga at Farakka clearly exceeded the highest recorded water level. Several tributaries of the Ganga also exceeded their own previous record flood levels. The simultaneous excess flow from several tributaries, which is a rare event, was directly responsible for both the severity and the unusually long duration of the flood.
- This flood resulted from a combination of a number of factors, including excessive rainfall in the catchment area (both inside and outside Bangladesh).
- The flat terrain and sediment accumulation in the river beds contributed to the magnitude of the floods.
- Obstructions created by human-made infrastructure (roads, railways, barrages, embankments) aggravated flood conditions.
- In July 1998, the Bangladesh Meteorological Department recorded the highest temperature in more than a century.
- Above-normal snowfall in the Himalayas was followed by a warm July, which substantially increased snowmelt. As a result, the Brahmaputra peaked three times during July and August.
- In the north, between Nepal and West Bengal, it rained 40 per cent more than usual. The same happened in Assam.

Literature sources

BWDB (1998a); Choudhury (1998); FAO/WFP (1998); GOB (1998: 41); IDNDR (1998); ReliefWeb (1998); World Bank (1998); FAO (1999, 2000b); Jegillos and Mearns (1999).

Monthly rainfall (Figure 5A.40, Table 5A.7)

Since it was not possible to calculate R(pot) and R(relev) for 1998, the following discussion is based on variations in monthly rainfall from the long-term average for selected stations, both inside as well as outside Bangladesh, for the months of May to September. It is very unfortunate that, except for Kathmandu, no information is available for Himalayan stations.

◄

Figure 5A.40 Monthly rainfall variations (May–September) in 1998 as a percentage of the average for selected stations in India and Nepal (left side of the figure) and Bangladesh (right side of the figure).
Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2.

"During May and June, very insignificant rainfall occurred both in the country and upstream in the catchment" (BWDB 1998a). According to the graphs in Figure 5A.40, this statement holds true for the situation in Bangladesh: most of the rainfall anomalies in May and June were negative. Outside Bangladesh the situation is much more heterogeneous and several graphs, such as those for Delhi, Allahabad, Daltonganj and Dibrugarh, show significantly positive anomalies.

In July and August the positive rainfall anomalies in Bangladesh were quite significant. During July, rainfall was above average at all stations and most accentuated in the central and eastern parts of the country. In August, too, the positive variations dominated; those in Mymensingh and Dhaka were quite significant. Choudhury (1998: 13) states: "in July and August, Bangladesh rainfall was 40% and 35% more than the normal value". The rainfall situation outside Bangladesh was much less striking. Most of the anomalies were rather small and in a number of cases the rainfall was below average. The positive anomalies in Cherrapunjee during both months were rather modest.

In the first part of September the flood reached its maximum dimension. However, on a monthly basis, the rainfall situation was not remarkable: at 9 of the 14 available stations the monthly totals of precipitation were below normal. Within Bangladesh, only Khulna in the south recorded above-average rainfall.

Based on the very limited information available for Kathmandu, precipitation in Nepal does not seem to have deviated very much from the average situation. Although the anomalies were positive from June to August, they were insignificant compared with the other stations.

Overall, the rainfall situation within Bangladesh seems to have been quite homogeneous and distinct during the monsoon season of 1998: a rather dry pre-monsoon and early monsoon period, wet conditions in July and August, and again a rather dry September. This situation is further confirmed by Table 5A.7, which summarizes the rainfall situation for a large number of stations within Bangladesh. Outside Bangladesh the rainfall patterns were more heterogeneous and location specific. A key to the development of the flooding seems to have been the significant amount of water that accumulated in the water bodies within Bangladesh during July and August through local input. Regarding the relevance of the highland areas, there was some significant rainfall in the Meghalaya Hills, but in the Nepal Himalayas the situation was close to normal.

To summarize, it is not easy to understand the dimension and duration of the 1998 flood in Bangladesh on the basis of the analysis of monthly rainfall data. Moreover, the available information for the mountain regions is completely inadequate for understanding the flooding processes in the adjacent lowlands.

Table 5A.7 Statistical analysis of monthly rainfall anomalies, May–September 1998, for a large number of rainfall stations within Bangladesh

	Ganga basin		Brahma-putra basin		Meghna basin		Total	
Month	+	−	+	−	+	−	+	−
May	3	7	1	8	3	7	7	22
June	1	9	0	10	2	9	3	28
July	8	3	9	2	10	0	27	5
August	6	6	10	1	7	4	23	11
September	6	6	6	5	1	10	13	21

Source: BWDB (1998a).
Notes: + = number of stations with positive rainfall anomalies; − = number of stations with negative rainfall anomalies.

Daily rainfall (Figure 5A.41)

Generally speaking, the monsoon rains started on 5 July and lasted until 6 September. At the stations in the north-east, rains were already continuous throughout June. Within this overall pattern, there are three distinct periods during which rainfall was recorded more or less throughout the country: 5–23 July; 11–18 August; 31 August–6 September. The rainfall period in July was the most important. It lasted for 19 days, and there were very few days and stations without precipitation. A number of rainfall events with a return period of two or more years occurred during this period. The other two rainfall periods both lasted for approximately one week, and no rainfall records exceeded the two-year return period.

As stated in the first section of this Appendix, the floods lasted more or less continuously from 17 July to 15 September. According to the literature sources, the flood situation was particularly severe on three dates: 28 July, 30 August and 7 September. It is interesting that two of these flood peaks (28 July and 7 September) occurred immediately after rainfall periods of significant duration and geographical extent. This means that these flood maxima were probably built up through a gradual accumulation of water and were reached shortly after these widespread rains had stopped.

According to Choudhury (1998), a typical feature in 1998 was that there were comparatively short break periods between the major rainfall phases. This cannot be entirely confirmed with Figure 5A.41.

For the three monsoon months of June, July and August, daily rainfall data for Kathmandu were provided by the Department of Hydrology and

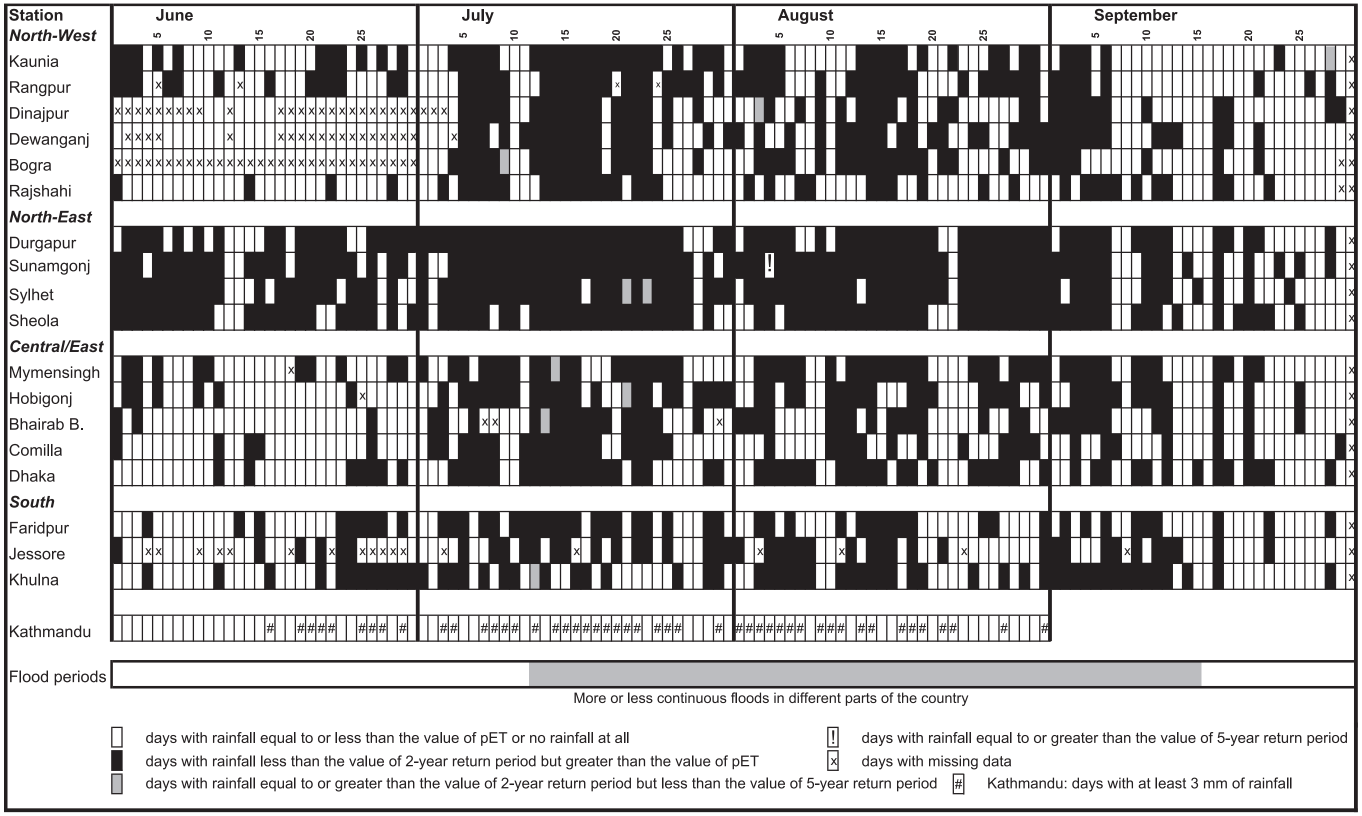


Figure 5A.41 Categories of daily rainfall for the period 1 June–30 September 1998 in Bangladesh and for Kathmandu.
Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2; for threshold values for the return periods, see Table 5A.2.

Meteorology of Nepal. In Figure 5A.41, all those days are highlighted on which rainfall reached at least 3 mm. From mid-June to the end of August, rainfall in Kathmandu was almost constant, with only short periods of interruption. There is a fairly good match with the rainy period in July identified for Bangladesh (see above), and a slightly less good match with the rainy period in August and the related phases of maximum flood extent. There were five days with above 50 mm of rainfall in Kathmandu, four of which were recorded in the first part of the monsoon season (21 June, 8 July, 9 July, 14 July, 21 August). All in all, it can be stated that the rainfall in Kathmandu was abundant, but it did not reach exceptional values nor did it coincide particularly well with the flooding processes in Bangladesh.

Considering all these findings, it is clear that the daily rainfall patterns within Bangladesh are linked to the flooding processes and their chronology. It also seems to be the case that rainfall periods, particularly the one in July, were recorded in significant parts of the basin and were most probably caused by large-scale monsoon depressions. However, that the flooding reached dimensions never before encountered in the whole century cannot be fully understood by studying only the daily rainfall patterns.

Daily water level

The 1998 monsoon season was hydrologically a very notable period (Figure 5A.42). These are some general characteristics of the Ganga, the Brahmaputra and the Meghna, which are depicted in the hydrographs:

- All three rivers were flowing above danger levels for a significant number of days.
- All three rivers responded to the main rainfall periods within Bangladesh.
- All three rivers reached a first high flow period at the end of July and their annual peak in the first days of September. The Brahmaputra reached another peak after mid August.
- Whereas the Brahmaputra and the Meghna had crossed the danger level already in July, the Ganga did so only after mid August.
- Whereas the water level of the Brahmaputra and the Ganga dropped rapidly after the flood peak in the first part of September, the Meghna continued to flow above danger level until late September.

The timing of the flood peaks of the three big rivers was very distinctive in 1998. Table 5A.8 lists the dates of two five-day periods encompassing the peak flows at the end of July and in early September for the three big rivers. At the end of July, the water level of the Brahmaputra was already receding by the time the Meghna reached its peak flow. In

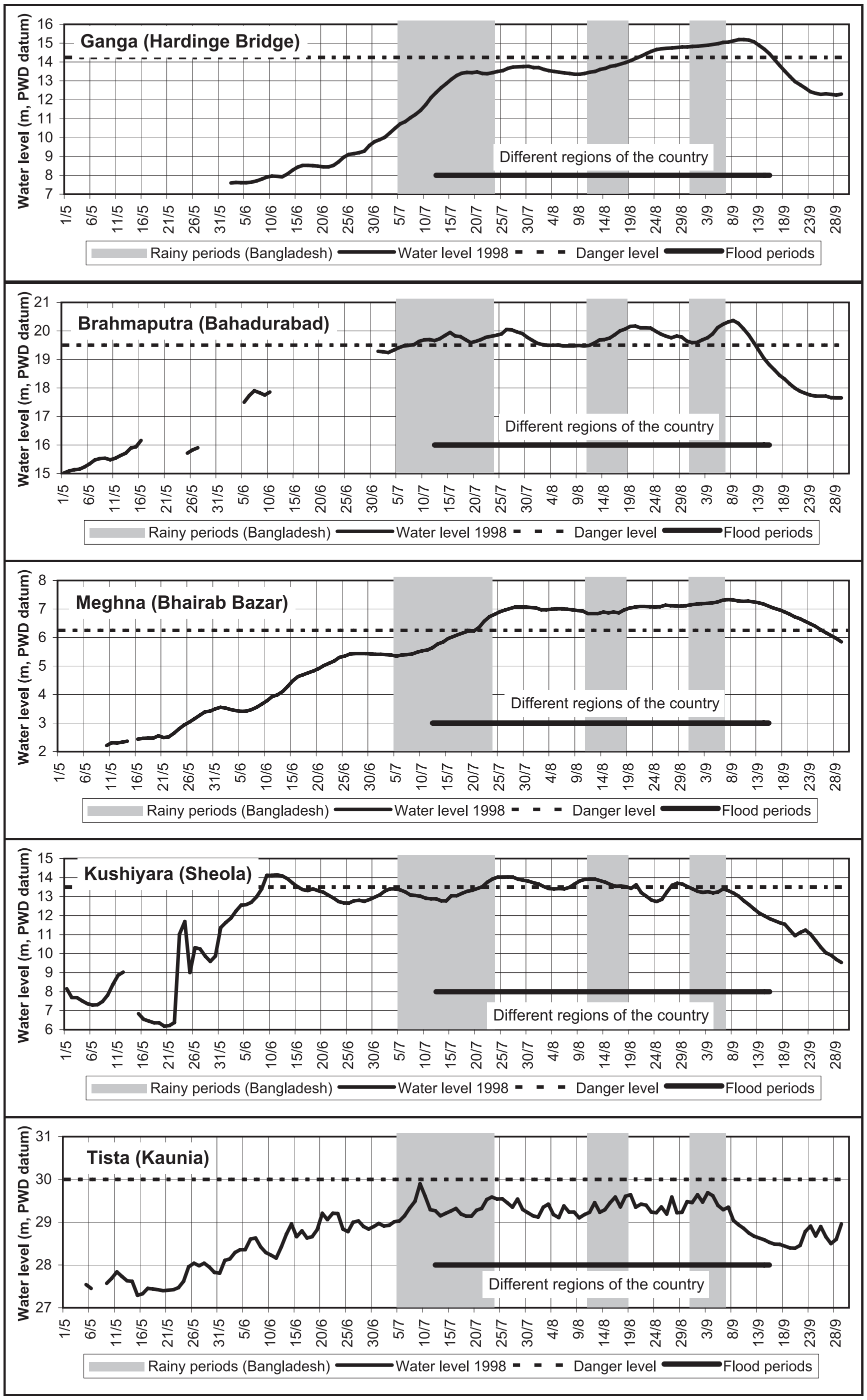

Ganga (Hardinge Bridge)
Water level (m, PWD datum)
16 15 14 13 12 11 10 9 8 7
1/5 6/5 11/5 16/5 21/5 26/5 31/5 5/6 10/6 15/6 20/6 25/6 30/6 5/7 10/7 15/7 20/7 25/7 30/7 4/8 9/8 14/8 19/8 24/8 29/8 3/9 8/9 13/9 18/9 23/9 28/9
Different regions of the country
Rainy periods (Bangladesh)
Water level 1998
Danger level
Flood periods
Brahmaputra (Bahadurabad)
Water level (m, PWD datum)
21 20 19 18 17 16 15
Different regions of the country
Meghna (Bhairab Bazar)
Water level (m, PWD datum)
8 7 6 5 4 3 2
Different regions of the country
Kushiyara (Sheola)
Water level (m, PWD datum)
15 14 13 12 11 10 9 8 7 6
Different regions of the country
Tista (Kaunia)
Water level (m, PWD datum)
31 30 29 28 27
Different regions of the country

Table 5A.8 Timing of the two peak flow periods of the Ganga, the Brahmaputra and the Meghna in 1998

	Peak flow period	
River	End of July	Early September
Ganga (Hardinge Bridge)	Not important (flow below danger level)	7–12 September
Brahmaputra (Bahadurabad)	24–28 July	6–10 September
Meghna (Bhairab Bazar)	27–31 July	5–9 September

Source: BWDB (1998b).
Notes: For the location of the stations, see Figure 3.2.

early September, however, the three rivers peaked almost simultaneously, with 7–9 September being the most obvious days of overlap. Indeed, according to the information presented in the first section of this Appendix, the largest extent of simultaneous flooding in the twentieth century, and maybe even since records began, was reached on 7 September, which seems to have been an extraordinary day: ''At one stage on 7th September, 25 water level stations out of 46 monitoring stations flowed above danger level, which was the worst day of the country'' (BWDB 1998a).

Table 5A.9 compares the hydrological characteristics of the three big rivers in 1998 with the situation in other major flood years. The figures confirm the literature statements that claim that the Ganga reached the highest water level ever recorded. However, in terms of the duration of above-danger-level flow and the dimension of the peak discharge of the Ganga, 1987 was much more important. This might be the result of changes in the river morphology and of the cross-section at the measuring site of Hardinge Bridge. The Brahmaputra flow broke previous records for both the maximum discharge and the number of days with above-danger-level flow. The hydrological features of the Meghna were in all respects less spectacular than in other flood years, for example 1988.

Table 5A.10 provides details regarding above-danger-level flow for a number of stations located on the three major rivers within Bangladesh

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Figure 5A.42 Daily water level of selected rivers in Bangladesh for the period 1 May–30 September 1998, compared with flood periods, rainy periods and danger level.
Notes: For the location of the stations, see Figure 3.2.
Source: BWDB (1998b).

Table 5A.9 Above-danger-level flow, peak water level and maximum daily discharge of the Ganga, Brahmaputra and Meghna for selected years

	Above-danger-level flow (days)				Peak water level (metres)				Maximum daily discharge (m^3/sec)			
River	1974	1987	1988	1998	1974	1987	1988	1998	1974	1987	1988	1998
Ganga (Hardinge Bridge)	41	**55**	23	27	n.a.	14.80	14.87	**15.19**	50,700	**75,800**	71,800	71,612
Brahmaputra (Bahadurabad)	47	14	27	**66**	n.a.	19.86	**20.62**	20.37	91,100	73,000	98,300	**102,534**
Meghna (Bhairab Bazar)	**81**	30	63	68	n.a.	6.91	**7.66**	7.33	19,500	15,200	**19,800**	14,670

Notes: Figures in bold are the highest record per variable and river. For the location of the stations, see Figure 3.2; data sources for 1998: BWDB (1998a); data sources for 1974, 1987 and 1988: see Table 3.4.

Table 5A.10 Details of above-danger-level flow in 1998 for a number of sites (in upstream–downstream order) on the big rivers within Bangladesh

River system	Station	Above-danger-level flow (days)	Peak water level above danger level (cm)
Ganga	Rajshahi	28	118
	Hardinge Bridge	27	94
Padma	Goalundo	68	**171**
Brahmaputra	Kaunia	0	0
	Chilmari	22	77
	Bahadurabad	66	87
	Serajgonj	48	101
	Aricha	68	**162**
Meghna	Sheola	37	64
	Bhairab Bazar	68	108

Source: BWDB (1998a).
Notes: Figures in bold indicate the highest ever water levels measured at these sites. For the location of the stations, see Figures 3.1 and 3.2; Goalundo is located below the confluence of the Ganga and the Brahmaputra/Jamuna; Chilmari is located on the Brahmaputra/Jamuna slightly upstream of Bahadurabad; Aricha is located on the Brahmaputra/Jamuna immediately upstream of the confluence of the Ganga and the Brahmaputra/Jamuna.

in upstream–downstream order. In general, the number of days of above-danger-level flow and, even more pronounced, the dimension of above-danger-level flow increased towards the confluence area of the three big rivers. The water levels of the Padma at Goalundo and of the Brahmaputra at Aricha were the highest ever measured at these sites. As a result, and as already concluded from Figure 5A.39, the flood situation in the area surrounding the confluence of the three big rivers was particularly severe. This situation can be attributed to strong backwater effects induced by the simultaneous peak flows of the big rivers and, according to the literature, to the high sea level in the Bay of Bengal.

The flow of the Kushiyara (Figure 5A.42) constantly fluctuated around the danger level from mid-June to early September. A large percentage of this water was certainly imported into Bangladesh from the adjacent eastern hills. The main flooding periods are to some extent reflected in the hydrograph, but the maximum flow of the year had already been reached in the first part of June.

The hydrograph of the Tista (Figure 5A.42) does not reflect the patterns of the other rivers. The flow never reached the danger level, and the only distinct peak was measured around 10 July, before the floods started in Bangladesh. From this example we must conclude that the in-

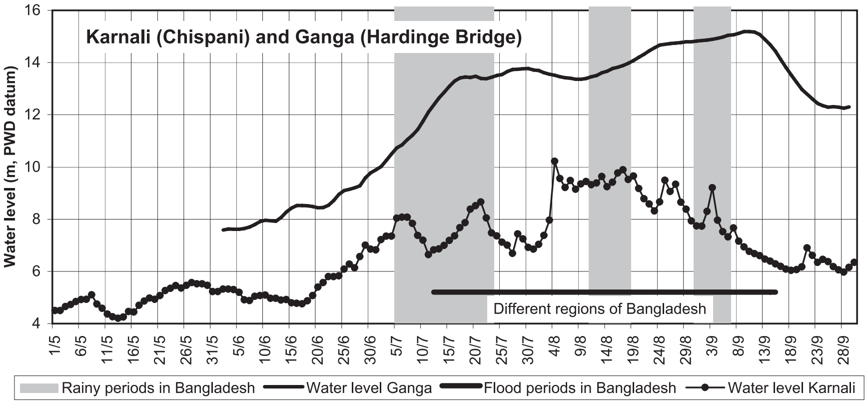


Figure 5A.43 Daily water level for the Karnali River at Chispani, Nepal, for the period 1 May–30 September 1998, compared with the hydrograph of the Ganga at Hardinge Bridge and the rainy and flood periods in Bangladesh.
Notes: For the location of the station, see Figure 3.2.
Sources: HMG (n.d.); BWDB (1998b).

put from the Darjiling Himalayas was not important for the development of the floods in Bangladesh.

We were able to obtain water level data for only one station in Nepal (Figure 5A.43). Because the data for the Karnali at Chispani were available only for this particular year, it is not possible to compare the hydrograph with other years and, accordingly, to know whether the water level of the Karnali was particularly high, normal or even below average in 1998. We therefore have to limit ourselves to some general and qualitative comments. The highest water level of the Karnali in 1998 was reached in the first few days of August, almost one month before the big rivers in Bangladesh reached their maximum flows. The hydrograph follows a rather individual pattern and does not share any obvious traits with the hydrograph of the Ganga. Moreover, the short-term peaks of the Karnali do not coincide with the periods of maximum flood extent in Bangladesh (see the subsection on the chronology of the flood in the first section of this Appendix). Based on these few observations and in accordance with the discussion of the rainfall situation, there is no reason to assume that the hydrological contribution from Nepal was particularly important before or during the big floods in Bangladesh.

It is almost certain that the inflow from Assam through the Brahmaputra and from the Indian Gangetic Plain through the Ganga was significant. From the literature statements and from the interpretation of NOAA-AVHRR satellite images carried out by the Dartmouth Flood

Observatory (Dartmouth College and Earth Science Enterprise n.d.), it is likely that in India the water levels of the Brahmaputra as well as of the Ganga and its tributaries were high during August and early September and that over certain stretches the rivers were even overflowing their banks (see also the first section of this Appendix on flooding conditions outside Bangladesh). However, with the available information it is difficult to assess whether and to what extent this inflow from India into Bangladesh was flood triggering or whether it was important just because of the synchronization of the peak flows.

Summary

The floods of 1998 were indeed the most severe of the twentieth century in terms of both duration and extent. Interpretation of the available data sets confirms most of the literature statements about the causes of the floods. Overall, the La Niña situation resulted in very humid monsoon conditions. At a number of hydrological stations the water table reached the highest ever recorded levels. The key to the development of the flood seems to have been the combination of continuous and widespread rains during July and August (particularly in Bangladesh), high inflow into Bangladesh through the main rivers, the almost simultaneous peaking of the flows of these rivers, and backwater effects from the Bay of Bengal owing to high tides. It is unfortunately not possible to quantify these tidal effects and we must trust the statements made in the literature sources in this regard. It was as if the water masses accumulating through rainfall in Bangladesh and through significant inflow from the Indian plains were backed up in the larger confluence area of the major rivers, which resulted in the spreading of the flood waters. The Brahmaputra basin in particular, but also the Ganga system, seem to have been more important than the Meghna system. Based on the limited information it was not possible to conclusively analyse and assess the hydrological contribution from the Himalayas to the extraordinary floods in Bangladesh. However, interpretation of the few available data sets does not provide any arguments or justification for assigning any particular importance to this contribution.

The analysis of the extraordinary floods in 1988 presented in this Appendix is a first approximation. A much more thorough investigation with more complete data sets is required to fully understand the dimension of the event as well as the complexity and interaction of the contributing factors.

Factors that were important for the nationwide flooding in Bangladesh from mid-July to mid-September:

- the La Niña situation;

- constant and intensive rains, particularly within Bangladesh, during July and August;
- simultaneous and constant above-danger-level flow of the three major rivers;
- backwater effects resulting from the synchronization of the peak flows of the three major rivers between 7 and 9 September and from high tides;
- the river systems, in decreasing order of importance: Brahmaputra, Ganga, Meghna.

Factors that were not important for the nationwide flooding in Bangladesh from mid-July to mid-September:

- rainfall in the pre-monsoon and early monsoon periods;
- input from the Himalayas (this statement is based on interpretation of the very few available data sets).

Appendix 5.9: 1923 – A "dry year"

As discussed in section 5.1, two years in which the extent of flooding in Bangladesh was particularly low (namely 1923 and 1978) were added to the list of cases studies. These examples will assist in identifying important differences between contrasting situations and sharpening our understanding of the specific processes leading to widespread flooding. The 1923 case study is based on investigations by project team member Roland Guntersweiler (Guntersweiler 1995). The summary of this case study is presented in section 5.12 (pp. 188–190).

The 1923 drought and flood situation at a glance

Throughout the subcontinent, the onset of the monsoon was late and in general the monsoon is described as having been weak. Favourable conditions for farming were reported from Assam (the Brahmaputra lowlands in India in the north-eastern part of the study area) and from Bihar (the Indian Ganga Plain). North Bengal, which basically covers the area of SC10 (the north-western part of modern Bangladesh, see Figure 5.1), was affected by a drought throughout the monsoon season. In July and particularly in August the situation was rated as "severe", and the water levels of the Ganga and Brahmaputra were very low. As a consequence of the drought, sowing of the winter crop was delayed and yields were below average.

However, 1923 was not entirely flood free in the Ganga–Brahmaputra–Meghna basin: at the end of June, a heavy storm caused a localized flash flood in the Sylhet area (SC11). According to the reports, this event was outstanding in terms of both its suddenness as well as amount of rainfall over a short time period. No information is available on the duration of the inundation or on damage to crops. The Patna region in the Lower Ganga Plain (SC5) was affected by a flood at the end of August. During this event, an area of 250–1,500 km^2 was inundated. The floods occurred after a rapid rise in the rivers Son (a southern tributary of the Ganga) and Gogra (a northern tributary of the Ganga from Nepal) as well as in the Ganga itself. The breaching of an embankment near Patna aggravated the situation. The flood caused the death of 38 people and 1,244 cattle as well as the destruction of 44,000 houses. Some time later, a flood in the area of Lucknow (SC4) occurred that caused damage to buildings.

Literature sources

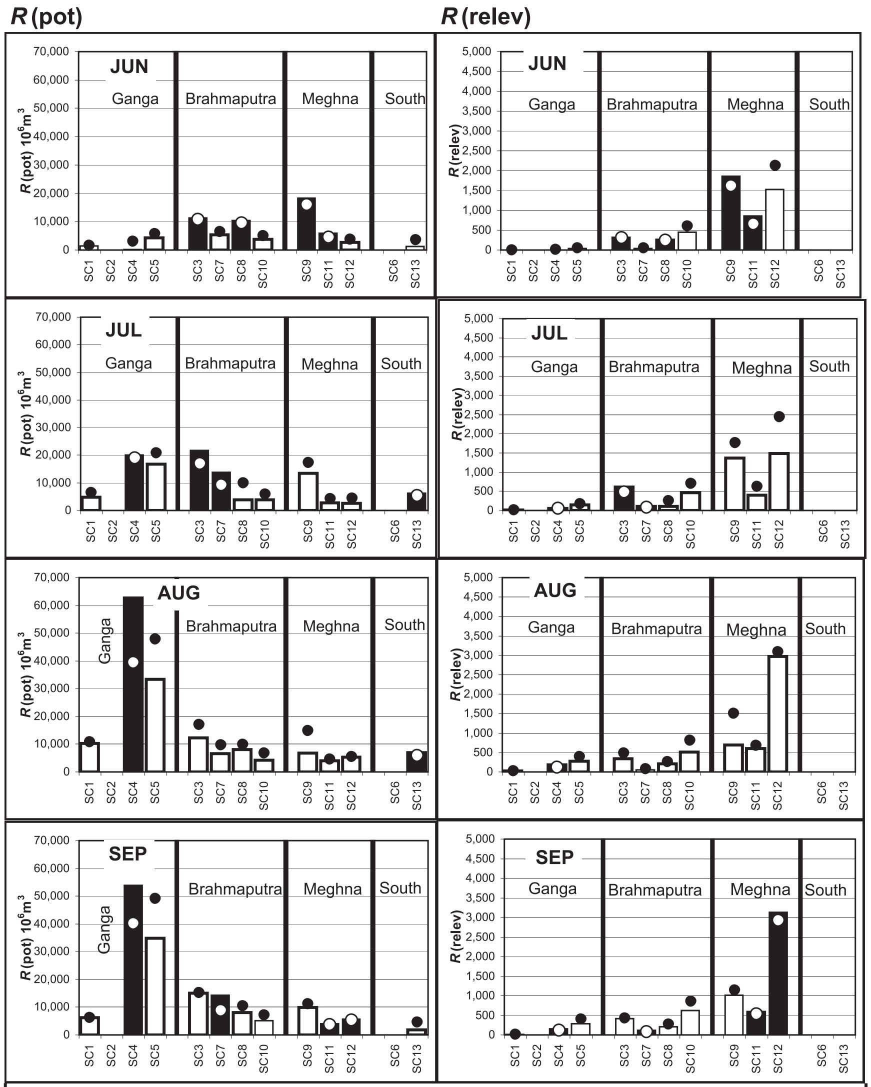
The Englishman (1923: 9 Jun, 16 Jun, 3 Jul, 4 Aug, 21 Aug, 23 Aug, 29 Aug, 4 Sep, 18 Sep, 22 Sep, 26 Sep); *The Statesman* (1923: 7 Jun, 14 Jun, 21 Jun, 28 Jun, 19 Jul, 9 Aug, 23 Aug, 30 Aug, 6 Sep, 20 Sep, 27 Sep, 4 Oct).

Hydrological contributions from the different subcatchments and their relevance to the flooding conditions in Bangladesh (Figure 5A.44, Figure 5.1)

Overall, the 1923 monsoon was rather weak: with some exceptions (e.g. SC4), negative anomalies in *R*(pot) and *R*(relev) dominated, particularly in August. In the Lower Ganga Plain (SC5), Lower Assam (SC8), North-western Bangladesh (SC10), Meghalaya Hills (SC9) and Central–Eastern Bangladesh (SC12), the anomalies were negative over three to four consecutive months. The severe drought reported in SC10 is related to this situation. Except for SC13, *R*(pot) was below average in all the subcatchments of Bangladesh during July and August, the two most important monsoon months.

The contribution from the Darjiling–Bhutan Himalayas (SC3) was slightly above average in June and significantly above normal in July. It can be assumed that, in the first part of the monsoon season, the flow of the Tista into the Brahmaputra was higher than normal. This situation obviously did not have any relevance further downstream, either in terms of flood generation or in terms of drought mitigation.

The situation in the Ganga system was mixed: whereas *R*(pot) in the North-western Himalayas (SC1) and in the Lower Ganga Plain (SC5) was below average throughout the four monsoon months, the opposite situation was recorded in the Upper Ganga Plain (SC4), where the hydrological contribution was constantly above normal from July to Sep-



LEGEND:

***X*-axis:**	**subcatchments, grouped according to the main river basins and the southern areas**
Dots (black, white):	**average, 1891–1950**
White columns:	**below-average values in 1923**
Black columns:	**above-average values in 1923**
Missing data for:	**SC2, SC6**

Figure 5A.44 Monthly potential runoff (*R*(pot)) and relevance for Bangladesh (*R*(relev)) in the 13 subcatchments for the four monsoon months of 1923.
Notes: *R*(relev) has no measuring unit. For the location of the subcatchments, see Figure 5.1; for the data sources, see Table 3.2.

tember. The anomalies were quite significant in August and September. The floods reported for the areas of Lucknow (SC4) and Patna (SC5) can most probably be related to this situation. These floods evidently levelled out and did not move further downstream.

The relevant calculations indicate that the anomalies in *R*(pot) during the pre-monsoon period (April–May) were positive for most subcatchments in the Brahmaputra and Meghna basin and negative for all subcatchments in the Ganga basin.

Daily rainfall (Figure 5A.45)

As expected, the number of rainy days was lower than in the flood years, which is an important explanation for the overall dry conditions in the study area. In addition, the rainfall patterns were temporally and regionally much more differentiated: no really long and widespread rainfall periods can be identified. The particularly scarce rainfall throughout August evident at most stations is a very striking difference from the situation in the flood years.

In the period 14–17 June, a concentration of high-intensity rainfall occurred at the stations of Gauhati (Lower Assam), Cherrapunjee (Meghalaya Hills) and Sylhet (North-eastern Bangladesh). Within only three days, from 14 to 16 June, 1,757 mm of rainfall was recorded in Cherrapunjee. The flash flood in the Sylhet area, discussed in the written sources, was clearly a result of this high-intensity rainfall. The duration and extent of this flood, however, were limited. Between 29 August and 2 September, and in parts extending until 5 September, a rainy period occurred that affected more or less the entire study area. The flood in the region of Patna falls within this period, but is the only event that is related to this rather widespread precipitation.

The above-average *R*(pot) in the Upper Ganga Plain (SC4) during August and September, discussed in the previous section, seems to be related not to an above-average number of rainy days (see the stations of Lucknow and Meerut) but rather to higher-intensity rainfall.

Daily water level (Figure 5A.46)

The available water level data are scanty. For the Ganga, information is too limited to be included in this discussion. The data series for the Brahmaputra and the Padma are acceptable, despite a number of data gaps.

The water level of the Brahmaputra at Gauhati never reached levels comparable to the flood years of 1910 (Figure 5A.8) and 1922 (Figure 5A.12). The patterns of the hydrograph reflect the rainfall situation: a

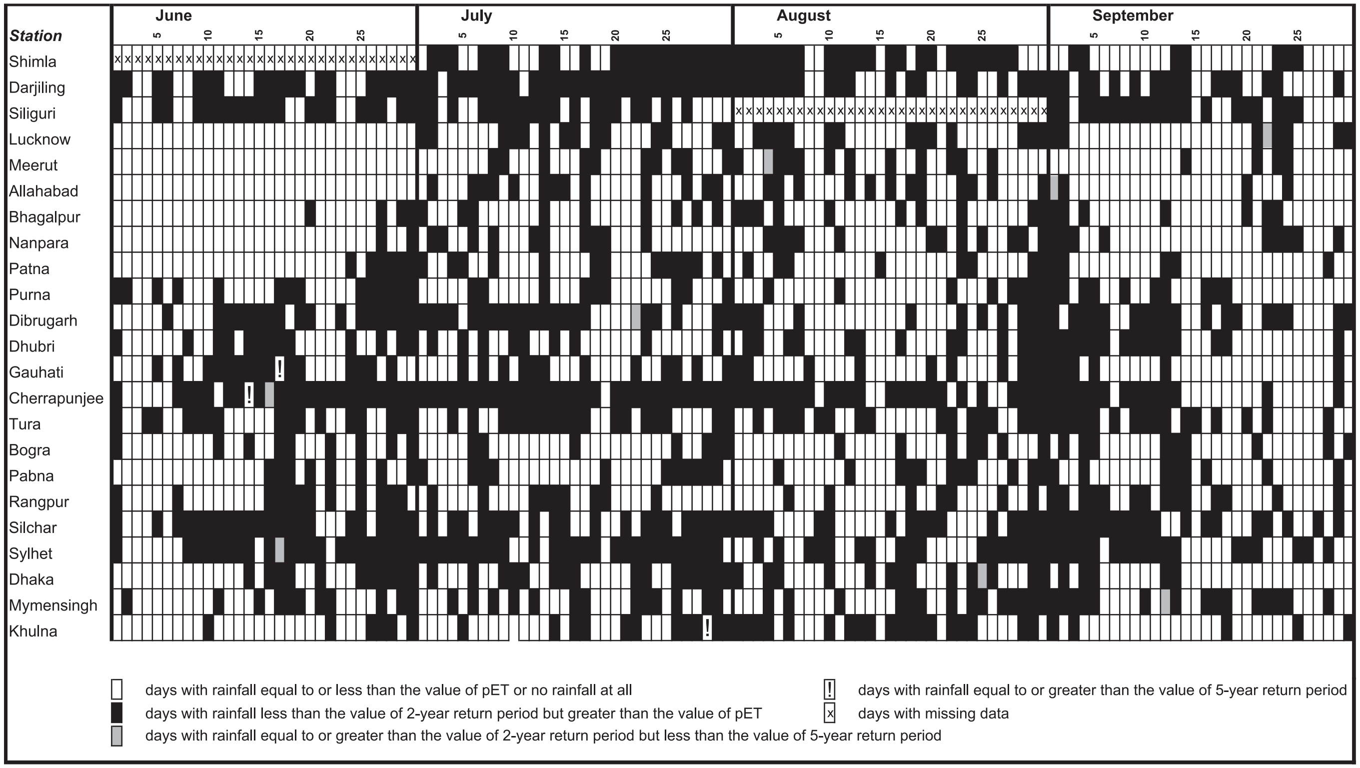


Figure 5A.45 Categories of daily rainfall for the period 1 June–30 September 1923.
Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2; for threshold values for the return periods, see Table 5A.2.

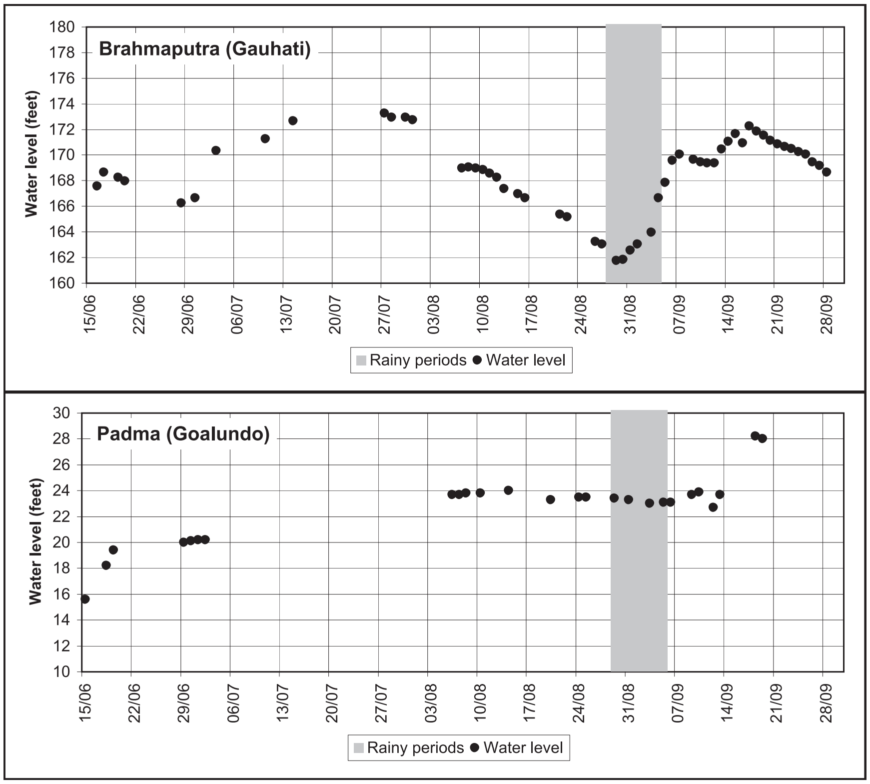


Figure 5A.46 Daily water level of selected rivers for the period 15 June–30 September 1923, compared with the rainy period.
Notes: For the location of Gauhati, see Figure 3.2. Goalundo is located immediately after the confluence of the Ganga and the Brahmaputra/Jamuna. The water level data are from *The Englishman* (1923).

significant drop in the water level during August, a month with particularly scarce rainfall; a reverse trend in the first part of September coinciding with the sole rainfall period identified for the 1923 monsoon season.

In early August, the water level of the Padma at Goalundo reached average values and remained constant during this month. The peaks measured in mid-September were significantly higher than those in any of the three flood years of 1906, 1910 and 1922. In view of the significant data gaps before and after these peaks, the reliability of these records may have to be questioned.

Summary

In the area of modern Bangladesh, 1923 was a characteristically dry year. Considering *R*(pot) and daily rainfall, the differences compared with the situation in the flood years seemed to be:

- in temporal terms: scarce precipitation in August (in most flood years, distinct and significant rainfall periods occurred during this month);
- in regional terms: below-average *R*(pot) and *R*(relev) in the subcatchments of Bangladesh, in the Meghalaya Hills and in Lower Assam (in the flood years the anomalies tended to be positive in these areas).

Whereas there was less precipitation in the Brahmaputra–Meghna system than in the flood years, there was considerably more in the Ganga lowland: *R*(pot) in the Upper Ganga Plain was almost constantly above average. Apart from short-term flash floods in June in north-eastern Bangladesh, the Ganga lowland was the only area where major and quite severe flooding occurred. The floods in the Patna area were most probably caused by a combination of local rainfall and high flows of the Ganga and two of its tributaries (the Son from the south and the Gogra from the north). These flood events in the Ganga Plain evidently levelled out and did not have any impact on the hydrological patterns further downstream in Bangladesh.

Appendix 5.10: 1978 – A "dry year" for Bangladesh

A summary of this case study is presented in section 5.13 (pp. 191–194).

The 1978 drought and flood situation at a glance

According to the statistics, only 10,800 km^2 (or 7.6 per cent) of Bangladesh was flooded in 1978 (Table 4.1), which is far below the average of 20.8 per cent. The areal extent of the inundation was one of the smallest of the period 1954–2004 for which statistics are available. Only the western part of Bangladesh experienced minor flooding processes. Interestingly, this area tends to be flood free or only marginally affected in severe flood years (see, in particular, the 1955, 1974 and 1988 case studies).

For the Indian Ganga system, however, 1978 was a severe flood year. In Uttar Pradesh and in West Bengal (parts of SC4 and SC5) the flood-affected area was the largest in the period 1954–1994 for which statistics are available (Figure 4.9). Three flood phases are described in the written sources:

- Continuous heavy rainfall in August over the plains of Bihar, causing severe flooding in the Burhi Gandak (a Ganga tributary from Nepal), which was flowing more than 3 metres above danger level.

- Severe floods in the Yamuna and the Ganga in Uttar Pradesh (SC4) in the first fortnight of September. This flood is perceived as the most severe event of the century. After 2 September, the gauge in the Yamuna is reported to have been completely submerged by flood waters.
- Catastrophic floods in Gangetic West Bengal in the last week of September. This flood was most likely triggered by a depression that moved from the east coast of the Indian Peninsula westwards, subsequently turning eastwards and ending up in the Bay of Bengal. "There has been no such case of southerly movement of a depression from Gangetic West Bengal into the head of the Bay of Bengal during the last 100 years" (Ramaswamy 1987: 335).

The impact of the floods on the Indian Gangetic Plain was significant: 6 million hectares of crops were lost and 3 million tons of cereals were destroyed; at least 40 million people were affected, and 1,200 people died; 8,000 cattle drowned in the flood waters.

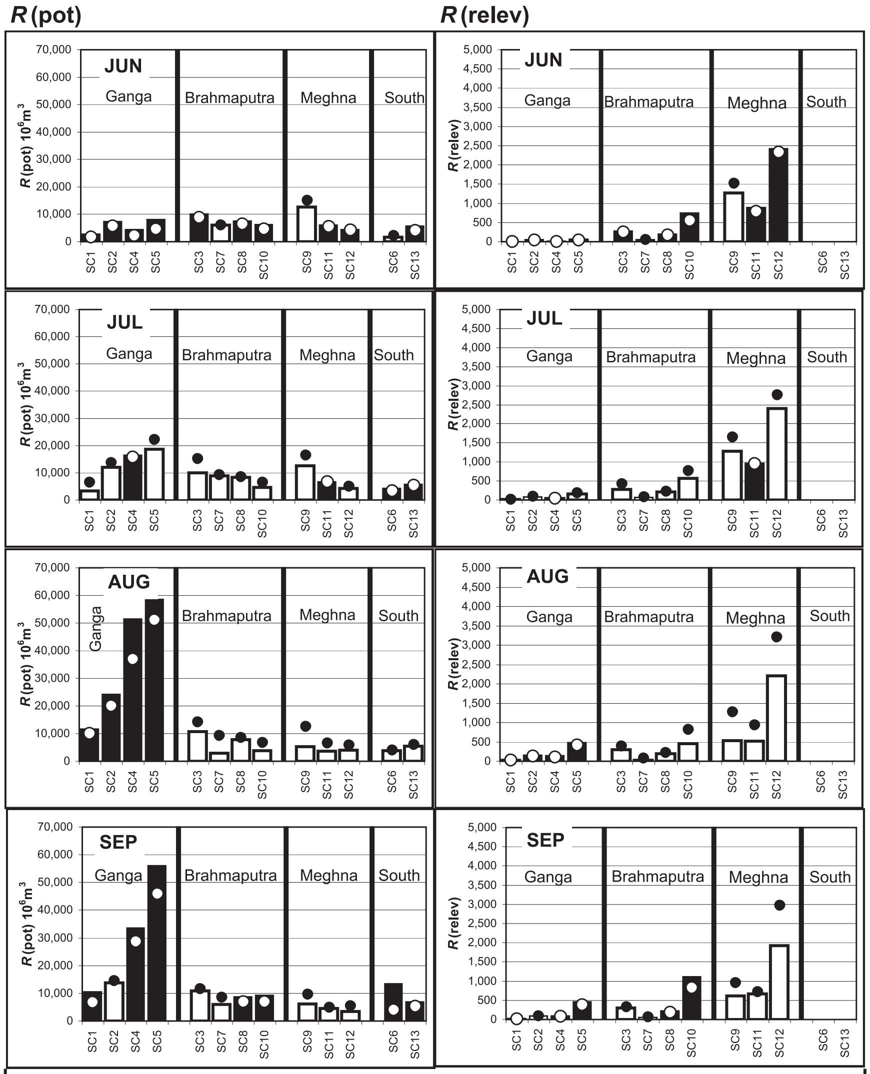
Literature sources

Winkelmann (1979); Chattopadhyay (1980); Gosh et al. (1982); Ramaswamy (1987); USAID (1990); Choudhury (1993).

Hydrological contributions from the different subcatchments and their relevance to the flooding conditions in Bangladesh (Figure 5A.47, Figure 5.1)

As expected, negative anomalies in R(pot) and R(relev) dominated in Bangladesh during July and August, and to some extent also in September. This situation can be observed far beyond the borders of Bangladesh in the entire basin of the Brahmaputra and the Meghna rivers. In August, not one single subcatchment in Bangladesh, either in the Brahmaputra or in the Meghna basin, had positive variations. The negative anomalies were particularly obvious in Meghalaya (SC9), where input was below average throughout the monsoon period, but most prominently in August and September.

In the Ganga basin, the situation was completely different. The positive anomalies in R(pot) were remarkable and, in the case of the Upper Ganga Plain (SC4), constant throughout the monsoon season. In August and September, the period of the most intensive flooding on the Indian Ganga Plain, the anomalies were particularly prominent and widespread. The positive variations in R(pot) in the Ganga system, however, did not result in any significant above-average relevance of the Ganga subcatchments to the hydrological processes in Bangladesh.



LEGEND:

X-axis: **subcatchments, grouped according to the main river basins and the southern areas**

Dots (black and white): **average, 1900–1990**

White columns: **below-average values in 1978**

Black columns: **above-average values in 1978**

Missing data for: **None**

Figure 5A.47 Monthly potential runoff (*R*(pot)) and relevance for Bangladesh (*R*(relev)) in the 13 subcatchments for the four monsoon months of 1978.

Notes: *R*(relev) has no measuring unit. For the location of the subcatchments, see Figure 5.1; for the data sources, see Table 3.2.

In each monsoon month, with the exception of July, the hydrological contribution was above average for at least one Himalayan subcatchment in the Ganga system (SC1 or SC2). These highland areas certainly contributed to the flooding processes in the Ganga Plain during August and September. However, it is not possible to assess the importance of this contribution because the anomalies in the lowlands were remarkable as well. The floods in West Bengal in late September, which were triggered by the depression over the area itself, certainly did not have much to do with the hydro-meteorological processes in the Himalayas.

According to the relevant calculations, *R*(pot) in SC2 and SC5 was above average during the winter and the pre-monsoon period. This indicates that a considerable amount of water had potentially already accumulated in parts of the Ganga basin before the monsoon started. This certainly provided favourable conditions for the development of the floods in the Ganga lowlands.

At the beginning of July, the conditions for large-scale flooding in Bangladesh would have been favourable as well: in the pre-monsoon period (April–May) and in June, the variations in *R*(pot) for all four subcatchments of Bangladesh (SC10, SC11, SC12, SC13) were above average. However, with predominantly below-average *R*(pot) and *R*(relev) in July and August, a key input for the development of floods in Bangladesh seems to have been missing.

Monthly discharge (Figure 5A.48)

The differentiation between a very active monsoon in the Ganga system and a rather weak monsoon in the Brahmaputra and Meghna systems is clearly reflected in the monthly patterns of river flow:

- The discharge of the Ganga was significantly above normal from May to October, with anomalies ranging between 20 and 40 per cent. In marked contrast, the flow of the Brahmaputra was below average during the monsoon season.
- The positive discharge variations in the Sapt Kosi, an important Himalayan tributary of the Ganga, were remarkable. Owing to lack of information, it remains open whether this important finding can be generalized for the entire Himalayan part of the Ganga basin or whether it was specific to this particular tributary from Nepal. However, the situation in the Tista, an important Himalayan tributary of the Brahmaputra, was so completely different (with below-average variations from July to November) compared with the Sapt Kosi that we have to assume some sort of a ‘‘meteorological divide’’ between these two Himalayan rivers (see also sections 5.15 and 5.16).
- The discharge of the Kushiyara, a main tributary of the Meghna, fluctu-

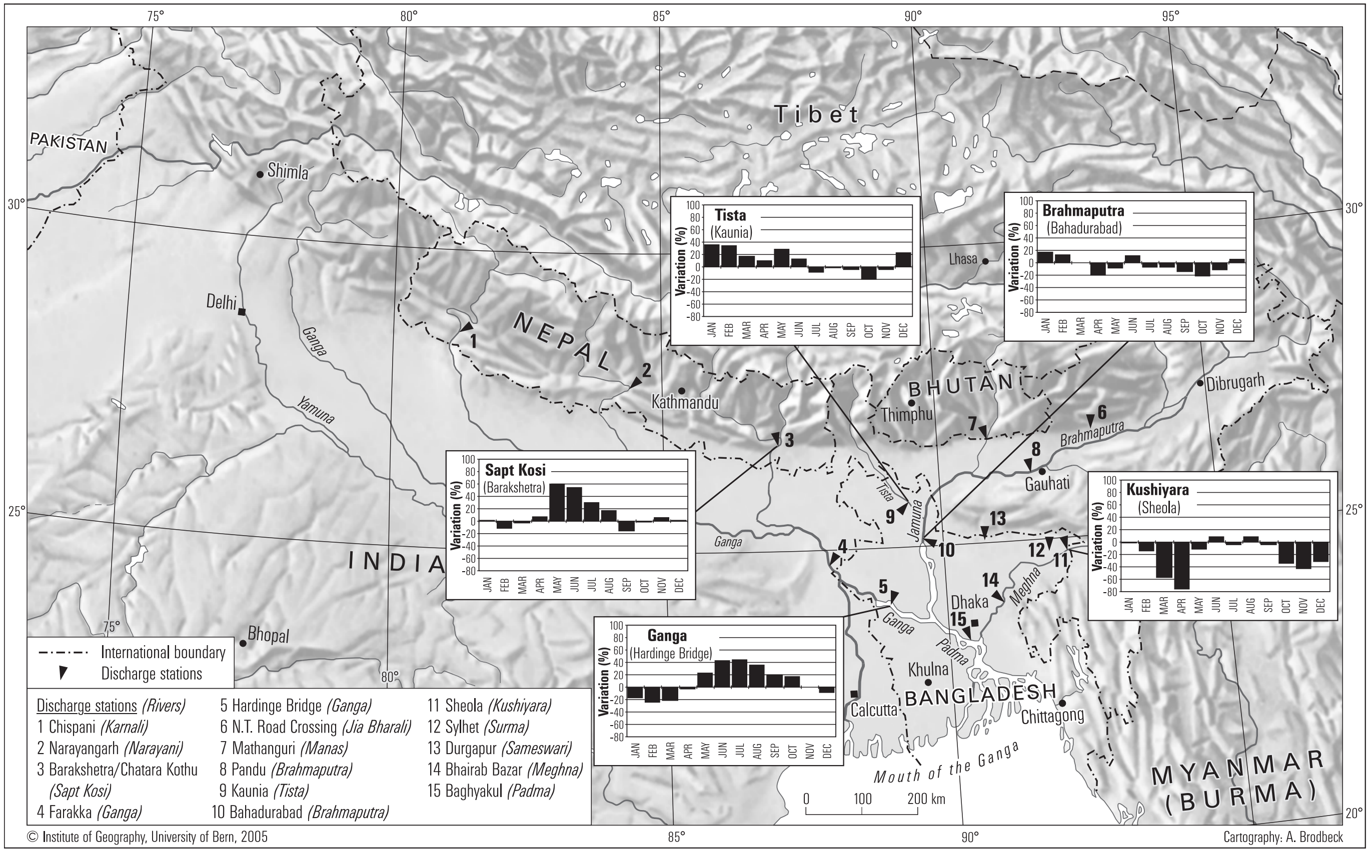


Figure 5A.48 Monthly discharge variations as a percentage of the average for selected rivers in 1978.
Notes: For the data sources, see Table 3.4.

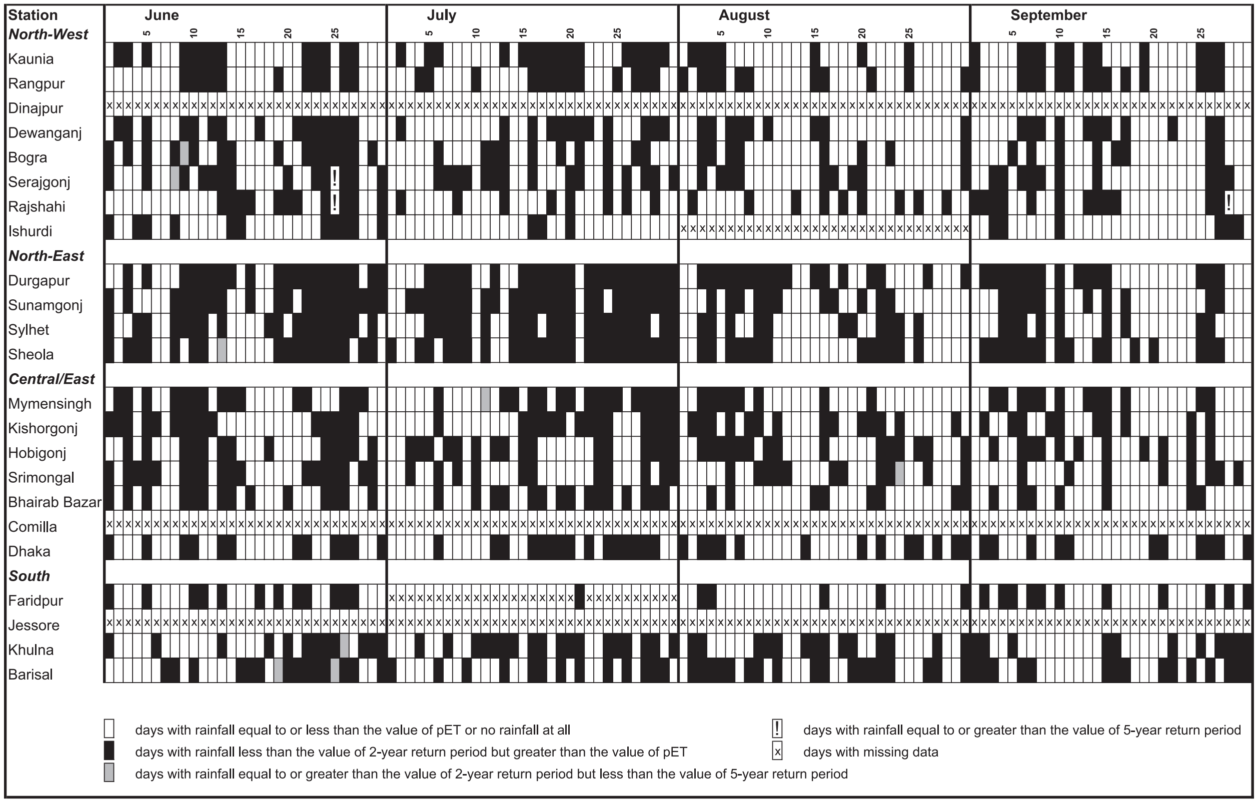


Figure 5A.49 Categories of daily rainfall for the period 1 June–30 September 1978 in Bangladesh.
Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2; for threshold values for the return periods, see Table 5A.2.

ated around average values during the monsoon months and was significantly below normal in the pre- and post-monsoon periods. Unfortunately, data for the Meghna are missing.

Daily rainfall (Figure 5A.49)

Three rainfall periods are worth mentioning:

- 20–27 June was the only period of the 1978 monsoon season during which rainfall in Bangladesh was widespread and, at some stations in the north-west and the south, intensive.
- In the second half of July and early August, rainfall was frequent or even continuous at a number of stations. However, none of these daily observations exceeded a return period of two years.
- Probably as a result of the depression that moved into West Bengal in the last week of September, rainfall was widespread in Bangladesh during four days, 25–28 September.

As in the "dry year" 1923, and in contrast to the situation in most "flood years" for Bangladesh, very little rainfall was recorded during most of August and large parts of September, in terms of both rainy days and rainfall intensities. Accordingly, rainfall in Bangladesh was insignificant during the period of widespread flooding in the Indian Ganga Plain (Uttar Pradesh and Bihar) and of subsequent high inflow into Bangladesh through the Ganga system.

Daily discharge (Figure 5A.50)

The negative flow variations are particularly obvious in the Brahmaputra system. The highest flow of the Tista and the Brahmaputra remained significantly below the maximum discharge that is on average reached during the monsoon season. The flow of the Kushiyara reached the level of the dotted horizontal line several times, but never exceeded it. The highest flow of the Ganga was significantly above the maximum discharge that is to be expected on average. For the peak discharge recorded on 21 August, a return period of approximately 15 years was calculated.

Reflecting the rainfall patterns in Bangladesh, the flows of the Tista, the Brahmaputra and the Kushiyara were highest during June and July and gradually decreased during August and September. As a result of hydro-meteorological processes in the Ganga Plain, the high inflow from the Ganga occurred during August and September, which obviously coincided with moderate flows of the Brahmaputra and, most probably, of the Meghna within Bangladesh. According to Choudhury (1993), this is one of the main reasons for the very low dimension of flooding in Bangladesh in spite of the high inflow from the Ganga system. This means that the

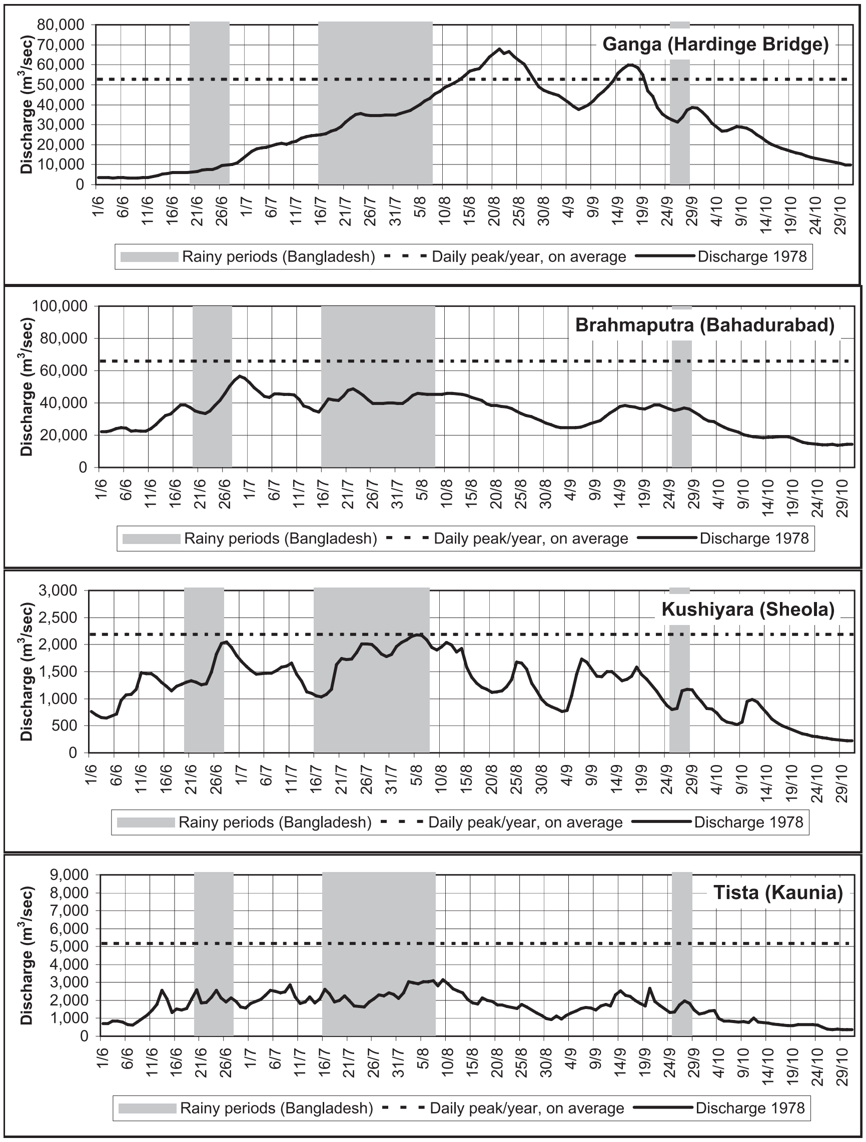


Figure 5A.50 Average daily discharge of selected rivers in Bangladesh for the period 1 June–31 October 1978, compared with the rainy periods and daily peak/year, on average.

Notes: For the location of the stations, see Figure 3.2; for the data sources, see Table 3.4. Unfortunately, data for the Meghna are missing.

Ganga does not have the same hydrological significance for Bangladesh as do the Brahmaputra and the Meghna. The Ganga on its own does not seem to be able to trigger major flooding processes in Bangladesh, even if its flow is very high.

Groundwater (Figure 5A.51)

As a result of above-average R(pot) in the four Bangladeshi subcatchments in the pre-monsoon period and in June, the groundwater table was higher than normal at almost all stations at the beginning of July (week 27). Potentially, therefore, the water retention capacity of the ground was reduced and, at least from this point of view, the conditions for flooding in Bangladesh would have been favourable. However, owing to the limited amount of rainfall during July and particularly during August and September (weeks 28–39), these positive anomalies gradually disappeared or even became negative. It is obvious that triggers for groundwater reservoirs in Bangladesh to overflow were missing.

One of the most important differences compared with the flood years is documented at station FA22, located downstream of the confluence of the Ganga and the Brahmaputra. In each of the flood years of 1974, 1987 and 1988, the groundwater level at this site reached the surface. In 1978, however, the graph documents average or even slightly below-average conditions.

The flooding in the Indian Ganga basin

Kuster (1995) analysed a number of twentieth-century flood events that occurred in the Yamuna basin (Figure 5A.52), from its source in the Himalayas all the way down to Allahabad at the confluence of the Yamuna with the Ganga. The investigations are based on a variety of literature sources as well as on available rainfall records. The case studies include a detailed account of the flood processes in terms of chronology and geographical pattern, as well as a discussion of the rainfall patterns over the study area before and during the flood events. The severe flood in the Yamuna lowlands in the first fortnight of September 1978 (see the first section of this Appendix) is one of the case studies analysed by Kuster. His findings are very interesting and provide important insights into several aspects of the highland–lowland linkages. In the following, we summarize Kuster's main findings.

The flood chronology

The first flood occurred on 4 August. This event affected some villages around Delhi and caused damage to the embankment of an irrigation

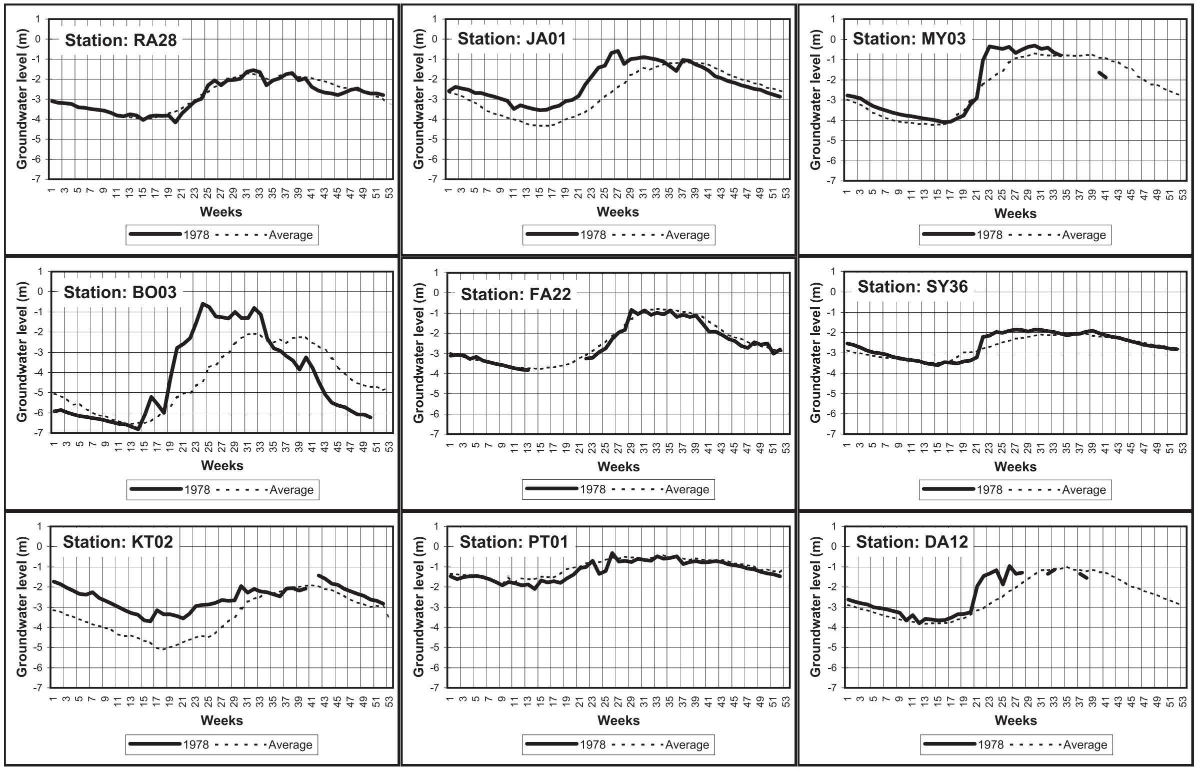


Figure 5A.51 Groundwater levels of selected stations in 1978, compared with average groundwater levels over roughly 20 years.

Notes: For the location of the stations, see Figure 3.3. The four monsoon months correspond to the week numbers approximately as follows: June, weeks 23–26; July, weeks 27–30; August, weeks 31–34; September, weeks 35–38.

Source: BWDB (n.d.[b]).

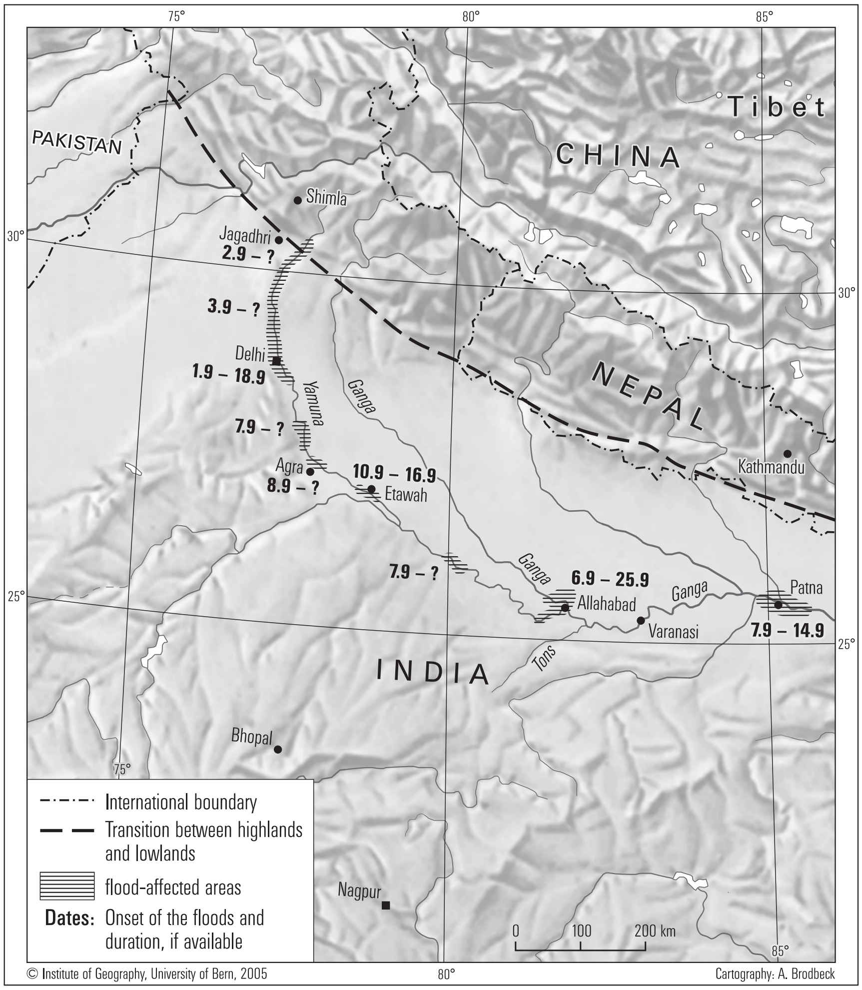


Figure 5A.52 Flooding in the Indian Ganga Plain in September 1978: Affected areas and chronology.
Source: Kuster (1995).

channel (*Hindustan Times*, August and September 1978). After a short improvement in the flood situation, 150,000 people along the Yamuna had to flee from a subsequent flood wave on 17 August. Rainfall in Delhi exceeded 140 mm and the Yamuna reached a first flood peak on 21 August. The most important flood was triggered in early September (Figure 5A.52). Both sides of the river Yamuna were flooded and embankments were breached in several places. Delhi was flooded on 4 September and the inundation reached a breadth of 20 km on both sides of the river. The movement of the flood wave along the Yamuna was observed from Jagadhri through Delhi and Agra down to Etawah. The city of Allahabad, which is located more than 820 km downstream of Delhi, was flooded only two days after Delhi on 6 September. Thus, the flood wave from Delhi cannot be considered to be a main trigger of the inundation in Allahabad. In the same period, floods were also recorded further downstream of Allahabad along the Ganga (Pathak 1985): Patna was inundated on 7 September. On 13 September, the Indian authorities announced that the Farakka Reservoir, which is located only a few kilometres upstream of the India–Bangladesh border, was full and that it was necessary to release water into Bangladesh.

The flood duration

The floods in Delhi lasted at least 13 days, until 18 September. Further downstream, in Etawah, the floods had almost receded after seven days. In Varanasi and Patna the flood situation had returned to normal on 14 September, whereas higher up in the basin several villages were still under water. Only in the district of Allahabad did the floods continue until 25 September, owing to the simultaneous flood flows of the Yamuna and the Ganga.

The rainfall situation

Heavy rainfall from 31 August to 3 September was first recorded in several villages around Delhi. Subsequently, with the movement of the depression, the rainfall area expanded further north into the Siwalik Hills (the foothills of the Himalayas) and the first Himalayan ranges. There is no doubt that the rains in the hills were significant. However, the most important rainfall occurred over the flood-affected areas to the north of Delhi. Unfortunately, no rainfall information is available for the areas to the south of Delhi and therefore the relevance of local rainfall for the floods in these regions cannot be determined.

Discussion of the findings

There was a direct link between the rainfall in the first Himalayan ridges and in the Siwalik Hills and the flood processes in the adjacent plains north of Delhi. However, the rainfall over the flood-affected areas themselves was at least as important if not more so. The floods between Delhi and Allahabad developed in isolated patches (Figure 5A.52). Most probably these events were not the result of the flood wave moving from the foothills downstream along the Yamuna system, but rather the result of local flood triggers such as heavy rainfall or high water levels in the tributaries. The fact that the flood in Allahabad started before the flood wave from Delhi could actually have reached this area is an important argument for this assumption. The dimension of the flood in the area of Delhi was most likely preconditioned by the preceding flood phases during August.

Based on the comparison of all flood case studies analysed for the catchment area of the Yamuna, Kuster (1995) draws some general conclusions related to highland–lowland linkages:

- Most of the precipitation that was responsible for the investigated floods was caused by depressions originating in the Bay of Bengal that subsequently moved north-west over the Indian Peninsula and finally turned north towards the Himalayan ranges. On their way, the depressions produced cells of precipitation and localized floods.
- Precipitation in the mountains may or may not have been important for the floods in the Yamuna Plain: generally, the centres of the flood-causing rainfall were located over the plain itself, but may have in part reached into the Siwaliks (foothills of the Himalayas) or the Himalayan ranges. Some floods were caused primarily by rainfall in the plains; none of the known large floods in the Yamuna plain were triggered by rainfall events focused on the mountain areas. The relevance of precipitation in the mountains to the hydrological processes in the plains decreases with increasing distance from the highlands, and almost disappears in the confluence area of the Yamuna and the Ganga.
- There was some limited downstream movement of flood waves and the shifting of flood-affected areas within the Yamuna floodplain.

The discussion of the 1978 floods in the Indian Ganga Plain and the illustration of these processes in Figure 5A.52 nicely confirm the appropriateness and importance of the relevance factor *R*(relev): rivers overflow mainly as a result of heavy rainfall, and produce flooding in the vicinity of the rainfall event. These floods disappear further downstream unless another precipitation event occurs or the river merges with a tributary that itself is in spate. The result of all this is a patchy occurrence of floods.

Summary

The monsoon characteristics in the Ganga system were the opposite of those in the Brahmaputra and the Meghna basins; this was particularly obvious in August. The significantly below-average flooding in Bangladesh was related to the dry conditions in the eastern part of the Ganga–Brahmaputra–Meghna basin rather than to the humid conditions in the western part. As in the "dry year" 1923, the main specific differences from the flood years seem to be below-average *R*(pot) and *R*(relev) during major parts of the monsoon season in Bangladesh itself, in the

Meghalaya Hills and to some extent in the Brahmaputra system, and in particular the scarce rainfall during August.

According to Figure 4.9, the flood dimension in the Indian Ganga Plain was outstanding – ranking first in Uttar Pradesh, fourth in Bihar and first in West Bengal in the available statistics covering the period 1954–1994. Interestingly, the floods reported from these three Indian states did not form one big flood event that would have extended simultaneously over the entire Ganga lowland, but represented three distinct flood waves, each with a different timing and geographical pattern. The three floods, therefore, were individual events, to a large extent produced by local rainfall and other triggers in the vicinity, such as high inflow from major tributaries.

In terms of highland–lowland linkages, important insight is provided by the flood in early September in the Yamuna basin, which was one of the most severe of the century in this area: there was a direct link between the heavy rainfall in the first Himalayan ridges and the Siwalik Hills and the flooding processes in the adjacent plains north of Delhi. However, the rainfall over these flood-affected areas themselves was at least as important, if not more so. Interestingly, and in spite of their rare magnitude, the floods in these areas to the north of Delhi did not create a flood wave that would have moved through the Ganga Plain all the way down to Bangladesh and would have produced a continuous area of inundation. There was indeed flooding downstream of Delhi, but these inundations occurred in isolated patches and levelled off across the Ganga Plain. Local triggers such as heavy rainfall or high water levels of tributaries were as important for the development of the flood patches as high inflows through the Yamuna River from the flood-affected areas higher up in the catchment. The only impact on Bangladesh of the high rainfall and the various flood events in the Ganga system was a high inflow through the Ganga and some areally limited flood processes in western Bangladesh. This is supported by the fact that the positive anomalies in R(pot) in SC4 and SC5 do not result in any significant increase in the relevance of these areas for Bangladesh as compared with the average. The low flow of the Brahmaputra, and most probably also of the Meghna, as well as scarce rainfall in Bangladesh in the period of the high inflow through the Ganga, were key factors preventing large-scale flooding in Bangladesh. Choudhury (1993) puts this consideration as follows: "There was comparatively less flooding in the Bangladesh part of the Ganga in 1978. This was largely due to the fact that water level was comparatively low in the other two great rivers which flow through Bangladesh namely the Brahmaputra and the Meghna during this time of the year in 1978."

In both "dry years" (1923 and 1978) there was a clear distinction between humid conditions in the Ganga system and dry conditions in the Brahmaputra and Meghna basins. This is in marked contrast to the flood years, when the situation tended to be the opposite. For the interpretation of this finding and for more information, see sections 5.15 and 5.16.

Appendix 5.11: 1993 – An ''average flood year'' for Bangladesh

We selected 1993 as a case study because Nepal was hit by one of the most severe floods of the twentieth century, whereas for Bangladesh 1993 was an average flood year. Accordingly, the highland–lowland linkages are a key aspect and are particularly interesting in that year. Because of the data situation, this example has a slightly different structure from the other case studies. In particular, the calculation of potential runoff (*R*(pot)) and relevance (*R*(relev)) was not possible. The summary of this case study is presented in section 5.14 (pp. 195–197).

The 1993 flood situation

On 19 and 20 July, an extraordinary flood with an estimated return period of 50–100 years occurred in eastern and central Nepal, with catastrophic effects (Dhital et al. 1993): several districts were affected by floods and landslides, a number of dams and roads were damaged, and up to 200 people died or were made homeless. Within only three days (19–21 July) the life-span of the Kulekhani Reservoir, which is located to the south of Kathmandu in the Bagmati watershed (see Figure 3.2), was reduced from 60–70 years to about 10 years owing to very high sedimentation. ''The number of deaths in Nepal has increased beyond 110 due to the onrush of water and due to landslides; the death toll could even be as high as 200 persons. Extraordinary rains over a number of days have produced catastrophic conditions in several southern areas of Nepal. Major parts of the crops in the wheat-growing zone in the Terai were destroyed, many roads and bridges were damaged. The southern part of the country will be isolated from the capital Kathmandu for at least another four to five days'' (translated from *Neue Zürcher Zeitung*, 22 July 1993). A second flood occurred around 10 August, for which however not much information is available and it will therefore be excluded from the following discussions.

In Bangladesh, in contrast, the floods reached average dimensions, affecting an area of 28,742 km^2 (19.48 per cent of the country; see Table 4.1). An overview of the flooding conditions was elaborated through an extended and systematic review of three daily newspapers: *The Bangla-*

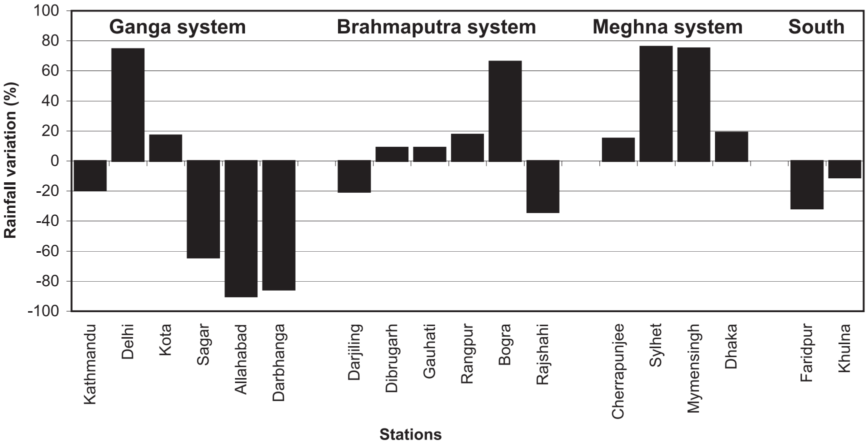


Figure 5A.53 Monthly rainfall variations in July 1993 at selected stations in the Ganga–Brahmaputra–Meghna basin.
Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2.

desh Observer (1993), *The Daily Star* (1993) and *The Bangladesh Times* (1993) (Bärtschi et al. 1995). Based on this review, the flood in Bangladesh occurred mainly in two phases: 18–25 June and 10–26 July. The inundations almost exclusively affected the Meghna and the Brahmaputra/Padma systems. Although the severe flood in Nepal on 19 and 20 July coincided temporally with the second flood period in Bangladesh between 10 and 26 July, there is no reason to assume a causal relationship between the flood in Nepal (in the Ganga system) and the floods in Bangladesh (in the Meghna and Brahmaputra systems).

Monthly rainfall (Figure 5A.53)

Since our discussion of the 1993 case study concentrates on the flooding processes in July, the monthly rainfall data are presented only for that particular month. In Figure 5A.53, the percentage variations of the July rainfall from the long-term average are documented for selected stations in the study region. The figure is structured, from left to right, to show the Ganga, the Brahmaputra and the Meghna systems as well as the southern areas. The figure documents the following overall rainfall features for July:

- above-average rainfall at all the stations in the Meghna catchment;
- predominantly above-average rainfall for the Brahmaputra catchment,

with the exceptions of Darjiling (located in the Himalayas) and Rajshahi, the most western site in Bangladesh;
- predominantly below-average rainfall for the Ganga system, except for Delhi and Kota, which are located in the Upper Ganga Plain (SC4);
- below-average rainfall at the stations in southern Bangladesh.

There is an obvious difference between the rainfall situation in the Ganga system and that of the Brahmaputra and Meghna systems. Furthermore, these monthly rainfall anomalies are helpful for understanding the flood processes in Bangladesh but not for understanding the severe flood in Nepal: in Kathmandu and Darbhanga, the two stations located closest to the flood-affected areas, the July rainfall was significantly below average. Obviously the heavy rains that triggered the floods in Nepal must have been geographically limited, as is confirmed in the next paragraph (see also section 6.3.1).

Daily rainfall

The study by Dhital et al. (1993) of the floods in Nepal concentrates on rainfall and flooding processes in the Bagmati–Rapti and Trisuli river systems, which represent the area around Kathmandu and the regions located to the south and south-west of the capital city. Intensive and heavy rainfall occurred in the Mahabarat Range (first Himalayan ridges) as well as in the Siwalik Range (Himalayan foothills). Based on the available precipitation data for these areas, the authors of the report made the following rough rainfall estimations for their study area:

19 July: on average 352 mm of rainfall over an area of 530 km^2;
20 July: on average 500 mm of rainfall over an area of 500–800 km^2.

In Figure 5A.54, five rainfall phases can be identified during the 1993 monsoon period for Bangladesh: 7–9 June; 17–20 June; 16–24 July; 22–24 August; 26–30 September. Particular attention must be paid to the precipitation in the third period (16–24 July), when rainfall was widespread and continuous. Particularly in the Meghna catchment (north-eastern and central–eastern Bangladesh), precipitation was intensive. In Sunamgonj, 810 mm of rainfall were recorded over just four days – 19–22 July (average July rainfall in Sunamgonj is 1,246 mm). Both flood phases in Bangladesh were temporally and geographically related to the rainfall periods within the country. Precipitation over the flood-affected areas themselves was obviously a very important factor in the development of the inundations. We know that the days with most abundant rainfall in Bangladesh coincided temporally with the days of heavy precipitation in Nepal. However, we do not know if the floods in the Meghna catchment in Bangladesh and those in the Nepalese Terai were triggered by the same overall meteorological situation.

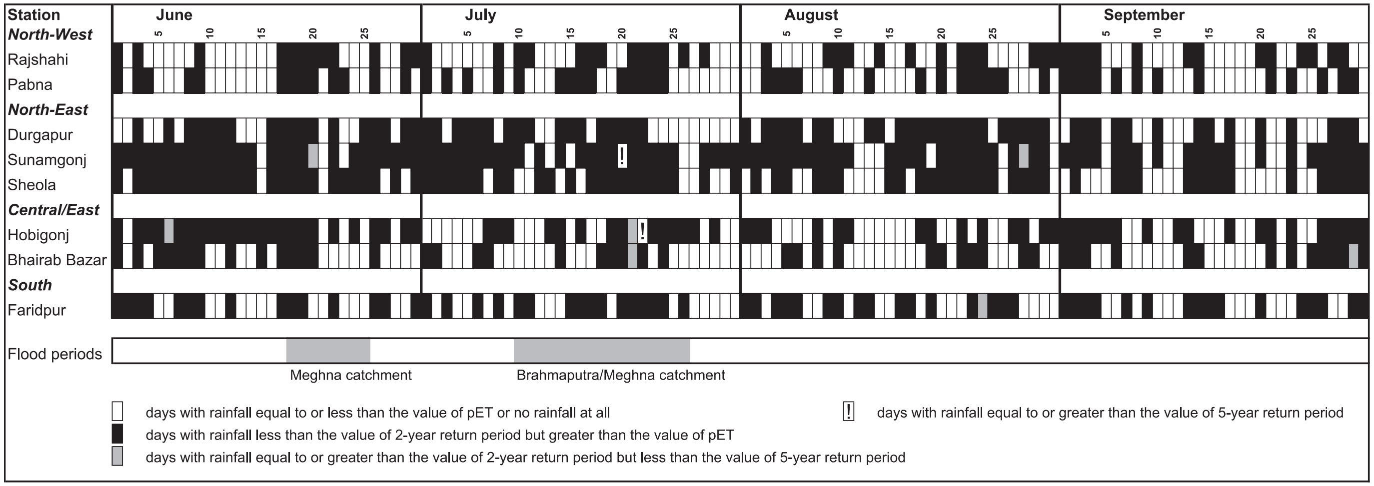


Figure 5A.54 Categories of daily rainfall for the period 1 June–30 September 1993 in Bangladesh.
Notes: For the location of the stations, see Figure 3.1; for the data sources, see Table 3.2; for threshold values, see Table 5A.2.

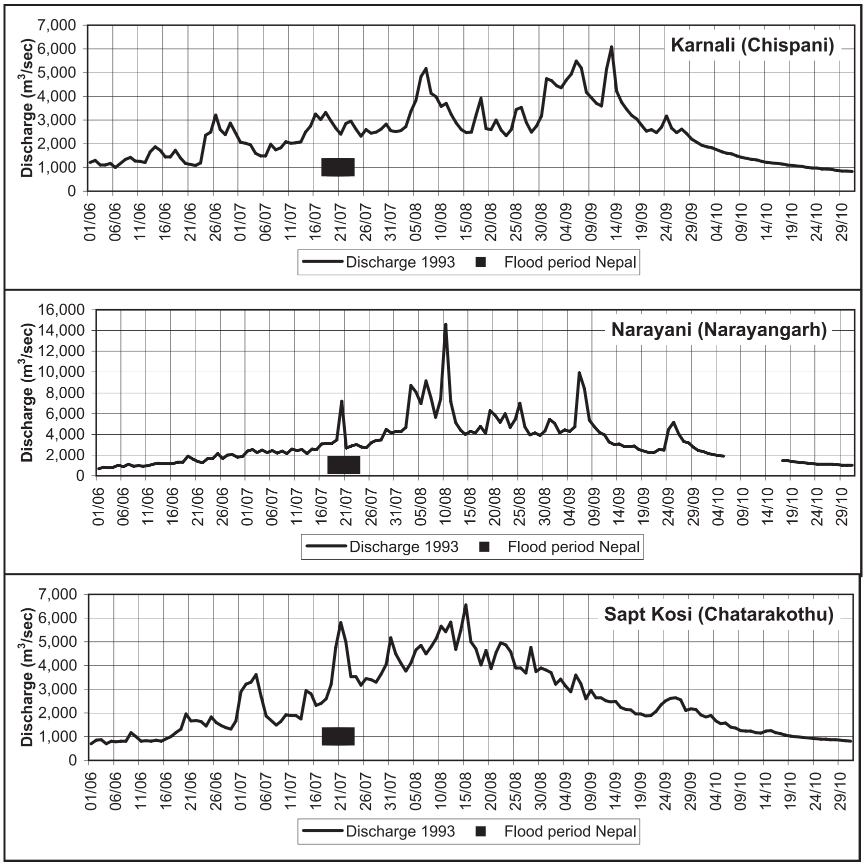


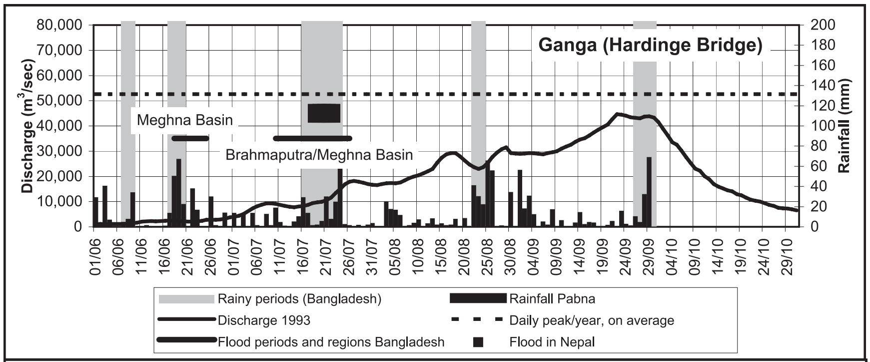
Figure 5A.55 Average daily discharge of selected rivers in Nepal for the period 1 June–31 October 1993, compared with the flood period in Nepal.
Notes: For the location of the stations, see Figure 3.2; for the data sources, see Table 3.4.

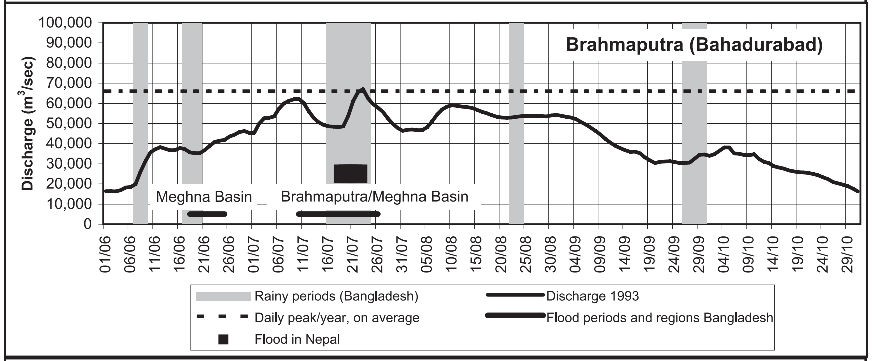
Daily discharge

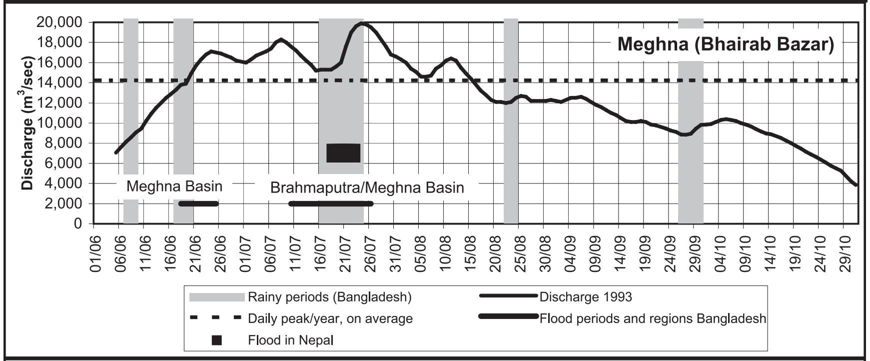
His Majesty's Government in Nepal generously provided daily discharge information for three major tributaries from Nepal (Figure 5A.55). The gauging sites are located in the transition zone between the Himalayas and the plain. The catchment of the Bagmati, including the Kulekhani Reservoir, where the disastrous flood occurred and which is the core area analysed in the study by Dhital et al. (1993), is located approximately half way between the Sapt Kosi and the Narayani rivers. Unfortunately, no continuous daily discharge data were available for the Bagmati River. Around 19 and 20 July, the days of the extraordinary flood in the Bagmati catchment, the hydrographs of the Narayani and the Sapt Kosi recorded a discharge peak that was, however, far short of the highest peak of the year. The hydrograph of the Karnali does not reveal any increase in discharge around these days. As already concluded in the previous section, it seems that the severe flood on 19 and 20 July in the Bagmati system was of rather limited geographical extent but of high intensity. The question now is whether this disastrous flood event in the Bagmati catchment on 19 and 20 July had any important downstream effect.

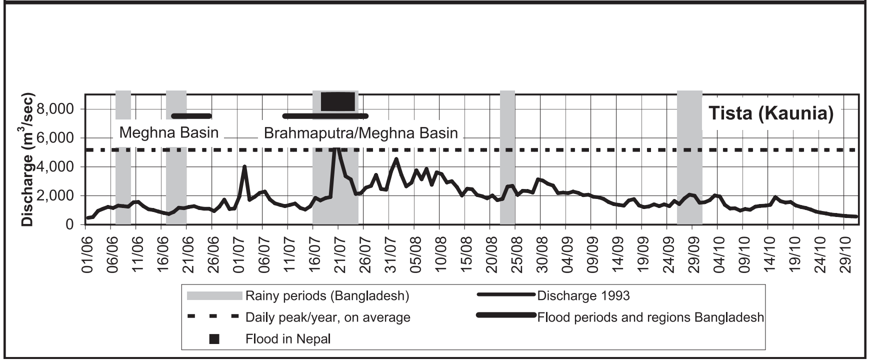
The discharge gauging site on the Ganga at Hardinge Bridge (Figure 5A.56) is located approximately 600 km downstream of the flood-affected areas in Nepal. Assuming a flow velocity of 1.5 m/sec or 130 km/day, the flood wave of 19/20 July in the Bagmati River should have reached Hardinge Bridge four to five days later, around 25 July. Indeed, within the gradual rise in the Ganga discharge, a short-term fluctuation was recorded between 24 and 30 July, with a peak on 27 July, which might have been the result of the Nepal floods. However, this situation could just as easily be attributed to local rainfall between 20 and 24 July (see the rainfall patterns at Pabna, located very close to Hardinge Bridge). The reaction of the Ganga flow to the flood in Nepal was, if any, very small. The flood flow of the Bagmati in Nepal obviously levelled out once it reached the main river. A similar statement has already been made in the section on daily discharge in Appendices 5.6 and 5.7 (1987 flood and 1988 flood respectively). The dimension of the short-term Ganga peak around 25 July was too small to trigger flood processes in Bangladesh, especially because the Ganga was flowing far below its danger level during that period. It can therefore be concluded that even an extraordinary flood event of rare dimension in the Himalayan foothills has almost no impact on hydrological conditions in Bangladesh, and particularly not on the development of floods. Of course, the situation might be different if extraordinary meteorological events occurred simultaneously over large areas of the basin. However, in none of the case studies was it possible to identify such situations: heavy monsoon rains tend to be regionally limited events (see also the 1978 case study in Appendix 5.10).

Another interesting observation supports the statements made above about the levelling off of flood peaks in the Himalayan tributaries on their way downstream towards the main river channel. The cumulated daily discharge of the Karnali, Narayani and Sapt Kosi rivers on 20 July at the transition from the Himalayas to the plains amounted to 14,620 m^3/sec. This figure is very close to the flow of the Ganga at Hardinge Bridge in Bangladesh five days later, which reached 16,800 m^3/sec. Con-


Ganga (Hardinge Bridge)
Discharge (m³/sec)
Rainfall (mm)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
0
20
40
60
80
100
120
140
160
180
200
Meghna Basin
Brahmaputra/Meghna Basin
01/06
06/06
11/06
16/06
21/06
26/06
01/07
06/07
11/07
16/07
21/07
26/07
31/07
05/08
10/08
15/08
20/08
25/08
30/08
04/09
09/09
14/09
19/09
24/09
29/09
04/10
09/10
14/10
19/10
24/10
29/10
Rainy periods (Bangladesh)
Rainfall Pabna
Discharge 1993
Daily peak/year, on average
Flood periods and regions Bangladesh
Flood in Nepal


Brahmaputra (Bahadurabad)
Discharge (m³/sec)
0
10,000
20,000
30,000
40,000
50,000
60,000
70,000
80,000
90,000
100,000
Meghna Basin
Brahmaputra/Meghna Basin
01/06
06/06
11/06
16/06
21/06
26/06
01/07
06/07
11/07
16/07
21/07
26/07
31/07
05/08
10/08
15/08
20/08
25/08
30/08
04/09
09/09
14/09
19/09
24/09
29/09
04/10
09/10
14/10
19/10
24/10
29/10
Rainy periods (Bangladesh)
Discharge 1993
Daily peak/year, on average
Flood periods and regions Bangladesh
Flood in Nepal


Meghna (Bhairab Bazar)
Discharge (m³/sec)
0
2,000
4,000
6,000
8,000
10,000
12,000
14,000
16,000
18,000
20,000
Meghna Basin
Brahmaputra/Meghna Basin
01/06
06/06
11/06
16/06
21/06
26/06
01/07
06/07
11/07
16/07
21/07
26/07
31/07
05/08
10/08
15/08
20/08
25/08
30/08
04/09
09/09
14/09
19/09
24/09
29/09
04/10
09/10
14/10
19/10
24/10
29/10
Rainy periods (Bangladesh)
Discharge 1993
Daily peak/year, on average
Flood periods and regions Bangladesh
Flood in Nepal


Tista (Kaunia)
Discharge (m³/sec)
0
2,000
4,000
6,000
8,000
Meghna Basin
Brahmaputra/Meghna Basin
01/06
06/06
11/06
16/06
21/06
26/06
01/07
06/07
11/07
16/07
21/07
26/07
31/07
05/08
10/08
15/08
20/08
25/08
30/08
04/09
09/09
14/09
19/09
24/09
29/09
04/10
09/10
14/10
19/10
24/10
29/10
Rainy periods (Bangladesh)
Discharge 1993
Daily peak/year, on average
Flood periods and regions Bangladesh
Flood in Nepal

sidering that the Karnali, Narayani and Sapt Kosi rivers are only three of many Ganga tributaries from the Himalayas in the north as well as from the Deccan Plateau in the south (Figure 2.1), this rough calculation could indicate that large quantities of water disappear, mainly through seepage into the groundwater or diversion for irrigation, even before the tributaries join the main river. As documented in Hofer (1998a), the cumulative discharge of the Himalayan tributaries is on average much higher than the actual flow of the Ganga below their confluence. In this discussion, the effect of the Farakka Barrage in India on the discharge characteristics of the Ganga at Hardinge Bridge in Bangladesh remains an unknown factor (see also Box 4.3).

As expected, the flow of the Meghna was very high (Figure 5A.56). From mid-June to mid-August, its discharge was consistently above the daily peak/year that is on average reached at this station. The peak flow coincided temporally with the main rainfall period in Bangladesh as well as with the flood period in the Meghna/Brahmaputra basin within Bangladesh.

The discharge patterns of the Tista and Brahmaputra hardly exceeded average conditions. In both cases, the annual peak was reached during the main rainy and flood period in Bangladesh. The rapid increase in discharge of the Tista on 19 July and the marked peak reached on 20 July indicate that heavy rainfall must have occurred in the Tista catchment outside Bangladesh during these days. This peak of the Tista coincided temporally with the extraordinary flood in the Bagmati catchment in Nepal.

Summary

Floods were recorded simultaneously in the foothills of Nepal, which are part of the Ganga catchment, and in the Meghna/Brahmaputra basin within Bangladesh. The flooding in Nepal was caused by heavy rains in the first Himalayan ranges as well as the Siwalik Hills; the inundations in Bangladesh were the result of widespread and heavy rainfall within the country, particularly in the Meghna catchment. Accordingly, there is no reason to assume a causal relationship between the floods in Nepal and those in Bangladesh. In accordance with the findings in the 1978

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Figure 5A.56 Average daily discharge of selected rivers in Bangladesh for the period 1 June–31 October 1993, compared with flood periods in Bangladesh and Nepal, rainy periods and daily peak/year, on average.
Notes: For the location of the stations, see Figure 3.2; for the data sources, see Table 3.4.

case study (Appendix 5.10), it can be stated that heavy rainfall in the first Himalayan ranges and the foothills can trigger extraordinary floods of rare dimensions in the immediate downstream areas. However, the impact of such an event on the hydrological conditions in Bangladesh, and on the floods in particular, is almost negligible: as already concluded from the discussion of the 1987 and 1988 case studies, a flood wave originating in the Himalayan foothills tends to level off, and the water tends to be integrated into the base flow of the main river channel further downstream. Furthermore, a significant amount of water seeps into the groundwater reservoirs even before the tributaries join the Ganga.

6

Erosion and sedimentation processes in the Ganga–Brahmaputra basin in the context of highland–lowland linkages

6.1. The data situation

On several occasions, the results of the project on flooding in Bangladesh have been presented to institutions and authorities, particularly in Bangladesh and Nepal. Many experts had difficulty accepting the project findings, which demonstrate that the hydro-meteorological processes in the Himalayas do not seem to have any significant impact on the floods in Bangladesh. Again and again, it was argued that, although this might be true in strictly hydrological terms, the cutting of forests, unadapted land-use practices and watershed degradation in the Himalayas certainly must have led to an increase in sediment load in the Himalayan rivers, to a reinforcement of siltation in the lowlands and finally to an intensification of the flooding processes. Such argumentation can be found in a statement by Hossain (1990): "silting up of the river beds of the major rivers and their tributaries and distributaries caused by the deposition of sediments coming from the accelerated catchment erosion is considered to be a vital factor for increasing the intensity of flood in recent time." It has always been difficult to respond in a satisfactory way to such pertinent and relevant interventions and concerns, because the linkages between the Himalayas and the lowlands in terms of erosion, sediment transport, intermediate deposition and "final" sedimentation are very complex and depend not only on highly diversified conditions of climate, geology, soil, topography, vegetation and human activities, but also on the scale at which the processes are analysed.

The question of whether or not sedimentation rates on the plains have increased as a result of growing and massive human interventions in this huge highland–lowland system is indeed very important and difficult to answer. Our knowledge is still limited, but recently a series of publications based on new or improved methods and techniques have led to new ideas and to a better understanding of these complex processes. The following discussion is an attempt to present the current state of knowledge, always with the focus on the floods in Bangladesh. In this context we should also keep in mind that better measurements, calculations and simulations will be achieved only once the open exchange of data takes place among the countries sharing the huge highland–lowland system and the political authorities have understood the great significance of these transboundary processes. For instance, in the overall context of research into highland–lowland linkages in the Himalayan region (see Chapter 1), a request was made in 1987 to a Ministry of Water Resources for discharge data for some selected Himalayan rivers. The reply from the representatives of the ministry was symptomatic: ‘‘We regret our inability to supply such bulk data, for research as a matter of policy.’’ During a meeting in Kathmandu in 1998, 11 years later, which was jointly organized by the United Nations Educational, Scientific and Cultural Organization (UNESCO/International Hydrological Programme), the International Centre for Integrated Mountain Development (ICIMOD) and the Hindu Kush–Himalayan programme on Flow Regimes from International Experimental and Network Data (FRIEND), the participants identified five priority research areas: floods, low flow, rainfall runoff, river water quality, and snow and glaciers. They recommended the launch of research projects and the establishment of a regional database centre to be located at ICIMOD (ICIMOD/UNESCO/FRIEND 1999). The initiative was excellent but failed to be realized, because the political obstacles were still too strong.

In view of these conditions and complexities, we have to accept the difficult data situation (see also Chapter 3). Erosion and denudation rates for the Himalayan region (or parts of it) are given in a number of publications, such as Ives and Messerli (1989: 104), Galay et al. (1995: 14), and Ives (2004), or, with a more specialized areal and temporal focus, Allison et al. (1998), Goodbred and Kuehl (1998), Singh and France-Lanord (2002), and Allison et al. (2003). Worth mentioning as well are some outstanding studies on the Amazon (Dunne et al. 1998) and the Rhine (Middelkoop 1997). However, no systematic database is available on erosion and sediment load for different parts of the Ganga–Brahmaputra–Meghna river system, which would be important for understanding the processes from the small to the big watershed. Therein lies the difficulty in achieving a more precise determination of the impacts of human intervention, including deforestation, land-use changes and manipulation of water flow, and their differentiation from the natural processes as a proportion of the total rate of change (Ives 2004: 84). Despite this obstacle to geomorphic investigation, some important contributions can be made, provided they are put into the context of geological conditions and tectonic activities as well as of changing climate or at least of extreme climatic events.

6.2. The geological and historical dimension

In Chapter 4, section 4.2, we discussed the history of flooding in the lowlands and the evolution of the world's largest highland–lowland system. In this section, the focus is on the geomorphic processes, such as mass movements and soil erosion in the highlands and erosion, transportation and sedimentation in the lowlands. Apart from climatic conditions – in particular, extreme events with heavy and high-intensity precipitation – tectonic and geological conditions play a crucial role in all types of erosion and sedimentation processes. A determining factor is the uplift of the Himalayas and the Tibetan Plateau, as the Indian plate thrusts beneath Central Asia. Ives (2004) summarizes the available data on the rates of the ongoing Himalayan uplift: it varies from 1 mm/year for the Nepalese Himalayas to 9 mm/year for Nanga Parbat, 4–5 mm/year for Tibet and the northern slopes of the Himalayas, and as much as 15 mm/year for the tectonically very active western Pamir. The estimation of these uplift rates is certainly very difficult and therefore the figures may represent only an order of magnitude.

In spite of the uncertainties, such estimated rates are still very interesting, because tectonic uplift can lead to slope instability, either through catastrophic mass movements, or through the incising of rivers and the undermining of banks and slopes. Uplift and erosion or denudation processes are strongly linked, but perhaps it will never be possible to know precisely, for the different geological regions, whether or not the uplift of the Himalayan range plays a larger role than the denudation rates. It is interesting to compare the uplift data with the accumulation rate in Figure 4.2: a piece of wood found buried under 100 metres of sediment in Bangladesh was dated at about 28,000 years BP. This would give an order of magnitude of about 3.5–4.0 mm accumulation per year. Of course it is not possible to link these data directly with the uplift of the mountain system, because a lot of material is deposited in the huge Bengal Fan, which covers 3 million km^2 and has a length of 3,000 km. Moreover, a lot of transported sediment is temporarily or even permanently stored inside the mountain range. The Kathmandu Valley, for example, which was formed by tectonic movements and active faults, rapidly filled up. Lake sediments are more than 500 metres thick and include 10,000–30,000-year-old peat layers. Tilting and faulting have been frequent processes in the Himalayas, especially since the upper Pleistocene (Valdiya 1993), and have created a highly diversified topography, with basins and valleys that are ideal sites for long-term storage of sediment. These deposits might never reach the ocean.

Based on the above, denudation is mainly a theoretical way of defining the lowering of the landscape resulting from erosion and transport processes. Determination of the total sediment discharge necessitates the long-term monitoring of rivers where they exit a particular watershed (Ives 2004). Again, to get reasonable results, measurements from the small uppermost catchments in the mountains to the main checkpoints at the transition between mountains and plains should be linked to hydroclimatic data in order to understand the complex processes of erosion, transport and deposition and then the further removal, transport and sedimentation in the delta or in the ocean. The conditions for the successful implementation of such an integrated study, which requires good cooperation between highland and lowland countries, are at present not yet in place. However, knowledge about the Ganga and the Brahmaputra, which drain the foreslope and the backslope of the Himalayas and are the main sediment sources for the delta and the fan, has improved tremendously over recent years.

The Ganga–Brahmaputra river system ranks first in the world in terms of sediment discharge. Various estimates of the suspended sediment load flux of these two river systems to the Bay of Bengal range from 316 to 729 million tons per year (t/yr) for the Ganga and from 402 to 1,157 million t/yr for the Brahmaputra (Islam et al. 1999 and references therein). From Singh and France-Lanord (2002: 645) we quote the following interpretation of the differences between the two river systems:

> In most of these studies the sediment flux of the Brahmaputra river system is consistently estimated to be higher than that of the Ganga river system. This is despite the fact that the Brahmaputra river drains a shorter arc of the Himalaya than that of the Ganga. Based on sediment flux and basin area, the average denudation rate in the Brahmaputra Basin is estimated higher than that of the Ganga Basin. This may be related to several processes. The monsoon climate generates higher runoff for the Brahmaputra than for the Ganga. Tectonic uplift may be more active in the eastern side than on the western side of the Himalaya. The erosion in the non-Himalayan parts of the basin, such as the Indo-Burmese Range, the Shillong Plateau and the Tibet-Tsangpo Basin may be important. The total erosion rate in the eastern Himalaya is about 1.5 times higher than that in the central and western Himalaya. Nevertheless, little is known about erosion in

the eastern Himalaya and it is difficult to analyse the origin of the difference between the two Himalayan basins.

This uncertainty about the sediment load also makes it difficult to understand the sedimentation on the big floodplain of these two rivers, which is well over 100,000 km^2 in size and where complex erosion–storage–erosion processes again take place before the "final" sedimentation on land or in the ocean (Millman and Syvitski 1992; Anwar 1993; Goodbred and Kuehl 1999).

Coming back to the overall context of this discussion, it can be confirmed, as already stated in section 4.2, that massive erosion, high sediment load, exceptional siltation rates and large floods are not new to the highland–lowland system of the Ganga–Brahmaputra basin. They have taken place for all geological and historical time and will continue to occur. Carson (1985: 21) states that, "throughout history as described in ancient Vedic tales to the careful chronicles kept during the British Raj, the Ganga appears to have been behaving in exactly the same manner as it behaves today. The extent of Himalayan river action is phenomenal: drill holes have intersected more than 5,000 m alluvial sediments adjacent to the Himalayan foothills."

We have no reason to assume, or evidence to prove, that anthropogenic impacts have visibly and measurably intensified these geomorphological and hydrological processes. This hypothesis will be further discussed in the course of this chapter.

6.3. Mass movements and soil erosion in the highlands

This section focuses on those processes that have the most significant impact on the sediment load in the rivers. The discussion will primarily deal with two very difficult questions. First, how much of the sediment load is produced by human activities in mountain areas and how much through natural processes? Second, how much of the transported sediment load in the highlands will reach the floodplains in the lowlands? To enhance the clarity of the discussion, it is appropriate to distinguish between mass movements and soil erosion, although many processes are interlinked.

6.3.1. *Mass movements*

There are two types of mass movement. The first are slow and continuously operating processes under the influence of gravity, such as soil creep, movements of weathered and fractured rock material, and all forms of solifluction at higher altitudes. Much more important in our context are the faster, larger and often more dramatic processes, such as landslides, debris and mud flows, rock falls and rockslides, but also glacial lake outburst floods.

One of the most spectacular geomorphic events to have occurred in the Nepal Himalayas over the course of their history was the outburst of a moraine-dammed lake behind the mountain of Machapuchare approximately 600–800 years ago (Fort and Freytet 1982). This outburst caused a flood surge down the Seti Khola that deposited 5.5 km^3 of debris in the Pokhara Valley, damming Lake Phewa. This major natural event shaped and completely changed the landscape in the area. The transport of sediment in the course of such glacial lake outburst floods (GLOFs) can be enormous and the concentration of suspended sediment can reach values as high as 350 g/litre. In addition, the resulting flood wave has the potential to destabilize talus slopes, to reactivate former debris flows and landslides, and to trigger new ones through vertical and lateral erosion of the stream channel (Mool 1995). Some interesting estimates are available for the glacial lake outburst that occurred on the Tamur River in July 1980 (Galay 1985). The suspended sediment load at Mulghat increased by a factor of three. The sediment concentration during the event must have been in the range of 50–200 g/litre. According to a rough computation, the sediment load that was moved during the event, which lasted for approximately four hours, corresponded to about 10 per cent of the total annual suspended sediment load. This dimension of sediment load is never accounted for in sediment yield estimates because it is almost impossible to carry out measurements during such outstanding events.

On 4 August 1985, a moraine-dammed glacial lake called Dig Tsho, in the Khumbu area of eastern Nepal, burst above Thame. This event was observed in detail and analysed by Vuichard and Zimmermann (1987). The breaching of the moraine was triggered by wave action following an ice avalanche of 150,000 m^3 into the lake. For the region close to the origin of the outbreak, the consequences were catastrophic: 5 million m^3 of water roared down the Bhote Kosi and Dudh Kosi valleys, causing the destruction of a newly built hydroelectric power plant, 14 bridges, about 30 houses and many hectares of valuable arable land. The surge had a peak discharge of 1,600 m^3/sec. About 3 million m^3 of debris were moved within a distance of less than 40 km, which is not even half the way down to the hydrological station at Rabuwa Bazar, 460 metres above sea level (masl). Unfortunately, this station was not working at the time of the event and accordingly no hydrological data were recorded. However, the following detailed observations and calculations are most interesting and instructive. The total amount of eroded material from the moraine reached approximately 900,000 m^3, but all this material was deposited again within the first 2 km, and the very coarse material of 2–5 metres in diameter was even sedimented immediately below the V-shaped trench of the moraine. Fine material consisting of fine gravel and sand was deposited at the termini of a large cone. Further down, the surge mobilized large amounts of debris from the river terraces, debris cones and the river bed itself, but this material was re-deposited within a short distance. The movement of bed load was strongly pulsating owing to sudden changes in the transportation capacity of the river. Finally, it is assumed that only 10–15 per cent of the material left the region as suspended load.

In 1977, another glacial lake outburst occurred in the Khumbu region, which had a peak discharge of 1,200 m^3/sec, 400 m^3/sec less than the outburst in 1985. At that time, the hydrological station at Rabuwa Bazar was operational. The measurements are very interesting and surprising. The flood flow resulting from the lake outburst was 800 m^3/sec above the basic discharge, which is much less than the peaks of 1,600 m^3/sec above the basic discharge that were reached during the monsoon period of the same year. The figures from both these examples show that the sediment load resulting from such catastrophic events may be strongly reduced over a fairly short distance and that the flood flow of the river drops below the level of the normal monsoonal peaks before entering the floodplain (Messerli 1983; Vuichard and Zimmermann 1987).

One of the most recent flood events in eastern and central Nepal occurred over a period of only two days, between 19 and 21 July 1993, with catastrophic effects (see also section 5.14 and Appendix 5.11). A rainstorm of the magnitude of 540 mm in 24 hours and with maximum intensities of 70 mm per hour hit the Kulekhani watershed, which has an area of 125 km^2. This watershed is dammed by a large barrage that represents 45 per cent of the hydropower capacity of the country. This reservoir is one of the biggest sediment traps in the Nepalese Himalayas (Galay et al. 1995; Schreier and Wymann von Dach 1996). Sthapit (1996) provides some more precise figures, based on surveys carried out before and after the event: the dam was designed for an estimated average annual sediment input of 11.2 tons per hectare (t/ha). However, from 1984 to 1993 the average annual rate of sediment accumulation was calculated in the range of 20–45 t/ha/yr. The extreme event in 1993 produced a staggering rate of 410–500 t/ha/yr of sediment, a result of massive failures in the watershed. The reservoir was planned to last for 60–70 years, but the 1993 event reduced its life-span to approximately 10 years. Dhital et al. (1993) estimated that, during that particular storm, about 47 landslides occurred per km^2. Interestingly, more slides occurred on grassland and forest slopes than on human-made terraces under cultivation. A large percentage of the forest in the catchment grows on intensively weathered rocks (slate, quartzite, phyllites and marble), and it appears that this kind of environment is more fragile and sensitive to failures than are human-made and managed terrace systems. The large areas where landslides occurred became unprotected against soil erosion. Together with all the sediment in transitional storage within the watershed, this created a long-term legacy of much higher rates of sediment transport in the future than during the pre-storm period. Dhital estimated the annual rate for 1994 to be 85 t/ha, which is twice the pre-storm average. It is impossible to predict how long it will take for the watershed to re-establish a more or less steady-state condition (Schreier and Wymann von Dach 1996).

Three results from the presentation of this major event are important for future discussions. First, this extreme rainfall event was very localized. For instance, it was not recorded in the Jhikhu Khola watershed 30 km north of Kulekhani (see below), which has good instrument coverage. Second, the fact that the landslides occurred particularly on grassland and forested slopes is evidence that the soil and parent material conditions are much more important than the type of land cover for the creation of landslides (see also Bruijnzeel 2004). Third, the floods in Nepal did not have any impact on the flood conditions in Bangladesh. In 1993, Bangladesh experienced only an average flood situation, mainly connected to the Brahmaputra and Meghna systems, but not to the Ganga system (see also section 5.14 and Appendix 5.11). In this context, it is interesting to read the following comment in a Nepalese newspaper related to a scientific meeting: "Immediate [real-time] information of rainfall and flood events of Nepal can save life and property in Bangladesh, said an expert from Bangladesh" (*Kathmandu Post* 2004). Assuming that the journalist reported it accurately, this comment is evidence that the participants at the scientific meeting were not aware of the significant spatial variation of extreme rainfall events, of the fact that the peak flows within the middle and lower Himalayas are levelled out in the adjacent plains and, finally, of the travel time needed for flood flows to reach the Bangladesh border, if they manage to get there at all.

6.3.2. Soil erosion

Soil erosion occurs in entirely natural environments as well as in areas transformed by human activities. Sometimes it is difficult to disentangle natural and human processes, especially in intensive agricultural systems, where the land-use techniques are decisive in increasing or decreasing the rate of soil erosion. However, there is an almost insuperable problem in translating or extrapolating rates of soil erosion measured on small plots, or even in small watersheds, to large river basins such as the Ganga and Brahmaputra. As Hamilton (1987) explains, at each higher level of scale, measurement problems increase perhaps exponentially, more variations occur in the different factors being investigated (e.g. soil, rainfall), and more factors come into play. It is relatively easy to treat a small plot of 10 × 3 metres on a slope and compare the erosion of this plot with the erosion on an adjacent control plot without any treatment. Almost all of the eroded material will cross the lower plot boundary as sediment. In contrast, if an entire small catchment is treated in a controlled, paired catchment experiment (say, of 80 ha in size each), the resulting sediment will move out of the watershed into the main stream of the catchment. This volume can be expressed as a rate per hectare for the 80 ha area. This rate will be substantially less than the rate of loss per hectare calculated on the basis of the measurements of a series of 10 × 3 metre plots in the treated watershed. This difference results from the fact that eroded material moves into temporary storage within the watershed (in topographic depressions, footslopes, river banks, small alluvial fans, etc.). This material may be shifted at various times by larger storm events but is just as likely to be colonized by plants and remain as an altered relief feature for decades. This same process of erosion/deposition/storage–removal/deposition/storage is even more evident in a large river basin such as the Ganga and Brahmaputra basins.

The relationship between erosion occurring on-site and sediment load measured at a specific point in a stream is expressed as a sediment delivery ratio for the catchment. Whereas this ratio may be 90 per cent for a drainage area of 1 ha, it may reach only 50 per cent on average for an 80 ha area and less than 30 per cent for a drainage area over 500 ha, and it might drop below 10 per cent for river basins of the size of the Ganga. This differentiation according to scale helps us to understand why there would be little reduction for decades in sediment transport in the lower reaches of a major river, even if land conservation activities could virtually eliminate all human-caused, accelerated erosion in the hills. There is so much material in storage from past human-induced and natural erosion processes that it forms a long-term supply. Thus, when computing erosion and sediment reduction benefits from maintaining forest cover or from improved crop and grazing management for conservation, it must be realized that, for watersheds exceeding 10,000 ha in size, off-site sediment will not be reduced for decades. On-site benefits, however, may be immediate and well worth the effort in terms of the productivity of the land. In very large basins such as the Ganga and Brahmaputra, it may take centuries before current erosion reduction efforts result in a measurable reduction in sediment yields in the lower reaches of the main channels (Hamilton 1987).

In 1988, as part of a watershed study to determine water and sediment transfer, Schreier, from the University of British Columbia, initiated the Jhikhu Khola watershed project, which is still ongoing today. Jhikhu

Khola is a tributary of the Sunkosi River, which flows into the Ganga. The watershed, which is situated in the Middle Mountains of Nepal approximately 40 km east of Kathmandu, has an area of 11,000 ha. It is densely populated and intensively farmed, with much of the area under double or even triple crop rotation. The situation in the Jhikhu Khola watershed is representative of many similar areas in the Middle Mountains. Questions have been raised about the sustainability of such intensive use and it has been assumed that such watersheds experience serious nutrient depletion and substantial soil erosion. The long-term and scientifically well-equipped Jhikhu Khola watershed project came up with very different and highly fascinating results (Carver and Schreier 1995; Schreier and Wymann von Dach 1996), which we shall try to summarize here.

The research team started the investigations on a typical farmer's field, a two-terrace rain-fed system (*bari*) of 70 m^2 in size under double annual crop rotation. They built an erosion plot from which all the runoff water and sediment were collected after storms. The monitoring continued over three monsoon seasons and more than 100 events were recorded. Further downstream, three river monitoring stations were built: the first station drains a mini-watershed of 70 ha; the second station, located some 4 km below the first, drains a sub-watershed of 520 ha; the third station is located at the lower end of the Jhikhu Khola watershed and drains an area of 11,000 ha. All stations were equipped with an automated pressure transducer. Flow and sediment sampling was carried out at frequent storm intervals by three teams of two people each, who were permanently present at the sampling sites throughout the monsoon seasons. The quantity of the sediment and the phosphorus content within the sediment were measured for as many storms as possible. In addition, a network of 50 24-hour raingauges and 4 automated tipping bucket gauges were installed to investigate the rainfall patterns.

The results of the investigations were very interesting. First of all, the data demonstrated that the rainfall was episodic and characterized by high spatial variability. This obviously has a direct effect on water and sediment dynamics. As mentioned above, the catastrophic rainfall event in the Kulekhani watershed between 19 and 21 July 1993 was not recorded in the Jhikhu Khola project area, which is 30 km north of the Kulekhani region. Secondly, investigation of the relevant data sets indicates that the highest sediment loss occurred during the pre-monsoon period. In fact, 60–80 per cent of annual soil loss was pre-monsoonal, because at that time of the year the terraces are barren and ready to be planted – the soils are unprotected and hydrophobic, generating more runoff and sediment losses in the uplands (Carson 1985; Carver and Schreier 1995).

The figures in Table 6.1 show a reduction by a factor of 200–300 in sediment and phosphorus discharge per hectare in a pre-monsoon rainfall

Table 6.1 Sediment and phosphorus budgets of different reference areas for a pre-monsoon rainfall event in the Jhikhu Khola watershed, Nepal

Reference area (size)	Sediment (t/ha)	Phosphorus (g/ha)
Upland terrace (70 m^2)	20.0	300
Mini-watershed (70 ha)	5.0	200
Sub-watershed (520 ha)	2.0	40
Watershed (11,000 ha)	0.1	1

Source: Carver and Schreier (1995).

storm of 50 mm as one moves from the small uppermost plot to the mini-watershed, to the sub-watershed and finally to the whole watershed. The reasons for the different responses of the systems are complex and can be understood only by looking at human interventions. The authors discovered that one reason for the sediment and phosphorus budgets of a pre-monsoon storm being so different across the four spatial scales, and also different from the results of the monsoon period, is that local farmers have built 72 small check-dams in the area between the erosion plot and the sub-basin station in order to divert as much water and sediment as possible into the adjacent *khet* (irrigated) fields. During the particular storm documented in Table 6.1, more than 75 per cent of all check-dams were destroyed, which obviously reduced the opportunities to retain sediment. However, since all these storms are rather localized, there was no particular response in sediment and phosphorus load at the watershed scale. All these elements indicate that:

- most of the soil that is lost at the plot level is redistributed many times before it actually reaches the mini- and sub-watersheds and finally leaves the whole watershed;
- human interventions play a critical role in sediment dynamics at the local scale, particularly in the redistribution of the losses created by the cultivation of steep slopes;
- upland farmers with rain-fed agricultural land (*bari*) are losing nutrients and soils, whereas farmers who are able to irrigate their fields (*khet*) below the *bari* land enrich their soils through the redistribution processes;
- the expansion of agriculture into marginal land has little effect on watershed-scale processes.

All these interesting findings are further evidence against the myth of human impact at the Himalayan scale (Schreier and Wymann von Dach 1996). Smadja (1992: 1) captures this in an interesting formulation: “negative effects of rain and human pressure on the soil resource are infrequent, localised, and of limited scope. Thus, these impacts should be seen as stabilising elements in a naturally fragile environment, rather than destabilising agents in a mountain area that some have described as severely degraded as a result of human abuse.''

In contrast to these interesting results from the Middle Mountains of Nepal, there are also watersheds where human-induced degradation seems to be much more evident and where the protective function of forests seems to be very effective. The Nana Kosi watershed, situated in the Indian Kumaun Himalaya, has an area of 55 km^2 and is an open landscape in a relatively inactive tectonic environment. In the framework of a watershed project, 25 hydrometric sites were selected, representing different land-cover types (forest, barren land, agricultural land, and land with mixed use) and different scales of sub-watershed (first-, second-, third-, fourth- and fifth-order streams). In order to determine the suspended and dissolved sediment loads at different measuring sites, samples were taken once a month over a two-year period – 1986 as a normal monsoon year and 1987 as a drought year – and complemented by the corresponding rainfall measurements (Rawat and Rawat 1994). The average rate of suspended sediment yield for the whole Nana Kosi watershed calculated with the monthly records was 143.1 t/km^2/yr for the normal monsoon year (1986) and 48.6 t/km^2/yr for the dry year (1987). In July 1986, the month with the heaviest rainfall (449 mm), the rate of suspended sediment flow reached its maximum, and the sediment yield from the most disturbed micro-watersheds was found to be 20 times higher (173 t/km^2/month) than from the least disturbed forested land (9 t/km^2/month). On an annual basis, the agricultural land generated sediment at a rate of 477 t/km^2/yr in 1986, whereas in oak and pine forests the rate was only 54 t/km^2/yr. These findings were used to prove the protective function of forests. However, we need to reflect and comment on these data, which result from a pioneer project in remote and inaccessible terrain:

- If these rates of suspended yield are converted from per km^2 to per hectare and then compared with the rates from the Kulekhani or Jikhu Khola watersheds (see above), it becomes obvious that these rates are actually very low. This means that a lot of sediment did not reach the sampling sites, but was stored before reaching them.
- The order of magnitude of these rates of suspended sediment yields is clearly within the rate of natural regeneration of the soils.
- The project compared forest and non-forest land in small watersheds of different size. However, different-sized watersheds involve different storage processes and accordingly the data on sediment delivery ratio are not comparable.
- It seems that, in the two years of measurements, no extreme, high-

intensity rainfall events were recorded that would have triggered landslides and mass movements and that would have allowed the real difference between forest and non-forest land to be evaluated.

- The farmers in these remote areas are not under the same pressure as the farmers in the Jhikhu Khola watershed to increase production for a market. Therefore the practice of capturing eroded soils with check-dams and redistributing them to lower terraces is as yet unknown.

Heavy monsoon rains are important triggers of soil erosion and mass wasting. According to Bruijnzeel and Bremmer (1989), the most important geological features for mass movements are steep slopes, the unstable nature of the rock, the depth and degree of weathering, high seismicity and over-steepening of slopes through undercutting by rivers. The impact of forest cover on deep and on shallow (less than 3 metres) landslides is totally different: deep-rooted landslides are not influenced by the presence or absence of a well-developed root network (Starkel 1972; Carson 1985; Ramsay 1987); small and shallow failures are influenced by vegetative cover, but are only modest contributors to the sediment load of streams.

The specific role that mountain forests play in slope stability as well as in soil and water conservation is widely debated (Ives and Messerli 1989; Bruijnzeel 2004; Ives 2004; see also Box 4.2). In this context, Hamilton (1992: 13) makes a very clear statement:

> [W]hile additional research is needed on the hydrological and erosion effects of changes in mountain forests, sufficient knowledge is available, or may be inferred from existing research, to question, refute or reaffirm some of the conventional wisdom about the protective role of these forests. A major difficulty is sorting out the consequences of natural processes from those caused by anthropogenic actions.

Statements by Galay (1985: 10) point in a similar direction:

> The frequent contention that reforestation is the key to solving the erosion problem and the subsequent downstream flooding problem comes into question. There is undoubtedly extensive deforestation with its attendant problems, but it is unlikely that a massive reforestation program will significantly reduce the occurrence of mass wasting and therefore the heavy sediment loads of the rivers in the Kosi watershed.

A lot of data are now available to prove that the rates of soil erosion are much lower for well-maintained and terraced irrigated fields (*khet*) than for forests. Only on non-irrigated fields (*bari*) is soil erosion higher than on forested land, but it is still in the order of magnitude of natural regeneration. Brown (1985) determined soil erosion rates on a variety of land-use types in eastern Nepal as follows: bare, denuded land 13.350 t/ha/yr; old reforested landslide 8.146 t/ha/yr; grassland 2.547 t/ha/yr; *bari* terraces 2.885 t/ha/yr; and *khet* terraces 0.088 t/ha/yr. Based on a fairly large data bank, Gerrard and Gardner (1999) calculated annual soil and sediment losses from slope failures under different land-use types as follows: scrub and abandoned land 23.95 t/ha/yr; grassland 1.86 t/ha/yr; forest 0.80 t/ha/yr; *bari* terraces 3.65 t/ha/yr; *khet* terraces 0.48 t/ha/yr. All these figures clearly show that soil erosion on carefully managed agricultural fields such as grassland and *bari* and *khet* terraces is in the same order of magnitude as under forests. Once again, however, erosion data from small plots or mini-watersheds do not give any indication about the rate of transport of material that leaves the big watershed. The question of scale is fundamental to understanding the highland–lowland processes.

In addition to these considerations of scale, it has to be borne in mind that human activities, as well as climatic and geological conditions, change from the high to the low Himalayas. The high Himalayas are dominated by ice and snow; the north-facing slopes are more arid and the south-facing slopes get summer monsoon precipitation, which decreases with increasing altitude. The Middle Mountains are characterized by high population densities, significant precipitation and a diversified lithology consisting of sedimentary rocks, metamorphics and granite. Also, deeply weathered phyllites and schists are widespread and are highly susceptible to mass movement and to disturbance by human activities, especially to road construction. The Mahabharat Lekh, together with the Siwaliks, constitute the lesser Himalayas, which are exposed to extreme monsoonal rainfall events. The Siwaliks in particular are composed of the most easily erodible bedrock of the entire Himalayan region, mainly unconsolidated sand and gravels. Isolated data from the Nepal Himalayas indicate that specific sediment yields in the higher Himalayas range from 500 to 1,000 t/km^2/yr, whereas further down, in the Siwaliks, the specific yields can be as high as 15,000 t/km^2/yr (Galay 1998; Ives 2004).

Starkel and Singh (2004) provide some very interesting new data on the Meghalaya Hills and Shillong plateau. This area consists of an asymmetric horst situated between the Himalayan foredeep and the Bengal Plains and in its central part it reaches elevations of up to 1,960 mas1 (see also Figure 2.1). It is built up mainly of very old gneiss, quartzites, granites and minor greenstone plutons, which are deeply weathered and offer varying resistance to erosion. Cherrapunjee (1,313 mas1) is a well-known climatic station that receives the highest rainfall on a global scale, fluctuating between 7,000 and 24,000 mm annually. Daily rainfall totals can exceed 500–700 mm. About 90 per cent of the annual precipitation is concentrated in four to five months during the rainy season. The expansion of grassland on the degraded surface, accompanied by overgrazing and fires, has caused either the formation of an armoured pavement composed of coarse rock fragments and iron concretions or even exposure of bedrock. The study of soil erosion in the region indicates that sediment delivery ratios are very low for the slope surface but probably high in active gullies in the headwater areas. Dense grass-covered footslopes and valley bottoms act as filters to retain eroded soil particles. Yet it is still not known when this ‘‘sterile’’ system evolved; it might be the effect of several centuries or of only the last two centuries. It is, however, certain that the current situation in this very humid geo-ecosystem is the result of massive human impact on a very fragile environment.

In summary we shall try to merge our studies and observations with the results of Kienholz et al. (1983), Carson (1985), Lauterburg (1985), Ramsay (1985), Mou (1986), Hamilton (1987), Vuichard and Zimmermann (1987), Bruijnzeel and Bremmer (1989), Ives and Messerli (1989), Carver and Schreier (1995), Schreier and Wymann von Dach (1996), Galay (1998), Hofer (1998b), Bruijnzeel (2004), Ives (2004) and others. Heavy monsoon rains are important triggers of soil erosion and mass movements. In addition, steep slopes, the unstable nature of rocks, the depth and degree of weathering, high seismicity and over-steepening of slopes through undercutting by rivers significantly contribute to the release of mass movements. The fact that during a late monsoon the suspended sediment load is still high, even though surface erosion should be reduced by greater vegetation cover, reinforces the assumption that mass wasting and activation of stored sediment in river beds and intra-montane basins must be the major factors in sediment transport. Better management of eroding fields in the uplands has an important positive effect on small plots and small catchments, but may not necessarily show up as reduced stream sediment load in the lowlands; humans’ impact on surface erosion and denudation very much depends on the scale of the area under consideration. Each watershed will respond in a unique manner to soil conservation measures. Generally speaking, there is considerable storage capacity in valleys and intra-montane basins within large watersheds. Small and micro watersheds, however, have less storage capacity and accordingly show a stronger relationship between erosion processes and sediment load in the rivers. Rates of surface erosion are usually very site specific and should not be generalized over larger areas. As a whole, it can be said that sediment transport in big Himalayan rivers depends mainly on natural features such as catchment size, intensity of monsoon rains and storage capacity in intra-montane basins rather than on human interventions.

6.4. Erosion, transportation and sedimentation in the lowlands

6.4.1. Shifting river courses and lateral erosion

The shifting of river courses in the eighteenth century was discussed in section 4.3.2. The most impressive change was of the ‘‘Old Brahmaputra’’ after 1787. Previously a tributary of the Meghna, it became the ‘‘New Brahmaputra’’ or ‘‘Jamuna’’ and joined the Ganga (see Figure 4.5). The ‘‘Old Brahmaputra’’ flowed east of the Madhupur Tracts (see Figure 4.1). The shifting of the river to the present course, which lies approximately 70 km further west than in former times, most probably occurred gradually. Brammer (1996) states that the continued widening of the Brahmaputra might be an indication that channel adjustment is still ongoing. The reason for the gradual westward movement of the Brahmaputra is still unclear: earthquakes and differential subsidence within a tectonic trough between the Madhupur and Barind Tracts (see Figure 4.1) are one possibility. Some people suggest the Coriolis force as a cause of the westward shift of the Brahmaputra. This seems very unlikely since, historically, the Ganga further to the south has progressively moved eastward (Brammer 1996: 5). Also the Tista River, originally a tributary of the Ganga, moved eastwards during or after the floods of 1787 and joined the Brahmaputra near Bahadurabad through an old, abandoned course (Figure 4.5). The formation of the Bengal delta over the past 200 years is discussed in a number of publications, for example in Chowdhury (1964), Kausher et al. (1993), Huq and Rahman (1994), Allison (1998). Haque’s (1997) account of the gradual formation of today’s river system on the Bengal delta reaches far back into history to the times of the ancient Hindu scriptures.

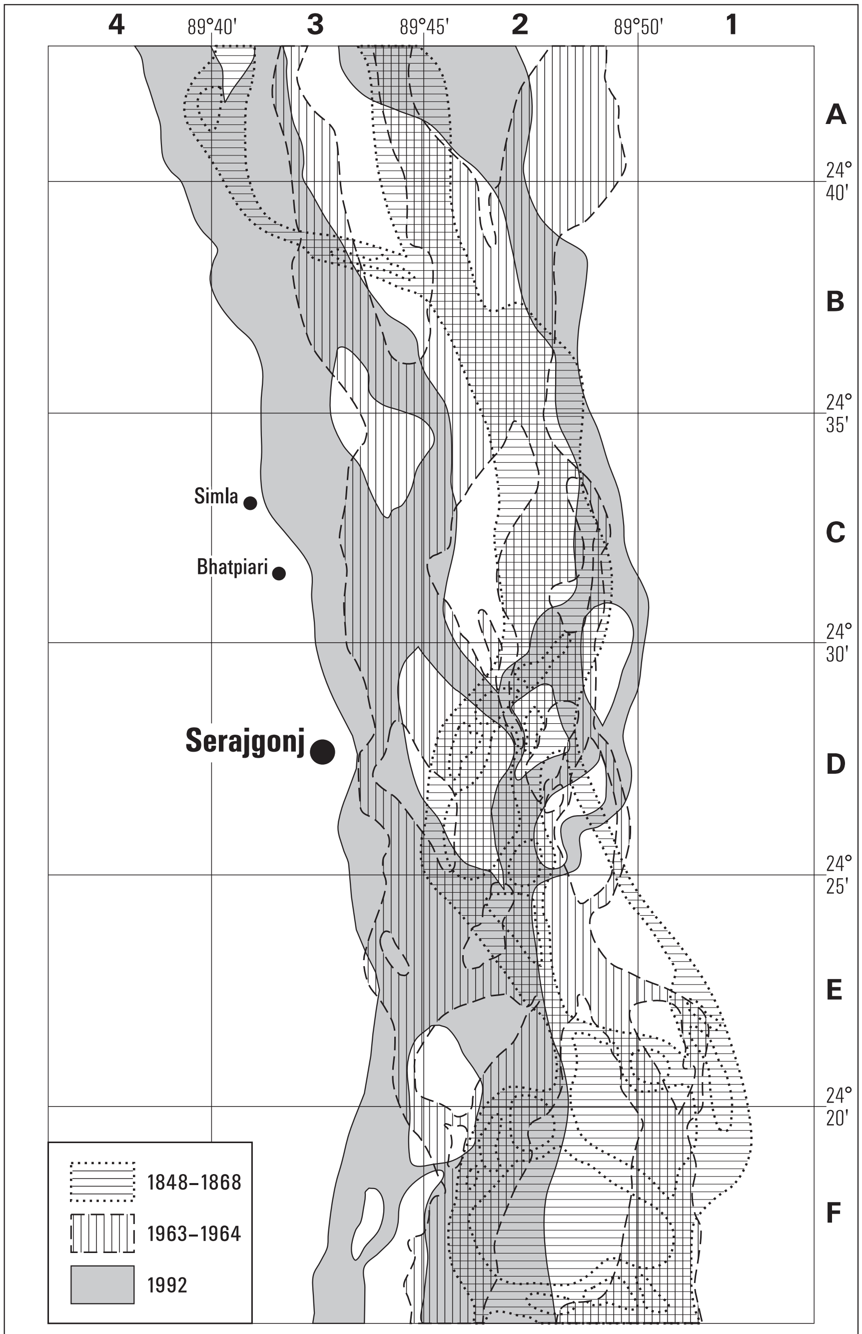
Another example of a major shift in river course is provided by the Sapt Kosi (Ives and Messerli 1989). Over the past 250 years, the channel of this river has moved 100 km to the west, creating a vast alluvial fan (Figure 4.5). As a result, the Sapt Kosi has deposited huge volumes of sediment in this fan for a period much longer than that of recent (post-1950) intensive human intervention in the watershed. Ives and Messerli argue that the ratio of human-induced erosion to natural erosion in the Kosi watershed must have been very low or even not measurable.

After this short historical introduction, attention needs to be drawn to the most recent fluvio-morphological processes of the Ganga and the Brahmaputra. The Ganga is a meandering river system, the Brahmaputra a braided one. Meandering channels show more or less regular inflections in the direction of the channel and are quite sinuous in plan. Braided channels are characteristic of rivers that have major fluctuations in flow and that carry large amounts of sediment. A braided channel is divided by bars or islands into several channels, and the divided channels subsequently join and re-divide. The Brahmaputra in Bangladesh is a river system 10–15 km in width. During floods, the maximum width can increase to as much as 17 km. In the dry season, the Brahmaputra is characterized by a large number of distinct channels and river islands called *chars* (Coleman 1968; Burger et al. 1991; Goswami et al. 1991).

A number of authors have published research findings on changes in the course of the Brahmaputra and the Ganga in Bangladesh (Elahi and Rogge 1990; BWDB 1991b; a number of papers in Elahi et al. 1991; SPARRSO 1993; Thorne et al. 1993; Brammer 1996; Haque 1997; Goodbred and Kuehl 1998; Allison et al. 2003). A typical feature of braided systems is that the river course is constantly changing. Erosion processes leading to a loss of land and sedimentation processes resulting in a gain of land occur simultaneously. It is estimated that in 1992 about 1.8 million people lived on land within or adjacent to the Brahmaputra River. Of these, about half lived on *chars*, and the remainder lived on unprotected floodplain and set-back land, which is land between the river bank and an embankment (Brammer 1996). We shall discuss in Chapter 7 how these dynamic fluvio-morphological processes of the Brahmaputra affect the population and how the people react or adapt to changing river courses.

Project team member Susanne Zumstein (Zumstein 1995) investigated the river course changes of the Brahmaputra and their consequences for the affected people. The first analysis was carried out over an approximately 50 km stretch of the Brahmaputra in the area of Serajgonj (Figure 6.1) and documents three time periods between 1850 and 1992. The investigation was based on a comparison of maps and satellite images (for details, see the caption of Figure 6.1). Over roughly 100 years, from the first period (1848–1868) to the second period (1963–1964), the maximum westward shift of the Brahmaputra river bank reached 6 km in sector C2/C3 (Figure 6.1), which corresponds to an average of 60 metres per year. Between 1963–1964 and 1992, however, the erosion rate in certain areas reached 130 metres per year, for example in sector C3, while remaining far lower in other areas, for example in sectors D3 and E3. Furthermore, a general trend of channel widening can be observed. This tendency seems to be representative of the entire river course: "Overall, the channel has widened at a long-term rate of 27 metres a year, but since 1914 it has widened at an average rate of 65 metres per year" (ISPAN 1993: 2–12). Another important phenomenon is the continuous fluctuation of the *chars* (river islands). Location and size vary greatly between the investigation periods. Not one single *char* remained the same between 1860 and 1992.

A second and more detailed investigation was carried out in an area on the western side of the Brahmaputra north of Serajgonj covering the period 1922–1994. The study included several villages situated close to



Cartography: A. Brodbeck

the river in the area of Simla (Figure 6.1). During the period of fieldwork in 1994, most of the area was prone to both continuous riverbank erosion and highly variable inundations during the monsoon season. The detailed investigation was based on one-inch maps for 1922 and 1934, SPOT satellite images from 1990, a Global Positioning System survey of 1994, and extended discussions with farming families regarding the river's history over approximately 20 years. The investigation produced the following findings. Over a period of approximately 70 years, the right river bank had moved westwards by 1.0–3.8 km, which corresponds to an average annual shift of 17–65 metres. As a result, a significant amount of land within the study area on the right side of the Brahmaputra was lost to river erosion. The GPS survey in 1994 indicates that the actual trend in the shifting of the river course can vary significantly and be very site specific. In Simla, for example, the shift reached 1,200–1,800 metres between 1990 and 1994, which corresponds to an erosion rate of 300–450 metres per year. These observations show that the dimension of erosion can be very great at certain times. Close to Simla there was also a zone of sedimentation in which, between 1990 and 1994, a land strip 600–1,000 metres wide was created.

Field observations and discussions with the affected people indicate that lateral river erosion occurs throughout the year, with an intensification during the monsoon season when swift currents are present. The erosion occurs gradually and mostly in a rather unspectacular manner: the river waves regularly hit the river bank, thereby undercutting the loose silt layers. From time to time, a major portion of the river bank collapses and disappears into the river. By monitoring these processes over a few days it can be observed how homestead gardens and house platforms are eroded and how people have to move their entire household.

6.4.2. *Sediment load and sedimentation*

The material transported by a river is classified as suspended load, dissolved load and bed load. Often only suspended sediment is sampled. Even this component is difficult to measure accurately for rivers that experience enormous variations throughout the year and from year to year, as is typical in monsoon climates with several extreme discharge peaks in one rainy season.

Figure 6.1 The river courses of the Brahmaputra at different times: 1848–1868 (quarter-inch map), 1963/1964 (Army Map Service), and 1992 (LANDSAT image).
Source: Zumstein (1995).
Notes: The scale is 1:250,000.

The second element, the dissolved load (particularly salts), is rarely measured. This knowledge gap is of critical importance because dissolved salts may form a significant proportion of the total sediment discharge, especially in warmer climates. In the context of the Nana Kosi watershed project in the Indian Central Himalayas, which has already been discussed in section 6.3.2 (Rawat and Rawat 1994), strikingly high figures for dissolved loads were recorded. It is astonishing that, in a normal monsoon year (1986), the dissolved sediment load, which was measured at 25 different sites, ranged between 6.19 and 166.0 t/km^2/yr compared with the suspended sediment load, which ranged between 7.2 and 288.4 t/km^2/yr. In comparing these data, aspects of scale should be kept in mind: the entire Nana Kosi watershed is 55 km^2 in area, but some of the 25 measured sites are tiny and cover only a very small part of the watershed.

The third element, the bed load, has probably not been recorded on any Himalayan river. For this component an estimate is usually made, for instance when calculating the design life of reservoirs. Today it is generally accepted that bed load has been grossly and systematically underestimated throughout the Himalayas and the Himalayan foreland (Ives 2004).

In the rest of this section we deal with the question of whether there was any trend towards increasing suspended sediment load in the major rivers in Bangladesh between the late 1960s and the early 1990s. The rather limited but very interesting analysis is based on scattered daily information on suspended sediment, which was available from the Bangladesh Water Development Board for one hydrological station each on the Ganga, the Brahmaputra and the Meghna. For the Brahmaputra and the Meghna, the fraction of suspended fine sediment was used, since this is the only variable for which more or less continuous records were available. For the Ganga, the total suspended sediment load (sand and suspended fine sediment) was taken into consideration. The investigation focused on the relationship between discharge and suspended sediment for different time clusters (Figure 6.2) and on the amount of suspended sediment in given discharge ranges over time (Figures 6.3a–6.3c). The depression area in the Meghna basin upstream of Bhairab Bazar and the Farakka Reservoir on the Ganga (Figure 3.2) certainly have a strong impact on the sediment concentration of each river. Therefore, the most relevant and most ‘‘natural’’ results can be expected for the Brahmaputra.

The relationship between discharge and suspended sediment over time (Figure 6.2)

For each investigated river, all the available sediment data were clustered into four defined time periods, spanning from the late 1960s to the early 1990s. Since the available data series are not identical, the selected time

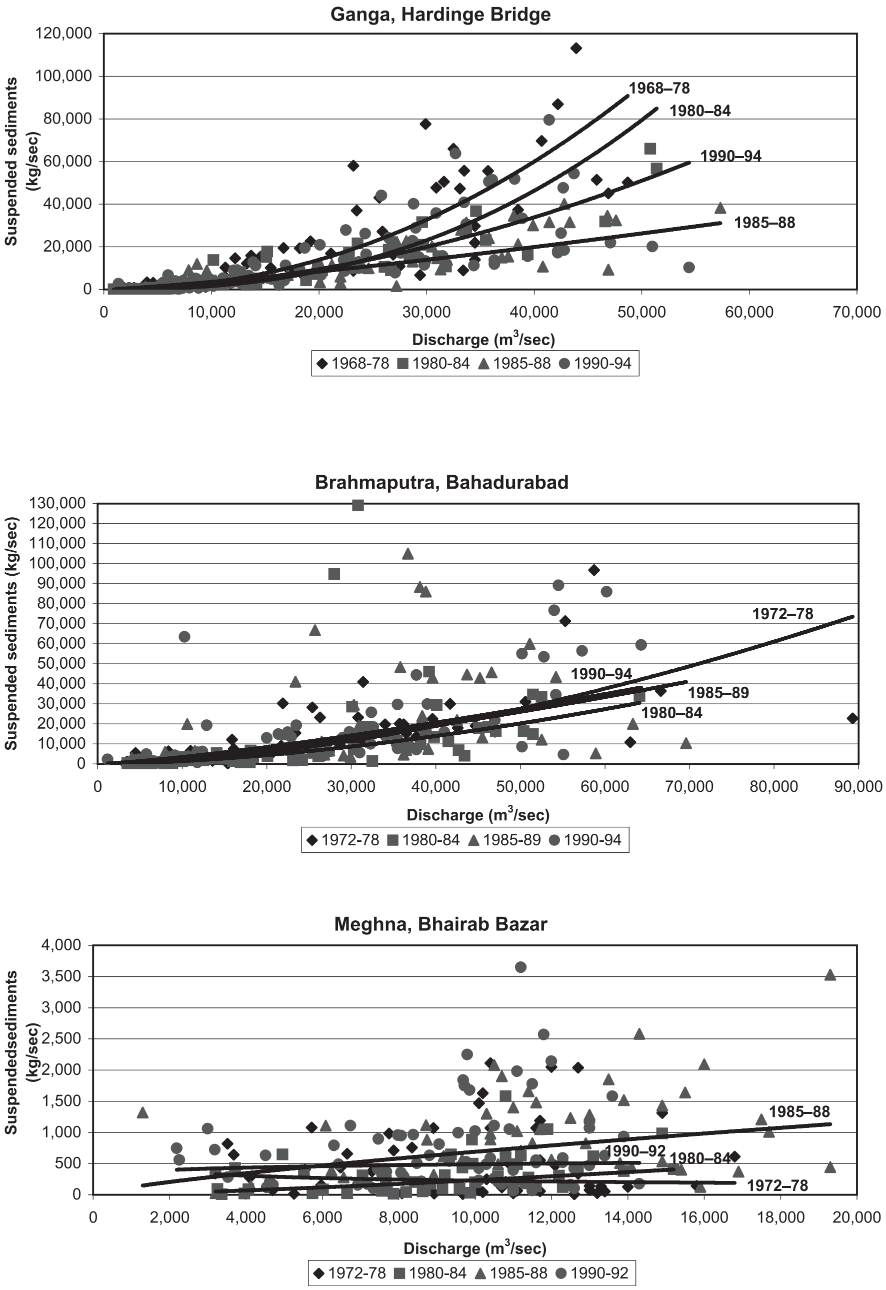
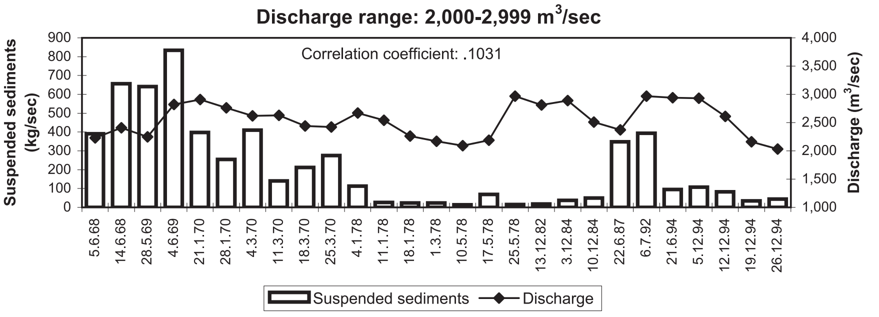
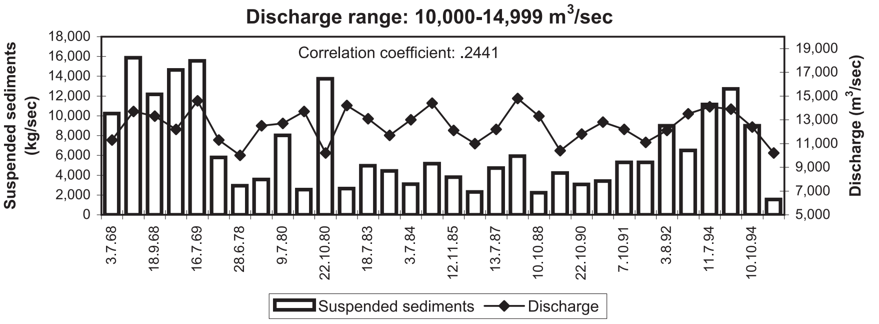


Figure 6.2 The relationship between discharge and suspended sediments in the Ganga, Brahmaputra and Meghna for different time clusters.

Notes: The curves represent power trend lines of suspended sediments and discharge. For the location of the stations, see Figure 3.2. Data source: BWDB (n.d.[b]).





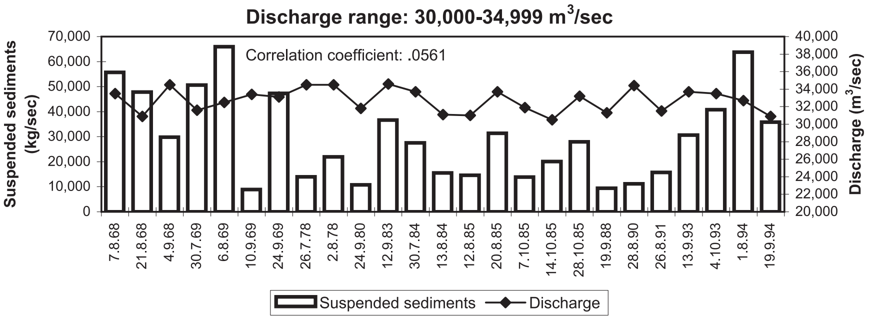


Figure 6.3a Suspended sediments in the Ganga (Hardinge Bridge) for specific discharge ranges.
Notes: For the location of the stations, see Figure 3.2. Data source: BWDB (n.d.[b]).

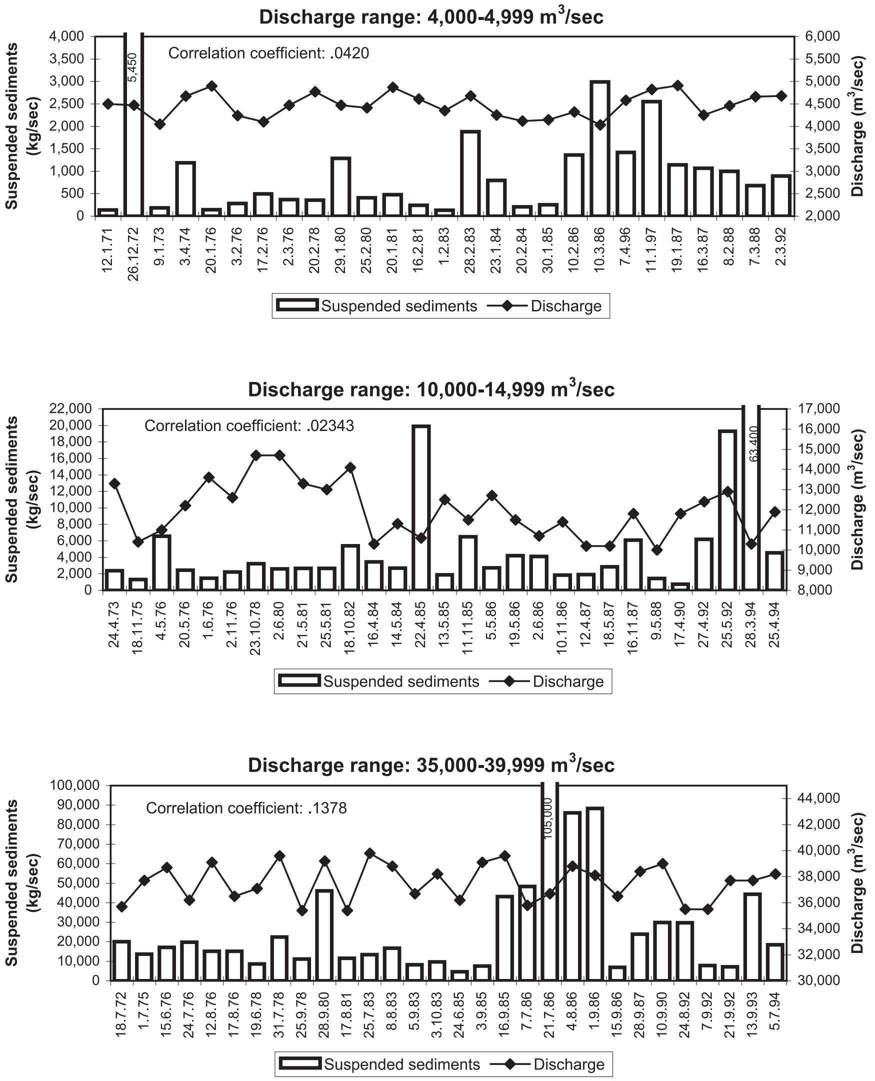


Figure 6.3b Suspended sediments in the Brahmaputra (Bahadurabad) for specific discharge ranges.
Notes: For the location of the stations, see Figure 3.2. Data source: BWDB (n.d.[b]).

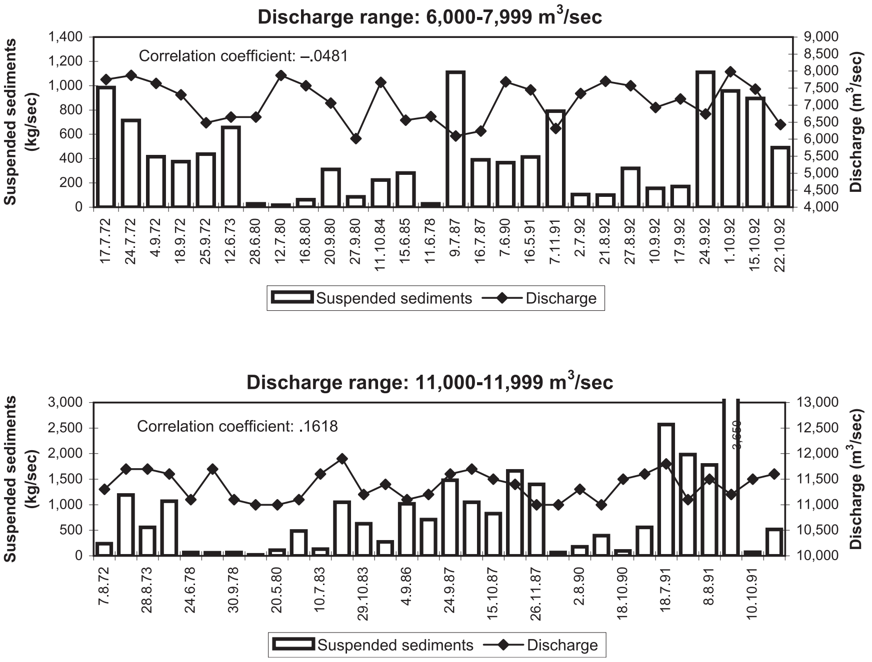


Figure 6.3c Suspended sediments in the Meghna (Bhairab Bazar) for specific discharge ranges.
Notes: For the location of the stations, see Figure 3.2. Data source: BWDB (n.d.[b]).

periods differ slightly for the three rivers. For each time cluster, daily suspended sediment was plotted against the relevant daily discharge and a power trend line was drawn. If there really is a gradual increase in suspended sediment load in the rivers, then the trend lines should grow steeper and steeper from one time period to the next. The graphs reveal the following facts:

- In general one would expect a high discharge value to be connected to a high value of suspended sediments. However, the figures show that the reality is much more complex: the dots in each of the graphs are very much scattered. The expected relationship between discharge and suspended sediments is to some extent evidenced in the Ganga, much less in the Brahmaputra and almost absent in the Meghna.
- *Ganga*: The difference in the position of the four trend lines is quite significant. However, the rising of the curve does not occur chronologically: it is notable that the graphs representing the earliest time clusters

(1968–1978 and 1980–1984) are the steepest, an observation that was not expected under the scenario mentioned above.

- *Brahmaputra*: The position of the four trend lines is very similar. It is again remarkable that the steepest line represents the earliest time cluster (1972–1978).
- *Meghna*: the dots are very scattered over the graph and the trend lines are almost horizontal. This indicates that, for any given flow, the amount of suspended sediment varies significantly and there is no clear relationship between the two variables.

The amount of suspended sediment in given discharge ranges over time (Figures 6.3a–6.3c)

For each river, the discharge and sediment data were clustered according to defined discharge ranges (see the titles of each graph). In each graph of Figures 6.3a–6.3c, the discharge within the defined range and the corresponding suspended sediment load were plotted chronologically against the dates of observation (note that the time axes of the different graphs cannot be directly compared). For each data cluster, the correlation coefficient between discharge and suspended sediment was calculated and added to the chart. If there really is a gradual increase in suspended sediment load in the rivers, then this should be evident in a gradual rise in sediment concentration within a given (narrow) range of river flow over time. The graphs reveal the following facts:

- The variation in sediment load within a given range of flow is extraordinary. The sediment load of a low discharge range might even exceed the sediment load of a higher discharge range. As a result, a clear relationship between discharge and suspended sediment does not exist. This is illustrated in the graphs, but even more so in the very low correlation coefficients.
- In none of the graphs is there any indication that the amount of suspended sediment within a specific discharge range is increasing over time.
- In some time periods, the concentration of suspended sediment was particularly high (e.g. 1968–1969 in the Ganga for all three discharge ranges; the 1991 monsoon season in the Meghna; 1986 in the Brahmaputra). Interestingly, none of these examples coincides with major flood years in Bangladesh.

The results of both these investigations first of all confirm that the sediment load of the big rivers flowing through Bangladesh is enormous and ranks among the highest in the world. Brammer (1996) estimates that the Brahmaputra carries between 387 and 650 million tons of sediment, on average, per year. Singh and France-Lanord (2002) give a range of as much as 402 to 1,157 million tons per year. This wide range is the result of both the difficulty of measuring the sediment content of such a huge, braided river system, and the question of whether the bed load is included or not. In any event, the sedimentation rates within the floodplains of Bangladesh are very high. In their study along a 110 km stretch of the Brahmaputra left bank, Allison et al. (1998) determined annual accumulation rates ranging from >4 cm per year on the natural levees near the river channel to <1 cm per year within 20–40 km of the basin. The most important factors determining sedimentation in the study area were inter-annual variation in the flood pulse, proximity to the distributary channels, and local topography. These figures express the difficulties of evaluating the sedimentation process on the basis of the data currently available.

The assumption that the sediment load of the big rivers is increasing as a result of human-made processes in the upland portions of the watersheds cannot be confirmed by the analysis of Figures 6.2 and 6.3a–6.3c. Goodbred and Kuehl (1999) report that no change in the sedimentation process could be observed during the past 7,000 years. In the modern Ganga–Brahmaputra system, the effects of short-term climate fluctuations or changes, basin tectonics and shifting land uses are probably tempered by the immense size of the drainage basin, which has the capacity to store eroded sediment for hundreds or even thousands of years before downstream release.

The suspended sediment load of the rivers in Bangladesh does not seem to be a direct function of discharge. As highlighted above, rivers in Bangladesh form large braiding or meandering systems. In some areas the banks are eroding, in other areas sedimentation processes are taking place. Strong erosion increases the sediment concentration further downstream, even in low-flow situations; aggradation processes reduce the sediment load, even in high-flow conditions. These processes are very dynamic and constantly change location. Obviously such geomorphological processes are the primary factors influencing the sediment load of the rivers at particular locations. This helps to explain the variability of sediment load and the occurrence of periods with high and low sediment concentration within given discharge ranges. These findings are supported by Goswami (1985): trends in aggradation or degradation at a particular channel cross-section may not be representative of an entire stretch of the river. The increased sediment discharge observed in the late 1970s at Pandu in Assam, for example, appeared to reflect temporary degradation of the stretch immediately upstream of the gauging site. Taking the Rhine as an example, Middelkoop (1997: 42) describes the situation thus: ‘‘The relationship between river discharge and suspended sediment concentrations is non-linear and highly variable. This is because the suspension load is not only determined by the transporting capacity of the stream flow, but it also depends on the availability of sediment. To date, in spite of the importance for the sediment budget in the lower Rhine delta, no models have been developed that adequately describe the instantaneous relationship between water discharge and suspended sediment concentrations in the river Rhine.'' Brammer (1996: 5) concludes:

> [T]he rates of bank erosion and channel widening appear to have increased over recent times. It is tempting to relate this increased aggression to increased sediment loads brought down by the Brahmaputra as a consequence of human-induced degradation and erosion in the Himalayas. There is no clear evidence for this.

New methods and techniques involving radioisotope geochronologies (^{137}Cs and ^{210}Pb) can be used for determining recent rates of floodplain accumulation over a time span of approximately 40–100 years. However, it remains open whether these methods may be successfully applied over large areas. Based on these methods, Goodbred and Kuehl (1998) estimated that more than 30 per cent of the 1,000 million tons of fluvial sediment discharge carried by the Ganga and the Brahmaputra is stored every year and does not reach the ocean. For Singh and France-Lanord (2002), the suspended sediment load of the two river systems together could range from less than 1,000 million t/yr to more than 1,800 million t/yr, and Allison et al. (1998) estimated that 39–71 per cent of the river sediment budget may be trapped landward of the Ganga–Brahmaputra mouth. In addition, Goswami (1985) reported that between 1971 and 1979 the Brahmaputra River in Assam underwent aggradation of approximately 16 cm within the channel belt over a stretch of more than 600 km, accounting for 70 per cent retention of suspended sediment. All these figures are evidence of the difficulties involved in understanding the spatial and temporal patterns of highly complex erosion–sedimentation–removal–storage processes between the highlands and the lowlands of the Ganga and Brahmaputra river systems.

New methods have produced new results for different parts of the river system. Geochemical data on Brahmaputra sediments highlight the characteristics of the different tributaries draining Tibet, the Himalayas and the region north of the Indo-Burmese range (Singh and France-Lanord 2002). Eastern Himalayan rivers have isotopic compositions similar to those of the central and western Himalayan rivers, implying similar lithologies. However, the far eastern tributaries of the Brahmaputra from outside the Himalayan system have very different compositions owing to the presence of the Transhimalayan plutonic belt in their drainage, and these tributaries are responsible for the clear difference between the isotopic compositions of the Brahmaputra and of the Ganga. This should make it possible to differentiate the relative contributions of each of the river systems to the sediments deposited in the delta or in the Bengal Fan.

The erosion processes in the mountain ranges are in general very similar, but particular attention must be given to the most north-easterly part of the Brahmaputra catchment upstream of Dibrugarh (Figure 1.2). From Tibet, the Tsangpo (Brahmaputra) first flows to the east then to the north-east at 3,000 metres altitude and finally makes a sharp U-turn towards the south in the area of Namche Bawar (not indicated on the map). From there, the Brahmaputra begins its descent of approximately 2,000 metres over less than 200 km to Assam (in this stretch the Brahmaputra is called Siang-Tsangpo), cutting through the lesser Himalayas and the Sub-Himalayas. The area around Namche Bawar is a metamorphic massif with extremely rapid exhumation and disintegration as a result of strong tectonic uplift and high precipitation, which account for the remarkably high erosion rates of this region. The river incision around Namche Bawar is among the highest in the world (Singh and France-Lanord 2002) and the Siang-Tsangpo stretch of the Brahmaputra accounts for the major source of sediment of the whole watershed. The geochemical budget implies that erosion in the Namche Bawar zone represents about 45 per cent of the total sediment flux of the Brahmaputra at its outflow before the confluence with the Ganga. This very interesting study provides another example of the dominance of natural factors over human-induced contributions in shaping the processes in large river systems such as the Brahmaputra.

The tributaries of the Ganga also play a special role in the erosion and sedimentation processes from the highlands to the lowlands. The main channel of the Ganga flows east along the Himalayan foreland basin (Figure 1.2), capturing several large tributaries from the north that drain the range's front slope. Several other tributaries from the south originate on the Indian craton and drain the Deccan basalt terrain. Of the total Ganga discharge, approximately 60 per cent is contributed by the Himalayan tributaries and 40 per cent by the southern tributaries (Singh 2001; Goodbred 2003). This clearly shows that the discharge from the Himalayas cannot completely dominate the hydrological regime of the Ganga.

New studies of the impact of tectonic movements as well as climate change or fluctuations provide additional evidence that only major natural forces are able significantly to influence the sedimentation processes on the floodplain and in the delta. Weber et al. (2003: 362) state: "Sediment deposits on both shelf and slope have been modulated by glacio-eustatic sea-level fluctuations, climate change and tectonic activities. Although tectonic processes mainly control the long-term changes in the flux of riverine sediments, climate change largely controls the shorter-time scales. Variability of the Bengal Fan is ultimately related to changes in monsoonal strength.'' Goodbred (2003) mentions the widespread aridity and reduced runoff during the Last Glacial Maximum (LGM, roughly 18,000 years BP). Well-known proxies and modelling records suggest a 25 per cent decrease in regional precipitation in relation to a weakened summer monsoon system. At 12,000 BP a period of increased precipitation began, evidenced not only by model reconstructions but also by lake sediments, pollen analysis and surface-ocean records. Together with the tectonic and geological conditions mentioned above, this climate change had significant impacts on floodplain formation.

To summarize, it has once again become very clear that human activities in mountain areas cannot have any significant impact on the hydrological and fluvio-morphological processes in the lowlands, more particularly on flooding and sedimentation in Bangladesh. Natural forces in the vast Ganga–Brahmaputra–Meghna basin, consisting mainly of tectonic uplift, intensively weathered and non-resistant lithological conditions, as well as high-intensity monsoon precipitation, are such powerful factors in the erosion and sedimentation processes that the effects of human interventions are comparatively negligible or even non-existent at this big scale. Moreover, the human-induced contribution may be detectable, if at all, only with a time lag of decades or even centuries. Nevertheless, it must be emphasized that this does not mean that the human impact on mountain ecosystems can be ignored. On the small scale of a slope, a valley or a mini-watershed, the on-site effects of human interventions can be disastrous. However, these small-scale impacts pale into insignificance in the continuous and major natural processes occurring at the large scale of the Ganga–Brahmaputra–Meghna system.

As has become clear in the course of the discussions in this chapter, there are a lot of uncertainties related to all these highly complex issues and questions. Improved understanding of the erosion and sedimentation processes in the entire Ganga–Brahmaputra basin still requires major efforts by the scientific community. Fascinating new analytical tools and methods for absolute dating are now available, but satellite data too can be used to detect sediment concentration (Middelkoop 1997). Even if not all of these methods are yet completely satisfactory, they can help to improve understanding of the processes in the big watersheds of our world, such as the Ganga–Brahmaputra basin. However, all new methods are useless and all scientific progress is hindered in the absence of a political decision by all the Himalayan countries to exchange scientific data freely – as is stipulated in the regulations of the International Council for Science (ICSU) – and to cooperate constructively in this common highland–lowland environment. To conclude this chapter we quote from a report by the International Geosphere Biosphere Program entitled *Modelling the Transport and Transformation of Terrestrial Materials to Freshwater and Coastal Ecosystems* (IGBP 1997): "We strongly recommend that a much greater effort be expended to answer the key scientific questions for South, Southeast, and East Asia. The rapid change of both human controls and material fluxes are greatest in this region."

7

Floods in Bangladesh: The human dimension

7.1. Introduction: Why should the human dimension be considered in a flood research project?

The previous chapters have focused on the historical and physical dimensions of floods in Bangladesh. On the basis of the investigation of climatic and hydrological data on the one hand and consideration of geological conditions and tectonic movements on the other, it became clear that the generation of floods in Bangladesh is dominated by natural processes. It also became clear that the farmers in the highlands are certainly not responsible for the suffering of the farmers in the floodplains. It would have been possible to conclude this book with these results. However, a very important aspect of the story would have been missing and a number of questions would remain unanswered. In our study we were looking at the highland–lowland linkages in the context of Bangladesh floods from a purely physical perspective. But what is the perception of the rural population living in the floodplains of Bangladesh of these processes? Do they have the same views when looking upstream towards the origin of the water? Will the political authorities and the engineering community ever understand the causes of the floods in the context of an integrated and complex highland–lowland system, which is a key to sound flood management and flood control planning in the future?

In a time of global climate and environmental change, it is no longer sufficient to consider the natural science dimensions alone; the human dimension needs to be understood as well. As the policy and societal relevance of a human–environment research agenda increases, so does the need to establish collaboration between natural and social scientists. But such a collaboration will be successful only if programmes and projects are initiated and planned by interdisciplinary teams representing both the natural and the social sciences. Sustainability problems demand integrated knowledge about natural systems, human society and human behaviour (Gash 2002; Wasson and Underdal 2002). The rural population in the lowlands of India and Bangladesh are exposed to gigantic forces and dynamic processes in the context of flooding. We have to understand their thinking about these forces and their strategies (which are often more reactive than proactive) in coping with them. Furthermore, it is critical to understand the thinking and reactions of the political authorities and engineers and, finally, to understand the interventions of technical experts from international organizations and institutions. In this sense, this chapter may be seen as somewhat isolated from the previous ones. This impression may arise from the fact that different methods and approaches had to be used in this part of the project. Furthermore, it will soon become clear that the perceptions of the rural population and those of the political and technological planners are very different and that there is a lack of solutions or results. However, we cannot yet present solutions because it is not just that perceptions are very different, but dialogue and cooperation between different countries and stakeholders are not yet in place in a way that would allow for the initiation of participatory problem-solving processes.

Following the advice of global change programmes, natural and social scientists formed an interdisciplinary team for the planning and implementation of the research project presented in this book. We all learned a lot from each other. In particular, it became very clear that the content of this chapter will play a prominent role in all discussions about future options and measures for the management and control of Bangladesh's floodplain. The key to finding appropriate solutions will be that all stakeholders are willing to integrate different solutions and to consider them within an overall context of a comprehensive highland–lowland system.

7.2. The fieldwork: How was the human dimension approached in this flood research project?

This part of the project was implemented mainly through fieldwork in three test areas within Bangladesh (Figure 7.1): Bhuanpur (Tangail District), Serajgonj (Serajgonj District) and Nagarbari (Pabna District). Interviews with local residents comprised the core part of the fieldwork and focused on the following thematic areas: perceptions of floods and

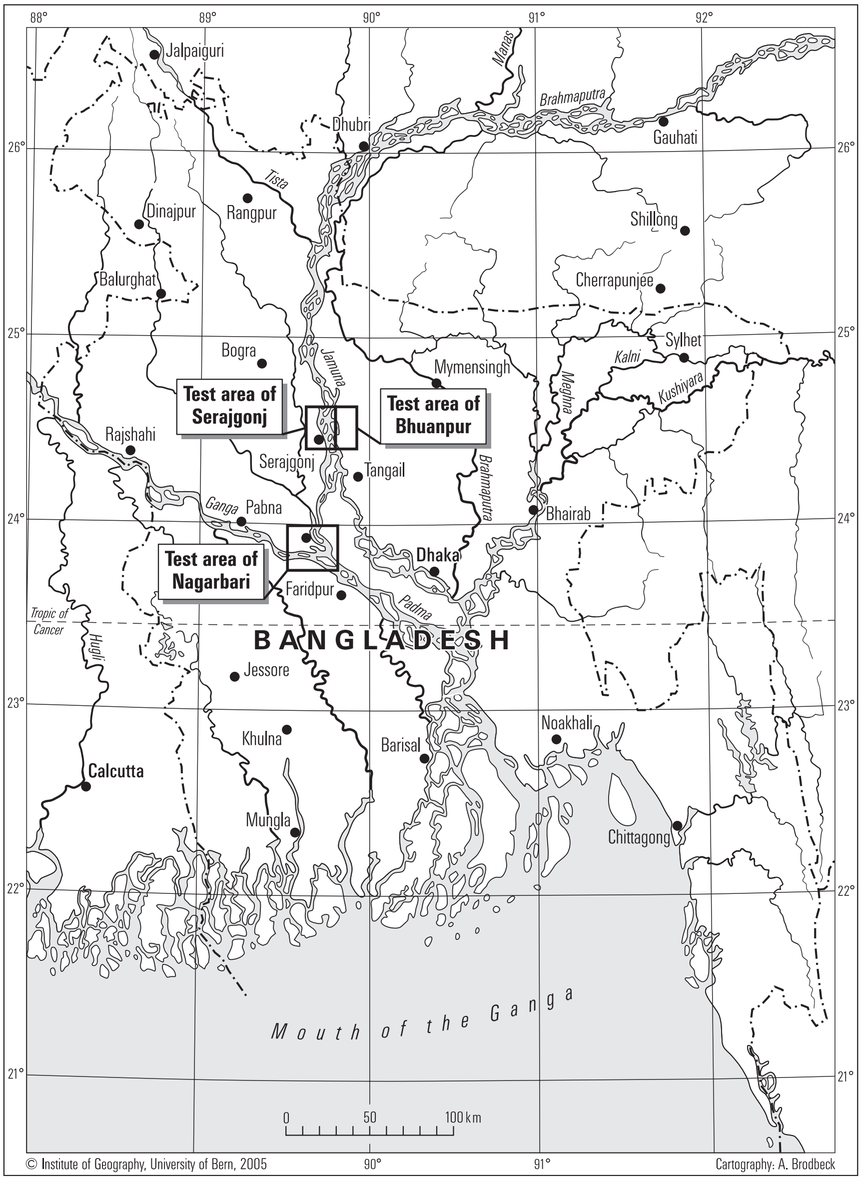


Figure 7.1 The location of the three test areas of the project.

adaptation strategies, perceptions of lateral river erosion and coping strategies, experiences with lateral river embankments. The main selection criteria for the test areas were:

- location in severely flood-affected regions;
- vicinity to one of the major rivers;
- accessibility;
- existence of flood protection embankments;
- possibility of comparing the situation on both sides of the river Brahmaputra/Jamuna (test areas of Bhuanpur and Serajgonj);
- confluence situation of the Ganga and the Brahmaputra/Jamuna (test area of Nagarbari).

In each test area, interviews were carried out in four categories of village: villages located approximately 15–20 km away from the river and the embankment; villages located just behind the flood protection embankment; villages located between the river and the flood protection embankment; and villages located on the river islands (*chars*). The period of intensive fieldwork extended from October 1992 to March 1994 and was structured into three main phases. In *the first phase* an overview of the geographical and environmental situation of the villages in the three test areas was elaborated. Altogether 148 interviews (one per village) were carried out following a structured but open-ended questionnaire. The questions were clustered into four main themes: flooding conditions; dynamics of the Brahmaputra river bed; embankments and their effects; and irrigation infrastructure. In *the second phase*, in-depth interviews using an unstructured questionnaire were carried out concentrating on flood perceptions, land use and agriculture, and strategies to adapt to flooding; 167 discussions in 62 villages were held with persons of different ages and occupational and economic groups. Separate interviews were held in 83 villages with 262 people who had migrated, specifically focusing on the reasons for migration and on the migration patterns. Finally, separate interviews were carried out with women in order to learn about the females' perception of flooding and about their adaptation strategies. In addition to the interviews, a large number of informal discussions were held with groups and individuals in the villages and many practical observations were incorporated into the findings of the fieldwork. The field investigations of *the third phase* focused on the dynamics of the Brahmaputra, to some extent also of the Ganga, and on people's strategies for coping with their dynamic and unstable environment (see also section 6.4.1).

The fieldwork was implemented by the following project team members: Talim Hossain, Regina Liechti, Susanne Zumstein, Jahan Akter Seema, Qumrun Nahar, Mahbuba Matin, Sayd Ferdous and Monica Nahar. Three key project documents resulted from this intensive fieldwork:

Hossain (1994), Zumstein (1995), and Liechti (1996). Based on the project experiences and on a Swiss federal scholarship, Talim Hossain continued his research and completed it in a successful and highly relevant PhD thesis (Hossain 2001).

7.3. Different stakeholders' flood perceptions

> The perception of extreme natural events, albeit subjective in nature, plays a profound role in decision-making on adjustments by people living in hazard-prone areas. The term ‘‘perception’’ implies the individual organization of stimuli relating to an extreme event or a human adjustment. An examination of hazard perception allows one to determine how people view occurrences or threats, how such attitudes are influenced, and how such views relate to the available options for coping with the hazard effects. (Haque 1997: 226)

> Natural hazard perception is intimately related to the question of risk, especially as the latter can often be divided into its objective and subjective forms – i.e., measured or calculated risk and perceived risk. (Alexander 1998: 163)

In this section we present and compare the flood perceptions of different stakeholders: the affected rural population, the engineers and politicians, and the journalists. The discussion of the people's perceptions is based on the fieldwork in the three test areas (see Figure 7.1) and complemented, where appropriate, with quotes from the vast literature. The perceptions of engineers, politicians and journalists are compiled from literature sources and summarized from conversations in various offices.

7.3.1. *Flood perceptions of the affected rural population*

In their language, the Bangladeshi people distinguish between *barsha* (flooding) and *bonna* (flood). *Barsha* is the normal seasonal inundation of floodplain land, to which farmers' traditional cropping practices are well adapted. *Bonna* represents abnormal flooding: flood water rises earlier, higher, more rapidly or later than farmers anticipate at the time they decide about what crops to grow on their different types of land (Brammer 1995a). Table 7.1 compares the most important features of *barsha* and *bonna* (after Haider 1991). The following discussion is based on a number of representative key statements made by flood-affected people; these are listed in Box 7.1.

Normal flooding is not a catastrophe for the rural people: *barsha* is part of the daily life and therefore life continues to be normal. People are used to normal flooding, and the crops and the cropping calendar are adapted to it. Floods create problems only if they are abnormal in terms of mag-

Table 7.1 The most important features of normal seasonal inundation (*barsha*) and abnormal flooding (*bonna*)

Barsha	*Bonna*
Normal water level	Abnormal rainfall
Normal rainfall	Houses submerged
Gradual rise of water	Sudden rise of water
No problem to move around	Transport problems
Helpful to cultivation	Large-scale crop damage
No shortage of food	Food shortages
Normal work possible	Normal activities disrupted
Less hardship for livestock	Need to live on raised platforms

Box 7.1 Oral testimonies: Flood perceptions of the affected population in the three test areas

1. ‘‘If the monsoon water remains within the limit, it is a normal flood. When houses and roads are under water, it is an abnormal flood.’’
2. ‘‘Normal flooding does not create problems. Crops do not suffer.’’
3. ‘‘During abnormal floods, crops are destroyed … houses go under water … movement is difficult … we cannot cook … we cannot get any drinking water.’’
4. ‘‘If the water reaches the house it is very uncomfortable for 5–7 days.’’
5. ‘‘It was not an abnormal flood but it came at the wrong time and harmed some crops.’’
6. ‘‘If there is no flood there will be no crops.’’
7. ‘‘People do not die if there is a flood but people die if there is no flood.’’
8. ‘‘One crop will be damaged and ten will grow well.’’
9. ‘‘If there is no flood the soil will burn into a desert.’’
10. ‘‘Lateral river erosion is a bigger problem than floods.’’
11. ‘‘Water comes from the Brahmaputra. Flood also occurs when the embankment is breached.’’
12. ‘‘If the roads are in good condition there are no problems in movement during abnormal floods.’’

Source: Fieldwork.

nitude and depth of water. The period of suffering linked to such situations usually lasts for one to two weeks. Floods can also create problems if their duration is abnormal or if they occur at the wrong time. In such cases, the flood is not considered unusual but it creates an abnormal situation for the crops. The water level as defined for normal and abnormal floods is site specific, and there are no standardized figures that would be applicable to the whole country. Obviously the average depth of water reached in a normal monsoon season is different in low areas (*beels*) and on medium- or high-level land. The conclusions from oral testimonies 1–5 in Box 7.1 are supported by Haque (1997: 229): "flooding in the Ganga–Brahmaputra Basin is a constituent part of rural village-life and is deeply imbedded in the culture. Only the bonna threatens riparian settlements and hence is considered a hazard in rural communities; barsha, the more frequent phenomenon, is a necessary and desired occurrence." Ralph (1975: 94) comes to similar conclusions: "the villagers' perception of flood is conditioned by the key role played by floods in their lives. The annual inundation is crucial for their crops, and is an accepted and much anticipated event. The onset of the monsoons and the rising of the water is a time of happiness, a time of planting and growth, and an end to the dry, dusty and hot months."

People are more afraid of droughts than of floods. According to testimony 8, crops may be damaged as a result of a flood but the surplus water stored in the soil produces high yields in subsequent crops. This means that the annual balance in the agricultural economy does not necessarily need to be negative, in spite of losses during the flood period. In testimony 9, the link between flooding and soil fertility is made, an issue that is still very much debated among experts.

In none of the interviews did the people rank floods first among the problems they face; in many cases, floods were not even mentioned. Lateral river erosion, landlessness and economic problems are concerns that were frequently raised by the respondents. Haque and Zaman (1993: 104) state: "the general problem of impoverishment is not a direct product of floods in the riverine plains of Bangladesh, but a significant proportion of floodplain users become marginalized and impoverished due to loss of income, assets and increased debt burden." The reason people perceive lateral river erosion as a bigger problem than floods is obvious: abnormal floods may create difficulties for a certain period but, once the floods have receded, the land is again available. Lateral shifts of the rivers, which can reach impressive dimensions (see section 6.4.1), erode the living space and existence base of entire families and there are no empty areas available where the affected people could move to (see also section 7.5). The significant concern of the people about lateral river erosion is supported by Haque (1997: 226 ff). In this context it has of course to be remembered that all three test areas selected for the project are located in the vicinity of the major river courses.

People have differentiated perceptions of the effects of embankments on flooding (see testimonies 11 and 12 in Box 7.1). They are afraid that embankments could be breached during floods. In many cases this fear is based on negative experiences they have had in the past when embankments did actually collapse. However, people also consider road embankments to be very important during abnormal floods because they are a safe place and provide access to the markets.

7.3.2. Flood perceptions of politicians and engineers

It needs to be underlined that our project was implemented in a period when the Flood Action Plan (FAP) still dominated the discussion of flood management in Bangladesh (see section 7.6). In recent years, a significant shift in thinking has taken place. Accordingly, some of the quotes listed in Box 7.2 and their interpretation may not be an accurate representation of current thinking.

In the perception of many politicians, floods are a problem for Bangladesh that needs to be resolved in a comprehensive and permanent way. Moreover, the causes of the floods in Bangladesh are perceived as originating outside the country. Floods, and the water question in general, are therefore a very sensitive political issue in the region (see also Box 4.3). Floods create significant incentives and arguments for attracting and channelling development money into Bangladesh. Finally, significant self-interest is involved in political discussions related to flooding. This discussion provides clear evidence that politicians' thinking and planning related to flooding are not necessarily based on current knowledge, either the available scientific field data or the actual field experiences expressed by the farmers in the affected regions.

Floods create a variety of job opportunities for engineers. The engineers' perceptions of floods are significantly influenced by external opinions. They are concerned not so much with the question of whether or not floods are a problem, as with how this problem can be resolved. In their perception, water needs to be controlled and this is possible through technical measures by importing and applying techniques that have been successful in other areas. Bangladesh is a test-bed for experimentation. The discussions with engineers of the Bangladesh Water Development Board in the framework of our project were very interesting. Those engineers who were in one way or another affiliated with the Flood Action Plan (FAP) clearly perceived floods as a major problem that needed to be resolved with technical measures. However, engineers who were not involved in the FAP perceived floods as natural recurring events that

Box 7.2 Quotes related to the flood perceptions of the World Bank (quote 1), politicians (quotes 2–4) and engineers (quotes 5–8)

1. "The severity of the recent floods in Bangladesh has led the government to look for a flood plan which would, in the long term, provide a comprehensive and permanent solution to the recent flood problem and so create an environment for sustained economic growth and social improvement." (World Bank 1989)
2. "As emphasized by the Finance Minister of Bangladesh during the third Flood Action Plan Conference, flood waters come from outside, from India." (Farooque 1993)
3. "Thus began a water dispute which, for some 30 years now, has plagued relations between the two neighbours." (Zaman 1983)
4. "The Flood Action Plan has developed towards a flood-action privilege for technology-oriented businessmen and profit-oriented institutions." (Farooque 1993)
5. "The approach of the Flood Action Plan clearly represents western thinking: there is a tendency among engineers to perceive water as a burden. Therefore, water should be controlled and conducted to the ocean as soon as possible." (Custers 1993)
6. "Among Dutch hydro-engineers there is an obvious desire to travel with hydrological structures and construction proposals for dikes and polders to Bangladesh." (Custers 1993)
7. "Consulting and construction firms from western donor countries as well as their local partners have a strong interest to participate in the components of the mega-project." (Hashemi 1993)
8. "The 'Kreditanstalt für Wiederaufbau' considers itself in a learning process, the result of which nobody knows." (Metschar and Reinhardt 1993)

are part of the environment of Bangladesh and to which people have adapted over centuries and generations. These engineers tended to opt for integrated, participatory and less technological approaches to flood management, which, as will be discussed in section 7.6, fortunately correspond to the strategies promoted and implemented today.

7.3.3. Floods in the perception of the international media

Box 7.3 lists a small selection of newspaper headlines related to floods in Bangladesh. The majority of these headlines were extracted from international media. Some of the headlines have been translated from Ger-

Box 7.3 Newspaper headlines on flooding in Bangladesh

1. ‘‘Floods in Bangladesh–Catastrophe in Asia’s house of the poor: hundreds of deaths, millions without shelter’’ (international press)
2. ‘‘Inundations in Bangladesh–death in floods’’ (international press)
3. ‘‘The main cause of the floods is the destruction of nature, particularly of the forests and the other vegetation types in the fragile mountain environment of the Himalayas’’ (international press)
4. ‘‘Floods in Bangladesh–drought in India’’ (international press)
5. ‘‘The flood catastrophe continues’’ (international press)
6. ‘‘Devastating consequences of the monsoon’’ (international press)
7. ‘‘Bangladesh in grave danger–deforestation in Himalayas aggravating floods’’ (*Bangladesh Observer*)
8. ‘‘Submerged houses in Bangladesh collapsed’’ (international press)
9. ‘‘Flood victims in Bangladesh’’ (international press)
10. ‘‘A country submerged’’ (international press)
11. ‘‘Have no fear: The children are enjoying diving in the river Jamuna’’ (*Daily Star*)

man into English. Floods provide exciting opportunities for the creation of attractive and catchy headlines as well as for reports in the international news. The political sensitivity of the issue is reflected in headlines 3 and 7, which make the ‘‘traditional’’, inappropriate and misleading link between deforestation in the Himalayas and floods in Bangladesh. In general, international newspapers create a perception of Bangladesh as a country of catastrophes, dominated by floods and cyclones. Have any international media ever reported that the onset of the monsoon season and the development of the first floods and ponds is a period of joy, of planting and growth for Bangladeshi people after a long period of drought and dust? It is therefore not surprising that development agencies and Western engineers consider assistance to Bangladesh to overcome the ‘‘flood problem’’ as a very high priority.

The following anecdote from the project work is enlightening in this context. On the occasion of a stay in Switzerland during the winter season, Bangladeshi project team member Talim Hossain was astonished to see and to experience that it is a lot of fun to play in the snow. According to Mr Hossain, the news in the Bangladeshi media about snow in the Alps is always dominated by reports of catastrophes such as avalanches, traffic jams, accidents, etc. As a result of such one-sided and misleading reporting, would not an expert from a Bangladeshi development agency have to perceive snow as the most important problem to be resolved in the Alps?

7.3.4. Comparison of flood perceptions

The various stakeholders' flood perceptions differ significantly and can even be opposed to each other. Each group of stakeholders has its specific, valid and logical perception. Alexander (1998: 161) puts this discrepancy as follows: "Perception is also an important issue in questions of vulnerability, development and mitigation, where startling discrepancies often develop between the attitude of residents, hazard managers and researchers." The problem is not the diversity of perceptions per se but the fact that there is often insufficient interaction and communication between the different groups of stakeholders. Instead of dialogue, there are often hard fronts of diverging opinions. This was particularly pronounced in the discussions and debates related to the Flood Action Plan (see section 7.6). In recent years, this dialogue among different stakeholders regarding flood management in Bangladesh has significantly improved and intensified.

The diversity of perceptions is particularly obvious in relation to the "internal view" (flood-affected people) and the "external view" (engineers from Dhaka and from abroad, politicians, journalists). Unfortunately, the "external view" often dominates the discussions and decision-making processes about approaches and solutions, and the views of the affected people, with their vast practical experience and knowledge, are not sufficiently taken into consideration. "The people of Bangladesh can be seen as being caught in a complex game between donor agencies and their local counterparts, with little say on how that game is actually played out" (Adnan 1991: S-9).

7.4. Flood events: Adaptation and mitigation strategies of the rural population

With their knowledge and experiences, as well as their local and traditional technologies, the rural people of Bangladesh have developed sophisticated strategies for adapting to floods and for living with floods. In this section, we discuss how the people deal with the floods in their different aspects of life, and how they avoid risk and damage to crops, houses, livestock and human lives in both normal and abnormal flood situations. The discussion is mainly based on the project fieldwork (Hossain 1997), again complemented by literature statements where appropriate.

7.4.1. House platforms

From experience, the people know exactly the water level that is to be expected on average every year in their particular residential area. Accordingly, they build their houses slightly above this average level by raising the house courtyard on earthen platforms. The height of these platforms varies slightly depending on how much money a family can spend to construct them. The roads through the villages are also elevated. As discussed above, a flood is normal (*barsha*) if the water level is below the level of the house courtyard. If the water reaches the level of the courtyard and floods the village roads, then the flood is perceived as abnormal (*bonna*). There is considerable scope for development projects to assist the people in further raising their house platforms or to establish central functions on earthen platforms.

7.4.2. Agriculture and crops

Floodplain landscapes comprise higher areas (river banks, ridges) and lower areas (depressions, basins), in which obviously the depth of flooding is different. Almost every village in the floodplain of Bangladesh has both ridge and basin land, and individual farmers generally cultivate fields that are located at different levels of this micro-relief (see also Brammer 1988). In adapting to the topographical situation and to the expected depth and timing of the inundation, the farmers have chosen the appropriate crops and crop rotation for each of their plots (see Figure 7.2). Brammer (1988: 26–27) states that "a Comilla farmer studied by the Comilla Academy had 17 plots in his 1 ha holding on which he had 17 different crop rotations in the year of study and a total of 65 different rotations over a 5-year period". According to ISPAN (1992: xiv), "agricultural production systems are closely adjusted to monsoon cycles, with depth and duration of normal inundation or average flood dictating the choice of crops during the Kharif-1 and Kharif-2 growing season" (*Kharif* are summer rainy season crops). The following paragraphs describe some important monsoon crops:

- One of the most extraordinary rice varieties is deepwater *aman* rice, which is grown in areas where the flood water is more than 3–4 feet deep and where flood water stays for a long period. Deepwater *aman* is able to grow up to 20 cm/day as an adaptation to fast-rising water levels. The plants can attain heights of 4–5 metres to keep their fruit stands above the flood level. Without flooding there would be no harvest from deepwater *aman* (for more information about deepwater rice, see Khan et al. 1994).
- On medium-level land, transplanted *aman* rice is grown (T. aman in

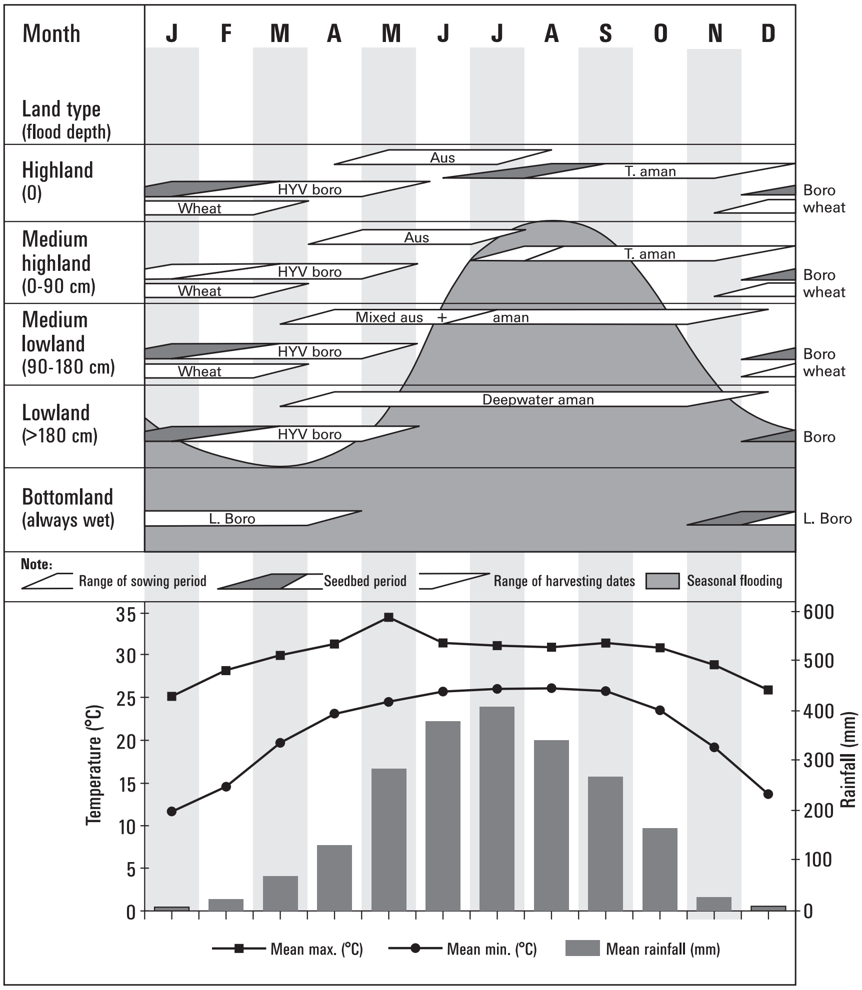


Figure 7.2 The rice and wheat crop calendar in relation to seasonal flooding, rainfall and temperature.
Source: After Brammer et al. (1993).
Notes: boro, aus and aman are rice varieties; HYV = high-yielding varieties.

Figure 7.2). There are several varieties of transplanted *aman*, which have different adaptive capacities to different water depths. *Aman* rice grows best on shallow flooded land. Seedlings are prepared in June–July and are transplanted in July on those fields that farmers do not expect to be flooded by more than 1–2 feet in the course of the monsoon season. As soon as the water starts receding, farmers start transplanting *aman* rice to low-level fields as well, and they continue to do so until the beginning of September. Transplanted *aman* is particularly vulnerable to abnormal flooding and, accordingly, farmers have developed special strategies to cope with such situations. If farmers foresee an abnormal flood or an untimely rise in the water level, they prepare extra seedlings on the higher-level fields. As soon as the flood water recedes, the farmers plant a second time on those plots on which the first planting has been destroyed by the flood. This discussion emphasizes the crucial importance of timely flood forecasting.

- Jute and sugarcane are also grown in the monsoon season. Both crops can stand for some days in water as long as the whole plant is not submerged. There are several varieties of jute and sugarcane adapted to different water depths. For the harvesting of jute, flood water is essential.
- In some areas there is a practice of intercropping *aus* rice and broadcast *aman* rice: ‘‘This measure ensured that at least flood-tolerant *aman* would be secured during an abnormal flood regime, even if flood-vulnerable *aus* were lost or damaged. During a normal flood regime both *aman* and *aus* would succeed, often resulting in a bumper crop’’ (Rasid and Mallik 1995: 11).

All these monsoon crops depend on flood water. Without floods there are crop failures and unfavourable conditions for the subsequent winter crop (Schmuck-Widmann 1996). Rasid and Paul (1987: 161) state that ‘‘agriculture in Bangladesh is both flood dependent and flood vulnerable’’. Traditional monsoon crops are neither high input oriented nor labour intensive. Since farmers usually cultivate lands located at different levels and since not all fields normally are equally affected by one specific flood event, farmers do not become despairing or demoralized in times of floods. They accept partial flood damage and subsequently make a special effort to grow winter crops, which have been becoming more and more important over recent years. Farmers often assert that even abnormal floods can have positive effects, particularly on the following winter crops: ‘‘Famine was predicted after the floods in 1987 and 1988; in fact, record crops followed, largely because the floods left behind moisture, fertile silt and algae’’ (Pearce 1991: 40).

7.4.3. Daily life

During a normal flood, daily life is also normal; people have adapted to it. This is very striking for an external observer. During abnormal floods, many houses will be inundated, but people do not leave their homes unless the flood becomes a real physical threat to their survival. It takes one to three days for the flood water to reach abnormal levels and so the families are not trapped. People wait and observe. If the water reaches the house floor, they construct a bamboo or wooden platform above the water level inside the house or raise their bed so that they can still sleep and put their essential household goods in a dry place (for details, see Schmuck-Widmann 1996). People usually anticipate the maximum limits of the abnormal floods and they prepare for emergency action during and after a big flood event.

Women's activities during an abnormal flood are clearly defined. They always keep a portable stove and firewood stocks for the wet season and they prepare dry food such as puffed rice with molasses. Anam (1999: 29–30) describes the specific roles and the courage of women as follows:

> Those working among flood victims come back with astounding stories of women's courage and strength. Even in these adverse circumstances, they are responsible for feeding and taking care of their children. Poor women who are already resource poor find themselves in a situation where even the means of producing food are not available. Yet they do not give up or abandon their young ones. They beg, borrow and stand in line for hours to get something for their children. Women are constantly trying to improvise and feed their families with whatever little relief they get, as usual eating last and the least.

For more information on the situation of women during abnormal floods, see also Nasreen (1999).

If abnormal flooding becomes a real threat and people are forced to leave their homes, the women and the children along with their cattle first take shelter on the road/embankment or in a relative's house, which might not be flooded. Some people remain in the house to guard the remaining household goods. As soon as the water recedes, which is usually after two to three days, all the family members return to their home and initiate the necessary repair work.

7.4.4. Transportation

Traditionally people have developed a large variety of small country boats for the flood season. Until recently, country boats were the only, easiest, most comfortable and cheapest means of transportation during flooding conditions. However, more and more roads of different types and sizes between cities, between villages or within villages are being constructed. These road embankments reach above the normal flood level and can, depending on their size, be used by cars, buses, rickshaws and bicycles and on foot. These roads significantly reduce the remoteness of the countryside during both the flood and the dry season and they make movement and transportation faster and more reliable. The people in the three test areas assured us that movement during the flood season is no longer a problem except in those areas located between the embankment and the river where roads have not yet been built.

During abnormal floods, the small earthen roads within and between the villages are usually inundated for a few days. In such periods, boats continue to be very useful. People also make rafts from banana trees to travel from their house to their neighbours or to the nearest main road. In such abnormal flooding situations, road embankments can also be breached, completely disrupting movement and transportation. In most cases, this happens as a result of inappropriate construction of the roads and bridges or insufficient consideration of the local hydrology.

For further references to flood adaptation strategies, see Ralph (1975), Alam and Chowdhury (1992) and Rasid and Shuncai (1998).

7.5. Lateral river erosion: From perception to survival strategies

As discussed in section 7.3.1, the people affected by lateral river erosion perceive it as a bigger problem than floods. The geomorphological processes leading to massive shifting of river courses are discussed in section 6.4.1. There are no precise estimates about the extent of the displacement of people as a result of river erosion. Haque (1997: 154) states that “the size of the population at risk to bank erosion has been estimated to be nearly one-fifth of the entire population of the country”. Hughes et al. (1994: 30) provide the following examples: “During November 1991, 4000 people were reported to have been displaced by erosion along the banks of the Brahmaputra and Padma. In January 1992, erosion along the Brahmaputra alone was reported to have uprooted 10,000 people; and during the period 1991–1992, 40,000 people were reported to have been forced to abandon their homes in Kurigram District (in the far north west of the country). Nearer to Dhaka, 30 villages were subject to severe erosion by the Padma River during June–August 1992, and nearly 30,000 households were displaced.” Erosion along the Ganga, which is a meandering river system, is more predictable than erosion along the Brahmaputra, which is a braided river system. Erosion is not limited to the flood season; it is a threat throughout the year.

7.5.1. *Perceptions and experiences*

Different stakeholders’ perceptions of lateral river erosion are documented in a number of selected quotes in Box 7.4. For the people living in the villages near the Brahmaputra, river erosion is a much greater

Box 7.4 Different stakeholders' perceptions and experiences of lateral river erosion

Affected people

1. "If the house is burnt, the plot is still there. If the house plot is eroded, we are like a floating object in the river."
2. "It took only one day to erode approximately 200 metres. My family didn't have time to shift the house and to take the rice from the fields with them. It was harvest time."
3. "The water sometimes goes crazy, there are strong waves against the river bank. We say that the 'water calls the person'. This means, if a person is on the river bank, the sounds of the river might call her. Or in other terms, she is in danger."
4. "Erosion goes on the whole year."
5. "The erosion became strong at 11 p.m. last night, until 4 a.m. this morning. Today it's less. Maybe tomorrow it will have increased again."
6. "30 years ago the river was far away."
7. "Erosion has developed fast in the last 20 years."
8. "If there is a *char* in the east, then the pressure of water hits in the west. If there are two *chars*, the pressure will be in the south."
9. "Lateral river erosion is more important than flooding."

Engineers

10. "It is obvious that, under these conditions, stabilization of the banks is highly desirable to protect the riverine population which, due to the population pressure of Bangladesh, is also continuously increasing, even in unsafe areas." (Brühl 1996)
11. "The total cost for the river bank protection component of the Jamuna Bridge is about US$290 million, amounting to approximately half of the total cost of the Jamuna Bridge." (Brühl 1996)

Journalists

12. "Erosion engulfing huge areas of land" (*Daily Star*)
13. "Jamuna erosion renders 2000 homeless, embankment threatened" (*Bangladesh Observer*)
14. "Jamuna erosion hits 2000" (*Daily Star*)
15. "Erosion renders thousands homeless in Kurigram, Bogra" (*Daily Star*)
16. "Hundreds of erosion-hit people in distress" (*Daily Star*)
17. "Erosion leaves 315 families homeless in 24 hours in Sirajgonj District" (*Daily Star*)

threat than floods. It is very common to be forced by the river to shift house 10–15 times in a lifetime (see also Elahi and Rogge 1990: 38), and every year several villages are washed away by the river.

Erosion can be called a silent disaster. As we have already stated above, floods may inundate cropland, submerge houses and cause suffering to the people. However, people's most valuable asset, the land, remains where it was. Lateral river erosion, in contrast, carries away this asset, leaving nothing behind for the farmers and day labourers who owned a small piece of land. Based on their practical experience, people have a very clear and differentiated understanding of the erosion processes, which is essential for them to be able to anticipate when a house will have to be moved. For engineers, river erosion is an important problem as well. To solve this problem, technical solutions are usually proposed, which are very costly and difficult to realize owing to the unstable ground, the dynamic natural environment, and the difficulty of obtaining solid building material. Only the Bangladesh national press reports river erosion as a major problem for the population concerned. For the international media, erosion is not spectacular enough to create headlines and therefore erosion hazards hardly get any attention outside Bangladesh.

7.5.2. Coping strategies

People living on *chars* (river islands), on riverbanks or nearby closely observe the dynamics of the river course. Should their house plot be threatened with imminent erosion, they are prepared to react fast and to move to another place with their household and livestock. Typical houses in these areas are constructed with a bamboo frame and reed mats or corrugated iron sheets and not with bricks as in other parts of the country situated far away from big rivers. The structure of these houses is secured by jute ropes and can be dismantled within one hour in an emergency.

Migration is usually the only option in the face of lateral river erosion. Migration strategies differ between the inhabitants of the *chars* and those living on the mainland. In the event of a forced move owing to erosion, people on the *char* migrate with their household and livestock to another place on the same *char* or to another *char* where new land is emerging. Only rarely do people migrate to the mainland, since no land is available there. People living on the mainland are less adapted to river erosion and have several migration options (Figure 7.3). Which option is actually selected and implemented greatly depends on the wealth of the migrants or on the situation of their relatives. In general, people try to stay as close as possible to their former settlement, because they feel tied to the land of their fathers and forefathers and because they want to maintain the social structures as long as possible. This finding is confirmed in Elahi and

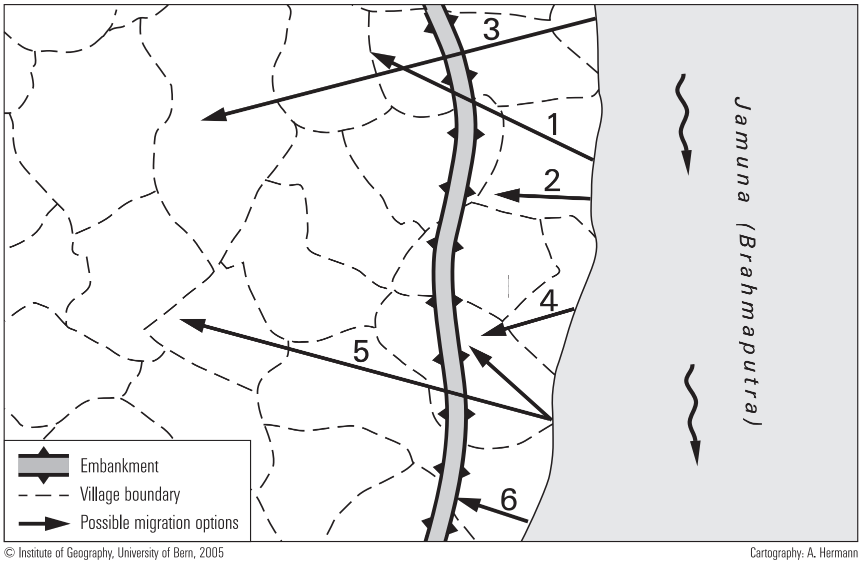


Figure 7.3 Simplified scheme of migration strategies of people affected by river erosion on the mainland (in decreasing order of priority).
Source: Fieldwork.
Notes: 1 = Shifting the house to another plot on one's own land behind the embankment; 2 = Shifting the house from one plot to another on one's own land in the village itself; 3 = Buying a plot and moving there; 4 = Leasing or renting a plot; 5 = Moving to the home of relatives; 6 = Taking shelter on the embankment.

Rogge (1990: 36). The hope that sedimentation will follow river erosion and restore the lost land is another reason for not moving far away. However, for many people affected by erosion it is not possible to stay in the vicinity of their original land. If there is no other solution, families sometimes move to other people's land (option 5 in Figure 7.3). However, in such conditions their social status is low and people generally try to avoid this situation. Another alternative is to move from the mainland onto a *char*, which again results in a lower social status. The last option exercised by people who are forced to migrate is to move to the embankment, which is government land where settlement is officially prohibited. Settlement on embankments can lead to a locally high population density. The main misfortunes of these new settlers are the limited space, their dependence on external earnings for their livelihood, and joblessness. In many cases, none of the options illustrated in Figure 7.3 is realistic and people have to move to the nearest town (e.g. Serajgonj; see Elahi and Rogge

1990) or even to the capital city of Dhaka. Alexander (1993: 534) writes: "It appears that one quarter of the residents of Dhaka were driven there by the effects of disaster." Currey (n.d.) makes a similar statement: "A quarter of the migration into Dhaka city, one of the fastest growing metropolises in the world, is caused by river erosion."

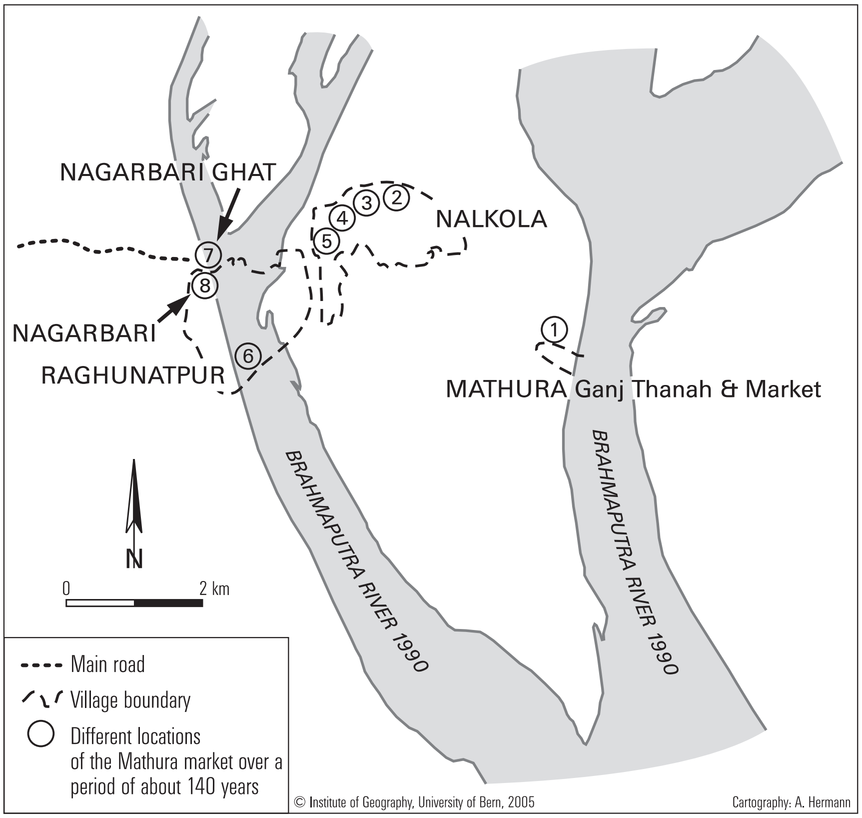
In spite of people's competent crisis management, migration as a result of river erosion can have far-reaching consequences. In the interviews, the affected people expressed a number of fears and sorrows. As mentioned above, the loss of land often leads to a lowering of social status. When people lose their property, their subsistence is endangered and staple foods need to be purchased. Landlessness creates difficulties when sons and daughters get married. The urgency to earn money results in children working and as a consequence education becomes more difficult. Other consequences are a high rate of unemployment and the splitting up of families. Hughes et al. (1994: 30) mention not only losses of personal assets as a result of river erosion, but also losses of infrastructure and facilities:

> Erosion can take place so rapidly and unexpectedly that the victims are unable to relocate even their movable assets and many become destitute overnight. Widely reported losses include facilities for health, education, and administration; shops, market places and factories; mosques and temples; roads, bridges and other infrastructure; and a wide range of other non-land assets. In the wake of these impacts follow a sequence of secondary social, economic and demographic effects which may be as devastating to those affected as the direct impacts of erosion.

Rahman (1991: 184) even states that famine conditions occur indirectly as a result of river erosion: "The number of land sales, assets sales, loss of employment, increased migration, malnutrition, begging and so on, are the inevitable outcomes, and these are but few symptoms of a famine condition."

The interviews provide clear evidence that women face specific problems in the event of landlessness caused by river erosion. If women can no longer avoid violating "purdah" (seclusion and protection against being seen by foreign men), the risk is that "the respectability of their household can suffer as a consequence of their 'visibility'" (Jansen 1990: 57). The generally low social status as a result of landlessness is particularly problematic for young women who are to be married.

Lateral river erosion affects not just individual households but important marketplaces too. For Bangladesh, waterways have always been and still are important trading routes. Accordingly, marketplaces on the riverside are regional and supra-regional economic centres of the country. The example of Nagarbari illustrates how traders have to adapt to shift-



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Cartography: A. Hermann

Figure 7.4 Dynamic geomorphological processes of the Brahmaputra: The shifting location of the Mathura marketplace since approximately 1850.

ing river courses and how the economic potential and growth of centres situated on the bank of big rivers are limited because lateral river erosion prohibits big investments. In Figure 7.4, the numbers 1 to 8 indicate the different locations of the Mathura marketplace (which is now called Nagarbari) since the middle of the nineteenth century. The first recorded site dates back to approximately 1850. Site 2 shows the position of the marketplace after a phase of intensive erosion between 1901 and 1925. Subsequently, until 1954, the river shifted westwards in small steps. After 1954 the Mathura market was again moved over a great distance, to Raghunatpur, and finally to its position in 1994 as a result of the continuous gradual westward shift of the Brahmaputra.

To conclude this section we give the floor to Sir William Willcocks, who wrote in 1928:

> It is a sickening sight going up and down the Ganga to see scores of miles of old trees and hamlets and beautiful gardens falling into the river and being engulfed. This is never seen on the Mississippi or the Nile today. It is a disgrace on the Ganga ... If action such as I have seen on the Ganga is not controlled immediately by training works, the Ganga will go out of hand and ravage the country. I have seen a hundred times more destruction on the Ganga than I have seen elsewhere in the whole of my life. Villages, fruit trees, gardens and rich crops and ancestral trees ... had fallen like ninepins into the tormented water. (Willcocks 1928)

For further reading on lateral river erosion and related themes, see Elahi and Rogge (1990), Elahi et al. (1991), Schmuck-Widmann (1996) and Haque (1997).

7.6. The engineering and political approach to flood control and flood protection: A brief historical account

Flood control, flood management and flood mitigation have been burning issues for discussion and action in Bangladesh for decades. There is a wide variety of opinions about how Bangladesh should cope with floods and, as has become evident from section 7.3, perceptions among the different stakeholders vary significantly. Whenever Bangladesh is hit by a severe flood event, discussions about possible measures and solutions intensify. Accordingly, the available literature on development approaches and priorities with regard to floods is vast and it would go beyond the scope of this publication to provide a detailed analysis of this discussion. In this section, we shall only briefly elaborate on how the thinking and approaches with regard to this complex topic have evolved over time and present the results from the project fieldwork. Wherever possible we shall refer to the relevant literature, which obviously can never be complete and exhaustive. A detailed and comprehensive account of the history of flood management approaches is provided by Adnan et al. (1992).

7.6.1. Approaches before 1989

In his pioneering work in the first part of the twentieth century, Mahalanobis (1927: 6–7) was already making clear statements about how to cope with big floods and about the effects of flood control embankments:

> [E]mbankments in the riparian tract may for a time prevent overflow from the rivers, but would tend to raise the bed of the rivers still further, and thus make the situation much worse in the long run. They are also of no use in the central area. It is therefore necessary to advise and educate the inhabitants to adapt their

life to the changing conditions: to build their houses on raised grounds, and to take other precautionary measures.

In 1957, 30 years after Mahalanobis, the report of a United Nations Technical Assistance Mission, headed by J. A. Krüg, was published for the government, which at that time was the government of Pakistan. This report noted:

> [T]he problem of controlling floods in East Pakistan is so difficult and available engineering data so meagre that no firm recommendation for solutions can be made at this stage. Opinions are divided on the merits of flood embankments and experience has varied; the effects differ in the long term from the short term. There are obvious benefits, but also some possible adverse effects and recurring liabilities. A careful study should be made before embankments are erected on a large scale, with or without flushing channels. Account should also be taken of other possible adverse effects, in particular the disturbance of the regime of rivers and its effects on navigation. Approximate estimates of cost would be needed, taking into account land rights, costs of relocating the affected population. But only after careful study should the decision be made whether or not to proceed with such projects. (Krüg et al. 1957: 26–29)

In December 1964, a Master Plan was prepared by the East Pakistan Water and Power Development Authority (EPWAPDA). The plan had a portfolio of 58 flood control and drainage (FCD) and/or irrigation projects consisting of thousands of miles of embankments, nearly a hundred polders, and innumerable sluices and other water control structures, covering most parts of the country. The implementation of the Master Plan was to be spread over a 20-year period, 1965–1985. One of the principal arguments in favour of the Master Plan was formulated as follows: "Completion of those Master Plan projects which include embankments will confine flood flows in the river channels and thus permit intensified cropping" (EPWAPDA 1964a: 1; 1964b: CIV-1). The implementation of the Master Plan and simultaneous attention to more integrated approaches after 1970 are described by Adnan et al. (1992: 39) as follows:

> During the 1970s and 1980s, priority was given to small-scale projects with irrigation components, compared to large-scale FCD projects. Interest in integrated management of surface and ground water led to the establishment of the MPO [Master Plan Organization] and the formulation of the National Water Plan under its auspices. These developments reflected the appearance of broader concerns beyond the earlier preoccupation with flood control and surface water alone. However, implementation of the remaining projects of the Master Plan also continued during this period. Interested donors continued to fund these structures. No fundamental rethinking of the Master Plan's strategy took place

> despite the shift from the Pakistani to the Bangladeshi state. This meant construction of further embankments, polders, etc., as envisaged in its original 20-year perspective. It is estimated that, by the end of the 1980s, the cumulative total amounted to at least 7,907 hydraulic structures and 7,555 kilometres of embankments, of these, 3,674 kilometres were coastal embankments and 3,881 kilometres were inland embankments (see also Khan 1991: 11). In addition, there were 1,082 river closures.

The available documents do not specify if the structures that were built represent a complete or only a partial implementation of the original Master Plan.

For further references on the history of the discussion about flood management and flood control before 1989, see also Abbas (1964), Santema (1964), Ministry of Flood Control and Water Resources (1972).

7.6.2. The Flood Action Plan (FAP), 1989–1995

Hughes et al. (1994: 40–42) provide an excellent summary of the origins and the components of the FAP:

> The severe floods of 1987 and 1988 stimulated international interest in flood control in Bangladesh. Joint studies were undertaken by the Government of Bangladesh with UNDP (UNDP/GOB 1989) and with French Engineers (French Engineering Consortium 1989), and separate studies were also carried out by USAID (Rogers et al. 1989) and the Japanese experts (Japanese Flood Control Experts 1989). Most of these studies were conducted by commercial consultants from both international and Bangladesh firms. The UNDP study recommended a National Flood Master Plan involving embankments along the major rivers and "controlled flooding" within large compartments (a compartment is a type of polder, bounded by embankments and divided into sub-compartments). The French study recommended an expensive and long-term programme which involved the construction of massive embankments along all the major rivers and channels, in combination with river training works. In contrast, the USAID-funded "Eastern Waters Study" concluded that the construction of extensive river embankments and other flood control infrastructure was unfeasible for both technical and economic reasons. The study also drew attention to the adverse environmental impacts that such a strategy might entail. Instead, it recommended efforts to reduce flood vulnerability, including the improvement of emergency planning and relief services, the flood proofing of towns and villages and improved data-sharing between co-riparian countries. Finally, the Japanese report cautioned against long and continuous river embankments without further studies for assessing their technical and economic viability. It recommended a staged programme of physical works including embankments in combination with existing or planned road embankments, and also the use of polders. Other non-structural measures such as flood forecasting and warning were also included.

Hughes et al. (1994: 40–42) continue as follows:

> In July 1989, major donors at the G-7 Summit (the group of seven most industrialized nations) called for "effective, coordinated action by the international community in support of the Government of Bangladesh in order to find solutions to this major [flood] problem which are technically, financially, economically and environmentally sound". The World Bank agreed to coordinate international efforts and subsequently chaired an international conference in London in December 1989 at which it presented the five year (1990–1995) Action Plan for Flood Control (World Bank 1989). The Plan was approved by the representatives of the Government of Bangladesh and donor agencies and this subsequently became known as the Flood Action Plan (FAP). The FAP represents an uneasy compromise between each of the four previous studies. On its launch in 1989, the Flood Action Plan consisted of 26 components, comprising of 11 main components and 15 supporting studies [see Box 7.5]. The status of the FAP components changed considerably between 1990 and 1993 and there have been some notable departures from the original Action Plan document formulated in 1989.

By the beginning of 1993, the number of components had grown to 33 (see Box 7.5).

The Flood Action Plan had triggered a marked controversy within Bangladesh as well as internationally about the feasibility of technical measures, the advantages and disadvantages of flood control embankments, and so on. To illustrate this debate, Box 7.6 lists some titles and key statements from the vast available literature both in favour of and against the FAP.

7.6.3. 1995 and beyond

The Flood Action Plan culminated in the Bangladesh Water and Flood Management Strategy Report prepared in 1995 (FPCO 1995). This report presents a strategic framework for the development and implementation of a national water management plan for Bangladesh. It builds on the extensive programme of work undertaken under the Flood Action Plan and the earlier National Water Plan. It recommends a five-year programme that involves the preparation of a national water management plan and the strengthening of water sector organizations responsible for the planning, construction, operation and maintenance, as well as the implementation of a compact portfolio of high-priority projects. The strategic framework is based on the Government of Bangladesh's water sector goals, on the examination of past experience as well as on a critical review of the issues and options for water resource development in the future.

The Bangladesh Water and Flood Management Strategy is evidence

Box 7.5 Status of the Flood Action Plan components as at March 1993

Main studies
1 Brahmaputra right embankment strengthening
2 North-west regional study
3 North-central regional study
  3.1 Jamalpur priority project
  3.2 Bhuapur–Gopalpur feasibility study
4 South-west area management study
5 South-east regional study
5B Meghna estuary study
6 North-east regional study
7 Cyclone protection project
8A Greater Dhaka protection project
8B Dhaka integrated town protection project
9A Six secondary towns protection projects
9B Meghna left bank protection project
10 Flood forecasting and early warning project
11 Disaster preparedness programme

Supporting studies
12 FCD/I agricultural review
13 Operation and maintenance study phase–1
14 Flood response study
15 Land acquisition and resettlement study
16 Environmental study
17 Fisheries study and pilot project
18 Topographic mapping
19 Geographical information system
20 Compartmentalization pilot project
21/22 Bank protection, river training and active flood plain management pilot project
23 Flood proofing pilot project
24 River survey programme
25 Flood modelling/management project
26 Institutional development programme

Others
Guidelines for project assessment
Macroeconomic study
Guidelines for people's participation

Source: Hughes et al. (1994).

Box 7.6 Titles and key statements of publications related to the Flood Action Plan

1. *State of the FAP – contradictions between policy objectives and plan implementation* (Adnan and Sufiyan 1993)
2. *Floods, people and the environment. Institutional aspects of flood protection programmes in Bangladesh, 1990* (Adnan 1991)
3. ‘‘Technical review of the Bangladesh Flood Action Plan’’ (Sklar and Dulu 1994)
4. ‘‘Flood Action Plan report achievements and outlook’’ (Smith 1994)
5. ‘‘Development possibilities in flood-prone areas, part III’’ (Brammer 1989)
6. ‘‘Living with floods in Bangladesh’’ (Shaw 1989)
7. ‘‘Conquering nature: Myth and reality of flood control in Bangladesh’’ (Alam 1990)
8. ‘‘The Flood Action Plan: A review’’ (Brammer and Jones 1992)
9. ‘‘Let the delta be a delta: An essay in dissent on the flood problem of Bangladesh’’ (Islam 1990)
10. ‘‘Birth of a megaproject: Political economy of flood control in Bangladesh’’ (Boyce 1990)
11. ‘‘An investment trap’’ – Aid agencies play a near-dictatorial role in Bangladesh’s water sector. Floodplains have become the grazing grounds for foreign experts. Implementation of the Flood Action Plan could wreak country-wide environmental devastation (Mirza 1992)
12. ‘‘Floods in Bangladesh – II. Flood mitigation and environmental aspects’’ (Brammer 1990b)
13. ‘‘Flood control in Bangladesh’’ (Bingham 1991)
14. ‘‘The rivers that won’t be tamed’’ – an ambitious scheme costing billions of dollars to protect the cities and plains of Bangladesh from floods could be a disaster in the making (Pearce 1991)
15. ‘‘Banking on a flood-free future? Flood mismanagement in Bangladesh’’ (Custers 1992)
16. ‘‘Flood action: An opportunity for Bangladesh’’ (James 1994)
17. ‘‘Environmental aspects of flood protection in Bangladesh’’ (Brammer 1995b)
18. ‘‘Can Bangladesh be protected from floods?’’ (Brammer 1996)
19. ‘‘The Flood Action Plan: A new initiative confronted with basic questions’’ (Wescoat 1992)
20. ‘‘The Flood Action Plan: A one-sided approach?’’ (Chowdhury 1992)

Box 7.6 (cont.)

21. "The Flood Action Plan: Social impacts in Bangladesh" (Parker 1992)
22. "Flood Action Plan: Some issues need attention" (Chowdhury 1991)
23. "Flood Action Plan: A view from abroad" (S. Rashid 1991)
24. "Bangladesh's Flood Action Plan: A critique" (Custers 1993)

that, during its five years of operations, the FAP evolved from its original focus on physical control interventions towards a more comprehensive approach. The following two quotations illustrate this fact. The first is from the Prime Minister, Khaleda Zia:

> The report on Water and Flood Management Strategy provides a sense of direction for the integrated development and management of this precious resource [water], keeping in view the needs of all with emphasis on poverty alleviation, environment and, above all, people's participation at all stages of development which has been the avowed policy of our government. Only this way, can development be pursued in harmony avoiding unfair competition and conflicts among various water users. (FPCO 1995)

The second is a quotation from the Minister of Water Resources:

> I am happy, the study wisely widened its horizon from the narrow focus on flood alone to year-round water management. The report sets the stage for high priority interventions and careful planning aimed at optimum utilization of every drop of our water resources to meet the needs of all combating subsectors. Beside its comprehensive nature the study emphasizes and introduces stakeholders' active participation which holds the key to success of all development efforts. (FPCO 1995)

According to the Water and Flood Management Strategy, there are three main water resources development options open to the Government of Bangladesh (FPCO 1995):

a) minimum intervention: strengthening the capacity for flood forecasting and disaster management, and improving the operation and maintenance of existing projects, but leaving water sector development to the private sector (e.g. minor irrigation and water supply);

b) selective intervention: in addition to a), protecting densely populated urban areas and key infrastructure from floods and erosion, ensuring water supply and providing flood proofing for vulnerable rural communities, possibly with development of water and flood management projects to enhance agriculture and fisheries; and
c) major intervention: in addition to a) and b), implementing large-scale measures such as embankments and river engineering works to prevent flooding and erosion by major rivers, and multi-purpose barrages on the main rivers.

Options a) and b) are both feasible and probably affordable in the short- to medium-term, though their successful implementation would require substantial institutional reform of planning and implementing agencies. Option c) may be a long-term possibility, if the macroeconomic, environmental and other issues could be satisfactorily addressed.

Today, the Water Resources Planning Organization (WARPO, the former Master Plan Organization) is the key institution dealing with the water sector in Bangladesh. In the National Water Policy (see Box 7.7), which was published in January 1999, a clear and revised role is established for WARPO as an apex planning body in the water sector. WARPO will also act as a secretariat to the executive committee to the National Water Resources Council, and is charged with acting as custodian of the National Water Resources Database and as a clearing-house for water sector projects (see also WARPO 1999). The objectives of WARPO are to upgrade the National Water Plan with an intersectoral focus and an interdisciplinary approach, particularly emphasizing environmental issues. One of its main mandates is to evolve national policies and strategies for the utilization and conservation of water resources (FPCO 1995).

This new way of thinking with regard to the water sector, which prioritizes holistic water management as well as interdisciplinary and participatory approaches, is very positive and promising. However, as soon as an extraordinary flood hits Bangladesh, such as the major event of 1998 (see section 5.11 and Appendix 5.8), old ideas of flood control with a focus on purely technical interventions are taken up again:

> Bangladesh will launch its largest-ever program to build dikes and dams to fight floods and cyclones that have devastated the nation, Prime Minister Sheikh Hasina Wajed said on Tuesday. Sheikh Hasina said the ambitious project would cost millions of dollars and that she was trying to gain assistance from the international community. We are trying to get foreign aid to dredge our rivers so that the next time the floods come, our people will not be hit ... We plan to change habitation in a way that they are flood proof. We plan to do it in a massive way. (*Mainichi Daily News*, Tokyo, 16 September 1998; quoted in GOB 1998: 53)

Box 7.7 Foreword to the National Water Policy by the Prime Minister, Government of the People's Republic of Bangladesh

"The declaration of a National Water Policy is a bold step towards good governance in Bangladesh. In the absence of such policy, much damage has already been done to the bio-diversity and environment of the country. Many adverse and counter-productive situations have been created due to lack of coordination in development programmes and use of water resources. For a water-dependent country like Bangladesh, this situation is highly detrimental to its overall development and this needs to be remedied urgently.

"The National Water Policy seeks a remedy to this chaotic situation bringing order and discipline in the exploration, management and use of water resources in Bangladesh. It clearly and unequivocally declares the intention of the government that 'all necessary means and measures will be taken to manage the water resources of the country in a comprehensive, integrated and equitable manner'. It sets out the objectives of such a policy and provides the broad guidelines for achieving those objectives. The policy has successfully integrated internationally accepted water management principles, norms and standards, with the demanding social and economic needs of a developing country. The true strength of this policy, however, emanates from its decentralised and democratic nature that gives every user the opportunity to vote for the use and sharing of water in an efficient, equitable and environmentally sustainable manner.

"The publication of this Policy is only the beginning of a long process of water resources management in the country. Attaining the objectives of the policy would depend largely on quick follow-up action and concerted effort by all concerned agencies and the people in general. I call upon all concerned to implement this Policy in right earnest. I hope the National Water Council will oversee its implementation with diligence and determination."

Source: GOB (1999).

7.7. The approach of the rural population to flood control and flood protection

As discussed in section 7.2, the existence of flood control embankments was one criterion for the selection of the test areas in which the project fieldwork was implemented. Accordingly, people's experiences of existing flood control structures were an important element in the fieldwork.

A clear distinction has to be made between those interviews carried out in "protected areas" located behind the embankment and those carried out in "unprotected areas" located between the embankment and the river. The following discussion is again based on a report edited by project team member Talim Hossain (Hossain 1997).

Flood control embankments were built with the aim of protecting land from river floods and facilitating intensive cultivation during the flood season. The embankments in the test areas of Bhuanpur and Serajgonj (Figure 7.1) were completed before the independence of Bangladesh; those in the test area of Nagarbari were built after the war of independence of 1971. The people in all three test areas therefore had at least 25 years of experience with flood control embankments at the time of the fieldwork. The people who are affected by and at the same time benefit from both the floods and the embankments are probably the best judges in the debate about the advantages and disadvantages of embankments in their areas.

A number of positive aspects of embankments were mentioned during the interviews. As already discussed in section 7.5, lateral river erosion makes hundreds of people homeless and landless every year. In most cases these people do not have any other choices than to seek temporary shelter on the embankments until the flood recedes. In such situations the embankments play a critical role for the people living close to the river. In Serajgonj, where the erosion was particularly severe, a lot of people were living on the embankments at the time of the field investigations.

Roads are very important all the year round, but particularly during the monsoon season. All the flood control embankments in the three test areas provide for convenient movement, transportation and trade. The northern part of the embankment in the test area of Bhuanpur is paved with bricks and there is a public bus service. Even during abnormal floods, these embankments are not submerged and access from the villages to the marketplaces and the trade centres is ensured. Accordingly, people living near the embankments do not feel isolated and have access to basic requirements.

To some extent, embankments may provide flood protection. During normal floods, the water depth in the areas behind the embankments has decreased. Many of the previously deeply flooded areas are now flooded by shallow water, and areas previously flooded by shallow waters are no longer flooded every year. The decrease in the depth of flooding resulted in the introduction of transplanted *aman* rice, which is more productive. However, particularly in the Bhuanpur and Serajgonj areas, the transplanted *aman* crop suffers serious damage during abnormal floods, which cannot be prevented by the embankments if they are partially breached. In the test area of Nagarbari, the embankments usually are not breached. However, although the flood water has decreased in depth, it is still too deep for the introduction of transplanted *aman* paddy in the flood season. There are many low-lying areas that remain waterlogged for most of the year and where the cropping pattern is still traditional. Because the embankments are not breached and the early arrival of water can be regulated with a sluice gate, the traditional deepwater *aman* rice is never affected by the floods. The breaching of embankments further upstream does not affect this area. Even in the severe flood of 1988, the deepwater *aman* paddy was only partially affected.

During the fieldwork, the interviewees also expressed some concerns about embankments. Breaching and erosion of the embankment are among the main preoccupations. During almost all abnormal floods, some parts of the embankments in the test areas of Serajgonj and Bhuanpur are breached. As a result, there is a sudden onrush of water, for which people are not prepared and which causes widespread damage to crops and houses. The strong current on both sides of the embankment at the breaching points is particularly damaging. Because of the existence of the embankments, the people have a false feeling of security. As discussed above, people have introduced transplanted *aman* rice in the areas where the flood depth has decreased as a result of the embankment. However, once the embankment is breached, this crop is almost completely destroyed. Also, because of the reduced average flood level since the construction of the embankments, house platforms are normally kept lower than before. Obviously, these houses are flooded if the embankments are breached. A sudden onrush of water will also disrupt minor roads through the villages and destroy bridges and culverts. Because people are not prepared for this unexpected onrush, the losses are much higher than they would have been in an abnormal flood situation without embankments. Embankments are breached not only as a result of abnormal flooding but also as a result of lateral river erosion, which can occur at any time of the year. Over the past 20 years, embankments have had to be removed and rebuilt several times and in many places as a result of shifting river courses.

People who live in the villages situated between the river and the embankment, i.e. in the unprotected areas, are now suffering more from floods through faster-rising and higher water levels. They state that losses during abnormal floods are bigger than they used to be before the construction of the embankments. Because of the embankments, the total discharge is confined to the river bed and water can no longer spread out laterally on both sides of the river. This inevitably results in higher water levels in the unprotected areas. House platforms, which were adapted to the normal water level before the construction of embankments, have to be further elevated, which often is too costly. The cropping patterns in these areas remain traditional and people do not know of any suitable crops that are adapted to these new flooding conditions. Even during normal floods, the water level sometimes rises more rapidly than before the construction of the embankments, and faster than the traditional deepwater *aman* paddy is able to grow. At the beginning of the flood season, the rise in water level occurs earlier and quicker than previously. As a result, *aus* paddy very often has to be harvested before it is mature and deepwater *aman* paddy is still too young to grow with the rising water level. The people in the unprotected areas and on the *chars* feel isolated and blame the government for neglecting them.

In general, people do not want the normal floods to disappear because they are essential to the crops. As already mentioned above, embankments generally reduce the flood level in the areas ''protected'' by them. Many agricultural fields that were characterized by shallow flood levels and by the cultivation of transplanted *aman* rice before the construction of the embankments are no longer flooded. Today, these fields need artificial irrigation and extra fertilizer to achieve the same yields, which is very expensive for poor farmers. In addition, there is less moisture available for the very important dry season *boro* paddy, which grows well in fields that are flooded during the monsoon season. In this context, Alam and Chowdhury (1992: 37) make an interesting observation based on fieldwork carried out on the eastern side of the Meghna River close to the confluence with the Padma: ''construction of embankment has stopped normal inundation at Chandraikandi and Nischintapur since 1986 forcing the farmers to use heavy chemical fertilisers.'' In the Bhuanpur and Serajgonj test areas, the owners of land that is no longer flooded have in general a negative attitude towards embankments.

Flood water carries a significant amount of alluvial silt, which is deposited on the land and regenerates the soil. For the past 10–15 years, IRRI (International Rice Research Institute) paddy, which is a high-yielding variety, has been cultivated in the dry season. This paddy needs a significant amount of fertilizer and irrigation. The farmers generally believe that the use of chemical fertilizer gradually destroys natural soil fertility. However, flood water neutralizes the soil, washes away the negative effects of fertilizer over-dose and regenerates the soil. Accordingly, those fields that are flooded every year by normal floods are considered the best fields for IRRI paddy cultivation. If the fields are no longer flooded during the monsoon season as a result of the embankments, the farmers need to increase their fertilizer input in order to produce the same amount of crops, and irrigation becomes more difficult. The natural regeneration of the soils through flood water does not take place any more. The farmers are seriously concerned about this and fear that in a few years there will be no more harvests. All these arguments and the farmers' distrust raise the question of whether these observations are really true or whether other factors are contributing to these negative perceptions, such as growing population and food insecurity, but also the introduction of high-yielding rice varieties or the increased need for irrigation, with all its financial and social consequences.

Yet another element emerged from the fieldwork in the three test areas. Over the past few decades, many highways, small roads and slightly raised tracks have been built through the villages located behind the main embankments. These road and track embankments do not have sufficient bridges and culverts. As a result, water from abnormal floods that enters these areas cannot drain away fast enough, producing local flooding and crop damage. Local people claim that, previously, water did not stay as long as today during an abnormal flood event. Even heavy rainfall causes waterlogging in the plots between the various tracks and affects crops.

8

Conclusions

This concluding chapter summarizes the project results according to the main elements of the book title as well as in the context of their practical implications in terms of approaches and solutions. This chapter also puts the project findings into the larger context by providing insights into the discussions related to flood events in other big river systems such as the Yangtze, the Rhine and the Mississippi. The chapter concludes with a final outlook.

8.1. The history of floods in Bangladesh

The Ganga–Brahmaputra basin is a huge highland–lowland system in which massive tectonic movements, large floods, shifting river systems and delta formation processes have occurred since far back in geological history and continue to occur. Natural processes such as global climate and sea-level changes, regional tectonic movements, earthquakes and subsidence in the delta have dominated the shaping of flood history. The large depositions in the Bangladesh delta indicate that massive floods must have occurred regularly long before humans' impact in the large watersheds of the big rivers started.

For the period since 1890 there is no statistical evidence that the frequency of major floods in Bangladesh has increased. However, there is some evidence that the inter-annual variation in flood dimensions, particularly the areal extent of big floods, has been increasing since 1950. Interestingly, this tendency has occurred alongside a general trend towards increasing monsoonal rainfall, inter-annual rainfall variability (see also Palmer and Räisänen 2002), monsoonal discharge of the investigated rivers as well as inter-annual variability of the daily peak flows of the big rivers. These trends are particularly in evidence in the Brahmaputra–Meghna system. Our investigation of the available time series of suspended sediments in the Ganga, Brahmaputra and Meghna does not indicate any trend towards increased sediment load. The sediment concentration is highly variable over time and is not well correlated to the amount of river flow. It is interesting to note that, whereas the dimension of the big floods in Bangladesh seems to be increasing, the forest situation at least in parts of the Himalayas is improving.

In the discussions about the history and causes of floods there is more and more evidence that human influences within the lowlands significantly contribute to the increasing dimension of flooding and flood damage. The construction of lateral river embankments or the cutting off of feeder channels isolate the large river systems from open water bodies and swamps that were natural storage areas for surplus water but are gradually being converted into agricultural land. According to Khan et al. (1994: 48), in the Ganga–Brahmaputra floodplain alone approximately 2.1 million hectares of wetlands have been lost to flood control, drainage and irrigation development. Hughes et al. (1994: 19) state that "the floodplains are losing their most skilled environmental managers". With this interruption of the connection between the rivers and their natural water storage areas, water masses accumulate within the river bed much more than before the construction of the embankments, and they move downstream in the confined and narrow river bed until a point where the water overflows the embankments or breaches them and may cause a catastrophic flood. Road and railway embankments within the floodplains, which often are built across drainage channels without sufficient sluices, lead to reduced discharge of rainwater and accordingly to increased waterlogging and flooding. In this overall context of floodplain management, we need to mention the still rather controversial approach of compartmentalization, which would allow for controlled flooding, water storage and drainage (see also section 8.7).

8.2. The dynamics of floods in Bangladesh

The complexity of the processes leading to large-scale floods in Bangladesh as well as of the flooding patterns themselves is striking. The project results have shown that Bangladesh floods are generated by a combination of a large variety of factors. This complexity has a regional dimension (for example, the large-scale circulation, the flood-relevant subcatchments and their characteristics within the Ganga–Brahmaputra–Meghna basin), a temporal dimension (for example, the chronology of a specific flood and the factors influencing it) and a process-oriented dimension (for example, the patterns of rainfall, the patterns of discharge and the combination of various factors). In view of this complexity, it is evident that each flood event is an individual combination of regional, temporal and process-oriented factors. ‘‘A key feature of flooding in Bangladesh is that each flood is different. There are a number of reasons for this’’ (Hughes et al. 1994: 21). However, analysis of the case studies in the context of the project has shown that, in spite of the complexity of flood processes and the specificity of each flood, it is possible to find commonalities, similar factors or repeating combinations of parameters that distinguish ‘‘flood years’’ (>30 per cent of the country flooded) from ‘‘average flood years’’ (10–30 per cent of the country flooded) or ‘‘dry years’’ (<10 per cent of the country flooded; see also section 5.1). In the following discussion we reflect on some of these elements.

8.2.1. The regional dimension

Large-scale circulation

La Niña conditions with a positive Southern Oscillation Index seem to favour the development of widespread flooding in Bangladesh. The extraordinary flood of 1998 is a prominent example of this situation (see section 5.11 and Appendix 5.8). The strength of the monsoon trough and the position of its axis over the Indian subcontinent also significantly influence the flooding conditions in Bangladesh (see section 5.15). If the trough is very strong and located over the north of India (in the foothills of the Himalayas) and Bangladesh, heavy rainfall occurs in Bangladesh and Assam and the likelihood of flooding increases. If the axis of the monsoon trough lies more to the south (over the central parts of India), rainfall occurs over large parts of India, but not over Bangladesh and the likelihood of floods is very small. The storm trajectories of the monsoon depressions lead to a west–east differentiation of monsoon rainfall and flooding: dry years in the Ganga basin tend to be humid years in the Brahmaputra and Meghna catchments, and vice versa. As a consequence, major flood years in Bangladesh are normally also important flood years in the Brahmaputra Valley of Assam (see, for example, 1987 and 1988). In contrast, the dimension of flooding in the Indian Ganga Plain usually differs significantly from the flood dimension in Bangladesh (see, for example, 1978).

Flood-affected areas

The large depression to the south of the Meghalaya Hills in the Meghna catchment is the area with the most regular annual occurrence of floods.

Interestingly, the coastal areas of Bangladesh are almost never affected by monsoon floods. A particularly important region for the development of floods seems to be the area of confluence of the Ganga and the Brahmaputra. Whereas in the eighteenth and nineteenth centuries the western part of Bangladesh was frequently affected by floods, in the twentieth century these areas were almost never inundated during the major flood events. This shift in the flood-affected areas over time may be attributed to river course changes, and thus to natural phenomena (see also Figure 4.5).

8.2.2. The temporal dimension: The timing of the floods

August seems to be the most important flood month. As a result of a gradual accumulation of water in the different water bodies, a high groundwater table and soil saturation in the course of the monsoon season, the situation becomes particularly severe if flood-triggering hydro-meteorological conditions develop after mid-August.

8.2.3. The process-oriented dimension

Rainfall patterns

Intense precipitation within Bangladesh just before and during the flood event is a key factor in the development of large inundations. In general, the rainy periods in Bangladesh during flood years are more numerous and of longer duration than the rainy periods in dry years.

Discharge patterns

The temporal synchronization of the peak discharges of the three main rivers, which occurred for example in the flood years of 1987, 1988 and 1998, seems to be a crucial factor in the development of large-scale flooding. The combination of high "base flow" and short-term discharge peaks of the big rivers is important for flood processes as well. The base flow is the result of the large-scale hydro-meteorological conditions in the respective basin and is mainly imported into Bangladesh. The short-term peaks are often the result of rather localized precipitation events.

The Ganga, Brahmaputra and Meghna basins in comparison

There is no doubt that the Brahmaputra River is very important in the formation or even triggering of large floods. The Ganga on its own does not seem to be able to trigger major flooding in Bangladesh, but becomes important if its flood flow synchronizes with the peak discharge of the Brahmaputra. In purely quantitative terms, the Meghna cannot compete with the Ganga and the Brahmaputra. However, there are several reasons to assign particular importance to this river system: the rainfall in the headwater regions of the Meghna (Meghalaya Hills) is extraordinary and the amount of water that accumulates in the Meghna floodplains is outstanding. In addition, the anomalies in potential runoff (R(pot)) in the Meghalaya Hills are systematically and strikingly well correlated with the flood dimension in Bangladesh. Finally, it seems quite certain that the Meghna backs up the joint Ganga–Brahmaputra flow at the point of its confluence, which exacerbates the flood situation further upstream.

The combination of factors

The following combination of factors seems to be particularly important in the development of large-scale flooding: synchronization of the peak discharge of the three main rivers, the resulting backwater effects in their confluence area, heavy rainfall in Bangladesh, a high groundwater table, soil saturation and waterlogging. The combined effect of all these factors might be reinforced by spring tides.

8.3. Rethinking the role of the Himalayas

The case-study investigations (sections 5.4–5.14 and Appendices 5.1–5.11) have shown that hydro-meteorological patterns in the Himalayas do not in most cases have any effect on the flood processes in Bangladesh. The chain of processes in a highland–lowland context can be characterized as follows. A major rainfall event in the first Himalayan ranges or in the adjacent foothills immediately triggers flooding in the hills themselves and in their forelands. With increasing distance from the Himalayan foothills and with increasing catchment size, the discharge peaks are levelled out and transformed into a high "base flow". The flooding begins to disappear unless the river flows through another area of heavy precipitation or joins another river with high flow (as happened in 1978 in the Indian Ganga system). Down in Bangladesh, the original flood wave is evident, if at all, in the magnitude of the base flow of the Ganga or the Brahmaputra entering Bangladesh. An additional argument is the fact that the potential runoff (R(pot)) in Nepal and in the Darjiling–Bhutan Himalayas tends to be below average during major flood years in Bangladesh. This finding is supported by the analysis of satellite images carried out for the main flood periods in 1987 and 1988: cloud coverage was very high over Bangladesh itself, over Assam and over the Meghalaya Hills, whereas there were hardly any rain-producing clouds over the relevant parts of the Himalayas. All these elements provide strong arguments in favour of rethinking the role of the Himalayas in the generation of large floods in the lowlands and against the common myth that the inhabitants of the Himalayas are to blame for the flooding in the Indian Plains and in Bangladesh.

The research on the flooding processes in Bangladesh clearly supports the scale concept related to highland–lowland interactions proposed in Lauterburg (1985) as well as in Ives and Messerli (1989): at the ‘‘microscale’’ (small watersheds) in the Himalayas, the effects of human interventions can be directly documented (e.g. through soil erosion, mass movements, higher sediment load and discharge peaks); at the ‘‘large scale’’ (the Ganga–Brahmaputra–Meghna basin in Bangladesh), however, natural processes are so dominant that the impacts of human activities in the Himalayas are not identifiable or measurable. Applied to the context of the Bangladesh flood project, this scale concept suggests that, in small- and medium-scale river systems in the Himalayan foothills or in the immediate forelands of the Meghalaya Hills, there are obvious links between highlands and lowlands. In the case of large-scale floods in Bangladesh, the issue is much more complex. There is no doubt that the Himalayas strongly influence the monsoon circulation and the trajectories of monsoon depressions. In addition, the Himalayan ranges trigger orographic precipitation and contribute high base flows to the hydrological system. However, the connection between highlands and lowlands is much less direct and obvious than at the small scale, and in particular the impact of human interventions cannot be shown at the large scale. Research efforts in the Himalayan highlands and within the lowlands of Bangladesh, both focused on the questions of ‘‘highland–lowland linkages’’ within the Ganga–Brahmaputra–Meghna system, have reached the same conclusions.

This call for rethinking the role of the Himalayas obviously has significant political implications as well as implications for traditional watershed and floodplain management approaches (see also FAO/CIFOR 2005). It also indicates that, although integrated watershed management projects in the Himalayas are very important for the Himalayan ecosystems themselves, they should not be initiated with the objective of reducing the dimension or the effects of large floods in the vast floodplains of the Ganga and Brahmaputra in India and Bangladesh.

8.4. Natural disasters and their impacts – A brief comparison

There are four main types of natural disasters in Bangladesh: floods, lateral erosion, cyclones and earthquakes. A country-wide survey and comparison are essential in order to prioritize political and scientific decisions and responsibilities. We initiated the project with the notion and "Western" perception that monsoon floods are the most serious and important hazard in Bangladesh. Mainly through the work with the farmers in the test areas of the project, we gradually got a more differentiated picture and the priorities regarding natural hazards began to shift. A more systematic search for information revealed that the different types of hazard had the following effects on people in Bangladesh over the recent past:

- Deaths during the most dramatic floods in the twentieth century – 1987: 2,055; 1988: 2,379; 1998: 1,000–1,500 (USAID 1990; for 1998 see Table 5A.6 in Appendix 5.8).
- People made homeless by lateral river erosion – November 1991: 4,000 along the Jamuna and Padma; January 1992: 10,000 along the Jamuna; 1991–1992: 40,000 in Kurigram District; June–August 1992: 30,000 along the Padma near Dhaka (Hughes et al. 1994).
- Deaths owing to major cyclones – 1822: 40,000; 1876: 100,000; 1897: 175,000; 1970: 300,000; 1991: 138,868 (Talukder et al. 1992).

Looking at these figures it is very clear that it is not the monsoon floods but the cyclones that have the most dramatic consequences. The number of deaths during monsoon floods, even during extreme events, is comparatively small. River erosion, which can be a year-round hazard, poses serious risks as well, not in terms of deaths but in terms of the number of people impoverished and made landless. Based on this comparison, the following (revised) prioritization of hazard management and mitigation can be made:

1. cyclones: early warning, shelters, protection of mangrove belts;
2. erosion: support for affected people, adapted technical measures for erosion protection in key locations (protection of cities, of traffic routes and power lines, of infrastructure with high value and strategic importance) – effective protection against river erosion in rural areas is almost impossible because of the high costs;
3. floods: support for indigenous strategies of flood management (particularly in rural areas), communication and early warning, adapted technical measures for flood protection in key locations (protection of cities, of traffic routes and power lines, of infrastructure with high value and strategic importance).

Overall, economic development, new job opportunities and family planning are important long-term development strategies to deal with the impacts of the different types of natural hazard. Finally we should not forget that poverty too is a disaster. "Floodplain management refers to all actions society can take to responsibly, sustainably and equitably manage the areas where floods occur and which serve to meet different social, economic, natural resource and ecological needs" (MRC 2001).

8.5. Different perceptions, integrated approaches and common solutions

In the project we identified a wide range of perceptions among farmers, engineers, politicians and journalists regarding floods, erosion and development priorities:

- Floods are part of farmers' daily life. River erosion is considered to be a bigger problem than floods. During abnormal floods life is hard but, after the water has receded, the land becomes available again. River shifting and lateral erosion, in contrast, destroy the livelihood of the whole family.
- For engineers, flooding is a problem that needs to be resolved, mainly with technical measures.
- For politicians, flooding is a major international problem that can attract considerable foreign investment. Many politicians still believe that the main causes of the floods lie outside Bangladesh.
- For journalists (mainly from the West), floods provide substance for catchy headlines, whereas river erosion is not spectacular enough to be reported on.

These divergent opinions often lead to disputes between engineers, environmentalists, scientists and politicians. James (1998: 25) states: "Within Bangladesh, the problems are exacerbated by 'top down' management that neglects the poor. Internationally, they are exacerbated by nonproductive debate between engineers who favor embankments and environmentalists who prefer natural conditions. All forms of confrontation just add obstacles to getting the best experts to work." The decision-making on development priorities has to be collaborative and participatory; each stakeholder should be given the chance to take responsibility – local people with their experiences and priorities, scientists with basic information and knowledge, engineers with concepts and designs, politicians with the provision of institutional frameworks, and the media ensuring dissemination of appropriate and correct information. It is very encouraging that the collaborative approach is an important element in the current National Water Policy of Bangladesh (see Box 7.7).

Decision-making on development priorities also has to be based on the principles of integration: only integrated approaches and management strategies can take the complexity of flood processes in Bangladesh sufficiently into consideration and will lead to adapted and adaptable flood management. Different measures have to be carried out simultaneously and in combination: implementing technical interventions, where appropriate; supporting and refining traditional strategies and approaches, for example elevating house platforms; including natural storage areas such as swamps and wetlands as a recognized land-use category in development plans; improving the traffic system, for example the traffic routes on embankments; establishing flood-proof centres with food, drinking water and medicaments; promoting economic development through the creation of jobs in order to make people less dependent on scarce land resources; and so on. In this context, Nasreen (1999: 35) firmly states that "any step in flood management should incorporate the indigenous methods used by rural poor as a way of improving their chances of survival". Understanding the complexity of flood processes has to be improved, because there is considerable potential for flood forecasting, early warning and precautionary measures (based on information about danger levels, rainfall intensities and frequency, groundwater, tides, etc.). The World Commission on Dams (WCD 2000) categorizes the components of an integrated approach to floodplain management as follows: those that reduce the scale of floods, those that isolate the threats of floods, and those that increase people's capacity to cope with floods.

8.6. A short comparison with recent processes in three floodplains of three continents

In the recent past, severe inundations have occurred in the floodplains of several big rivers around the world, such as the Mississippi flood of 1993, the Rhine floods of 1993 and 1995, and the Yangtze floods of 1998. In the aftermath of all these events, the question of causes was intensively discussed. A short summary may be of interest in connection with our conclusions.

The Mississippi flood of 1993

The Mississippi flood of 1993 was undoubtedly the greatest hydrological event of the century in North America (Bhowmik and Demissie 1994; Rasmussen 1994) – 420 counties were flooded and the cost of the damage was estimated at around US$20 billion. Most of the levees along the Mississippi and Missouri rivers were either breached or overtopped and millions of acres of fertile floodplain croplands were inundated. Interstate highways and bridges were impassable throughout the region. Record-breaking precipitation over a region that was fully saturated from a wet spring resulted in rapid and repetitive rising flood levels over a six-month summer period. Most hydraulic structures along the major rivers were not designed for a flood of such magnitude and duration. The Great Flood brought many water resources issues to the forefront of discussions and resulted in great debates – even at a national level – about river and floodplain management, disaster assistance, the impact of land-use changes, the impact of flood control structures and the role of state and federal agencies. The most important message from the Interagency Floodplain Management Review Committee was that floodplain management in the United States needed to change significantly. Some very interesting specific statements resulted from the debate around the great Mississippi flood:

- There is an indication that the 1993 flood was caused by nature (extreme and persistent precipitation and discharge conditions) and hardly influenced by human intervention within the basin (i.e. land-use and agricultural practices).
- Reforestation in Wisconsin appears to have a mild impact on the average flow in the Mississippi River.
- Reservoirs reduce downstream flood threats.
- It is debatable whether upland watershed treatment and restoration of wetlands would have significantly altered conditions in 1993.

Not only are some of these conclusions very similar to our results from the Bangladesh flood project, but the Mississippi flood led to some overarching and pertinent questions that are close to those raised in other river basins of the world, including the Yangtze and the Ganga–Brahmaputra floodplain:

- Are flood control structures the best way to manage extreme events?
- What are the criteria for disentangling natural and human-induced impacts on flood processes?
- What is the responsibility of government agencies?
- How good is scientific know-how in predicting floods?

The Rhine floods of 1993 and 1995

The Rhine is one of the major rivers of Europe (Dombrowsky and Ohlendieck 1998; Eikenberg 1998). With a total length of about 1,320 km, it serves as an artery for water supply and transport, for sewerage and drainage, and for settlement and urbanization from the Alps to the North Sea, covering approximately 185,000 km^2. The severe floods of 1993 and 1995 primarily hit the areas of Koblenz at the confluence of the Moselle and the Rhine, and Cologne downstream from the incoming Sieg. The melt water or drainage from the Alpine Rhine did not cause the 1993 and 1995 floods – both floods were fed by drainage from the middle mountains along the Rhine.

Some very interesting and specific statements and arguments resulted from the debate about the Rhine floods:

- The fact that the causes and consequences of floods often go beyond domestic and international borders makes national and international cooperation essential.
- An increasing number of experts point out that environmentally ac-

ceptable and technically sound flood protection has political and financial limits and that people must accept the fact that they will have to live with flood risks in the future.

- The scarcity of available space in the river valleys has resulted in the increasing loss of water retention areas, especially around the embankments. In recent decades, communities have frequently used retention areas for developing industry, business and housing. This has diminished the potential of retention areas to reduce the impact of riverine floods.
- The argument about natural or human-induced causes has been very controversial. Politicians favoured the argument that there is no clear evidence for human-induced effects. Scientists find it rather difficult to come up with solid proof, since they have focused on the creation of new and more complex models for understanding the global climate and its regional effects. The media discovered ecological disasters as a favourite topic, and rather tended to follow the argumentation of the more critical scientists and environmentalists who clearly defined the human factors as being the most responsible for the floods.

The Yangtze floods of 1998

The Yangtze has a total length of 6,300 km, its source is on the Qinghai Plateau at 5,400 metres above sea level, and the entire catchment covers an area of 1.8 million km^2. The river has two completely different sections. For 4,500 km, until the Three Gorges, it is a relatively small mountain river with a strong current and with annual precipitation of some 100 mm in the upper catchment. Then it changes abruptly: for the remaining 1,800 km the difference in elevation is only 50 metres, the river meanders through an alluvial plain of 250,000 km^2 and precipitation increases to 1,800 mm. Accordingly, more than 50 per cent of the average annual flow of the Yangtze is fed into the river system in the lower part of the catchment.

During the 1998 monsoon, the Yangtze basin experienced extraordinary rainfall. In June, July and August, precipitation was well above the average for the period 1961–1990, some stations receiving the highest rainfall ever recorded. As a result, widespread flooding occurred along the Yangtze in the lower part of the basin. As a reaction to the flood, the government declared a logging ban in the upper parts of the basin in order to reduce the dimension of future floods. However, the appropriateness of this drastic measure is doubtful. Sauer (1999: 341 and 345) states: "contrary to the conventional wisdom, deforestation in the upper reaches had no influence on the flooding. If it is true that a natural and intact forest is able to absorb 300 m^3/ha of water, this corresponds to only 30 mm of precipitation. During the monsoon season of 1998, daily precipitation of 40–140 mm was recorded and the monthly rainfall reached 800 mm.''

In terms of the floodplains, owing to encroachment by agriculture, the storage capacity of natural lakes has dropped by two-thirds over the past 30 years. The central government has decided to return the lakes and river beds to their natural situation. However, we have to bear in mind that it is almost impossible to restore farmland to its natural state on a large scale. This would necessitate the resettlement of millions of farmers, who traditionally have strong ties to their land. This is evident in the fact that they immediately rebuilt their homes after the floods.

This short discussion of three different floodplains in three different continents evidences a lot of interesting and instructive natural similarities, whereas the history of human activities in these particular floodplains has been and will continue to be very different.

8.7. A brief outlook: Research, development and cooperation

In the early to mid twentieth century, engineers debated ''flood control'' and identified the construction of dams, embankments and levees and the dredging, straightening and deepening of stream channels as the necessary measures. However, as early as 1923, in a report on investigations of floods, the Bengal Flood Committee had formulated much more differentiated strategic ideas: ''On the embankments more openings should exist for an improved water flow. More artificial reservoirs should be built for a better storage capacity in addition to the natural beels. Better maintenance of the drainage and irrigation canals was also recommended. In terms of the benefits of embankments, the committee discussed whether the effects of normal and abnormal flood events would have been the same with or without embankments, but a final conclusion was not drawn'' (*The Statesman*, 20 September 1923).

In the second half of the twentieth century, and especially in recent decades, new discussions emerged, taking into consideration, on one side, the rather negative experience of local farmers with breached embankments and, on the other side, international mega-projects to embank whole river systems. New priority was given to appropriate local and regional technical solutions for the protection of cities and of expensive infrastructure such as bridges, traffic routes and power lines that provide a high return on investment. For flood management in rural areas, the concept of compartmentalization came up again, but this demanding technological and managerial approach is still controversial and must be considered only as a long-term option. Integrated approaches increasingly replaced one-sided technical solutions.

This very short summary reveals the present limitations of the available knowledge and the uncertainties about future strategic development. In this situation it is imperative to rethink three priorities, which must be further developed to open up new horizons for integrated and innovative approaches and solutions at different political levels and at different scales of space and time: research, development and cooperation.

8.7.1. Research and cooperation

Understanding the natural processes and the human impact on these processes is fundamental for any long-term solution. The various chapters of this book may have shown how this understanding has improved over recent decades, but also how difficult it is to communicate new knowledge to society and policy. An instructive example is the myth that forests can prevent big floods. Many years ago it was proved that this assumption was wrong. Yet the myth continues to influence the media, policy and development-oriented decision-making processes in different parts of the world, particularly in the vast highland–lowland system of the Himalayan region. This means that a much more efficient dialogue between science, policy and society is crucial to finding sustainable solutions.

Such a dialogue could become even more important in view of potential climatic and environmental changes in the coming decades. River courses and landforms in the Bengal delta are the result of complex interactions between accumulation, erosion, subsidence, tectonic shifts, sea-level changes and human activities. Climate change and sea-level rise will lead not only to more flooding and submerging of land, but also to increased sedimentation as a result of different runoff regimes and sediment transport rates, even though the time lag between the different processes is not known (Grosjean et al. 1996). For all these reasons, science has additional responsibilities: besides advancing basic knowledge on well-defined topics, scientists have to integrate their findings – if possible and realistic – into the interdisciplinary context of a human–environment relationship in order to contribute new ideas for the sustainable development of this most sensitive ‘‘Highland–Lowland Interactive System’’ of the Himalayan region.

However, this noble task can never be fulfilled by science if cooperation between all the countries concerned is limited. Water flows are transboundary processes. How can the lowest country in a river system implement sound flood management without real-time information and open access to all available hydrological data series in the upstream countries? All the institutions in the Himalayan countries – especially governmental ones – should be reminded that the International Council for Science (ICSU) has concluded and published a commitment for all member countries called "Statement on Freedom in the Conduct of Science". It says: "Scientists must have free access to each other and to scientific data and information. On the basis of its firm and unwavering commitment to the principle of universality of science, ICSU reaffirms its opposition to any actions which weaken or undermine this principle" (ICSU 2004: 7–8). To this important statement it should be added that China, India and Nepal are national members of ICSU, and that Bangladesh and Pakistan are national scientific associate members. Accordingly, the main concerned Himalayan countries should follow these commitments. If not, ICSU has a responsibility to intervene in order to establish the urgently needed scientific cooperation.

8.7.2. Development and cooperation

The creation of knowledge, as well as the application of knowledge in cooperation with the affected population, is important and urgently needed, particularly for all aspects of flood management. In future, it is very likely that not only high flows and floods but also low flows and droughts will play an increasingly important role, especially if more irrigation is required for food production in the dry season (for high-yield rice to feed a growing population). Living with droughts could become as challenging as living with floods. Considering the most recent report of the Intergovernmental Panel on Climate Change (IPCC 2001), such extreme scenarios are not unrealistic. Based on an Atmosphere–Ocean Circulation Model, two scenarios were evaluated for predicting precipitation changes up to 2050 and their consequences for annual average discharges. For the Himalayas and the Indo–Gangetic Plain, one scenario predicts an increase, the other a decrease, in precipitation. The first scenario could mean more floods, the second more droughts. Accordingly, coming decades will be characterized by uncertainty, and the scientific community has a responsibility to communicate, in a careful and timely manner, information about any types of change or variation, especially for this most sensitive part of the developing world.

With the currently available technical knowledge, human activities as well as natural processes can change river systems and water regimes. The "River Link Mega Project" in India is an impressive example, even though for the time being it is only a theory. In a situation of increasing drought conditions and critical food production in India, however, it could very quickly become a realistic option. Transferring water from the Brahmaputra and the Ganga to southern India, linking 37 big river systems, by constructing 32 dams and 9,600 km of canals and water carriers (Imhasly 2003), would change all these river systems dramatically. This concept may show that we have reached the point where the human impact on the natural hydrological system will be much bigger than any natural climatic or environmental change. If there should be any doubt about the possibility of such human impact, then we only have to consider the South-to-North Water Transfer in China, which is under construction.

Water resources are fundamental for development, from the level of the farmer to the level of a whole country. Water conflicts are and will be unavoidable, and solutions will be possible only through cooperation, be it on a local, national or international level, and development will be possible only with amicable arrangements about the use of water resources. For the whole Brahmaputra–Ganga–Meghna basin, we should keep in mind the words of Lonergan (2005), published in UNEP's *Our Planet*: "If there is a political will for peace, water will be no hindrance. If you want reasons to fight, water will give you ample opportunities." Along the same lines, International Mountain Day 2004, with the theme "peace on high" (FAO 2004), was dedicated to cooperation and to reducing conflicts – both of which are important preconditions for sustainable mountain development.

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