Mahmoud Abu-Zeid
and
I. A. Shiklomanov

Tenth IMO Lecture

WATER RESOURCES AS A CHALLENGE OF THE TWENTY-FIRST CENTURY

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FOREWORD

Starting with the Fifth World Meteorological Congress in 1967, an IMO Lecture has been delivered at each Congress to commemorate the International Meteorological Organization (IMO), the predecessor of the World Meteorological Organization (WMO). Each of these lectures reviews progress in a fundamental aspect of meteorology. All of them were prepared by acknowledged experts in their chosen fields.

The lectures that follow are the tenth in the series of IMO Lectures, which were presented at the Fourteenth World Meteorological Congress in May 2003. They present a view of the water resources and the challenge they will pose in the twenty-first century. In keeping with the traditionally high standard of these lectures, this year's lectures were delivered by Mr I.A. Shiklomanov and H.E. Mr M. Abu-Zeid.

Mr M. Abu-Zeid is highly respected at the international level as a leader in the field of water resources research and management. For 20 years he held the post of Chairperson of the Water Research Centre within the Ministry of Public Works and Water Resources of Egypt. He was elected President of the World Water Council in 1996 and re-elected to that position in 2000. In 1997, he was appointed Minister of Water Resources and Irrigation of Egypt, a post he has held with great distinction.

Mr I.A. Shiklomanov, Director of the State Hydrological Institute of ROSHYDROMET, is a world-renowned expert on assessment of the world's water resources. During the last 25 years, Mr Shiklomanov has greatly contributed to international hydrological cooperation, being a member of international councils, committees and working groups on hydrology and water resources, and author and editor of international publications on the assessment of world water resources.

The present publication contains the full text of their lectures. Like its predecessors in the series of IMO Lectures, this publication will be welcomed by meteorologists both as a stimulus to further thought and as a valuable reference book.

I wish to take this opportunity, on behalf of the World Meteorological Organization, to express our appreciation to Messrs Shiklomanov and Abu-Zeid for their contribution to the IMO Lecture series.

(G.O.P. Obasi)
Secretary-General

WATER RESOURCES AS A CHALLENGE OF THE TWENTY-FIRST CENTURY

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SUMMARY

Water means life. It is a basic resource in all human activities. Since early times, people have been searching for adequate water supply systems to meet their needs, and historically, most cultures were established and grew around major water sources. This means that water is a major factor determining the demographic map of the whole world.

Water is becoming scarce in quantity and inadequate in quality in many areas around the world. This is mainly due to ever-increasing demands that persistently exceed available supplies. Increasing water consumption due to population and economic growth is the most crucial feature and will continue at an accelerating rate so long as current attitudes and patterns of water utilization remain unchanged.

Current water-related challenges require urgent actions. These actions must include not only new policies at national level, but also strong international support with well-coordinated donors. This paper highlights the current water stresses and the magnitude of the problem worldwide, then defines the major challenges facing water resources management. It also presents the major issues requiring more negotiation and coordination among the different stakeholders to reach an agreement. The major international commitments and targets set by the world community to face the water-related challenges and to ensure proper management of limited freshwater resources are reviewed. Finally, a set of priority actions is proposed.

1. THE HARD FACTS

As reported in 2001 by the United Nations Fund for Population Activities (UNFPA), the global population has tripled in 70 years while water use has grown six-fold. As a result, the world average per capita share of fresh water declined from over 12 000 m^3 in 1960 to about 8 000 m^3 in 1990 and it is expected to fall down below 4 000 m^3 in 2025 as shown in Figure 1.

That means, within the next 25 years, one third of the world's population is expected to experience severe water scarcity. Right now, more than one billion people lack access to safe drinking water and three billion people (half the world's population) lack access to basic sewage systems. More than 90 per cent of all the sewage produced in the developing countries returns to the land and water untreated. Statistics show that the current global consumption of accessible fresh water is about 54 per cent. This amount is expected to increase to about 70 per cent by 2025 owing to population growth alone. Figure 2 shows the projected water scarcity in 2025 based on the "business as usual" scenario.

For many millions of people, freshwater scarcity is defined as much by poor quality as by insufficient quantity. The pattern of water consumption varies depending on several factors related to the rate of development in a region and the availability of natural resources. In Africa, agriculture consumes as much as 88 per cent while industry consumes only 5 per cent, whereas in Europe, more than half of the water is used in industry (54 per

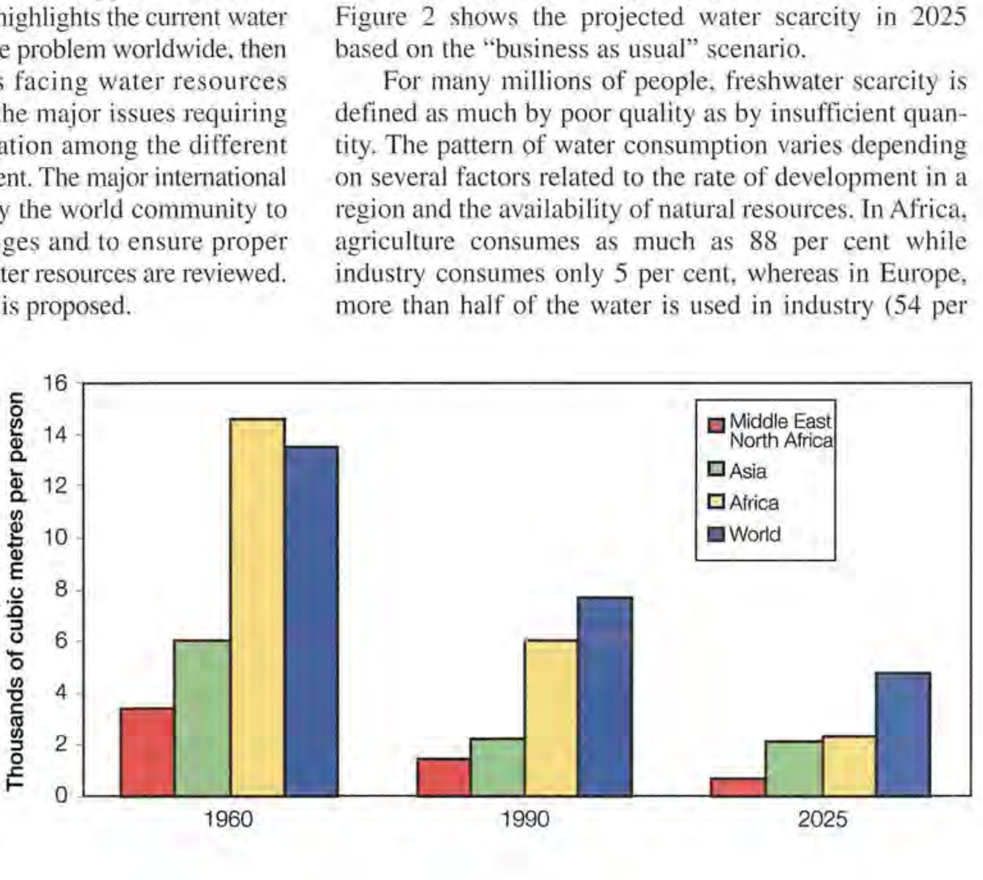

Figure 1—World average share of fresh water per person
(Source: World Bank. Water Resources Sector Strategy, 2002)

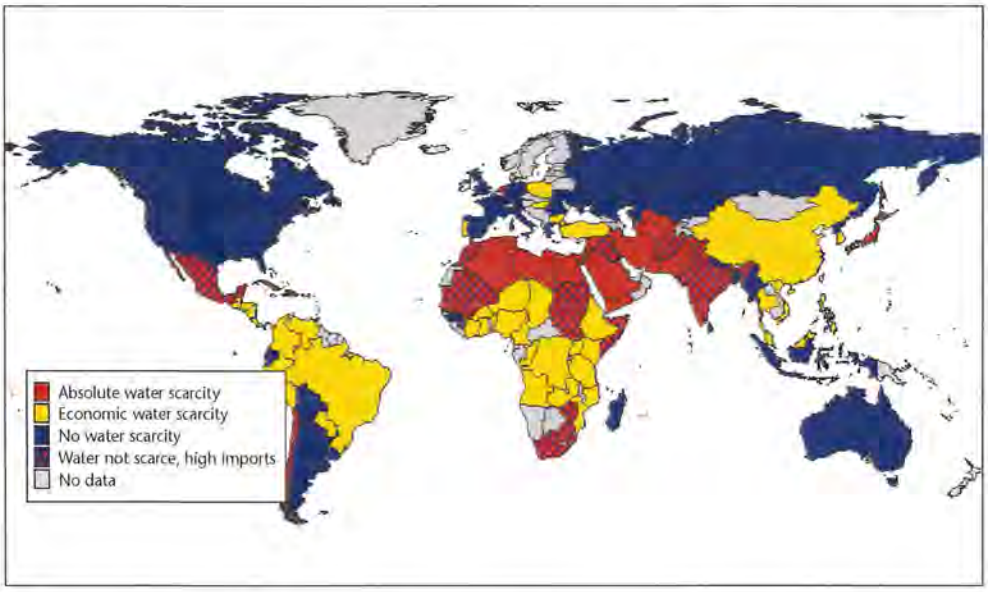

Figure 2—Projected water scarcity in 2025 (Source: World Bank. Water Resources Sector Strategy, 2002)

cent), while agriculture consumes 33 per cent and domestic use 13 per cent.

There is a worldwide consensus that the need for water and water supply systems is increasing rapidly as a direct result of human population growth, improved standards of living and industrial expansion, as well as an escalating need for food in dry climate areas.

Many freshwater ecosystems have been seriously damaged and must be considered for rehabilitation or restoration to comply with sustainability requirements. Water pollution is also a growing problem worldwide, partly because it stems from a complex set of parallel sources. Decisive efforts are needed to find realistic ways out of this dilemma, including identification of critical pollution sources and better approaches in land and water management.

Environmental monitoring systems need to be well designed to ensure that the information collected is relevant to health and environmental concerns, and to provide information on the effectiveness of the environmental control measures.

On the other hand, a major threat to sustainable development is the relationship between upstream and downstream water users when the water is in a transboundary river. The allocation of water among different riparian countries as well as among different economic sectors cannot be handled only through legislation but requires a common understanding and the coordinated efforts of all stakeholders involved.

The international community has a vital role to play in helping developing countries achieve objectives related to health and environment for sustainable development. Clearly, various cooperative actions are needed on the part of governments, businesses, civil society, international organizations and other relevant stakeholders to address these challenges. Without an integrated water resources management framework, disputes over limited and vulnerable water resources will continue to develop between rural, industrial and urban users.

1.1 Water scarcity and water poverty levels

Countries with water scarcity have been defined as countries with a freshwater per capita reserve of less than 1 000 cubic metres per annum. Recently a new Water Poverty Index (WPI) was introduced (DFID, 2002), which uses the impact of population growth and quantity of water resources as a measure of water availability. Monitoring progress in the water sector requires an interdisciplinary approach involving both quantitative and qualitative assessments. The WPI reflects the characteristics that link water and poverty. Five key components of the WPI were identified in order to incorporate a wide range of issues: resources (the physical availability of surface and groundwater), access (access to water for human use), capacity (people's ability to manage water effectively), use (different purposes for which water is used), and the environment (environmental integrity regarding water and the ecosystem as needed for goods and services).

The highest score of the index on a scale of 0 to 100 is taken to be the best situation while zero is the worst. The WPI provides a better understanding of the relationship between the physical extent of water availability, its ease of extraction, and the level of community welfare.

2. MAJOR GLOBAL WATER CHALLENGES

In March 2000, the Netherlands Government, in partnership with the World Water Council, hosted the Second World Water Forum and convened a parallel Ministerial Conference. The overall theme that emerged from the World Water Vision and the Ministerial Conference was "Water Security in the Twenty-first Century", which links water resources management issues to wider development and environmental concerns. These issues are reflected in the seven challenges identified in the Ministerial Declaration. The challenges reflect the international consensus on water security and provide a structure in which the key themes for future support to the water sector can be identified. The seven challenges are the following: meeting basic needs, securing the food supply, protecting ecosystems, sharing water resources, managing risks, valuing water and governing water wisely.

2.1 Meeting basic needs

Access to safe water and sanitation is a universal need and basic human right. They are vital for health and well-being. Although tremendous efforts have been made in the last two decades to provide improved water and sanitation services for all people, more than 1.1 billion people worldwide still do not have an adequate supply of clean water and about 2.4 billion people do not have acceptable sanitation.

UNFPA estimates that in 2000 about 508 million people living in 31 countries experienced water stress (less than 1 000 cubic metres of available fresh water per person per year); by 2025 these numbers will likely rise to 3 billion people in 66 countries, primarily in developing countries, doubling the number of people suffering water scarcity in the next 25 years. This will happen even though global water consumption has recently begun to level off, growing now only at about the same rate as global population.

2.2 Food security

The rapid growth in population and changing diets as incomes increase mean that the demand for food will grow in the future. The World Water Vision and framework for action of the Second World Water Forum stressed that meeting the water demand for food and environmental security would be one of the most demanding challenges of the coming decades. A major threat to sustainable food production is the availability of the limited water resources. The rate of increase in these resources is much less than the rate of growth in agricultural demand, which represents more than 70 per cent of the global water demand.

2.3 Protecting ecosystems

There are many ways in which human use of water resources is impacting ecosystems. Many freshwater ecosystems have been seriously degraded; industrial and communal effluents being major sources of pollution of the water system. Agricultural practices may also lead to pollution and salinization. Traditional conservation approaches can work in some settings but will have only a limited impact on the overall degradation of ecosystems, which can only be protected through integrated approaches taking into account the whole system.

2.4 Sharing water resources

There are more than 260 transboundary rivers in the world. International support should be given to regional initiatives that promote peaceful cooperation and develop synergies between different users of water at all levels through sustainable river basin management. These issues represent a significant political challenge and addressing them not only requires political will, but also sound technical solutions. One of the fundamental solutions to meet this challenge is to develop, strengthen and enforce agreements at bilateral, basin-wide, regional or global levels, as appropriate. Building trust among basin countries is another key aspect of meeting this challenge. Sharing information, improving understanding of common water resources, and technical cooperation should help promote confidence between the basin countries.

2.5 Managing risks

The discussions at the Second World Water Forum gave further exposure to the issue of managing the risks resulting from climate change and climate variability. The challenge is to provide security from floods, drought, pollution and other water-related hazards.

Hazards of natural origin cannot be prevented, and in most cases there is no absolute protection. Prevention measures are the key to reducing risks and are far more cost-effective than post-disaster responses. Figure 3 shows the distribution of water-related natural disasters. Asia has experienced 35 per cent of these disasters while Europe experienced only 13 per cent. Figure 4 shows the distribution of the different types of water-related disasters, 50 per cent being floods and 28 per cent water-related epidemics.

2.6 Valuing water

One of the major challenges facing water resources planners and decision makers is how to treat water as a natural resource that has economic and social value. The challenge is to manage water in a way that reflects its economic, social, environmental and cultural values for all its uses. Water should be treated as a basic human right but it should not be provided free of charge. A balance should be struck between pricing water as a commodity and the cost of providing good quality water in sufficient quantity. Growing recurrent costs for operation and maintenance of irrigation services and facilities are creating huge budgetary demands in all countries. There is a need for US$ 4 500 billion in the next 25 years as investment in water-related activities. Renovation and rehabilitation works need US$ 180 billion annually. Greater emphasis is now being put on cost-recovery mechanisms whereby at least the resources for operation and maintenance must come from the direct beneficiaries, namely the water users.

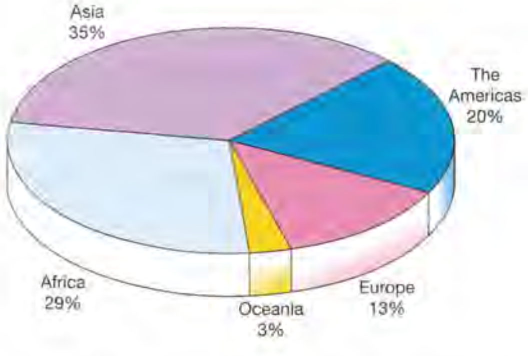

Figure 3—Distribution of water-related natural disasters

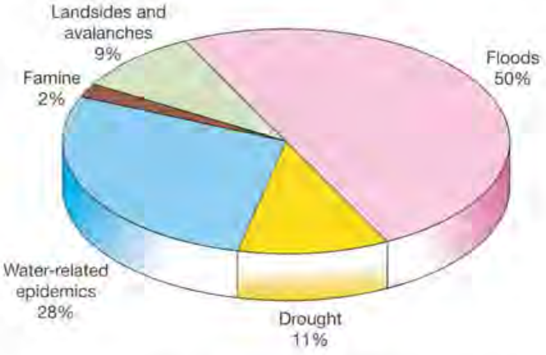

Figure 4—Types of water-related natural disasters

The World Water Council (WWC) and the Global Water Partnership (GWP) formed a world panel in 2001 chaired by Mr Michel Camdessus, former Managing Director of the International Monetary Fund, to address the financial needs of the water sector especially for the developing countries. This includes household services, irrigation, hydroelectric power, resource development and management, flood control, and others. Current spending on new water infrastructure in developing countries is very roughly US$ 80 billion a year. This needs to be more than doubled over the next 25 years, to around US$ 180 billion. The panel prepared a report to the Third World Water Forum where a number of proposals and recommendations were presented.

The panel highlighted the water sector's problems of weaknesses in governance, namely: low priority given to water sector, confusion of social, environmental and commercial aims, political interference, poor management structure, an inadequate general legal framework and resistance to cost-recovering tariffs.

The panel stressed the need for governments to give priority to the water sector and strengthen the sector's institutions. Decentralization of power to local governmental and non-governmental bodies was recommended. Implementation of full cost-recovery mechanisms and individual affordability to pay were stressed.

Aid funding needs to be doubled and targeted to stimulate flow from other resources. Because banks and private companies are now more aware than ever of the risk-reward trade-off, it is expected that participation of private funds will increase. The panel also suggested the creation of a global "Control Tower" for monitoring the progress towards achievement of the Millennium Development Goals.

2.7 Governing water wisely

This is another challenge facing all water resources stakeholders (that is planners, decision makers and end users). The challenge brought out by the World Water Vision was to ensure good governance so that the involvement of the public and the interests of all stakeholders are included in the management of water resources. Transparent and flexible national laws are a prerequisite for integrated water resources management policy development. Better coordination and institutional strengthening are needed to overcome fragmented responsibilities in the field of integrated water resources management. More involvement of women in water management as important stakeholders will also be needed. The institutional changes observed at international level evince certain common trends and patterns. With globalization and the increasing integration of economic systems worldwide, countries have begun to realize that learning from mutual experiences is an important means for improving performance in various areas including water management.

The old development paradigm that focused on centralized decision-making, administrative regulation, and bureaucratic allocation is fading fast and giving way to a new paradigm rooted in decentralized allocation, economic instruments, and stakeholder participation. The main concern in the water sector is the inherent limitations of the existing institutions in dealing effectively with a new set of problems that are not related to resource development but to resource allocation and management.

Figure 5 represents the general framework of an effective water management scheme. The water administration and water sector decision process must accommodate an increasing role of users, organizations and non-governmental agencies, and identify ways in which information technologies can be used to resolve water problems.

3. INTEGRATED WATER RESOURCES MANAGEMENT

Efficient water resources management should contain seven components: a national water policy, legislative system, allocation scenarios and action plans, coordination, financing and monitoring mechanisms to implement plans, governance mechanisms to ensure transparency and accountability, and a single organization responsible for the whole concept. These components form the framework of the Integrated Water Resources Management (IWRM) that is urgently required for the management of freshwater resources. The principles underlying IWRM have not yet fully found their way into

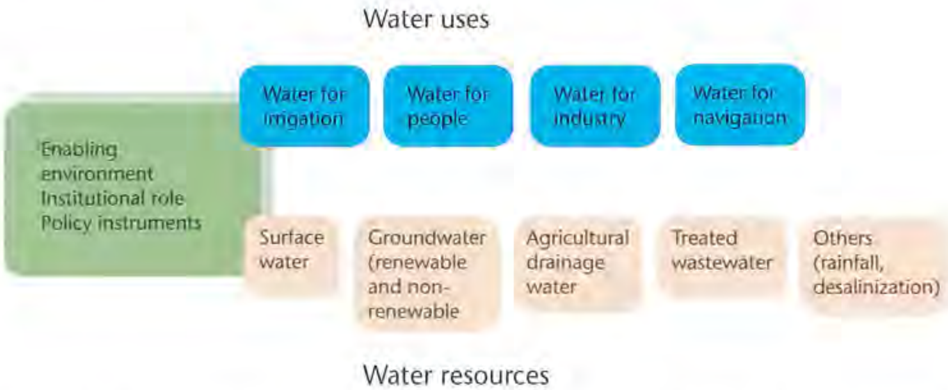

Figure 5—Diagram of an effective water management scheme

the socio-economic development policies and legislation of many countries, nor have people been brought to the centre of the decision-making process through decentralized planning and management of water resources at the basin level.

Efficient water resources planning, development and management in many countries are also seriously constrained by the lack of data from monitoring networks and other information concerning water resources: volume and availability, water demands, water-use patterns and other socio-economic variables. Fragmented institutional structures, a lack of regulatory mechanisms and of market-based incentives such as those included in public-private partnerships and technical and socio-economic constraints, as well as inefficient public awareness and demand management practices, are all contributing to the unsustainable exploitation of water resources.

Water interacts with almost all other sectors of the economy, and could potentially become a major constraint on economic expansion and growth. This is especially true because the amount of available water resources remains fixed, while water demands will continue to grow in the years ahead due to population growth, increased food demand, and expansion and modernization of industry. Thus, the economic challenge is to maximize social and economic benefits from available water resources while ensuring that basic human needs are met and the environment is protected. In terms of the issues discussed earlier, this means implementing IWRM principles as well as mechanisms leading to the efficient allocation and use of water resources, improving the performance of existing water supply systems, making existing systems and future investments sustainable, using debt-swap instruments and extracting the maximum economic potential from available water resources.

4. GOVERNANCE

The looming water crisis has been referred to by many as a crisis of governance and a lack of political will. Governance, in the water resources sense, could be defined as the manner in which power is exercised in the management of water resources. Good governance is ensuring that the management of the resources is done through equitable, transparent and accountable institutions. Good governance has two objectives: to encourage greater transparency, accountability and administrative efficiency, and to ensure stakeholder and public rights and participation. Specifically, good governance is concerned with the appropriate scale for planning and management of the resources, defining the costs and charges to be included in pricing water and the ownership of the process.

Governance includes both efforts to ensure that desired solutions are possible to implement (legislation, institutions/administration, financing, etc.), and efforts to secure real-world implementation (incentives, motivation, information campaigns, education, etc.).

A fundamental issue is to break the link between economic development, lifestyle and water degradation. Another issue is the need for constructive links between professionals, planners and politicians, with regard to the water sector.

Wise management of water resources always requires action on three levels: national, regional and international. However, such action is not sufficient for sound management. Experience around the world proves that local management is also essential for sustainable exploitation of scarce water supplies.

Community-based natural resource management, and specifically water management, must play a critical part with those larger-scale approaches in solving scarcity problems. Local water management permits a democratizing decentralization of decision-making and accountability. It helps people take part in the decisions that define their own future. Moreover, it encourages the integration of traditional knowledge with innovative science to promote fair and efficient supply management. In these ways water degradation and shortage can be transformed into sustainable sufficiency.

5. MAJOR ISSUES

Despite the agreement on future challenges and an evolving consensus on the importance of adopting an integrated approach to water management, there still remain several controversial issues on which more work is needed and further consultation required to reach consensus. Among these are the impact of climate change on water resources, transboundary river basins,

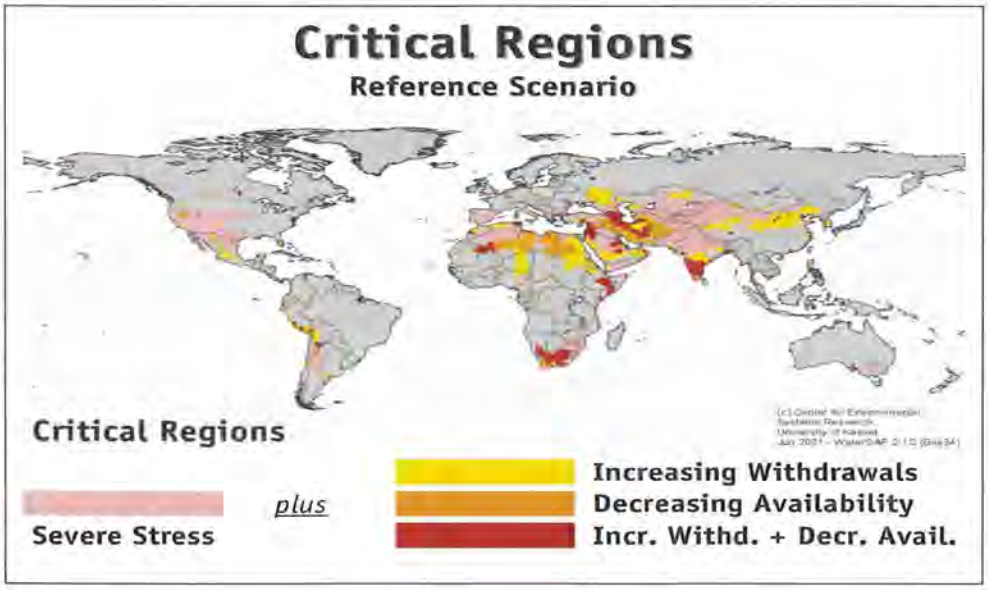

Figure 6—Estimated effects of climate change on water resources and withdrawals. (Source: Dialogue on Water, Food and Environment, Progress Report 1, 2001)

public-private partnerships and the role of dams in development.

5.1 Impact of climate change on water resources

Because water challenges are closely interrelated with climate-related risks, humans have always struggled to cope with climate variability. In recent centuries, climate variability has increased the frequency of floods and droughts. Indisputably the last two decades were the warmest of the twentieth century, indeed the warmest of the last 1 000 years. The sea level is rising, precipitation patterns are changing, Arctic sea ice is thinning and the frequency and intensity of El Niño events appear to be increasing.

In addition, many parts of the world have recently suffered major heat waves, floods, droughts and extreme weather events leading to significant loss of life and economic costs. Consequently, climate change has emerged as one of the key environmental issues over the next 50 to 100 years. However, there are still many uncertainties relating to the effects of climate variability, including the impacts of climate change on water resources, that society is not yet well prepared to handle. Moreover, land cover change, altered housing patterns, etc., may have increased the vulnerability of society to floods. Figure 6 shows the geographical distribution of expected climate change effects on both water resources and water withdrawals.

Prominent climate researchers have noted that the question is not so much whether the Earth's climate will change, but rather by how much, how fast and where. While individual extreme weather events cannot be directly linked to human-induced climate change, the frequency and magnitude of these types of events are expected to increase in a warmer world. Climate models, using the latest emissions projections from reports of the Intergovernmental Panel on Climate Change, project an increase in global mean surface temperature of 1.5 to 6°C between 1990 and 2100, with land areas warming more than the global average, especially at mid- and high northern latitudes. These changes in temperature will be accompanied by changes in precipitation patterns and a rise in sea level. Carbon dioxide concentrations will be higher than those occurring during the last few hundred thousands of years, and the projected temperature changes will lead to global average temperatures higher than have occurred over the last ten thousand years. However, in reality there will probably be winners and losers. Given the uncertainties of climate predictions, particularly when changes in precipitation on regional scales are considered, we cannot be sure who might benefit from climate change and who might lose. For example, there is evidence that increases in precipitation might halt and even reverse desertification; there is evidence that the world will become "greener". Most climate models predict that precipitation in the Nile River Basin will increase, which might lead to increases in the annual volume of the Nile, beneficial for all Nile Basin countries, not least my own, Egypt.

Since, over the time-span of climate projections, decades, socio-economic as well as technological changes can be large, it is impossible to predict future capabilities for adapting to the changed conditions. Uncertainties are therefore still large, making decision-making an uneasy task. To illustrate this, projected changes in the annual River Nile volume due to climate change range from minus to plus 70 per cent depending on assumptions. This makes planning for water resources more difficult and the decision-making process more complex.

It should be noted that changes on planet Earth include more than just climate change. With much more confidence than in the case of climate projections, we can predict that in the near future we will have to feed an additional three billion people. Production of the extra food requires space, which means that the Earth's natural reserves will be more and more under pressure. Careless agricultural practices might lead to deforestation, land degradation and decreasing biodiversity. Although much can be achieved by managing water more carefully, more water will most certainly be needed to meet increased demand. All these changes represent new challenges for future water management on very different scales, with respect to both floods and droughts.

Such changes will make water resources management more and more complex as water policies must take all the possible effects of these changes into account. To give some examples, these possible changes should be taken into account when considering exploitation of new irrigation areas; different expectations of flood hazards in river valleys could affect planning of build-up areas in these regions, as well as water conservation policies. Global change should be considered when evaluating large-scale engineering works in upstream countries in large river basins. Some of these works might be locally beneficial for a country, but this does not necessarily mean that they will also benefit the water supply in downstream countries.

To summarize, decision makers should carefully consider the messages from the scientific community as regards climate change as well as the other expected changes. Given the current state of the art of climate research, the research community may be expected to do no more than provide a range in which the change will fall. Obviously, a lot of effort will be made to reduce this range and international organizations such as WMO can play an important role in this. However, in view of the inherent uncertainties of global change, it is clear that the decision makers can no longer take the position of "wait and see". Therefore, there is a need to look for flexible ways to manage water resources in order to cope with the uncertainties. This means that we should learn to manage water and other natural resources very carefully and sustainably.

5.2 Transboundary river basins

Managing shared water resources requires mutual agreement between basin countries which, in many cases, is hard to achieve. There are more than 260 transboundary river basins.

Increased water demand will lead to stronger competition among water users to satisfy their needs. In the long run, competition over large transboundary river basins or transboundary groundwater aquifers easily leads to friction between neighbouring states. To avoid aggravating such friction, international cooperation is a prerequisite for sustainable management of river basins.

As competing demands for water are causing increasing discord within and between countries around the world, efforts are under way to develop innovative solutions to water disputes. Some of the most promising opportunities for effective water resources management involve the entire basin rather than just localities downstream. Approaches include implementing conservation measures, developing and implementing strategies for demand management and joint use, permitting easier water transfer and making the recognized value of instream water uses a matter of standard practice.

Dispute resolution refers to a wide variety of consensual approaches whereby the disputing parties voluntarily seek to reach a mutually acceptable settlement. Such approaches differ from strategies using judicial or political means. Dispute resolution is an inherent part of social interaction, something that in practice goes far beyond conflicts over natural resources.

Successful negotiation depends on balancing the forces of cooperation and competition among the disputing parties and on creating a problem-solving process that realistically addresses the role of power. However, negotiations must be carried out within certain guidelines including agreement on an objective, information sharing and generation of alternative solutions, using objective criteria to evaluate the alternatives, seeking joint gains, and drafting an implementation plan.

The Nile Basin Initiative (NBI) is one of the success stories as regards building a framework of cooperation and trust between the ten countries involved. Despite the extraordinary natural endowment and rich cultural history of the Nile Basin, its people face considerable challenges. Today, the basin is characterized by poverty,

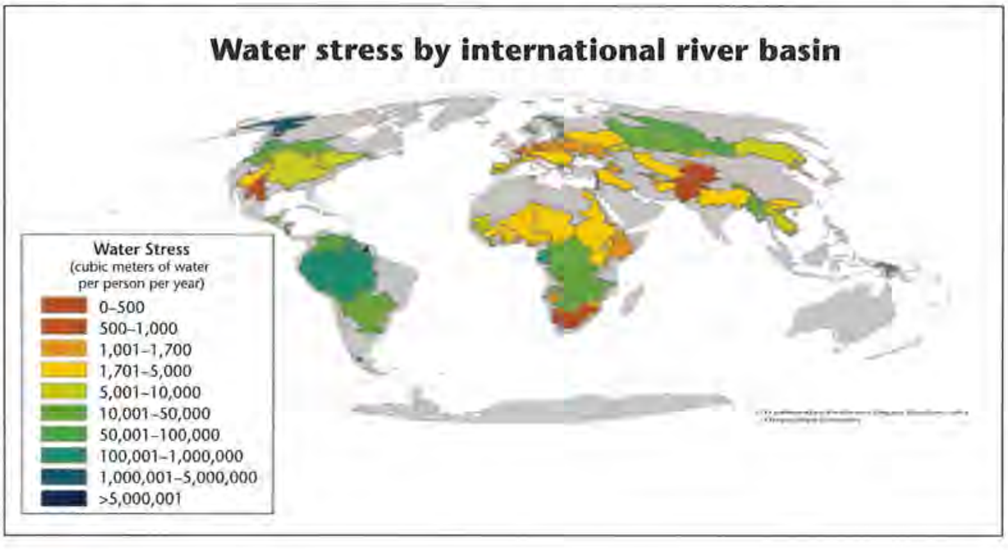

Figure 7—Geographic distribution of water scarcity by international river basin (Source: Oregon State University. Transboundary Freshwater Dispute Database, 2002)

instability, rapid population growth and environmental degradation. Recognizing that cooperative development holds the greatest prospects for bringing mutual benefits to the region, all riparian countries, except Eritrea, joined in a dialogue in 1998 to create a regional partnership to facilitate the common pursuit of sustainable development and management of the Nile waters. The transitional mechanism was officially launched in February 1999 in Dar es Salaam, Tanzania, by the Council of Ministers of Water Affairs of the Nile Basin States under the title of Nile Basin Initiative (NBI). The shared vision of the NBI is: "To achieve sustainable socio-economic development through the equitable utilization of, and benefit from, the common Nile Basin water resources". A Subsidiary Action Programme (SAP) was designed to plan and implement investments and activities "on the ground" at the lowest appropriate level, taking into account the benefits from, and impacts of, these activities in all riparian countries.

5.3 Public-private partnerships

The water sector is capital-intensive. In Africa, the level of investment in agriculture between 2002 and 2015 is expected to be around US$ 240 billion, out of which US$ 69 billion is for operation and maintenance. It costs an average of US$ 105 per person to provide water supplies in urban areas and US$ 50 in rural areas, while sanitation costs an average of US$ 145 in urban areas and US$ 30 in rural areas. Figure 8 shows the growing trend of private investment in infrastructure in developing countries.

It is clear that governments alone will not be able to provide all the financial resources needed to operate and maintain the water systems efficiently. New partnerships must be forged, and the business community, among others, must actively engage in implementing water management projects.

Growing awareness of the crucial role that water plays in achieving the objectives of sustainable development has prompted wide-ranging discussions at national and international levels on how best to promote new concrete actions and partnerships to provide water for sustainable development. The intent is to enable a wide range of stakeholders to make tangible contributions to the achievement of the objectives of sustainable development in the field of water and related programmes.

Because of the very public nature of the sector, public authorities continue to play an important role. Rather than actually managing and providing a service, governments must act as regulators and guarantors of a certain level and quality of service provision. The objectives may remain the same, but the instruments have changed. In this respect, private sector participation may actually create more, rather than less, demand for effective, capable public authorities. Intervention through incentives requires more skill than intervention through investment. A new regulatory capacity is required to deal with these new roles.

Policy reform aimed at public-private partnerships is always difficult and needs strong believers in their eventual benefits. Implementation of reform programmes now will help avoid costly and often more difficult adjustments in the future.

Public-private partnerships help in the development of new water infrastructure and in overcoming financial constraints. Over the last decade, a number of partnerships in the field of water have emerged, such as those between governments and the Water Supply and Sanitation Collaborative Council (WSSCC), Water Users Associations (WUAs), the Global Water Partnership (GWP), the Water and Sanitation Program, the Water Utility Partnership in Africa, and the New Partnership for Africa's Development (NEPAD). Although each of these partnerships has evolved around specific objectives, most of them could be viewed as umbrella organizations and initiatives.

The critical issue is how to translate the idea of building partnerships through global or regional-level discussions and advocacy campaigns into local action. New and innovative partnerships will have to be formed that may involve a wide range of stakeholders and provide many different ways for partners to participate.

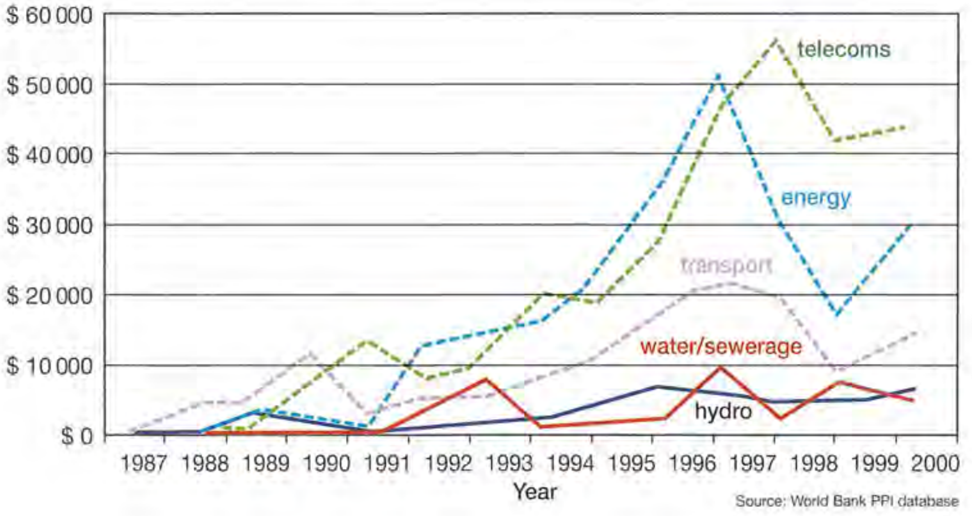

Figure 8—Private investment in infrastructure in developing countries. (Source: World Bank Private Participation in Infrastructure database)

5.4 The role of dams in development

Heated international debate is currently taking place on the role of dams in development. Some consider dams vital for national security, economic prosperity and agricultural survival, while others view them as degrading ecosystems and damaging the environment.

The relationship between dams, development and their impacts on environment actually is very clear. Before 1900, only 40 reservoirs had been built with storage volumes greater than 25 billion gallons. Today, there are almost 4 500 reservoirs of this size, and they store more than 1 500 cubic miles of water. However, more dams are needed, particularly in developing countries.

In areas of the world where approximately two billion people live and where river waters are only intermittent, flows are virtually unusable for development, and storage through dams is the only solution to water problems. Large, growing populations in such areas cannot possibly be supplied with water without large-scale surface water storage.

On the other hand, whenever dams are to be built, reasonable application of state-of-the-art knowledge, laws, rules and guidelines concerning sustainable social, environmental, technical and economic aspects must be required. New guidelines prepared by the World Commission on Dams (WCD) provide an internationally recognized standard for responsible planning, construction and operation of dams.

6. INTERNATIONAL COMMITMENTS AND TARGETS

The world faces the difficult challenge in the twenty-first century of securing environmentally sustainable development of water resources and the penalties of not overcoming this challenge are severe and will certainly worsen. The international community has committed itself to certain targets at various international conferences and world summits. The following highlights some of these commitments and targets.

6.1 United Nations Water Conference (Mar del Plata, March 1977)

Twenty-five years ago, the United Nations Water Conference held in Mar del Plata, March 1977 adopted many recommendations concerning development of shared water resources through regional and international cooperation.

One of the recommendations is that "countries sharing water resources, with appropriate assistance from international agencies and other supporting bodies, on the request of the countries concerned, should review existing and available techniques for managing shared water resources and cooperate in the establishment of programmes, machinery and institutions necessary for the coordinated development of such resources. Areas of cooperation may, with agreement of the parties concerned, include planning, development, regulation, management, environmental protection, use and conservation, forecasting, etc. Such cooperation should be a basic element in an effort to overcome major constraints such as the lack of capital and trained manpower as well as the exigencies of natural resources development."

The conference also recommended the establishment of the International Drinking Water Supply and Sanitation Decade, 1980. The goal of the programme was that all peoples, whatever their stage of development and their social and economic conditions, have the right to have access to drinking water in quantities and of a quality equal to their basic needs by 1990.

6.2 The WEHAB initiative

This important initiative was proposed by United Nations Secretary-General Kofi Annan as a contribution to the preparation of the World Summit on Sustainable Development in 2002. The WEHAB initiative seeks to provide focus and impetus to action in the five key thematic areas of water, energy, health, agriculture and biodiversity and ecosystem management.

Within the framework for action on water and sanitation, water is recognized as the key resource for all aspects of life. Nevertheless, addressing the water needs of the poor has not been given enough priority, even though water has been recognized as playing a central role in sustainable development and poverty alleviation. Access to safe drinking water and sanitation is a basic human right for all people around the world. In the poorest countries, one in five children dies before the age of five mainly from water-related infectious diseases arising from insufficient water availability, in terms of both quantity and quality. By 2025, the urban population in developing countries is expected to double to four billion. Unfortunately, sanitation and water programmes worldwide are not geared up to keep pace with the shifting and growing populations and are saddled with a traditional top-down approach with almost no participation by those needing the services. Thus, provision of safe drinking water and sanitation services to more than one billion people over the next decade remains one of the most critical challenges facing humanity today.

Water resources in many countries remain fragile, mostly because of poor demand-and-supply management rather than actual water scarcity. Measures adopted to promote sustainable use of water are still unsatisfactory. There is competition between use for agriculture, power, industry, the environment and human development needs, leading to political and civil tension. The situation is dramatically worsened by society's inability to manage water resources in a coordinated and participatory manner or to provide efficient and equitable water services.

Allocation mechanisms should be proposed to balance competing demands both within and between different water-using sectors and countries and should incorporate the social, economic and environmental value of water. The problem of cross-sector subsidization to different user groups makes it even more important to allocate water optimally depending on its value for the different uses. Currently, it still remains highly undervalued.

The existing water supply delivery systems are overburdened and their services are constantly deteriorating. Many towns and cities in developing countries have unreliable piped water systems with supply interruptions, high leakage rates and unaccounted connection losses. The systems suffer from deferred repairs and maintenance; for example, as many as 30 per cent of hand pumps in rural areas may not be functioning properly. Rehabilitation and well-chosen technologies for household or community-based water and sanitation services can reduce water wastage as well as operation and maintenance costs. In this regard, community participation in planning, development and management of water supply schemes is of paramount importance.

It is worth mentioning that water and sanitation infrastructure projects are usually capital-intensive, financial resources for implementation of these projects being the most limiting constraint. The flow of financial assistance from donors and multilateral institutions to developing countries has been much lower than warranted by the magnitude of the crisis. The debt situation continues to discourage investments in infrastructure, while at the same time domestic resource mobilization (such as efficient tariff systems, recovery of overdue bills and taxes and a systematic reduction of subsidies) has not been sufficiently promoted. Nor have countries seriously pursued the use of debt-swap mechanisms that would have generated local currency to finance local needs. Political will is crucial to encourage investment in improving services, and extending those services to poor communities. Too little has gone into developing appropriate frameworks that could contribute by sustaining the impacts of investment in infrastructure development.

The WEHAB framework for action on agriculture expressed the crucial role of that sector in sustainable development and in reducing hunger and poverty. Some 70 per cent of poor and hungry people in developing countries live in rural areas and depend directly or indirectly on agriculture for their livelihood. Agriculture also dominates water consumption. The United Nations Food and Agriculture Organization estimates that water use for agriculture accounts for some 70 per cent of water withdrawals in a range of small-, medium-, and large-scale irrigation initiatives. The performance of many of the large-scale irrigation schemes is poor because water management has failed to respond to changing markets for irrigated produce, farmer preferences, hydro-environmental limitations and competition for raw water. As a result, there is considerable scope for improving the productivity and efficiency of certain types of agricultural water use, not only to maintain the integrity of natural freshwater systems but also to be able to negotiate continued allocations for municipalities and other major productive uses. This is most apparent in the inherently water-scarce countries in South Asia, sub-Saharan Africa and the Middle East, where reliance on groundwater, in particular, has led to a significant increase in quantity and quality of irrigated produce but also a rapid decline in water tables and pollution of key aquifers.

6.3 World Food Summit (Rome, 2002)

In Rome, 2002, the World Food Summit called for an international alliance to accelerate action to reduce world hunger. It also unanimously adopted a declaration calling on the international community to fulfill an earlier pledge to reduce the number of hungry people to about 400 million by 2015.

Several commitments were made during this summit. Although these commitments are related to poverty reduction and food security, they are strongly linked to securing environmentally sustainable development of water resources.

Three of these commitments are worth mentioning. The first is to ensure an enabling environment designed to create conditions for the reduction of poverty and for durable peace. The second is concerned with implementing policies aimed at improving physical and economic access by all, at all times, to sufficient nutritionally adequate food. And the third commitment is to promote allocation and use of public and private investments to foster human resources and rural development.

6.4 World Summit on Sustainable Development (Johannesburg, 2002)

Other commitments and initiatives were tabled during the World Summit on Sustainable Development held in Johannesburg 2002.

The summit put sustainable development back on the global agenda and more importantly has kick-started global action to fight poverty and protect the environment. Governments have agreed upon an impressive range of concrete commitments for tangible action that will continue beyond Johannesburg.

The summit represents a leap forward in the development of partnerships, with the UN, governments, and civil society coming together to increase the pool of resources to tackle global problems on a global scale. Around 60 partnerships were announced during the summit and included major activities by the European Union, France, Germany, Japan and the United States of America.

The summit entailed an unprecedented level involvement of civil society, with almost as many delegates from major groups as from governments. This was reinforced by parallel events, including conferences for groups from civil society, including NGOs, women, indigenous people, youth, farmers, workers, business leaders, scientists, local authorities and legal experts, all of which ensured that the voice of civil society was heard by governments.

The summit built on the momentum of recent meetings in Doha and Monterrey to address issues related to development and poverty, providing a sustainable basis for more resources to be committed to the goals of environmental protection and poverty reduction.

The legacy of this summit goes beyond the political commitment to accelerate action for sustainable development. Instead of concluding only with the adoption of a political agreement, the summit has generated real action through partnerships and between governments, business and civil society.

Two major commitments were made at this summit: first, a commitment to halve by 2015 the number of people without access to sanitation and safe drinking water.

In this respect, the United States announced US$ 960 million in investment over the next three years on water and sanitation projects. The European Union announced the "Water for Life" initiative which seeks to encourage partners to meet goals for water and sanitation, primarily in Africa and Central Asia. The United Nations has received 21 other water and sanitation initiatives with at least US$ 20 million in extra resources.

The second major commitment is concerned with agriculture where the Global Environment Facility will consider the Convention to Combat Desertification as a focal area for funding. Again, the United States pledged an investment of US$ 90 million in 2003 for sustainable agriculture programmes and the United Nations has received 17 partnership submissions with additional resources of at least US$ 2 million.

6.5 Third World Water Forum (Kyoto, March 2003)

At the Third World Water Forum a number of reports covering water-related issues were discussed. There were also two ministerial meetings. Among the most important reports and studies was the World Water Action Report, which emphasizes the general and urgent needs facing the water sector. It also presents a number of regional issues and examines the needs of the WEHAB sectors (water and sanitation, energy, health and environment, agriculture, biodiversity and ecosystem management). The report containes a database of 3 000 worldwide actions in the water sector.

World Water Assessment Programme (WWAP), which is hosted in UNESCO with 23 United Nations agencies participating in the program, presented a draft report at the forum identify and describing the nature of the water crises; assess the coping capacity of societies and the effectiveness of policies; developing indicators to monitor and report progress in reaching targets; and enhancing the capacities of participating countries to perform in-country assessments. The World Water Development Report (WWDR) reviewed progress on 11 challenges, including to provide water for basic needs and health, enhance food security, promote cleaner industry, develop energy, protect ecosystems, mitigate risk and govern water resources.

The Ministerial Meeting on Water, Food and Agriculture highlighted the need to increase water productivity. Food security and poverty alleviation, sustainable water use and partnerships are key challenges for the agricultural sector. The meeting's declaration presented at the forum outlines a plan of action, including improvement of agricultural water use and water productivity, promotion of better governance, consideration of environmental aspects, the undertaking of research and development, and fostering of international cooperation.

The Ministerial Conference's declaration covered several points, including the financial resources needed to achieve the Millennium Development Goals and cost-recovery approaches which suit local climatic, environmental and social conditions and the polluter-pays principle, with due consideration for the poor, and new mechanisms of public-private partnerships. The declaration also emphasized the importance of integrated water resources management, full participation of all stakeholders, and transparency and accountability in all actions, cooperation between riparian states on transboundary and/or boundary watercourses, the role of hydroelectric power, and the need for legislative frameworks for the protection and sustainable use of water resources and for water pollution prevention.

7. CONCLUSIONS

Water interacts with almost all other sectors of the economy. It could potentially become a major constraint on economic growth, as the amount of available water resources remains fixed while water demands continue to grow in the years ahead owing to population growth, increased food demand and expansion and modernization of the industrial sector. The following immediate actions are therefore needed to face this challenge:

- Implementation of integrated water resources management principles;
- Promotion of good governance that ensures transparency and participation of stakeholders in water resources management;
- Capacity building to enable developing countries manage their water resources sustainably;
- Creation of mechanisms leading to the efficient allocation and use of water resources;
- Improvement of the performance of existing water supply systems;

- Encouragement of participation of the private sector in water resources management;
- Transfer of the management of water to users through decentralized mechanisms;
- Strengthening of the sustainability of existing systems and future investments; and
- Use of debt-swap instruments and exploitation of the maximum economic potential of available water resources.

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WATER RESOURCES AS A CHALLENGE OF THE TWENTY-FIRST CENTURY

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SUMMARY

This monograph attempts a worldwide examination of the major factors affecting the highly complex problem of water, which is bound up with changes to replenishable water resources, largely represented by river flow, which is the prime source for meeting water requirements. Water resources govern the availability of water and water shortages in different countries and regions. The data assembled here are primarily the result of complex integrated research studies conducted in recent years under the direction of the author at the Russian State Hydrological Institute (SHI) (St Petersburg, Russia).

The monograph analyses the worldwide dynamics of renewable water resources for a single long-term period (1921–1985) for all natural-economic regions, continents, major river basins and selected countries. It also considers the intra-annual distribution of runoff and changes over many years to discharge into the seas, giving greatest attention (using data for the most recent years) to the Arctic Ocean, which is why fresh river water discharge rates are of particular importance. For the first time ever, such detailed global assessments are based on observations from the worldwide hydrological station network (WHYCOS) for a single long-term period; this has helped fashion a relatively reliable picture of the breakdown of replenishable water resources in space and time.

At the same time, it must be pointed out that the precision of water resources dynamics depends on the state of the hydrological network and on whether the requisite hydrological information can be subjected to early processing. The most detailed and dependable data come from regions and countries in Europe and North America, since more than half of all hydrological gauges (70 per cent of them equipped with recorders) are located along the rivers of these areas and offer particularly long observation series. It is also important to note that hydrological information from the countries of Europe and North America is the easiest to process, whereas it is practically impossible to obtain the necessary hydrometeorological data for the last 10–15 years from many countries in Africa, Asia and South America.

The lack of a current dependable, constantly and quickly updated global hydrological database is why a long-term period for data processing (up to 1985) was chosen. This means that no assessments can be made for changes to worldwide runoff and runoff for the last two decades, at a time when a steep increase in global air temperatures has been observed. This same circumstance has made for enormous problems in studying the world hydrological cycle under the World Climate Research Programme (WCRP).

It is also important to note that, despite the extensive work by international organizations, first and foremost WMO and UNESCO, in drafting guidelines and making recommendations on regional water assessments, so far there have been no reliable data on medium-term renewable world water resources, let alone their time dynamics. This is a major hindrance to any proper assessment of water availability in the world or future changes.

Crucial to present-day assessments of water resources is to allow for changes resulting from human activities, including the changes that are expected over the next few decades. The monograph shows that, to assess the impact of economic activities on world water resources, it is crucial to make allowance for human activities stemming from water use for community or domestic needs, industry, irrigation, dam building and reservoirs. These factors have a world impact, are everywhere growing in importance, and may have a great effect on water resources over large areas and countries. Due attention must also be paid to the potential effect of man-made climate change on water resources and their use.

This monograph describes methodologies and results of assessments and analyses of the dynamics of community, industrial and agricultural water use, as well as water losses through additional evaporation from reservoirs in the twentieth century, for all natural-economic regions and continents and for selected countries. It also gives an outlook up to 2025 based on two radically differing water use scenarios.

The steepest rise in world water use was in the second half of the twentieth century, from 1951 to 1980, when, every decade, water use grew by an average of 550–650 km^3, four times more than in preceding decades. This was due to steep population increases and the spread of irrigated lands worldwide, and to a rapid rise in industry in the wake of the scientific and technological revolution. After 1980, worldwide water consumption increases fell off considerably following a contraction of irrigated areas and more efficient

industrial use of fresh water in the world's developed countries; but the rates still remain high.

Forecasting at the SHI followed two scenarios:

- Conventional Scenario (CS), basing the water use forecast in each region over the coming 25–30 years on the model of preceding decades;
- Sustainable Development Scenario (SDS), where the future development of water use was based on considerable increases in water savings by different users, making allowance for the prospects and interests of each region.

Under the Conventional Scenario, world water use will grow by 10–12 per cent every decade up to the year 2025, when it will be 1.37 times higher than in 1995; the steepest rise in water use can be expected in Africa and South America (1.5 to 1.6 times) and the lowest in Europe and North America (1.2 times).

Under the Sustainable Development Scenario, future world water draw-off will more or less stabilize; by the year 2010 it will rise by 5–6 per cent; thereafter it will begin to fall, and by 2025 it will have fallen to near present-day levels. At the same time, world industrial water consumption will fall by 10 per cent as compared with 1995 levels; and in Europe and North America, a fall-off in aggregate water consumption of 22–24 per cent may be expected.

In evaluating and analysing the dynamics of world water consumption, the hardest obstacle to tackle is the fact that most countries lack reliable data on water discharge rates for economic use and in particular water consumption in different sectors of the economy. There are hardly any country data for assessing water losses through extra evaporation from reservoirs.

Two criteria were employed to make an overall assessment of the use of water resources in any given region (country):

- The coefficient of water use, as defined by the ratio of aggregate water consumption to available water resources;
- The specific water availability of a region, by identifying how much fresh water (with an allowance for water consumption) is withdrawn per capita.

The analysis based on these two criteria showed that whereas in 1950 the world water resources situation was completely satisfactory, by 1995 there had been a dramatic decline. Some 40 per cent of the world's population now live in a state of critical stress on water resources and exceptionally low water availability. This means that water shortages are becoming a critical factor for economic growth and community life.

In future, if the use of fresh water in the world remains at present levels (Conventional Scenario), then, calculations show, by 2025 some 60 per cent of the world's population will be experiencing a critical situation in terms of stress on their water resources and a catastrophic situation in terms of water availability, i.e. it will be quite reasonable to talk about a global freshwater catastrophe.

The development of future water use under the Sustainable Development Scenario would alleviate the burden on water resources over the next two to three decades, though specific water availability would remain catastrophically low, since the amounts would mainly be determined by population growth. If that happened, the populations of developing countries would be by far the worst off.

Analysis of data from the world's natural-economic regions and countries for 1950–2025 shows that the rate of contraction in specific water availability is a function of two main factors: the socio-economic development of countries in a given region and the latter's climate. For industrially developed areas the fall in specific water availability for the same period will be some 1.7 times, whereas for regions that include developing countries, specific water availability will fall by 4–5 times where there is enough or too much moisture, and 7–8 times where climates are arid or semi-arid.

Thus, the great natural worldwide inequities occurring in the world in water availability will be steadily exacerbated, as a function of economic activity and population growth in both developed and developing countries, and will grow even faster. On every continent, along with regions where water availability is catastrophically low, there will remain wide areas where there are surplus water resources and where water availability is unusually high.

The brief analysis in this monograph of results of research into the effects of man-made climate changes on water resources leads to the following general conclusions:

- In the past 20–25 years, there has been a discernible trend towards increased water resources and considerable changes in their intra-annual distribution in cool and temperate climates, and towards their reduction in arid climates as a result of similar changes. There are good grounds for presuming that such changes result from global warming, whose intensity has increased considerably in the last few decades.
- Together with the possible doubling of carbon dioxide concentration by the end of the twenty-first century, it is highly likely that there will be a rise in annual runoff and streamflow in cool and temperate areas (30–50 per cent), or so modern forecasts will have us believe, and still more significant changes by season. For humid tropical, and particularly arid and semi-arid regions, quantitative assessments of possible change in water resources are very uncertain, mainly so far as precipitation forecasts are concerned. Here it is noteworthy that river systems in regions of inadequate precipitation are particularly sensitive even to minor climate changes.
- Bearing in mind forecast global warming rates (by 2020–2025 rises in world temperatures will average 0.6°C as against the pre-1990 period), and the vagaries of existing climatic scenarios, when estimating water resources and water use for major natural and economic regions and continents in the 2010–2025 period, the effect of man-made changes on the global climate may be completely ignored. Possible errors are much smaller than those from

forecasts of economic growth or population size, which are crucial to deciding on the stress on water resources and availability.

- Beyond the 2040–2050 horizon, it is absolutely essential to take account of man-made climate changes on water resources and availability, particularly for regions where precipitation is inadequate.

As studies show, to cut the stress on water resources and stabilize specific water availability in regions with water deficits, two issues must be dealt with simultaneously: decrease water consumption, and find out how to increase available water resources.

The following conclusions are drawn from the technical, socio-economic and ecological aspects of possible decreases in freshwater use and increases in available water resulting from the different kinds of water management covered in this monograph (river flow regulation, use of fossil water, desalination, artificial rain, increased water use efficiency in industry and irrigation, and geographical diversion of water).

All the most important and promising ways of obtaining additional water resources and freshwater savings in industry and irrigation are generally comparable in costs and possible scale. Eventually they are likely to be used in countries and regions where the geographical conditions and types of water use make them sensible, ecologically safe and economically worthwhile.

Of the steps to increase available water, the geographical diversion of rivers has obvious advantages; first and foremost it is governed by existing realities in world water formation and is a feature of all physical-geographical zones, regions and continents; world river flow that could be diverted is now two orders of magnitude greater than all desalinated water resources and still growing. In the author's opinion, when taken in combination with the spread of modern technologies in water use and runoff treatment, the territorial diversion of river flow can be a realistic way of both reducing stress on water resources and stabilizing specific water availability in different regions and countries.

The gravest problems with water resources and availability are the ones faced by developing countries, whose characteristics include steep population growth rates and low incomes, both affecting socio-economic development. At the same time, the bulk of developing countries are in geographical areas where rainfall is inadequate, and even in ordinary circumstances renewable water resources are not great; where there is large variability; and sensitivity to even minor man-made world climate changes.

The key to water availability in such areas, arising from numerous activities associated with modern freshwater savings techniques, introducing the most efficient technologies and finding new sources of water, will require major capital outlays clearly beyond the means of developing countries. However, in the author's opinion, for both developed and developing countries, the problem can be completely solved in the first half of the twenty-first century, provided there is the will to ensure steady development of the world economy and keep renewable fresh water, the basis of all life on our planet, in good condition.

But first there needs to be a radical change in attitudes to fresh water. It has to be recognized everywhere as an invaluable resource, without which there can be no improvement to the well-being of the community or development of the world economy; and, secondly, as a key part of the environment in which we live. It is essential to initiate effective international accords, strict legislative measures, and governmental decisions to conserve and properly use water sources, protect human rights to water, acknowledge the value of water, increase the role of both public and private sectors in dealing with water problems, and develop a water resources management strategy through an integrated long-term programme of action in each region so as to reach the essential goal of ensuring permanent long-term water availability.

The monograph presents top-priority scientific methodological studies, which the author is convinced are needed to encourage reliable, scientifically based improvements of the worldwide use and conservation of water resources.

Chapter 1

INTRODUCTION

Water has a special place on our planet and is the most widespread material found on it: in varying quantities and in forms it is found everywhere and plays an integral part in the lives of men and the world surrounding us. Fresh water is of particular importance. To begin with, it is a resource of consummate importance; without it there would be no human activity and no life could exist, and nothing can replace it. But no less importantly, it is an indispensable part of the natural kingdom and a prime component of our environment. Lastly, it is the most fearsome of the elements, visiting on mankind dreadful disasters and terrible destruction.

Thus, human beings cannot help using water, but they must also conserve it so as not to damage the environment, they must fight it and protect themselves from it as a threat and a hazard that can at any moment escape out of control. Its multifaceted role engenders a prolific set of interactions between itself and humans, that vary widely from region to region and country to country and change significantly as human society develops and economies grow.

The present publication considers just one aspect of the overall interlocking issue of water, examining fresh water as the vital natural resource that the development of human society depends on heavily.

In our time, at the beginning of the twenty-first century, water resources have become one of the most important and complex of scientific and technical challenges we face. To tackle the challenge calls for ever greater efforts and resources; it has already moved far beyond the nation state and is global in scale, and of direct concern to the billions of people living on our planet.

Man has always used fresh water for his own ends, but for many hundreds of years the effect of his activities on water resources was insignificant and strictly local in character. The wonderful properties of natural water; its constant recharging in the water cycle, and its ability to rehabilitate itself meant that fresh water long remained comparatively clean, was never in short supply and was of high quality. This gave rise to the illusion that it was unalterable and inexhaustible, and a gift of Nature. It also led to an entrenched devil-may-care attitude to water use, with minimum outlay on treating wastewater, and on conserving water resources.

The situation has changed beyond all recognition in the last few decades: in many regions and countries it has become steadily easier to see the fruit of so many years' unreasonable behaviour both towards direct use and the changing surfaces of river catchments. A considerable spur to this was the sudden leap in world water use, beginning in the 1950s, that resulted from the great expansion of productive forces in many spheres of the world economy as the scientific and technological revolution took off. There was a more than quadrupling of annual water withdrawal between 1951 and 1960 compared with preceding decades (Shiklomanov and Markova, 1987), occurring through a steep increase in irrigated land area, water withdrawals for industry and heat and power generation, and an enormous number of new reservoirs on every continent.

In the last 25–30 years, particularly rapid man-made changes have been observed in the hydrological regimes of rivers and lakes, water quality, resources and balance. The volume of water, its dynamics over time and territorial distribution is now governed not only by the vagaries of the natural climate, as was always the case, but also by the economic activity of human beings. In many regions and countries, the depletion and pollution of water resources means that the ever-growing needs for water cannot be met and economic development and living standards are being set back.

Particularly grave water-related problems have been occurring in arid regions, whose outstanding feature is their extremely limited natural water resources and high degree of over-use, along with rapid population growth rates. As long ago as 1977, the First United Nations Water Conference, held in Argentina, stressed the adversity faced by developing countries, many of them in areas of insufficient precipitation, and the great likelihood that such hardships would be facing most countries in the world by the end of the twentieth century. The conference helped strengthen and coordinate international cooperation in studying and assessing water resources, promoted the development of country studies, and attracted attention from the general public, governments, planning bodies and decision makers to water problems, water management and the development of hydrology as a science.

In the last few years, interest in reliable assessments and the quantitative forecasting of changes in water resources have advanced a long way because of the looming critical global climate change and as a result of human activities, symptomatic of the rising levels of carbon dioxide and other greenhouse gases in the atmosphere. The man-made changes forecast by climatologists by the mid-twenty-first century may be so great (IPCC, 1995; IPCC, 2001) that they induce significant changes in the water cycle and available water resources, the latter's use, distribution in time and space and extreme characteristics as well as variability of runoff. All this has to be allowed for in developing long-term integrated water use and conservation plans or drafting long-term water management objectives and measures.

Reliable assessment of water resources, use and availability in river basins on a country, regional or global level, and for individual sectors of the economy, have all been receiving steadily growing international attention. Such major activities as the International Conference on Water and the Environment (ICWE) (Dublin, Ireland, 1992), and the Ministerial Conference on Drinking Water Supply and Environmental Sanitation (Noordwijk, Netherlands, 1994), concentrated the minds of governments and the community at large on the nature of the impending water crisis and the gravity of the water problem. The United Nations Conference on Environment and Development (Rio de Janeiro, Brazil, 1992), which adopted the landmark Agenda 21 resolution, also dramatically helped draw world attention to water problems and the urgent need to take worldwide action to deal with them.

At present, water resources issues on regional and worldwide scales come under the umbrella of a plethora of governmental and non-governmental organizations, particularly UNESCO, WMO, UNEP, FAO, IAHS, IWRA, and so forth. Many scientific conferences and symposia have been held on these subjects and there is a huge amount of literature on them published in various countries.

The most detailed and comprehensive assessments of the water balance and water resources for all continents and natural zones of the planet were made with tight international cooperation and published by the Russian State Hydrological Institute in the ground-breaking monograph "The World Water Balance and Water Resources of the Earth" (Korzun, ed., 1974), and in the 1975 monograph "The World Water Balance", published in Germany by Baumgartner and Reichel. The data contained in these works have been widely used by experts, as they are considered the most comprehensive and dependable. None of the later publications, during the 1980s and first half of the 1990s, where information is provided on water resources around the world, contribute any new information to the above monographs, since they are either to all intents and purposes based on the conclusions drawn in them or they use earlier and now obsolete assessments, which do not concur with observational findings.

In many publications well known to experts, e.g. "Sustaining Water: Population and the Future of Renewable Water Supplies" (Engelman, 1993), or the periodically published findings of the World Resources Institute (WRI, 1992, 1996, 2000), very comprehensive data on water resources and use are sometimes to be found, not only for separate continents but for every country in the world. The use of the latter data for different types of general review should be treated with great circumspection, given their lack of homogeneity and unreliability. This stems from the fact that they are based on out-of-date sources, use heterogeneous methods and baseline data, cover different years and long time-periods and are not underpinned by the requisite critical analysis or compared with observational information from hydrological networks.

Unfortunately, so far for developed and developing countries alike, extremely widely varying assessments of water resources may be encountered in the literature. For example, according to data contained in the report of the European Environmental Agency (EEA, 1999), even for certain highly developed European countries (Belgium, Great Britain, Germany, Denmark), total renewable water resources can vary from 20 to 100 per cent or more, depending on the source. Even greater discrepancies are encountered when assessing freshwater use levels for different countries and regions of the world.

Relatively reliable twentieth century assessments of water use dynamics for all continents, with approximate assessments for the period up to the year 2000, were first made by the present author in collaboration with Professor G.P. Kalinin and published in 1974 (Kalinin and Shiklomanov, 1974). More detailed data for continents and the world's different natural-economic regions were presented by us in an earlier monograph (Shiklomanov and Markova, 1987). There is unfortunately a yawning gap in reliable data on all countries, despite the periodical publications issued by the World Resources Institute. Data on freshwater use from a range of sources can differ by 200 to 300 per cent or more, even for certain developed countries in Europe (EEA, 1999).

Given the position with regard to the assessment of world water resources, a project was instituted under the UNESCO International Hydrological Programme to make a new review of water resources data and their use and issue a monograph on "World Water Resources at the Beginning of the 21st Century". The State Hydrological Institute (SHI) at St Petersburg, Russia was mandated to develop this project during the period 1991–1997. Under the present author, a team of researchers at the institute duly carried out the work and prepared the monograph for publication. Its full text was published in 2003 by Cambridge University Press (Shiklomanov, ed., 2003).

Its main conclusions were published by WMO and other international organizations as a technical report (Shiklomanov ed., 1997) and used when drafting the report of the Commission for Sustainable Development (UN CSD) on the integrated assessment of world freshwater resources. The monograph's main methodological approaches and results obtained were also used in 1998 in the reports by the Russian scientists who were its main authors – reports that were presented to "Water: a looming crisis?", an international conference on world water resources in Paris, 3–6 June 1998 (UNESCO, 1998).

In the period 1998–2000, workers at the SHI, led by the author, played an active part in preparing data and developing scenarios for future world water resources as part of the Scenario Development Panel, established under the long-term project on forecasting for world freshwater resources, World Water Vision, set up in 1997 by the World Water Council following a decision of the First World Water Forum, held in Marrakesh, Morocco. For the latter, the SHI did substantial work to analyse and collate findings on water resources and their uses in different basins, countries and regions of the world, along with data on the basic principles and details involved in forecasting world water use and availability for the period to 2010–2025. The panel's experts used the initial SHI data to work out three scenarios for freshwater use in 1995–2000. Analysis of the world freshwater situation according to the three scenarios, and the SHI one, were presented to the Second World Water Forum in The Hague, Netherlands, and published in a monograph (Rijsherman ed., 2000). The main conclusions of the SHI research were published in abridged form in the IWRA journal "Water International" (Shiklomanov, 2000).

The present publication, an effort to analyse world water resources at the present time, draws extensively on SHI results cited in the above-mentioned works. It also gives a number of results obtained by the author and his colleagues in obtaining and exchanging hydrological data and information on the state of the world hydrological network; in assessing the effect of reservoirs on water resources and world water use; in drawing up new scenarios for world water use and assessing their expected consequences; in determining the effect of global warming on water resources; and on analysing ways and means of eliminating freshwater scarcity in different countries and regions.

The author wishes to express his deepest gratitude to his colleagues at the SHI. They include the SHI departmental heads: Drs V.I. Babkin and V.Y. Georgievsky; Scientific Secretary of the Institute, Dr Z.A. Balonishnikov; senior scientific officers Drs N.V. Penkova, I.L. Zaretskaya, T.E. Girigorkina, A.V. Izmailova and V.L. Yunitsina; and engineers L.P. Babkina, E.V. Golovkina, T.V. Grube, L.V. Lalazarova, I.A. Nikiforova, T.I. Printseva, E.L. Skoryatina and V.G. Yanuta. Through their devoted work, it has proved possible to collect new data on the dynamics and use of water resources.

Chapter 2

THE WORLD'S WATER RESERVES; TYPES OF WATER RESOURCES

Water is one of the most widespread materials in nature, and can come in three different states: as a free liquid, a solid or as vapour. Water forms the oceans, lakes, rivers and groundwaters in the upper strata of the Earth's crust and soil cover, and mantles of ice and snow in circumpolar and high mountain areas. Some of the water remains in the atmosphere in the form of water vapour, water droplets and ice crystals and also in the biosphere. An enormous amount of water is to be found in the bound state, forming part of different minerals in the planet's crust and inner core.

It is no easy task to obtain a reliable assessment of water reserves round the world, as water is very dynamic, in constant motion, passing from the liquid to the solid or vapour phase and back again. What is more, in any quantitative assessment of stored water, the form (free or bound) and amount (or sphere) that water is found in has to be determined so as to make proper allowance for it. Water in the hydrosphere is usually included: all water in a free state in the liquid, solid or gaseous phase in the atmosphere, on the Earth's surface or inside its crust, and which takes part in the hydrological cycle. In so doing, all water found down to a depth of 2 000 metres below the surface of the planet is normally taken into consideration.

Studies for a quantitative assessment of the hydrosphere have a very long history, and are quite comprehensively reviewed by Fedoseev (1967). In the last 30 years the fullest assessments are those published by Nace (1967), Kalinin (1968), Korzun, ed. (1974), Lvovich (1974), Baumgartner and Reichel (1975), the National Research Council (1986), and Berner and Berner (1987). A comparison of these data, given as an example, is shown in the monograph by Gleick, ed. (1993).

For comparison purposes, Table 1 gives the basic components of the hydrosphere from the data of three publications where the information is best shown. The data in the table show extremely wide discrepancies in the assessments. It unfortunately shows the limits to our knowledge, even of the global characteristics of the hydrosphere, and underscores the need for more research. There are particularly great discrepancies when it comes to assessing the Earth's freshwater reserves (ice and snow, groundwater, water reserves in permafrost zones), this being a consequence of the great problems in determining them obliquely (because of the paucity of basic data).

It is very hard to make an objective assessment of the reliability of data by various authors on quantitative indicators for the hydrosphere. In the work of the SHI, preference is given to data in the monograph edited by Korzun (1974) because, unlike other publications, it provides data on a considerably larger number of components of the hydrosphere and contains a

Type of water	*National Research Council USA, 1986*	*SHI, Russian Federation (World water balance, Korzun, ed., 1974)*	*Baumgartner and Reichel, Germany, 1975*
Water content in atmosphere:	15 500	12 900	13 000
above land	4 500	3 100	-
above seas	11 000	9 800	-
Precipitation (annual):	505 000	577 000	496 000
above land	107 000	119 000	111 000
above seas	398 000	458 000	385 000
Evaporation and transpiration (annual):	508 000	577 000	-
from land	71 000	72 000	71 400
from sea surface	434 000	505 000	424 700
Water storage on land	59 000 000	47 565 210	36 020 000
Snow and ice	43 400 000	24 064 100	27 820 000
Surface water	360 000	189 990	225 000
Subsurface water	15 300 000	23 400 000	8 062 200
Biological water	2 000	1 120	-
Annual river runoff to the ocean	36 000	44 700 + 2 200 (sub-surface)	39 700
Water storage in ocean	**1 400 000 000**	**1 338 000 000**	**1 348 000 000**

Table 1—Basic global hydrological cycle components (km^3) from different sources

description of the sources and assessment methods used. Data taken from the monograph are given in Table 2.

It should be stressed that data on the Earth's water reserves are fairly approximate, given the lack of information on individual components. Least reliable of all are the assessments of groundwater storage in permafrost zones, and water reserves in bogs and swamps. Most reliable are the assessments of water reserves in the oceans of the world, lakes and reservoirs, ice caps and mountain glaciers, and saline or brackish and fresh groundwaters.

According to the data in Table 2, the Earth's hydrosphere contains an enormous quantity of water, approximately 1 386 million km^3, 97.5 per cent of it saline, while only 2.5 per cent is fresh water. Moreover, of this figure, a large proportion of the fresh water (68.7 per cent) is in the form of ice caps in the Antarctic, Arctic and high mountain areas, a further 30.1 per cent is taken up by fresh groundwater, and only 0.26 per cent of the Earth's freshwater resources comes from lakes, reservoirs, and river systems, the most economically easily accessible and most important for water ecosystems (Figure 1).

The figures describe the so-called natural static water reserves in the hydrosphere, i.e. the amount of water that, averaged out over many years, is to be uniformly found in bodies of water, aquifers and the Earth's atmosphere. For shorter periods of time (years, seasons, months), the water in the hydrosphere varies as it is exchanged between the oceans, land and atmosphere, i.e. in the world's water circulation process or hydrological cycle. The individual components of the hydrosphere in the process have a function that is not only one of volume, but also of their dynamism in the cycle, which is usually taken quantitatively as being how long it takes to turn full circle. It is the time that different forms of water in the hydrosphere take to recharge completely. Rough data on renewal duration are given in Table 3.

According to the table data, the time for a full water cycle varies extremely widely. For example, the time taken for ocean water to recharge completely is about 2 500 years, ice in permafrost and the polar ice caps takes more than 10 000 years to do so, and deep-lying groundwater takes more than 1 500 years. Water stored in the Earth's lakes is fully recycled approximately every 17 years, the complete recharging of river waters takes no more than 16 days, while water in the atmosphere is recharged every 8 days. The rapid recharging of river waters shows the enormous significance of streamflow as a basic source of water for sustaining the economic requirements of human life.

Proceeding from the water recharging that occurs in the hydrological cycle, hydrologists and water management experts use two concepts to underpin their water resources assessments in any given region: static or secular fresh water reserves and renewable water resources. Static or secular

Kind of water	*Area of distribution (m^2 x 10^3)*	*Volume (km^3 x10^3)*	*Depth (m)*	*Proportion (%) of*	
				total water storage	*freshwater storage*
World ocean	361 300	1 338 000	3 400	96.5	-
Groundwater	134 800	234 001*	174	1.7	-
Freshwater included	134 800	10 530	78	0.76	30.1
Soil moisture	82 000	16.5	0.5	0.001	0.05
Glaciers and permanent snow cover, including:	16 227	24 064	1 643	1.74	68.7
Antarctica	13 980	21 600	1 546	1.56	61.7
Greenland	1 802	2 340	1 298	0.17	6.68
Arctic islands	226	83.5	369	0.006	0.24
Mountain regions	224	40.6	181	0.003	0.12
Underground ice in the permafrost zone	21 000	300	14.0	0.022	0.86
Water storage in lakes including:	2 059	176.4	85.7	0.013	-
Freshwater storage	1 236	91.0	73.6	0.007	0.26
Saltwater storage	822	85.4	104	0.006	-
Water storage in swamps	2 683	11.5	4.28	0.0008	0.03
Water in river channels	148 800	2.12	0.014	0.0002	0.006
Biological water	510 000	1.12	0.002	0.0001	0.003
Atmospheric water	510 000	12.9	0.025	0.001	0.04
Total water storage	510 000	1 385 984	2 718	100	-
Freshwater storage	148 800	35 029	235	2.53	100

Note: Does not include groundwater storage in Antarctica, approximately estimated at 2 000 000 km^3 including mainly freshwater storage of about 1 000 000 km^3.

Table 2—Water storage on the Earth

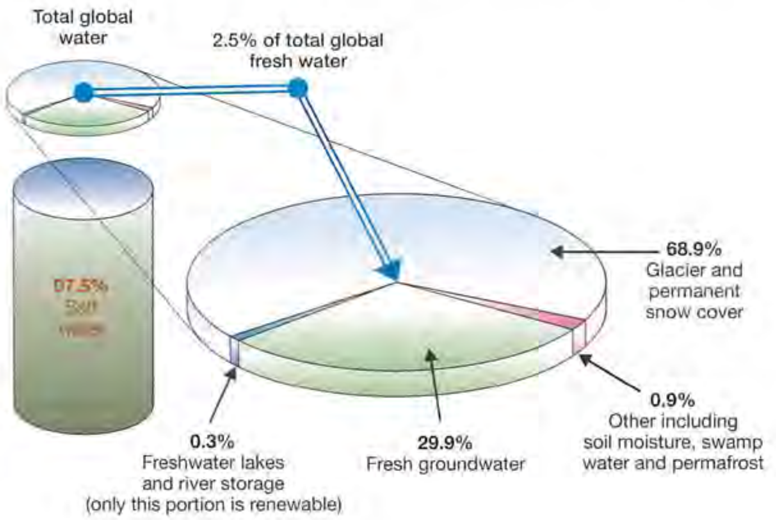


Figure 1—Global freshwater availability

reserves are arbitrarily taken as meaning those forms of fresh water (major lakes, groundwaters, glaciers, etc.), with full recharging taking many years or decades to complete. Their intensive exploitation inevitably leads to exhaustion of reserves and harmful ecological consequences, disturbing the age-long balance of Nature, which may take scores if not hundreds of years to recover.

Renewable water resources cover waters that are annually recharged in the Earth's water cycle: primarily river runoff, measured in quantities for a given unit of time (m^3/sec, km^3 per annum, etc.), originating in a given region or flowing in from outside, to which may be added groundwaters entering the river system. This form of water resources also includes annually renewed groundwaters in near-surface aquifers that do not run off into river systems. Their volume is not great by global standards in terms of river volume, however, and they can be of significance in individual specific regions (e.g. coastal areas of seas and oceans).

It is important to stress the exceptional importance (particularly when planning freshwater use) of the differences between static or secular water reserves and those

Kinds of water	*Period of renewal*
World ocean	2 500 years
Groundwater	1 400 years
Soil moisture	1 year
Polar ice floes and permanent snow park	9 700 years
Mountain glaciers	1 600 years
Underground ice in the permafrost zone	10 000 years
Water storage in lakes	17 years
Water in swamps	5 years
Water in river channels	16 days
Biological water	Several hours
Atmospheric water	8 days

Table 3—Periods of complete renewal of water storage on the Earth

that are renewable. Unfortunately, the literature (even that of the specialized hydrometeorological type) sometimes confuses the two extremely varied categories; they are often mingled with one another, or not separated rigorously enough. Yet that is perfectly inadmissible: they are radically different in terms of their significance in Nature and require completely distinct approaches in the way they are used.

In work by Sokolov (1986), the relationship between static water reserves and renewable water resources may be illustrated in the example of Lake Baikal. The lake has enormous reserves of static fresh water: some 23 000 km^3, though its renewable resources are no more than 60 km^3 per annum (discharge from the River Angara at its outlet from the lake). Nevertheless the renewable water sources are all that can be used for economic purposes, since any use of fossil water storage invariably has harmful ecological consequences. This fact is sometimes not taken into account when referring to the enormous freshwater reserves in Lake Baikal and other major lakes.

Runoff not only forms the core of renewable river resources on the planet, but in the water cycle it considerably restores river water quality. And if mankind suddenly stopped discharging pollutants into rivers, water would gradually re-assume its pristine purity through the natural rehabilitation processes that all river systems possess.

In this way, river runoff, to all intents and purposes representing replenishable water resources, is a key to the hydrological cycle, with an enormous impact on the ecological state of the Earth's surface and the economic development of society. River systems have the widest geographic distribution, and their flow is the basic source of world water consumption. Water availability and scarcity in any given region are nearly always measured from runoff and streamflow. That is why, in the following chapters, fundamental attention will be paid to assessing runoff, its dynamics in time and its geographical spread round the globe, as well as analysing how it is used for different economic needs in our day and age, and how it will be used in the future.

Chapter 3

REPLENISHABLE WATER RESOURCES

3.1 GENERAL APPROACHES TO ASSESSMENT METHODOLOGY

Two radically different sets of methods can be employed to determine the quantities of renewable river resources in a given region or river basin: meteorological data or the direct observation of runoff and streamflow.

The former is widely used where there are too few hydrological observations or where meteorological data are much fuller and more detailed. In practice, it is usually made by:

- Making water balance calculations for runoff, taking normal annual precipitation and evaporation as a model;
- Establishing how runoff depends on precipitation and other characteristics; or
- Using runoff formation models.

The methodological basis for water balance calculations is to use a very simple equation taking an average water balance for a river catchment measured over a period of several years of (runoff being the difference between precipitation and evaporation). This was first formulated in the late nineteenth century by A.I. Voeikov (1884) and A. Penck (1896). In that exercise, precipitation was calculated from observational data, and evaporation was worked out from various formulae.

It was a relatively simple assessment technique, widely used in many countries in the early twentieth century, when the hydrological network had not been fully established and meteorological data were considerably greater. By that time, the foundations for calculating evaporation from land had been laid by the German scientist Schreiber (1904) and the Russian hydrometeorologist Ol'dekop (1911), who were the first to design equations for estimating normal annual evaporation in various physical-geographical circumstances. Ol'dekop's investigations were of particularly great importance, and are useful to this day; he developed a non-linear equation for calculating evaporation norms as a function of precipitation and potential evaporation. Ol'dekop's evaporation calculation method remained unchanged for many decades and was only extended much later in the work of M.I. Budyko (1948), who first suggested that evaporability might be calculated by using the ratio of the radiation balance of a wet surface to the specific heat of evaporation, thereby linking up the equations for the water and heat balances.

Budyko's method, as later refined by L.I. Zubenok (1976), is still widely used for calculating both mean long-term characteristics and overall evaporation from river basins for selected individual years and months. It is not the only method employed; other approaches by Russian scientists are made much use of, such as those by A.P. Konstantinov (1968), A. I. Bugadovsky (1964), V.S. Mezentsev and Karnatsevich (1969) and V.G. Adreyanov and V. I. Babkin (1974). Prominent methods outside Russia include those put forward in the 1940s and 1950s by Penman (1948), Thornthwaite (1948), and Turc (1954), which are still widely used in many countries.

It should be noted that, since the 1940s, the calculation methods for evaporation have been mainly used, not to assess renewable water resources but to study the dynamics of evaporation and calculate the water balance of river basins and individual areas of land in different physical-geographical conditions. This is because normal annual runoff calculations for the water balance equation proved unacceptable because the results obtained were not reliable enough, in particular for arid lands where runoff is low and in terms of absolute significance close to the margin of error for determining precipitation and evaporation. Evaporation calculations using formulas for specific years and months may also have extremely large margins of error for regions where precipitation is adequate or even comes in excess (Konstantinov, 1968; Budyko, 1971; Babkin, 1979).

In using the water balance equation for assessing renewable water resources, significant errors arise, not just with regard to the calculation of evaporation but also in determining precipitation from observations. This is particularly true for temperate and high latitudes where a significant portion of the precipitation falls as snow and cannot be properly assessed by precipitation gauges. In such circumstances, the incorporation of various kinds of corrections in the data, corrections that vary considerably in time and space, vastly undermine the reliability of precipitation assessments at observation points and their mean for any given area.

In this way, the water balance equation method used in assessing renewable water resources can only provide rough-and-ready results, which means that it cannot be recommended for detailed calculations, in particular for countries and regions with low water resources.

In the first place, because of its inaccuracy the method cannot be used for arid and semi-arid regions, where runoff is very low, and in absolute terms is close to the permissible margin of error for evaporation and precipitation, and for calculations where there is no reliably measured precipitation. Secondly, with this method, no reliable assessment of water resources for every individual year can be arrived at (not to mention each season and month); but such data are extremely necessary for modern water resources use planning. It is also an unsound technique for assessing water resources in countries and regions that form part of international river basins, when a considerable volume of the streamflow does not originate in the given territory but flows in from outside.

Nonetheless it should be recalled that the water balance method is frequently used at the present time for regions where the hydrological network is spread thin. For example, in 1996, the South American Region of UNESCO was charged with using it to make an assessment of the water resources of Latin American countries, as it was fully suitable for wet tropical and subtropical conditions.

The same water balance method was successfully used in Russia by M.I. Lvovich (1974) and in Germany by Baumgartner and Reichel (1975) for all continents. The approach allowed these authors to run a fairly simple study of the relationship between components of water balance averaged out over a period of many years for the different continents and oceans of the northern and southern hemispheres, and for major land areas. However, in so doing, a key component of balance, such as runoff, which defined the renewable water sources of dry land, is assessed in a rather rudimentary fashion, particularly in areas where there is little moisture.

In the last decade, interest in the water balance approach has risen steeply because of the looming water crisis, and the need to study changes in water resources in major regions of the world under the impact of anthropogenic climate changes (Shiklomanov, 1989; Shiklomanov and Lins, 1991; Shiklomanov and Babkin, 1992; Arnell, 1999).

The establishment of different kinds of flow functions for different characteristics, with a view to using them for areas not yet studied, began as soon as relatively long series of observations on individual rivers became available. Originally (in the late 19th to early 20th centuries), attempts were made to establish linear functions of runoff for precipitation alone. However, they failed to find large-scale practical application, as they did not reflect physical interactive processes between precipitation and runoff and were basically of strictly local importance, suitable for only a small range of changes in precipitation (e.g. for northern areas with excess moisture and little evaporation, changing only slightly from year to year).

In the following years in many countries, formulae defining the relationship of runoff to precipitation, lack of moisture and air temperatures, began to be worked out in different ways. These formulae also found extremely limited application as they did not fully correspond to physical impressions of the link between components of the water balance and its spectrum of changes and did not provide enough reliability for runoff calculations, particularly in areas where there was insufficient moisture.

In the 1970s, multiple regression and factorial analysis models requiring specific hydrographic parameters for the catchments and climate characteristics under study were proposed for determining long-term and average annual values for water resources in river catchments and regions (Babkin et al., 1972; Rozhdestvensky and Chebotarev, 1974; Kuzin and Babkin, 1979).

The regression model is of the simplest kind. To develop it, the amounts of runoff (function) and those factors that determine runoff for a given number of river catchments in a given region are needed. The task is to find out which multiple regression equations will give the smallest margins of error when comparing calculated and observed runoff for all catchments.

The factors used as arguments for assessing perennial water resources values in a region include: the surface area of a basin, its average height above sea level and incline, the surface areas of lakes, swamps and forests, and other parameters. The factors used as arguments for calculating runoff are meteorological characteristics such as atmospheric precipitation, atmospheric moisture deficit, air temperature, etc.

Factorial analysis models are extensions of regression models; in both, long-term factors such as those of the underlying surface and climatic characteristics are considered as a uniform system. As research has shown (Babkin et al., 1972), annual water resource assessments using regression and factorial models yield practically identical results. Regression equations and factorial analysis models are fairly widely used in many countries to assess runoff characteristics for individual river basins. However, it is more or less impossible to use these methods to assess renewable water resources worldwide, given the extremely wide range of natural conditions and the need for a huge amount of basic data.

In situations where the hydrological network is undergoing development, the different possible kinds of runoff functions of meteorological factors are not used for assessing water resources but are of subsidiary importance and, for example, are used in extending series and filling in blank spaces in observations. However, in the past 10–20 years, the practical significance of these functions has risen sharply; they have come to be widely used for identifying natural flow characteristics of river catchments subjected to intensive economic activity (Shiklomanov, 1979; 1988; 1989).

For various tasks connected with calculations and forecasts of hydrological characteristics of river basins, a large number of models for runoff formation have been developed with both distributed and concentrated parameters (Kuchment et al., 1983; Lindsley, 1985; O'Donnel, 1986; Vinogradov 1988; Eagleson, 1991; etc.). To use these models properly, it is first and foremost essential to have hydrological observation data, as well as a great deal of basic meteorological and detailed data on the underlying surface of river basins. For the time being, they cannot be used to assess water resources worldwide, or even water resources in individual major regions and countries.

This is why the approach primarily based on meteorological information to assess renewable world water resources and their dynamics (for all regions, countries, and continents) cannot yield reliable results. For this purpose, the prime need is for data from direct observation of runoff on the world hydrological network. In this, it is useful to employ meteorological data from water balance calculations, different kinds of regression functions and runoff formation models, as additional data where observation series are missing, in short supply or unreliable. This approach was already used by Russian scientists in the 1970s in preparing the above-mentioned monograph "The World Water Balance and Water Resources of the Earth" (Korzun, ed., 1974). The approach is better grounded now, as more extensive series of hydrological observations have been built up and a potential capacity has emerged for obtaining data that used not to be available for many regions in Africa, Asia and Latin America that were poorly studied in hydrological terms.

Directly monitored hydrological observation data have unquestionable advantages over any oblique method of water resources assessment. Observation data for runoff are a basic integral feature of climatic characteristics and physical-geographical features for any basin, and the data's general results can be used for the most reliable assessments of a very wide range of water resources characteristics for separate months, seasons and years, and for calculating their variability in time and space.

At the same time, in using data from the worldwide hydrological network to make a global assessment of water resources, there are many shortcomings and difficulties, of which the following deserve to be signalled first and foremost:

- The very uneven spread of hydrological stations with stations covering areas that can range from 100–300 km^2 to 20 000–50 000 km^2 per station;
- Varying ranges of observation series (from a few years to 180–200 years);
- The existence of gaps in observations taken;
- The existence of large geographical areas without any hydrological networks (approximately 15–20 per cent of the Earth's surface, not counting Antarctica);
- Very great problems in having the requisite hydrological data despatched on time from many countries and regions.

All these shortcomings and problems are themselves a function of the present state of the worldwide hydrological network, caused firstly by the way it has developed itself closely associated with the world's general state of scientific and technical progress, and secondly by the steps taken by countries and international organizations to provide the scientific community, the economic system, and the community at large with the hydrological information they need.

The key issues of reliability in assessing water resources and their use in different regions and worldwide directly depend on the state of the world hydrological network, and also on the main trends being followed by present changes and future forecasts. This issue is treated in greater detail below.

3.2 THE WORLD HYDROLOGICAL NETWORK: ITS PRESENT STATE, PROBLEMS OF INFORMATION EXCHANGE AND GENERALIZATION

3.2.1 General

The hydrological network was mainly set up not for scientific purposes but to provide for economic development in different countries and regions; to meet community needs, and those of irrigation and industry; to obtain the information needed for water transport, for designing and operating power supply systems; for regulating runoff; and for flood protection. Hence the establishment and development of the hydrological network is directly associated with the economic development of a given country.

The hydrological networks along many of the major rivers of Europe and North America were set up in the second half of the nineteenth century at the peak of industrialization. For example, the beginnings of regular streamflow observations along the major rivers of Russia date to 1880–1883, roughly at the same time as measurements were beginning to be organized on rivers in other European countries. Thus, it is natural for countries in Europe and North America to have the densest hydrological network and the longest series of regular observations.

In recent decades, the hydrological network, including along smaller rivers and streams, has been set up not just because of economic considerations but also for scientific purposes, including the study of processes attached to runoff formation, for improving hydrological calculations and forecasting, and for evaluating the effect of human activities on the hydrological cycle and water ecosystems. In some places, experimental water balance stations are being set up, carrying out observations that are more frequent than was previously the case on all components of the hydrological cycle in the system that links the atmosphere, vegetation cover, soil and groundwater.

An understanding of the special importance of sustained regular hydrological observation series has emerged in the last few decades in the wake of long-term research into climate variations and changes, improving general circulation models, and setting up long-term international global and regional experiments to study the water-power cycle.

WMO data on the present-day world hydrological network (including the network for scientific purposes) and its distribution by continent, taken from the work of J.S. Rodda (1995) are given in Table 4. According to these data, there are about 64 000 observation points in the regular hydrological network for measuring river water discharge rates; of these, 52 per cent are situated in Europe and North America, which also account for 70 per cent of all gauging instruments taking unbroken observations. The same is more or less also true for all other components of the hydrological cycle.

Numbers of observation points for selected countries of the world are given in Table 5. The data show that the

Table 4—Global Hydrological Network (Rodda, 1995)

Variable	Type of station	Africa (RA I) (1)	Asia (RA II) (2)	S. America (RA III) (3)	N. & C. America (RA IV) (4)	S.W. Pacific (RA V) (5)	Europe (RA VI) (6)	Global total
		Number of stations						
Precipitation	Non-recording	17 036	39 456	19 247	19 973	15 276	40 367	151 355
	Recording	2 639	18 864	4 124	5 280	3 332	8 422	46 661
	Telemetry	8	1 916	211	1 023	515	459	4 132
	Radar	9	56	3	82	8	35	193
Evaporation	Pan	1 508	3 686	2 031	2 716	1 120	1 499	12 560
	Indirect method	374	7	40	11	1 049	488	1 969
Discharge	Total (*)	5 703	11 543	7 924	13 211	5 838	19 798	64 017
	Non-recording	3 045	8 479	5 691	2 080	2 043	6 137	27 457
	Recording	1 856	3 064	2 233	11 128	3 795	13 661	35 737
	Telemetry	39	2 033	158	3 613	1 075	2 561	9 479
State (water level)	Total (*)	3 410	6 405	5 872	11 274	1 167	10 474	38 602
	Non-recording	2 244	3 800	4 244	1 725	522	5 826	18 361
	Recording	877	2 300	1 628	9 549	642	4 599	19 595
	Telemetry	15	1 257	194	1 734	192	1 768	5 160
Sediment discharge	Suspended	859	3 820	1 561	5 217	619	3 712	15 788
	Bedload	6	685	505	0	1	549	1 746
Water quality		5 297	5 045	2 752	31 462	1 690	55 379	101 625
Groundwater	Water level							
	Observation wells	4 884	16 657	1 133	19 818	18 585	85 075	146 152
	Production wells	31 804	63 705	14 150	14 099	13 504	38 452	175 714
	Temperature							
	Observation wells	287	2 541	5 200	21 097	4 888	18 967	52 980
	Production wells	243	88	5 539	21 501	888	1 641	29 900
	Water quality							
	Observation wells	4 898	1 964	320	13 757	7 935	14 889	43 763
	Production wells	5 674	45 187	3 416	14 825	3 127	23 711	95 985

(*) The total includes stations not distinguished between "recording" and "non-recording".

world hydrological network's density varies widely: from one station for every 150–500 km^2 in developed countries of Europe to one per 5 000–10 000 km^2 in countries in Asia, Africa and South America. Thus, the extremely uneven dissemination of the hydrological network around the world is a prime shortcoming.

Another no less serious defect is how the world community is deprived of access to observation data in most of the hydrological stations referred to in the tables. This is explained by a host of objective and subjective factors, and first and foremost the lack, in most cases, of data on proper computer systems (in particular for past observation series), delays in their processing or simply resistance by those responsible for hydrological data to release them free of charge, considering the information to be a commodity or of value in some other way. All this has produced a situation where there is still no systematic or reasonably comprehensive worldwide hydrological observation database. This is particularly true for daily and monthly global river runoff data, for all continents or physical-geographical regions. It should be noted that the data in Tables 4 and 5 do not fully reflect the contemporary state of the world hydrological network (see section 3.2.3), since the information they contain is based on information submitted by countries to WMO in the late 1980s and early 1990s.

3.2.2 World hydrological databases

Mindful of the need to collect and collate world hydrological data, in the late 1980s it was decided, on the initiative of WMO and in cooperation with UNESCO and the German government, to establish a permanent Global Runoff Data Centre (GRDC) near Koblenz and a Global Precipitation Climatology Centre at Offenbach. More or less at the same time, WHO and UNEP set up a Collaborating Centre for Surface and Ground Water Quality at Burlington, Ontario, jointly with the Government of Canada, under the "GEMS/WATER" programme.

The Global Runoff Data Centre has so far been the great hope for providing the world scientific community with systematic information on the key component of the hydrological cycle, aggregate world runoff. The centre was established in 1988 at the Federal German Institute of Hydrology. The centre's main goal is to provide the international scientific community with systematic global hydrological data, in particular for the long-term international projects of WMO and UNESCO.

The GRDC's hydrology data mainly come from WMO Member States in accordance with special requests. When first founded, the centre requested monthly and daily data for relatively small river basins (up to 10 000 km^2), with natural runoff. Later (from 1993 onwards) it gave priority to collecting hydrological information for all years with observation series, for major rivers with the following characteristics:

- Mean annual flow rates of more than 100 m^3/sec;
- A catchment of greater than 1 000 000 km^2;
- A population of more than 100 000 living in the catchment.

In collecting the information, the centre is guided by the following basic principles:

- The information providers are responsible for accuracy, as a result of which all materials sent in are entered in the databank without being analysed;

Country	*Area (km^2 × 10^3) (rounded)*	*Number of observation stations*			*Network density (km^2 per station)*	
		Water level measurements	*Discharge measurements*	*Total*	*Discharge measurements*	*Total*
Russia	17 080	669	3 314	3 983	5 150	4 300
Canada	9 976	461	1 998	2 459	5 000	4 060
China	9 561	10 000	3 300	16 300	2 900	590
USA	9 356	10 979	10 941	21 920	860	430
Brazil	8 512	1 804	1 472	3 276	5 800	2 600
Australia	7 686	757	2 991	3 748	2 600	2 000
India	3 280	74	829	903	4 000	3 600
Mexico	1 973	240	979	1 218	2 000	1 600
Indonesia	1 904	32	420	452	4 500	4 200
Iran	1 648	-	828	828	2 000	2 000
Angola	1 247	46	128	174	9 700	7 200
Mozambique	783	268	192	460	4 100	1 700
Turkey	780	86	806	892	970	870
France	547	-	-	2 564	-	210
Spain	504	262	505	767	1 000	760
Germany	357	2 100	2 500	4 600	143	78
United Kingdom	244	-	720	720	340	340

Table 5—Number of observation stations on rivers in selected countries

- The centre collects data only from direct observations and any conclusions drawn from them are filed only on the basis of these data (i.e. it does not extend series, fill in blank spots, or run any economic impact studies, etc.).

By the beginning of the new millennium, the GRDC's databank contained daily and monthly information on runoff from some 3 200 stations in 2 900 river catchments (including tributaries). These data were drawn from around 140 countries on every continent and had series going back different lengths of time, from just a few years to 100–150 years. The reliability and precision of the data varied widely, and unfortunately most data covered only the period up to 1980–1985. It should also be noted that the bulk of the information arriving at the centre was provided in the first few years of its existence, after which the datastream dried up radically. The centre's administrators are doing all they can to expand the databank, improve the quality of its information, collate it and assemble data on runoff for use with such long-term World Climate Research Programme (WCRP) activities as GEWEX, ACSYS and so forth. However, the situation is improving only slowly and so far the centre does not have a reliable or complete hydrological databank for the whole world, in particular the past five to ten years.

The traditional collection and collation of hydrological data on the global and regional scales is also being done as part of various projects in the UNESCO International Hydrological Programme (IHP UNESCO) and the WMO Hydrological Water Resources Programme (HWRP WMO). This work was conducted in Russia between 1970 and 1974 to try and assess different components of the world water balance and water resources as part of work on the drafting of Korzun's 1974 monograph. In drafting the work, an enormous amount of hydrometeorological information was collected from all continents, in particular on world runoff (for the years 1960–1967), but the archive is more or less inaccessible for wide use, as it has not been collated or computerized.

In the last ten years, under the UNESCO IHP-4 project in Russia, the SHI has done a great deal to push forward runoff data collection, systemization and collation on the world's rivers (only monthly and yearly) for the drafting of a new monograph entitled "World Water Resources at the Beginning of the 21st Century" (Shiklomanov, 2003). For this activity, as well as the data selected from the GRDC, much additional information was obtained by requests to different countries. A lot of the data was systematized and sent to UNESCO, but it is far from being the definitive hydrological data bank needed to study the global hydrological cycle. It consists only of information directly used in assessing world water resources; at the same time for most of the world, there is also a more or less complete lack of observational data for the last 10–15 years.

3.2.3 Present-day state of the network

The above data (Tables 4 and 5), based on information provided to WMO by national hydrological services, mainly date to the 1970s and 1980s and provide for many countries more or less the most optimistic picture of the number of gauge stations and, in any case, cannot reflect the dynamics of the hydrological network over time. Unfortunately, the past two decades have shown a noticeably declining trend in the number of hydrological gauges and a considerable fall in standards.

As noted by many authors, the contraction in the hydrological network has primarily occurred in many developing countries of Asia, Africa and Latin America. The largest number of gauges were set up in the late 1970s and early 1980s, only to see a scale-back of the network, which is still ongoing.

A similar picture of retrenchment can be seen in countries with economies in a state of transition, chief of them the countries of the former Soviet Union. One example can be seen in Figure 2 which shows a curve in the number of hydrometric stations along Russia's rivers. Their establishment peaked in 1986 but in subsequent years there has been a noticeable cutback in their number down to 30 per cent. The largest fall was in Asiatic Russia, the sparsely inhabited areas of Arctic Siberia and the Russian Far East, which had never supported a very dense hydrological network. The data in the figure are typical for more or less all the countries of the former USSR. The hydrological network also contracted in the

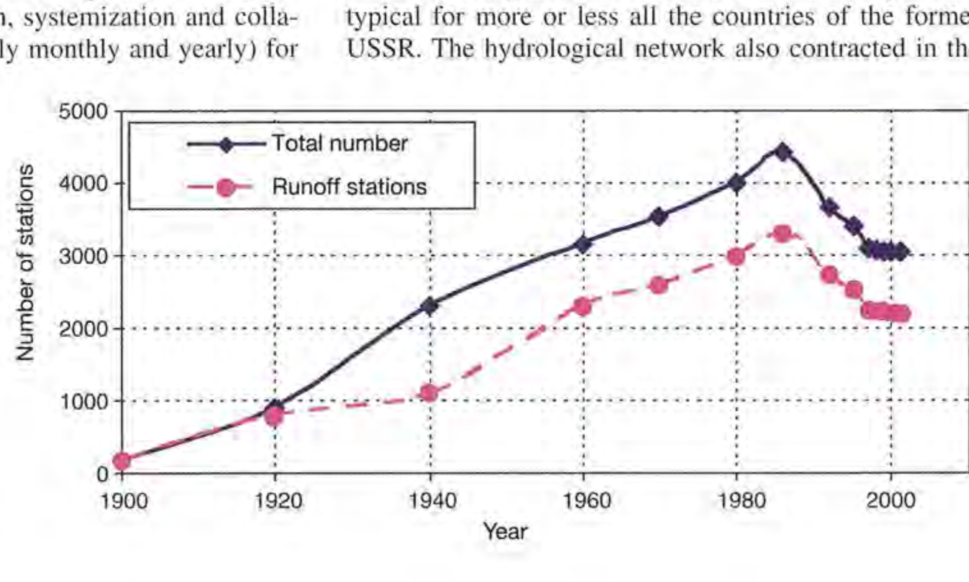


Figure 2—Variations in the number of hydrological stations in Russia

Aral Sea basin (Chub, 2000) (Table 6), generally recognized as an ecologically distressed area following the over-intensive economic use of water resources in it.

However, the scale-back of hydrological stations in the last 20 years is not confined to developing countries or those in a state of economic transition. It is also occurring in certain developed countries and, unfortunately, the tendency is becoming worldwide. Thus, as our data show (Lanfear and Hirsch, 1999), even the US hydrological network is becoming sparser. Figure 3 shows the dynamics of the hydrological network in the Arctic Ocean basin (Shiklomanov A. et al., 2001). Beginning in the mid 1980s, the basin's hydrological network fell by approximately 30 per cent, the reduction being more or less equivalent in the North American portion of the basin to that in the Russian portion. Moreover, in some major areas of both Canada and Russia, there were 50–60 per cent fewer stations (Figure 4).

Evidently, the main causes of the decline in the hydrological network are the constantly rising maintenance and repair costs, associated with insufficient funding; the absence or shortage of technical resources for observations; difficulties in hiring observers because of the harsh working conditions and very low wages. The situation is explained in no small measure, in the author's opinion, by the fact that decision makers and budget holders do not fully understand or are not well enough informed of the great scientific and practical importance of providing an unbroken flow of observations on hydrological regimes.

Country	*Number of stations*		*Difference between 1998 and 1985 (%)*
	1985	*1998*	
Kyrgyzstan	147	111	75
Tajikistan	139	85	61
Turkmenistan	38	23	60
Uzbekistan	155	119	77
South Kazakhstan	80	58	72
Total	**559**	**396**	**71**

Table 6—Number of hydrological stations in the Aral Sea drainage area in 1985 and 1998 (Chub, 2000)

Along with the dwindling network, in many countries there has been a deterioration in hydrological data as a result of deviation from the requirements laid down in guidelines and manuals. The reasons are:

- A lack of reliable technical and measurement equipment, and of facilities for metrological calibration; in many countries, the hydrological network is in a technically critical condition;
- Too few measured water discharge rates, particularly during times of flooding or in winter;

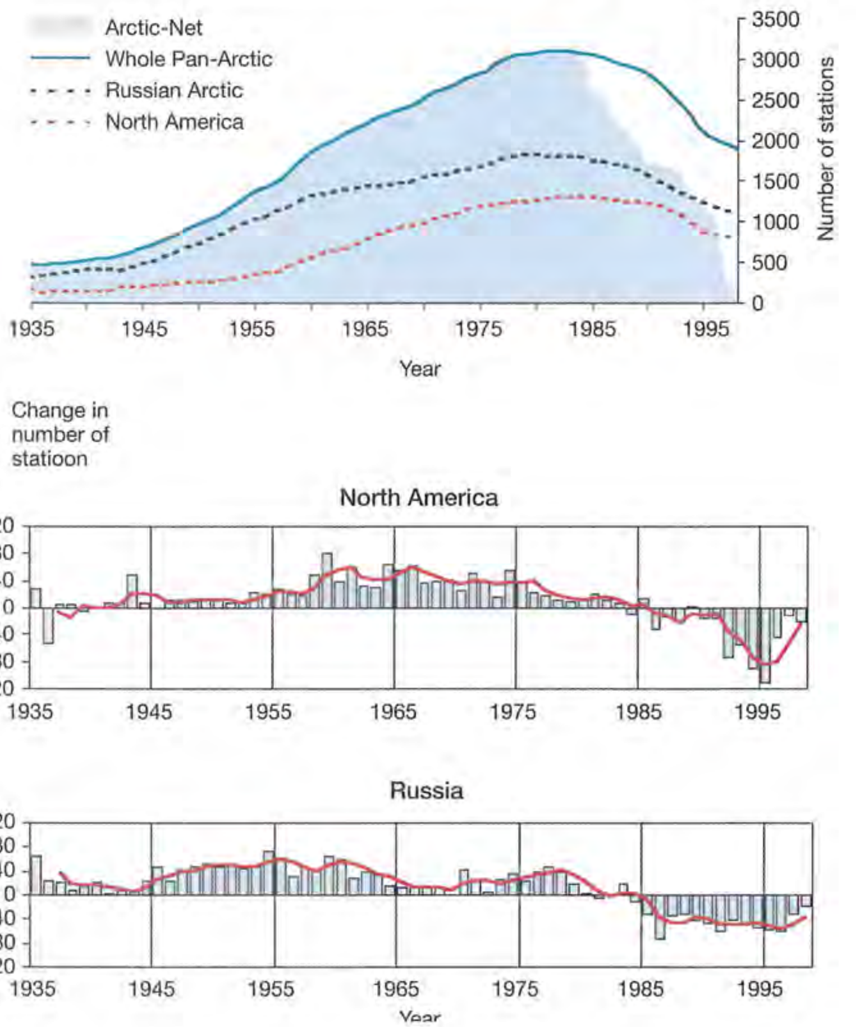
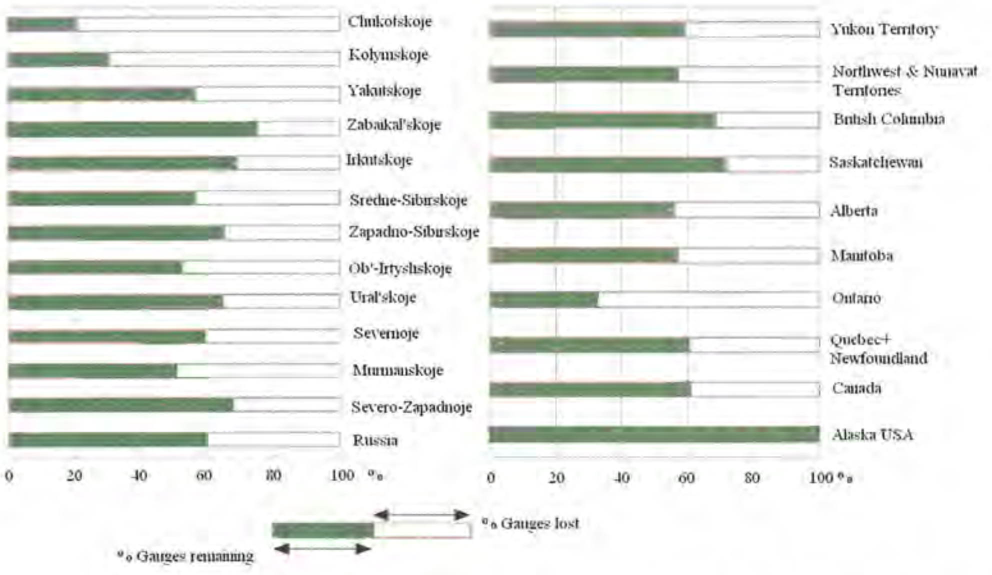


Figure 3—Dynamic of the river gauges in the pan-Arctic drainage basin and data available

Figure 4—Reduction of the hydrological network in different regions of Russia and Canada within the Arctic Ocean drainage area



- Delays in processing observation data for want of human resources and computer systems;

Incompatibility between measurement methods and runoff calculations used in different countries; this means that runoff calculations from neighbouring stations but in different countries have major discrepancies as high as 10–20 per cent or more (e.g. transboundary rivers such as the Nile, Congo and Amu Darya).

3.2.4 Problems in obtaining and exchanging hydrological information

One feature of hydrological information is how hard it is to obtain and process speedily, for both objective and subjective reasons. Objectively, unlike meteorological information used for transmission and exchange, it takes a long time to prepare. Measurements of water discharge rates and river levels are not the same thing as runoff. Runoff data (monthly and daily) are usually obtained by analysing measured discharge rates and levels in the course of the year or else flow rates for previous years. This means there can be an objective delay in obtaining streamflow data of one or two years. However, the lack of resources and technical equipment often means that it is many years before measured discharge rates and water levels are processed, and then runoff data cannot be obtained for exceptionally long periods of time.

Another problem lies in the fact that unlike meteorological data, many countries see no interest in a regular exchange of information. For example, countries lying upstream in river basins do not normally need information from down-river areas and so presume that there can be no exchange of hydrological information that is equal in value. It is particularly hard to obtain reliable hydrological information from water-starved areas in international catchments where there are freshwater sharing conflicts between countries in the catchment. Here, hydrological data are often considered as invaluable economic information not intended for exchange or for wide dissemination.

Thus it is that, taking as a departure point the present state of the world hydrological network and the specific nature of hydrological information, for all the various WMO resolutions (resolutions 40 and 25, on the exchange of data), international and national centres experience major difficulties in trying to reach conclusions on worldwide runoff generalizations. The difficulties include the following:

- Differing degrees of comprehensiveness and heterogeneity as to reporting deadlines in different countries; though fairly comprehensive information can be obtained from countries in Europe and North America for even the last few years, it is practically impossible to obtain data from developing countries for the last 10–15 years;
- Data are normally reported, not from the hydrological gauges needed for analysis and generalization, but from those that countries consider of interest in reporting data;
- Considerable range of quality in the information obtained, often with no analysis of reliability or accuracy;
- Data on streamflow at river mouths are normally absent; for many major rivers, flows are measured at gauges hundreds of kilometres upstream from their mouths (for example, streamflow in the Amazon is measured 1 000 km above its estuary, and from the Yenisei 350 km from its mouth);
- There are no analyses of the impact of economic activities on the hydrological regime, especially river flow regulation; many kinds of runoff and flow data (monthly, daily) are sent to information collection centres but do not reflect the natural hydrological regime in the basin, rather the flow as regulated by reservoirs.

The present-day state of the world hydrological network, difficulties in data exchange, and production of findings, are all responsible for the extremely poor or even absurd world situation with regard to the study of the global hydrological cycle. For example, though global temperature and precipitation data are available for scientific use more or less in real time (the delay in furnishing them is no more than one or two months), then it may take no less than 15 years (see section 3.3) to have such crucial components of the hydrological cycle as the values for renewable water resources and freshwater discharge into the world's oceans determined more or less in detail and reliably. Naturally, this situation makes for extraordinary difficulties in studying the global hydrological cycle and requires urgent measures to remedy it.

3.2.5 World Hydrological Cycle Observing System (WHYCOS): the idea behind it and its present realization

To try and collect hydrological data in close to real time, in the early 1990s, WMO and the World Bank joined forces in an initiative setting up the World Hydrological Cycle Observing System (WHYCOS). It was proposed to establish some 1 000 special platforms at existing hydrological stations along the world's greatest rivers. The platforms would undertake automatic measurements of water levels, various physical-chemical components of water quality, meteorological features (15 in all) and use geostationary satellites to despatch the data to country, regional and global centres (Rodda et al., 1993; Rodda, 1995). It was planned to set up this system over a period of 20 years, thereby laying solid foundations for swift inputs of global hydrological data.

It should be recalled that every WHYCOS platform is a complex and expensive device in its own right; and the establishment of a system will require major R&D if reliable data on overall streamflow and discharge into the ocean are to be received. For example, in many rivers, particularly around river mouth gauges, the link between river levels and discharge rates is not very good; it is also essential to find a way of allowing for streamflow from areas not covered by observations (downstream from interconnected gauges), many great rivers are regulated, and methods for reconstructing the streamflow regime, etc., need to be developed.

It seems obvious that, from the standpoint of establishing the WHYCOS in practice as an international worldwide observation system, any technical, R&D, budgetary and legal matters, as well as priorities, order of precedence, and deadlines for setting up platforms on given river systems must be set out in general outline in the WHYCOS plan. Unfortunately, this concept was not developed in the overall plan, and implementation of the system, beginning in 1995, was based on the principle of establishing regional hydrological cycle observing systems (HYCOS). For example, regional projects for the Mediterranean and South Africa are already being implemented, and project documentation is being drafted for projects in the Black Sea, the Baltic, the Caspian and Aral Seas, West and Central Africa, and the Arctic Ocean (WHYCOS, 1998).

Countries of the region have an interest in organizing regional projects, and, in drafting project documentation, they are first and foremost trying to solve their own burning regional problems related to the exchange of hydrological data, those for example that are needed for the early forecasting and management of water resources, emergency early warning systems, etc. At the same time, the global aspects of studying the hydrological cycle, the original reason for establishing WHYCOS, have to all intents and purposes been shelved, and no R&D is provided for under the plan.

The foregoing means we can safely say that the adoption of WHYCOS on a regional basis will not make it very likely that in the next 10 to 15 years the operational hydrological data can be obtained that are needed for a reliable assessment of overall global river flow and discharge into the world's oceans. Evidently, other ways will have to be found to deal with this problem.

3.2.6 Proposals for improving the collection and generalization of global hydrological data

To assess renewable water resources, study changes to the global hydrological cycle, and improve present atmospheric circulation models, it is first of all crucial to have swiftly-accessible and reliable monthly and annual characteristics available on:

- River discharge into the world's various seas and oceans;
- Average streamflow and its geographical distribution across major river basins and natural economic regions, selected countries and continents.

To obtain these numbers, the data existing in the present network for runoff into rivers, precipitation and air temperature are made use of.

As shown by the analyses and assessments of world runoff and streamflow, to deal with the first of the two tasks it is crucial to:

- Have information for only a few hundred (no more than 400–500) hydrological gauge stations at the mouths of the world's great rivers;
- Have monthly precipitation and air temperature observation data for specially selected weather stations in areas round major river mouths;
- Develop methods of assessing inflow from areas not covered by observations; these make up some 15–20 per cent of the land below the gauges on selected rivers and include basins of smaller rivers discharging directly into the sea.

These data will be insufficient to deal with the second objective; what will be needed is also to obtain runoff data in areas where water resources for the main river systems originate (approximately 800–1 000 gauges). In addition, meteorological data may also be needed in the mid- and upper reaches of selected rivers. A key stage in this part of the work is to develop a dependable model for assessing mean monthly and annual flow values for any regions drawing on available data from meteorological and hydrological observations and detailed geographical information systems (GIS), which provide information on the underlying surface.

Thus, if these proposals for assessing the global characteristics of runoff and discharge into the world's oceans were accepted, it would be enough to have a relatively small amount of basic hydrological and meteorological data. In the author's opinion, given a small effort by international organizations, these could quite easily be made accessible to the hydrometeorological community in next to no time comparatively speaking (no more than a few months). The development of models to calculate streamflow for monthly and annual periods from areas not covered by observation data, and for assessing renewable water resources in those regions, cannot be a serious obstacle. The chief factors in conducting the work are, in the author's opinion:

- A proper selection of the most representative and reliable hydrological gauges and meteorological stations;
- The use of a simple streamflow calculation model that is physically properly grounded, for use in different physical-geographical conditions;
- A clearly defined plan of work for collection, transmission, analysis and dissemination of information.

It seems completely realistic for a team of experienced specialists (some 5–6 individuals in all) based at an international centre such as the Global Runoff Data Centre (GRCD), to do the work within 1.5 to 2 years. That would subsequently provide the hydrometeorological community with reliable analysed worldwide runoff data within deadlines of no greater than 3–6 months.

3.3 BASIC DATA AND ASSESSMENT METHODS USED BY THE SHI

The methodological approach to assessments of renewable global water resources employed at the Russian SHI in recent years has been the extensive use of observation data from the world hydrological network. In this effort, meteorological information, consisting of data on air temperatures and precipitation, has been used as auxiliary data.

According to WMO data (Rodda, 1995), the world now has some 64 000 hydrological stations regularly measuring water discharge rates in rivers. The geographical distribution of the stations is extremely irregular (see section 3.2.1), with observation series ranging from just a few months to 180 years. We have had up to 40 000 streamflow data observation points available to us in varying degrees; they provided information of all sorts of quality on runoff in different countries, including fragmented and unsystematic data for individual years or even months. The information included data used for building up country or regional mean annual streamflow and runoff. The data came from the most varied sources:

- SHI archives amassed in the 1970s when the monograph "World Water Balance and the Earth's Water Resources" with its atlas of world maps (Korzun, ed., 1974), was being prepared. Unfortunately, this consists of raw, unsystematic data not available in digital form;
- The WMO Global Runoff Data Centre (GRDC) and UNESCO publications on runoff from selected rivers of the world;
- Various countries, based on special questionnaires circulated by the SHI or periodically arriving at the institute under an information exchange system;
- Different publications from international and regional organizations, as well as from individual authors on every continent.

Not all available data for assessing the global dynamics of water resources can be made direct use of, because they are so heterogeneous (and in any case there is no need to use them directly). The hydrological gauges were therefore chosen in accordance with the following main criteria:

- The existence of the longest possible series of unbroken observations;
- The location of gauges on large and medium-sized rivers, with a geographical distribution that is as even as possible;
- Observations should show streamflow that is either natural (or nearly natural).

Thus, the monthly and annual observation data directly used to assess worldwide renewable water resources came from approximately 2 500 hydrological gauges, including some 800 from Asia, 600 from Europe, 400 from North America, 250 each from Africa and South America, and about 200 from Australia and Oceania. The distribution of these stations by continent is shown in Figure 5.

The existence of extended observation series was of prime importance for choosing hydrological gauge stations, since it was in line with the chief methodological principle used at the SHI: that the assessment of water resources for all continents and regions of the world must be based on one and the same relatively extensive period of many years. Compliance with this principle is crucial in obtaining homogeneous and comparable results. Unfortunately, a large number of selected hydrological gauge stations, particularly ones located in developing countries of Africa, Asia and Latin America, have very short observation series (10–15 years); what is more, for most stations, observation data were available only for the period 1980–1988 (see section 3.2).

In the light of the above, it proved possible, in the assessment and analysis of the dynamics of renewable water resources for all continents and regions of the world, to adopt a single counting period from 1921 to 1985, although for many countries of Europe and North America there are data available for later periods too, including for the most recent years.

The adoption of a single, long calculation period (65 years) has meant that comparable mean figures for

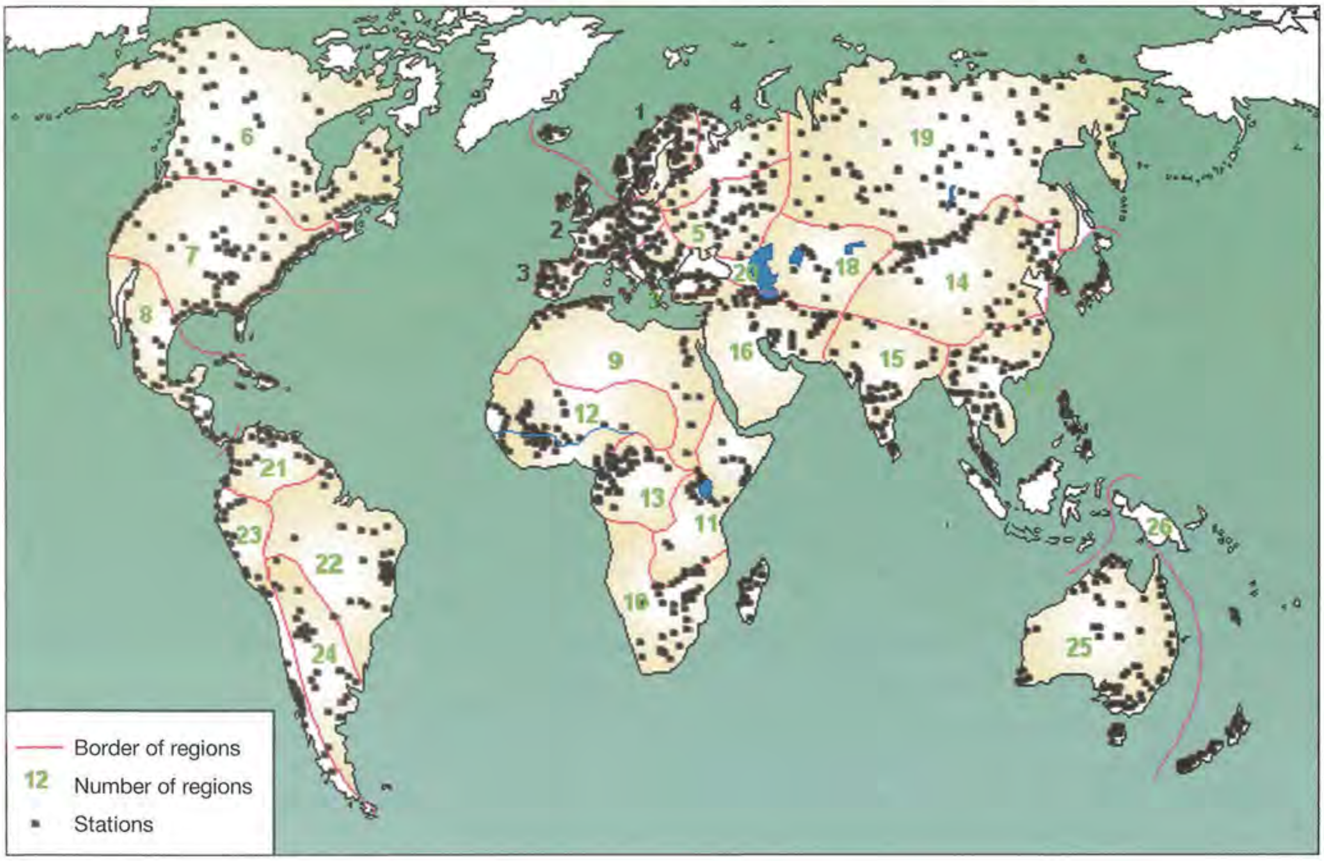


Figure 5—The natural-economic regions of the world and gauge stations

water resources in every part of the world can be obtained together with a reliable assessment of extreme values and their long-term variability.

Observation series for monthly and annual streamflow for all the hydrological gauges selected were analysed to identify and eliminate various coarse errors in the data, and gaps in observations when no readings had been taken. Blank periods in monthly data tended to be filled in by calculations that normally used twin or multiple correlations. Moreover, the factors normally used were streamflow observation data from nearby gauges on the river in question or its tributaries. Where there were no such observations, data were often taken from similar river flows, from basins located in the same region and with identical physical-geographical conditions and hydrological features. Annual flow values for blank years in observation series were worked out by integrating calculated monthly values.

Such procedures were used for observation series at selected gauges to cover the period 1921–1985. However, data from analogous rivers had more often to be made use of; in many cases, meteorological data such as observations for precipitation and air temperatures were resorted to, to get more reliable results. For this purpose we had available a worldwide meteorological information databank giving monthly precipitation and air temperature for the whole period from 7 000 weather stations. As a rule, when filling in the blank periods in observations and extending the series, it proved possible to obtain regression equations with a correlation coefficient of $r \geq 0.80$.

The characteristics of catchment water resources, where streamflow rises as one travels downriver, was determined using standard statistical techniques on runoff data at the gauge where it is at its largest and on streamflow from tributaries entering the main stream, below the gauge but upstream from where it enters the ocean or sea.

Where there were no data for tributaries, the volume of flow below the most downstream gauge on a river was assessed using available charts showing mean annual runoff and streamflow from similar rivers in the region under examination. In some cases, meteorological data were drawn on. It should be noted that on many of the world's major rivers, the lowest gauge stations are fairly far from river mouths, and, if the only data used are those coming from these gauges, as is often the case, then a determination of overall water resources in the river basins, particularly those from side rivers flowing into the seas, can lead to grave errors of appreciation.

Many major river basins, particularly those in southern areas, have upper and lower stretches of their basins that differ sharply in terms of runoff formation. The upper reaches of such catchment areas are usually situated in mountain and piedmont regions where the main water resources of the basin originate and can be considered the runoff formation zone. The downstream portions of basins, plains and depressions with hot dry climates, are areas where streamflow is drawn off through natural evaporation or for economic needs. Almost all rivers in endorheic regions have such basins (e.g. Amu Darya, Syr Darya, Kura, etc.), and also many rivers from areas of external streamflow, located in low latitudes (Ganges and Brahmaputra, Tigris and Euphrates, Indus, Nile, Zambesi, Colorado, Rio Grande and many others). The outstanding feature of rivers with such basins is a fall-off in the volume of streamflow from the main channel from the river's headwaters to its mouth.

For these rivers, the characteristics of renewable water resources are determined from streamflow data measured at the hydrological gauge on the main watercourse, at the bottom end of the headwater zone (the mountain portion of the basin) or, where no such gauge exists, they are calculated from the cumulative streamflow from all tributaries in the headwaters area. These are determined from observation data or by means of regression functions, from similar catchment areas or annual runoff charts.

Discharge into the seas and oceans from catchment areas with runoff formation and utilization zones, are assessed using streamflow characteristics taken from the lowest gauge in a basin, making rough calculations of losses (or tributaries) between gauge and mouth. In this way, in calculating figures for tributaries, losses through evaporation and economic utilization are taken account of in areas where this takes place.

Overall streamflow into the seas and oceans from a continent's seaward-facing slopes is calculated by combining runoff for all river catchment areas, except for areas where there are endorheic regions; there are such regions in very considerable areas on every continent (see Chapter 4). For small and medium-sized rivers flowing directly into seas and oceans and not covered by observation data, streamflow characteristics are calculated using equivalents from similar rivers as a model, employing regression functions, and sometimes incorporating meteorological data.

Water resources and outflow into oceans from islands were determined by using available observation data on streamflow and the hydrological analogy method. Water from islands in South and East Asia, Africa, South and Central America, where no data are available and the analogy method cannot be used, was determined on average for long-term periods from available streamflow charts and from precipitation module coefficients for separate years.

Water resources from islands in the Arctic Ocean are chiefly determined by the analogy method or by water balance, and analogous catchment areas chosen from the mainland are used in most cases.

To determine the quantitative characteristics of renewable water resources in natural and economic regions, countries, and different administrative entities whose borders do not follow the boundaries of river basins, required the development of special calculation models and methods. The methods used are based directly on observation data, and include runoff isolines, runoff linear equations, integrated regression and integral averaging equations for runoff surfaces, taking account of the height of a given position above sea level (Babkin et al., 1977, 1986; Shiklomanov, 1988).

Water resources in any given region are determined by the following basic runoff characteristics: local runoff, inflow, and river water discharge. Local runoff for a region consists of the streamflow from all rivers, temporary and seasonal watercourses that accumulate on its territory: the inflow of river waters aggregate volume of streamflow brought into a given region from neighbouring areas; outflow of river waters: i.e. the total volume of streamflow carried outside a given region by all rivers, temporary and seasonal watercourses. The total size of local streamflow and inflow consists of the aggregate or general renewable water resources in a region. As a whole, the larger the region, the smaller the difference between overall and local water resources. For continents, the two notions practically coincide, for most larger countries and natural-economic regions the difference between the two is either largely non-existent or insignificant. However, so far as small countries and individual natural-economic regions are concerned, general water resources can be many times greater than local runoff. In this case, if the ratio of overall to local water resources is ignored when assessing figures for active water availability, it can lead to the wrong results and conclusions.

In the work of the SHI, the characteristics of annual water resources from each region were determined from observation data, using either the so-called streamflow linear equations method or an integral averaging method for streamflow surface.

Under the first of the two methods, calculations for each region are made by linear equations using annual streamflow values from stream gauges and taking into account weight coefficients representing the ratio of streamflow volume at the observation gauge to streamflow volume in relation to that portion of the catchment lying within the boundaries of the given region. The values of the weight coefficients are usually accepted as constant for all years in a calculation period and are determined by the runoff values obtained from runoff layer charts or standard modules (Gidrometeoizdat, 1981) or the relationships between the corresponding areas of water catchments (Babkin et al., 1977).

Under the second method, an assessment of the characteristics of water resources for each region can be reduced to a determination of the double integral from the function of the runoff surface, while taking into account the coordinates of water catchments and the height of the locality above sea level (Babkin et al., 1977). The equation usually comes in the form of a polynome. In principle, the method makes it possible to take account both of coordinates and the height of a locality, and of other figures governing the amount of runoff, such as soils, land use, swamps, etc. The advantage of this method is the capacity it confers for using identical calculation equations and coefficients for different hydrological gauges, whose number can vary from year to year.

The fundamental difficulty when making wide practical use of the method is the need to develop dependable runoff functions on the height of a locality and other factors, which presuppose the existence of detailed hydrological information for each region. This method can therefore be used only in selected areas of the former USSR. Generally speaking, both these methods yield practically the same results when used over largish territories, as trials have shown.

The existence of annual values for water resources and inflow into the world's oceans for an extended period (1921–1985) allows their long-term variability to be assessed; the latter is expressed, as is customary in hydrological calculations, as the variability coefficient Cv, whose value is a square root of the ratio of the standard deviation. What is more, maximum and minimum annual or mean values for two to three years are also analysed for all series for renewable water resources over a long-term period.

As we are aware, renewable water resources vary very widely not only year on year but also intra-annually, seasonally and from month to month. When applied to river basins they are determined directly from observation data, as an average for the entire period, or for a number of years with differing precipitation and runoff levels (high, medium or low). For natural economic regions and continental slopes, monthly water resources values were determined as fractions of annual values by totalling monthly runoff data for the main river basins located within them.

3.4 WATER RESOURCES OF RIVER BASINS

The key to assessing renewable water resources for countries, regions and continents is the runoff from river basins, calculated on the basis of observation data from the hydrological network. Table 7 shows water resources data for the world's largest river basins: these are the thirty separate river basins that have mean annual water resources of greater than 100 km^3 (tributaries flowing into them are not included).

The world's greatest river in terms of its catchment area and volume of annual streamflow is the Amazon, drawing down 16 per cent of the entire world's total streamflow, while the water resources of the five largest river systems (Amazon, Ganges-Brahmaputra, Congo, Yang-Tse and Orinoco) account for 27 per cent of the world's entire renewable water resources. The rivers with data shown in Table 7 are spread out on every continent, and their aggregate water resources amount to 40 per cent of the world's renewable water resources. The data in the same table show that the Amazon is the largest river in the world in the size of its annual streamflow and catchment area. However, in terms of length it comes second to the Nile in Africa (6 670 km); among the longest rivers are also the Mississippi and its tributary the Missouri in North America (5 885 km), and the Yang-Tse (5 520) in China.

It is worth comparing the specific flowrate in river basins shown in the table, usually expressed in millimetres as the depth of runoff evenly distributed across the entire area of a catchment. The river basins with the greatest runoff depths are those in wet tropical and equatorial belts with heavy rainfall (Orinoco, Amazon, Magdalena, Mekong, Ogowe, Yang-Tse), whose streamflow depths range from 500 to 1 000 mm; and Papua-New Guinea's rivers (Sepik and Fly) with annual streamflow depths of 1 500 to 2 000 mm.

The lowest specific flowrates (50–150 mm) are characteristic of rivers with a considerable portion of their catchment area lying in zones where humidity and precipitation are in short supply (Nile, Niger, Zambesi and Ob).

A key feature of rivers is their long-term variability or the changes in annual streamflow from year to year, which can be expressed as the range of runoff variations for the period of observations or variability coefficients Cv. For the world's great rivers (Table 7), the coefficient ranges from 0.04–0.10 to 0.20–0.26 in magnitude. Evidently, the lower the variability in a basin's water resources, the greater the prospects for using them for economic needs without resorting to long-term regulation.

By way of example, Figure 6 shows long-term water resources variations for the chief river basins of South America and Africa during the period covered (1921–1985). It is interesting to note that in the last two decades of that period there was a noticeable decline in water resources in the river basins of Africa and a rise in those of South America. Analyses of long-term variations in water resources and their monthly and seasonal distribution, which are more detailed for almost all the river basins shown in Table 7, are given in the 2003 monograph edited by the present author. (Shiklomanov, ed., 2003)

It should be noted that the data in Table 7 and Figure 6 are characteristic of aggregate renewable water resources in river basins. For some basins, that have both headwater areas and areas of draw-off (see section 3.3), the figures given can be significantly larger than those at river mouths where they enter the seas or oceans, as a result of losses in streamflow through natural evaporation and withdrawal for economic needs.

In this regard, the data given in Figure 7 on long-term variability in renewable water resources and outflow at the mouths of the Amu Darya and Syr Darya rivers in Central Asia are extremely indicative. The total area of these two rivers' catchment areas, which flow into the endorheic Aral Sea, is some 1.54 million km^2; the basins fall into two parts: the mountain areas of the Tien Shan and Pamir Alay, where their headwaters originate, and the great plains areas (desert and semi-desert of the Turan depression), where the water resources are drawn off, through natural evaporation or for economic needs (chiefly irrigation).

As shown in Figure 7, the dynamics of water resources from the rivers referred to, as determined from observation data taken from the headwaters area, were more or less stable throughout the period under consideration (1930–1995), and averaged 114 km^3 per annum, including 76 km^3 per annum for the Amu Darya basin and 38 km^3 per annum for the Syr Darya basin.

Outflow from the two rivers have completely different characteristics at their mouths where they flow

River	Continent	Area (mln. km²)	Length (km)	Water resources (km³)			Variation coefficient Cv	Depth of average water resources (mm)
				Average	Min	Max		
Amazon	S. America	6.92	6 280	6 920	5 790	8 510	0.08	1000
Ganges	Asia	1.75	3 000	1 389	1 220	1 690	0.04	794
Congo	Africa	3.50	4 370	1 300	1 050	1 775	0.10	371
Orinoco	S. America	1.00	2 740	1 010	710	1 380	0.15	1010
Yang-Tse	Asia	1.81	5 520	1 003	610	1 410	0.15	554
La Plata	S. America	3.10	4 700	811	450	1 860	0.26	262
Yenisei	Asia	2.58	3 490	642	466	749	0.08	249
Lena	Asia	2.49	4 400	539	424	670	0.11	216
Mississippi	N. America	2.98	5 985	515	281	881	0.24	173
Mekong	Asia	0.79	4 500	505	376	610	0.16	639
Ob	Asia	2.99	3 650	404	270	586	0.16	135
Amur	Asia	1.86	2 820	355	225	538	0.21	191
Mackenzie	S. America	1.78	4 240	325	284	427	0.12	183
St. Lawrence	N. America	1.03	3 060	320	242	405	0.10	312
Niger	Africa	2.09	4 160	303	163	482	0.26	145
Volga	Europe	1.38	3 350	250	161	390	0.19	181
Columbia	N. America	0.67	1 950	237	144	331	0.18	355
Magdalena	S. America	0.26	1 530	230	-	-	0.08	846
Danube	Europe	0.82	2 860	225	137	321	0.18	274
Indus	Asia	0.96	3 180	220	126	359	0.19	229
Yukon	N. America	0.85	3 000	196	122	335	0.26	231
Nile	Africa	2.87	6 670	161	94.8	248	0.16	56.1
Zambezi	Africa	1.33	2 660	154	-	-	0.19	116
Ogowe	Africa	0.203	850	149	-	-	0.15	734
Fly	New Guinea	0.064	620	142	-	-	0.16	2219
Pechora	Europe	0.32	1 810	136	115	174	0.12	425
Kolyma	Asia	0.65	2 130	128	74.4	203	0.23	197
Sepik	New Guinea	0.081	700	120	-	-	0.16	1481
Fraser	N. America	0.23	1 110	115	82	155	0.13	494
N. Dvina	Europe	0.36	744	105	81.8	152	0.17	294

Table 7—Renewable water resources of largest major rivers of the world

into the Aral Sea, both in terms of volume and time dynamics. Until 1961, the shape taken by outflow into the sea was more or less static and averaged out at 50 km³ per annum, i.e. approximately 64 km³ per annum of water were lost to natural evaporation and economic demands. Moreover, increased water use in this area for the region in question was entirely made up for by the cutback in unproductive evaporation (Shiklomanov, 1989; Tsyetsenko, 2003). In the last few years, however, as irrigated areas in the basin and adjoining areas have continued to expand and compensatory resources have been exhausted, streamflow at the mouths of the two rivers suddenly fell sharply, and the steep falls in levels of the Aral Sea began (it has so far fallen by 20 m), with ever more damaging ecological and economic consequences. The damage has affected huge areas of land in the Aral Sea region, now declared an economic disaster region (UNESCO, 2000).

Extremely significant differences between total water resources and streamflow at river mouths also play a part in other river systems whose headwaters are separated from the zones where their water resources are found. For example, water resources in the Nile river basin are assessed at 161 km³ annually, with 54 km³ per annum arriving at the delta, with the equivalent figures for the River Niger being 300 km³ and 134 km³ per annum respectively, for the Zambesi 154 km³ and 111 km³ per annum at the river mouth, for the rivers Ganges and Brahmaputra 1390 km³ and 1250 km³ per annum, etc. It is very important to allow for these differences when assessing discharge of river waters into the seas and oceans and studying their water balances.

3.5 WATER RESOURCES IN DIFFERENT NATURAL AND ECONOMIC REGIONS AND CONTINENTS

Under the method developed at the SHI, major natural and economic regions of the world are prime research goals and used not only for assessments of global water

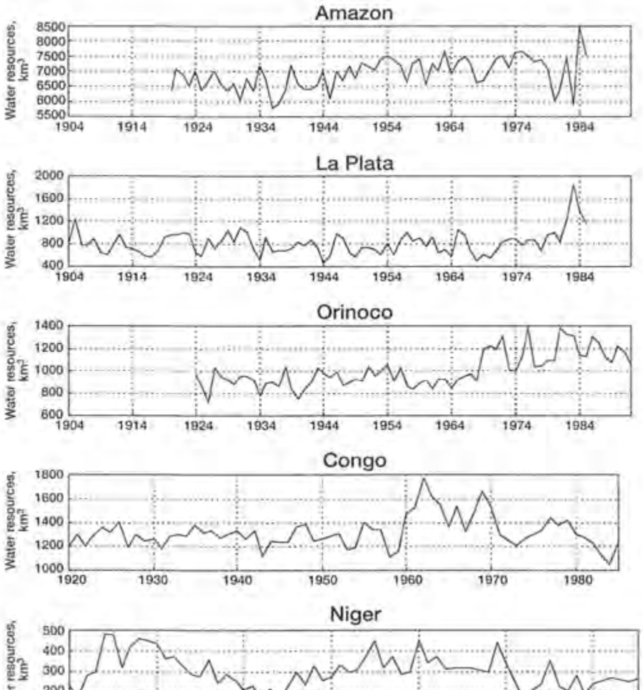


Figure 6—Water resources dynamics by largest rivers of the South America and Africa (km^3/year)

resources but also for water use, the distribution of water in time and space for determining water availability in different areas, and establishing the worldwide level of stress on water resources.

The natural and economic regions were selected for territories for each continent, according to whether their physical-geographical and socio-economic conditions were more or less homogeneous. In all, 26 such regions were identified, with from 3 to 8 on each continent. In most cases, the boundaries of the different regions followed the state administrative frontiers, and in this way each region included entire countries (between 1 and 15–17 countries). This was mainly due to the need to analyse water resources volumes as well as population dynamics, irrigated land areas, water consumption and other features of socio-economic development, statistics for which are published only by country. Exceptions are the world's largest nations (Russia, China and the USA), parts of them coming under different natural and economic regions. Figure 5 is a map of the world showing the boundaries and numbers of different regions. The areas of the selected regions vary widely: from 12–13 million km^2 (Siberia and the Russian Far East, Canada and Alaska) down to 0.19 million km^2 (the Caucasus), although most regions have areas of 1 to 8 million km^2. The distribution of countries by natural and economic regions is taken from Shiklomanov, ed. (1997).

Annual characteristics of renewable water resources for a single period (1921–1985) were obtained for every region, based on the observations and methods set out in section 3.3. Average values for these characteristics are given in Figure 8 and Table 8 as local water resources originating within a given region and total inflow of river waters from neighbouring regions. The data indicate that in most regions the basic water resources originate in the region itself but inflow from outside does not play a noteworthy role. Exceptions are Regions 3, 5, 10, 18 and 22, where inflows make up 20–25 per cent of local water resources, but in Regions 9 and 24 (North Africa and central South America), the inflow is comparable in size with local water resources or outstrips them several times over.

Analysis of the mean values obtained for water resources in the different regions shows that they are mainly determined by climate. This is backed up by, among other matters, the local water resources curve shown in Figure 9 (in mm deep) as a function of a complex climatic parameter, the dryness index $\frac{R_0}{PL}$ (where R_0 is the radiation balance from a wet surface, P is precipitation and L is the latent heat of evaporation). The dryness index was determined roughly for each region by using more detailed charts of radiation balance and precipitation (Budyko, 1956; Korzun, ed., 1974).

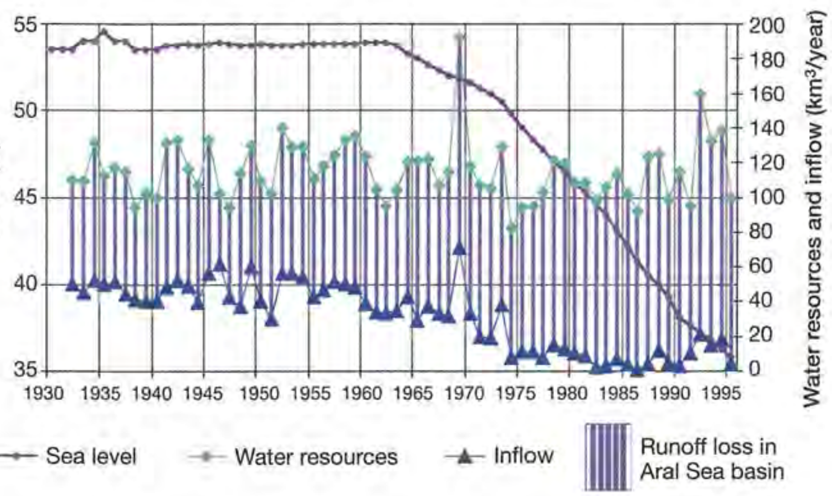


Figure 7—A long-term variability of the renewable water resources and inflow to the mouths of the Amu Darya and Syr Darya rivers

Figure 9 suggests that renewable water resources are mainly determined by climate: the maximum value for the dryness index is the same as the minimum level of water resources, and vice versa. Naturally, as the function we have cited does not include many of the factors involved in streamflow formation, such as topography, vegetation, soils, etc., it cannot be used to assess water resources reliably. It merely shows in graphic form that climate is the main factor in their formation.

The numbers shown in Figure 9 are calculated from mean long-term runoff characteristics, but the inter-annual variability of water resources for natural and economic regions may be very considerable and must be taken into account when assessing water availability. This is especially true in arid and semi-arid areas where there is a great shortage of water. Here, the variability coefficients $C_v = 0.20–0.35$, and in some years renewable water resources, can be 1.5–2 times lower than over a long-term period. In wet areas, variability coefficients amount to $C_v = 0.05–0.15$, and the difference between annual and mean long-term values for water resources is usually in the 15–25 per cent range (Table 8). By way of example, long-term differences in renewable water resources for natural and economic regions of Africa and Europe are cited in Figures 10 and 11. They demonstrate how cyclical are the variations in water resources; at the same time, in practically every region, periods of lower rainfall may continue for many years at a time. They are years when many regions experience particularly acute problems of water availability.

The drop in water resources in much of Africa that began in the 1970s is striking; in the Sahel zone, the decline was catastrophic in the last 15 years, when water resources were almost half those of preceding years.

The last columns of Table 8 show data on the potential specific water availability for different regions and the populations living in them, in the form of depths of streamflow (in mm), evenly distributed geographically and in terms of volume of river water (in thousands of m^3 per capita). Potential water availability of a given area is determined by the available amount of local water resources, and that available for the population by the sum of local water resources plus half of runoff, inflow from outside i.e. it was arbitrarily assumed that the population of each region could count on being able to use no more than half the volume of water resources flowing in from outside the region. It is called potential water availability because it does not take account of the water consumption in each region.

When there are major variations in renewable water resources between one year and the next, assessment of domestic availability of mean long-term water resources always produces indicators that are too high; at the same time, the use of minimum annual runoff values for the purpose ends up with results that are obviously too low, particularly because in many regions there are ways of using some of the preceding years' flow to offset natural or artificial regulation. This suggests that in assessing water availability, it is more scientific to use the minimum annual volume of water resources for the period of

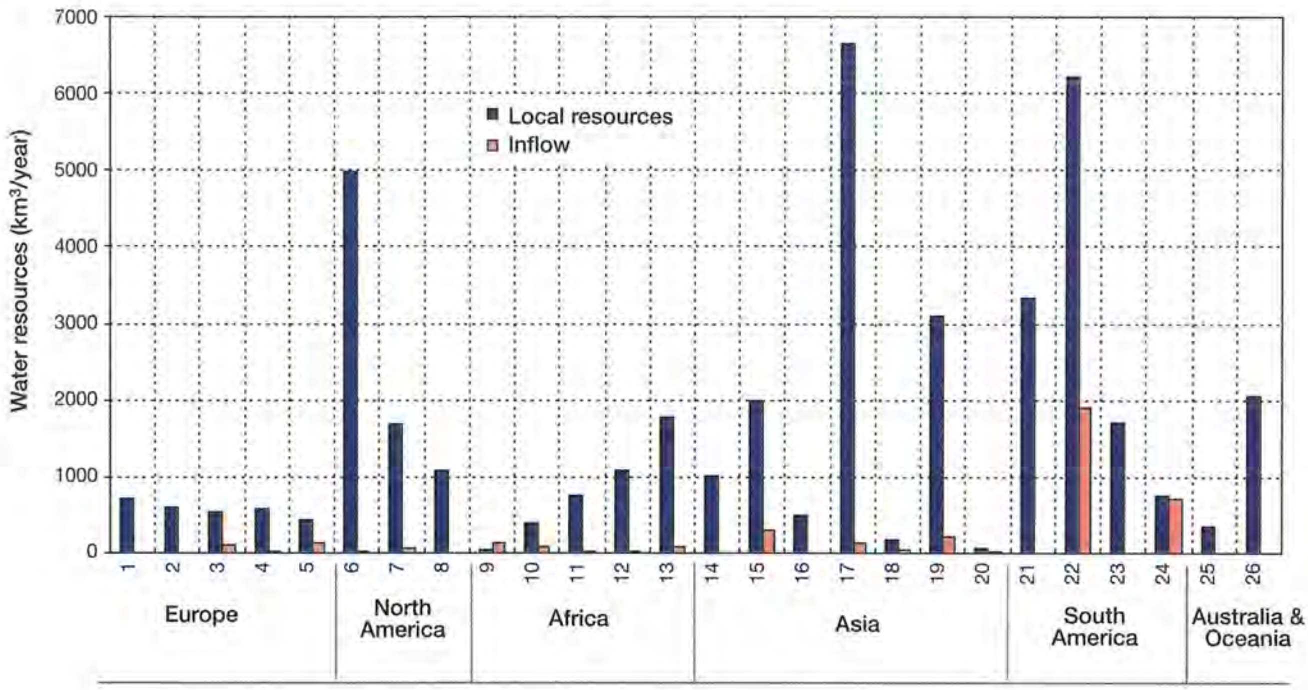


Figure 8—Renewable water resources by natural-economic regions of the world:
Europe: 1 - North; 2 - Central; 3 - South; 4 - North part of ETS SU; 5 - South part of ETS SU; North America: 6 - North; 7 - Central; 8 - South; Africa: 9 - North; 10 - South; 11 - East; 12 - West; 13 - Central; Asia: 14 - North China, Mongolia; 15 - South Asia; 16 - West Asia; 17 - South-East Asia; 18 – Middle Asia; 19 - Siberia, Far East of Russia; 20 - Caucasus; South America; 21 - North; 22 - East; 23 - West; 24 - Central; Australia & Oceania: 25 - Australia; 26 - Oceania.

Table 8—Renewable water resources and potential water availability by natural-economic regions of the world

Number of region	Continent, region	Area (mill. km²)	Population (mill.) 1994	Water resources (km³/year)				Reservoir capacities (km³)		Ratio of reservoir capacity to water resources (%)		Potential water availability*	
				Inflow	Local: Average	Local: Low	Local: Cv	Total	Active	Total	Active	Area (mm)	Population (10^3 m³/year per capita)
	Europe	**10.46**	**684.7**		**2 900**	**2 441**	**0.08**	**591**	**(341)**	**20.4**	**(11.8)**	**277**	**4.24**
1	Nothern	1.32	23.2		705	580	0.08	68.3	(45)	9.7	(6.4)	534	30.4
2	Central	1.86	293	6	617	423	0.21	49.0	(35)	7.9	(5.7)	332	2.12
3	Southern	1.79	188	109	546	373	0.18	100	(76)	18.3	(13.9)	305	3.19
4	North of the European part of FSU	2.71	28.5	27	589	497	0.10	97.4	56	16.5	9.6	217	21.1
5	South of the European part of FSU	2.78	152	123	443	337	0.18	276	129	62.3	48.8	159	3.32
	North America	**24.3**	**453**		**7890**	**7042**	**0.06**	**1796**	**1407**	**23.0**	**(17.8)**	**325**	**17.4**
6	Canada and Alaska	13.67	29	130	4 980	4 550	0.06	801	(587)	16.1	(11.8)	364	174
7	USA	7.84	261	70	1 800	1 390	0.17	796	714	44.2	39.7	230	7.03
8	Central America and Caribbean	2.74	163	2.5	1 110	969	0.10	199	(106)	17.9	(9.5)	405	6.82
	Africa	**30.1**	**708**		**4 050**	**3 340**	**0.10**	**919**	**(589)**	**22.7**	**(14.5)**	**135**	**5.72**
9	Northern	8.78	157	140	41	24	0.34	192	(93)	467	(227)	4.67	0.71
10	Southern	5.11	83.5	86	399	309	0.14	263	(114)	66.0	(28.6)	78.1	5.29
11	East	5.17	193.5	26	749	622	0.11	215	(212)	28.6	(28.3)	145	3.94
12	West	6.96	211.3	30	1 088	623	0.28	230	(156)	21.1	(14.3)	156	5.22
13	Central	4.08	62.8	80	1 770	1 510	0.09	19.3	(14)	1.1	(0.8)	434	28.8
	Asia	**43.5**	**3 445**		**13 510**	**11 879**	**0.06**	**2 085**	**(1 120)**	**15.4**	**(8.3)**	**311**	**3.92**
14	North China and Mongolia	8.29	482		1 029	597	0.23	339	(176)	33.0	(17.1)	124	2.13
15	Southern	4.49	1 214	300	1 988	1 592	0.10	334	(248)	16.8	(12.5)	443	1.76
16	Western	6.82	232		490	275	0.35	312	(186)	64.0	(38.0)	71.8	2.11
17	South East	6.95	1 404	120	6 646	5 609	0.09	273	(157)	4.1	(2.4)	956	4.78
18	Central Asia and Kazakhstan	3.99	54	46	181	130	0.17	160	87	88.4	(48.0)	45.4	3.78
19	Siberia and Far East of Russia	12.76	42	218	3 107	2 773	0.06	636	251	20.4	8.1	243	76.6
20	Transcaucasia	0.19	16	12.1	68	52.5	0.12	32.0	(15)	47.1	(22.0)	358	4.63
	South America	**17.9**	**314.5**		**12 030**	**10 690**	**0.07**	**882**	**(436)**	**7.3**	**(3.6)**	**672**	**38.3**
21	Northern	2.55	57.3		3 340	2 645	0.15	196	(89)	5.9	(2.7)	1 310	58.3
22	Eastern	8.51	159.1	1 900	6 220	5 260	0.08	474	(272)	7.6	(4.4)	731	45.1
23	Western	2.33	48.6		1 720	1 070	0.18	19.4	(12)	1.1	(0.7)	738	35.4
24	Central	4.46	49.4	720	750	570	0.17	192	(62)	26.6	(8.2)	168	22.5
	Australia and Oceania	**8.95**	**28.7**		**2 404**	**1 999**	**0.10**	**95.0**	**(59)**	**3.9**	**(2.5)**	**269**	**83.8**
25	Australia	7.68	17.9		352	282	0.24	73.2	(50)	20.8	(14.2)	45.8	19.7
26	Oceania	1.27	10.8		2 050	1 625	0.10	21.8	(9)	1.0	(0.45)	1 614	190
	The world (rounded)	**135**	**5 633**		**42 780**	**39 922**	**0.03**	**6 368**	**(3 952)**	**14.9**	**(9.24)**	**317**	**7.60**

* Potential water availability of area is estimated by average local water resources and per capita – by average local water resources plus a half inflow.

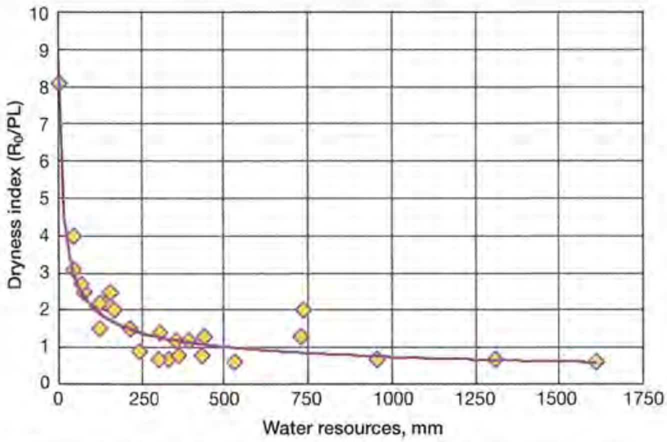


Figure 9—The relationship between water resources (mm) and dryness index

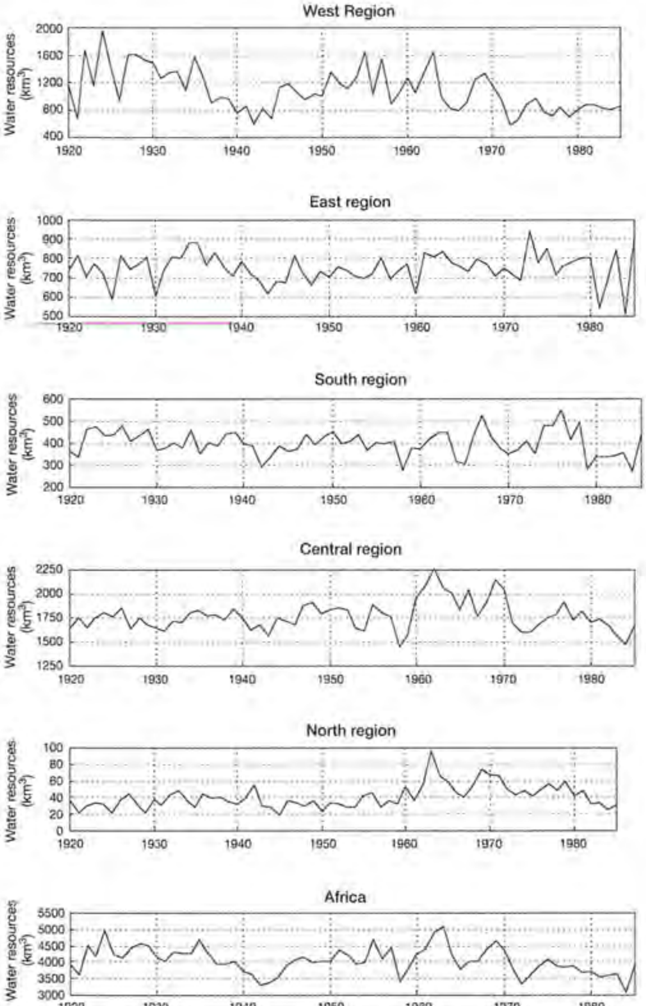


Figure10—Renewable water resources dynamics by natural economic regions of the Africa (km^3/year)

observation for the following two years one after the other. The figures are calculated for each region and shown in Table 8 as low water resources or average for low water years; naturally, they are a lot lower than for mean long-term volumes (ranging for 0.50 to 0.90).

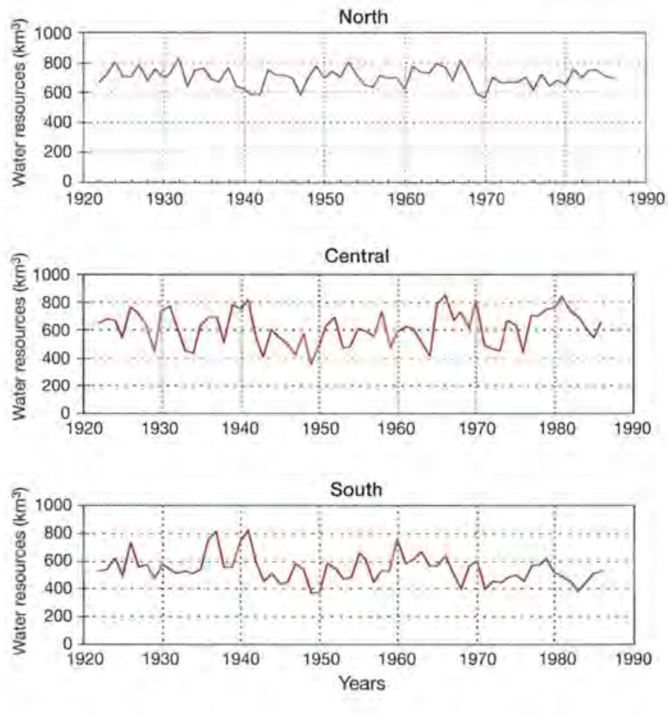


Figure 11—Renewable water resources dynamics by natural economic region of Europe (without FSU area)

The data in Table 8 for specific water availability show the uneven distribution of water resources worldwide, as they generally do not match the geographic distribution of population or their water needs. Water availability in a given area (the runoff depth) varies according to region from 13–50 mm to 1 300–1 600 mm, and water availability for populations from 700–2 000 m^3 per capita per annum to 40 000–190 000 (Table 8).

The prospects for putting water resources to economic use are governed not only by their year on year variability but also by the monthly and seasonal variations in them. The intra-annual distribution of total runoff for natural and economic regions of the world (by month, as a percentage of the annual figures) is given in Table 9. As can be seen from the table, many regions show an extremely uneven runoff in any one year, when between 50 and 70 per cent of the annual flow occurs in the course of the high water season, which lasts for three to four months. For example, 54 per cent of the annual flow takes place in the three flood months in the Northern and Southern European parts of the former USSR, while in Siberia and the Far East, South Asia and Australia the figure is 64–68 per cent.

At the same time, during the low-water period, which lasts between three and four months, in some regions the streamflow amounts to no more than 4–10 per cent of annual flow. For example, during the three low-water months in the northern areas of the European part of former USSR, Canada and Alaska, northern China and Mongolia, streamflow is 8–9 per cent of annual flow, in Central America and West Africa it is 6–7 per cent, and in Siberia and the Russian Far East it is 4–5 per cent (Table 9).

The uneven distribution of water resources year on year and within individual years is why dams for

Table 9—Streamflow distribution during a year for the continents and natural-economic regions (% of the mean annual value)

Number of region	Continent, region	Mean Annual Water Resources (local) (km^3/year)	Month												Year
			1	2	3	4	5	6	7	8	9	10	11	12	
	Europe	**2 900**	**6.2**	**6.6**	**6.9**	**8.9**	**14.3**	**13.3**	**9.2**	**7.6**	**7.3**	**6.9**	**6.6**	**6.2**	**100**
1	Northern	705	4.9	4.9	4.6	4.4	8.8	15	15.4	12.6	10.2	7.8	6	5.4	100
2	Western and Central	617	9.7	10.8	9.7	9.4	8.3	8.5	8.2	7.1	6.3	6.2	6.9	9	100
3	Southern	546	7.6	8.0	9.5	11	11.5	10.7	9	7.1	6	5.7	6.4	7.5	100
4	North of the European part of FSU	589	3	2.5	3	6.5	25.8	19.7	8.9	6.2	6.5	7.8	6	4.1	100
5	South of the European part of FSU	443	3.6	3.5	5.2	12.4	23.1	17.7	9.5	6.1	4.8	5	5	4.1	100
	North America	**7 890**	**4.7**	**4.9**	**5.0**	**7.0**	**11.6**	**15.2**	**12.6**	**9.9**	**9.6**	**8.6**	**5.9**	**5.0**	**100**
6	Canada and Alaska	4 980	3.8	3.6	3.5	6.1	13.1	17.2	13.8	10.3	8.9	8.6	6.4	4.7	100
7	USA	1 800	7.7	9.4	10.3	12.1	12.1	11.5	8.6	5.8	5.2	5.1	5.7	6.5	100
8	Central America and the Caribbean	1 110	3.6	2.7	2.2	2.4	4.8	12.8	13.8	14.6	19.8	14.9	4.8	3.6	100
	Africa	**4 047**	**6.7**	**6.2**	**5.5**	**7.1**	**8.4**	**6.5**	**6.7**	**9.3**	**14.8**	**13.6**	**8.5**	**7.4**	**100**
9	Northern	41	5.96	6.11	6.4	6.16	6.13	6.11	7.24	9.84	7.85	11.8	13.9	12.5	100
10	Southern	399	17.8	13.4	10.8	7.35	4.91	3	6	6.93	7.31	6.08	7.02	9.4	100
11	East	749	4.55	8	7.72	15.8	21.7	11.3	6.84	5.26	4.49	6.35	4.9	3.09	100
12	West	1 088	1.04	0.56	0.36	0.17	0.27	1.17	5.53	17.3	33.6	28.7	8	3.3	100
13	Central	1 770	8.56	7.22	6.64	7.57	8.63	8.65	7.54	6.57	7.9	9.02	10.5	11.2	100
	Asia	**13 510**	**5.1**	**4.1**	**4.7**	**5.1**	**8.8**	**13.7**	**14.9**	**13.8**	**11.2**	**7.2**	**6.8**	**4.6**	**100**
14	North China and Mongolia	1 029	2.3	2.2	3.0	4.7	6.2	9.2	14.7	20.6	14.3	11.3	7.5	4.0	100
15	Southern	1 988	1.6	1.3	1.4	1.8	5.2	6.9	19.5	26.2	20.8	9.5	3.6	2.2	100
16	Western	490	7.5	7.8	13.1	16.4	20.5	10.1	5.3	3.7	3.2	3.6	4.0	5.0	100
17	South-East	6 646	8.0	7.0	7.2	7.4	7.7	7.9	11.3	10.4	9.2	6.9	10.2	6.8	100
18	Central Asia and Kazakstan	181	3.4	2.9	3.5	6.6	13.1	19.4	18.6	11.7	7.4	5.4	4.2	3.7	100
19	Siberia and Far East of Russia	3 107	2.0	1.7	1.9	1.8	13.0	31.0	18.8	11.4	8.6	5.8	2.0	2.0	100
20	Caucasus	68	6.4	5.8	9.5	17.4	16.0	10.6	7.0	4.7	5.1	5.5	5.2	6.8	100
	South America	**12 030**	**5.9**	**7.0**	**8.1**	**10.0**	**11.4**	**12.1**	**11.1**	**9.7**	**7.6**	**6.0**	**5.5**	**5.6**	**100**
21	Northern	3 340	4.2	3	2.5	3.1	6.2	10.2	13.5	15.3	14.7	11.8	9.0	6.5	100
22	Eastern	6 220	6.8	8.2	9.4	10.4	11.0	11.0	10.2	9.1	7.3	5.6	5.2	5.8	100
23	Western	1 720	8.3	9.6	10.8	9.2	9.2	9.3	7.9	7.1	6.5	6.7	7.8	7.6	100
24	Central	750	9.2	11.8	12.8	12.2	9.5	9.3	6.6	5.2	5.4	5.3	5.9	6.8	100
	Australia and Oceania	**2 400**	**10.3**	**13.2**	**12.4**	**10.1**	**7.4**	**7.1**	**6.2**	**6.9**	**5.4**	**6.6**	**7.2**	**7.2**	**100**
25	Australia	352	15.4	21.7	30.9	5.29	3.2	3.63	3.35	3.23	3.2	3.74	3.21	3.15	100
26	Oceania	2 050	9.52	12.0	9.35	11.1	8.15	7.72	6.7	6.4	5.75	7.02	7.87	7.9	100

long-term and seasonal water regulation are built. Such reservoirs have been built in most regions of the world. On the basis of projections drawn up at the Russian SHI in the last few years (see section 5.5), the overall volume of water in the world is 6 400 km^3, with an active total of 4 000 km^3. The regional distribution of these bodies of water is shown in the relevant columns of Table 8, where the size of the relationship between the amounts of water in reservoirs (both full and active volumes) and average annual volumes of local water resources are also given.

The key indicator making it possible to stabilize flow is the active volume of reservoirs. The building in a given region of numerous dams with a relatively large active volume (by comparison with streamflow) makes water available in seasons or even years of drought. To stabilize intra-annual streamflow, it is usually enough if the river regulation coefficient, as determined from the ratio of the active capacity of the reservoir to annual streamflow, amounts to 20–40 per cent.

The figures in Table 8 show that the following regions have the highest regulation coefficients, of 40–50 per cent: the southern areas of the European part of the former USSR, continental USA (not including Alaska), Western Asia, and Central Asia and Kazakhstan. In these areas, a large number of reservoirs regulating intra-annual flow (and in some rivers, inter-annual flow as well) have been built, to provide water for economic needs and domestic use.

Certain regions of Africa (apart from the Central African region) also have extremely high regulation coefficients, according to data in Table 8. However, this is the kind of circumstance where the coefficient is not characteristic of how far water resources have been regulated in an entire region, but basically reflects the capacity of just one or two gigantic reservoirs built in each region. In Africa, there are five of the largest reservoirs in the world. These are the Nasser (Aswan) High Dam on the River Nile in North Africa, the Volta Dam on the River Volta in West Africa, the Owen Falls Dam near Lake Victoria in East Africa, and the Kariba and Cabora Bassa high dams on the Zambesi River in Southern Africa, which provide about 80 per cent of the full and active volumes of all reservoirs on the continent of Africa. These reservoirs provide fairly full regulation of streamflow in the water-courses where the dams are built (Nile, Volta, Zambesi), but the water resources of the rivers account for only about 9 per cent of Africa's total water resources.

In many parts of the world, the useful volume of reservoirs is very low and amounts to no more than 0.5–5 per cent of water resources; as a rule, they are regions with high indicators of water availability for entire areas and communities, or else without the right physical-geographical and ecological conditions for building major dams (for example, the Central European region).

Renewable water resources for whole continents, obtained by adding together local water resources from different regions, are given in Table 8 and Figure 12.

According to new data, the overall size of the world's renewable water resources calculated for the period 1921–1985, has been put at 42 800 km^3 per annum (not counting Antarctica). It is some 5 000 km^3 greater than the figures obtained by Baumgartner and Reihel (1975), but 1 800 km^3 less than those obtained from the SHI's most detailed assessments (Korzun, ed., 1974).

If the data for water resources assessment are compared for individual continents, then the differences between the SHI's 1974 assessments and more contemporary ones will be greater, as high as 5–12 per cent. The greatest differences are for Africa and Asia, mainly through the present work's use of more comprehensive and dependable data for the (hydrologically) poorly studied regions of West and Central Africa and South-East Asia. The second cause is the somewhat lower streamflow during the last two decades of the period under study, particularly noticeable in Africa, Asia and Europe. This is clearly seen in the chronological variation graphs for total annual runoff by continents in Figure 13.

Table 8 and Figure 14 give data for potential runoff availability for different populations and areas of the world. On average for 1994, the potential water availability amounted to 7.6 thousand m^3 per capita, ranging for different continents from 3.9 for Asia to 38 for South America, and to 84 for Australia and Oceania. Water availability by geographical area does not vary so steeply

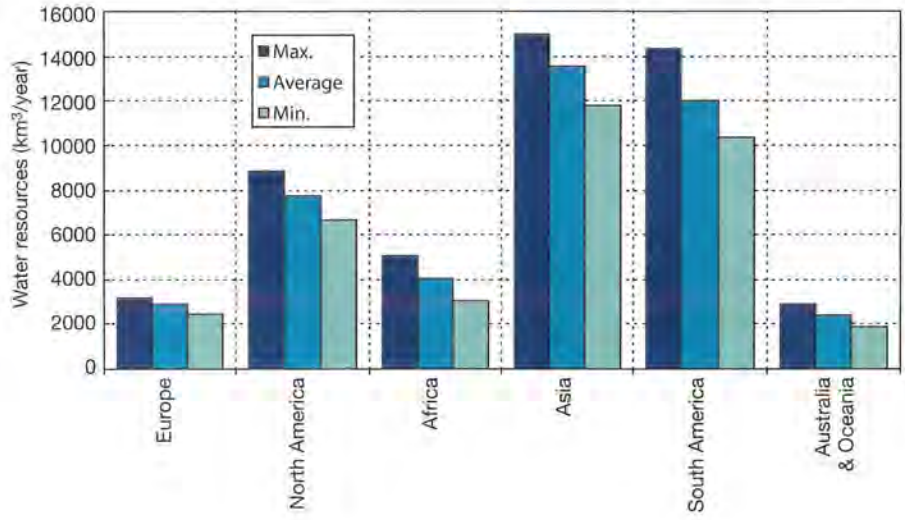


Figure 12—Renewable water resources by continent

(from 135 to 672 mm). It is worth noting that potential domestic water availability has fallen by 1.7 times (from 12.9 to 7.6 thousand m^3 per annum), since the previous estimate (over a 25 year period from 1970 to 1994). This has basically taken place because of the population increase of almost 2 000 million people. In the process, the sharpest fall in water availability has been for the population of Africa (2.8 times), Asia (2 times), and South America (1.7 times). This at a time when the potential water availability for the population of Europe fell by only 16 per cent (Korzun, ed., 1974). It must be noted that true water availability, taking into account not only population numbers but also the rise in water consumption and depletion of water resources in low-water years, has fallen still more considerably in Africa, Asia and South America (see section 5.8).

Studies of long-term runoff variations for different parts of the world unfailingly show their cyclical nature. The same applies to oscillations in aggregate runoff for continents and the world in general, as shown in Figure 13, where cycles of low-water and high-water years, alternating with one another and differing in length and scale of deviation from the mean, can be discerned. In the oscillations in world total runoff, for example, drier phases can be identified (1940–1944, 1965–1968, 1977–1979), when runoff volumes were 1 600–2 900 km^3 less than average; on the other hand, the periods 1926–1927, 1949–1952, 1973–1975 had considerably higher rates of flow.

While world runoff variations are cyclical in nature, there is also a characteristic lack of any clearly demarcated trend towards change for the whole of the 65 year period under study. This is by and large true for most continents too; nonetheless, there has been a fairly sharply marked rise in runoff for South America in the past two decades and a fall in the value for African rivers during the same period (Figure 13).

Changes in renewable water resources by continent for different months in each year are shown in Table 9 and Figure 15. A comparison of these data with the 1974 SHI assessment (Korzun, ed.) provides largely similar results for most continents except Africa, for which the inclusion of new streamflow documentation from major rivers has heavily altered the continent's intra-annual distribution of aggregate runoff.

According to present assessments, the bulk of runoff in Europe occurs between April and July (46 per cent), in Asia from June to September (54 per cent), in Africa from September to December (44 per cent), in North

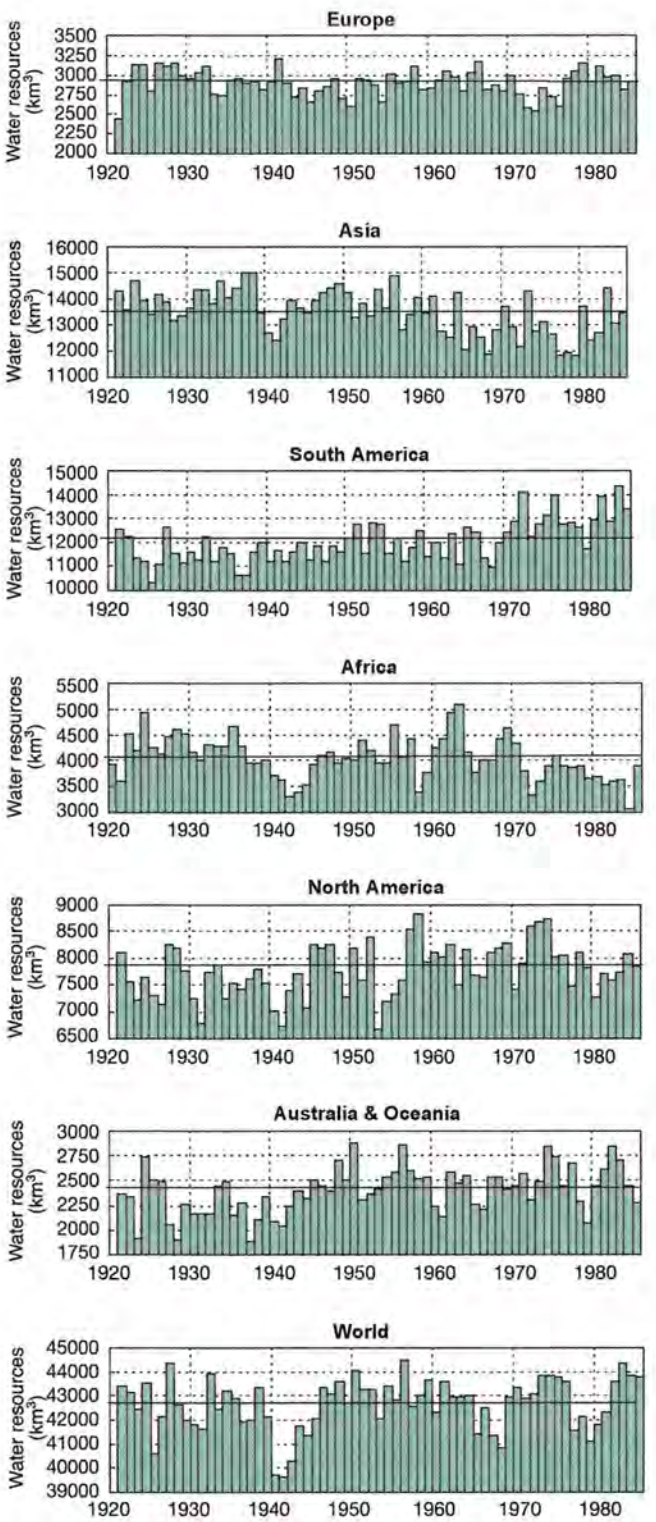


Figure 13—Renewable water resources dynamics (km^3/year) of the world and the continents

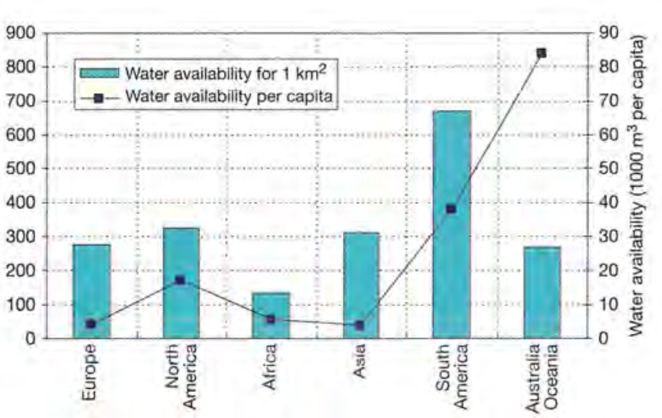


Figure 14—Potential water availability by continent

America from May to August (49 per cent), in South America from April to July (45 per cent) and in Australia and Oceania between January and April (46 per cent). Overall, the world has a wet season from May to August, when some 45 per cent of annual world runoff occurs.

Given the considerable variations in runoff for different months and seasons, there are considerable problems using water resources sparingly in dry seasons. Hence the most valuable thing, for water availability, would be a steady, scarcely changing basic river runoff which can be fully used without having to be regulated. Rough estimates give the ideal size as 37 per cent of total world runoff, or some 16 000 km^3 per annum. The establishment of reservoirs can considerably help stabilize water availability. As the world's reservoirs have an aggregate useful volume of 4 000 km^3 (see Table 8) in, it can be roughly considered that worldwide stable runoff has risen by 25 per cent, and at present stands at some 20 000 km^3 per annum.

So far as aggregate world renewable water resources concerned, the active volume of reservoirs amounts to 9 per cent and varies by 18–2.5 per cent, depending on the continent. The best water resources regulation is to be found in North America (17.8 per cent), followed by Africa (14.5 per cent), and Europe (11.8 per cent), the lowest being in Australia and Oceania (2.5 per cent) and in South America (3.6 per cent).

As pointed out, special circumstances apply to water regulation in Africa, where five extremely large dams, standing along four different rivers, provide 80 per cent of the entire active volume of the continent's reservoirs.

The above values for renewable water resources for different regions and continents (Table 8) are assessed from aggregate runoff. It is known that this includes water passing directly into the hydrographic network during rainy periods or snowmelt, and groundwater from the aquifers feeding rivers, more or less evenly during the year. At the same time, part of the groundwater that also comes under replenishable water resources, does not enter the rivers but flows straight into seas and oceans or is lost to evaporation. In this case, renewable water resources from runoff data alone are naturally somewhat under-evaluated.

There is great practical importance to be gained from having reliable data to indicate the size of renewable groundwaters that do not pass into the river network, as against streamflow rates, and the regions where they are most important. It is obvious that they are areas with poorly developed hydrographic networks, above all including flat plains areas with arid or semi-arid climates. In such areas, runoff is on a very small scale and groundwaters from the upper aquifers can be very important in the overall volume of renewable water resources.

It is an extremely complex task to provide a reliable quantitative assessment of such groundwater for different regions of the world, one which so far could not be carried out because the requisite data do not exist. Nevertheless, such assessments have been made for some areas and countries, and they can also be used to draw conclusions for different physical-geographical conditions prevailing in the world.

In particular, the most detailed assessment of renewable water resources, including runoff and groundwaters unconnected with the latter, was made in 1995 by FAO for all countries in Africa where arid or semi-arid areas account for more than half the land area (FAO, 1995). FAO data give the aggregate volume of renewable groundwater resources unconnected with streamflow as 188 km^3 per annum for the continent as a whole, or 5 per cent of total streamflow. For some countries in arid regions, however, such as Egypt, Libya, Tunisia, Morocco, and others, the figures are of very great importance in the total amount of renewable water resources and must be allowed for when assessing them.

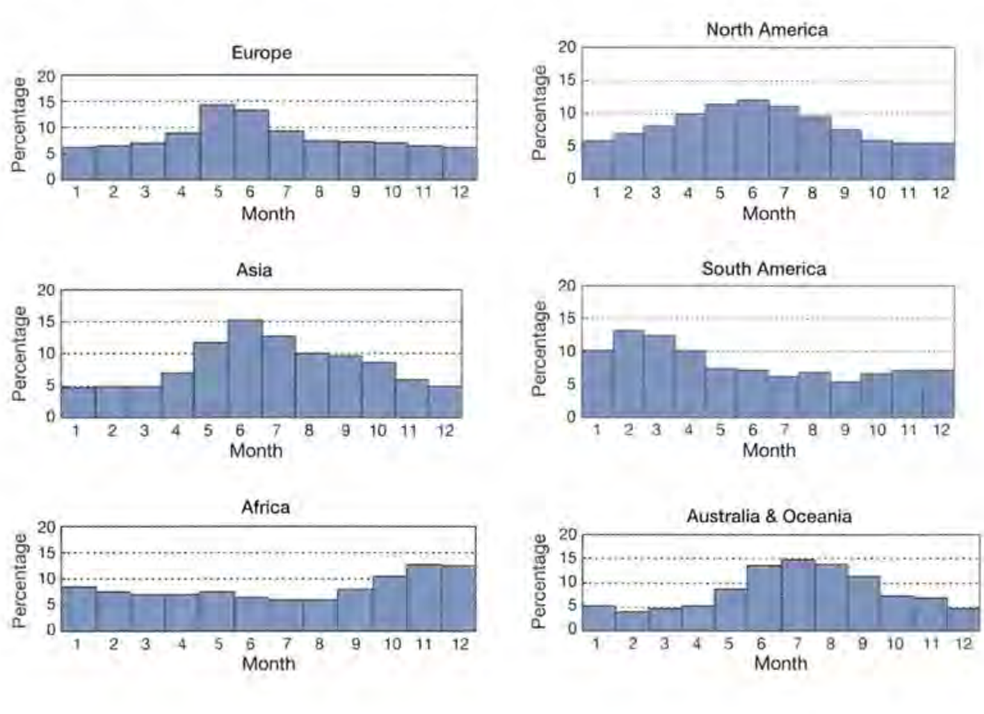


Figure 15—Streamflow distribution during a year by continent

The example we have taken of Africa provides grounds for supposing that similar ratios exist on other continents as well.

In this way, in assessing worldwide renewable water resources, i.e. for continents, major natural and economic regions, countries and river systems, it is quite alright to ignore values for renewable groundwater resources unconnected with runoff. However, one exception is for smaller countries in arid regions with poor hydrographic networks. Countries included are those in North Africa and the Arabian Peninsula. There, renewable groundwater resources account for the bulk of the renewable water resources and may even exceed (in a few countries they actually far outstrip) the total amount of runoff and streamflow (see section 3.6).

3.6 WATER RESOURCES IN SELECTED COUNTRIES

Any assessment of water resources in different countries, in particular publication of the results obtained, is an exceptionally complex and responsible work, requiring that the initial information available, physical-geographical and socio-economic conditions, results of national assessments and studies all be taken careful account of. It is for these reasons above all that, even in comprehensive works assessing worldwide water balances and resources such as those already mentioned by workers from Russia (Korzun, ed., 1974) or Germany (Baumgartner and Reichel, 1975), no worldwide country water resources assessments have been undertaken.

The first time that results of a fairly comprehensive assessment of renewable water resources for various countries made using a single uniform method, were provided was in a monograph by the renowned Russian hydrologist, Professor M.I. Lvovich (1974). Assessing mean values for local water resources in 127 countries, the same author employed small-scale maps of his own design constructing surface and groundwater runoff. Inflow from neighbouring areas was assessed in rough-and-ready fashion and only for certain countries; and the variability of water resources over time was not determined. By now, of course, Lvovich's assessments are out of date, both in regard to the initial data that the maps were based on, and so far as method was concerned. The degree of error for many countries is very high, particularly those with small land areas situated in parts of the world where there is not enough moisture. Nevertheless it was a first attempt to make use of uniform initial data and methods to evaluate water resources nearly every country in the world.

Beginning in 1991, data on renewable water resources and the use made of them (for practically all countries) have been periodically published in tabular form by the Washington-based World Resources Institute (WRI, 1992, 1996, 2000). The data are not the outcome of some new global assessment, but are collected from different sources for different years (from 1965 to 1987), without any account of how, the original information and methods were used, or their intended purpose, and without assessment results being subjected to the requisite analysis against factual observation data. For many countries, the tables included the data from Lvovich referred to above. It is of course easy to understand the compilers of the table, who included in it the data that they had access to, and were naturally not in any position to undertake the huge amount of work needed for meticulous analysis, as they had no dependable worldwide hydrological observation base or experience in assessing water resources and water availability for different regions of the world. It is still more understandable in that for many developing countries, reliable quantitative assessments of water resources and methods of using them simply do not exist.

Despite these shortcomings, the World Resources Institute documents on fresh water are widely used by many workers compiling global reports on water resources and availability, and for identifying countries with freshwater shortages and deficits (Falkenmark and Lindh, 1993; Kulshreshtha, 1992; Postel, 1992; etc.). They are given in full in the reference sections of the widely known publications by Gleick (1993, 1998) and have been widely employed in recent years by FAO (1999, 2001) in preparing reports on irrigation in different parts of the world.

Particular attention should be paid to work published in 1993 by Population Action International (Sustaining Water: Population and the Future of Renewable Water Supplies, 1993), since it is widely known in many countries, international organizations, the scientific community, decision makers and politicians. The document gives values for aggregate renewable water resources in 149 different countries and specific indicators for per capita water availability in 1955 and 1990, as well as prospects for the year 2025 that take account of projected population increases. It is generally understood that the quantitative data and conclusions in the work are the most reliable up-to-date information on water resources and availability in every country of the world.

Analysis of the data quoted in it that have been made by researchers at the State Hydrological Institute showed that they were drawn from different published sources and provided no new insights into country water resources round the world. The inference is that the conclusions do not fully reflect the present situation in the world in terms of water availability dynamics, and for many countries on nearly every continent, the values for water resources and availability are simply inexact and need to be considerably refined and corrected. The basic comments on the work can be summed up as follows.

First of all, in assessing water availability, it is not right to use aggregate renewable water resources values (that include river flow coming in from outside). For many countries lying in international basins, if that is the case, then the data are clearly overstated since streamflow from one and the same river is taken into account in different countries. This means that conclusions on the number of countries in a situation of water deficit or stress need to be considerably amended.

Secondly, figures for water resources in many countries are not mutually comparable, when they are based on different sources, years or methods; in some cases, they consist of total water resources, in others of runoff originating in the given country. At the same time, totally wrong figures are given for some countries that do not tally with data from hydrological observations and published country assessments.

Thirdly, to assess true availability of water and take account of the scale of water resources and population figures, water use dynamics by country or region need to be included.

More recently, as part of drafting work on a UN resolution on the First World Water Development Report (WWDR), it became a particularly pressing matter to decide which basic data on renewable water resources and water use should be employed in establishing values for countries round the world, so that various types of global indicators can be provided to show insufficient or surplus water resources, and on freshwater stress or deficit worldwide.

After the present author had met a number of experts, and taken part in discussions on the matter, it became clear that for this purpose most of them were planning to use the world country data cited in the latest publication of the World Resources Institute (WRI, 2000). Now this document presents a mass of statistical information from almost every country in the world, on the most varied aspects of economic activities and natural resources, including data on fresh water. We would like to dwell a little further on analyses of data concerned primarily with volumes of water resources.

The basic table on fresh water (FW.1) provides worldwide, continental and country figures on renewable water resources (originating within a given country), on the flow of river waters from neighbouring countries, and on outflow into other countries downstream. There are no data at all on the long-term variability of water resources or their intra-annual distribution.

The data in the table come from a variety of sources and share exactly the same shortcomings as those in the institute's earlier published findings. Moreover, data for individual continents are taken from one set of sources, while figures for countries within a given continent are drawn from a completely different set, with no attempt being made to harmonize statistical data in the way necessary.

To show what we mean, we provide the following examples. In the table (FW.1), the levels of water resources for separate continents and the world as a whole are taken from Russian State Hydrological Institute data (Shiklomanov ed., 1997). These are completely reliable indicators covering the same long-term period obtained from the world hydrological network documentation. However, the country figures in the table are taken from a wide range of other sources. The result is that if we combine together water resource figures for each country, we get totally different values for national renewable water resources than those for continents, differing from the true data by hundreds and thousands of cubic kilometres. For example, for Asia, they differ by 1 430 km^2, for North America by 1 370 km^2, for Australia and Oceania by 900 km^2, etc. Thus, within the same table, data for countries and continents fail to agree.

This situation will become completely clear if the data quoted for different countries are analysed. For some countries, values for local water resources and inflow from other countries are given, for others the inflow is not taken account of at all. For example, for some countries of the world and all countries in South America, the table shows only data on local water resources, though for many countries on all continents water resources flowing in from outside are comparable in volume with local water resources and may be 2–10 times or more greater than the latter (Argentina, Uzbekistan, Egypt, Hungary, Congo, Guyana, Paraguay, etc.).

A selective check against factual observation of the local water resources and flows from other countries in the table for a number of countries showed that the disparities are often between 1.5 and 3 times (especially for developing countries of Asia and South America). At the same time, the figures in the table are given to two decimal points, which is evidently intended to show their greater reliability.

One very important shortcoming in the data on water resources is the complete lack of information on their long-term variability and intra-annual distribution. This information is extremely essential for any analysis of water availability, or determination of stress or deficit.

In this way, it can unfortunately be stated that so far there have been no coordinated, adequate or dependable data on values for renewable water resources for all countries. This is also obliquely supported by publications of the European Environment Agency (EEA, 1999), where it is shown, for example, that even for European countries different assessments of aggregate renewable water resources (EEA, 1995; EC Environment Water Task Force, 1997; Eurostat, 1997) can differ from one another not just by 10–20 per cent but by 80–100 per cent or more.

Even greater problems arise when analysing water use data for different countries, since they differ widely from year to year, and trustworthy information for most of them is almost completely unavailable (see section 5.7).

With regard to the foregoing, international organizations (WMO, UNESCO, IAWR, etc.) are faced with the very serious and labour-intensive task of compiling a database on water resources that can be accessed by different users in every country of the world. This will presuppose the collection and analysis of the requisite hydrology and water management information, a painstaking analysis of national sources, traditions and experience in using fresh water in different regions and countries. The author considers that the build-up of such a database, initiated in recent years by UNESCO and other international organizations, must be a high priority under the ongoing World Water Assessment Programme (WWAP).

Because reliable data do not exist for every country, the natural-economic region has been taken as the basic unit of the analyses run by the Russian SHI into the dynamics of world water resources, water use and water availability (see section 3.3). On average for different regions, by exploiting the materials available on the world hydrological network and specially developed methods, it proved possible fairly successfully to obtain all the requisite data in uniform format for reporting on the state of water resources and global trends in their use.

At the same time, an effort has been made at the SHI to assess renewable water resources for a large number of selected countries, determining their dynamics in terms of time and variability. Some results are given in Table 10, for 57 countries on every continent. Among the countries selected, there were developed and developing countries, countries with economies in transition both large and small, North and South, both where water is in short supply and where it is plentiful. The table also includes countries where there are reservoirs with fairly considerable capacities for regulating runoff. The countries make up some 77 per cent of world renewable water resources and 70 per cent of the total world population. The sum of all water contained in reservoirs in these countries is approximately 6 000 km^3, or 94 per cent of the world total.

Table 10 gives figures for water resources in these countries, divided into local water resources and inflow of river waters, coefficients of variability *Cv* of local water resources, and for potential water availability by area (in mm of layer) and per capita. The latter are derived from mean values for local water sources, together with half the inflow of river waters from neighbouring countries. The table also provides data on the total and active capacities of reservoirs, and the ratio of these reservoir capacities to the size of local and total renewable water resources. These ratios describe the degree of regulation of water resources in every country.

The data in Table 10 reveal the extremely uneven distribution of renewable water resources and water availability for different countries. The values for specific water provision vary very widely: from 0.5 to 2 200 mm in area, and from 700–1 500 to 50 000–100 000 m^3 per capita per annum.

It should be noted that the values given in the table for specific per capita water availability for some countries are a function of the volume of river water flow from neighbouring territories. In some countries with small land areas, the scale of inflow is comparable with local water resources, but in such countries, for example, Argentina, Egypt, Sudan, Bangladesh and Uzbekistan, the inflow is 2–10 or more times higher than local water resources. In these examples, if the incoming flow is not taken into account, specific water availability will be considerably underestimated.

Moreover, the reservoirs are also very unevenly distributed in the countries cited in Table 10. The aggregate volume of reservoirs ranges from 2–4 km^3 (Austria, Switzerland, Zaire) to 800–950 km^3 (Russia, Canada, USA); there is a still greater range in the degree of regulation of overall water resources with an active reservoir capacity ranging from 0.2–1 per cent to 80–380 per cent. The greatest degree of water resources regulation is found in the developing countries of Africa, where there is a shortage of water resources but where gigantic reservoirs have been built (Uganda: 378 per cent, Ghana: 147 per cent, Egypt: 83 per cent, Côte d'Ivoire: 42 per cent, Zambia: 42 per cent); a high degree of regulation is also a feature of countries in Western and Central Asia with limited water resources but intensive use (Iraq: 80 per cent, Kazakhstan: 36 per cent, Turkey: 34 per cent, Kyrghyzstan: 29 per cent). The least regulated of water resources are to be found in economically poorly developed countries with high natural water availability (Zaire: 0.2 per cent, Indonesia: 0.3 per cent, Bangladesh: 0.4 per cent).

In developed industrial countries there is also a fairly wide range of water resources regulation: from 2–5 per cent (Austria, France, Japan, etc.) to 17–30 per cent (Spain, USA, Canada), as a function of physical-geographical, ecological and socio-economic conditions. In highly developed countries, the ecological impact is one of the key factors in building reservoirs.

As indicated in Table 10, the most renewable water resources are found in the six largest countries in the world: Brazil, Russia, Canada, USA, China and India. In these countries more than 40 per cent of gross world annual river flow originates; annual variations for 1921–1985 are given in Figure 16. For all countries, variations in water resources are very clearly cyclical in nature, with successive wet and dry periods lasting for differing lengths of time. The figure indicates that the greatest trends towards an increase in renewable water resources were to be found in Brazil and Canada, and their most prominent falls were in India and China.

The intra-annual and monthly distribution of water resources in these countries is given in Figure 17. Major land areas and widely ranging climatic conditions are factors that considerably smooth out the intra-annual flow of the countries listed. Nonetheless, in them too, periods of greater and lower runoff can be clearly distinguished. For example, the bulk of water resources formation (55–70 per cent) occurs in May–August, while in India and China, the three months from July to September account for 47 per cent and 65 per cent respectively of the annual figures for renewable water received.

It should be noted that the features of intra-annual water resources distribution we have referred to really do reflect the natural conditions that bring them about. The active capacities of reservoirs in a given country are of great help in smoothing out the seasonal shifts in water resources. In this connection, the USA and Canada have great potential with their high degree of streamflow regulation, of 23 per cent and 17 per cent respectively. The lowest possibilities for regulation are in Brazil, where the active capacity of reservoirs is no more than 3 per cent of the annual volume of renewable water resources. The capacity for regulation in Russia, China and India is more

Table 10— Renewable water resources in selected countries of the world and rate of their control

Number	Country	Area ('000 km²)	Population (mill.) 1995	Renewable water resources (km³/year)			Cv	Potential water availability		Reservoir capacities (km³)		Ratio of total reservoir capacity to water resources (%)		Ratio of the active reservoir to water resources (%)	
				Local	Inflow	Total		Area (mm)	Population (10³ m³/year per captita)	Total	Active	Local	Total	Local	Total
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Europe															
1	Austria	84	8.0	60.2	32.0	92.2	0.15	717	9.5	2.5	(1.8)	4.1	2.7	(3.0)	(1.9)
2	Finland	340	5.1	109	3.0	112	0.20	321	21.7	21.1	(14.7)	19.4	18.8	(13.5)	(13.1)
3	France	550	56.8	168	27.0	195	0.23	305	3.19	12.0	(9.5)	7.1	6.1	(5.6)	(4.9)
4	Greece	130	10.5	47.0	13.0	60.0	0.32	362	5.1	11.5	(8.4)	24.5	19.2	(17.9)	(14.0)
5	Italy	300	57.2	160		160	0.27	533	2.8	10.2	(7.5)	6.4	6.4	(4.7)	(4.7)
6	Netherlands	40	15.5	12.4	58.0	97.4	0.24	310	2.7	10.0	(6.9)	80.6	10.3	(55.6)	(7.1)
7	Norway	320	4.33	350	7.0	357	0.15	1 094	81.6	25.0	(16.0)	7.1	7.0	(4.6)	(4.5)
8	Russia	17 080	148	4 053	222	4 275	0.05	237	28.1	960	416	23.7	22.5	10.3	9.7
9	Spain	510	39.6	109		109	0.48	214	2.75	45.0	(35.0)	41.3	41.3	(32.1)	(32.1)
10	Sweden	450	8.79	164	3.6	168	0.17	364	18.9	21.0	(14.3)	12.8	12.5	(8.7)	(8.5)
11	Switzerland	40	7.2	40.0		40.0	0.14	1 000	5.56	4.1	(3.0)	10.3	10.3	(7.5)	(7.5)
12	Ukraine	600	51.4	51.0	159	210	0.30	85.0	2.54	55.2	26.8	108	26.3	52.5	12.8
North and Central America															
13	Canada	9 970	30	3 290	130	3 420	0.06	330	112	801	(587)	24.3	23.4	(17.8)	(17.1)
14	Costa Rica	50	3.42	110		110	0.16	2 200	32.2	16.8	(7.6)	15.3	15.3	(6.8)	(6.8)
15	Honduras	110	5.49	93.0		93.0	0.14	845	16.9	9.4	(6.2)	10.1	10.1	(6.7)	(6.7)
16	Mexico	1 960	94.8	345	2.5	348	0.12	176	3.65	145	74.0	42.0	41.7	21.4	21.3
17	USA	9 360	262	2 900	148	3 048	0.11	310	11.4	796	714	27.4	26.1	24.6	23.4
Africa															
18	Angola	1 250	11.1	150		150	0.26	120	13.5	8.9	(4.4)	5.9	5.9	(2.9)	(2.9)
19	Cameroon	480	13.2	194	24.5	219	0.18	404	15.6	15.3	(10.4)	7.9	7.0	(5.4)	(4.7)
20	Côte d'Ivoire	320	14.2	70.0	7.8	77.8	0.21	219	5.20	38.7	(32.5)	55.3	49.7	(46.4)	(41.8)
21	Egypt	1 000	62.9	0.5	91.8	92.3	0.40	0.5	0.74	162	(76.3)		175		(82.7)
22	Ethiopia	1 220	55.1	116	0.9	117	0.24	95.1	2.11	2.55	(1.8)	2.2	2.2	(1.5)	(1.5)
23	Ghana	240	17.4	38.6	22.0	61.0	0.20	161	2.85	148	(90.0)	383	243	(233)	(147)
24	Kenya	580	28.3	60.0	5.5	65.5	0.34	103	2.22	5.63	(3.4)	9.4	8.6	(5.7)	(5.2)
25	Mali	1 240	10.5	39.6	54.8	94.4	0.32	31.9	6.38	15.3	(13.4)	38.6	16.2	(33.8)	(14.2)
26	Mozambique	800	16.0	57.0	127	184	0.24	71.3	7.53	66.8	(54.4)	117	36.3	(95.4)	(29.6)
27	Nigeria	920	108	275	43.7	319	0.26	299	2.75	25.1	(17.6)	9.1	7.8	(6.4)	(5.5)
28	South Africa	1 220	41.5	52.0	2.5	54.5	0.24	42.6	1.28	18.6	(9.1)	35.8	34.2	(17.5)	(16.7)
29	Sudan	2 500	27.4	25.0	140	165	0.31	10	3.47	17.2	(10.3)	68.8	10.4	(41.2)	(6.2)

Number	*Country*	*Area ('000 km²)*	*Population (mill.) 1995*	*Renewable water resources km³/year*			*Cv*	*Potential water availability*		*Reservoir capacities (km³)*		*Ratio of total reservoir capacity to water resources (%)*		*Ratio of the active reservoir to water resources (%)*	
				Local	*Inflow*	*Total*		*Area (mm)*	*Population (10³ m³/year per captita)*	*Total*	*Active*	*Local*	*Total*	*Local*	*Total*
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Africa (contd.)															
30	Uganda	240	21.3	30.3	24.0	54.3	0.21	126	1.99	205	(205)		(378)		(378)
31	Dem. Rep. Congo	2 340	42.6	989	313	1 302	0.10	423	26.9	3.0	(2.9)	0.3	0.23	(0.29)	(0.22)
32	Zambia	750	9.5	94.0	15.3	109	0.35	125	10.7	160	(46.0)	170	147	(48.9)	(42.2)
Asia															
33	Bangladesh	140	120	225	1 167	1 390	0.14	1 607	6.74	7.0	(4.8)	3.1	0.50	(2.2)	(0.35)
34	China	9 600	1 222	2 700		2 700	0.15	281	2.21	443	(223)	16.4	16.4	(8.3)	(8.3)
35	India	3 290	936	1 456	581	2 037	0.11	443	1.87	299	223	20.5	14.7	15.3	10.9
36	Indonesia	2 027	198	2 080		2 080	0.12	1 026	10.5	9.0	(6.3)	0.43	0.43	(0.30)	(0.30)
37	Iran	0.16	67.3	136	5.0	141	0.34	850	2.06	21.5	(13.5)	15.8	15.2	(9.9)	(9.6)
38	Iraq	440	20.4	48.4	66.0	114	0.40	110	3.99	142	(91.3)	293	124	(188)	(80.0)
39	Japan	380	125	450		450	0.17	1 184	3.60	24.5	(19.0)	5.4	5.4	(4.2)	(4.2)
40	Kazakhstan	2 720	16.7	68.4	55.9	124	0.28	25.1	5.77	90.0	45.2	132	72.4	66.1	36.4
41	Kyrgizstan	200	4.67	48.9		48.9	0.15	245	10.5	20.5	14.4	41.9	41.9	29.4	29.4
42	Malaysia	334	20.1	456		456	0.15	1 365	22.7	23.6	(12.3)	5.17	5.17	(2.69)	(2.69)
43	Pakistan	804	140	40.2	186	226	0.37	50	0.95	27.0	(16.7)	67.2	12.0	(41.5)	(7.39)
44	Syria	185	14.7	25.5	27.5	53.0	0.38	138	2.67	13.5	(8.7)	52.9	25.5	(34.1)	(16.4)
45	Tajikistan	140	5.93	47.2	46.9	94.1	0.15	337	11.9	26.5	15.1	56.1	28.2	32.0	16.0
46	Thailand	510	58.8	198	120	318	0.20	388	4.39	66.5	(44.1)	33.6	20.9	(22.3)	(13.8)
47	Turkey	770	61.9	213	1.5	214	0.30	277	3.45	135	(72.9)	63.2	62.6	(34.2)	(33.9)
48	Uzbekistan	450	20.3	9.5	94.8	104	0.25	21.1	2.80	13.3	8.2	140	12.8	86.3	7.9
49	Vietnam	332	74.5	320	546	866	0.18	964	7.96	16.5	(9.3)	5.16	1.9	(2.9)	(1.07)
South America															
50	Argentina	2 780	34.2	270	623	893	0.27	97.1	17	146	(85.0)	54.3	16.4	(31.5)	(9.5)
51	Brazil	8 510	159	6 220	1 900	8 120	0.08	731	45.1	474	(272)	7.6	5.8	(4.4)	(3.4)
52	Chile	75	14.0	354		354	0.13	4 720	25.3	10.5	(7.2)	2.9	2.9	(2.0)	(2.0)
53	Colombia	1 140	34.3	1 200		1 200	0.06	1 053	35.0	28.2	(16.3)	2.35	2.35	(1.36)	(1.36)
54	Paraguay	410	5.0	48.9	500	549	0.30	119	59.8	33.1	(20.8)	67.7	6.0	(42.5)	(3.8)
55	Uruguay	180	3.20	68.1	74.1	142	0.50	378	32.9	11.7	(6.4)	17.2	8.24	(9.41)	(4.5)
56	Venezuela	916	21.8	1 470	337	1 807	0.21	1 605	75.2	154	(65.1)	10.5	8.53	(4.43)	(3.6)
Australia & Oceania															
57	Australia	7 680	18.1	352		352	0.24	45.8	19.4	73.2	(50)	20.8	20.8	(14.2)	(14.2)

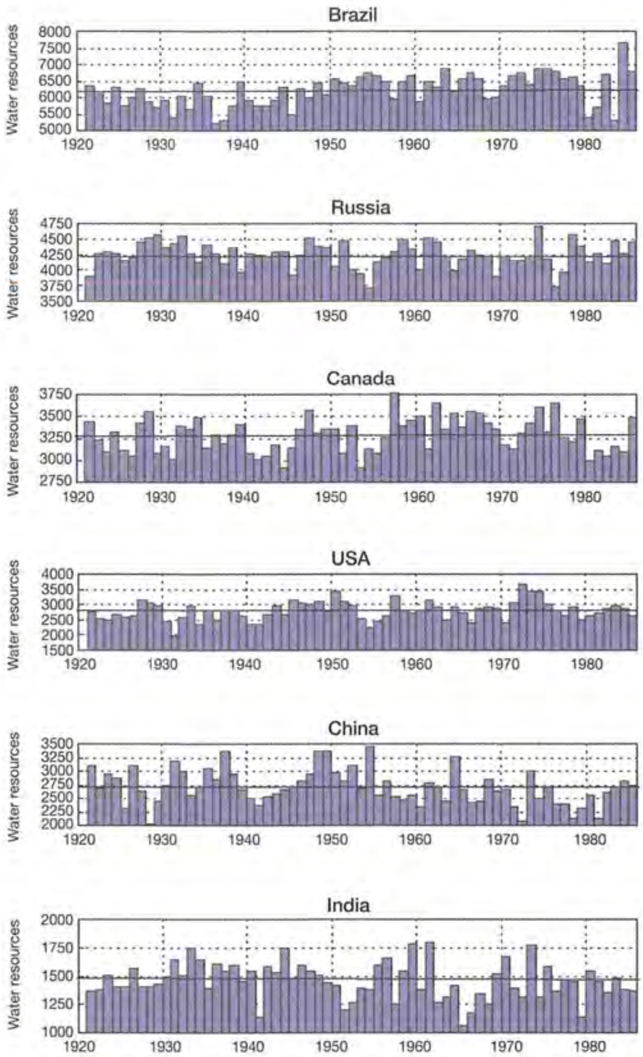


Figure 16—Renewable water resources variations (km^3/year) by countries of the world with largest volume of renewable water resources

or less identical, with a regulation coefficient of 8–10 per cent.

The figures given above for renewable water resources in selected countries (Table 10) do much to refine the assessments published in various sources round the world, such as those issued by the World Resources Institute (2000). For many countries, the differences amount to several dozen percentage points, and for some characteristics of water resources, the differences are many times more.

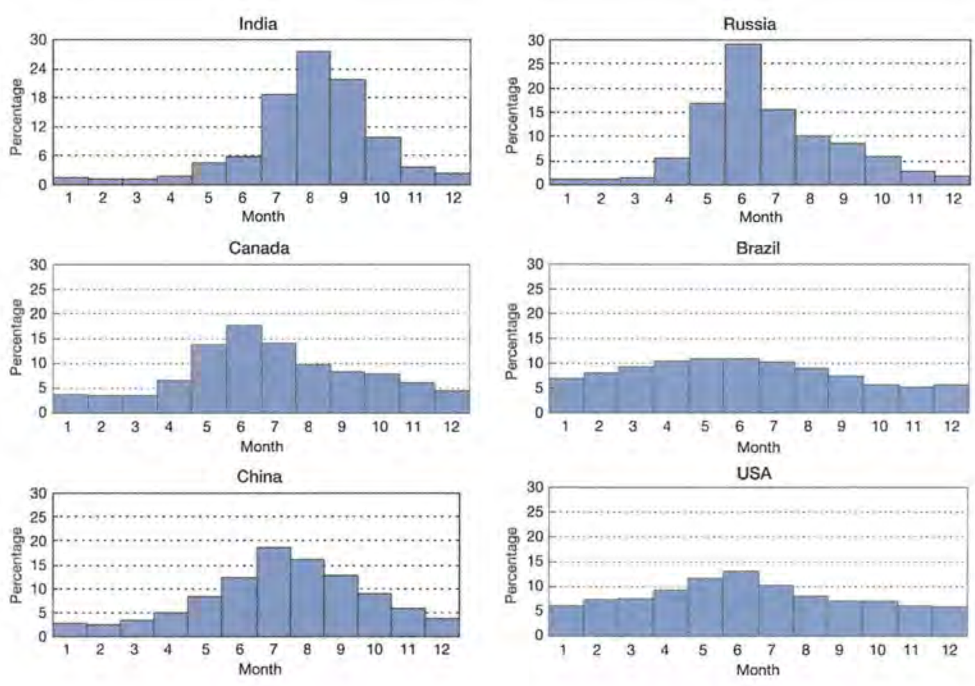


Figure 17—Streamflow distribution during a year in percentage of annual runoff by selected countries

Chapter 4

RIVER WATERS INFLOW TO THE OCEANS

4.1 WATER RESOURCES AND INFLOW OF RIVER WATERS INTO OCEANS

The discharge of river waters to the world's oceans is a key component of the global hydrological cycle, contributing considerably to the exchange of waters between land and sea.

Though river waters are far smaller in quantity than the sea water in the oceans of the world, they are extremely significant in the water balance and the exchange of waters between its different parts, particularly in the physical processes that occur in the seas and oceans. As they enter the seas and oceans, they are the cause of the discharge currents in offshore areas, which shift according to the vagaries of the seasons and the years.

Fresh river water, which differs considerably in its physical-chemical make-up from the salt water of the sea, mingles with the latter and affects the general movement pattern of ocean water masses. Even relatively small volumes of river water produce lighter weight water originating in the surface layers of seas; water that is no longer fresh but has spread out across large areas of the ocean surface and considerably altered the latter's physical-chemical and dynamic processes.

River waters have a particularly great impact when they flow into so-called inland lakes and seas, where there are no outlets to the world's oceans. Discharge to such bodies of water is among the basic factors underlying their water balance and levels.

Oceans, seas and lakes have vastly differing fresh water inflows, geographical distribution and time dynamics, factors crucial to studies of the impact of river waters on the state of the bodies of water they supply.

The size of river water discharge to oceans has been assessed by different investigators in differing degrees of detail, beginning with the 1880s through the study of world water balance. Initially, in the late nineteenth and early twentieth century, the aggregate annual discharge of river waters into the world's oceans was estimated to be in the 15 000–25 000 km^3 range (Voeikov, 1886; Brickner, 1905).

In subsequent years, as observation data accumulated, the figures for river discharge became much more precise and, as a rule, the volumes estimated rose noticeably; thus, assessments by most authors in the first quarter of the twentieth century produced estimates of annual discharge in the 26 000–29 000 km^3 range (Schmidt, 1915; Kaminsky, 1925), in the 1940s and 1950s in the 30 000–34 000 km^3 (Lvovich, 1945; Budyko, 1955), and in the 1960s and 1970s in the 36 000–42 000 km^3 range (Budyko, 1963; Kessler, 1969).

The most detailed assessments of the Earth's water balance and discharge to the various oceans of the world were made independently and published by Korzun in Russia (*op. cit.*, 1974) and Baumgartner and Reichel in Germany (*op. cit.*, 1975). The Russian figures give total average discharge to the world's oceans as 42 500 km^3 a year, whereas the data of their German colleagues are significantly lower, at 36 000 km^3. Such significant differences are explained by the different methods and initial data used by the authors (see section 3.1).

The figures for river discharges in this publication are based on the initial data and methodologies referred to in section 3.4.

It is important for river water flows into the world's oceans not to be equated with world renewable water resources. This is for two reasons:

In the first place, many river catchment basins form part of endorheic or landlocked areas, with no discharge to the world's oceans. The main features of endorheic discharge and size of water originating in them are given in Table 11. The distribution of such areas is given on the map in Figure 18. The overall area of endorheic discharge is 30 million square kilometres (20 per cent of the Earth's land surface), but only 2.3 per cent of annual streamflow, or some 1 000 km^3 per annum, stems from areas of this type. This is because the bulk of endorheic areas are desert or semi-desert with very low rainfall levels. The largest endorheic areas are the Caspian Sea

Continent	*Area (mill. km^2)*	*Water resources (km^3)*
Europe	2.16	311
North America	0.88	15
Africa	9.6	150
Asia	12.3	415
South America	1.41	56
Australia & Oceania	3.92	9.4
World	**30.27**	**956.4**

Table 11—Major characteristics of endorheic regions of the world

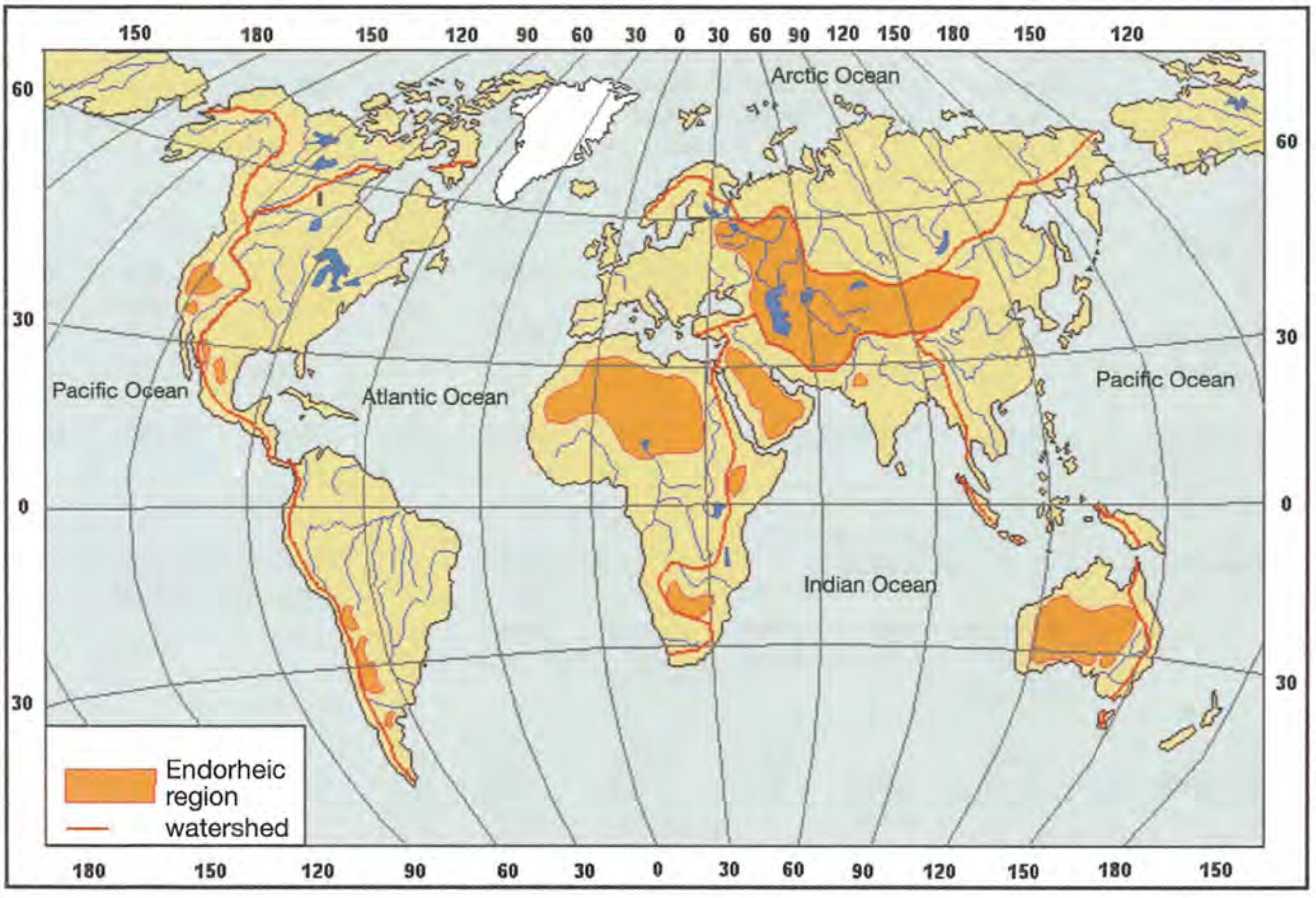


Figure 18—The endorheic regions of the world and main watersheds of the oceans

basin in Europe and Asia, the bulk of Near and Central Asia, the Arabian Peninsula, North Africa and Australia.

Endorheic basins that are insignificant in area exist in other regions, including North and South America (Figure 18). Certainly, discharge arising in landlocked areas does not flow into the oceans but evaporates from the ground or the surfaces of bodies of water, or may be drawn off for economic purposes, in particular for irrigation.

Secondly, in areas where there is external discharge directly into the oceans, water resources in river basins are far from being always the same as discharge at main river mouths. This is particularly the case in catchments where there is discharge formation accompanying heavy precipitation, but where, as streamflow travels down towards the river mouth, much of it is lost to unproductive evaporation and economic needs in plains areas and depressions (see section 3.4). As a rough guide, for all continents in areas with external discharge, some 1 100 km^3 per annum is lost and fails to reach river mouths, due to unproductive evaporation. In addition, some 1 100–1 200 km^3 (on average, over a 40–50 year period) is irretrievably lost to economic needs; it too never reaches the oceans.

Thus, overall river water discharge to the oceans will be considerably lower than the renewable water resources on every continent.

For a quantitative assessment of river water discharge from land masses into the oceans that fringe the shores of the different continents, and as distinct from endorheic areas, the limits of continental slopes are demarcated by the watersheds of rivers flowing into the different oceans (Figure 18); these areas are the Atlantic and Arctic oceans for Europe; the Atlantic, Pacific and Arctic oceans for North America; the Atlantic and Indian oceans for Africa; the Pacific, Indian, Arctic and the Atlantic oceans for Asia; and the Pacific and Indian oceans for Australia.

It is worth noting that the watershed between the Arctic and Atlantic oceans on the east coast of North America is somewhat arbitrary, as some of the discharge into Hudson Bay flows into the Arctic Ocean. This has often made geographers allocate the river basins discharging into the Hudson Bay and Hudson Strait to the Arctic Ocean, as in the monograph edited by Korzun (1974).

The mean long-term values for discharge of river waters into oceans from all continents are given in Table 12 and Figure 19, while Figure 20 shows annual dynamics for the long-term period under study (1921–1985).

The total discharge to the world's oceans is put at 39 500 km^3 per annum; the greatest discharge being from South America and Asia (approximately 11 800 km^3 per annum), and the lowest coming from Australia and Oceania (2 300 km^3 per annum) and Europe (2 500 km^3 per annum). In calculating water balance for the oceans, it must be borne in mind that as well as discharge from rivers, they are fed from the continents by fresh

Continent	*Pacific Ocean*			*Atlantic Ocean*			*Indian Ocean*		
	Drainage area (10^3 km^2)	*Inflow* (km^3/year)	*Layer* (mm)	*Drainage area* (10^3 km^2)	*Inflow* (km^3/year)	*Layer* (mm)	*Drainage area* (10^3 km^2)	*Inflow* (km^3/year)	*Layer* (mm)
Europe	-	-	-	6 769	1 850	273	-	-	-
North America	5300	1 950	368	12 620	4 400	349	-	-	-
Africa	-	-	-	14 900	2 990	201	5 610	530	94
Asia	11 900	5 800	487	620	201	324	7 000	3 440	491
South America	1 240	1 000	806	15 190	10 750	708	-	-	-
Australia & Oceania	1 720	1 740	1 012	-	-	-	3 310	560	169
Total land area (without Antarctica) rounded	20 160	530	522	0100	20 190	403	15 920	4 530	284

Continent	*Arctic Ocean*			*World Ocean*		
	Drainage area (10^3 km^2)	*Inflow* (km^3/year)	*Layer* (mm)	*Drainage area* (10^3 km^2)	*Inflow* (km^3/year)	*Layer* (mm)
Europe	1 531		453	8 300	2 544	306
North America	5 450	694	215	23 370	7 560	323
Africa	-	1 170	-	20 510	3 520	172
Asia	11 670	-	207	31 190	11 859	380
South America	-	2 418	-	16 430	11 750	715
Australia & Oceania	-	-	-	5 030	2 300	457
		-				
Total land area (without Antarctica) rounded	18 650	4 280	229	104 830	39 530	377

Table 12—River runoff to oceans from continents

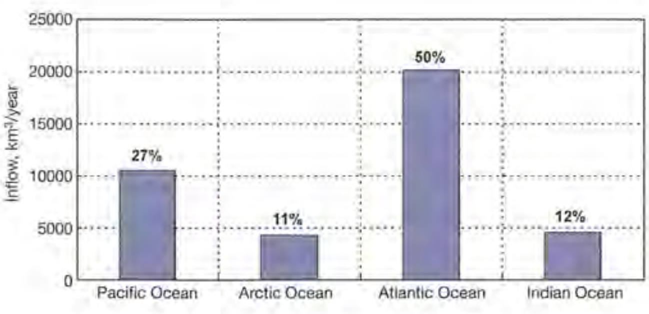


Figure 19—River water inflow to the World Ocean

groundwater that is not drained by rivers, by calving icebergs as they break up, and by meltwater from Antarctic pack ice. According to the latest assessments from the Russian Academy of Sciences Institute of Water Problems (Zektser, 2001), the aggregate discharge of groundwaters into the oceans is 2 400 km^3 per annum; in the data edited by Korzun (1974), meltwater from Antarctic sea-ice was put at 2 300 km^3 per annum.

According to Table 12, approximately half of all river discharge to the oceans drains into the Atlantic, which is fed by the waters of four of the six greatest rivers in the world (Amazon, Congo, Orinoco and La Plata). The lowest flow of all (4 300 km^3 per annum) is into the Arctic Ocean, but river waters are particularly important to the latter's regime, since its water volume is much lower than that of other oceans (see below).

Analysis of the data in Figure 20 shows that the total discharge of water into the oceans is fairly stable, and does not display any distinct trend for the period under review. At the same time, there has been a noticeable slackening of flows out into the Indian and Pacific oceans (to some extent explicable by the growth in water losses for economic requirements) and a rising curve for discharge into the Atlantic.

In modelling the oceans' dynamic processes, the overall volume of river discharge is not the only crucial factor, but its territorial distribution in different parts of the World Ocean is also of extremely great importance. Discharge to the oceans is extremely uneven, as is borne out by the data in Figure 21, showing the distribution of discharge to the oceans of the world according to bands of latitude. Around the Equator between the latitudes 100°N and 100°S latitudes, an average of some 40 per cent of all discharge enters the ocean (three of the world's five largest rivers have their mouths in this belt: the Amazon, Congo, and Orinoco). The data for individual years or seasons from data observations for the world hydrological network may be of great interest for

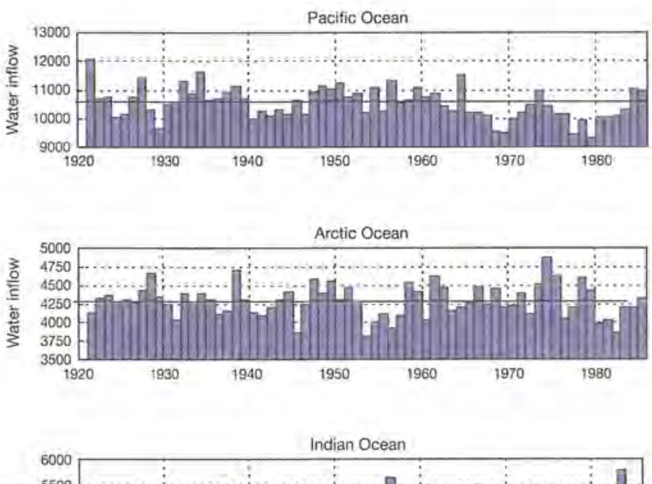


Figure 20—River water inflow (km^3/year) to the World Ocean

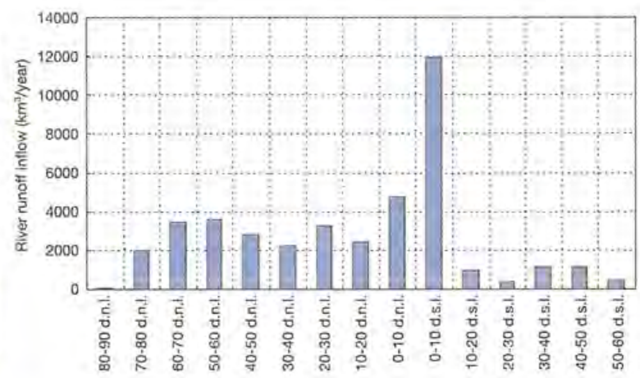


Figure 21—River runoff inflow to the World Ocean by latitudinal zones

oceanographers when developing methods for building ocean water circulation models.

4.2 CLIMATE CHANGES AND RIVER WATER DISCHARGE DYNAMICS INTO THE ARCTIC OCEAN*

Analysis of river water discharge dynamics to the oceans based on observation data is of great scientific interest to studies of the global hydrological cycle This has been specially true in the past few decades, because of the steep increase in economic activity in river system basins and the processes involved in global warming, which became particularly noticeable from the 1980s onwards (International Panel on Climate Change, IPCC 2001).

* This section was drafted jointly with Dr A.I. Shiklomanov, Candidate of Hydrological Sciences.

Unfortunately, the data from Figure 20 do not permit such an analysis, as they do not cover the last 15–20 years because of the major difficulties in obtaining data from hydrological observations in many countries and regions of Asia, Africa, and South America (see section 3.2).

In recent years it has proved possible to obtain more detailed hydrological data for the Arctic Ocean than in the past, under a joint project bringing together investigators from Canada, Russia and the United States (Lammers et al., 2000). Under this project, a hydrological database was established for monthly and yearly river basin discharge for the entire observation period up to and including 1999, for more than 5 000 gauge stations. The data were used to carry out a comprehensive analysis of the dynamics of river discharge to the Arctic Ocean during the last few decades, because of their association with global warming processes (Shiklomanov et al., 2000; Shiklomanov, I. A. and A. I Shiklomanov, 2003).

The changing trend in river water outflow is particularly important for processes in the Arctic Ocean, where the volume of sea water is relatively small as compared with the amount stemming from discharge. Data from Table 13 show that the Arctic Ocean contains no more than 1.2 per cent of all the water in the oceans, but for a long time has been receiving on average 11 per cent of the world's annual discharge.

Unlike other oceans, the Arctic Ocean has a basin with a land drainage area much greater than its water surface. The ratio of the area within its watershed to the ocean surface is 1.29, whereas the equivalent for the Atlantic is 0.55, for the Indian Ocean 0.27, and for the Pacific 0.14 (Table 13).

Before analysing the dynamics of river discharge to the ocean, the drainage area's watershed must be carefully determined and an estimate made of how far it is covered by observations. Many quantitative assessments have been made of the outflow of river waters into the Arctic Ocean, but they all differ extremely widely (Korzun, ed., 1974; Ivanov, 1976; the Russian Arctic and Antarctic Research Institute, 1985; Grabs, 1999), mainly explained as being for the following reasons:

Ocean	*Water surface area*	*Drainage area*	*Water volume*		*River runoff inflow to the ocean*	
	10^6 km^2	10^6 km^2	10^6 km^3	%	km^3/year	%
Pacific	178.7	24.9	707.1	52.8	10 530	26.6
Atlantic	91.7	54.2	330.1	24.7	20 190	51.1
Indian	76.2	20.9	284.6	21.3	4 530	11.5
Arctic	14.7	18.9	16.7	1.2	4 280	10.8
World Ocean	361.3	118.9	1 338.5	100.0	39 530	100.0

Table13—Basic morphometric and hydrological characteristics of the World Ocean

- Different surface areas are used for the ocean basin;
- Discharge from areas uncovered by observations may or may not be allowed for;
- Varying lengths of time are used to obtain averages.

The Arctic Ocean drainage area occupies a huge area in the northern part of the Eurasian and North American land masses, stretching far outside the Arctic proper, the southern edge of the catchment being usually determined by the line dividing forest and tundra, which roughly follows the +10°C isotherm at mid-July temperatures. The southern boundary of the Arctic Ocean basin in Asia and North America, where the discharge originates for the largest rivers flowing into the ocean, is thousands of kilometres outside the Arctic, as far south as 45–50°N.

The Arctic Ocean basin is rimmed by areas with discharge that does not flow directly into the ocean, but may exercise one kind of an impact or another on processes occurring in it. These include, first and foremost, the North American river basins draining into Hudson Bay and Hudson Strait, where discharge flows into the Atlantic, although part moves into the Arctic Ocean. A somewhat analogous situation occurs in relation to the Yukon River and the rivers in the Gulf of Anadyr, the latter belonging geographically to the Pacific Basin, but with some of their flow perhaps passing through the Bering Strait into the Arctic Ocean. This underscores the need to take account of discharge from such areas in one way or another when assessing the dynamics of river waters flowing out into this ocean, particularly as it accounts for more than 1 200 km^3 per annum of the discharge. Moreover, discharge into Hudson Bay and Hudson Strait basins sometimes flows entirely through to the Arctic Ocean Basin (Korzun, ed., 1974).

Table 14 gives the land areas of different parts of the basin and adjacent lands and, more importantly, also gives the sizes of zones not covered by hydrometric observations. The same table gives the numbers of gauge stations in every area contained in the ocean basin hydrological database that we used.

The largest number of gauge stations are found in US territory, but they are especially numerous in the Hudson Bay and Hudson Strait basin as well. And in general the density of this station network in North America is considerably greater than in the huge land mass of Asiatic Russia or even those parts of Europe related to the Arctic Ocean basin. On the other hand, the North American hydrological network has relatively short observation series (usually of no more than 30–40 years); whereas the series are considerably longer in Asiatic and European parts of the basin (55–65 years). There is one more significant shortcoming so far as North American hydrological data are concerned, namely the many gaps in the observations series. This is particularly true of Canada, where winter discharge is simply not measured. In all, some 20 per cent of North American monthly discharge data is missing, whereas for Asiatic and European areas the equivalent figures are 5–10 per cent.

However, the main weakness of North American hydrological information is its extremely uneven distribution through the area, leaving out more or less all the northernmost parts of the continent, Canada's Arctic islands and Greenland; the same is true for islands in the European Arctic (Spitzbergen, Novaya Zemlya, and so forth), and for Russia's far northern tundra.

The data in Table 14 also show that the area best covered by hydrological observations is the Asiatic part of the Arctic Ocean basin (85 per cent), followed by the European part (70 per cent), while North America has only 50–60 per cent coverage In all, some 26–33 per cent of the territory of the basin has not had coverage by hydrological observations, which militates against a dependable quantitative assessment of river outflow to the ocean and makes for a considerable degree of imprecision.

The above-mentioned hydrological database was used as the foundation for assessing the outflow of river waters into the Arctic Ocean, helping in the adoption of a long-term period (1921–1999) to monitor the whole basin, quite enough for reliable statistical analysis. At the same time, the methodologies in section 3.4 were used to assess annual discharge values from areas not covered by observations.

The mean long-term figures (1921–1999) and extremes for annual river discharge to all regions of the Arctic Ocean Basin are given in Table 15.

The total long-term freshwater discharge to the Arctic Ocean, together with discharge from Hudson Bay and Hudson Strait, amounts to 5 250 km^2 per annum, with Asia accounting for 46 per cent, North America for 41 per cent and Europe for 13 per cent. The figures include 948 km^2 a year for Hudson Bay and Hudson Strait. The river discharge in the area of the Bering Strait (Yukon and others) is assessed at 300 km^2 per annum. If

Table 14—Drainage areas, number of stations, gauged and ungauged areas in different regions of the Arctic Ocean basin

Region	*Drainage area* (10^3 km^2)	*Number of stations*	*Ungauged area* (10^3 km^2)	*Gauged area* (in % of the total area)
North America (Arctic Ocean basin only)	4 012	588	1 997	50.2
North America (Arctic Ocean basin with the adjacent territory)	8 646	2 233	3 452	60.1
Asia (Arctic Ocean basin only)	11 186	2 203	1 668	85.1
Asia (Arctic Ocean basin and the Anadyr Bay basin)	11 409	2 222	1 735	84.8
Europe	1 501	598	440	70.7
Greenland	2 176	0	2 176	0.0
Basins of the adjacent territories	4 869	1 664	1 531	68.6
Arctic Ocean basin	18 875	3 389	6 281	66.7
Arctic Ocean basin with the adjacent territories	23 732	5 053	7 803	67.1
Arctic Ocean basin with the adjacent territories, but without Greenland	21 556	5 053	5 628	73.9

Table 15—Statistical characteristics of annual freshwater inflow to the Arctic Ocean during 1921–1999

Basin	*Mean inflow* (km^3/year)	*Variation coefficient* (C_V)	*Max. inflow* (km^3)	(year)	*Min. inflow* (km^3)	(year)
Bering Strait	301	0.09	362	1990	259	1999
Hudson Bay and Hudson Strait	946	0.09	1 140	1966	733	1989
North America (Arctic Ocean basin)	1 187	0.09	1 510	1996	990	1953
North America with Hudson Bay and Hudson Strait	2 133	0.07	2 475	1996	1 800	1998
Europe	697	0.08	884	1938	504	1960
Asia (Arctic Ocean basin)	2 430	0.06	2 890	1974	2 100	1953
Arctic Ocean basin	4 314	0.05	4 870	1974	3 820	1953
Arctic Ocean basin with Hudson Bay and Hudson Strait	5 250	0.04	5 950	1974	4 700	1953

the outflow into Hudson Bay and Hudson Strait is left out, the proportion from Asia will account for 56.5 per cent of the inflow, North America for 27.4 per cent and Europe for 16.1 per cent.

The long-term variability (C_V) of annual discharge in the basin is not very great and is in the range C_V = 0.04–0.09; the extreme figures for the period under consideration differ from the average long-term figures by 15–20 per cent (Table 15). The variability of overall discharge to the ocean is C_V = 0.04–0.05; discharge was at its highest in 1974, 5950 km^2 for the year (13 per cent higher than the mean annual value), and its lowest was in 1953, at 4700 km^2 for the year (11 per cent below the mean).

It should be pointed out that for the first 20–30 years of the period studied, when the hydrology observation network in the basin was still spread very thin, and there were no observation data even for some of the larger rivers, assessment results for annual figures largely depended on the reliability of methods used to recreate discharge series. Naturally, the accuracy of the discharge assessment for that early period was much lower, for example, than in the last 40–50 years of the period under study. Nonetheless, the series analysis carried out for all regions during the whole period 1921–1999, demonstrated their statistical homogeneity.

The dynamics of discharge into the Arctic Ocean from the Asian part of the drainage basin and from

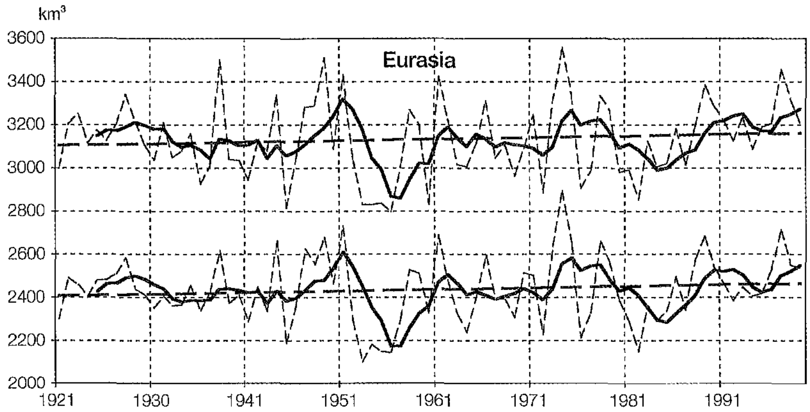


Figure 22a—River runoff to the Arctic Ocean from the Asian and Eurasian parts of the drainage basin during 1921–1999. Annual values smoothed by 5-year periods and trends

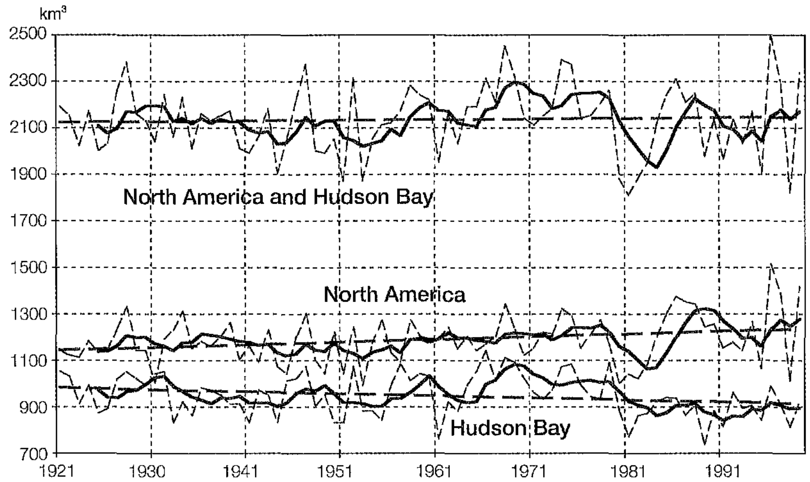


Figure 22b—River runoff to the Arctic ocean from North American part of the drainage basin during 1921–1999. Annual values smoothed by 5-year periods and trends.

Eurasia as a whole are given in Figure 22a (annual figures and values smoothed by five-year periods). In the figures there appears a fairly distinct, though only slightly rising, trend in discharge throughout the period under consideration, but it has become more clear-cut in the past 15 years.

More or less the same picture holds true for North America, not including Hudson Bay and Strait (Figure 22b). Here, the rising trend in the discharge is even more striking than in Eurasia; in North America for the whole period it amounts to 7.8 per cent, in Eurasia to 1.6 per cent. However, for the same period in North America there was a marked decline in discharge to Hudson Bay and Hudson Strait basin. If the latter region is also taken into account, then the discharge to the ocean from the North American continent has stayed more or less stable.

As a whole, for overall river discharge to the Arctic Ocean, there is a fairly clear rising trend, particularly when the effect of discharge in Hudson Bay and Hudson Strait (Figure 23) is ignored. For the entire period, the trend amounts to +2.9 per cent, i.e. a 125 km^2 per annum increase overall.

Thus, the general conclusion can be drawn that the approximately 0.5°C air temperature rise in the northern hemisphere during the last 80–100 years has been accompanied by a slightly rising level of river discharge to the Arctic Ocean. Is this rise a consequence of human-induced global climate warming, or a general natural long-term fluctuation in hydrometeorological components? The answer is still open to discussion and in the opinion of the present authors it is still not really possible to arrive at an unambiguous answer.

Figure 24 shows the long-term (beginning in 1867) progress of air temperature anomalies in the northern hemisphere and its higher and lower latitudes, where the basic discharge of river waters into the ocean originates. According to these data, the greatest growth in air temperatures has occurred in the last few years, in effect since 1987. It is of undoubted interest to make a quantitative assessment of the response of discharge into the ocean to the very high degree of warming. In purely visual terms, to judge by the curves shown in Figure 23 for the period, a rise in discharge has been occurring in all parts of the ocean basin (except for Hudson Bay and Hudson Strait).

The values for river discharge for different periods, expressed as mean values and modular coefficients for the entire long-term period (1921–1999), are shown quantitatively in Table 16. The data given there indicate that the increased discharge during the past 12 years as compared with the period 1921–1965 amounted, in all parts of the basin, to 3–7 per cent; the exception being the basin of Hudson Bay and Hudson Strait, where there was a 6 per cent fall in discharge during the later period. All in all, the discharge for the ocean basin rose (as against the period 1921–1965) by 208 km^3 per annum, i.e in the space of 12 years the ocean additionally absorbed almost 2 500 km^3 of fresh water; for the Eurasian region the figures amounted to 127 km^3 per annum or 1 500 km^3 (Table 16).

A study of the dynamics of river discharge in relation to man-made global climate changes is of enormous

Figure 23—Dynamics of river inflow into the Arctic Ocean for the period 1921–1999

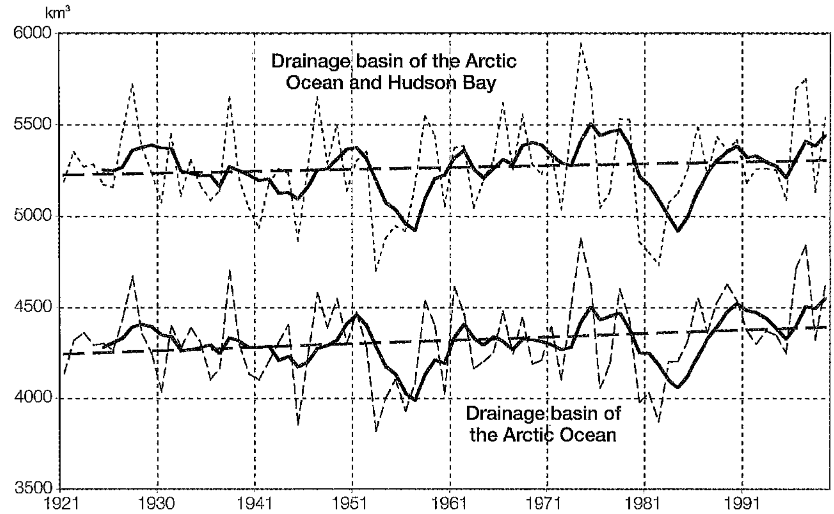
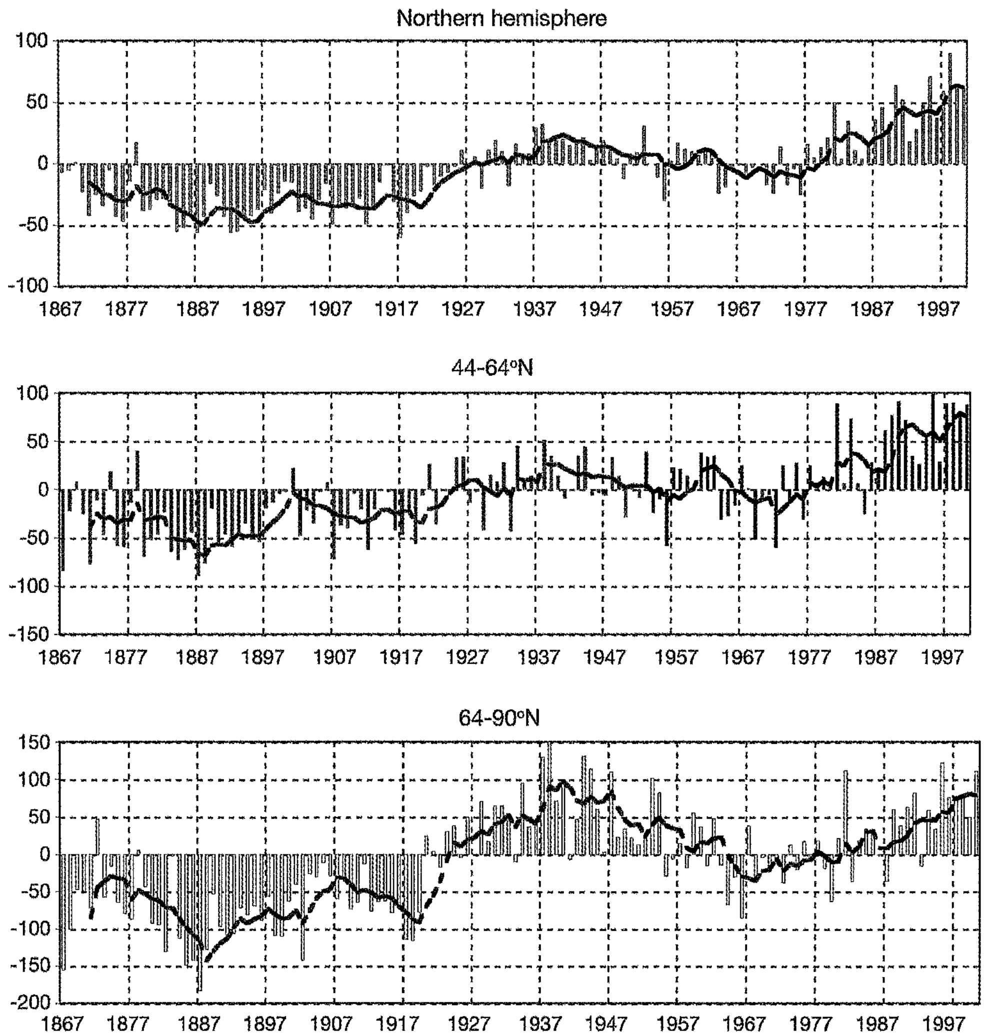


Figure 24—Mean annual anomalies of air temperature of 0.1°C from the selected zonal mean values
Sources: GHCN 1701-04/2000, NASA Goddard Institute for Space Studies; basic period: 1951–1980



importance not only for the Arctic Ocean, but also for the water circulation processes occurring in the North Atlantic, which largely govern the climatic situation in the higher and lower latitudes of the northern hemisphere.

A large number of studies in different countries have convincingly shown that any freshening of water in the Arctic Ocean increases the North Atlantic Oscillation (NAO), and reduces North Atlantic Deep Water (NADW) formation and the Atlantic Thermo-Haline Circulation. The part played by fresh water entering the ocean from the Eurasian landmass is particularly important.

However, the above-mentioned conclusions on the discharge increase in recent years, based on the figures in Table 16, may seem inconclusive as they are based not only on observation data but also on the results of calculations for re-establishing series for the 1920s and

Basin	*Period*	*Mean inflow* (km3/year)	*Modulus coefficient*
Hudson Bay and Hudson Strait	1921–1965	952	1.01
	1966–1976	1 034	1.09
	1977–1987	908	0.96
	1988–1999	878	0.93
North America basin	1921–1965	1 165	0.98
	1966–1976	1 218	1.03
	1977–1987	1183	1.00
	1988–1999	1 246	1.05
North America with Hudson Bay	1921–1965	2 117	0.99
	1966–1976	2 251	1.06
	1977–1987	2 091	0.98
	1988–1999	2 124	1.00
Europe	1921–1965	699	1.00
	1966–1976	674	0.97
	1977–1987	687	0.98
	1988–1999	721	1.03
Asia	1921–1965	2 412	0.99
	1966–1976	2 482	1.02
	1977–1987	2 379	0.98
	1988–1999	2 517	1.03
Arctic Ocean basin (total)	1921–1965	4 276	0.99
	1966–1976	4 370	1.02
	1977–1987	4 248	0.98
	1988–1999	4 484	1.04
Arctic Ocean basin with Hudson Bay and Hudson Strait	1921–1965	5 228	0.99
	1966–1976	5 408	1.03
	1977–1987	5 157	0.98
	1988–1999	5 362	1.02

Table 16—Annual water inflow to the Arctic Ocean for different long-term periods

assessments of discharge from areas with no observations at all.

To obtain more dependable conclusions, a group of investigators from Germany, Russia and the United States undertook an analysis of the dynamics of river discharge to the ocean, global air temperature changes and the index of the North Atlantic Oscillation (NAO) for the period 1936–1999, with the results being published in the journal "Science" (Peterson et al., 2002).

The analysis employed aggregate annual discharge data from the six largest rivers flowing into the Arctic Ocean from the Eurasian continental mass: Yenisei, Lena, Ob, Kolyma, Pechora, and Northern Dvina. All these rivers have an unbroken series of reliable observations at river-mouth stations for the entire period under consideration by the group (1936–1999).

The dynamics of overall annual discharge for the six rivers in this period, given in Figure 25, show a significant positive trend, with a mean annual rise of 2.0 ± 0.7 km^3 per annum. Thus the overall mean annual discharge for the rivers has now risen to 124 km^3 per annum, i.e. 7 per cent higher than in the 1930s when observations began.

As the analysis showed, the change in discharge from the Eurasian rivers shows good agreement with changes during the same period in the North Atlantic Oscillation and global surface air temperature (Figure 26). During the period in question, global temperatures rose by 0.4°C, those in the Arctic Ocean basin by 0.6°C, and the temperatures in the Eurasian portion of the basin by 0.7°C.

The relatively good agreement between the changes in discharge from Eurasian rivers flowing into the Arctic Ocean and global air temperatures means that certain coarse conclusions pointing towards the future may be drawn.

The Intergovernmental Panel on Climate Change (IPCC, 2001) forecast a global surface air temperature change by the year 2100 within the 1.4–5.8°C range. According to data from Figures 25 and 26, that would mean a rise in aggregate discharge from the six important Eurasian Arctic rivers of between 315 and 1 260 km^3 per annum, i.e. from 18 to 70 per cent more than under present circumstances (Peterson et al., 2002).

Very similar results for the expected rise in annual discharge from the Eurasian rivers in the Arctic Ocean basin as a result of global warming (≈35 per cent) were

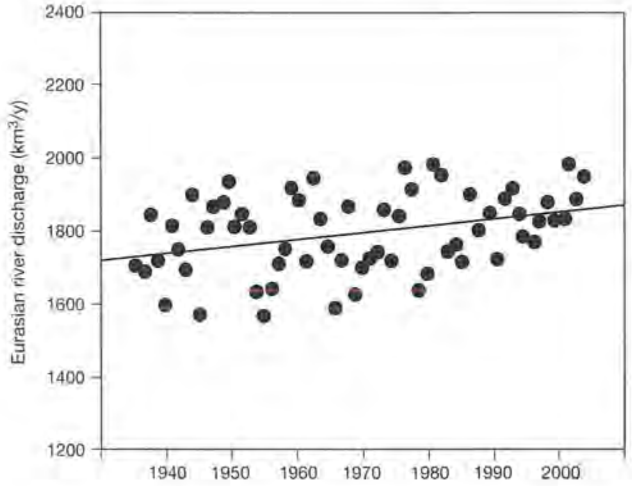


Figure 25—Annual discharge of the six largest Eurasian rivers inflowing into the Arctic Ocean for 1936–1999

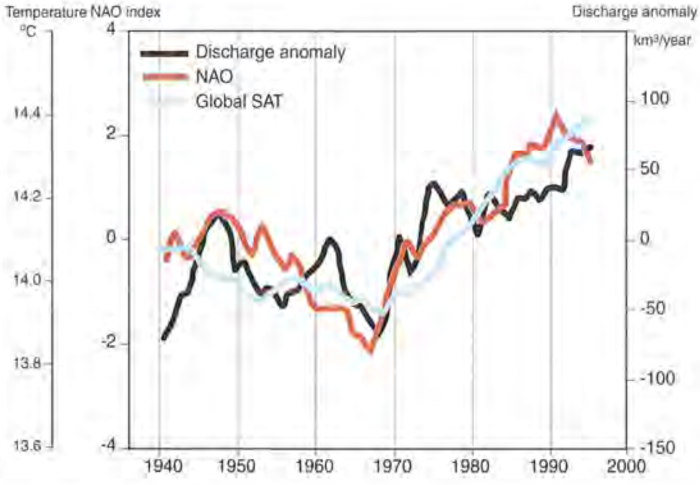


Figure 26—Ten-year running averages of Eurasian arctic river discharge anomaly, winter NAO index and global mean SAT for 1936–1999

River	*Period*	*Winter* (Nov-Mar)	*Spring* (Apr-Jun)	*Summer-Autumn* (Jul-Oct)	*Year*
Yenisei at Igarka	1936–1965	26.5	122	86.5	236
	1966–1976	34.3	119	79.9	233
	1977–1987	40.7	123	73.2	237
	1988–1999	48.8	126	77.8	253
Lena at Kiusiur	1936–1965	12.8	85.9	113	212
	1966–1976	13.1	91.5	114	219
	1977–1987	16.0	85.9	113	215
	1988–1999	17.8	96.4	117	231
Ob at Salekhard	1936–1965	24.6	55.1	83.4	163
	1966–1976	25.7	55.5	90.4	172
	1977–1987	29.1	57.2	90.6	177
	1988–1999	28.5	59.6	74.9	163
Northern Dvina at Ust-Pinega	1936–1965	42.7	170	71.5	285
	1966–1976	40	174	58.5	272
	1977–1987	52.1	163	77.4	292
	1988–1999	46.8	188	76.0	311
Mackenzie at Red River	1936–1965				
	1966–1976	30.3	57.6	85.0	173
	1977–1987	28.2	56.3	79.3	164
	1988–1999	31.1	59.9	79.2	170
Yukon at Pilot Station	1936–1965	31	84.8	143	259
	1966–1976	32.9	79.3	123	234
	1977–1987	34.1	75.5	132	242
	1988–1999	30.6	84	132	247

Table 17—Seasonal runoff of large rivers within the Arctic Ocean basin for different periods (mm)

obtained by Miller and Russell (1992), given a doubling of carbon dioxide in the atmosphere (≈ global warming of 4°C), and also by Russian researchers (from 15 to 45 per cent for 2 × CO_2) (Shiklomanov A.I, 1994; Shiklomanov I. A and Shiklomanov A.I., 2003), and from the United Kingdom (from 10 to 25 per cent for 2050) (Arnell, 1999).

Such changes to the discharges of river waters are extremely important in North Atlantic Deep Water (NADW) formation, in particular because global warming will march hand in hand with a melting of the Greenland ice-cap, and an increase in precipitation over the ocean surface is to be expected.

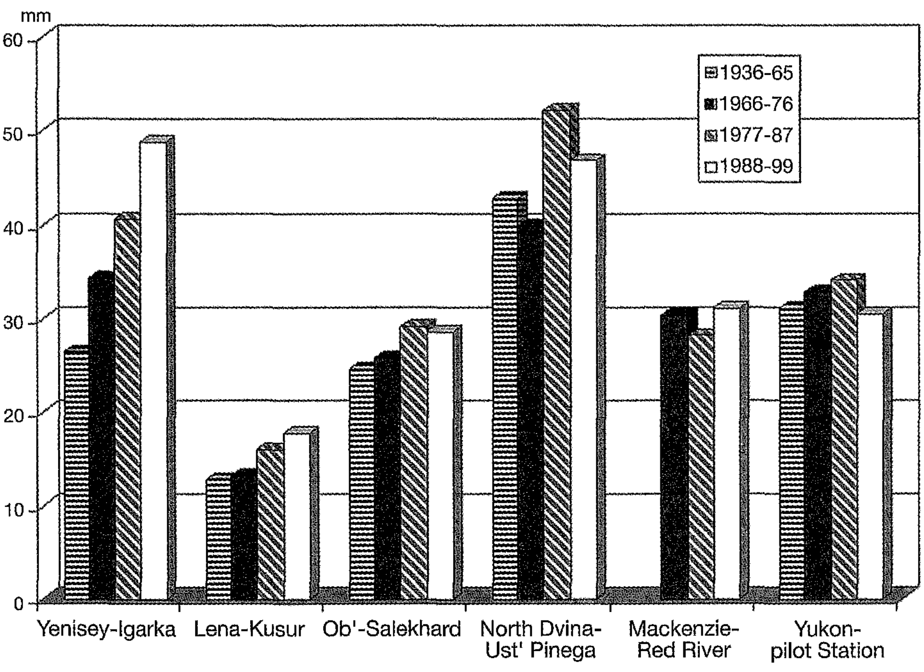


Figure 27—Winter monthly runoff (I-III, XI-XII) of the large rivers into the Arctic Ocean drainage basin (mm)

All this may potentially disrupt stable North Atlantic Deep Water formation and change the Atlantic Thermo-Haline Circulation, with possible major impacts on the climate as early as the twenty-first century in higher and temperate latitudes of the northern hemisphere. It all calls for careful study of all components of the hydrological cycle in the basin, the waters of the Atlantic Ocean, and surrounding land masses.

The hydrological database for the Arctic Ocean basin (Lammers et al., 2000) means that long-term seasonal river discharge changes in the basin can be analysed.

Data for changes in seasonal discharges to the Arctic Ocean drainage basin in different seasons are given in Table 17. The table shows that for the period in question, changes in trends in spring and summer-autumn discharge from all rivers do not follow any particular pattern; at the same time the dynamics of winter runoff abide by certain rules, which is of undoubted interest. This is particularly evident from Figure 27. On the major rivers of Asia and Europe there has been a fairly distinct rising trend in discharge since 1977. During the last 12 years, the rise on the Yenisei, by comparison with the period 1936–1965, has been 84 per cent, for the Lena 39 per cent, for the Ob 16 per cent, and for the Northern Dvina 10 per cent. Rising discharge rates have not been observed on the Mackenzie and Yukon rivers.

It should be noted that the 50–60 per cent of the increase in winter discharge on the Yenisei can be explained by the influence of reservoirs (Shiklomanov A.I, 1994; 1997). The remaining changes in winter discharge from this river, as well as the entire change in discharge from the Lena, Ob, and Northern Dvina, all of them with a more or less natural hydrological regime, can be put down to climatic factors, including evidently a noticeable rise in winter air temperatures in the southern portions of the river basins we are discussing. We should note that a considerable increase in winter discharge has been observed in the last 15–20 years on many small and medium-sized rivers in European and West Siberian Russia (Georgievsky et al., 1996).

Together with a further global air temperature rise, as has been shown by first-approximation assessments (Shiklomanov, I.A. and Shiklomanov, A. I, 2003), in all likelihood there will be a still more noteworthy change in seasonal discharge from rivers in the Arctic Ocean basin. In particular, if the concentration of carbon dioxide in the atmosphere doubles, we can expect an increase in winter river discharge to the ocean that will be 1.5–2 times above present levels.

Chapter 5

WORLD WATER USE: CURRENT STATE AND TRENDS

5.1 CONTRIBUTORY FACTORS AND THE PART PLAYED BY ECONOMIC ACTIVITIES IN A WORLD OF CHANGING WATER RESOURCES

To obtain a dependable assessment of present or future water resources and availability in a region, not only discharge fluctuation data are needed but also a quantified assessment of changes under the impact of human economic activity.

Since the dawn of time, man has been unstinting in his efforts to employ runoff and streamflow to assist him in his activities; it has been of huge importance in the development of economies and human society. This is because ramified river systems wind their way across practically every part of the Earth's surface and are easily accessible for man to use. They provide mankind with fresh water and at the same time help eliminate different kinds of pollution. In the most thickly settled regions of the globe, today there remain no major river systems whose regimes have not to some extent been touched by the hand of man.

In the largest river catchments, countries and wide expanses of natural and economic regions located in the economically most well-tamed areas of the Earth, runoff is usually affected at one and the same time by a multiplicity of factors resulting from human activity, the most important being, in terms of their impact on the quantitative features of runoff and streamflow, the regulation of river flows, irrigated agriculture, diversion of rivers, industrial, community and agricultural water supply, the draining of swamps and marshland, the cutting down of woodlands and reforestation, farming and forest improvement schemes, urban development, quarrying operations and water pumping from mines, the damming and shoring-up of river banks, the straightening and removal of bottom sediment and rubble from river beds and channels, and so forth.

5.1.1 Classification of economic activities factors

So far as their type and impact on the hydrological cycle are concerned, all economic activities may be grouped under the following four headings:

(*a*) Those bound up with changes to the surfaces of a catchment, changing evaporation and runoff formation in the basin. They include:
- Cutting down forests and their restoration (by natural re-growth or artificial reforestation);
- Ploughing up of land, miscellaneous modern agricultural techniques, use of water meadows as pasture, etc.;
- Draining of swamps and marshlands;
- Urbanization.

(*b*) Those connected with radical changes to a river system:
- The establishment and operation of reservoirs and ponds;
- The damming and strengthening of riverbanks to prevent flooding, the straightening of river channels and excavation of bottom sediment, rocks and gravel from river beds, etc.

(*c*) Those directly to do with water withdrawal from the river network, lakes, reservoirs, groundwater-bearing strata, use of the water by consumers and return thereof to bodies of water. This heading includes:
- Water use for community and domestic needs, industry, heat-and-power engineering and operation, transport, agriculture;
- Diversion of a portion of streamflow outside the basin.

(*d*) Those affecting water balance, resources and the hydrological regime by changes in general meteorological and climatic characteristics. The changes are caused by a range of physical processes that differ widely in the degree of their impact and the area they affect. They include:
- Local climate and weather changes resulting from human impacts on vegetation cover, the development of towns and cities, creation of artificial bodies of water;
- Possible changes to regional climates and the hydrological cycle as a result of large-scale freshwater use;
- Man's influence on the composition of the atmosphere as a result of additional heat entering it, increases in concentrations of carbon dioxide, and minor gas components (freons, nitrogen oxides, methane, etc.), and atmospheric aerosols.

In any major river basin or natural economic zone, many of the above types of economic activity are carried on at one and the same time under one or other of the headings we have cited, with varying impacts on water resources and the hydrological regime, depending on natural cyclical variations in hydrometeorological components, type of water use, changes in land use, physical-geographical conditions in a given area, and factors affecting the underlying surface.

5.1.2 Surface changes to river catchments

Cutting down of forests and reforestation. Among the most important factors, some of them still under threat, is the hydrological role of woodland and its effects on water resources because of changes to forest cover.

The issue has been studied in various countries for many decades or even centuries. There may be no more widely discussed topic in hydrology and more publications have been devoted to it than to any other issue, while there have never been so many conflicting opinions or different views expressed. A particularly large number of studies have been carried out, beginning in the second half of the twentieth century, as a consequence of increased economic activity, steeply rising world freshwater use and water scarcities. Mass cutting of woodlands and reforestation are governed on the one hand by rising demand for timber and its products, and on the other hand by the ever-more important use of woodlands for recreation and nature conservation.

Publications on the issue have been constantly growing in number. Along with a plethora of scientific articles and papers in learned journals and conference proceedings, between the 1970s and 1990s alone, numerous general works were produced on the hydrological and nature conservation roles of forests, among which it is worth singling out the Russian publications by Idzon (1980), Krestovsky (1986), Lebedev (1982), Molchanov (1973), Rakhmanov (1981), Sokolov (1982), Fedorov (1977), Shiklomanov (1989), Shpak (1968), etc.

Many of the key aspects of the hydroclimatic role played by forests are fairly generally admitted and are not open to doubt. These include the beneficial impact of forests on microclimates, on regenerative processes in air and water, the water-regulating and anti-erosion capacities of woodland and forest blocks; it all underpins the known enormous value of woodlands and their great contribution to nature conservancy and recreation. However, scholars around the world are still discussing the influence of woodlands and silvicultural activities on water resources and balance in different major areas and river basins. Moreover, sometimes arguments and views are voiced that are not merely different but are in direct conflict with one another.

On these questions even among hydrologists and forestry researchers in Russia, points of view were long maintained that were at variance with one another (and this is sometimes still the case). However, in the last two decades most authors have been finding more noticeably common ground, it should be noted. At least, theoretical and experimental data have now been assembled and lay the foundations for scientific evaluation and forecasting of the effect of silvicultural activities on water balance, resources and the hydrological regimes of catchments. This means that quite reliable assessments can now be made of the kind of impact forestry has on hydrological regimes and resources of basins, at least for the temperate zones of the northern hemisphere (Krestovsky, 1986; Shiklomanov and Krestovsky, 1988; Shiklomanov, 1989).

In assessing the effect of forestry on runoff in Russia over many decades, integrated studies have been made on changes in precipitation and evaporation in woodlands as against treeless areas, which also govern alterations to runoff (Molchanov, 1973; Fedorov, 1977; Krestovsky and Sokolov, 1980; Bratsev, 1982; Lebedev, 1982; Robinson, 1989).

These studies have been used to conclude that there is no doubt about the positive influence on runoff that woodlands have had in Russia and the former USSR. This is not only seen in relation to the greater capacity for regulation, by increasing dry season runoff, cutting back maximum amounts and improving water quality, but also by the way it provides a certain increase in aggregate annual runoff from forest and woodland (on average, roughly 10–15 per cent). This is basically a result of more build-up and drifting of snow in woodland for an equal evaporation rate for both woods and open ground. However, for some areas and hydrometeorological conditions in some years, the ratio of runoff from woodlands to that of open ground may swing wildly, though it depends on the type and age of the woodland, their location in the catchment area, the size and nature of precipitation, and snow drifting and melting.

Taking as a starting point the increased annual runoff from woodland areas in temperate zones, it is often assumed that the cutting down of forests is bound to produce an immediate fall in this figure. However, if long-term experimental studies (Bratsev, 1982; Krestovsky, 1986; Shiklomanov, 1989) are examined. this simple notion turns out to be inexact.

True, for a number of decades after timber cutting, the entire range of forest ecosystem types radically alters. In the place of stands of old woodland (whether natural or artificially reforested), new types of tree spring up. For several dozen years, the hydrological properties and water balance of the reforested areas change constantly as trees grow and replace one another; their aggregate runoff into the hydrographic network changes all the time: it can rise or fall, in the same way as before the forest was cut down. For the same amount of precipitation, there are varying degrees of aggregate evapotranspiration, as shown in some studies, displaying a close link between the biological yield of a forest, i.e. its additional growth, and the phytomass volume. The latter parameters do not remain constant but change according to the age of the woodland and its species make-up.

As woodland develops, its compositions alters along with evapotranspiration and the various relationships among the constituents of its water balance. This can be seen from studies like those shown in Figure 28.

The figure shows (upper graph) the time dynamics of forest growth and its natural replacement rate. After conifer forest is cut down there is a quicker regeneration of deciduous species (birch, aspen, etc.), which subsequently die out and are gradually replaced by conifer varieties (pines, firs, etc.), whose life cycle is considerably longer. Within 120–140 years of cutting, a conifer

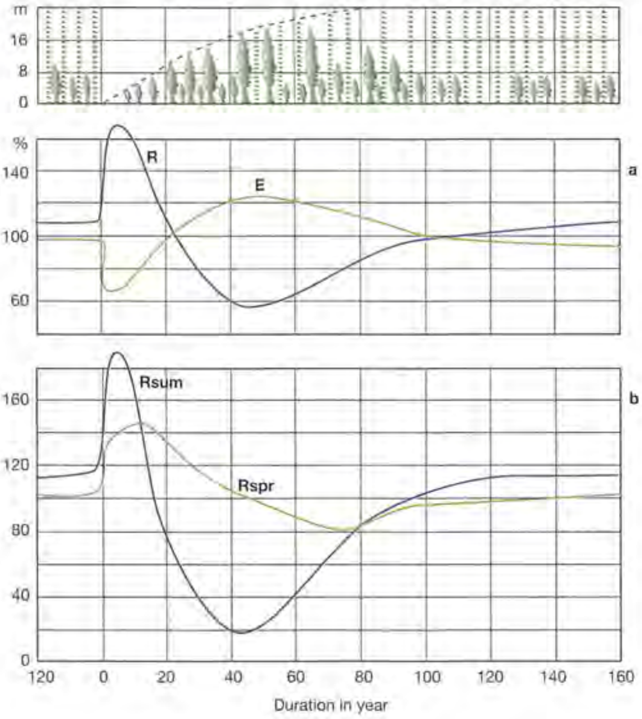


Figure 28—Dynamics of forest growth (m), evaporation and runoff changes in percentages of long-term mean values
a) annual values of evaporation and runoff
b) annual values of summer and spring runoff

forest will have been fully regenerated by natural processes.

The lower graph shows the dynamics of total annual evaporation from forests and annual runoff as a forest evolves.

Immediately after cutting, evaporation drops sharply (by approximately 30–40 per cent), before slowly rising as the trees grow back. It peaks some 50 years after cutting. During that time, the clear-cut areas get gradually covered over by mixed woodland with deciduous varieties predominating; evaporation is 20–25 per cent higher than before the old conifer forest was cut down. In later years, evaporation levels fall and 100 years later they are almost back to what they were before cutting took place.

Where precipitation is regular, runoff follows a converse curve due to evaporation. Immediately after cutting, it rises (by 50–60 per cent), before gradually falling, and 50–60 years after cutting it reaches its lowest value (40–50 per cent of pre-cutting levels). In later years, runoff gradually rises, taking 100–120 years to reach the amounts that prevailed before cutting. However, we should note that after cutting, forests can be restored in different ways: either naturally (as in Figure 28); or artificially, by planting. But in principle, the evaporation dynamics are a regular function of the age and species type of the forest.

All this means that it is impossible to decide whether runoff falls or rises after a forest is cut down. The answer depends on the period considered after the cutting. In the first 10 years, runoff from an area cut down rises fast (by 50–70 per cent); after 40–60 years, in the same area it will be much lower (40 per cent) than before cutting. Averaged out over 100 years, runoff will be some 10–15 per cent lower than for older woodland.

The above findings clearly go a long way towards explaining the conflicting results in different countries when assessing the effect of forest cutting on runoff.

It is important to note that such significant changes in evaporation and runoff as those cited in Figure 28 under the influence of forest cutting and regeneration are for comparatively small stands of woodland or catchment areas where an entire forest has been cut down (over several years).

In large forest areas, cutting is gradual and covers major areas or river basins. Even when clear-cutting is at its greatest, it rarely affects more than 5 per cent, and more likely only 0.7–2 per cent of the woodland in a given administrative region or catchment. The species and age structure of stands in major forest blocks is usually highly variegated, smoothing out the dynamics of runoff change in the area in question; lower runoff from different lots of young trees or slightly more mature stands will be largely compensated for by increased runoff from areas of cutting and from patches of older forest.

Following on from this, even when forests in temperate climates are radically clear-cut, the values for changes in annual runoff in small and medium-sized river basins where this practice is carried on will be in the ±10 per cent range, while for major river systems they do not usually exceed ±1–3 per cent.

Finally, the destruction of forests over wide areas, which has occurred over hundreds and thousands of years and has resulted in changes to the albedo (the reflective capacity) of the Earth's surface, might also have affected the global hydrological cycle. For example, it has been established by climatologists that the present albedo is $\alpha_3 = 0.14$, and that a 0.01 change in albedo will alter average global temperatures by 2.3°C (Budyko, 1980). Thus, if the size of this change is known when forests are cut down then it is not hard to measure its possible effects on the global climate. These questions are considered in greatest detail by Sagan et al. (1979), where a quantitative estimate is made of the change to the global albedo and the average air temperature at the Earth's surface due to the impact of human activity on vegetation cover, beginning in earliest times. The authors referred to largely blame two factors for global climate changes:

- The destruction by man of vegetation in the savannahs and their transformation into desert, which took place over several thousand years in an area of 9 million km^2, and was accompanied by a considerable rise in the albedo at the Earth's surface; and
- The cutting down of tropical woodlands and forests over thousands of years on an area of seven million km^2, which also increased the albedo.

Mainly under the influence of these two factors, the global albedo of the earth-atmosphere system has risen by 0.006, which should have resulted in a fall in mean air temperatures by 1.0–1.5°C.

The prominent Russian climatologist Budyko (1980) considered that the temperature changes quoted by the American authors were clearly too high, though the destruction of forests doubtless had an impact on the albedo at the Earth's surface. However, the cutting down of forests is accompanied by the emission of considerable amounts of carbon dioxide which, because of the greenhouse effect, leads to a rise in air temperatures. As a result of this, the impact of forest cutting on the albedo of the Earth's surface is offset significantly.

Ploughing of farmland, use of modern agricultural techniques, and conversion of water meadows to pasture. The ploughing of farmland and the introduction of a range of modern agricultural techniques on wide areas of land can have a multifaceted integrated impact on the hydrological regime, first and foremost seen in changes to slope runoff. In the world's main farming areas, up to 70–80 per cent of all land in even largish rivers basins is taken up by crop cultivation and pasture (Revenga et al., 1998). Modern agricultural activities make for increased porosity and permeability of soils, and strengthen penetration by meltwater and rainfall, thereby reducing runoff from hillsides and slopes and simultaneously raising soil moisture, facilitating groundwater recharge and increasing evapotranspiration.

Data from Lvovich (1963, 1974, 1980) indicate that the fall in runoff from fields through ploughing is mainly a function of annual precipitation. In steppe-lands, where precipitation ranges between 350 and 450 mm per annum, the reduction in slope runoff oscillates between 4 and 7 times; in the forest-and-steppe zone where there is 450–600 mm precipitation per annum the equivalent fall is from 2 to 4 times, and in forest areas it is 1.3–2 times. Correspondingly, in one and the same area, the fall-off is much lower in wet years than in dry ones.

At the same time, experimental findings from the Russian State Hydrological Institute (Vodogretsky, 1974, 1979) showed how modern agricultural techniques played a big part in reducing surface runoff not just of general moisture, but also of the composition of soils and, to no less an extent, of slope gradients.

Modern farming techniques that reduce runoff and retain water in tilled fields and plots intensify the percolation and replenishment of moisture in the aerated zone, which partly feeds into the subsurface runoff into rivers, and into the evapotranspiration in crops as well. As a result, overall evaporation may rise somewhat, which to some extent reduces general runoff while increasing its groundwater component. For example, according to assessments at the SHI (Shiklomanov, 1979), as a result of agricultural improvements on 50–70 per cent of the catchment area, annual streamflow from medium-sized rivers flowing through the forest-and-steppe zone of Russia fell by 5–9 per cent but was compensated for by a 7–12 per cent increase in the groundwater component. The reduction in annual flow from major river systems in Russia due to such water management is in the 0.5–3 per cent range.

It should be noted that the changes in runoff quoted here relate only to modern agricultural techniques in continental climates in the forest-and-steppe and steppe-land areas of Eurasia, where streamflow originates mainly in the spring flood period. In other physical-geographical circumstances, modern agricultural techniques of a different character are not the same, and may have a different effect on the hydrological cycle in river catchments. For example, data produced by American researchers in the state of Iowa, where annual precipitation is 800 mm, falling as rain and mainly during the growing season, shows the switch of large areas of land from pasture with deep root systems to tilled crops, increases annual runoff by approximately 30 per cent while recording lower aggregate evaporation losses (Shiklomanov, 1976).

Somewhat differing data exist for other regions of the USA. Thus, figures quoted by Jones (1966) for two small catchment areas in the state of Pennsylvania indicate that intensive agricultural reclamation and anti-erosion measures failed to produce any noticeable change in annual streamflow from a river investigated, as against control catchments. Research in four experimental catchment areas in the Northern Appalachians (Ohio) for 1939–1967 (Ricca et al., 1979), showed that developing land use and increased crop harvests meant that annual and seasonal runoff diminished somewhat with the passage of time, but eventually the fall came to an end.

For many regions of the world, the effect of improved crop yields on general moisture and water levels in rivers is of great importance, given the actual and planned increases in agricultural productivity that are in prospect with the use of fertilizers and pesticides, varietal improvements and state-of-the-art agricultural techniques. Many studies in different countries have been devoted to the effect of harvest size on the processes and volume of water taken up by plants. Reviews and analyses of the literature have been conducted (Rakhmanov, 1973; Shiklomanov, 1989); and the link between water use and harvest of biomass has been studied in detail by Alpatiev (1974).

Results from much of the research claim that increased cultivation and improved crop sizes have been matched by a fall in specific water use and more economic water take-up by plants, and by falls in unproductive evaporation from the soil, as a result of which the aggregate water loss from farmland either remains as it was or else rises only slightly. This is also obliquely confirmed by an analysis of changes to streamflow. Thus, investigations by Rakhmanov (1973) on streamflow in the River Don following the spread of modern farming in its catchment and improved crop yields (crops cover more than 60 per cent of its land area) show that the more than tripling of harvests from 1888 to 1970 had no notable effect on the catchment's water resources.

However, many researchers note that quantitative assessments of changes due to evaporation and runoff that accompany improvements to farming and increased crop sizes are complex issues, requiring careful objective analysis and an all-round validation of conclusions reached. To some extent, the issues are still unresolved, particularly where specific physical-geographical conditions and individual agricultural improvement techniques are in play.

Only rough conclusions can be drawn from analysing research carried out in different countries on the effect of better crop yields on the structure of the water balance in catchments. Research studies have shown that, all things being equal, improved bio-productivity, starting from low or medium crop yields, leads to considerable increases in water take-up rates for evapotranspiration. With high initial crop yields, further increases in productivity have scarcely no effect on evapotranspiration, however. But, where moisture is insufficient, water take-up by plants is considerably less than requirements and the amount of evapotranspiration tends to be determined by soil moisture resources. In such areas, where there is deep-lying groundwater, the direct effect of crop yields on runoff can be more or less ignored.

In general, in regions where there is intensive non-irrigated farming, improved crop yields even several times over present levels will not bring about any significant increase in aggregate discharge, nor will it will it deplete river flow over extensive areas. This is particularly true in major river systems, countries and natural economic regions where intensively farmed lands make up only a small proportion of the overall land area.

The draining of swamps and marshland. Globally, in the second half of the twentieth century, particularly in countries of the North, there has been a great extension of land reclamation schemes, i.e. the draining of swamps and marshland for agricultural use. For example, from 1950 to 1990, the area of drained lands in the former USSR tripled (rising from six to 18 million hectares). In Finland by 1980, 5.2 million hectares had been drained, amounting to some 20 per cent of the country's land area.

Reclamation schemes that draw in large areas of land can have a noticeable effect on such components of the hydrological cycle as evaporation and runoff. As shown by numerous experimental research projects reviewed in the literature (Novikov and Goncharova, 1984; Shiklomanov, 1989), evaporation falls slightly during the first few years after draining, and there is a depletion of groundwater, bringing about a noticeable rise in annual and seasonal runoff; at a later stage, when the reclaimed land comes under cultivation, evaporation increases and annual runoff approaches initial values and may even fall.

For medium-sized river catchments draining off all types of groundwater, as shown in special research and surveys (Novikov and Goncharova, 1978; Shiklomanov, 1989), changes in annual runoff through the largest scale reclamation schemes lie in the ± 5–8 per cent range. The effect of drainage on the intra-annual distribution of runoff from reclaimed lands can be seen in the more even distribution by month and season.

Urban development. The urbanization of an area has an impact on the environment that grows with every passing year, as both in terms of quantity and quality, runoff from urban areas is radically different from that of natural drainage basins. The effect of urban development on regional water resources and runoff regimes from catchments naturally depends on the size of the town or city in question, i.e. built-up areas, roads, quarries, communications infrastructure and other manifestations of urban development.

The dynamics of land development in built up areas differ radically from country to country, but the general tendency across the world is for city populations to grow uninterruptedly and for urbanized areas to spread. In the 1970s, built-up areas occupied some 2 per cent of the Earth's land surface, or 13 per cent of its most highly used land space. Since then, these areas have roughly doubled (Kuprianov, 1977; WRI, 2000). The urbanized areas in different countries range from tenths of one percent to 6–10 per cent. In the 1970s, the areas occupied by towns and cities in the USA amounted to about 1.5 per cent of the country's entire land area, but the figure now exceeds 2 per cent. In Germany, the Netherlands and Denmark, urban areas occupy 6–10 per cent of the land area.

The area occupied by built-up areas in present-day Russia can be put at 0.7 per cent of the entire country, whereas in certain industrially developed regions (Central Russia, the Urals, etc.), the figures are approximately one order of magnitude greater. The world's greatest cities occupy 1 000–2 000 km^2 of the world's surface area.

Taking the figures that we have given as a starting point, built-up areas can obviously not have much of an effect on the quantities of runoff or water resources in the world's major river basins and natural-economic regions. However, runoff in medium-sized and small drainage basins in particular, where runoff flows through the hearts of industrially developed areas or the vicinity of major cities, undergoes major changes because of urbanization, which must be borne in mind when calculating different hydrological characteristics and measuring water quality.

Runoff from built-up areas is radically different from natural catchments in both quantity and quality. In one way or another the differences concern the volume of annual runoff, maximum and minimum discharge rates, water quality, and relationships between its surface and groundwater components.

Annual runoff from built-up areas is much greater (10–15 per cent on average) than natural runoff, because of heavier precipitation and a rise in runoff coefficient. In urban areas where runoff comes from heavy showers and storms, the added annual runoff may be as high as 100–200 per cent. A considerable increase in runoff also stems from the large volumes of water piped in by aqueducts from out-of-town sources or pumped from deep underground aquifers (Kuprianov, 1977, 1978; Lvovich, 1986; Stephenson, 1986; Rahman, 1989).

At the same time, where wastewater or winter snow is removed in large amounts to sites outside the cities, annual urban runoff may fall off considerably. The same thing happens to small and medium-sized catchments located in zones where there are depressions and polje formations with lower ground flow into rivers. Thus, some data (Dobroumov and Ustyuzhanin, 1982) show that annual runoff from small and medium-sized rivers in built-up areas around the Kursk magnetic anomaly and in the Moscow Artesian Basin is 30–40 per cent lower than from natural catchments.

Urban development has its keenest effect on the discharge maxima, volume and hydrographic form of flooding rains. Researchers in many countries have data showing that mean maxima on small catchment basins in built-up areas can be 3–8 times higher because of increased runoff speed and amounts from poorly permeable road surfaces, guttering and roofs of different kinds. However, by comparison with natural catchments, those in built-up areas have the highest torrential rainfall discharges when they are of small or medium scale. For rarely occurring torrential downpours the differing maxima are lower as a result of the very high rainfall and smaller differences in runoff coefficient between natural surfaces and those with artificial covering (Kuprianov, 1977; UNESCO, 1985).

Practically, the most important effect of urban development on water is the change in its chemical content and quality. As a result of wastewater disposal in industry and by local authorities and of storm flow in urban areas, large masses of polluted water form, containing high concentrations of mineral and organic substances and heavy metals which are usually simply discharged into rivers and lakes, polluting them over great distances.

In conclusion, it should be noted that urban development cannot have a noteworthy effect on the amounts of water contained in major river basins or large areas, both because of the comparatively small land areas occupied by built-up areas and because of the different ways it impacts on annual runoff.

In reality, mining activities and large-scale withdrawal of groundwaters, which cause drawdown of water levels and foster the creation of depressions and subsidence, sometimes covering hundreds and thousands of square kilometres, can have radically different effects on water balances in river basins. Where groundwaters lie close to the surface, any drawdown can markedly reduce cumulative evaporation in the river basins, thereby increasing runoff. On the other hand, drawdown can cut into the natural leaching of aquifers into the river network, producing shrinking cumulative streamflow. All this apart, the tapping of water during mining operations is usually accompanied by water discharge into rivers, which in small rivers raises streamflow (Holda et al., 1989).

Thus, mine workings and pumping of groundwaters for community water supplies can set in motion a whole series of factors that potentially either increase or decrease natural runoff. The same applies to the different industrial and transport systems and infrastructure, as well as the development of built-up areas. All the above can therefore have an impact one way or another on streamflow from small and even medium size rivers, but so far as water resources in major river basins and regions are concerned, their effect can safely be ignored (Shiklomanov, 1979, 1989).

5.1.3 Changes to the river-bed network

Among the factors under this heading, the building of dams and operation of reservoirs have a particularly great impact on water resources. The creation of separate gigantic reservoirs with their penstocks, sluices and working falls can radically alter the hydrological regimes of rivers, and alter water quality and aggregate water resources in basins, particularly those in regions with warm dry climates. The effect is usually the more marked the higher the ratio of water stored in a reservoir to aggregate flow in a given river, and the greater the overall additional area of the reservoir surface.

Reservoirs first began to be built thousands of years ago, during the flowering of the ancient civilizations, but as world-scale structures they first appeared in the twentieth century. From 1940 to 2000, the overall full volume of reservoirs in the world rose by almost 1 800 per cent; they now amount to about 6 400 km^3, and their total water surface is almost 400 000 km^3. In many countries and regions of the world, reservoirs have a very considerable impact on the management of renewable water resources (see Tables 8 and 10). As a result of the introduction of reservoir storage, hydrological regimes have been significantly transformed, for example on such major river systems as the Mississippi and Missouri, Yenisei, Angara, Volga, Columbia, Colorado, Nile, Dnieper, etc.

Because of the large surface areas of reservoirs, they can affect not only the regulation of streamflow, but also the size of cumulative water resources, so they must be included when assessing water availability in major natural and economic regions and individual countries.

In many catchments, in addition to reservoirs, innumerable ponds* and other artificial water impoundments are built on small rivers and temporary watercourses, to store water during spring flooding and torrential rainfall, and use it in times of low water to meet various economic needs. For example, in some administrative districts of Russia and Ukraine, several thousand ponds are built every year, with total surface areas of between 0.2 and 1 per cent of the aggregate surface areas of the administrative units concerned (Rodionov, 1975). As a rule of thumb, according to estimates for the Volga basin, up to 40 000 ponds are sunk, with slightly fewer in the Dnieper basin.

* Ponds usually arbitrarily include all artificial impoundments with a cumulative volume of less than one million m^3, possessing no major spillway structures.

Despite the large numbers of ponds, as analyses of studies show (Shiklomanov, 1989), their effect on hydrological regimes is significant only for medium-sized or small rivers and streams in areas where there is insufficient water. At the same time, ponds with no regulatory function leave streamflow more or less unchanged in wet years though they sharply reduce it in drought years, thereby increasing the long-term variability and variation coefficients for annual and spring streamflow (Gopchenko and Loboda, 1984).

For small and medium-sized rivers in parts of Russia where there is enough or moderate precipitation, the fall in annual runoff caused by the sinking of ponds in years of average runoff lies in the 3–6 per cent range, but in arid regions the fall can be as high as 20–40 per cent (Rodionov, 1975).

At the same time, the effect of ponds on runoff regimes in major river basins, even those located in moderately wet areas, is insignificant. Thus, according to detailed research (Shiklomanov, 1979, 1989; Shereshevsky and Voitsevich, 1984), the fall in annual Volga River streamflow in 1985 was no more than 0.2 per cent of the norm, whereas for the Dnieper and Dniester, the figures were 1.2 and 0.9 per cent respectively.

Apart from storing up reservoirs behind dams and sinking ponds and other impoundments, river networks are often the sites of such works as the embankment of river beds and flood plains to reduce flooding, straightening out watercourses for navigation, dredging of shallows and removing of shoals from river beds to use them as landfills for building projects, etc. All such undertakings are local in nature, and may have a considerable effect on river levels and streamflow rates in different places as well as on water quality, but their role in changing the annual streamflow of the rivers in question is as a rule so small that it can be ignored.

However, for some basins in arid regions, works to stop river overspills during rainy seasons can, because of the fall in non-productive evaporation, noticeably affect both the water balance in a basin and the annual streamflow at a river mouth (for example, the Kura River in the area of the Kura-Araks Depression) (Shiklomanov, 1979; Shiklomanov and Futulayev, 1983).

5.1.4 Water withdrawal from river networks and groundwater

This heading includes water for community use, industry and power, agriculture (irrigation and rural water supplies), or for partial diversion outside a given river basin.

With continuing world population growth and economic development, the above-mentioned forms of economic activity in changing water supplies are becoming continually more important. Water use for economic purposes is of the following main types:

- Water withdrawal, this is the amount of water withdrawn from the source;
- The amount of discharged wastewater or, return water; this is the amount of water returned to the network after use, whether treated or not;
- The amount of water consumption, the difference between water drawn off and returned water; that is, water that has mainly evaporated during use; though a small amount has also gone into making up finished goods.

The relationship between water use types varies very widely; and depends on the consumer, the water use system used and the climate. For example, the amount of water consumption used against the amount withdrawn usually ranges between 40 and 90 per cent for irrigation, 5 and 40 per cent for community use, and 2 and 20 per cent for industrial purposes. The additional evaporation from the surfaces of reservoirs of water losses constitutes fully non-return water losses (water consumption).

The impact that water use has on hydrological characteristics and water quality is governed by the relationship of the types of use to the characteristics of a body of water, from which water is withdrawn, and to which it is returned after use. Depending on the relationships, the type of water use may have a major impact on smaller and medium-sized, and sometimes on large river systems, while runoff formation in the catchment area remains practically unchanged. It should be noted that the volume of wastewater taken up or diverted is a key characteristic in assessing pollution and changes to natural water quality.

Systems for diverting part of streamflow outside a given river basin are equivalent to a special type of water withdrawal in their own right, when the volume of water drawn-off is identical to water consumption (so far as the basin in question is concerned).

From the standpoint of its effect on the hydrological cycle, an assessment of water consumption is of crucial importance, as to all intents and purposes it fully represents an increase in total evaporation and a corresponding fall in renewable water resources.

5.1.5 Impact on local and global climate characteristics

Mankind's effect on the climate can naturally change various hydrological characteristics, effects that are governed by physical processes differing widely in their intensity and the area they affected, and can lead to changes in:

- Meteorological conditions and local climate;
- Regional climate and the hydrological cycle;
- Global climate.

Changes in meteorological conditions and local climate result from the effect of human actions on vegetation cover, development of built-up areas and towns, the building of dams and reservoirs, and the expansion of irrigated and drained lands. In areas where such activities are carried out, direct changes may occur in the reflective capacity (albedo) of the Earth's surface, evaporation and the moisture content of soil, aerodynamic roughness and other conditions governing a meteorological regime, which can cause changes to the water balance and hydrological regimes governing small streams and even medium-sized rivers. At the same time, there are no perceptible changes to the water resources of major river catchments and regions (Budyko, 1972; 1980; Fedorov, 1979; Sagan et al., 1979; Xafale et al., 1976; Shiklomanov, 1989).

Changes to the global hydrological cycle and climate may be caused by large-scale freshwater use. The additional moisture entering the atmosphere as a result of evaporation from large blocks of irrigated lands or major reservoirs stimulates additional precipitation and generates additional water resources. This effect naturally depends on the amount of world water use and may be seen when assessing water balance for very large areas where the hydrological cycle coefficient* is considerably greater than unity. As shown in certain studies (Kalinin, 1969; Korzun, ed., 1974; Drozdov et al., 1976; Shiklomanov, 1989), these are areas of more than 2–3 million km^2. At a later stage (see section 8.1) we provide coarse assessments of this effect at water consumption levels that may be expected by the year 2025.

One key aspect of the present impact of human activities on climate is the effect of ever growing amounts of combustible organic fuel on the changing composition of the atmosphere, i.e. in the rising levels of carbon dioxide and so-called minor gases (freons, nitrous oxides, methane and the like). The latter inevitably brings about temperature rises in the lower levels of the atmosphere, changes in the global circulation, precipitation, evaporation and hence in water resources and their use. How great the impact of global warming on water resources will be will naturally depend heavily on how high the expected air temperature increase is, and what changes in precipitation occur. According to the most recent assessments of the United Nations Intergovernmental Panel on Climate Change (IPCC, 1995, 2001), by the end of the twenty-first century carbon dioxide levels in the Earth's atmosphere can be expected to double and air temperature can be expected to rise by between 1.0 and 5.5°C. This scale of warming may engender major changes in the water balance and resources in many regions of the world (see Chapter 8). However, in the next 20–30 years when making global assessments of water resources and their use, it will evidently be possible to base them on a steady-state climate situation. This is particularly true as there have not yet been any reliable data for forecasts of climate change characteristics (particularly precipitation) for different physical-geographic zones and regions of the planet that could be used in assessing the quantities of water resources likely to be available.

* The hydrological cycle coefficient for any area is determined by the ratio of aggregate precipitation falling in it to the precipitation caused by an influx of water vapour from outside.

5.1.6 Different aspects of economic activity on runoff and water resources 'brief conclusions'

When analysing the effect of different kinds of economic activity on runoff and water resources, the following clear conclusions may be drawn.

For a quantitative assessment of man-made changes to worldwide renewable water resources (annual runoff) for continents, major natural and economic regions, and individual countries, the effect of factors linked to changes in river catchment area surfaces may be ignored. Such economic activities have an effect on runoff from small and medium-sized rivers, but less often on annual streamflow, rather on intra-annual distribution, extreme runoff characteristics and water quality. At the same time, as a function of specific physical-geographical circumstances, the human factors we have referred to usually impact on runoff in different ways, i.e. in some cases they may add to annual runoff from small and medium-sized rivers by cutting down aggregate evaporation in their catchments.

When we evaluate the effect on runoff in major river systems and natural-economic regions from human factors connected with changes to rivers, studies may be limited to reservoirs alone (particularly medium size or major ones) as the effect of other activities under this heading (ponds and impoundments, dykes and levees, and straightening of river channels, etc.), being of local importance, can be ignored.

Thus, when assessing the impact of economic activities on worldwide water resources, the first thing to be borne in mind is the human factor as associated with direct freshwater withdrawals from bodies of water and the creation of major reservoirs. These factors exist everywhere in the world, are developing intensively, and may have a great impact on the water resources of major regions and countries.

Given the foregoing, the following chapters of this monograph devote particular attention to the dynamics of water use by natural-economic region, continent and country, so as to meet the lifestyle needs of the community, industry, and agriculture, and also water losses through evaporation, brought about by building dams and reservoirs.

Consideration will also be given to various aspects of possible changes to water resources and balance stemming from the impact of human activities on the regional hydrological cycle and global climate (see Chapter 8).

5.2 WATER USE FOR COMMUNITY NEEDS

Water used for community needs comes under two headings: water drawn off directly to meet the needs of the urban population (economic and daily household water use) and general urban needs (needs of the metropolitan area as a whole and commercial water use). Economic and household water use covers household water used for drinking, food preparation, personal hygiene, washing, watering of lawns and gardens belonging to individuals. Communal urban water use includes water for hosing down streets and watering green areas, by fire brigades, various municipal departments and utilities that directly meet community needs and draw off high-grade water from town or city mains supply systems (Zamakhayev et al., 1974; Tate, 1990).

The amount of water drawn off by a community depends on its population size and its living standards in a built-up area, i.e. the existence or otherwise of water and wastewater and sewerage systems, area heating systems, and climate. It is usually considered that to meet all personal needs, every individual needs 150–250 litres per day (2.5–5 litres for drinking and food preparation), and another 150–200 litres per inhabitant is required to operate utilities and services, town cleansing and law and order maintenance. Water withdrawn over and above these figures is usually to do with its use by urban industries, or major leaks from water supply systems. In smaller towns where effective mains water supply and treatment systems do not exist, water use falls to 75–100 litres per person per day.

In some countries, various standard community use rates have been established for built-up areas. They are usually a function of the living standards in a city and its climate; for more northerly countries water use rates are lower, for southern countries with hot dry climates, they are considerably higher. In some countries community water use rates differ from town to town as a function of their population size and the kind of work they engage in. For example, in Japan, water withdrawal figures for small towns with populations of less than 10 000 are 150–300 litres per day per capita, rising to 400–560 litres per day for cities with more than a million inhabitants; moreover, there is some difference in water withdrawal rates (of up to 5–10 per cent) depending on the main sector of the economy that the bulk of the population is engaged in.

The foregoing figures are generally in line with actual figures for water withdrawal in many major cities, where they generally oscillate between 300 and 600 litres per day per capita (Zarubaev, 1976; Shiklomanov and Markova, 1987).

As a result of the swelling cities, their improving infrastructures, rising living standards and greater sophistication of the population, specific community water withdrawal rates have been constantly growing in most countries. Whereas in the early twentieth century, in built-up areas with mains water supply systems, there was per capita water withdrawal of 5–30 litres, the urban population of present-day Russia draws off on average 300 litres per day per capita. In the USA, from 1900 to 1995, the specific withdrawal of urban populations rose from 100–150 litres to 700 litres per day (Murray and Reeves, 1972; Gleick, 1998), i.e. it rose by 5–7 times. Studies in the USA and Canada show that specific water withdrawal of 700 litres per day is enough to ensure a comfortable standard of living (Schetter, 1990). In hot climates the figure may be proportionately higher and in cold climates somewhat lower.

Equally it should be noted that of the highly developed industrial countries of the world, the USA and Canada have exceptionally high specific water use rates for community needs, which is due to the fact that the bulk of urban populations are housed in individual dwellings with suburban gardens and yards. In Western Europe, however, a community water withdrawal rate of no more than 300–350 litres per capita (Gleick, 1996) is considered enough to provide a comfortable lifestyle.

At the present time, when the water of requisite quality consumed in most cities is based on secondary treatment and re-use, the dominant tendency in developed countries is towards water savings and dwindling specific water withdrawal (Fleming, Daniell, 1994; Seckler et al., 1998), and the regulatory factor is considered to be the price of water. For example, in the USA in the period 1980–1990, both for public and private use, in many cases water prices grew by 200 or 300 per cent as a result of general inflation, the high cost of capital investments and stricter environmental controls (Russell, Woodcock, 1993). However, effective measures to reduce specific community water withdrawal are, first of all, expensive and can only be indulged in by wealthy countries; or secondly, when there is a pressing need and interest in carrying out such measures (for example, shortage of high-quality water, ecological restrictions, etc.). In any case, no reduction in community water use has been recorded in the last two decades in either the USA or Canada (Gleick, 1998; Shiklomanov, ed., 2003).

In the developing rural economies of Africa, Asia and Latin America, specific community water withdrawal rates are in the 50–100 litre per day range, even for countries with very low rainfall and inadequate water resources, withdrawal does not exceed 10–40 litres per day per capita.

According to Gleick's assessments (1996), the minimum amount of drinking water required to sustain individual human needs is 50 litres per day. Gleick proposes that this amount be considered an inalienable right of every person in the world, whatever the circumstances.

The aggregate amount of water for community needs in any given country or region is governed by the specific water withdrawal and population size. Annual community water withdrawal figures for different years or periods are quoted in many national and international publications, in particular those by Shiklomanov and Markova (1987); WRI (1990, 1996, 2000); Kulshreshtha (1992); Gleick (1993, 1998); and the World Bank (1993, 1995). It should be noted that published data on individual countries are not always comparable because some authors jumble together water withdrawal figures for urban and rural populations (for example, the USA, Australia and Brazil), while others confine themselves to urban populations (for example, Russia, Eastern European and African countries). Some countries also add in water drawn off by industries located in metropolitan areas.

When calculating the water balance in order to define discharge and the quantity water resources used, great importance is to be attached to the amounts of water consumption for general community needs and the water actually drawn off. Where there is an effective sewerage system, most of the water drawn off in urban areas is returned (whether treated or not) after use to the hydrographic network in the form of runoff. Most water consumption comes from losses due to evaporation; leaks from water supply and sewage pipes; during the watering of parks, gardens and other green areas, streets, recreation areas, suburban plots and gardens, etc. and so it depends largely on climate. In hot arid areas, the losses are naturally greater than in cold, wet ones. Water consumption for direct use on personal needs is not great by comparison with water losses due to evaporation.

The relative sizes of water consumption, usually expressed as a percentage of the water withdrawal, depend heavily on the total volume of specific water withdrawal for community needs. Thus, in modern cities with an advanced infrastructures, mains water supplies, and effective sewerage systems, non-return water losses do not normally exceed 5–10 per cent of total water withdrawal. Smaller cities with large stocks of individual housing, not fully equipped with mains sewerage systems, where specific water withdrawal averages out at 100–150 litres per day, non-return losses are considerably greater and may attain 40–60 per cent of their water intake. Here the lowest values relate to northern regions, the greatest to dry southern areas.

Thus, water consumption, depending as it does on a variety of factors, changes radically from one city to another, from one region to another, and from one country to another. For Russia, for example, non-return urban water losses for economic and everyday use are estimated at present as being 15–20 per cent (according to different sources) of all water drawn off, changing by 10 to 30 per cent from one major river basin to another. In the United States, figures are considerably higher (20–35 per cent), as they also include water consumption in rural communities. According to data from special surveys for 46 communities in the United States, losses from water supply systems range from 2 to 50 per cent (Khadam et al., 1991). In industrial countries and regions of Western Europe, water consumption for economic and everyday use is estimated to range from 5 to 30 per cent; these figures are for regions with very old mains water systems, constructed more than a hundred years ago.

Throughout the world the trend has been for community water use to evolve gradually, as seen in the construction in cities large and small, of effective mains water supply and sewerage systems, hooking up to them ever growing numbers of buildings and human settlements, and increasing specific water withdrawal. In this connection the amounts of non-return water consumption in the future, particularly as expressed in percentages of total water intake, must fall significantly. For example, whereas in 1980 in the former USSR, they amounted to 15–20 per cent of the total, by the end of the twentieth century a fall of 10–15 per cent may be expected to occur (Shiklomanov, Markova, 1987; Shiklomanov, 1988). This must be taken allowed for in any long-term water use forecast for different regions.

5.3 WATER USE BY INDUSTRY AND FOR THERMAL POWER NEEDS

In industry, water is used to cool machinery and other plant, smaller apparatus and instruments that heat up in the production process; for transport and cleaning; as a solvent; and sometimes as part of the end-product. Considerable amounts of water are used in industry and on work sites as part of mandatory health and hygiene precautions and for employee needs. The greatest volumes of water in industry are those taken up by thermal and nuclear power stations, which need large amounts of water for cooling power units.

The amounts of industrial water used differ not only according to sector of industry but also as a function of one and the same finished product, depending on the technology used. They also differ according to climate. As a rule, water use by industry is lower in northern regions than in southern areas with high air temperatures. The greatest users of water in industry, apart from electrical power, are the chemical and petrochemical industries, ferrous and non-ferrous metals, cellulose and paper mills, and machine tools. For example, in the former USSR in 1980, out of 107 km^3 of water drawn off by industry, power accounted for about 66 per cent, while the other five sectors mentioned took up 89 per cent of the residual industrial water withdrawal.

Data in the Global 2000 Report (1980), indicate that in the United States in 1977 the power industry accounted for 76 per cent of all water withdrawal, in Japan 72 per cent, in Australia 60 per cent, in Brazil 14 per cent, and in India 11 per cent. In the power industry, water use depends on the type of fuel used.

To describe the water capacity drawn off in the manufacture of finished products, the usual approach is to employ specific indicators for freshwater take-up (per tonne of finished product, per kWh, per unit spent, etc.). Thus, in the ferrous metal industry, an average of 2–4 m^3 of fresh water is used in mining and refining every tonne of ore, between 40 m^3 and 50 m^3 of fresh water is expended to produce one tonne of pig-iron, while 10–15 m^3 is used to produce the same amount of rolled steel, 500 m^3 goes on copper, and 4 000 m^3 on nickel. A particularly large amount of fresh water is drawn off in pulp and paper mills, and the petroleum products industry: to produce one tonne of pulp, between 400 m^3 and 500 m^3 of water is needed, viscose rayon requires 1000–1 100 m^3, synthetic resins need up to 2 800 m^3, man-made fibres and plastics need between 2 500 m^3 and 5 000 m^3, capacitor tissue needs 6 000 m^3, etc. A thermal power station with a capacity of million kWh needs 1.0–1.6 km^3 per annum. Much more water (1.5–2 times and according to some findings, 3–4 times) is required for nuclear power stations of the same capacity. We would point out that nuclear power stations now exist or are being designed and built with capacities of 3–5 million kWh or more. A pulp and paper mill with an output of 500 000 tonnes requires 435 million m^3 of fresh water a year, while a medium-sized metalworking plant needs approximately 250 million m^3 (Levin, 1973).

The figures are proof positive that in the past two to three decades there must have been a drastic increase in water use on the part of industry, since in the same time frame throughout the world there has been an abrupt rise in the power generated by thermal and nuclear power stations, and a rapid growth in the production of man-made fibres, artificial rubber, plastics, and cellulose, all of which call for particularly massive amounts of water.

The main features of industrial water use (the volumes of fresh water drawn off, water consumption, and the diversion of water) to a very great extent depend on the mains water supply employed.

As we know, two basic systems exist, of thoroughly different types: single-pass and return flow. With the single-pass or straight-through system, water drawn off at source is returned to watercourses, whether treated or not. Under the return flow system, water is cooled, treated and re-used in the mains supply system. Thus, return flow ensures that wastewater is not discharged into bodies of water or watercourses but allows it to be used several times over for industrial purposes. The amount of new water needed with return flow systems is insignificant and is governed only by the discharge required to make good the water consumption in the production process and regeneration, and for periodic replacement of water in re-use cycles.

Technical progress in industrial water use, viewed from the standpoint of rational water use is not just a spreading use of return flow systems, it is also the incorporation in the industrial process of water-free technologies or processes that make considerable savings in the fresh water needed. In those sectors of industry where the bulk of the water is used for cooling, a key factor in making savings is to replace water by air as a coolant. This can reduce the amount of fresh water used in different sectors by between 50 and 70 per cent (Shiklomanov and Markova, 1987).

As a rule, industrial water consumption is an insignificant proportion of all water drawn off, but varies enormously according to the sector, type of water supply, technological process used and climate, amounting in the power sector to 0.5–3 per cent of water intake, 5–20 per cent in most sectors of industry, though reaching 30–40 per cent in some sectors. Moreover, with the single-pass mains supply system, water consumption, expressed as a percentage, is significantly less than in the re-use system, but the intake of fresh water is significantly higher.

The development of industrial water use is one of the main causes of pollution in natural waters. This is explained first and foremost by the steep growth of industry in general; secondly, by the particularly rapid rise of the water heaviest users (man-made fibres, petrochemicals, pulp and paper, etc.); thirdly, by the runaway growth of thermal power and the building of nuclear power stations; and fourthly, by the very low water consumption, when the vast bulk of water drawn off for industrial needs is discharged after use as often raw or only partly treated wastewater, polluting the water it is discharged into.

The massive use of water by thermal and nuclear power stations is followed by a return to rivers and lakes of large amounts of wastewater heated by 8–12°C. This interferes with the natural temperatures of water that the heated waste is discharged into, significantly altering many of the natural processes and causing so-called "heat pollution".

Industry is the second most important freshwater user in the world after irrigation. Data from the Global 2000 Report (Barney, 1980) states that aggregate world industrial water withdrawal for 1977 was 805 km^3, including 502 m^3 for heat and power; according to estimates by Shiklomanov and Markova (1987) for 1980, world industry (including the power industry) drew off 710 m^3 a year. Of that amount, 75 per cent of industrial water withdrawal was in Europe and North America.

Despite the general growth in world industrial water use, in many highly industrialized countries, in the last few decades beginning in the 1980s and 1990s, the withdrawal of water specifically for industrial production needs has undergone a stabilizing trend or even some decline. This has happened through a regular fall in specific water discharge for different types of industry and a switch to return-flow systems with an increase in the number of return cycles for the greediest water guzzlers.

By way of example, Figure 29 a) and b), using data from a single work (David, 1990), show for the United States the dynamics of the fall in water withdrawal per unit of production (Figure 29 a) and the rise in the number of water re-use recycles (Figure 29 b) in the greediest water users among the manufacturing sectors. As the figure shows, in a 30-year period, water withdrawal per unit of industrial output in the United States fell by between 50 and 20 per cent and the number of water re-use cycles rose by between 20 and 200 per cent (depending on the sector). Needless to say, this means a noticeable cutback in aggregate United States industrial water use in the last two decades (Gleick, 1998).

A similar trend is happening in most developed countries in Western Europe as well. Figure 30 is a well-known graph, showing a halving in industrial water use in Sweden between 1965 and 1975 (Falkenmark, 1977). This was assisted by legislation adopted in that country, requiring industrial entrepreneurs to introduce effective water recycling systems.

Thus, assessing the amounts of industrial water use forecast for individual regions, countries or river basins, it must be borne in mind that they change under the impact of different trends: on the one hand, they are bound to increase as industry and power generation expand, but on the other the rise will not be proportional to industrial growth, as in the future in many countries

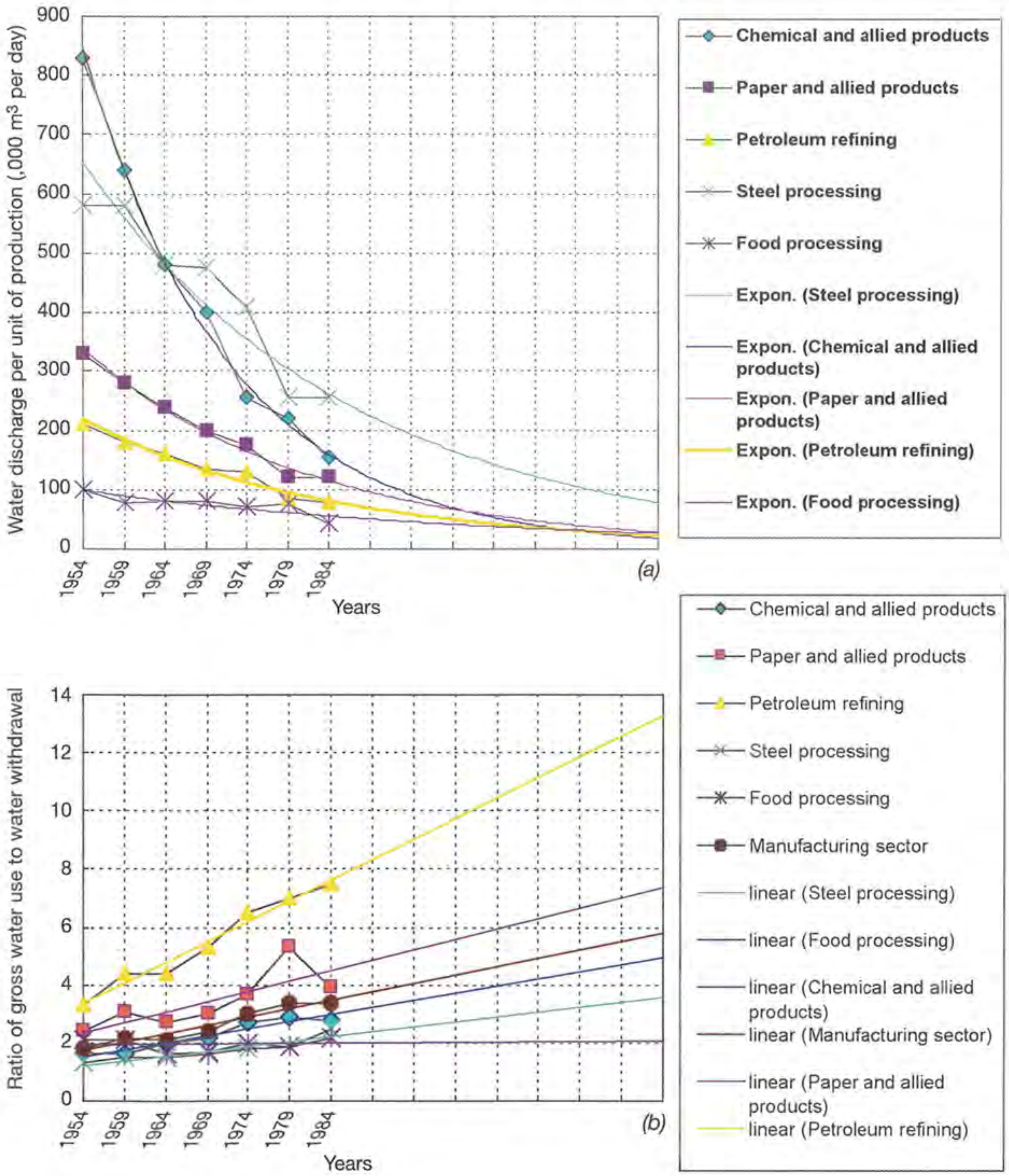


Figure 29—Dynamics of water discharge per unit of production (a) and quantities of water use recycles (as ratio of gross water use to water withdrawal) (b) for the major water-using manufacturing sectors in the United States (David, 1990)

there is bound to be a growing shift towards water recycling, and in some branches, so-called water-free or dry technologies. It should also be noted, however, that all modern progressive technologies require major capital expenditure and, unfortunately, they are mainly a prerogative of wealthy developed countries (see Chapter 9).

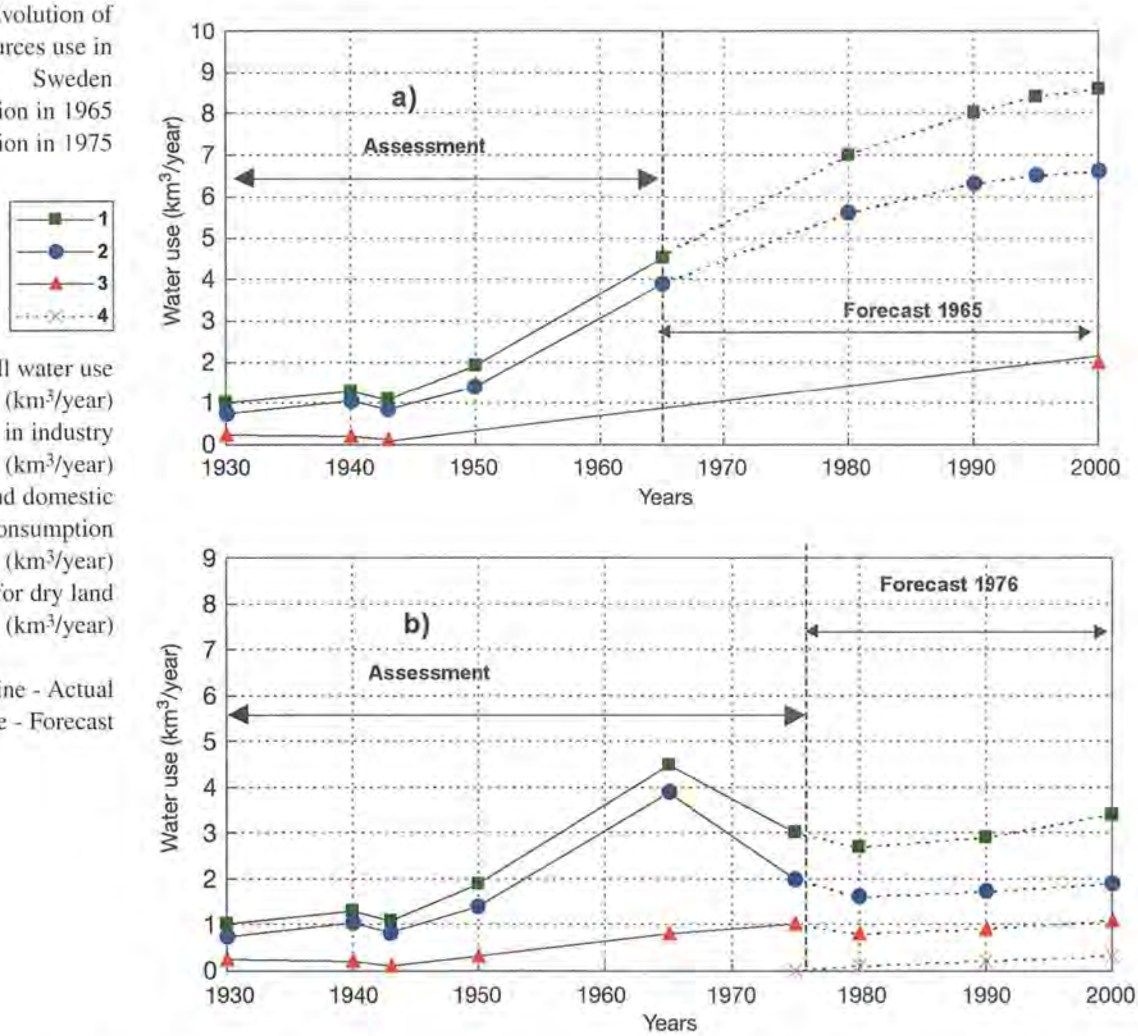
In some countries and regions of the world, there is a tendency towards a wider use of sea water by industry and heat and power (e.g. in the United States, Japan and Germany). Thus, as far back as 1970 almost 24 per cent of water withdrawal came from sea water, a figure that had risen to 28 per cent by 1995 (Gleick, 1998).

Despite the positive trends in industrial processes towards freshwater savings and the stabilization of industrial water withdrawal in the world's developed countries, an analysis of available data and forecasts shows that aggregate industrial water use in coming years is likely to go on rising, at least over the coming 15–20 years. However, the rates at which water withdrawal figures increase will be significantly lower than the industrial output growth curve.

Figure 30—Evolution of water resources use in Sweden
a) condition in 1965
b) condition in 1975

1. Total full water use (km³/year)
2. Water use in industry (km³/year)
3. Public and domestic water consumption (km³/year)
4. Water use for dry land irrigation (km³/year)

Solid line - Actual
Dotted line - Forecast



But an assessment of water consumption by industry and the power generation sector can be broken down structurally into different parts:

- Additional evaporation losses from the sun's energy when water is being transported from its source to the industrial undertaking, when water is being cooled as part of a technological cycle, and as a result of wastewater discharge (often heated water) into a hydrographic system;
- Evaporation losses within an industrial undertaking, as a result of energy released as part of a technological process;
- Water losses deriving from the fact that the water is part of a finished product.

The second and third categories are almost completely unconnected with climate and wholly governed by the nature of the finished product.

Analysis of non-return water losses from industry and power generation showed that the overwhelming bulk thereof are generally in the first category and that the water consumption, all other things being equal, must be greater in drier southern regions than in wet northern climates where moisture is in surplus.

Moreover, non-return losses in industry and power production are largely a function of the mains supply system employed. With a single-pass system, enormous amounts of water must be used, but water consumption is lowest, whereas with a return flow system, freshwater intake is lowest but water consumption is extremely large, sometimes as high as 150–300 per cent. There is therefore a prospect, what with the general expansion of return flow systems where water is re-cycled several times over by industry, of there being some general rise in water consumption (as a percentage of the water uptake) for some countries, regions and major river basins.

5.4 WATER USE IN AGRICULTURE

Water used by agriculture is primarily governed by the amount of irrigation, and to some extent by rural water supplies. In many countries and regions of the world, irrigation is the prime freshwater user and is responsible for water shortages, particularly in drought years. Irrigation, as we know, is an age-old practice, though the main irrigated areas originated in the twentieth century, particularly in its second half. During the twentieth century, the world's irrigated land area increased by 500 per cent and by the year 2000 covered 264 million hectares. More than half of all areas under modern irrigated cultivation are concentrated in four countries: China, India, the United States and Pakistan.

At the present time, some 15 per cent of all workable lands in the world are irrigated, yet they grow about 36 per cent of all farm produce. This is in part because of their better harvests, but also because of their far more intensive crop rotation. The effectiveness of cultivation expressed as the value of output from one hectare depends on its intensity and, first and foremost, on the amount of fertilizer used. It has been established that the more efficient the farming, the greater the proportion of irrigated land to the overall area of land being tilled in a given country. FAO assessments for the early and middle 1980s indicated that this rule of thumb was likely to continue to apply at least until the early twenty-first century (Alexandratos, 1988). It was assumed that during that period, the proportion of produce from irrigated lands worldwide was bound to exceed the amount produced from dry-land cultivation.

Until the early 1970s there was a continuing tendency in more or less all developed and developing countries on all continents for an accelerating growth of irrigated lands, thereby increasing guaranteed crop yields. A peculiarity in the development of irrigation has been its northwards spread into areas with enough or too much rainfall; here, irrigation was considered an integral part of agricultural progress, making for regular good yields from all crops, irrespective of weather conditions. In present-day Europe, there is not one country where irrigation is not practised; there are, for example, considerable irrigated stretches of land in Poland, UK, Germany and the Netherlands, and irrigation is growing apace in Canada. There has been a great expansion of "twin-track regulation" of soil-water regimes in northern Europe, using a mix of irrigation and drainage techniques on reclaimed lands.

In the last two decades, the spread of irrigated lands has greatly slowed down, both in developed and developing countries, and on every continent. Whereas in the 1970s, the rate of increase in truly irrigated lands in the world kept pace with or outstripped population growth, in the last few years the amount of irrigated land per head of population has fallen off noticeably (Figure 31). The data in this figure indicate that the fastest rate of increase round the world as a proportion of population was in the 1950s, but then contracted considerably; in the 1970s, and more particularly the 1990s, rates fell further behind world population growth rates. That was due to various reasons, in particular the very high capital costs of new irrigation systems, increased salinity, depletion of irrigation water sources and environmental protection. In some developed countries, the amount of land under irrigation has now stabilized, and in countries where there is insufficient irrigable land, Japan and Hong Kong for example, a steady contraction of irrigation has been observed. These countries evidently do not need to expand their irrigation systems; they are either fully self-sufficient agriculturally, or it is cheaper for them to shop in other countries.

Considering the problem with a global perspective, it should be noted that the spread of irrigation in arid lands stems from the need to provide mankind with food. Given the high population growth rates and severe shortages of foodstuffs now suffered by almost two-thirds of the planet's inhabitants, irrigation has a prominent part to play in improving the efficiency of cultivation and stock-raising. Irrigated lands are therefore still spreading in the overwhelming majority of countries and regions of the world (Figure 32) and in the future, irrigated crops are bound to become more sophisticated and develop, and a further growth in irrigated lands should be expected, particularly in countries where there is fast population growth and enough water and land resources. This is supported by the data in Figure 32 on the continuing high rate of expansion in regions and countries where irrigation has a long tradition (Northern China, South and South-East Asia, India, Central Asia and Kazakhstan, etc.).

In all likelihood, the global irrigated land area will continue to grow, though not at the same speed as in the 1970s.

Irrigation constitutes the largest water use in the world. Some data (Shiklomanov, ed., 1997) indicate that in 1995 it accounted for some 66 per cent of world water withdrawal. An accurate determination of water use therefore largely depends on a precise calculation of irrigated land areas, for the world as a whole and particularly for Asia, Africa and South America, where in many countries irrigation makes up 80–90 per cent of aggregate water withdrawal.

A dependable assessment of long-term dynamics of irrigated land is no mean task; in many countries there are no data at all, and in others they are very inaccurate, even conflicting; reported in widely differing and often unofficial sources, they give counts for various years and heterogeneous classes of indicator. For example, FAO data for 1999 indicate that in 1996 the irrigated land area in India was 56 million hectares, whereas in the most recent publication (Narauanamoorthu, 2002), it is stated that India's irrigated land area in 1996–1997 was 73 million hectares.

More or less reliable information for the different countries of the world has been published by the FAO since 1961–1964, though even these data, reported annually, are far from compatible. Various calculations and assessments of water withdrawal dynamics would be best obtained by using country data on irrigation, as quoted in the official FAO yearbooks (FAO, 1995), together with those published since 1995 in the FAO Water Reports for different continents and regions of the world (for example, those issued by FAO in 1999 and 2000).

Analysing the FAO data, it can be reckoned that the cumulative irrigated land area in the world in 2000 stood at 264–268 million hectares. This is much lower than the various assessments forecast by different authors in the last 20–30 years (Shiklomanov and Markova, 1987). For example, the following total areas (in millions of hectares) of irrigated lands worldwide for the year 2000 were forecast by researchers in different years: Lvovich (1974) put them at 500, Kalinin and Shiklomanov (1974) at 420, Batisse (1976) at 420, Ambroggi (1980) at 302, Zonn and Nosenko (1981) at 538, Framgi (1982) at 400, and Shiklomanov and

Figure 31—Dynamics of population size and irrigated areas in the world during the 20th century

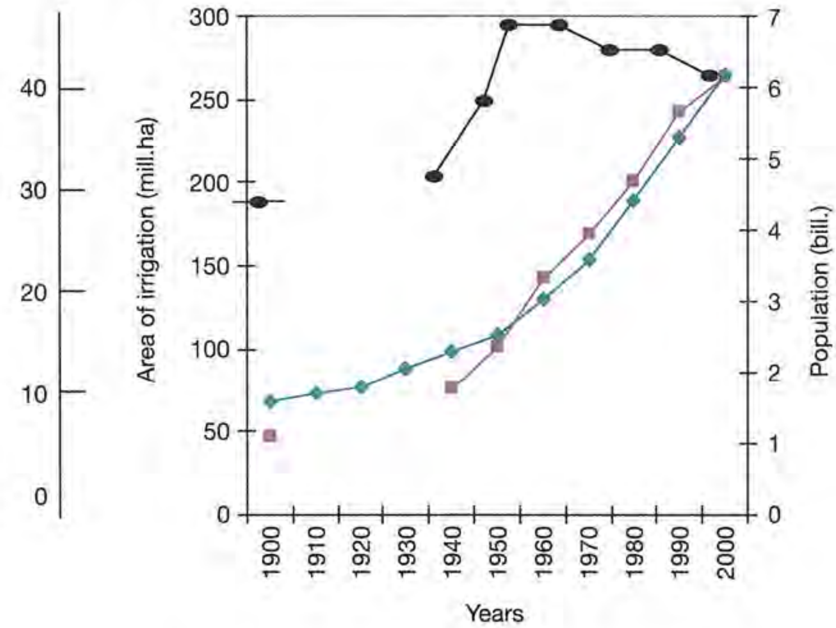
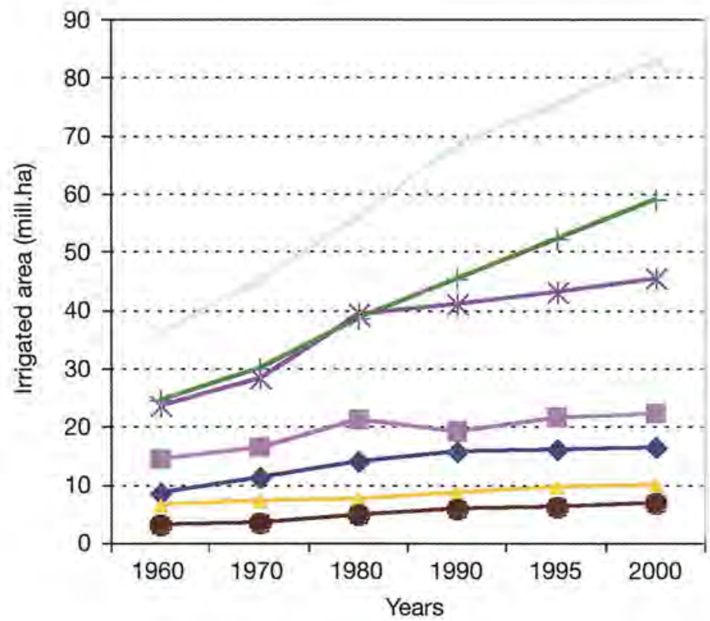


Figure 32—Dynamics of irrigated area by natural-economical region of the world



Markova (1987) at 317. All the forecasts were based on high levels of reclamation works undertaken during the 1960s and 1970s, and extremely optimistic contemporary national forecasts which were evidently not borne out. The development of reliable forecasts for the very long-term expansion of irrigation is an extraordinarily tough nut to crack. To solve the problem, there is a need not only for a careful analysis of present-day irrigation trends in each country, but for account to be taken of the various socio-economic and physical-geographical factors and also the different globalization processes, the importance of which is growing constantly.

Water withdrawals for irrigation are determined not only by the irrigated land areas, but by the size of specific withdrawal usually expressed in cubic metres per hectare per annum, and the quantities of return water (as a percentage of the water intake) which are a function of physical-geographical conditions, the technical state of irrigation systems, the existence of drainage infrastructure, watering methods, and the composition of crops. The difference between the amount of water intake and return water represents the water consumption through irrigation, mainly due to evaporation.

Effective water withdrawal and return water data taken account of in irrigation do not exist in many countries, and they are very imprecise. This is particularly true for return water and non-return water losses, which are at best determined by analysing documentation for individual irrigated areas, that are more often than not based on analogy, adopted from project data, purely speculative conclusions, general logical premises, and expert assessments. For example, the above-mentioned FAO Water Reports for different regions of the world contain tentative information on the water withdrawal for irrigation, but there are practically no data for return water and water consumption (FAO, 1999, 2000). This is a major hindrance in assessing true water availability in different countries and regions of the world where irrigation is the prime use to which water is put, and water consumption from irrigation are almost fully determined by the overall water consumption volume for economic needs.

The information to hand on water withdrawal and irrigated lands can be used to calculate specific water withdrawal for irrigation purposes in different physical-geographical situations and can often, after suitable analysis and review, be employed in calculating overall water withdrawal from the world's largest natural and economic regions and continents. It is natural for the smallest amounts of specific water withdrawal to be found in northern Europe: in Sweden, Germany, Britain, Finland, Belgium and Switzerland, they amount to 300–900 m^3/ha; but in southern France, Italy and Spain they can reach 5 000–6 000 m^3/ha or even 8 000–10 000 m^3/ha. Almost the same amounts are on average characteristic for the countries of Eastern Europe (excluding Russia); return water is estimated to amount to 20–30 per cent of the water intake. In the United States of America, specific water withdrawal for irrigation is put by some authors at 8 000–10 000 m^3/ha, with 40–50 per cent of the water taken up being returned. There were fairly high values for specific water withdrawal for irrigation purposes in the former USSR, on average some 10 000 m^3/ha, which is explained by large quantities of water drawn off by major canals and channelled across hundreds of kilometres from their water source; for the former Soviet Union, the values for return water from irrigation have been estimated by different authors as averaging between 20 and 30 per cent of water withdrawn (Shiklomanov, 1979, 1989).

In Asia, given the wide variety of climatic conditions, technical state of irrigation systems and type of agricultural crops, specific water withdrawal by country varies extremely widely. FAO data for 1979, for example, show that for China and India specific water withdrawal averages between 8 000 and 9 000 m^3/ha, for Thailand the figure is 6 000 m^3/ha, for Indonesia and Sri Lanka 17 000 m^3/ha, and for Japan 18 700 m^3/ha. The lowest specific water withdrawal values for irrigation are found in the Philippines and Bangladesh (3 000–3 800 m^3/ha), while the highest are in Nepal and Malaysia (25 000–27 000 m^3/ha). Almost the same range in the amounts of specific water withdrawal can be seen for African countries (from 7 000 to 20 000–25 000 m^3/ha). There is a still wider variety of figures for the countries of South and Central America. FAO data for the year 2000 show specific water use as varying from 3 000–4 000 m^3/ha in Cuba and Colombia to 32 000 m^3/ha in Panama and 46 000 m^3/ha in Costa Rica; for countries with the largest irrigated areas in the region the figures for specific water withdrawal by irrigation are as follows: Mexico (9 700 m^3/ha); Brazil, (11 500 m^3/ha), Argentina (14 000 m^3/ha), Peru (13 600 m^3/ha) and Chile (9 000 m^3/ha).

In researching the dynamics of water use for irrigation in major countries and natural-economic regions round the globe, it must be borne in mind that specific water withdrawal is not a constant, and can alter considerably as a function of improvements to irrigation systems, refinement of standards used, regimes and sprinkler technologies. In this regard great importance is attached to measures to replace small and large open canals by piping and to concreting the linings along major canals, which helps raise the irrigation network performance coefficient from 0.4–0.6 to 0.8–0.9 (Botzak, 1988). Considerable water savings may also be made by more sophisticated technical methods and spraying techniques (sprinkler systems, fogging or misting, drip systems, etc.), helping to raise agricultural crop yields and radically reduce the irrigation water used.

In the last few decades, sprinkler irrigation has been growing by leaps and bounds worldwide, permitting the use of fully mechanized and automated watering systems and considerably reducing unproductive water losses. The latter, which is particularly important from the water resources use standpoint, comes about through a more even distribution of moisture and by dwindling deep percolation. There are also fewer losses from water adduction systems, which are mainly piped.

Tentative calculations suggest that the overall area of the world with sprinkler systems is approximately 20–30 million ha at present (about 10 per cent of all irrigated land areas). The largest areas and proportion of sprinkler systems are in the USA, Italy, France and Bulgaria, together with other developed countries in Europe. In the United States, for example, the area covered by sprinkler systems now accounts for about a third of all irrigation. There is about the same proportion of sprinkler irrigation in Russia; in Italy, 25 per cent of all irrigation is based on sprinklers, in Japan the figure is 8 per cent; this progressive method of spraying is becoming ever more widespread in other countries too. However, it is very poorly developed in countries with the largest irrigated land areas (China, India).

In the past two decades, a revolutionary new type of sprinkler system has undergone development and come into use in various countries: fine spray misting or aerosol sprinkling ("fogging"), in which water is pulverized into very fine droplets, regulating the microclimate of the air layer at ground level, raising humidity, lowering air temperatures and those of plant-life, thereby providing better conditions for plant development, reducing aggregate evaporation and more or less halving specific water withdrawal for irrigation while increasing crop yields.

Another new technique that holds out the prospect of greatly reducing specific water consumption is drip irrigation, whereby water is fed directly to the plant and is more or less entirely used for evapotranspiration, keeping to a minimum water losses through filtration and unproductive evaporation, and eliminating drawdown in near-surface water tables or the salinization of irrigated land. An important advantage of the method is the great amount of water it saves (between 25 and 90 per cent) as compared with surface watering methods, while increasing crop yields by 50–100 per cent.

Drip irrigation has been used in a number of countries (Australia, USA, Israel, Italy, Mexico, Tunisia, etc.) for watering orchards, vineyards, vegetables and field crops with widely spaced rows. However on the global scale it accounts for only 0.7 per cent of all irrigated land (Postel, 1992) and is spreading only very slowly. This is because such fine-spray aerosol and drip systems are still very costly (some 3–5 times dearer than conventional sprinklers), but they almost halve water losses, so that they can be clearly expected to be more widely distributed throughout the world than hitherto.

The mean specific water withdrawal values in irrigation obtained nowadays for different countries are characteristic of the modern level of irrigated farming, which in many places is far from sophisticated. In the future, as new irrigated areas come under the plough, and as improvements and radically new technologies and systems are introduced into irrigation to improve crop yields and make water savings, they will doubtless be ever more widely used around the world, cutting down on average water withdrawal levels. Savings are also aided by improvements to existing irrigation systems, performance coefficients and general efficiency. But in the effort, huge capital outlays are needed, which is not a real option for most developing countries. It is important to bear in mind as well that in many parts of the world there is a rapid degradation of irrigated lands taking place due to salinity, which need large extra amounts of quality fresh water to alleviate. All that must be taken into account in assessing how much water will be used for irrigation in tomorrow's world.

In rural areas, along with irrigation, water is also used for community needs, is drunk by livestock, and is used for improving community infrastructure. Water withdrawal to meet the needs of farms mainly depends on climate and on whether or not there are water mains supplies and sewerage systems, and usually ranges from 200–250 down to 20–30 litres per day per capita. The provision of quality drinking water to rural areas and stock-raising is crucial in the life of many developing countries in arid areas, however, so far as water resources and water balance of major regions are concerned, water use for mains supply is not quantitatively much greater than draw-off for irrigation, and figures for it are very often grouped together with the latter.

For example, for the former USSR in 1980, mains supply to rural communities and stock-raising accounted for some 7 per cent of water withdrawal and 5 per cent of water consumption in irrigation. It is expected that the proportion of rural community water supply systems to overall water use by agriculture will fall still further. In 1993, water supply systems supplying the huge rural population of China accounted for no more than 5.4 per cent of total agrarian water; in India and in most other countries of Asia the figures are insignificant by comparison with water use for irrigation and are normally grouped together in calculations (FAO, 1999).

A rough assessment of aggregate water use for rural needs in different regions is usually based on the figures for specific water withdrawal (measured in litres per day per capita) and the size of the rural population. It is also accepted that the change in livestock numbers will be proportionate to the change in population numbers. Just as in community water withdrawal, water consumption, expressed as a percentage of water drawn off, depends primarily on the amount of water intake and on climate. For a water withdrawal of 100–200 litres per day per capita, water consumption are not normally more than 15–30 per cent of the water withdrawal, whereas for smaller water withdrawals, of 20–50 litres per day, they may be as great as 70–100 per cent.

In studies at the Russian SHI, assessing water use for major natural and economic regions of the world and countries, the values for rural water supplies are not separated out, but counted together with water use for irrigated agriculture.

5.5 RESERVOIRS AS FRESHWATER USERS*

The building of high dams can cause a radical transformation of runoff distribution in time, and a rise in water resources in the vicinity during limiting low-water seasons and dry years. At the same time, the attendant flooding of large areas for reservoir storage makes for much increased evaporation from the reservoir surfaces, which diminishes total water resources, as they come to be among the more important users of fresh water. That seems to make it essential to take into account this aspect of reservoirs when assessing overall water use by country and continent, though most authors fail to do so.

Reservoirs were already being built thousands of years ago, but on the global scale they first began to appear in the second half of the twentieth century. The era of massive construction of reservoirs on continents everywhere began after the end of the Second World War and continued more or less up to 1985–1990. That was the period when the largest dams in the world were built with storages of more than 35 km^3. According to some data (Avakian et al., 1987), whereas in 1950 the cumulative full volume of water stored in the world's reservoirs with a capacity of more than 100 million m^3 amounted to 532 km^3, by 1985 it had reached 4 920 m^3, i.e. it had risen by almost 1 000 per cent. It was during that time that reservoirs became world-scale edifices, not only contributing to economic development, providing water and protecting communities from flooding, but also having a considerable effect on the hydrological regime, state of water resources and the environment, within major river basins, countries and natural-economic regions of the world.

In the last 10–15 years the rates of dam building, particularly ones holding back large reservoir storages with great water surface areas, have fallen off drastically. This is mainly due to the fact that in many regions well

* This section drafted jointly with Dr Zh. A. Balonishnikova, Candidate of Hydrological Science.

provided for, streamflow is already more or less completely controlled, or there are no suitable places for building major reservoirs without flooding human settlements and valuable agricultural land and harming the environment. One major handicap to the development of large reservoirs in our times is their very high cost, caused by the need for all-round account to be taken of possible harmful ecological impacts and for countermeasures to be taken to remove them. The present-day trend in hydraulic engineering is for reservoirs to be built in thinly populated areas, where there is no need to flood large areas, for effective regulation and for minimizing any harmful impact on the environment.

These observations are supported by data in Figures 33 and 34, which give aggregate full volumes and reservoir surface areas for all continents built at different times: before 1940, 1941–1960, 1961–1980, and 1981–2000. The data come from the the latest reviews by the Russian SHI, based on a databank holding data on all reservoirs in the world with storage volumes of more than 0.1 km^3.

The data we have given show the aggregate full volume of reservoir storage in the world for the year 2000 as 6 370 km^3, not counting the areas contained in lakes that have themselves been submerged. At the same time there was a steep rise in volume in the world's reservoirs (3 200 km^3, or more than 50 per cent) between 1961 and 1980; during the last 20 years the rate of dam building has fallen off steeply, and the increased storage volume has amounted to only 1 530 km^3. From 1941 to 1981, reservoirs were built with an aggregate volume of about 4 500 km^3, i.e. about 70 per cent of the entire volume in all the world's present-day reservoirs (Figure 33).

The dynamics of dam building differ significantly from continent to continent. In Europe, the largest increments to overall volume and reservoir area took place between 1941 and 1960; in North America, Africa, Asia and Australia, most were built during the period 1961 to 1980, while in South America the bulk came after 1980 (Figures 33, 34).

Figure 35 shows the distribution of full and active volumes and surface areas of all existing reservoirs by natural and economic regions of the world. In section 3.5 above (see Table 8), the volumes of reservoirs for all regions are compared with renewable water resources, and an analysis is made of regulatory characteristics according to area.

The aggregate surface areas of reservoirs, as seen in Figure 35, for a whole range of regions of the world, are enormous (covering many tens of thousands of square kilometres). In hot dry climates this inevitably leads to very high additional losses to evaporation, a factor to be taken into account when analysing the dynamics of total water use in regions and assessing available water supply.

The worldwide distribution of reservoirs by country is extremely uneven. Figure 36 shows the 20 countries with the greatest volumes of reservoir storage in declining order (from 950 km^3 to 50 km^3). Six countries account for the largest volumes (Russia, Canada, USA, Brazil, China and India); they have the highest figures for renewable water resources (see section 3.6, and Table 10).

The largest full volume of reservoirs is possessed by Russia (950 km^3), in the USA and Canada the figures are slightly lower (800 km^3), but they outstrip Russia in terms of their active volumes; the United States has the largest active reservoir volume in the world, estimated at about 700 km^3 (see Figure 36 and Table 10).

The largest reservoirs in the world volume are: the lake reservoir of Owen Falls (Lake Victoria, in the basin of the Nile) in Uganda (205 km^3), and Bratsk on the Angara River in Russia (169 km^3); by surface area they are: the Volta in Ghana (8 500 km^2), and the Kuybyshev Reservoir in Russia (6 500 km^2). In all, the world has seven reservoirs with storage volumes of over 100 km^3: four of these in Africa, one of them with the largest volume and the other with the largest surface area. More than 60 reservoirs round the globe have volumes greater than 20 km^3, and are to be found in many countries and on every continent except Australia. Russia apart, the largest reservoir surface areas are to found in European countries: Ukraine, Spain, Norway, Sweden and Finland.

With present-day trends and the long-term plans existing in many countries, it may be supposed that in the next two decades the building of dams and reservoirs around the world will continue, and their total volume will rise by roughly between 600 and 1 000 km^3. This is mainly due to the increasing importance of hydroelectric power and the shortage of liquid and solid fuels. As we know, hydroelectric power has an important part to play in offsetting peak loads, which cannot be effectively met by either thermal or nuclear power stations. Moreover, reservoirs supply much of the water used by industry, thermal and nuclear power stations, rural areas and agriculture; they lay the foundations for major water management systems, regulating streamflow in time and space, and protecting human settlements from flooding of different kinds.

Reservoirs will continue to be built in the longer-term future too, but it must be supposed that the types of reservoir, their purpose and geographical distribution will alter considerably. They will be built in mountainous and piedmont terrain without flooding wide swathes of rich agricultural land; in developed countries, small and medium-sized dams will predominate.

The construction of dams and reservoirs in different regions of the globe causes a reduction in freshwater resources as a result of additional evaporation losses; in some areas their amounts play no mean part in the overall volume of water consumption. The additional losses caused by dam building may be calculated from the difference between evaporation figures from the surface of a reservoir and from the same area before flooding, including the area of dry ground on the future reservoir site and a river in its natural conditions. As a rule, reservoirs situated in moderately wet areas or those with insufficient moisture, not to mention arid regions, reduce

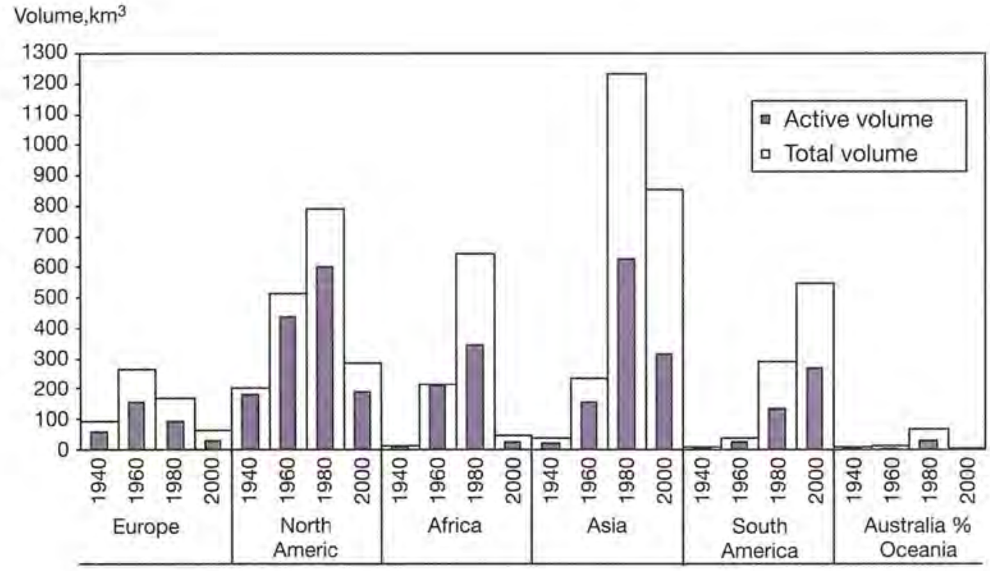


Figure 33—Increment of the total and active volumes of reservoirs by continents for different periods: up to 1940, 1941–1960, 1961–1980, 1981–2000

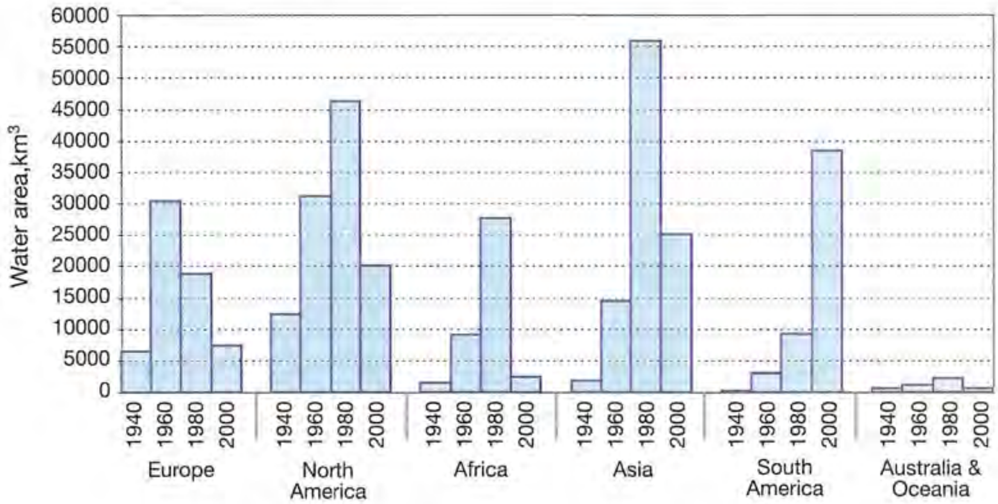


Figure 34—Increment of the total area of reservoirs by continents for different periods: up to 1940, 1941–1960, 1961–1980, 1981–2000

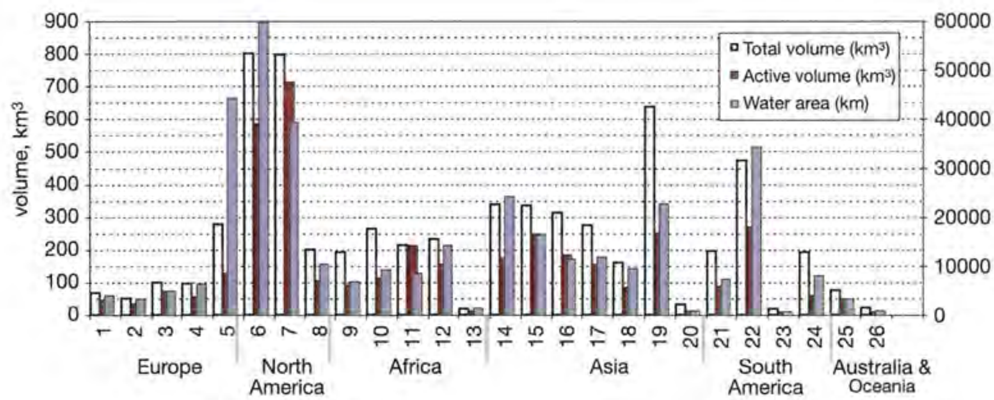


Figure 35—Total volumes and water areas of reservoirs by natural-economic regions of the world

water resources in the lower-lying parts of a catchment area due to the greater evaporation from the reservoir storage surface than from the dry ground before flooding.

For reservoirs of the river type, the size of this reduction is usually unimportant because the extra water surface area is not great, and evaporation from flood meadows is similar to the evaporation from the water surface. In some cases, when large areas of flood plain, where highly evaporative vegetation predominates, are covered over by a reservoir, the building of a dam is not necessarily accompanied by any fall-off in water resources, even in dry climates.

The size of additional evaporation losses from the world's reservoirs in the twentieth century has been generally reviewed in such works as Shiklomanov and Markova (1987) and Shiklomanov (1988); in 1980 they made up some 120 km^3 and by the end of the century a considerable increase in them was expected.

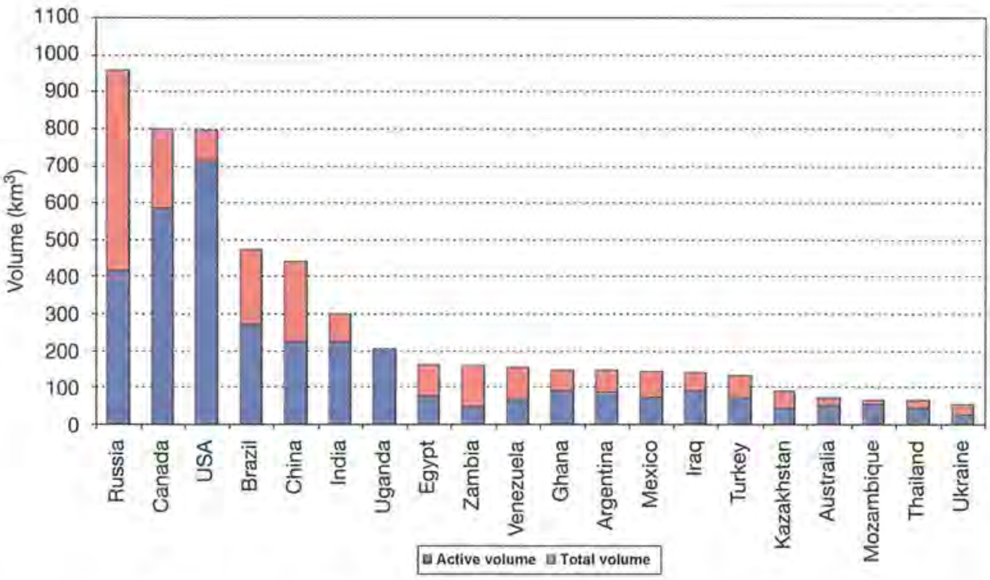


Figure 36—The countries with largest total volume of reservoirs

5.6 METHOD OF ASSESSING AND FORECASTING WATER USE AND AVAILABILITY

To study long-term worldwide changes in water resources and availability, a quantitative assessment of water use (both water consumption and withdrawal) in its present state, and for the past few years and decades of the twentieth century has to be made, along with a forecast for an extremely long-term future (up to 2010–2025). Studies at the Russian SHI analysed the dynamics of water use and figures for renewable water resources for all continents and major natural-economic regions of the world, and for selected developed and developing countries situated in various physical-geographical regions of the planet, and arrived at a fairly reliable determination of the characteristics of water resources.

Natural-economic regions were selected for every continent, taking as their starting point physical-geographical conditions and socio-economic development, and based on generally accepted principles of geographical and economic zoning. The demarcation lines of the different regions as a rule follow administrative boundaries of the countries forming part of a given region. This is because more or less all data needed for assessing and forecasting water use (population, irrigated areas, and indicators for industrial development, etc.) always follow national frontiers rather than the basins of major rivers or seas. Exceptions include the largest countries in the world in land area: the former USSR, the United States, and China. The former USSR is divided geographically into five regions, and the United States and China are divided into two regions. The entire world (not including Antarctica) is divided into 26 natural-economic regions, as shown in Figure 5 (Table 8 provides the areas of each region).

For every continent, region or country selected, water withdrawal and water consumption were separately assessed for urban community needs (community water use), industry (including power generation), rural areas (irrigation and water supply for agriculture), and water losses through additional evaporation from reservoir surfaces. All assessments were made for the following arbitrary dates: 1900, 1940, 1950, 1970, 1980, 1990 and 2000; and the future: 2010 and 2025. This means that the dynamics of world water use, in space, and time can be monitored for the 20th and early 21st centuries.

In the first phase, an assessment of water use was made for every country, and then the figures obtained were reviewed by natural-economic region, continent and the world as a whole. In all, in one way or another for different years, data on the characteristics and factors governing them were analysed for 160 countries. In so doing, national data were mainly used for actual or arbitrary groups of countries. We now have data of varying levels of detail and reliability for many countries on every continent. The most comprehensive figures for relatively long periods (several decades) come from publications put out by international organizations or individual authors, for example for the United States, the countries of the former USSR, most countries in Europe, Canada, China, India, Mexico, Cuba, Brazil, Argentina, Egypt, Kenya, UAR, Japan, Turkey and Australia; for several of them there exist forecast assessments up to the year 2000 approximately.

Analyses of water management and water use in the world have been made by many authors (see section 5.7.1). In the past few years, data reviews have been published on water use for many countries in the 1970s and 1980s and for 1990. Among them should be mentioned publications by the WRI (1996–2000), Kulshreshtha (1992), Gleick (1993), UN (1993), and Seckler et al. (1998). Detailed study by analysing present-day and long-term water availability has been carried out on the countries of the Mediterranean, Arab and African countries (Margat, 1995; Rostas, 1995; UN/DPCSD, 1995; UNESCO, 1995; FAO, 1997).

It should be noted that reviews of published data for individual countries or groups of country encounter serious problems because the results from different authors are often contradictory and not very compatible. Information is often incomplete, and covers only certain water uses, or else the data fail to indicate the period they are covering; amounts of water take-up vary considerably from year to year. There is a particular lack of figures for water consumption, which do not exist for most of the world; they are not given in the reviews we have cited. There is an extreme paucity of reliable data on water use in different countries for the 1960s and 1970s and for forecasting water use after the year 2000; and there is no information on the dynamics of water losses due to additional evaporation off the surface of reservoirs by country or region.

With regard to the foregoing, along with an extensive use of country data on water use, assessments for the present, past and future, have all been made using specially developed methods based on making allowance for the chief factors governing the quantity and dynamics of water use (withdrawal and consumption). Here, it was assumed that the quantitative characteristics of water use in different fairly large regions and countries are governed by the following main factors: level of economic and social development, population size, physical-geographical features (including climate) and total area of the region or country. All of these taken together determine the volume and shape of water use, its dynamics and future trends. The analogy method was widely used, based on the above-mentioned factors. For the purpose, the countries chosen were ones with reliable water-use data, whose physical-geographical circumstances and developmental status resembled those with missing data.

Community water use. Water withdrawn by the community in urban and rural settlements was estimated from (urban and rural) population data and figures for specific water use per capita per day. Population growth dynamics for past and present were taken from statistical handbooks, and for the future they were drawn from a United Nations forecast (UN, 1995) with population forecasts for every country in the world up to the year 2050. Specific per capita water withdrawal and the proportion of water consumption by individual countries were taken from published country assessment data or documents produced by international organizations. Where such paperwork did not exist, the data were based on specific water use in similar countries. For retrospective and future assessments, the figures used were for changing trends in specific water use by urban and rural populations, as indicated in section 5.2, along with water consumption as a percentage of water withdrawal.

Water use to meet rural needs*. An assessment of water use for irrigation in the present day and past years was made by analysing the dynamics from 1960 to 1994 of the following characteristics: population size (from UN data); irrigated land areas by year (FAO data), including their specific sizes (in ha per 1 000 population), and the per capita gross national product (GNP), expressed in US dollars. In so doing, the values for specific water withdrawal and for water consumption were taken from data for country assessments or analogous countries. Water consumption due to irrigation (as a percentage of water drawn off) varies by country and region of the world, and ranges between 50 and 95 per cent, depending on whether or not drainage exists, on the type of irrigation and technology used, and on physical-geographical circumstances. In many cases, to check the values arrived at, evaporability data were taken from country sources or the world atlas of maps annexed to Korzun's 1974 monograph.

The forecast assessment of irrigation water use to respectively 2000, 2010 and 2025 was mainly based on forecasting dynamics for irrigated lands (F_{op}). These forecasts were based on the integrated trend, where the main factors governing irrigation needs on the one hand, and prospects for developing irrigation on the other, are both borne in mind. The first heading includes climate and the historical development of countries; population dynamics generally, and urban and rural population size; the specific nature of the internal and external market, and how countries operate in the world economic system, and national water-use strategies. The second includes the general economic development of countries (expressed through figures for GNP), available water resources; the size of potentially irrigable land and how far irrigation has been introduced, the essential limitations stemming from environmental pollution and land degradation.

Forecasts were made for each country by analysing integrated graphs showing long-term (1965–1995) dynamics of annual GNP (in US dollars) (IMF, 1994), areas of irrigated land (F_{op}, '000 ha), specific area of the same (F_{op} spec. expressed per ha/1 000 pop.), with a subsequent extrapolation to 2025. The extrapolation took account of long-term population dynamics (N) and the size of GNP, country irrigation development forecasts, and fairly precise, objective trends in the development of irrigation, population and GNP dynamics for the last 30 years for various groups of countries.

As a result of the studies it was established that irrespective of GNP, for most countries a link could be seen between GNP dynamics and the intensity and nature of changes in F_{op}. The only exceptions are highly developed industrial countries with restricted land areas (Japan, Germany, Hong Kong, etc.) where the value of F_{op} is quite stable and hardly depends on GNP dynamics. As an example, Figure 37a shows an integrated graph for Japan with an extrapolation of irrigated land areas up to 2025.

For highly developed countries with high GNPs, traditional types of irrigation and large reserves of uncultivated land, the rate that F_{op} grows at, falls off considerably during periods of economic crisis if there are not enough resources to continue with planned irrigation developments. In the past decade there has been a marked tendency for F_{op} in such countries to falter, caused either by the need to undertake expensive

* This section was drafted jointly with Dr N.V. Penkova (SHI).

environmental protection measures (e.g. Australia, New Zealand, etc.) or by a very slow population growth as well. Figure 37b and c shows comparable integrated graphs for the United States and New Zealand.

The development of irrigation in middle-income industrial-agrarian countries is to a large extent governed by the degree to which available irrigable land has been improved. If there is next to no irrigable land left, then low rates of F_{op}, depending on income dynamics, will be observed. It is obvious that in this case, considerable resources must be spent on cultivating less suitable lands or improving irrigation systems. An example of this is Morocco, for which an integrated graph is shown in Figure 37d.

In developing countries with high population growths and considerable amounts of unrealized irrigation potential, irrigation is often extended through state planning, which should also be seen as a crucial factor in the dynamics of F_{op} in the future (China, India, Pakistan, etc.). Under this heading, particularly high rates of growth of F_{op} are typical for agrarian countries where produce from the agricultural sector is a prime source of national income (e.g. Bolivia, Tanzania, etc.). Here, growth in irrigated land areas is very regular and only slows when rises in GNP are exceptionally low. This is illustrated in the integrated graphs in Figure 37e, f, g for China, Bolivia, and Tanzania.

It should be noted that the available irrigated land statistics series for most countries are not long enough, and are essentially too close to the period forecast, so that an analysis of the dynamics of absolute figures for F_{op} and their future outlook is not effective enough and may induce major error. More reliable data are obtained by incorporating additional information in the shape of population dynamics, in particular because for every country there are long-term forecasts for the latter. In particular, the size of the specific irrigation area (F_{op} specific expressed in ha/'000 population) makes for more informative analyses. This amount is fairly stable and is more sensitive to changes in GNP than the irrigated area expressed in absolute values (see graphs in Figure 37). Hence for most countries it is the figures for F_{op} specific that are given (allowing for the standard trends illustrated above) and absolute figures for irrigated lands are determined for them using forecast population sizes.

With long-range forecasting for irrigated lands, the boundary conditions taken into account include the area of land suitable for irrigation and water resources accessible for use. In many natural-economic regions of the world, in particular those that include fairly "rich" countries, national water resources strategies are considered as being among the most important factors limiting the spread of irrigation. As a rule, they focus on more fully meeting the requirements of the priority water user, the community sector of water use, while rural water use is rationalized and economized.

To assess future water use for irrigation, not just the irrigated land area has to be known but also the figures for specific water withdrawal in m^3 per ha, which may change significantly as time passes. In forecasting, it was assumed that the volume of specific water withdrawal for irrigation would be likely to fall somewhat as measures were introduced to improve technologies and procedures along with irrigation equipment for more economic use of water resources. The size of the fall differed for different regions and countries as a function of their development and physical-geographic circumstances; in most cases it was in the 5–10 per cent range. The greatest amounts came from the relatively "rich", fast developing countries with limited water resources. It was arbitrarily assumed that water consumption in irrigation (as a percentage of water withdrawal) would not change in the future, i.e. it would remain at 1990–1995 levels.

Industrial water use. Water used by industry was calculated on the basis of industrial production dynamics in different parts of the globe; in doing so, data for such water use in the countries listed earlier followed the analogy approach; this includes countries at different stages of economic development in different physical-geographical circumstances. Calculations for past and present were made separately for power generation but cumulatively for all other industrial sectors, with their significantly different tendencies, rates of development, and sizes of water consumption, and were then combined together regionally. Water consumption for power generation was assumed to be between 1 and 4 per cent, while in other sectors of industry it was taken as from 10 to 40 per cent of draw-off, depending on the degree of industrial development, return water use and climate.

Assessments for the long-term future to 2025 were produced separately for each country, taking into account special forecasts carried out for UNIDO (Strzepek and Bowling, 1995). This work was based on an assessment of the present world situation and GNP projections, and forecast the industrial development figures for all the main countries in 2025 by comparison with 1990. The forecast is made for high, moderate and low levels of electrical power generation in the world, for four alternative global development scenarios (Global Shift, European Renaissance, Global Balance and Global Crisis). We took as a basis the most optimistic development scenario (Global Balance), but for a moderate growth in electrical power production. This UNIDO scenario proposed a water withdrawal rise by 2025 of 1.4–2.9 times for developed countries and 3–10 times for developing countries. Fairly similar increases were proposed for the other optimistic scenario, the so-called European Renaissance. Analysing the growth figures for industrial water withdrawal proposed (using all four scenarios), we concluded that they were far too high and did not make allowance for present changing trends in water use patterns. This led us to reduce the UNIDO 2025 data for our model (Global Balance) by 20–30 per cent for developing countries and 40–60 per cent for developed countries.

The figures for industrial water withdrawal in 2000 and 2010 were obtained by interpolation, making

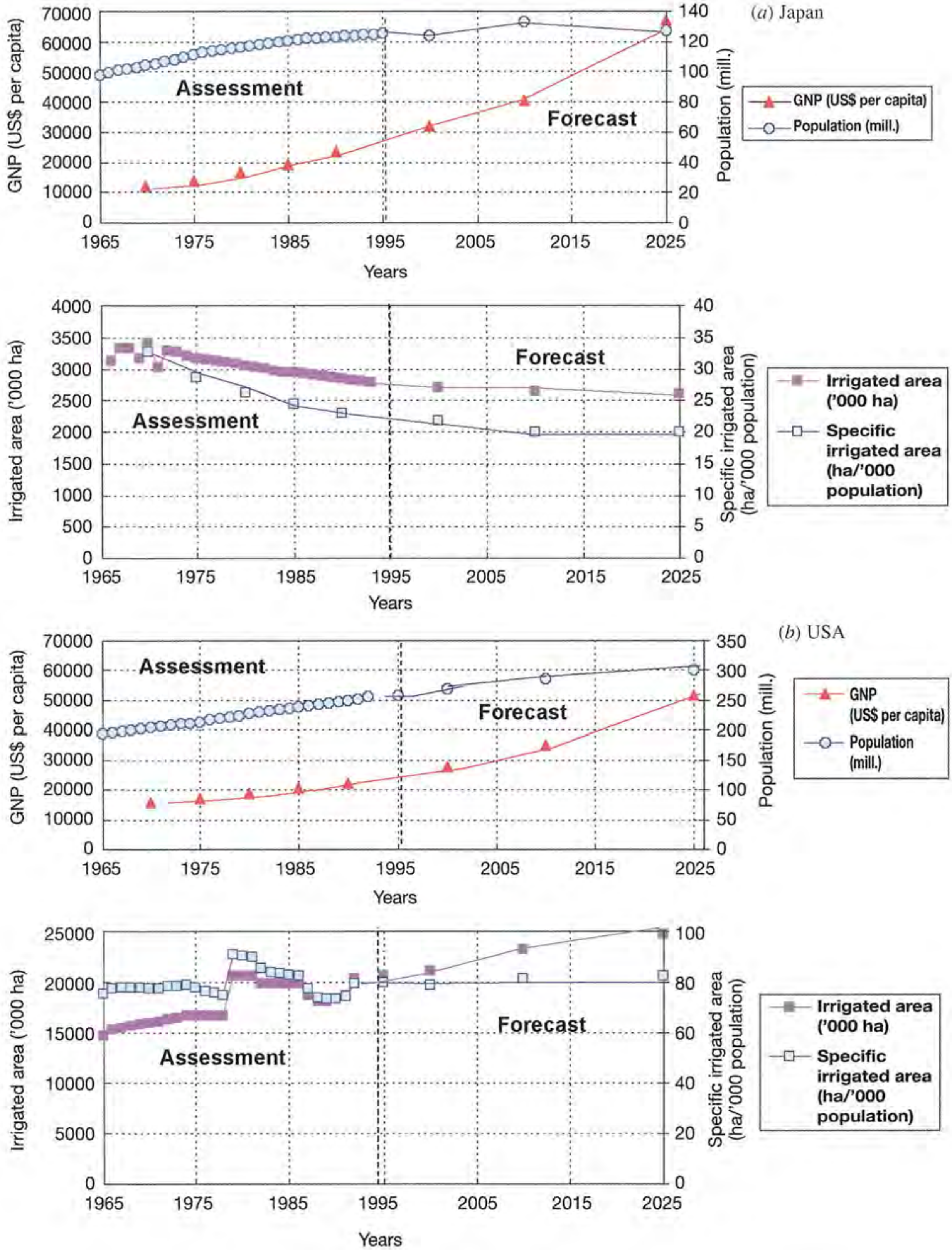


Figure 37—Dynamics of main indicators of irrigation development in individual countries of the world: (*a*) Japan; (*b*) USA

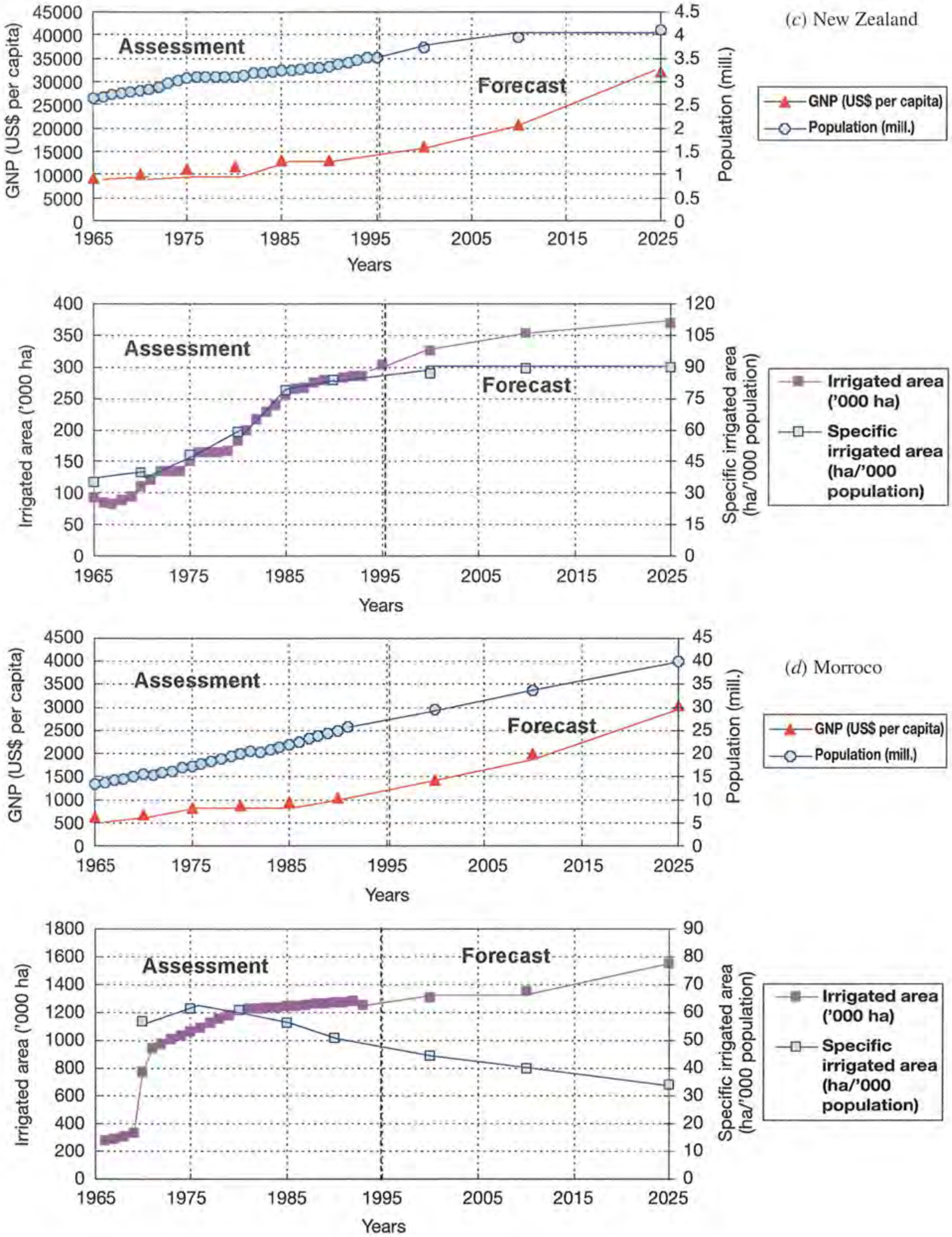


Figure 37—Dynamics of main indicators of irrigation development in individual countries of the world: (*c*) New Zealand; (*d*) Morocco

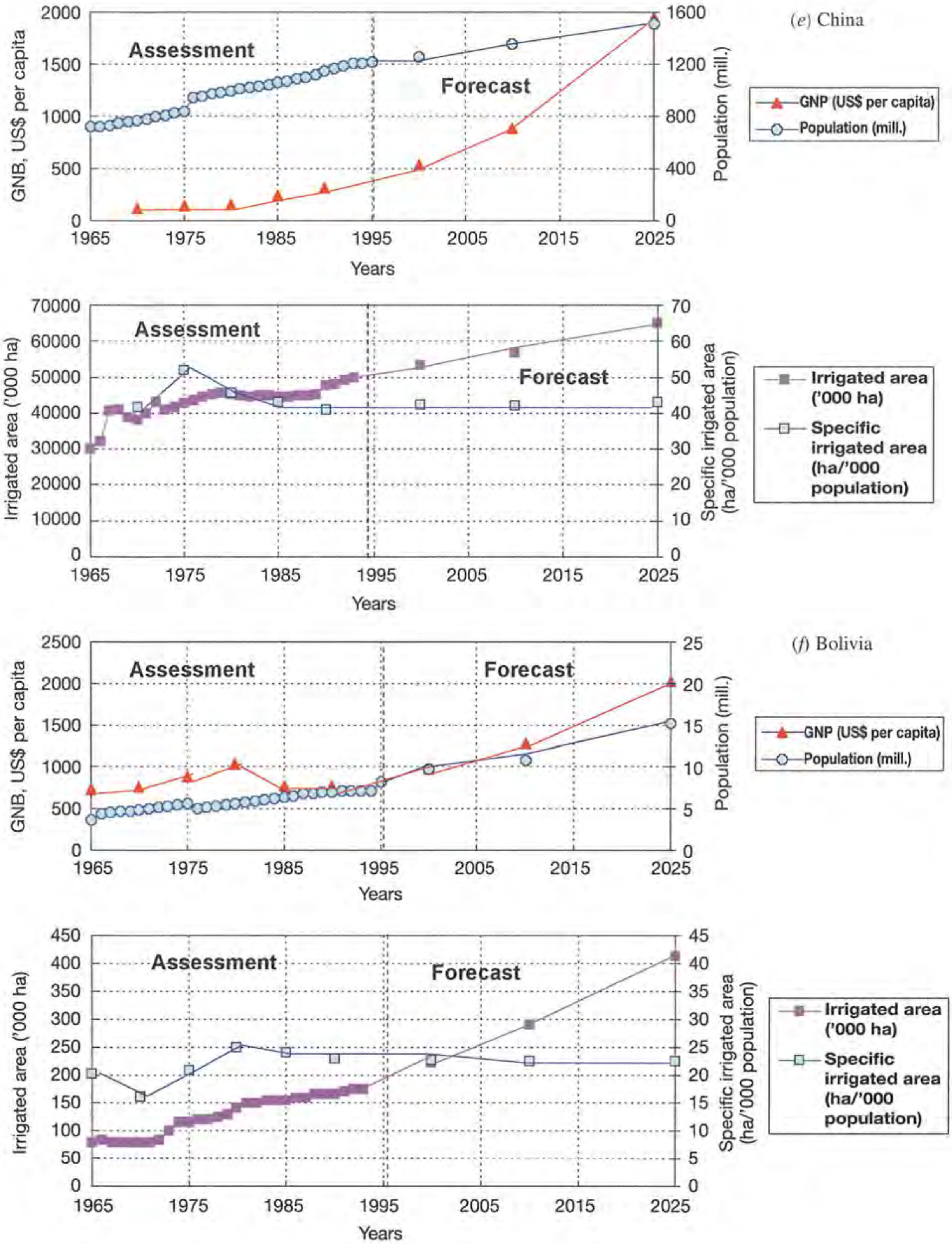


Figure 37—Dynamics of main indicators of irrigation development in individual countries of the world: (*e*) China; (*f*) Bolivia

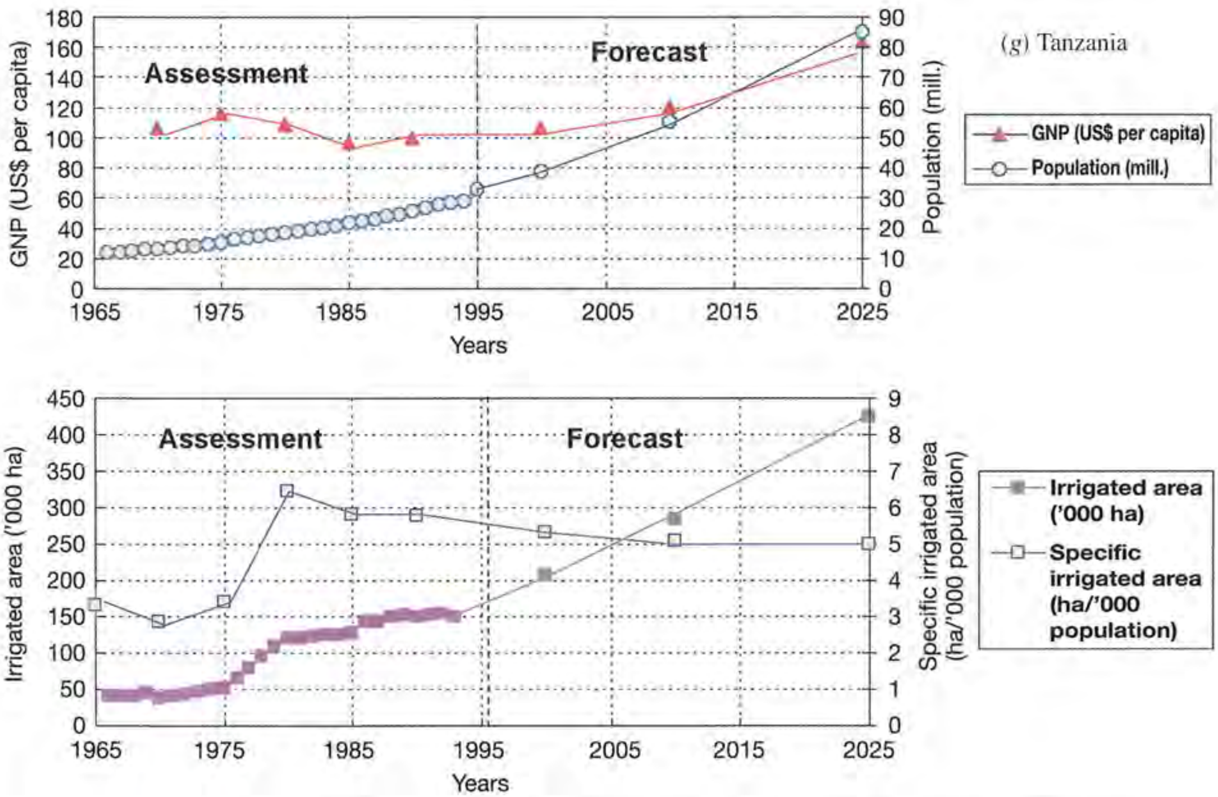


Figure 37—Dynamics of main indicators of irrigation development in individual countries of the world: (g) Tanzania

allowance for national forecasts available from many countries, and where these did not exist, taking into account GNP forecasts for the Global Balance scenario developed for UNIDO.

Reservoirs. Additional water losses through reservoir evaporation are assessed using a method developed by the present author, based on detailed studies for two of the great river basins of Europe, the Volga and the Dnieper, which both have a large number of dams and reservoirs of the widest possible variety (lake and river-type) in volume and area of reservoir surface (Shiklomanov, 1979, 1989). In the Volga River basin (catchment: 1340 thousand km^2, mean annual streamflow: 254 km^3) there are nine dams along the Volga proper and its most important tributary (the Kama River), with a total volume of 164 km^3 and a water surface area of 21 160 km^2. The Dnieper River basin (catchment: 505 thousand km^2, mean annual streamflow: 53.9 km^3) has six reservoirs with a total volume of 44 km^3 and a water surface area of 6 974 km^2.

When applied to countries and major natural-economic regions, the method can be used for making simple calculations, not for individual years in specific terms but averaged out over the long term, meaning that the amount of data required at the outset can be kept to a minimum and the calculations left simple. Using the method, losses from the area flooded are determined from the difference between standard evaporation from the surface of the storage lake and that occurring on dry land in the area surrounding the reservoir. To assess the losses, the mean area of flooded land is roughly calculated as a function of the reservoir's design surface area, its type, and the type of discharge regulation, for which the coefficients K_1 and K_2 are brought into play.

The value of the coefficient K_1 is determined by the ratio of the actual mean surface area of water for the period to the design surface area of the full reservoir, and this obviously depends on the type of runoff regulation (daily, weekly, monthly, seasonal, perennial) and how the reservoir surface curve depends on its level. $K_1 \approx 1$ for seasonal regulation of most mountain and piedmont reservoirs, and for daily and weekly regulation of most of those located in plains areas. For seasonal regulation in plains reservoirs $K_1 = 0.80$–0.90. The average for the nine reservoirs of the Volga basin for several years is $K_1 = 0.89$, while for the six reservoirs in the Dnieper basin it is $K_1 = 0.93$.

The value of the coefficient K_2 is determined by the ratio of the areas flooded to the water surface area of the reservoir, and mainly depends on the type of reservoir (river, valley, lake) and on the river stage fluctuation range in natural conditions. For lake reservoirs on plains rivers $K_2 = 0.90 \div 1.0$; for those of the valley-lake type $K_2 = 0.80 \div 0.90$; for the lake-river type $K_2 = 0.70 \div 0.80$ and for the ordinary river type $K_2 = 0.65 \div 0.70$; the average for reservoirs in the Volga River basin is $K_2 \approx 0.80$, for reservoirs in the Dnieper River basin it is $K_2 \approx 0.90$.

It should be pointed out that large reservoirs have an impact on evaporation not only in the flooded areas but also in river reaches downstream of their dams as a result of the changes in regime and flood plains through streamflow regulation. Thus, in data from studies by the present author (Shiklomanov, 1979), the creation of a series of reservoirs along the Volga, the largest river basin in Europe, caused a reduction in the duration and area of flooding on the Volga-Akhtubinsk flood plain and the Volga River delta, with accompanying evaporation losses, as against the natural period, of 1.4 km^3 more per annum. A similar effect may occur in other basins too, in more southerly dry regions they will be greater, but in areas of adequate or excess precipitation they can be ignored.

On the other hand, rises in groundwater levels at points bordering on areas flooded by reservoirs normally generate some increase in evaporation runoff losses. If the contrasting effects of these two factors are borne in mind and that they to some extent offset one another, then a failure to take them into account will not noticeably affect the mean values for changes in water resources resulting from high dams and obtained by making allowance only for evaporation from the additional surface area of the reservoir.

By using a simplified system of calculation, estimates were made of reservoir evaporation losses for all natural economic regions by the Russian SHI in 1996–1997. In so doing, basic reservoir data (area, volume, location, year of construction and other characteristics) were taken from several monograph reviews of the literature (Korzun, ed., 1974; Avakian et al., 1987; Gleick, 1993; World Bank, 1993). The data in general provided information on the reservoirs of the world for 1980–1985. Benchmarks for evaporation from reservoir surfaces and dry ground were based on the maps in the world atlas annexed to Korzun, ed., 1974. The overall volume of additional losses through evaporation was calculated as a whole for each region by adding together data for every reservoir with a volume of more than 5 km^3 and adding 20 per cent to the result, i.e. it was assumed that the largest reservoirs count for about 80 per cent of the total volume and water surface area of all the world's reservoirs. The values for the coefficients were taken as 0.80 and constant for all regions of the world.

Reservoir evaporation losses in every region were assessed taking into account trends identified in the period 1950–1985, existing long-term plans for the construction of major high dams and reservoirs in different countries and regions, and their physical-geographical features. The data obtained are given in section 5.7 and published in the literature (Shiklomanov, ed., 1997; Shiklomanov, 2000; Shiklomanov, ed., 2003).

In 2001, the author, together with Dr Z.A. Balonishnikova, made new, more detailed assessments of the role of the world's reservoirs as regulators of renewable water and as water users, for all natural economic regions and selected countries of the world.

The calculations were likewise made, as originally, by using a simplified method, which also employed the Russian SHI database for reservoirs round the world (see section 5.5), where more comprehensive data are given for reservoirs, particularly those created in the 1980s and 1990s.

In calculating additional evaporation losses from reservoirs, the main task is to define a reservoir's water surface area. Unfortunately, in many articles (both national and international) these extremely important data are far from being reported for all reservoirs or are not reported at all. In Russia's SHI's water surface data bank, there are no data for a third of all reservoirs. The best reported of the data (up to 85–100 per cent) are those from the reservoirs of Russia and the countries of the former USSR, USA, Africa and Australia. For the reservoirs of Asia, South and Central America, and Canada, the information is available for less than half the reservoirs in the database.

Where there are no data for reservoir water surfaces, the size was worked out by oblique methods as a function of a reservoir's total volume. These functions were developed separately for different types of reservoir, situated in different physical-geographical conditions: for reservoirs of the plains lake type; reservoirs in piedmont areas and plateaus; and mountain reservoirs.

As an example, Figure 38 shows water surface areas as a function of volume for reservoirs of the plains type in countries of the former USSR. For these areas we had available more dependable and completer findings on volumes and areas of water surface and on the type of relief they are located in.

Analysis of regional ratios of reservoir surface areas to volumes showed that for lake type reservoirs with full volumes in plains areas, the water surface area needed will be 150–200 km^2, and for mountain reservoirs the figure will usually be in the 10–20 km^2 span. Reservoirs in piedmont and plateau areas are of intermediate size (40–80 km^2); the figures fit fairly well for river- and valley-type reservoirs situated in plains areas.

With calculations for individual countries and natural economic regions, the amounts for total reservoir water surface areas were determined for different periods: 1941–1960, 1961–1980, and 1981–2000. In so doing, for every reservoir, the storage area was taken from the data contained in the database as a function of the volumes shown in graphic form in Figure 38.

The size of the evaporation layer from the surface of water and off dry land were taken from the maps in the Atlas Mirovogo Vodnogo Balansa [World Water Balance Atlas] (Korzun, ed., 1974), and the values of the coefficients for each region were reckoned to be in the 0.80–0.90 range.

Water availability. For a given region (country, basin), water availability is usually taken to mean the amount of renewable water resources available per capita per annum or unit area (volume per km^2 of area or layer in mm, which amounts to the same thing). In the present work, figures are given for various types of water availability.

Potential water availability. This is estimated by dividing the volume of water resources by population size (usually in thousands of m^3 per annum). Here, water resources are usually taken to mean their average annual quantity per annum (season, month) for average values

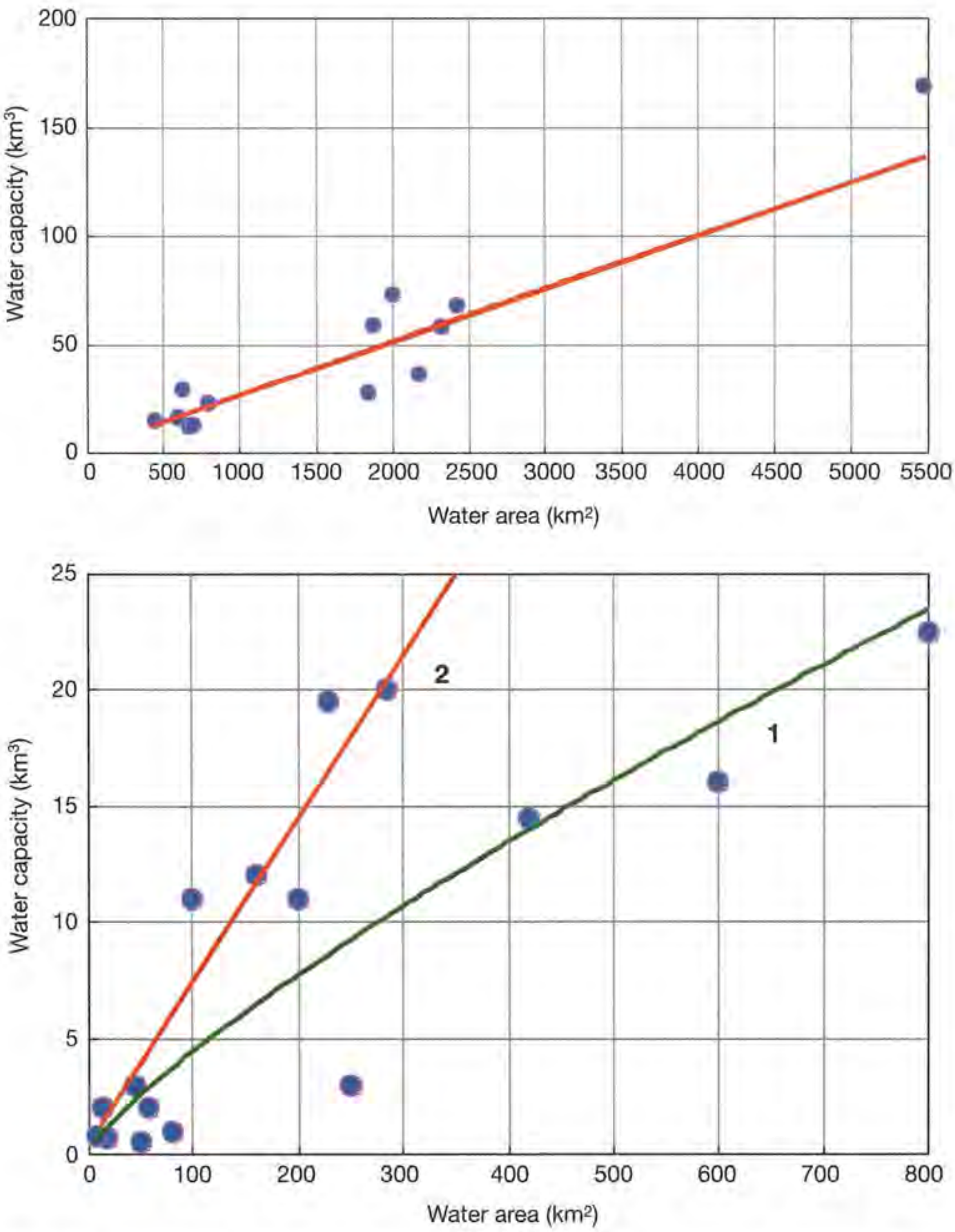


Figure 38—Relation between reservoir capacity and water area for reservoirs in (1) piedmont and (2) mountain regions

during dry years, or their minimum values for the entire long-term period being studied.

The potential water availability does not take account of non-return water losses when drawn off for economic purposes and, when water use is high enough, it does not reflect true water availability. Thus, for a more objective analysis of the dynamics of water availability for different regions and countries, this work uses figures for so-called actual water availability. ***Actual water availability*** (per capita) is assessed for each calculation level by dividing water resources and subtracting water consumption by population size.

In this way, actual water availability is taken to be the residual amount of fresh water per capita remaining after use. True water availability can also be assessed by various water resources characteristics.

In calculating water availability (potential and actual) for different administrative areas, it has to be asked which water resources should be used: only local, those originating in the given area, or full, i.e. taking into account inflows from neighbouring areas. In the first case, there is a clear underplaying of water availability figures, since practically always, inflows from neighbouring areas are nearly always used, if only partly. In the second case there is an obvious exaggeration of water availability, since the neighbouring territories also claim the inflowing water.

This question does not have a single answer to all administrative units, and it must evidently be resolved by special agreements between different countries. Since such agreements do not exist for most countries, for our assessment we took figures for local water resources, plus half the inflow of fresh water emanating from outside areas. Thus it is arbitrarily assumed that each region (or country) may exploit half of all water from neighbouring areas. This arbitrary figure helps in fairly objectively investigating the dynamics of water availability for all regions of the world and countries.

5.7 WORLD WATER USE DYNAMICS

5.7.1 Analysis of past assessments and forecasts

In the last 30 years, experts from different countries have made many an attempt to assess present world water use for different economic purposes and make both short- and long-term forecasts. Given the absence of water use data for most countries (and still more the lack of reliable long-term forecasts), as well as how hard it is to collect and review available information worldwide, most workers used oblique methods to assess the requisite water use for economic purposes in different continents and for the world in general. These techniques are based on analysing the main factors governing the amounts of water used: the size of urban and rural populations, the dynamics of industrial production in developed and developing countries, trends in water availability, the development of agricultural output, the growth in irrigated land areas, and so forth. In so doing, directly used water use data were employed only for selected individual countries and sectors of the economy.

It is extremely hard to analyse and compare conclusions because of the lack of uniform results. Some authors quote only calculations of aggregate world water use, others differentiate between water use by continent and individual users; some provide assessments of both present and future water use, others give only one of the two; and so forth. In their assessments, most workers neglect water consumption (giving only withdrawal) and fail to record water lost to additional evaporation from major reservoirs. Add to this the fact that nearly all authors use heterogeneous original data and base their assessments for past and future on differing premises or fail to describe their methods, then the difficulty of comparing results and analysing the reliability of conclusions will be plain to see. Nevertheless, such an analysis of data for world water use dynamics was made by the present author in 1987 (Shiklomanov and Markova), again in 1997 (Shiklomanov, ed., 1997), and in greater detail in a monograph (Shiklomanov, ed., 2003). Here, we provide just a few brief extracts from the analysis.

Assessments and forecasts of water withdrawal and consumption in the world based on data from different authors can be seen in Figures 39 and 40.

Analysing the data, the following conclusions may be drawn about results obtained from the 1960s to the 1980s:

- ***1960s to early 1970s*** (Doxiadis, 1967; Kalinin, 1968; Lvovich, 1969–1974; Holy, 1971). Because of the shortage of factual data, assessments even of overall water use are extremely vague; assessments for the future foresaw exponential growth in water but were exaggerated;
- ***1970s to early 1980s*** (Kalinin and Shiklomanov, 1974; Falkenmark and Lindth, 1974; Yermolina and Kalinin, 1975; De Mare, 1977; Barney, 1980; Ambroggi, 1980; Rioha, 1982). Assessments for current world water use, including individual water user, are by now accurate enough, but there is a considerable variation in assessments by continent and in particular by region of the world. Future assessments remain very much on the high side;
- ***Second half of the 1990s*** (Shiklomanov and Markova, 1987). Relatively reliable assessments of present-day water use by continent and natural-geographic region. Assessments of future situations are still too high, but not as overplayed as they were once, and can mainly be explained by a failure to use long-term irrigation extension plans in many countries round the world. Where there are long-term assessments stretching into the future, there is already a certain tendency to stabilization and even to decrease water withdrawals for the needs of industry and power generation in developed countries.

We should also note that in all periods, including until very recently, both current and future data on water consumption (Figure 40) are extremely limited. Most workers dealing with world freshwater use simply do not possess such data, and they are not cited in reviews of the literature and periodical publications such as Gleick (1993, 1998), WRI (1992, 1996, 2000) and so forth. Data on water consumption are not only harder to come by than figures for freshwater withdrawals, but are also less detailed and not very accurate. All this greatly hinders the task of making reliable assessments of actual water availability for different countries and also any study of the influence of water use on water quality in bodies of water and along watercourses.

Long-term world water use forecasts from the 1990s have already largely allowed for current trends towards a sharp retrenchment in the spread of irrigation in most countries and also in stabilizing or diminishing industrial water use in developed countries. These forecasts include activities already undertaken or planned for water resource savings and protection of natural waters from pollution.

Incorporating the above-mentioned factors in its work, in 1992 the World Resources Institute estimated that world water use would reach approximately 4200–4400 km^3 per annum by the year 2000 (Figure 39).

In 1994, French researchers gave assessments for future world water use in different publications (Andreassian, 1994; Margat, 1994). These works forecast water withdrawal and water consumption for 30 regions worldwide for 2010 and 2025, as compared with data for the late 1980s. The authors used an extremely simplified approach to assessing water use for community needs, irrigation and industry, based on integrated indicators already reported (population and irrigated area), constant coefficients for all countries and arbitrary hypotheses about the future. For example, disregarding the physical-geographic and socio-economic conditions of all countries and regions of the world, water consumption from irrigation was assumed to be 75 per cent, and 10 per cent of water withdrawn was assumed to be for industrial purposes. At the same time, figures for power generation were totally absent from the full volume of water

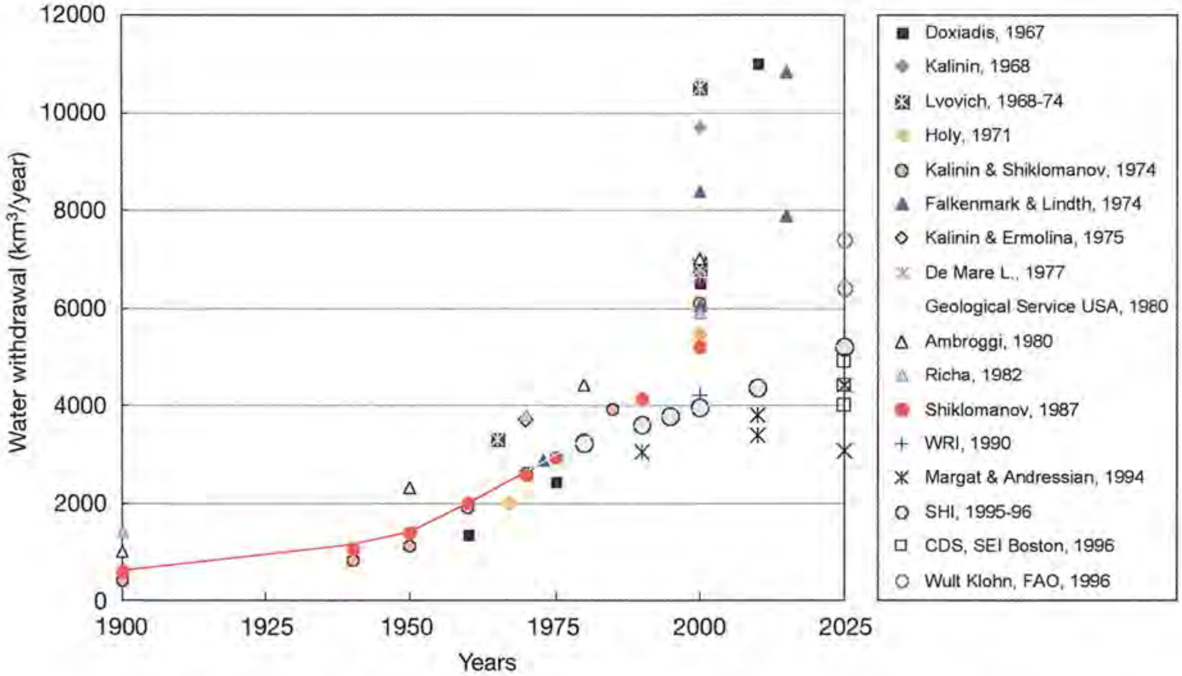


Figure 39—Comparison of the values of water withdrawal in the world by the data of different authors

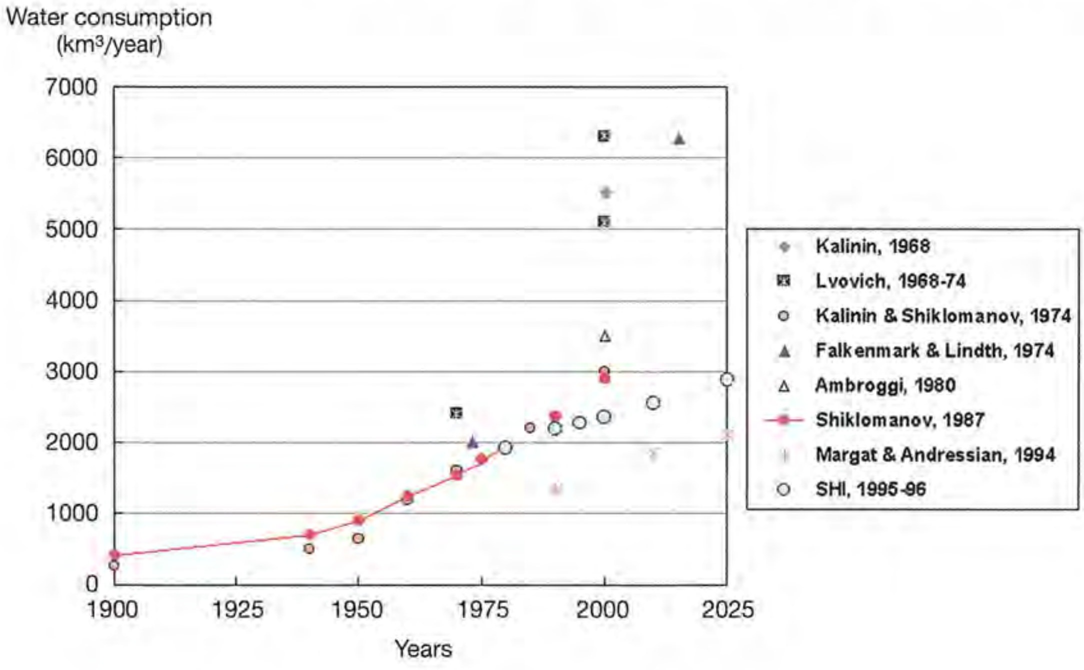


Figure 40—Comparison of the values of water consumption in the world by the data of different authors

assumed. In their calculations for the future, it was presumed that by the year 2010 all countries of the world (except the USA) would have reduced specific industrial water withdrawal by 40 per cent, and by 2025 it would have fallen by 50 per cent. The latter assumptions are not very realistic and are contradicted by the UNIDO data (Stztrepec, 1995), giving country-by-country assessments of future world industrial water use dynamics.

The French forecast assessments are given in Figure 39. According to the highest figures, they are considerably lower than all earlier assessments, which is mainly explained by their undervaluing industrial water withdrawal and failing to include water withdrawal for power generation. The calculations also make no allowance for water lost to additional evaporation from reservoirs and rural water supplies. This means that the assessments and forecasts made by the French authors will differ considerably from more detailed assessments at the Russian SHI, produced from the baseline data and method set out in section 5.6. Nevertheless, the results of Professor Margat's 1994 critique of present world water use and forecasts, which covers different countries and regions, was extremely interesting and useful for those trying to assess future world water use.

New data from the Russian SHI on the dynamics of world water use up to 2025 were first presented by the present author to UNESCO at its expert meeting on world water resources, and published in 1997. The data are included in Figures 39 and 40 and are considered in detail in subsequent chapters of this monograph. The data from the beginning of the twentieth century up to 1980 inclusive, quoted by the Russian SHI for different continents and the world as a whole are the same as the author's earlier assessments dating from 1987 (Shiklomanov and Markova). They are fully confirmed by all the most recent investigations. For subsequent years to the end of the twentieth century and into the future, there are new data responding to modern world water use development trends and long-term population forecasts. The data reported that in 1995 aggregate world water use was 3 790 km^3 per annum, water consumption was 2 070 km^3 per annum; and for the future up to 2025, it is expected that water withdrawal will be as high as 5 200 km^3 per annum, and of water consumption will be 2 800 km^3 per annum. The figures for the future presuppose a stable climate on every continent and in every natural-economic region. They are based on analysing water use in countries and regions for past decades (since 1960) allowing for population size, economic development, present trends in improving water use technologies in industry and agriculture (see section 5.6). Thus, it is assumed that water use developments in different countries and regions during the next 25–30 years will follow the precedent of past decades. In the Russian SHI, the scenario has been dubbed the SHI Conventional Scenario. In all likelihood, it is the most realistic one as it implies that the same relationship to freshwater use will apply for all countries in the future as it does at present.

The forecast figures for water use under the Russian SHI relate to average climatic conditions, ignoring world climate changes possibly due to human action, and to the most likely world economic development model. Allowing for the vagaries of economic development, population forecasts and climate, an expert hypothesis suggests that for 2025, aggregate world water use could oscillate between +10 and +12 per cent around mean values, i.e. between 4 600 and 5 800 km^3 per annum.

In 1996, while preparing the report on the quality and future world use of fresh water for the United Nations Commission on Sustainable Development, an international expert panel convened by the Stockholm Environment Institute (SEI) developed world freshwater assessment forecasts up to 2025 (UN/WMO/SEI, 1997).

Simultaneously (in 1996), a forecast of water use up to 2025 was drafted by FAO, which proceeded from the demands on fresh water for providing potable water for the world's growing population.

The SEI and FAO forecast figures for 2025 are shown in Figure 39. As we can see, they differ considerably from one another (on average from 4 500 to 7 000 km^3 per annum at 2025 figures), though from many standpoints they are evidently the most solidly based long-term prognoses. The forecast assessments of the Russian SHI obtained earlier and independently under the Conventional Scenario (CS) are situated between the extreme figures forecast by the SEI and FAO, which generally speaking are seen to be fairly reliable. A more detailed analysis of the SHI data on world water use dynamics and availability and their geographical distribution is shown in the following chapters.

5.7.2 Water use dynamics by continent

The dynamics of water use by continent and worldwide for the new century up to 2025, worked out on the basis of data reviewed for natural-economic regions of the world, are shown in Table 18 and Figure 41a and b. World water use for 1995 was about 3 790 km^3 per annum and water consumption was 2 070 km^3 per annum (55 per cent of water withdrawal). The steepest rise in world water use began in the second half of the twentieth century. Where for the first 50 years of the twentieth century, water use grew by some 800 km^3, or 160 km^3 every decade, for the next three decades it rose to 550–650 km^3 per decade, in other words it grew by almost 400 per cent. That was a result of the steep population rise, the spread of irrigation, and the rapid development of industry under the impact of the technological revolution. After 1980, worldwide water use growth rates fell back as a result of the slower expansion of irrigated lands and improved freshwater use efficiency in many countries, principally the developed nations. Nevertheless, they are still fairly high.

In the future, under the Conventional Scenario, water withdrawal will rise by 10–12 per cent every 10 years, and by 2025 it will reach some 5 200 km^3 per annum (a rise of 137 per cent); water consumption will grow some more slowly: a rise of 125 per cent.

At present, about 57 per cent of world water withdrawal and 70 per cent of the water consumption is in Asia, where the bulk of irrigated lands in the world are situated and where most of the world's population live. During the last few decades there has been a difference in the dynamics of water use between Europe and North America (where countries are for the most part developed) and other continents (Figure 42). Beginning in 1980, total water withdrawal in Europe and North America either stabilized or declined slightly. This was mainly the result of a considerable decline in industrial water use following the introduction of more effective freshwater use technologies. In other continents, there has been a steep rise in water withdrawal ever since 1950.

Up to 2025, according to the Russian SHI's Conventional Scenario, the greatest rise in water use is expected to be in Africa and South America (1.5–1.6 times) and the lowest in Europe and North America (approximately 1.2 times).

The part played by individual water users in world water use dynamics, and growth in population size and irrigated areas, are shown in Table 19 and Figure 43a and b. In 1995, agricultural water use amounted to 66 per cent of water withdrawal and 85 per cent of water consumption worldwide; at the beginning of the twentieth century, the part played by agriculture was greater and the equivalent figures were 89 and 97 per cent respectively. It is important to note that down to 1970 the rise in irrigated areas worldwide was higher than the population increase; since 1970 the opposite has been true, and the amount of irrigated land per capita has been gradually falling. Let us also note that in the past 45 years, water use efficiency in agriculture has improved only slightly; whereas in 1950 an average of 10 700 m^3 per annum was being withdrawn per hectare of irrigated land; in 1995 the figure was 9 900 m^3 a year, i.e. it had fallen by 7.5 per cent.

The future amount drawn off by agriculture will fall as a proportion of aggregate water use, basically because of a greater expected growth of other water users, first and foremost industrial and community water users. Thus, though agricultural water use is expected to rise by 1.27 times by the year 2025, industrial water use by 1.5 times, and community use by some 1.8 times. In aggregate world non-return water losses, a significant part is played by additional evaporation from reservoirs, greater than the combined non-return water use both by industry and the community.

According to data that have been further refined, in 1995 the total irrigated land area in the world was 253 million ha; under the Conventional Scenario, by the year 2010 it is expected that this figure will rise to approximately 290 million ha, and by 2025 to 330 million ha.

Comparing the forecasts in Figures 41 and 42 with forecasts published previously by different authors (see Figures 39 and 40), it should be noted that the latter provided considerably higher values for the future. This is fully in line with the long-term forecasts made by the present author, published earlier (see Figures 39 and 40).

The main cause of exaggeratedly high forecasts, as indicated earlier, was two factors. In the first place, all those working on forecasts developed between the 1960s and the 1980s had predicted a steep increase in the irrigated land area, based on very high rates of world development of irrigation, at that time considerably ahead of population growth rates (see Figure 31). Secondly, forecasts failed to take wholly into account the stabilizing trends that first appeared in the 1970s and 1980s and even the fall-off in industrial water use in many developed countries (see Figures 29 and 30). To no small extent, the errors in forecast assessments resulted from unreliable basic data and the extremely unrefined methodological techniques employed.

The part played by individual users in water use figures from all continents for 1950, 1995 and 2025 are given in tables 20 and 21. These data indicate that Europe and North America enjoy similar structures for both present and future water use. Here, a great deal of water withdrawal is taken up by industry (41–45 per cent at 1995 levels, and approximately the same for perspective under the Conventional Scenario).

For water consumption, both in Europe and in North America great importance should be attached to agriculture, responsible for about 70 per cent of total water consumption.

Continent	*Assessment*								*Forecast*					
									CS			*SDS*		
	1900	*1940*	*1950*	*1960*	*1970*	*1980*	*1990*	*1995*	*2000*	*2010*	*2025*	*2000*	*2010*	*2025*
Europe	37.5	96.1	136	226	325	449	482	455	463	535	559	444	416	353
	13.8	38.1	50.5	88.9	122	177	198	189	197	234	256	193	198	201
N. America	69.6	221	287	410	555	676	653	686	705	744	786	669	634	527
	29.2	83.8	104	138	181	221	221	237	243	255	269	237	234	223
Africa	40.7	49.2	55.8	89.2	123	166	203	219	235	275	337	232	259	292
	27.5	32.9	37.8	61.3	87.0	124	150	160	170	191	220	165	176	182
Asia	414	682	843	1 163	1 417	1 742	2 114	2 231	2 357	2 628	3 254	2 310	2 476	2 487
	249	437	540	751	890	1 084	1 315	1 381	1 458	1 593	1 876	1 428	1 509	1 470
S. America	15.1	32.6	49.3	65.6	87.0	117	152	167	182	213	260	175	190	201
	10.8	22.3	31.7	39.6	51.1	66.7	81.9	89.4	96.0	106	120	92	97	99
Australia &	1.60	6.83	10.4	14.5	19.9	23.5	28.5	30.4	32.5	35.7	39.5	30.5	30.8	29.1
Oceania	0.58	3.30	5.04	7.16	10.3	12.7	16.4	17.5	18.7	20.4	22.3	17.9	18.9	18.8
Total	**579**	**1 088**	**1 382**	**1 968**	**2 526**	**3 175**	**3 633**	**3 788**	3 973	4 431	5 235	3 860	4 006	3 889
(rounded)	**331**	**617**	**768**	**1 086**	**1 341**	**1 686**	**1 982**	**2 074**	2 182	2 399	2 764	2 133	2 233	2 194

Note: First line = water withdrawal; second = water consumption.

Table 18—Dynamics of water use in the world by continent (km^3/year)

Figure 41a—The dynamics of water withdrawal in the world by continent

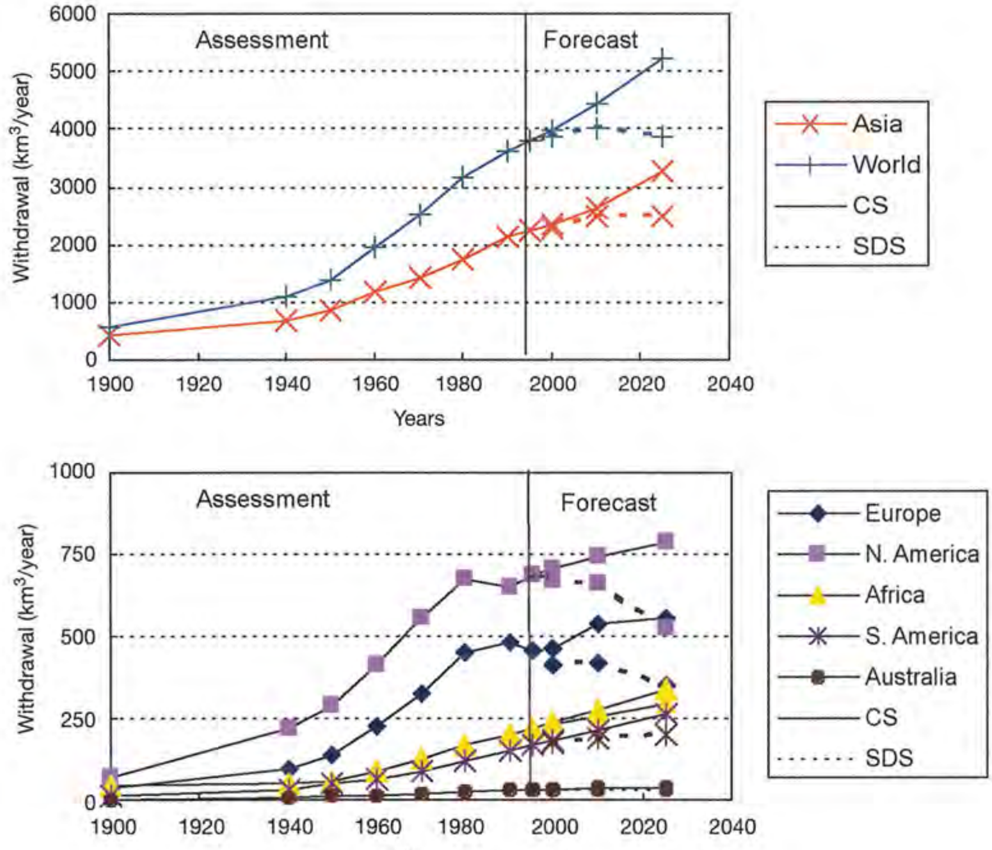
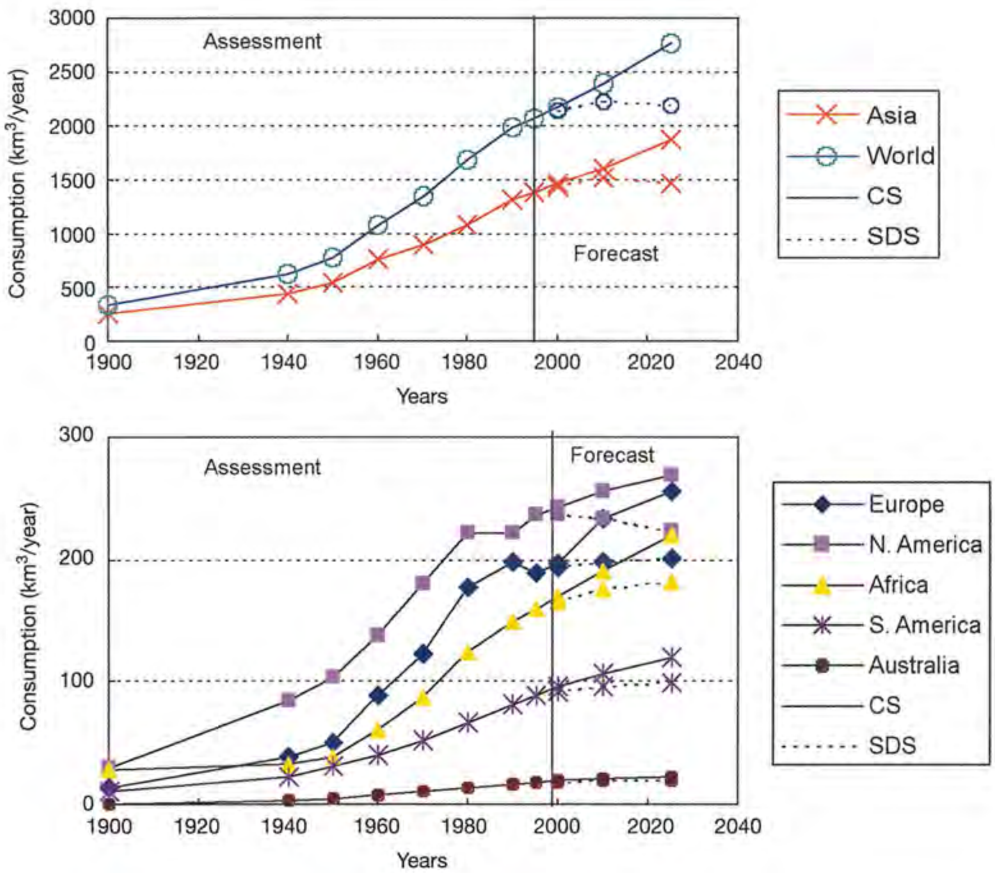


Figure 41b—The dynamics of water consumption in the world by continent



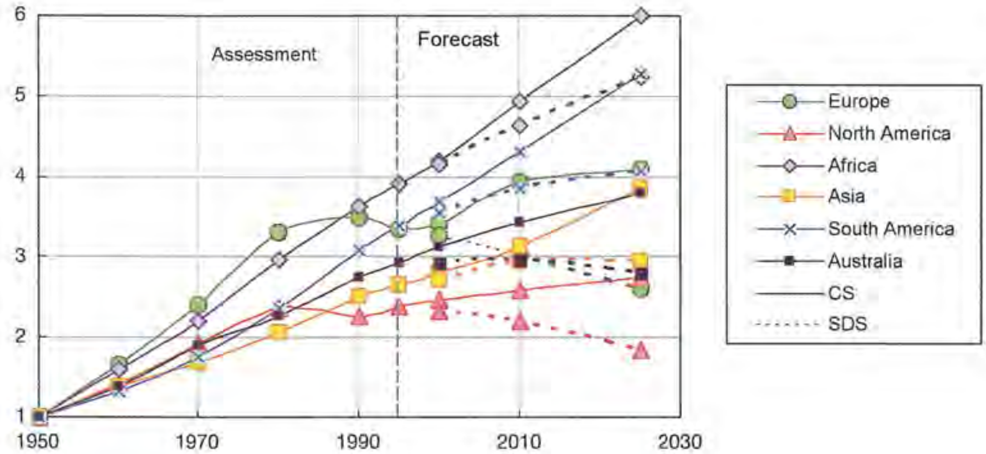


Figure 42—Dynamics of water use by continent during 1950–2025 (1950: water use equals 1)

Sector	*Assessment*								*Forecast*					
									CS			*SDS*		
	1900	*1940*	*1950*	*1960*	*1970*	*1980*	*1990*	*1995*	*2000*	*2010*	*2025*	*2000*	*2010*	*2025*
Population (million)			2 542	3 029	3 603	4 410	5 285	5 735	6 181	7 113	7 877	6 181	7 113	7 877
Irrigated land area (mill. ha)	47.3	75.9	101	142	169	198	243	253	264	288	329	265	286	306
Agricultural use	513 321	895 586	1 080 722	1 481 1 005	1 743 1 186	2 112 1 445	2 425 1 691	2 504 1 753	2 605 1 834	2 817 1 987	3 189 2 252	2 541 1 789	2 646 1 867	2 535 1 793
Municipal use	21.5 4.61	58.9 12.5	86.7 16.7	118 20.6	160 28.5	219 38.3	305 45.0	344 49.8	384 52.8	472 60.8	607 74.1	379 60.2	422 61.0	456 63.0
Industrial use	43.7 4.81	127 11.9	204 19.1	339 30.6	547 51.0	713 70.9	735 78.8	752 82.6	776 87.9	908 117	1 170 169	745 88.0	731 97.0	673 113
Reservoirs	0.30	7.00	11.1	30.2	76.1	131	167	188	208	235	269	196	208	225
Total (rounded)	**579** **331**	**1 088** **617**	**1 382** **768**	**1 968** **1 086**	**2 526** **1 341**	**3 175** **1 686**	**3 633** **1 982**	**3 788** **2 074**	3 973 2 182	4 431 2 399	5 235 2 764	3 860 2 133	4 006 2 233	3 889 2 194

Note: First line = water withdrawal; second = water consumption.

Table 19—Dynamics of water use in the World by economic sector (km^3/year)

In Asia, Africa and South America a dominant role has always been played in the part played by agricultural water use, in other words to all intents and purposes by irrigation. In 1995, 60–80 per cent of water withdrawal and 64–91 per cent of the water consumption originated in irrigation. These indicators will change only slightly even by 2025, although by that time, according to the Conventional Scenario, a doubling or tripling of industrial water use is expected for these continents. At the same time, the proportion of aggregate water use going to industry will be no greater than 24 per cent in South America, 15 per cent in Asia and 6 per cent in Africa. A distinguishing feature of African water use is the very large part lost to evaporation from reservoirs; at present and in the future it will account for 23–25 per cent of aggregate water consumption on the continent.

5.7.3 The dynamics of water use according to natural-economic regions

The dynamics of full and non-return water withdrawal and consumption by natural-economic regions of the world during the twentieth century and for the future are shown in Table 22, and for 1995 and 2025 in figures 44 and 45. The regional water use figures are very unevenly distributed by continent and as a rule do not agree with figures for water resources. For example, in Europe, 95 per cent of water use occurs in southern and central parts of the continent; in North America, the United States is responsible for 73 per cent of water used; in Australia and Oceania, 89 per cent of water used is drawn off by Australia. In Asia, the largest amount of water is withdrawn in South Asia, including India, Pakistan and

Figure 43a—Dynamics of total water withdrawal in the world over the kinds of economic activities by two scenarios

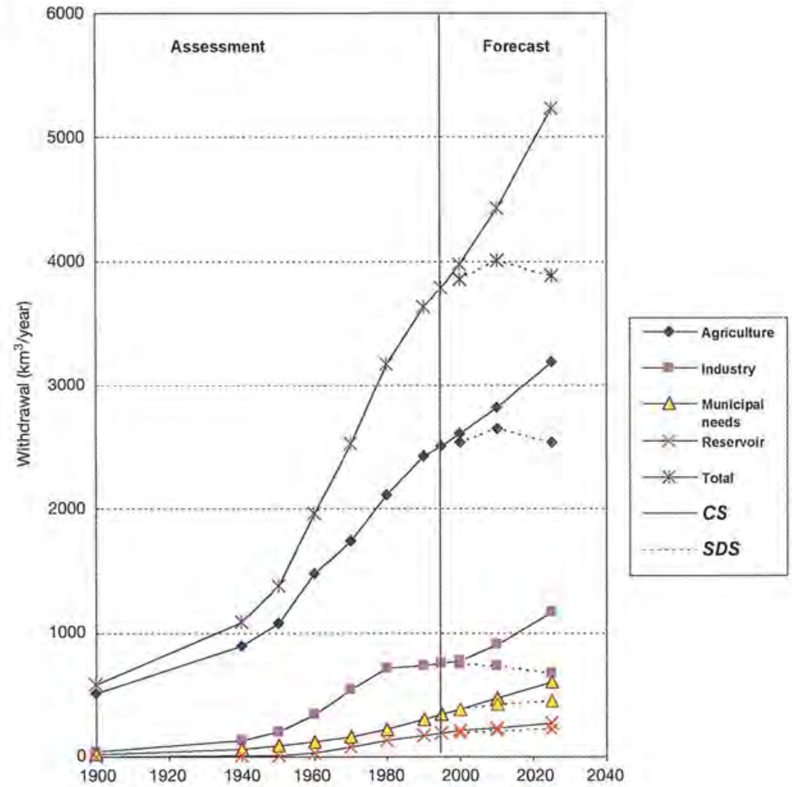
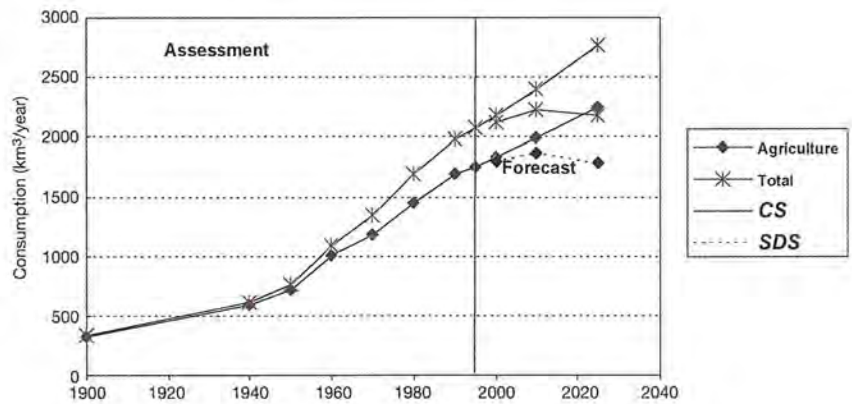
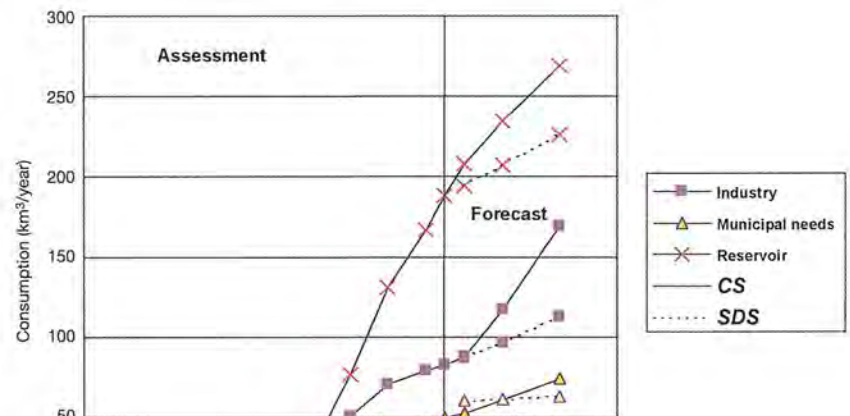


Figure 43b—Dynamics of water consumption in the world over the kinds of economic activities by two scenarios





Bangladesh and South-East Asia, where a wide swathe of the irrigated lands in China is located.

In Africa, the largest proportion of water use comes from North Africa; it is responsible for half the total water use by the continent. In South America, water use is more or less equally distributed by different parts of the continent. The dynamics of growth in water use to 2025 differ considerably by region. Where there are developed countries and countries with limited water resources, it is expected that water use under the Conventional Scenario will rise by 15–35 per cent, but in regions with developing countries with adequate water resources, the rise in water use may reach 200–300 per cent.

Figures 46–48 give examples of regional water use dynamics, showing figures for countries with differing socio-economic conditions.

Figure 46 shows water withdrawal dynamics from the central area of North America (USA without Alaska) and Central and Western Europe, all three of them regions of highly developed industrial countries. Characteristic dynamics included a steep rise in water use down to the nineteen-seventies, followed by a notable degree of retrenchment and stabilization of water use through the wide use of water-savings technologies (mainly in industry). Under the Conventional Scenario, a stabilization or insignificant increase in water use is to be expected, given that in many branches of the economy the main water savings methods in technological processes may have exhausted their potential.

Figure 47 shows a typical example of water use in countries with economies in transition. The southern region, covering the European part of the former USSR, includes part of Russia, Belarus, Ukraine and Moldavia. Characteristic of water use dynamics was a rapid growth in water use to 1980 followed by some stabilization due to improving technologies, followed by a steep decline from 1990 to the year 2000, through a fall in industrial and agricultural output resulting from politico-economic change. Under the Conventional Scenario, it must be

Continent	***1950***				***1995***				***2025***							
									CS				***SDS***			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Europe	32.2	25.4	41.2	1.5	37.4	14.7	44.8	3.2	37.2	14.0	45.8	3.1	45.0	17.0	33.0	5.0
N. America	53.5	7.9	36.0	2.9	43.5	10.7	41.5	4.4	41.4	12.3	41.3	4.8	50.0	13.0	31.0	6.0
Africa	90.5	7.0	2.6	0.0	63.0	8.1	4.4	24.7	53.1	18.0	6.0	22.8	48.0	20.0	9.0	23.0
Asia	93.4	2.4	4.2	0.0	80.0	6.9	9.9	3.2	72.0	9.5	15.2	3.3	75.0	9.0	13.0	3.0
S. America	82.4	9.5	7.9	0.4	58.6	17.2	15.4	8.7	44.2	22.7	23.8	9.2	50.0	19.4	22.4	8.2
Australia & Oceania	50.0	7.2	39.4	3.3	51.0	10.9	23.5	14.8	46.8	11.3	26.1	15.7	54.3	12.0	16.5	17.2
World	**78.1**	**6.3**	**14.8**	**0.8**	**66.0**	**9.1**	**19.9**	**5.0**	**61.0**	**11.6**	**22.3**	**5.1**	**11.7**	**65.2**	**17.3**	**5.8**

Water use: 1 = agricultural; 2 = domestic; 3 = industrial; 4 = reservoirs.

Table 20—Ratio of water withdrawal by sectors of economic activity to the total water use (in %) by continent

Continent	***1950***				***1995***				***2025***							
									CS				***SDS***			
	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
Europe	67.7	12.6	15.6	4.0	71.4	5.6	15.3	7.6	66.8	4.3	22.3	6.7	64.7	4.5	22.4	8.4
N. America	83.5	4.7	3.6	8.0	75.1	5.0	7.2	12.8	72.4	6.0	7.5	14.2	69.0	8.0	8.0	15.0
Africa	97.9	1.6	0.5	0.0	63.8	1.5	0.8	33.8	60.5	3.4	1.3	35.0	57.1	3.8	1.6	37.5
Asia	98.0	0.7	1.1	0.0	91.0	1.5	2.3	5.1	88.4	1.8	4.1	5.7	89.8	1.7	2.6	5.9
S. America	95.0	2.5	1.9	0.6	76.4	4.0	3.2	16.3	67.4	4.7	8.3	20.0	71.7	4.0	7.0	17.3
Australia & Oceania	81.3	2.0	9.9	6.7	69.1	2.2	3.1	25.7	64.1	2.1	6.4	27.8	65.2	2.2	5.4	27.2
World	**93.9**	**2.2**	**2.5**	**1.4**	**84.5**	**2.4**	**4.0**	**9.1**	**81.5**	**2.7**	**6.1**	**9.7**	**81.7**	**2.9**	**5.1**	**10.3**

Water use: 1 = agricultural; 2 = domestic; 3 = industrial; 4 = reservoirs.

Table 21—Ratio of water consumption by sectors of economic activity to the total water use (in %) by continent

Table 22— Dynamics of water withdrawal by continent and natural-economic region (km^3/year)

Region number	*Continent, region*	*Assessment*								*Forecast*					
										CS			*SDS*		
		1900	**1940**	**1950**	**1960**	**1970**	**1980**	**1990**	**1995**	**2000**	**2010**	**2025**	**2000**	**2010**	**2025**
	Europe	**37.5**	**96.1**	**136**	**226**	**325**	**449**	**482**	**455**	**463**	**535**	**559**	**444**	**416**	**353**
1	Northern	1.40	2.80	3.80	7.30	9.80	10.3	10.3	11.0	11.7	12.7	13.4	10.4	9.4	7.3
2	Western and Central	12.8	33.7	51.5	87.2	120	142	146	154	161	172	176	147	132	99
3	Southern	16.1	40.2	60.0	95.3	120	157	177	186	194	204	204	183	174	149
4	North European part of former USSR	0.30	0.75	0.89	1.76	3.13	9.80	13.4	10.8	10.5	14.1	16.8	10.4	10.5	10.2
5	South European part of former USSR	6.90	18.6	20.2	34.4	71.5	130	135	94.5	85.4	133	149	93	90	87
	North America	**69.6**	**221**	**287**	**410**	**555**	**676**	**653**	**686**	**705**	**744**	**786**	**669**	**634**	**527**
6	Northern	2.60	8.80	13.2	19.2	26.1	41.4	52.2	55.8	58.4	64.9	73.7	53.1	47.9	34.7
7	Central	54.2	191	248	347	470	538	492	503	512	530	549	484	446	351
8	Southern	12.8	20.9	25.5	44.1	59.4	97.5	109	127	135	149	163	132	140	141
	Africa	**40.7**	**49.2**	**55.8**	**89.2**	**123**	**166**	**203**	**219**	**235**	**275**	**337**	**232**	**259**	**292**
9	North	36.6	41.0	43.0	68.3	84.8	98.7	106	110	114	127	145	114	122	124
10	South	1.90	4.41	6.50	9.38	14.7	21.8	25.5	27.3	29.2	34.4	44.8	29.1	32.6	35.8
11	East	1.04	2.10	3.70	7.20	13.6	25.3	46.6	52.6	58.5	71.2	85.7	55.6	62.5	73.7
12	West	1.00	1.50	2.30	3.93	8.74	18.4	23.2	26.5	29.8	37.5	52.4	30.1	37.8	50.7
13	Central	0.10	0.20	0.30	0.40	0.82	1.64	2.07	2.60	3.14	4.90	9.21	3.12	4.50	7.60
	Asia	**414**	**682**	**843**	**1 163**	**1 417**	**1 742**	**2 114**	**2 231**	**2 357**	**2 628**	**3 254**	**2 310**	**2 476**	**2 487**
14	North China and Mongolia	37.0	66.0	93.0	153	186	215	241	268	295	319	372	252	297	301
15	South Asia	201	312	366	426	523	667	850	887	925	1025	1339	922	997	301
16	Western Asia	42.8	68.0	90.0	133	157	183	232	249	267	299	356	259	277	277
17	South-East Asia	99.0	165	220	357	419	478	572	631	683	760	949	656	706	722
18	Central Asia and Kazakhstan	28.7	55.0	57.2	67.4	94.4	151	170	154	147	174	182	156	162	155
19	Siberia and Far East of Russia	0.61	4.90	5.62	10.4	16.3	25.4	26.5	21.0	20.6	27.2	30.4	21.0	21.3	21.1
20	Transcaucasia	5.20	11.3	11.4	15.8	20.7	22.9	23.7	20.4	19.4	24.5	26.4	20.5	20.9	20.3
	South America	**15.1**	**32.6**	**49.3**	**65.6**	**87.0**	**117**	**152**	**167**	**182**	**213**	**260**	**175**	**190**	**201**
21	Northern	1.70	4.20	6.40	9.12	13.0	17.4	22.0	24.1	26.3	30.9	38.3	25.0	27.3	31.2
22	Eastern	0.99	2.04	2.88	7.34	13.6	25.2	43.0	49.0	54.6	68.8	87.6	52.5	59.8	65.7
23	Western	8.80	19.9	26.7	29.4	33.1	38.8	45.1	48.0	50.8	55.9	65.0	49.6	51.5	52.4
24	Central	3.60	6.41	13.32	19.79	27.4	36.1	42.2	46.1	49.9	57.6	69.2	47.7	51.4	51.8
	Australia and Oceania	**1.60**	**6.83**	**10.4**	**14.5**	**19.9**	**23.5**	**28.5**	**30.4**	**32.5**	**35.7**	**39.5**	**30.5**	**30.8**	**29.1**
25	Australia	1.59	6.60	10.0	13.8	18.9	21.6	25.5	27.1	28.9	31.7	35.0	27.1	27.0	25.0
26	Oceania	0.01	0.23	0.37	0.69	1.04	1.93	2.98	3.29	3.60	4.02	4.49	3.42	3.80	4.10

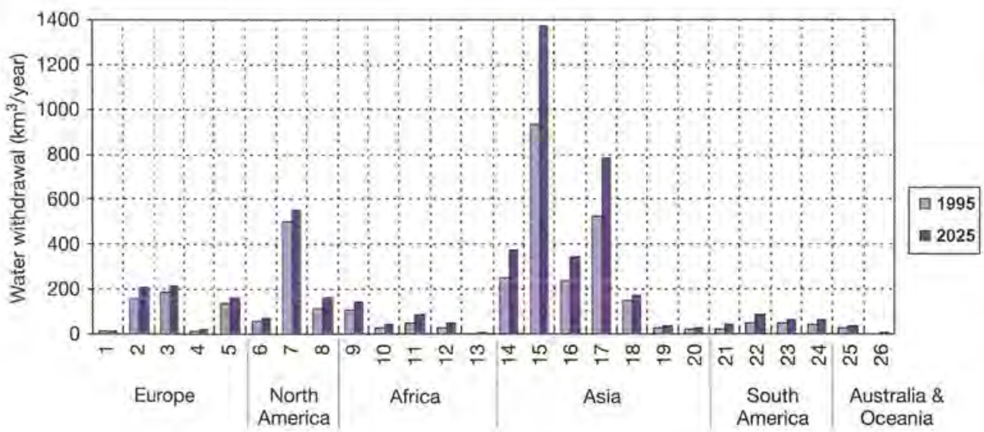


Figure 44—Water withdrawal of natural-economic regions at 1995 and 2025 by continent: 1 - North; 2 - Central; 3 - South; 4 - North part of ETS SU; 5 - South part of ETS SU; 6 - North; 7 - Central; 8 - South; 9 - North; 10 - South; 11 - East; 12 - West; 13 - Central; 14 - North China, Mongolia; 15 - South Asia; 16 - West Asia; 17 - South-East Asia; 18 - Middle Asia; 19 - Siberia, Far East of Russia; 20 - Caucasus; 21 - North; 22 - East; 23 - West; 24 - Central; 25 - Australia; 26 - Oceania

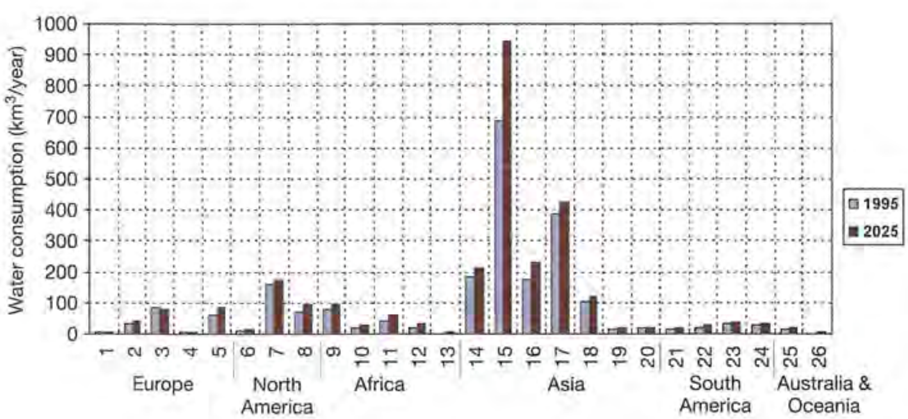


Figure 45—Water consumption of natural-economic regions at 1995 and 2025 by continent as above

expected that by 2010 water use will reach 1990 levels and slowly fall back, on the one hand following a fast rise in economic output and on the other by the extensive application of water-saving technologies.

Figure 48 shows the dynamics of water use in regions that include developing countries in Africa and Asia, whose distinguishing features include a steady rise in water use but with varying degrees of rapidity, to be explained by the differing tempos of economic development and population increases.

5.7.4 Water use in different countries of the world

The data in Table 22 and figures 46–48 on the dynamics of water use for various natural-economic regions give a picture of only the broadest trends, characteristic of groups of countries with differing climates and levels of socio-economic development. For individual countries the situation can vary extremely widely, depending on the specific features of a particular nation's economy and the prevalent climatic conditions (for example, wet or dry years) during the period under consideration.

Unfortunately, no reliable long-term data at all exist for water use dynamics in most countries in the world. Moreover, in the author's opinion, no countries have even reliable average data on current water use, though some figures on individual country water use are periodically published by the World Resources Institute (WRI, 1992, 1996, 2000). A critical analysis of these documents is given in section 3.6 above, in particular for WRI, 2000, in relation to figures for renewable water resources.

Difficulties that are no less important when making use of data on water use arose because of their lower homogeneity and reliability. This is because they are drawn from disparate sources, defined in different ways, and are based on initial data for different years, without the requisite critical analysis.

In its last publication, for example (WRI, 2000), Russian SHI water use data are quoted by continent for 1990 (Shiklomanov, 1997), but the country figures are drawn from a number of different years (1965–1997). Thus, total water use data for different countries do not correspond to data by continent. Use of such data for reviews and analyses if they are not based on a uniform time period (for example, 1995 or 2000) is totally impossible, as they are not comparable. For certain countries, some physically impossible data are given for water resources and water use. At the same time no data exist at all for water consumption (for individual countries and continents), which is mainly needed to assess water resources deficits and active water availability; while data on water losses due to additional evaporation from reservoirs are also totally ignored.

The most detailed contemporary data analysing water use dynamics in different sectors or the economy are for the United States (Gleick, 1998), a number of European countries (EEA, 1999; ETC/IW, 1998), Russia (Russian State Water Registry, 1982–2002), Ukraine

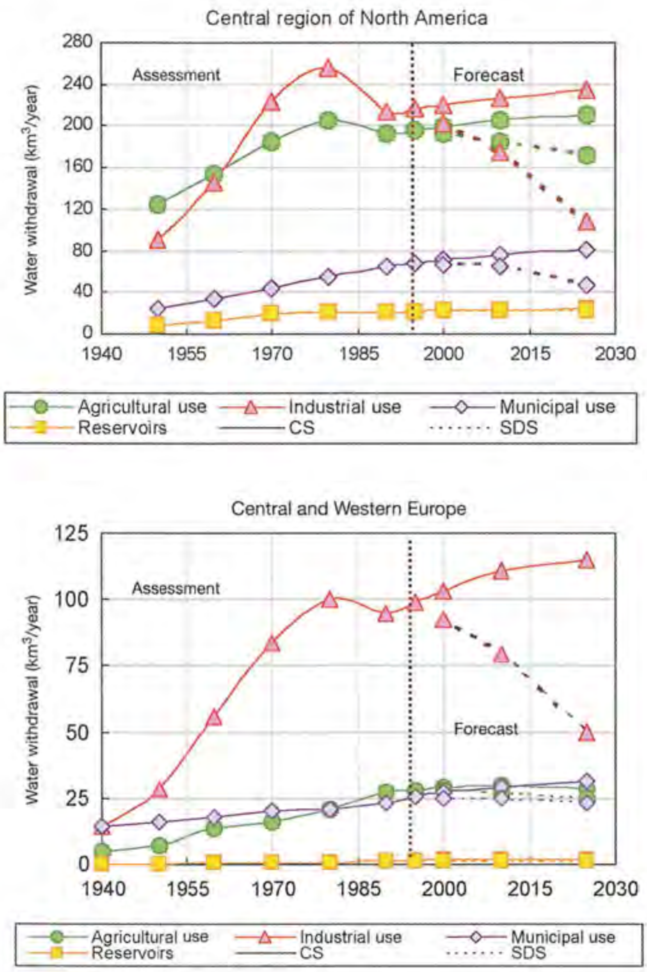


Figure 46—Dynamics of water use in the central region of North America and Central and Western Europe by kind of economic activity

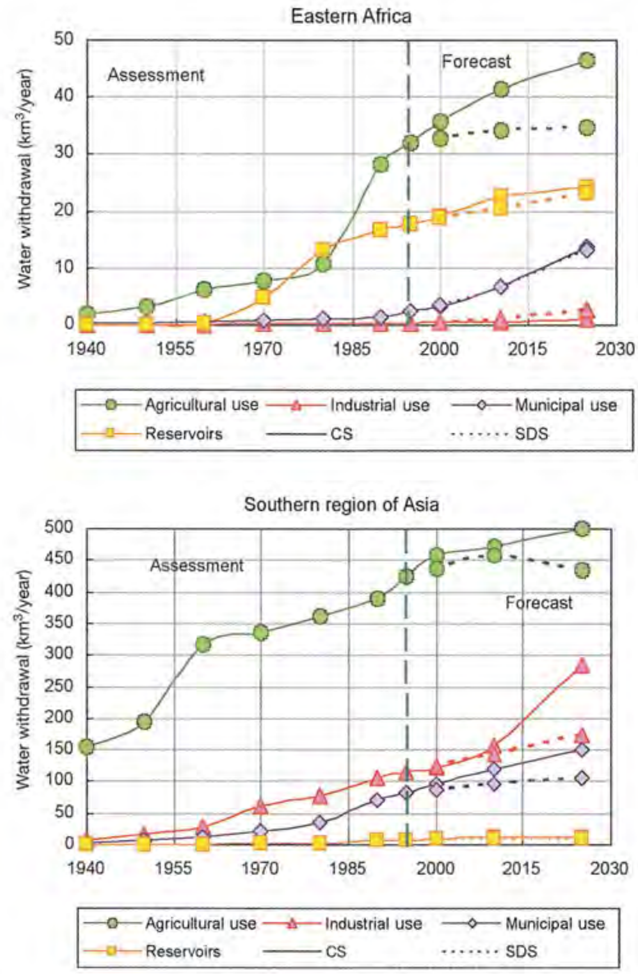


Figure 48—Dynamics of water use in Eastern Africa and the southern region of Asia

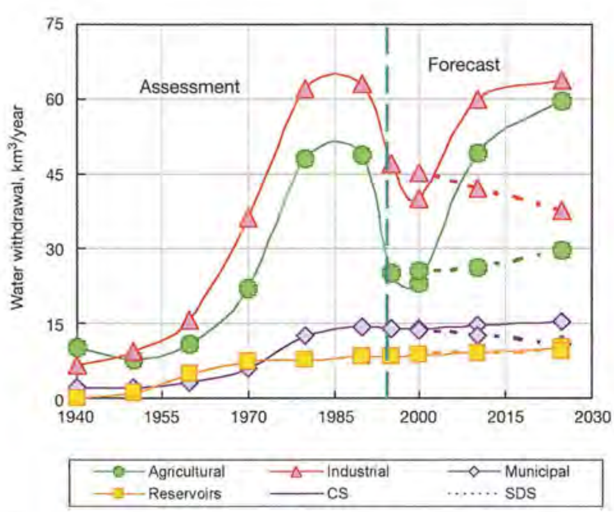


Figure 47—Dynamics of water withdrawal in the southern part of the FSU by kind of economic activity

(Yatsik and Khorev, 2000; Yatsik, 2001), and countries opening onto the Mediterranean basin (Margat and Vallee, 2000).

Table 23, taken from the EEA figures for 1999, gives data on water withdrawal trends in Europe by country for 1970–1980 and 1980–1985. The table shows that during the period 1970–1980 in practically every country except Belgium, there was a tendency for aggregate water withdrawal to rise. In the past 15 years, however, the situation has changed radically. In Greece, Spain, Italy, Hungary and Poland, for example, water use rose steeply in the period 1970–1980 (by 3–5 per cent per annum), yet thereafter in all countries the rise slackened noticeably, and in Finland, Netherlands, Spain, United Kingdom and Poland there was a significant retrenchment in water use. At the same time, in the EEA document (1999) one reason for the contraction in water use in Denmark, Finland and the United Kingdom was the series of droughts in the immediately preceding years, which created water supply difficulties and made it essential to bring in a range of freshwater savings use measures.

It should be noted that along with a general trend towards a fall in aggregate water use in Europe, for the

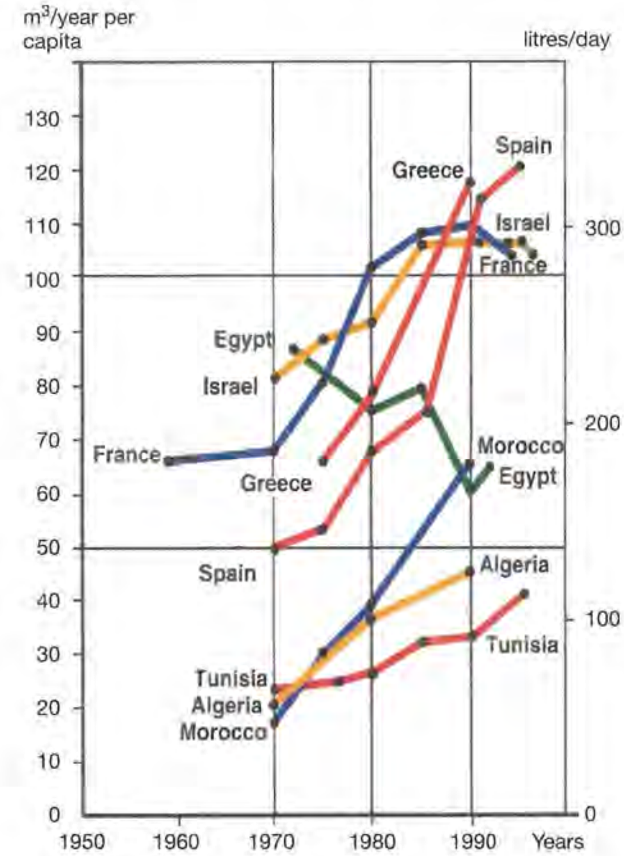
Country	Mean annual trend in total withdrawal (%)	
	1970–1980	1930–1995
Austria		0.2
Belgium	-0.5	
Denmark		-1.9
Estonia	0.5	
Finland	1.2	-2.9
France	4.1	1.1
Germany	2.9	0.8
Greece	5.0	
Hungary	1.9	4.9
Italy	3.0	0.0
Luxembourg		
Netherlands	1.1	-1.5
Norway		1.6
Poland	-1.1	3.4
Portugal	1.0	
Spain	-1.2	5.0
Sweden	-2.7	0.1
United Kingdom	-1.5	0.2

Table 23—Trend in total water withdrawal in countries of Europe (EEA, 1999)

past 15 years there has been a considerable growth in the areas of irrigated land. According to some findings (ETC/IW, 1998), between 1980 and 1995 the average rise was some 11 per cent in the countries of Western Europe, which increased the amounts of water drawn off for use in agriculture. In the same period in European countries there were also increases in water withdrawn for community use. According to the data (ICWS, 1996; IWSA, 1997) for 1980–1995, the figures in litres per day per capita for specific water use to meet the needs of the population rose in more or less every country of Western Europe, and for 1975–1990 this increase, so far as France, United Kingdom and Netherlands were concerned, was 22–27 per cent.

The rising trend in community water supply noted in the past few decades is characteristic not only of the highly developed countries of Europe, but equally of developing countries, which is borne out in Figure 49 for countries surrounding the Mediterranean Sea (Margat and Vallee, 2000). We should note that Figure 49 gives specific water withdrawal figures (in litres per day per capita). Given the fast population rises in the developing countries of North Africa (more or less doubling in the past 25 years), the increase in absolute values for community water use will be even greater.

Thus, the fall in aggregate water withdrawal in the world's advanced countries mainly occurred through savings in water use from industry and power generation. For example, industrial water use in France fell from 5.1 km^3 per annum in 1985 to 3.9 km^3 per annum in 1995, i.e. by 22 per cent. In the USA, industrial water use from 1980 to 1995 fell by 15 per cent (Gleick, 1998).



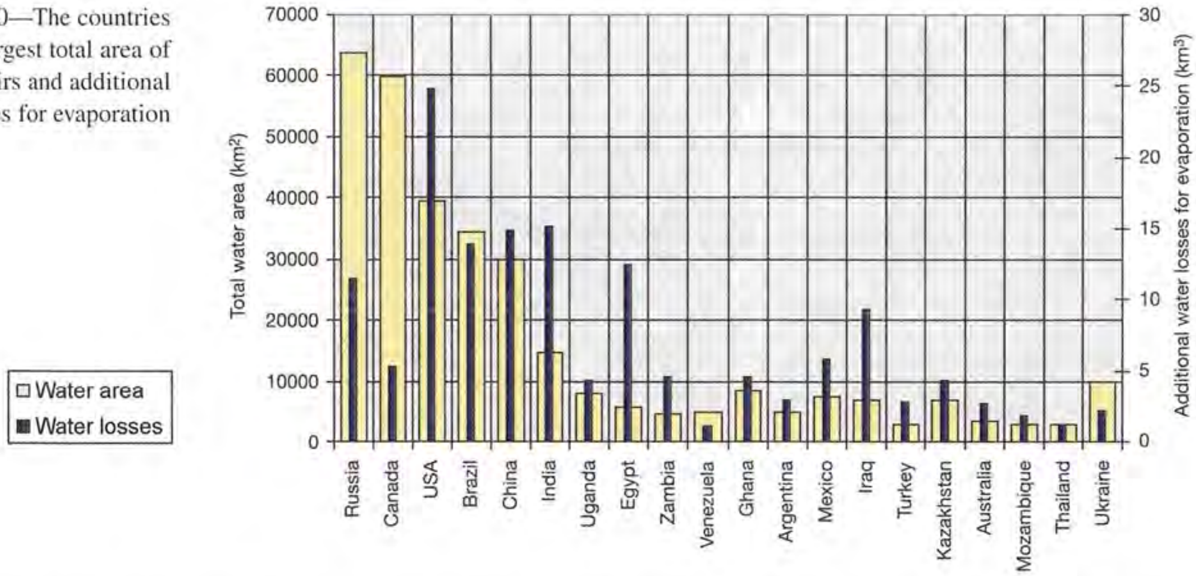
Figure—49 Changes in drinking water production per inhabitant in several countries over recent decades (in m^3/year and litres per day) by national sources

Here, community water use for the same period rose not only in absolute terms (by 22 per cent) but in specific water use per urban resident (from 685 to 705 litres per day); in Canada for the period 1980–1995 specific urban water use rose still more steeply (from 575 to 700 litres per day) (Shiklomanov, ed., 2003).

The declining trend in industrial water use can be explained in many different ways, one of them directly relating to increased efficiency and improved technology, while others relate to external factors governing the circumstances in which industrial activity is carried on. The former includes water use by new technologies with low water needs and the growing predominance of less thirsty branches of industry. The second may also include rising water costs, which forces companies to cut the amounts of water they draw off, as well as the strict controls and increased costs of disposing of industrial wastewater, as tools for reducing environmental pollution.

The amounts of fresh water drawn off by individual water users in the year 2000 (including additional evaporation losses from reservoirs) are given in Table 24 for 57 countries on every different continent. These are the same countries for which data on water resources and reservoir volumes are given in Figure 10 (section 3.6). The aggregate volume of water use in these countries, including evaporation losses from reservoirs, amounts to

Figure 50—The countries with largest total area of reservoirs and additional water losses for evaporation



81 per cent and that of water consumption to 83 per cent of total worldwide figures. According to the data provided, industry (including power generation) is the main water user (from 50 to 70 per cent of total water withdrawn) in developed countries in temperate climates. In almost all developing countries on every continent, and developed countries as well, with a noteworthy area of irrigated land (such as Japan, Italy, Spain or Greece), agriculture accounts for the greatest volume of water withdrawals (between 50 and 90 per cent).

The volume of water consumption, for more or less all countries of the world (except the most northerly: Finland, Norway and Sweden), is primarily determined by water evaporation losses from irrigated agriculture and the building of major dams. At the same time, for the largest countries of the world with advanced irrigation systems and considerable water consumption for community needs, industry and farming (USA, Canada, Russia, Brazil, Egypt and Australia), additional evaporation losses from reservoirs make up between 17 and 84 per cent of the total volume of water consumption (see Table 24). For some countries in Africa (Uganda, Ghana, Zambia and Mozambique), where the largest dams have been built, but where water use for different household and economic needs is insignificant, evaporation losses from reservoirs are very much greater than not only amounts of water consumption but also of the water withdrawal variety (see Figure 50). Naturally, the types of water loss referred to cannot be left out when calculating water management balance and availability for different countries and world natural-economic regions both now and in the future. The individual ways of identifying the dynamics of different forms of water withdrawal in developed and developing countries have been fully taken into account in working out these characteristics for different natural-economic regions to the year 2025 (Table 22).

Table 24—Water withdrawal, water consumption, total water area and additional evaporation losses from reservoirs in selected countries of the world in 2000

	Country	Area (mill. km²)	Water withdrawal (first line); water consumption (second line) (km³/year)				Total area of reservoirs (without flooded lakes), (km²)	Volume of additional losses through evaporation from reservoirs (km³)	Ratio of losses through evaporation from reservoirs to the volume of water use (%)	
			Municipal	Industrial	Agricultural	Total			Water withdrawal	Water consumption
1	2	3	4	5	6	7	8	9	10	11
Europe										
1	Austria	0.084	0.61	2.31	0.26	3.18	150	0.007	0.22	1.13
			0.06	0.35	0.21	0.62				
2	Finland	0.34	0.46	3.20	0.12	3.78	2 480	0.22	5.80	28.6
			0.06	0.61	0.10	0.77				
3	France	0.55	7.00	22.7	8.00	37.7	550	0.15	0.40	1.43
			0.70	3.20	6.60	10.5				
4	Greece	0.13	0.79	2.60	6.20	9.60	250	0.16	1.70	2.80
			0.10	0.47	5.22	5.80				
5	Italy	0.30	9.00	13.4	34.2	56.6	500	0.23	0.40	0.80
			0.79	1.70	26.7	29.2				
6	Netherlands	0.04	1.70	4.80	2.60	9.10	620	0.056	0.60	1.70
			0.19	0.97	2.10	3.30				
7	Norway	0.32	0.42	1.48	0.16	2.06	900	0.081	3.90	18.8
			0.05	0.23	0.15	0.43				
8	Russia	17.1	15.6	48.8	16.6	81.0	57 228	10.3	12.7	42.5
			3.50	6.40	14.3	24.2				
9	Spain	0.51	5.10	7.30	25.0	37.4	2 200	1.49	3.20	5.80
			0.59	0.78	19.0	20.6				
10	Sweden	0.45	1.10	1.90	0.30	3.31	613	0.055	1.70	7.40
			0.12	0.36	0.26	0.74				
11	Switzerland	0.04	0.74	2.36	0.14	3.24	140	0.006	0.19	1.10
			0.09	0.36	0.11	0.56				
12	Ukraine	0.60	3.60	9.90	5.50	19.0	9 800	2.21	11.6	27.6
			0.90	2.10	5.00	8.00				

1	2	3	4	5	6	7	8	9	10	11
North and Central America										
13	Canada	9.97	6.60 1.00	41.4 1.60	4.90 3.80	52.9 6.40	59 700	5.37	10.1	84.0
14	Costa Rica	0.05	0.15 0.02	0.26 0.04	1.30 0.91	1.71 0.97	270	0.06	3.50	6.20
15	Honduras	0.11	0.11 0.02	0.12 0.01	0.99 0.69	1.22 0.72	303	0.068	5.60	9.40
16	Mexico	1.96	8.27 1.77	20.2 1.77	63.4 40.7	91.9 44.2	7 200	5.83	6.30	13.2
17	USA	9.36	59.0 8.60	221 12.9	210 122	490 144	39 400	24.8	5.10	17.2
Africa										
18	Angola	1.25	0.15 0.02	0.067 0.01	0.34 0.29	0.56 0.32	454	0.25	44.6	78.1
19	Cameroon	0.48	0.38 0.04	0.10 0.01	0.22 0.18	0.71 0.23	790	0.21	29.6	91.3
20	Côte d'Ivoire	0.32	0.38 0.05	0.12 0.01	0.74 0.56	1.24 0.62	2 575	0.93	75.0	150
21	Dem. Rep. Congo	2.34	0.60 0.07	0.07 0.02	0.17 0.10	0.84 0.19	651	0.23	27.4	121
22	Egypt	1.00	4.00 0.42	4.80 0.57	45.4 37.0	54.3 38.0	5 720	12.4	22.8	32
23	Ethiopia	1.22	0.79 0.08	0.10 0.01	2.90 2.20	3.80 2.30	280	0.46	12.1	20.0
24	Ghana	0.24	0.41 0.06	0.10 0.02	0.31 0.23	0.82 0.31	8 480	4.58	558	1 477
25	Kenya	0.58	0.94 0.15	0.14 0.015	1.91 1.53	3.00 1.70	265	0.21	7.00	12.4
26	Mali	1.24	0.11 0.015	0.016 0.003	1.69 1.26	1.82 1.28	930	1.00	55.0	78.1
27	Mozambique	0.80	0.12 0.018	0.01 0.002	0.79 0.59	0.92 0.61	2 922	1.84	200	302
28	Nigeria	0.92	2.35 0.35	0.65 0.06	2.37 1.54	5.38 1.95	2 120	1.34	25.0	68.7

1	2	3	4	5	6	7	8	9	10	11
Africa continued										
29	South Africa	1.22	3.20	1.70	9.6	14.5	1 280	1.15	7.90	13.5
			0.33	0.21	7.9	8.50				
30	Sudan	2.50	1.10	0.29	17.2	18.6	585	1.05	5.60	7.90
			0.21	0.053	12.9	13.2				
31	Uganda	0.24	0.31	0.04	0.28	0.64	8 000	4.32	675	1 800
			0.03	0.005	0.20	0.24				
32	Zambia	0.75	0.21	0.067	0.67	0.95	4 450	4.60	484	884
			0.03	0.01	0.48	0.52				
Asia										
33	Bangladesh	0.14	2.00	0.30	28.2	30.5	800	0.43	1.40	1.90
			0.42	0.04	21.5	22.0				
34	China	9.60	57.5	90.6	433	581	30 000	14.9	2.60	5.00
			5.70	13.5	282	301				
35	India	3.29	23.0	23.0	564	610	14 600	15.1	2.50	3.70
			3.20	2.40	396	402				
36	Indonesia	2.03	11.1	5.60	37.2	54.0	273	0.15	0.28	0.49
			1.70	0.60	28.6	30.9				
37	Iran	0.16	5.10	8.60	65.7	79.3	1 140	1.43	1.80	2.40
			0.65	0.94	57.4	59.0				
38	Iraq	0.44	1.27	0.55	53.3	55.1	6 900	9.32	16.9	21.7
			0.17	0.04	42.8	43.0				
39	Japan	0.38	15.3	30.3	43.0	88.6	380	0.034	0.04	0.08
			1.07	4.80	37.1	43.0				
40	Kazakhstan	2.72	0.70	4.30	20.0	25.0	6 950	4.38	17.5	22.9
			0.49	0.27	18.3	19.1				
41	Kyrgizstan	0.20	0.43	0.17	7.90	8.50	320	0.17	2.00	2.30
			0.10	0.10	7.30	7.50				
42	Malalaisia	0.33	3.70	4.50	6.20	14.4	886	0.40	2.80	8.70
			0.40	0.46	3.74	4.60				
43	Pakistan	0.80	2.50	1.80	176	180	790	1.07	0.43	0.60
			1.00	0.70	158	160				
44	Syria	0.18	0.87	0.36	10.4	11.6	670	0.78	6.70	9.50
			0.09	0.04	8.07	8.20				

1	2	3	4	5	6	7	8	9	10	11
Asia continued										
45	Tajikistan	0.14	0.50	0.40	10.1	11.0	820	0.63	5.70	9.1
			0.10	0.20	6.60	6.90				
46	Thailand	0.51	3.00	2.40	39.4	44.8	2 750	1.24	2.80	3.90
			0.44	0.25	30.7	31.4				
47	Turkey	0.77	6.30	3.60	25.1	35.0	2 780	2.75	7.80	12.9
			0.68	0.55	20.1	21.3				
48	Uzbekistan	0.45	3.00	1.50	70.5	75.0	1 120	0.96	1.30	4.60
			0.97	0.30	40.9	42.2				
49	Viet Nam	0.33	4.00	17.5	48.7	70.2	705	0.28	0.40	1.00
			0.57	2.10	24.4	27.1				
South America										
50	Argentina	2.78	3.80	7.50	26.6	37.9	4 969	2.90	7.60	13.4
			0.45	0.90	20.2	21.6				
51	Brazil	8.51	9.60	10.5	24.5	44.6	34 310	13.9	31.1	75.1
			1.10	1.20	16.2	18.5				
52	Chile	0.075	2.10	9.40	12.6	24.2	340	0.17	0.70	1.50
			0.28	1.00	9.8	11.1				
53	Colombia	1.14	2.90	0.90	2.60	6.40	609	0.11	1.70	4.40
			0.37	0.13	2.00	2.50				
54	Paraguay	0.41	0.30	0.10	0.42	0.82	1 758	0.79	96.3	188
			0.05	0.0	0.37	0.42				
55	Uruguay	0.18	0.28	0.05	5.04	5.37	1 390	0.44	8.20	23.3
			0.03	0.008	1.85	1.89				
56	Venezuela	0.92	3.05	2.30	4.20	9.60	4 955	1.11	11.6	35.8
			0.30	0.25	2.50	3.10				
Australia and Oceania										
57	Australia	7.68	2.80	7.30	14.8	24.9	3 362	2.72	10.9	21.9
			0.30	0.60	11.5	12.4				

Chapter 6

WATER RESOURCES, WITHDRAWAL AND AVAILABILITY; WATER RESOURCES SHORTAGES

For a general assessment of water resources in any given region (or country) in the present or future, it is usual to compare amounts of water use with the characteristics of available renewable water resources. Here, two criteria are employed:

- The coefficient of water resources use (or the stress on water resources) in relation to figures for water withdrawal and water resources is determined;
- Water availability in a given region is calculated by determining the per capita amount of fresh water available (making allowance for water use).

Both criteria are used by the Russian SHI to assess water resources by country and region for a lengthy medium-term future, including up to 2025.

To arrive at an objective definition of the water resources use coefficient *Kw*, not only must local water resources be somehow incorporated but also inflow from adjacent areas, together with water resources contraction in drought years.

As water resources used for calculating K_w, the present work takes figures for local resources as mean values for dry years (see section 3.5) combined with half the external water inflow; in a figure termed "actual water resources". Values for K_w, by region and continent and expressed in percentages for 1950, 1995 and 2025 (under both scenarios), are shown in Table 25. They vary over a very wide range, both in time and in particular by continent and region as well. As a whole, for the world in 1950 K_w amounted to 3.6 per cent, in 1995 it was 10 per cent, and in 2025 under the Conventional Scenario (CS), it will already be 13 per cent. For 1995 by continent, the value of K_w varied from 1.5 to 1.6 per cent for South America and Australia with Oceania up to 19 per cent for Europe and Asia; by region, values of the coefficient K_w vary very widely, from 0.2–0.7 per cent up to as much as 100–117 per cent. In extrapolations for 2005, under the Conventional Scenario for Europe and Asia the coefficient K_w will be as high as 23 and 27 per cent respectively, and will be especially high in the African and Asian regions.

Based on studies in different physical-geographical and socio-economic circumstances, according to UN/WMO/SEI (1997), and depending on the degree of water resources use or burden on them, to analyse the situation by region and country K_w can be classified as follows:

Category 1: K_w < 10 per cent: low level of stress on water resources; as a rule, regions do not have serious problems with available water resources (apart from pollution);

Category 2: K_w = 10–20 per cent: moderate level of stress on water resources. The level of water availability becomes a brake on development; investments are needed in order to improve water provision;

Category 3: K_w = 20–40 per cent: high level of stress on water resources. For regular development, supply and demand for water must be regulated. Water issues require special attention; major investments are needed, which in developing countries amount to a considerable portion of their GNP.

Category 4: K_w >40–60 per cent: very high degree of stress on water resources. Water is in serious deficit and there is a need to introduce extremely expensive non-traditional sources of water supply, regulation and limitation of water consumption. Water deficits become a factor holding back economic growth and rising living standards.

Category 5: K_w >60 per cent: a critical level of stress. Water deficits become a critical factor on the development of economic activity and human life-support systems. Urgent and decisive measures are required, as well as an allocation of the (very considerable) resources needed to deal with problems of water supply.

Following the above classification (according to data in Table 25) in 1950, the world was experiencing a relatively satisfactory situation in relation to water resources. There was no region of the world with a critical level of water resources stress; only one region experienced a stress level of the fourth category (40 per cent) and that was North Africa; the overwhelming majority of countries experienced a low or moderate level of stress. By 1995, the situation had undergone a sea change, and many of the thickly populated regions of the world were experiencing high or critical levels of stress on their water resources.

Analysing the categories of region by levels of stress on their water resources, it is important to note that on every continent except South America, on the one hand there are regions where the degree of water resources use is extremely high, and on the other there are regions where water withdrawal is insignificantly low (see Table 25). For example, in the southern and central parts of Europe, present-day water withdrawal already amounts to 35–45 per cent of active water resources, whereas in the northern part of the continent the figure is no more than 2 per cent. In the more northerly parts of North America, water withdrawal is only 1.2 per cent of water resources, but for the continental United States

Table 25—Comparison of water withdrawal with renewable water resources by natural-economic region of the world

Number of region	Continent, region	Area (mill. km^2)	Water resources (km^3/year)				Water resources (km^3/year)			K_w* (%)			
			Inflow	Average	Local		1995	2025		1950	1995	2025	
					Low	Actual		CS	SDS			CS	SDS
	Europe	**10.46**		**2 900**	**2 441**	**2 441**	**457**	**559**	**353**	**5.6**	**19.0**	**23.0**	**14.5**
1	Northern	1.32		705	580	580	11.0	13.4	7.3	0.6	1.9	2.3	1.2
2	Central	1.86	6	617	423	426	154	176	99.0	12.0	36.0	41.0	23.0
3	Southern	1.79	109	546	373	428	186	204	149	14.0	43.0	48.0	35.0
4	North European part of former USSR	2.71	27	589	497	511	10.8	16.8	10.2	0.2	2.0	3.3	2.0
5	South European part of former USSR	2.78	123	443	337	399	95.0	149	87.0	5.0	24.0	37.0	22.0
	North America	**24.3**		**7 890**	**7 042**	**7 042**	**686**	**786**	**527**	**4.0**	**9.7**	**11.1**	**7.5**
6	Canada and Alaska	13.67	130	4 980	4 550	4 615	56.1	73.7	34.7	0.3	1.2	1.6	0.8
7	USA (without Alaska)	7.84	70	1 800	1 390	1 425	503	550	351	17.4	35.0	38.0	25.0
8	Central America and Caribbean	2.74	2.5	1 110	969	970	127	162	141	2.6	13.0	17.0	15.0
	Africa	**30.1**		**4 050**	**3 340**	**3 340**	**219**	**337**	**292**	**1.7**	**6.6**	**10.1**	**8.7**
9	Northern	8.78	140	41	24	94	110	145	124	46.0	117	154	132
10	Southern	5.11	86	399	309	352	27.3	44.8	35.8	2.0	8.0	13.0	10.0
11	East	5.17	26	749	622	635	52.6	85.7	73.7	0.6	8.3	13.5	12.0
12	West	6.96	30	1 088	623	638	26.5	52.4	50.7	0.4	4.1	8.0	8.0
13	Central	4.08	80	1 770	1 510	1 550	2.6	9.2	7.6	0.02	0.1	0.6	0.5
	Asia	**43.5**		**13 510**	**11 879**	**11 879**	**2 230**	**3 255**	**2 487**	**7.1**	**18.8**	**27.4**	**21.0**
14	North China and Mongolia	8.29		1 029	597	597	268	372	301	15.5	45.0	62.0	50.0
15	Southern	4.49	300	1 988	1 592	1 742	887	1 339	991	21.0	51.0	77.0	57.0
16	Western	6.82		490	275	275	249	356	277	33.0	91.0	129	100
17	South East	6.95	120	6 646	5 609	5 669	631	949	722	3.9	11.0	17.0	13.0
18	Central Asia and Kazakhstan	3.99	46	181	130	153	154	182	155	37.4	100	119	100
19	Siberia and Far East of Russia	12.76	218	3 107	2 773	2 882	21.0	30.4	21.1	0.2	0.7	1.0	0.7
20	Transcaucasia	0.19	12.1	68	52.5	65	20.4	26.4	20.3	17.5	31.0	41.0	31.0
	South America	**17.9**		**12 030**	**10 690**	**10 690**	**167**	**260**	**201**	**0.5**	**1.6**	**2.4**	**1.9**
21	Northern	2.55		3 340	2 645	2 645	24.1	38.3	31.2	0.2	1.0	1.4	1.1
22	Eastern	8.51	1900	6 220	5 260	6 210	49.0	87.6	65.7	0.05	0.8	1.4	1.0
23	Western	2.33		1 720	1 070	1 070	48.0	65.0	52.4	2.5	4.5	6.1	5.0
24	Central	4.46	720	750	570	930	46.0	69.2	52.0	1.4	5.0	7.4	5.6
	Australia and Oceania	**8.95**		**2 404**	**1 999**	**1 999**	**30.4**	**40.0**	**29.0**	**0.5**	**1.5**	**2.0**	**1.5**
25	Australia	7.68		352	282	282	27.1	35	25.0	3.5	10.0	12.0	9.0
26	Oceania	1.27		2 050	1 625	1 625	3.3	4.5	4.1	0.02	0.2	0.3	0.25
	World (rounded)	**135**		**42 780**	**39 900**	**39 900**	**3 789**	**5 237**	**3 889**	**3.5**	**9.5**	**13.0**	**9.7**

*K_w = (Water withdrawal/actual water resources) × 100%

(excluding Alaska), the figure is as high as 35 per cent. There is a still more striking contrast in Africa and Asia. In North Africa, at the present time renewable water resources are fully taken up, whereas in other regions (Central Africa in particular) water use is insignificantly small by comparison with water resources. In such parts of Asia as Southern and Western Asia, Central Asia and Kazakhstan, there are very high coefficients of water resources use (K_W = 51–100 per cent), whereas in the region that includes Siberia and the Russian Far East, the coefficient is no more than 1 per cent.

Only in South America in all regions is there a low level of water use, no more than 1–5 per cent.

The prospects to 2025, if water use develops under the Conventional Scenario, indicate that there will still be unevenness in the distribution of water withdrawal, and this will become still more acute. In many regions where present use of water resources is already on the high side, and the future will see even greater withdrawal rates, which will reach critical levels while in northern areas and regions that are excessively wet, water use will form a very inconsiderable portion of water resources, as in the past.

Table 26, based on the data in Table 25, shows the distribution of the world population living in regions with differing levels of stress on water resources for 1950 and 1995, and according to forecasts down to 2025, based on the two different scenarios for development of water use.

Whereas in 1950 76 per cent of the population enjoyed a comfortable water resources situation ($K_W < 20$ per cent) and there was no critical situation ($K_W > 60$ per cent) in any region, by 1995 more than 40 per cent of the world's population (2 360 million, at the time) were already living in situations of extremely or critically high levels of stress on water resources.

The future world situation under the Conventional Scenario looks even grimmer, and we may be fully justified in speaking of a worldwide freshwater catastrophe. According to that scenario, by 2025 40 per cent of the world population, i.e. 3 100 million people, will be living in a critical water resources situation ($K_W >$ 60 per cent). But that is just the quantitative dimension; when there is such a high level of stress on water resources, as a rule water quality drastically deteriorates as a result of pollution, there is a degradation of the natural environment, rising morbidity and mortality from waterborne diseases.

The level of stress on water resources cannot fully describe a water resources deficit in any given region, as it does not directly take account of population size. To assess the state of water resources and availability of water, therefore, one indicator is specific water availability, taken to mean the amount of available fresh water per capita.

Specific water availability is usually calculated by dividing medium-term (in years) values for renewable water resources by population size. In the author's opinion, this method is not precise enough, since only average potential natural water availability can be assessed in this way, which is always exaggerated by comparison with the real world. First of all, no allowance is made for the fact that some of the water is already irretrievably lost through economic and industrial activity, and secondly, in some years and periods, water resources are much lower than the average. To allow for these facts, the studies by the SHI for each region analyse so-called specific actual water availability which is defined as follows: actual water resources minus water consumption, divided by population size. In so doing, actual water resources are assessed by active runoff in dry years by comparison with inflow from elsewhere (see Table 25).

In this way, specific actual water availability indicates the remaining amount of water (after use) per capita during dry periods. Naturally, as population size and non-return water use rise, specific water availability will fall.

The values for specific water availability have been calculated at the SHI for all natural-economic regions and selected countries from 1950 to 1995 and for the future up to 2025. The main results for these calculations are given in Table 27. In 1950, specific water availability for the world's population was put at 15 200 m^3 per annum, but by 1995 it had shrunk by 230 per cent, to 6 600 m^3 per capita per annum. As expected, water availability varies widely by continent and especially by natural-economic region.

For example, the highest specific water availability figures in 1995, 140 000–160 000 m^3 per capita per annum, were for two regions: Canada and Alaska, and

K_w (%)	*Population*							
	1950		*1995*		*2025*			
					CS		*SDS*	
	Mill.	%	Mill.	%	Mill.	%	Mill.	%
≤ 10	1 197	46.4	1 032	18.1	1 236	15.7	1 412	17.9
11–20	752	29.1	1 582	27.7	2 587	32.8	2 411	30.6
21–40	580	22.5	722	12.7	426	5.4	936	11.9
41–60	51.4	2.0	1 914	33.6	510	6.5	2 363	30
> 60	0	0	451	7.9	3 118	39.6	755	9.6
Σ	2 580	100	5 700	100	7 877	100	7 877	100

Table 26—Population of the Earth by region with different rates of water resources use

Table 27—Actual water availability by continent, natural-economic region of the world (in 1 000 m3/ year per capita) in 1950, 1995, 2025

Number of region	*Continent, region*	*Population (mill.)*		*Actual water resources (km3/year)*	*Water consumption (km3/year)*			*Actual water availability (1 000m3/year per capita)*			
		1950	*1995*		*1995*	*2025*		*1950*	*1995*	*2025*	
						CS	*SDS*			*CS*	*SDS*
	Europe	**684**	**684**	**2 441**	**189**	**256**	**201**	**4.61**	**3.3**	**3.2**	**3.3**
1	Northern	23.2	23.4	580	2.9	3.9	3.3	32.0	24.9	24.6	24.6
2	Central	293	298	426	40.8	51.7	44.2	1.9	1.3	1.26	1.28
3	Southern	188	193	428	107	117	101	2.8	1.7	1.6	1.7
4	North European part of former USSR	28.5	25.6	511	1.9	5.0	4.4	24.3	17.8	19.7	19.8
5	South European part of former USSR	151	144	399	37.2	77.8	47.7	3.4	2.4	2.2	2.4
	North America	**453**	**562**	**7 042**	**237**	**269**	**223**	**31.8**	**15.0**	**12.0**	**12.13**
6	Canada and Alaska	29	31.0	4 615	11.0	15.3	11.6	332	159	148	148.5
7	USA (without Alaska)	261	282	1 425	163	177	144	8.8	4.8	4.42	4.54
8	Central America and Caribbean	163	249	970	63	77	67	18.4	5.6	3.58	3.63
	Africa	**710**	**1 503**	**3 340**	**160**	**220**	**182**	**15.1**	**4.5**	**2.07**	**2.1**
9	Northern	157	258	94	79.8	97.2	82.6	1.24	0.09	0	0.04
10	Southern	84	154	352	20.2	30.8	23.2	12.4	4.0	2.08	2.14
11	East	194	454	635	38.6	56.3	47.4	11.8	3.1	1.27	1.29
12	West	211	492	638	19.9	32.3	26.2	9.7	2.9	1.23	1.24
13	Central	64	145	1 550	1.6	3.5	2.5	75.2	24.2	10.6	10.7
	Asia	**3 498**	**4 626**	**11 879**	**1 381**	**1 876**	**1 470**	**7.5**	**3.0**	**2.16**	**2.25**
14	North China and Mongolia	487	563	597	143	187	155	2.4	0.93	0.73	0.78
15	Southern	1 239	1 800	1 742	611	856	634	3.1	0.91	0.49	0.62
16	Western	239	418	275	184	248	194	2.9	0.38	0.06	0.19
17	South East	1 419	1 708	5 669	319	421	344	8.4	3.8	3.07	3.12
18	Central Asia and Kazakhstan	55	79.0	153	102	132	116	6.4	0.93	0.26	0.47
19	Siberia and Far East of Russia	42	39.0	2 882	10.5	15	11.9	112	68.4	73.5	73.6
20	Transcaucasia	16.6	19.0	65	12.8	18.7	15.0	7.2	3.1	2.4	2.63
	South America	**326**	**465**	**10 690**	**89.4**	**120**	**99**	**96.9**	**32.5**	**22.7**	**22.8**
21	Northern	59.3	89.0	2 645	12.1	16.8	13.7	155	44.4	29.5	29.6
22	Eastern	165	232	6 210	25.4	36.4	32.0	119	37.5	26.6	26.63
23	Western	50.2	72	1 070	25.3	32.3	26.0	61	20.8	14.4	14.5
24	Central	51.5	72	930	26.6	35.0	26.8	39	17.5	12.4	12.5
	Australia and Oceania	**29.7**	**37.0**	**1 999**	**17.5**	**22.3**	**18.8**	**169**	**66.7**	**53.4**	**53.5**
25	Australia	17.9	22	282	15.4	19.7	16.5	33.8	14.9	11.9	12.1
26	Oceania	11.8	15	1 625	2.1	2.6	2.3	451	138	108	108.2
	World (rounded)	**5 701**	**7 877**	**39 900**	**2 070**	**2 220**	**2 190**	**15.2**	**6.6**	**4.78**	**4.79**

Oceania. At the same time, in the densely populated regions of Asia, Central and Southern Europe, this indicator was in the 1 000–4 000 m^3 per capita per annum range. In North Africa and the Arabian Peninsula, the indicator was no higher than 100–300 m^3 per capita per annum.

It should be noted that water availability of less than 2 000 m^3 per capita per annum is considered to be very low, and figures of less than 1 000 m^3 per capita per annum is catastrophically low. With such figures, there are bound to be grave problems to do with the community supply of high quality water, the development of industry and agriculture, and environmental conservation.

In analysing data by region and country, we should take the following sliding scale for specific water availability, in thousands of m^3 per capita per annum:

- < 1.0 : catastrophically low;
- 1.01 – 2.0 : very low;
- 2.01–5.0 : low;
- 5.01 – 10 : moderate;
- 10.01 – 20 : high;
- > 20 : very high.

Table 28 shows the distribution of population living in regions with different water availability levels for the years 1950, 1995 and 2025 (under the two SHI scenarios).

In 1950, only 11 per cent of the world's population lived in regions with very low water availability and there was no region of the world where the availability was catastrophically low. By 1995, the situation had changed radically for the worse: in many regions of the world (see Table 27), water availability had dropped to catastrophically low levels in North Africa and the Arabian Peninsula, Northern China, Southern and Western Asia, Central Asia and Kazakhstan. At present, 47 per cent of the world's population live in situations where specific water availability is either catastrophically low or very low (less than 2 000 m^3 per capita per annum) (Table 28).

The situation will deteriorate still further in coming decades. Already in nearly half the regions of the world specific water availability will be lower than or close to 2 000 m^3 per capita per annum, and in four regions it will be less than 500 m^3 per capita per annum (Table 27). From the data in Table 28, by the year 2025 it appears that the majority of the world's population (58 per cent) will be living in regions with very low or catastrophically low water availability, and 40 per cent or 3 120 million will have water availability lower than 1 000 m^3 per annum., i.e. catastrophically low availability of water (Table 28). Still worse, under the Conventional Scenario, more than 2 500 million of the world's population will have an average water availability lower than 500 m^3 per capita per annum. At the same time for all calculation levels, including future forecasts, very high specific water availability will continue to prevail in Northern Europe, Canada and Alaska, Central Africa, Siberia and the Russian Far East, Oceania and almost all of South America.

To find the scale of the future world water resources deficit, it is extremely important to analyse the trends and rates of specific water availability as a function of different factors. Analysis of data obtained by natural-economic regions of the world and by country shows that rates of deterioration in water availability depends on two main factors: the socio-economic development of countries and climatic conditions prevailing in any given region. This is convincingly shown by the graphs in Figure 51, which give the dynamics of specific water availability from 1950 to 2025 in relative units (in relation to 1950 levels) averaged out over three groups of regions, including:

- Industrially developed countries;
- Developing countries with enough or excessive precipitation;
- Developing countries with arid or semi-arid climates.

According to Figure 51 for regions which mainly include industrially developed countries, the fall in specific water availability has been relatively low, irrespective of climate and water resources and, for the period under consideration (1950–2025), will have risen by 170 per cent, 70 per cent of this figure during the period down to 1995. For regions that include mainly developing countries, the falls in specific water availability have been much more dramatic, and for the same period in areas of adequate or excessive precipitation they have shown an average fall of 4.5 times and 7–8 times in arid and semi-arid climates.

Water availability, ($10^3 m^3$/year per capita)	*Population*							
	1950		*1995*		*2025*			
					CS		*SDS*	
	Mill.	%	Mill.	%	Mill.	%	Mill.	%
< 1	-	-	2 177	38.2	3 118	39.6	3 118	39.6
1.1–2.0	273	10.6	481	8.4	1 437	18.2	1 437	18.2
2.1–5.0	1 047	40.6	2 337	41.0	2 556	32.4	2 556	32.4
5.1–10	906	35.1	163	2.8	-	-	-	-
11–20	134	5.2	98	1.7	337	4.3	337	4.3
> 20	221	8.5	445	7.9	429	5.5	429	5.5
Σ	2 580	100	5 700	100	7 877	100	7 877	100

Table 28—Population of the Earth by region with different water availability

Thus, with the passage of time the enormous natural disparities occurring in world water availability are growing ever wider, and accelerating, both for economic reasons and because of the way populations are growing in developed and developing countries.

The analysis made in this chapter of the water resources situation under two criteria (level of stress on water resources and specific water availability) has made it possible to reach more or less identical and extremely ominous conclusions. In the last few decades, the level of stress on water resources has been rising very steeply and water availability has been falling fast, particularly in developing countries. By now, more than 40 per cent of the world's population already live in conditions where the stress on water resources is far too great and water availability is exceptionally low, where water shortage governs economic development and acts as a brake on improving living conditions.

Looking to the coming two to three decades, if the freshwater use in the world remains at present levels (Conventional Scenario), most of the world's population will be living in a critical water resources and availability situation, i.e. there are very good grounds for speaking of a looming world freshwater catastrophe.

In the author's opinion, the outstanding issue in the short-term for decision makers, politicians, scientists and the general public, is not to allow world freshwater use to continue following the same model as in recent decades (i.e. the Conventional Scenario), since it may lead to catastrophic consequences in providing for the lives of most of the world's population.

It should be noted that the tables referred to above, tables 25–28 and Figure 50, on changes in the stress on water resources and specific water availability, are based on average data for major natural-economic regions of the world, where there are a large number of different countries. Naturally, more precise assessments can be obtained on a country basis and even for individual districts within different major countries, but this cannot be done at present, since reliable and comparable data cannot be obtained for water resources and water use in every country (see sections 3.6 and 5.7).

A test run at the Russian SHI for more 60 countries on all continents fully supported the trend for natural economic regions given in tables 25–28 and Figure 51 (Shiklomanov, ed., 1997, 2003). Specifically, industrially developed countries in areas with varying amounts of precipitation have relatively low rates of falling specific water availability, whereas developing countries, in particular those in parts of the world where there is not enough precipitation, low natural specific availability and very high rates of deterioration as a result of steep population rises and growing amounts of water consumption. Many such countries will reach critical levels of true water availability as early as in the coming decade.

The quantitative characteristics of stress on water resources and specific water availability given in Tables 25 and 27 for each region, naturally cannot be ascribed to every country in a given region. In different regions, mainly as a function of natural features and population numbers, there may be countries where water availability is either considerably worse or better off than the average.

For example, in Asia, in the Central Asia and Kazakhstan Region, there is a generally exceptionally worrying situation with regard to water resources, but in some countries in the region, such as Kyrgyzstan and Tajikistan, both of them in mountainous areas, there is so far little stress on water resources and high specific water availability. Yet both Uzbekistan and Turkmenistan have catastrophically low water availability. In the West Africa Region, on average, specific water availability is low, yet in smaller countries such as Gambia and Guinea-Bissau, specific water availability is 4–5 times more than the average for the region. Similar situations may also apply elsewhere.

Special approaches to the assessment of water availability are needed in very wealthy economically developed countries on the Arabian Peninsula where, unlike other countries, available water resources are constantly rising in quantity through the intensive use of deep-lying non-renewable groundwater reserves and the introduction of so-called non-traditional sources of fresh water, in particular through desalination of brackish and salt water. This is because the extremely scant runoff in

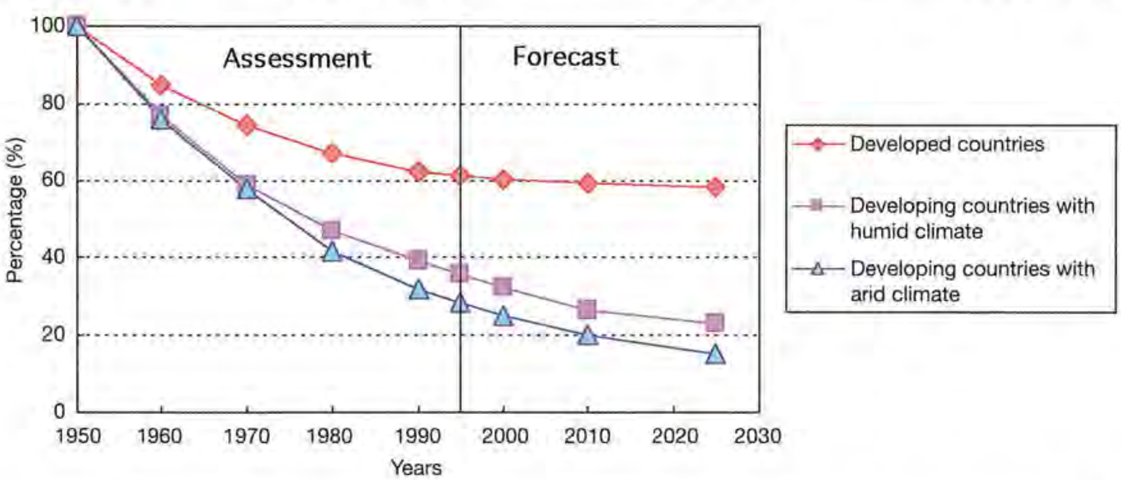


Figure 51—Dynamics of specific water availability for three groups of regions of the world, 1950–2025

these countries is already practically entirely exhausted, and these countries' fast economic growth, population increases, and rising living standards all foster a demand for constantly rising water use. Since there are enough funds available, the countries of the Arabian Peninsula can meet rising water needs by bringing in such extraordinarily expensive non-conventional sources of fresh water, but that is not available to the bulk of other countries in arid or semi-arid regions.

Table 29 gives figures for overall conventional and unconventional water resources, water withdrawal and water consumption, along with specific water availability for countries of the Arabian Peninsula from 1980 to 2025. They are based on reviews from numerous publications (Proceedings of Symposium on Water Resources and Utilization in the Arab World, 1986; ALECSO, 1992; UN/DPCSD, 1995; UNESCO, 1995, etc.) and forecast assessments conducted.

Country	*Characteristic*	*Design level*					
		1980	*1990*	*1995*	*2000*	*2010*	*2025*
Saudi Arabia	Water resources	3.69	17.6	21.0	24.4	27.9	32.8
	Total water withdrawal	2.36	16.3	19.7	23.1	26.6	31.5
	Water consumption	1.65	12.8	15.2	17.7	19.1	21.0
	Water availability	0.218	0.328	0.335	0.342	0.331	0.624
Yemen	Water resources	3.75	4.94	5.30	5.67	6.40	7.88
	Total water withdrawal	1.70	2.89	3.18	3.47	4.35	5.83
	Water consumption	1.39	2.19	2.16	2.12	2.57	3.62
	Water availability	0.394	0.235	0.28	0.326	0.260	0.151
United Arab Emirates	Water resources	0.685	1.119	1.376	1.634	2.210	2.833
	Total water withdrawal	0.610	1.044	1.302	1.559	2.135	2.980
	Water consumption	0.486	0.826	1.072	1.317	1.452	1.894
	Water availability	0.714	0.443	0.439	0.435	0.424	0.403
Oman	Water resources	1.308	1.441	1.570	1.698	1.973	2.593
	Total water withdrawal	0.665	0.798	0.926	1.055	1.330	1.950
	Water consumption	0.561	0.621	0.666	0.712	0.840	1.031
	Water availability	0.759	0.538	0.518	0.499	0.439	0.329
Kuwait	Water resources	0.186	0.383	0.512	0.640	1.071	1.721
	Total water withdrawal	0.186	0.383	0.512	0.640	1.071	1.721
	Water consumption	0.049	0.099	0.124	0.148	0.199	0.264
	Water availability	0.100	0.132	0.148	0.164	0.231	0.385
Bahrain	Water resources	0.138	0.225	0.266	0.306	0.365	0.425
	Total water withdrawal	0.138	0.225	0.266	0.306	0.365	0.425
	Water consumption	0.084	0.118	0.122	0.126	0.132	0.138
	Water availability	0.156	0.213	0.236	0.260	0.273	0.287
Qatar	Water resources	0.128	0.250	0.270	0.290	0.349	0.475
	Total water withdrawal	0.128	0.250	0.270	0.290	0.349	0.475
	Water consumption	0.102	0.102	0.122	0.143	0.160	0.196
	Water availability	0.116	0.347	0.302	0.258	0.262	0.324
Arabian Peninsula as a whole	Population	19.3	32.7	35.8	38.9	51.3	86.0
	Water resources	9.88	26.0	30.3	34.6	40.3	48.7
	Total water withdrawal	5.79	21.9	26.2	30.4	36.2	44.9
	Water consumption	4.32	16.8	19.6	22.3	24.4	28.1
	Water availability	0.288	0.281	0.300	0.318	0.308	0.239

Table 29—Total water resources, water withdrawal and water consumption (km^3/year) and water availability (1000 m^3/year per capita) for the countries of the Arabian Peninsula

The water resources in the table include surface flow from permanent and intermittent watercourses, water reserves in aquifers close to the surface, water withdrawn from deeper-lying water-bearing strata, and fresh water from the desalination of saline and brackish waters. The modern level of water resources and water use has been established from reviews in numerous publications, and the forecast assessments made with allowance being made for national strategies for water policy, financial and labour resources. Here, the chief priorities are the availability of drinking water to the community and the development of technologies that presuppose a more economic use of fresh water.

The data in the table show the increase in available water resources which in several countries (Kuwait, Bahrain and Qatar, for example) may even considerably outstrip population growth and water use. As a result, for the countries of the Arabian Peninsula as a whole, despite the great rise in population, a stabilization and even some rise in specific water availability is to be expected at some periods. All this obviously requires enormous expenditure. But, in absolute figures nevertheless, specific water availability in these countries remains catastrophically low (less than 500 m^3 per capita per annum), which calls for exceptionally economic use of fresh water in all spheres of the economy and community lifestyles.

Chapter 7

WORLD WATER RESOURCES IN THE EARLY TWENTY-FIRST CENTURY, GIVEN IMPROVED EFFICIENCIES IN FRESHWATER USE*

Analyses of trends in world water use during the twentieth century, and an assessment for its future condition up to the year 2025 under the Russian SHI's Conventional Scenario, produced results published by international organizations in the years 1997–1998 (Shiklomanov, ed., 1997; Shiklomanov, 1998), that were widely quoted in papers presented by Russian scientists attending the International Conference on World Water Resources, "Water: a looming crisis?", held in Paris, 3–6 June 1998 (UNESCO, 1998).

The data convincingly pointed out the critical present-day water availability situation in many regions and countries, mainly in developing countries. It is impossible to carry on developing the Conventional Scenario water use pattern if there are to be no catastrophic consequences on most of the world's population.

The Conference literature underscored the pressing need to adopt a range of urgent measures to improve the efficiency of freshwater use by all users, protect bodies of water from exhaustion or pollution, and find additional sources of water. The literature showed how sensible it would be for every country (region) to develop concepts and strategies for water resources management, an integrated long-term programme of specific measures to reach the goal of meeting long-term water availability with a steady development of economic development and rising living standards.

The need to improve the state of world water resources has led in recent years to various authors making long-term water use forecasts (scenarios) to 2025 for different regions or worldwide (Rijsberman, 2000). All the scenarios are based on population size and economic development forecasts, and presuppose the use of more efficient freshwater use technologies by different users. However, different authors adopt different degrees of sophistication of freshwater use technology. Some authors use extremely modest (but realistic) assessments of future technological improvements, that are based on progressive trends in past years, make allowance for the financial and feasible material resources available to different countries, both developed and developing, and are also based on how useful it is to engage in such exceptionally expensive measures.

Others promote extremely optimistic scenarios that presuppose sharp falls in aggregate world water use, and are based on obviously unreal hypotheses that fail to take account either of the capacities or the true interests of different countries and regions.

* This chapter was written jointly with Dr Zh. A. Balonishnikova, Candidate of Hydrological Science.

7.1 SCENARIOS UNDER "THE WORLD WATER VISION PROJECT"

At the end of June 1998 under the long-term World Water Vision Project, a Scenario Development Panel (SDR) was convened, with terms of reference that included the collection of data and the development of scenarios on future world water resources. In 1999–2000, basic data on water resources and their use for 1995 drawn up by the Russian SHI were used by the Panel members as the groundwork for three freshwater use scenarios for the period 1995 to 2010 and 2025; the three scenarios were dubbed respectively the Business-As-Usual (BAU), Technology, Economics and Private Sector (TES) and Values and Lifestyles (VAL) scenarios. The water use assessments of the scenarios for major regions and the world as a whole were presented in March 2000 to the Second World Water Forum at The Hague (Netherlands) and published in Rijsberman, ed. (2000).

The BAU scenario is based on the following hypotheses for the year 2025:

- The world population reaches 8 billion by the year 2025;
- Irrigated land in all countries of the world remains at more or less its 1995 levels; increases to 2025 amount to 6.8 per cent but only in India, Turkey and Brazil, which will give a global increase of 1.5 per cent; the efficiency of water use in agriculture rises by 0.3 per cent a year (with variations depending on the country concerned);
- Community water use (per capita per day) grows but then stabilizes as incomes rise; efficiency increases by 2 per cent per annum. until 2005, and thereafter by 1 per cent every year;
- Industrial production grows from 0.8 per cent per annum in developed countries to 10 per cent per annum in developing countries with low incomes; water use efficiency rises by 2 per cent per annum to 2005, thereafter by 1 per cent per annum.

Under the BAU scenario, by 2025 overall world water use will be 4 300 km^3 per annum, i.e. a 13 per cent rise since 1995. At the same time, there will naturally be a fall (of about 8 per cent) in agricultural water use but industrial water use will rise by 20 per cent but community water use will rise by 2.5 times. Moreover, the growth in community use is expected in developed as well as in developing countries.

In the author's view, hypotheses in the BAU scenario that there would be a complete end to the spread of irrigated land in the world are unrealistic, do not meet the interests of most countries and are simply unworkable technologically. In many countries, irrigated lands are considered as spreading relatively rapidly (see Figure 32), new irrigation projects are being introduced, and there are plans for increasing irrigated lands in the future, not merely in traditional irrigation areas such as China, India, Pakistan, Egypt and Mexico (UNESCO, 1995; FAO, 1999, 2000; ESCAP, 2002), but in other countries too, including both those with highly limited water resources and in developed countries in Europe. For example, according to EAR (1999), between 1995 and 2010 it is planned to increase irrigated land in the countries of Western Europe by an average of 10 per cent. There is also room for doubt about the very high rise in world community water use in this scenario, which is projected to exceed more than twice growth rates for the preceding 15 years, which is very unlikely.

The TES scenario is based on the following key premises up to 2025:

- World population 7.9 billion;
- Increase of 23 per cent in irrigated land, with variations ranging from -24 per cent (Saudi Arabia) to +122 per cent (Brazil);
- Farming water use efficiency rises by between 10 per cent (developing countries with low incomes) to 20 per cent (other countries);
- Specific community water use falls by one third lower than the BAU scenario by 2025; until 2005, efficiency increases by 2 per cent per annum and after 2005 by 3 per cent per annum.
- As with the BAU scenario, industrial production grows until 2005, after 2005 by 0.2 per cent per annum in developed countries, and up to 15 per cent in developing countries with low incomes; water use efficiency is also expected to rise until 2005 as with BAO scenario, after 2005 rise by an annual 3 per cent.

The VAL scenario is based on the following key premises up to 2025:

- World population reaches 7.5 billion;
- A 5 per cent expansion of irrigated lands worldwide, ranging from -100 per cent (Saudi Arabia) to +56 per cent (Benin, Burkina Faso);
- Agricultural water use efficiency increases by 0.9 per cent per annum (less in countries where efficiency is high even today);
- Specific community water use falls by two thirds of the figure under the BAU scenario by 2025; efficiency increases by 2 per cent per annum;
- Up to 2005, industrial growth follows the BAU model but thereafter, depending on the country, change subsequently ranges from –0.2 per cent annually (Japan) to 15 per cent (East Africa); the rise in water use efficiency matches the BAU scenario until 2005, and later rises work out at 2 per cent per annum.

Under both the TES and the VAL scenarios, there is a 4 and 26 per cent fall, respectively, in total water use in the world by the year 2025. Moreover, under the TES scenario, agricultural water use stays more or less at 1995 levels (the expansion in irrigated land areas is compensated for by increased efficiency), but under the VAL scenario it falls by 22 per cent. Both scenarios promise a drastic diminution in industrial water use (of 40 per cent under the TES projections and 2.5 times under the VAL scenario), with a 14 per cent rise (in total volume) for community use under TES, while the VAL pattern remains the same (Rijsberman, ed., 2000).

Analysing the basic assumptions of the TES and VAL scenarios, and the results obtained by the present authors with their assessments of future water use by country and natural-economic region, the following conclusions may be drawn.

To all intents and purposes, the sharp brake on the worldwide expansion of irrigated land under the VAL model (a rise of only 5 per cent in 30 years) is, in the view of the present authors, absolutely unrealistic for the reasons given above; in any case, the latest data show them as having risen by 4 per cent by the year 2000, but it is not very realistic and would be equivalent to a 20–30 per cent increment in irrigation efficiency. This may be technically feasible, clearly, but would require such colossal expenditures (see Chapter 9) that they would not be within the capacity, either of poverty-stricken developing countries, or of countries with high incomes. Moreover, in many regions with adequate resources, it would not really be worth carrying out such expensive undertakings. We should note that from 1960 to 1995, global irrigation water efficiency only rose by 5 per cent, and in the United States by 16 per cent (Shiklomanov, ed., 2003).

The promised cutback in industrial water withdrawal in the highly developed countries of the world, the United States, Western Europe and Japan, of 2.5 to 3.3 times under the TES scenario and 3.3 to 5 times according to the VAL model seems totally unrealistic. We should note in this connection that in the USA from 1975 (when water savings systems began to be widely introduced in industry) to 1995, industrial water use fell by 14 per cent (Gleick, 1998), almost the same contraction rates occurred in Japan and various countries of Western Europe, yet in Canada for the same period, industrial water use grew by 30 per cent (EEA, 1999; Shiklomanov I.A. ed., 2003). Moreover, it is widely known what colossal efforts and huge financial investments were made in different countries to reduce water use, but generally speaking they achieved only insignificant results. It is also important to note that the above data (see Figure 29) for industrial water use in the United States show that the prospects for increasing the efficiency of water-savings technologies in different branches of industry, decline steeply with the passage of time. This means that the five-fold cutback in water use over the next 30 years that is claimed under the VAL scenario (despite an overall rise in industrial output) would seem highly improbable and economically unfounded.

The forecasts of lower community water use in developed countries under the TES scenario, and still greater falls under the VAL option, where specific indicators fall by 3–5 times, are also a matter of grave doubt, not only in terms of their usefulness but also of how feasible such a reduction would be. It is a known fact that at present the community withdraws about 600–700 litres per day per capita, and the equivalent figure for Japan is 330 litres. Under the VAL scenario, specific community water withdrawal for the year 2025 will be 177 litres per day in North America and in Japan 77 litres per day. These indicators were the same as those in the USA and Canada in the early twentieth century.

The data from some authors (Gleick, 1993, 1998) showed that, from the 1980s onwards, energetic water-saving measures were undertaken in many parts of the United States to reduce community water use. *Inter alia*, much more economic toilets and washing machines began to be widely marketed, and the watering of parks and gardens, yards, lawns and other urban open areas began using water-saving technologies, including the recycling of reconditioned waste water. Despite such measures, the amount of water used for community purposes never stopped rising: between 1980 and 1995 the rise was 21 per cent; simultaneously, specific (per capita) water use rose by some 4.5 per cent. A similar situation prevails in Canada and most other highly developed countries (see section 5.7). Given this fact, in the opinion of the authors it is not realistic to hope for very steep cuts in community water use in developed countries, and it is not really likely to be in their interests. In any case, there is much doubt about the soundness of such measures, for example, in the northern parts of North America where excess water is an outstanding characteristic.

It is for these reasons that the present authors consider the three global water use scenarios developed by the International Panel of Experts (BAU, TES and VAL) are based on hypotheses that are poorly grounded and unreal, and that the 2025 figures are more or less unattainable and cannot really be used for planning water resources management. Hence, more realistic scenarios must be developed which mirror the present-day state of the economy, its capacities, the usefulness of the measures and the interests of an extremely wide variety of regions and countries.

7.2 SUSTAINABLE DEVELOPMENT SCENARIO (SHI)

In recent years the Russian SHI has developed a new scenario for the proposed development of world water use to the year 2025, known as the Sustainable Development Scenario (SDS). It is based on the same basic 1995 data as were used in the Conventional Scenario SHI (CS), but presupposes totally different approaches to freshwater use in the next few decades.

In the new SHI scenario, all premises and assessments are initially considered and analysed individually for each region, and for the main countries in a given region, and for each type of water use (community, industry, agriculture, reservoirs), and then added together by continent and for the world as a whole.

The Sustainable Development Scenario (SDS) developed by the SHI is based on the following premises, extrapolated to cover the entire world for the period 1995–2025:

- World population rises to 7.8 billion, i.e. just as in the Conventional Scenario, which is totally in line with the mean and most realistic present-day forecasts;
- The world's total irrigated area grows by 20 per cent, with variations by country and region: from 10 per cent (in highly developed countries) to 30–40 per cent (countries with transitional economies, and some developing countries in Africa and South America);
- Water use efficiency for irrigation purposes averages 15 per cent, with variations ranging from some 20 per cent, depending on country and region (countries with high incomes and limited water and land resources), down to 10 per cent. At the same time, one third of the efficiency will be reached in the first half of the period (before 2010), and two thirds during the second half;
- Community water use (in litres per day) in the countries and regions of Europe will fall by between 10 and 20 per cent, in North America by 40 per cent; moreover, two thirds of the fall will be in the second half of this period.

In countries and regions of Africa, community water use will grow by between 10 and 20 per cent (North and Southern Africa), and 100 and 120 per cent (other regions), with much of the growth being expected in the first half of the period.

In the southern region of Asia, a 50 per cent increase is expected, and in other countries and regions there will either be no change at all or a 10–20 per cent fall. In the poorest countries of Africa and Asia, at the end of the period, water use will be no less than 50 litres per day per person. In the richest countries of Asia, water withdrawal will be no more than 300 litres per day per capita. In the countries of South America and Australia, community water use will either fall by 10–25 per cent or remain unchanged.

- Industrial water use. In regions with highly developed countries, withdrawal water will be 0.5–0.6 the 1995 water figures. In the regions covering the former USSR, this figure will be 0.8 times. In the regions covering Asia, South and Central America, Northern and Southern Africa, and also Oceania, a rise in water consumption of 1.2–2 times is assumed, depending on the region. In the other regions in Africa, the rise will be 6–7 times. As water withdrawal falls, the proportion of water consumption (as a percentage of withdrawal) starts climbing, but where it rises, the proportion falls;
- Losses through evaporation from reservoirs will grow by 5–10 per cent in the regions of North America, Europe, the former USSR and Australia, in the other regions by 20–30 per cent.

In the opinion of the authors, the hypotheses adopted in the SDS are completely realistic for all regions, but for a series of positions they would be fairly hard to attain, mainly for financial reasons.

7.3 WATER USE, STRESS ON WATER RESOURCES AND WATER AVAILABILITY IN THE WORLD UNDER THE SUSTAINABLE DEVELOPMENT SCENARIO

The forecasts for global water use under the two SHI scenarios, the Conventional Scenario (CS) and the Sustainable Development Scenario (SDS), or the years 2000, 2010 and 2025 are shown in Table 19 and Figure 42, while more detailed assessments for 1995, 2010 and 2025 for the chief users are given in Table 30.

The calculations according to the SDS show future world water withdrawal more or less steadying; by 2010 it will rise by approximately 6 per cent before beginning to fall, and by 2025 it will amount to 3 890 km^3 per annum, i.e. just 2.7 per cent more than in 1995. The dynamics of water consumption are expected to perform within roughly the same limits.

By 2025, according to the SDS, unlike under the CS, all users will be using less water, but this will happen most of all to industry; industrial water use will be some 10 per cent less than in 1995 (under the CS, it is due to rise by 36 per cent).

Under the SDS, there will be 306 million hectares of irrigated land in the world by 2025 (20 per cent higher, as against a 30 per cent increase under the CS). At the same time, where the specific water use per hectare by 2025 is expected to be 9 660 m^3 per ha lower under the CS than in 1995, according to the SDS it will be 8 270 m^3 per ha, or almost 16 per cent lower, as a result of more efficient agricultural water use.

Comparisons of water use figures in 2025 under the two SHI scenarios, and the scenarios of the International Expert Panel, the BAU, TES and VAL scenarios, are shown in Figure 52, and in greater detail according to main users in Table 31.

The highest figures for future water use are naturally those obtained for the SHI's Conventional Scenario (CS), which assumes that the same relationship to problems of

	1995	*2010*		*2025*		*Change 2025/1995*	
		CS	*SDS*	*CS*	*SDS*	*CS*	*SDS*
Total values							
Population (mill.)	5 735	7 113	7113	7 877	7 877	1.37	1.37
Irrigated land areas (mill. ha)	253	288	286	329	306	1.3	1.3
Water withdrawal (km^3/year)	3 788	4 431	4 006	5 235	3 889	1.38	1.38
Water consumption (km^3/year)	2 074	2 400	2 233	2 764	2 194	1.33	1.33
Agricultural water use							
Water withdrawal (km^3/year)	2 504	2 817	2 646	3 189	2 535	1.27	1.01
Specific water withdrawal (m^3/ha)	9 897	9 781	9 252	9 693	8 284	0.98	0.83
Water consumption (km^3/year)	1 753	1 987	1 867	2 250	1 793	1.28	1.02
Domestic water use							
Water withdrawal (km^3/year)	344	472	422	607	456	1.76	1.32
Specific water withdrawal (l/day per capita)	164	182	163	211	158	1.28	0.96
Water consumption (km^3/year)	49.0	60.8	61.0	74.1	63.0	1.51	1.28
Percentage of water withdrawal	14.2	12.8	14.4	12.2	13.8	0.86	0.97
Industrial water use							
Water withdrawal (km^3/year)	752	907	731	1 170	673	1.56	0.9
Specific water withdrawal (m^3/year per capita)	131	128	103	148	85	1.13	0.65
Water consumption (km^3/year)	83.0	117	96.3	169	113	2.0	1.36
Percentage of water withdrawal	11	12.8	13.2	14.4	16.8	1.3	1.5
Reservoirs							
Additional evaporation (km^3/year)	188	235	208	269	226	1.43	1.2
Percentage of world water consumption	9.1	9.8	9.3	9.7	10.3	-	-

Table 30—Forecast of world water use by CS and SDS scenarios of SHI

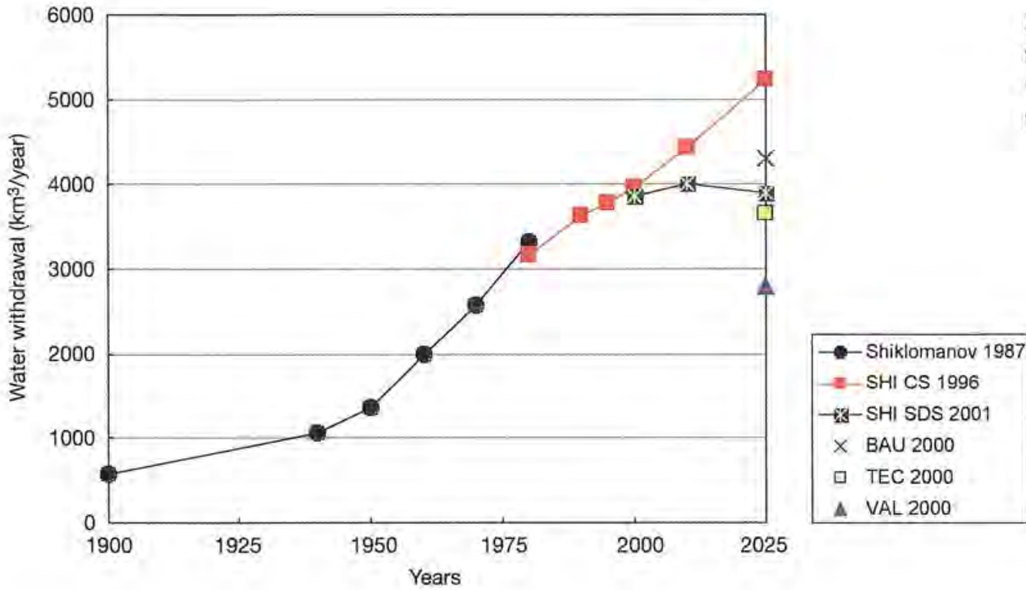


Figure 52—Comparison of the values of water withdrawal in the world by the SHI and SDP scenarios

Water use	*1995*	*2025*				
		SHI CS	*SHI SDS*	*SDP BAU*	*SDP TEC*	*SDP VAL*
Irrigated land area (mill. ha)	254	329	306	258	312	267
Population	5.7	7.9	7.9	8.0	7.9	7.5
Agricultural	2 490	3 200	2 500	2 300	2 550	1 950
Municipal	360	610	450	900	400	350
Industrial	750	1 170	670	900	450	300
Reservoirs	185	270	225	200	250	200
Total	3 790	5 240	3 890	4 300	3 650	2 800

Table 31—Water withdrawal in the world in 1995 and 2005 (km^3/year) according to scenarios of the SHI (CS and SDS) and the Development Panel

freshwater use that is at work in the present-day world will continue to apply in the next few decades, i.e. no major world change to the problem of freshwater use is likely to be experienced.

All other scenarios presuppose a radical change in factors governing water use; for global water use scenarios the Russian State Hydrology Institute's SDS scenario is nearest that of the TES, except for industrial water use forecasts, which in the TES are obviously underestimated (see section 7.2). When regarded from the standpoint of continent and region, the differences between the two scenarios are naturally greater.

Water use forecasts by continents under the two SHI scenarios are given in Figure 41 and Table 18. Whereas under the CS, a rise in water use is forecast for all continents, under the SDS the future dynamics of water use are likely to change significantly. In Europe, Northern America and Australia, a considerable curtailment in water use is expected (in Europe and North America by 22–24 per cent and in Australia by 5 per cent). On other continents, water withdrawal will rise but not very significantly: by 33 per cent in Africa, by 21 per cent in South America, and by 12 per cent in Asia.

More detailed forecast data according to the two SHI scenarios for all water users for every continent are given in tables 32 to 35.

Under the CS, agricultural water use rises on average by between 9 and 31 per cent, while the rise varies by very wide margins depending on region: from 2–11 per cent in regions of Europe and North America to 1.8–3.8 times in certain regions of Africa. In most regions, therefore, specific water withdrawal for irrigation will either fall slightly or remain stable, while in some regions there may even be a small rise, due to worsening salinity.

Under the SDS scenario, agricultural water use in Europe and North America will fall by 10 per cent, though on other continents an insignificant rise (1–4 per cent) is assumed (Table 32); the figures by region vary from a fall of between 10 and 12 per cent, and a rise of 15–20 per cent. Specific water use for irrigation will fall in all regions by between 10 and 20 per cent.

Under the CS, community water use (Table 33) will increase on all continents and in all regions, varying from between 10 and 15 per cent (for Europe and North America) to 3–5 times (for certain regions in Africa). Under the SDS, community water use for Europe and North America by volume is due to fall by 12–20 per cent as a whole, on other continents a growth in community water use is forecast (more than tripling in Africa). It is assumed that in some regions of North America (USA and Canada), specific water use in litres per day per capita, 700 litres in 1995, will fall to 400 litres, while in

Continents	1995			Scenario	2010			2025			2025/1995		
	Fir	Wir	Sir		Fir	Wir	Sir	Fir	Wir	Sir	Fir	Wir	Sir
Europe	25.2	170	6700	CS	27.5	202	7 300	29.7	208	7 000	1.18	1.22	1.04
				SDS	26.8	168	6 270	29.4	158	5 370	1.17	0.9	0.8
North America	29.3	283	9700	CS	33.3	300	9 000	35.4	308	8 700	1.2	1.09	0.9
				SDS	31.1	2 773	8 916	32.6	258.3	7 922	1.1	0.9	0.8
Africa	12.3	138	11 200	CS	14.6	160	11 000	16.5	180	10 900	1.34	1.3	0.97
				SDS	13.6	145	10 665	14.4	139.8	9 710	1.17	1.01	0.87
Asia	175	1 785	10 200	CS	200	2 610	10 000	233	2 340	10 000	1.33	1.31	0.98
				SDS	200.6	1 935	9 644	215	1 859	8 634	1.23	1.04	0.85
South America	9.1	97.9	10 800	CS	10.0	107	10 700	10.4	115	11 100	1.14	1.17	1.03
				SDS	10.9	104.5	9 587	11.6	99.9	8 612	1.27	1.02	0.8
Australia & Oceania	2.6	15.5	6 000	CS	2.9	17.4	6 000	3.1	18.5	6 000	1.19	1.19	1.0
				SDS	2.94	16.6	5 629	3.13	15.8	5 054	1.2	1.02	0.84

Note: Irrigated land area (mill. ha) (FIR); water withdrawal (km^3/year) (WIR); specific water withdrawal (m^3/ha) (Sir).

Table 32—Characteristics of agricultural water use by continent in 1995 and 2010–2025 according to SHI scenarios (CS and SDS)

Table 33—Characteristics of municipal water use by continent in 1995 and 2010–2025 according to SHI scenarios (CS and SDS)

Note: total water withdrawal, (km^3/year) (Wd); specific water withdrawal (l/day per capita) (Sd)

Continents	1995		Scenario	2010		2025		2025/1995	
	Wd	Sd		Wd	Sd	Wd	Sd	Wd	Sd
Europe	66.8	268	CS	75.4	298	78.3	314	1.17	1.17
			SDS	64.6	255	58.9	236	0.88	0.88
North America	87.9	530	CS	102	523	114	525	1.3	0.99
			SDS	88.5	447	70.0	322	0.8	0.6
Africa	17.7	68	CS	35.4	84	60.5	104	3.4	1.5
			SDS	36.1	85.4	56.8	97.5	3.2	1.43
Asia	155	121	CS	229	146	309	172	2.0	1.42
			SDS	195.3	125	227.6	127	1.5	1.05
South America	28.8	242	CS	42.6	282	58.9	327	2.0	1.35
			SDS	34.6	230	38.8	215	1.35	0.89
Australia & Oceania	3.3	304	CS	4	315	4.5	330	1.36	1.08
			SDS	3.51	276	3.38	239	1.02	0.8

Table 34 Characteristics of industrial water use by continent in 1995 and 2010–2025 according to SHI scenarios (CS and SDS)

Note: water withdrawal (km^3/year) (Wiw); water consumption (km^3/year) (Wic)

Continents	1995		Scenarios	2010		2025		2025/1995	
	Wiw	Wic		Wiw	Wic	Wiw	Wic	Wiw	Wic
Europe	204	28.9	CS	242	45.6	256	57.1	1.25	1.97
			SDS	169	36.7	118.7	44.4	0.58	1.54
North America	284	17.0	CS	307	18.9	325	20.2	1.14	1.19
			SDS	236	17.6	161.6	18.2	0.57	1.07
Africa	9.6	1.25	CS	12.4	1.95	20.2	2.85	2.1	2.3
			SDS	16.8	2.45	27.3	2.96	2.8	2.4
Asia	220	32.0	CS	295	44.4	496	77.4	2.25	2.4
			SDS	268.6	34.5	316.5	38.5	1.4	1.2
South America	25.8	2.9	CS	42.2	5.2	61.9	9.9	2.4	3.4
			SDS	34.7	4.2	44.6	7.1	1.7	2.4
Australia & Oceania	7.1	0.54	CS	8.8	1.05	10.3	1.43	1.45	2.6
			SDS	5.93	0.88	4.77	1.22	0.67	2.2

Europe there will be a contraction of between 10 and 20 per cent. In some regions of Africa and Asia, where specific water use is about 30–50 litres per day, it will more than double.

Under the CS, industrial water use (Table 34) will rise by between 8 and 25 per cent in the regions situated in Europe and North America, and the rise will be by 150–250 per cent in regions with developing countries. Under the SDS, industrial water use for the continents of Europe, North America and Australia will decrease by 33–34 per cent, and in some regions it will halve, while in most countries of Asia and South America water use

Table 35—Additional water loss through evaporation from reservoirs by continent in 1995 and 2010–2025 according to SHI scenarios (CS and SDS) (km^3/year)

Continent	1995	Scenario	2010	2025	2025/1995
Europe	14.4	CS	15.8	17.2	1.2
		SDS	15.5	16.6	1.15
North America	30.1	CS	34.0	38	1.26
		SDS	31.4	32.9	1.1
Africa	54.0	CS	66.0	77.0	1.4
		SDS	61	67.8	1.25
Asia	70.7	CS	92.2	106.8	1.5
		SDS	78.3	85.9	1.2
South America	11.65	CS	21.2	24.0	2.06
		SDS	16.1	17.8	1.5
Australia & Oceania	4.5	CS	5.5	6.2	1.37
		SDS	4.8	5.04	1.1

will rise by 150–250 per cent in some regions in Africa by 700 per cent.

Under the SDS, water losses through evaporation from reservoirs (Table 35) will rise by 10–15 per cent in Europe, North America and Australia (under the CS the growth will be 20–37 per cent); and in Asia, Africa and South America the losses will rise by 20–50 per cent under the SDS (under the CS, they will be 40–100 per cent).

By way of illustration, figures 46–48 compare the dynamics of water use for 1995–2025, under the two SHI scenarios for regions that include countries with differing levels of socio-economic development.

For the central region of North America and Central and Western Europe (Figure 46) (highly developed countries), under the SDS water use is to be expected to fall off considerably through the broad use of water saving technologies. Under the CS a growth in water use is forecast, albeit an insignificant one.

For a region with a transitional economy (Figure 47), the rise in water use after the year proportionate to the growth in the economy under the SDS will be insignificant and will not return to its 1990 peak even by 2025.

For regions with developing countries (Figure 48), a significantly lower curve in the rise of water use is to be expected under the SDS than under the CS.

The degree of water resources use, as seen in the coefficient K_W, is shown in Table 25 for all regions and continents. Under that scenario, in 2025 the stress on water resources worldwide will generally remain at 1995 levels; the changes by continent and region are extremely great; in some continents and regions they are lower than in 1995, in others they are rising (but much more slowly than under the CS).

Table 26 shows comparative world population data for 2025 for different levels of stress on water resources, under the two SHI scenarios.

The data in tables 25 and 26 are proof of the advantages to be reaped from developing water use according to the SDS scenario. Under this scenario, the average worldwide level of stress on water resources in the coming 25–30 years becomes more or less steady, but for several regions it might even fall a little lower than it is at present. At the same time, there will be a fall in the numbers of people in the world living under catastrophically high stress levels on water resources.

Somewhat different conclusions may be reached if the future situation in countries and regions is compared not by stress on water resources but by specific water availability, that is, by the amount of water available per capita, minus water consumption drawn off.

Such data up to 2025 for the two SHI scenarios are given in Table 27 and in summary form in Table 28. These figures indicate that more or less independently of the water use development scenario used, in coming decades specific water availability around the world will be constantly diminishing and that by the year 2025 a majority of the planet's population (58 per cent) will be living in conditions of either very low or catastrophically low water availability. This is understandable too, as water availability is mainly dictated by two factors: water resources and population size. It is natural because developing countries located in warm dry climates are already suffering from specially grave water availability conditions and will continue to experience them; their natural water resources are usually not great, and specific water availability is falling fast due to steep population growth and a concomitant increase in water consumption (Table 27).

Thus the data in tables 25–28, lead us to believe that if the water resources situation in countries and regions of the world is to improve, according to both criteria simultaneously (both the stress level on water resources and specific water availability), not only do a range of approaches need to be developed to increase freshwater use efficiency (under the SDS), but ways and means of increasing the amount of available water have to be worked out.

Chapter 8

THE EFFECTS OF MAN-MADE CLIMATE CHANGES ON WATER RESOURCES AND WATER USE

As seen earlier (in section 5.1), in studying man-made climate changes and water resources, as they apply to natural-economic regions and countries, special attention must be paid to two aspects of the issue:

- Potential climate changes resulting from the large-scale use of fresh water;
- The effect of human activities on gases contained in the atmosphere.

Study of these factors should be based on the data cited earlier on the amounts of fresh water used in the world and on analysing assessments made in the last few years of the effect of global warming on water resources in major river basins and regions.

8.1 THE INFLUENCE OF WATER USE ON THE CHARACTERISTICS OF REGIONAL AND GLOBAL WATER CIRCULATION

Intensive economic activities may not only have notable effects on the atmosphere in relatively limited areas but may also add to the input into the atmosphere of large amounts of additional moisture through greater evaporation than comes from the natural hydrological cycle. At the same time, despite a few caveats, the amount of additional moisture released into the atmosphere can be assumed to be a result of human activity in the form of water consumption to meet economic needs. It must be borne in mind that additional evaporation, which reached 2 500–2 800 m^3 per annum at the beginning of the twenty-first century, is already on an enormous scale. It should also be noted that the bulk, mainly due to the expansion of irrigation, occurs in arid regions where natural ground evaporation is low.

Under the general theory of moisture circulation, the additional moisture entering the atmosphere will initiate additional precipitation that will partly compensate for water used to meet economic needs. At the same time, considering the seeding effect of additional moisture, the extra precipitation may be very considerable and for some major regions more than conventional precipitation produced through human activities. Naturally, the effect may occur only over very large areas where the moisture circulation coefficient is considerably greater than one, for example, for entire continents and major regions (Kalinin, 1969; Drozdov et al., 1976; Shiklomanov, 1989).

A very approximate quantitative assessment of possible changes to precipitation and runoff in continents through the extra evaporation from man's economic activity using different calculation levels, was first made at the SHI by the author jointly with O.A. Drozdov and O.G. Sorochin and published in Kalinin and Shiklomanov (1974) and Drozdov et al. (1976).

In recent years the Russian SHI in St Petersburg refined the assessments by using new data on water use and balance characteristics, calculated not only for different continents but also for natural-economic regions of the world that are smaller in land area. The values for separate regions were then averaged out to fit different continents; the results are given in Table 36. Similar coarse assessments for natural economic regions of the world with highly developed irrigation systems are shown in Table 37.

According to data in Table 36, water consumption to meet economic needs are resulting in a rise in aggregate precipitation over Europe, Asia, Africa and North America, amounting in 1995–2025 to some 60–130 per cent of the values for water consumption. In Australia and South America, the growth of water consumption in conjunction with special features of the moisture cycle in those two areas produces scarcely any increase in precipitation.

For additional precipitation, ΔP, it is not hard to roughly calculate mean annual runoff, ΔR, using for the purpose the values of the mean runoff coefficient (α) for every continent, which were taken from Korzun, ed. (1974). For 1995, additional runoff amounted to an considerably high proportion of the amounts of non-return water used (from 16 to 23 per cent). Where there is a further rise in water consumption, additional runoff may increase noticeably. For 2025, its values will already form 14–32 per cent of total water consumption (Table 36).

At the same time, given the huge land masses of the continents, there is bound to be some shift in precipitation and water resources distribution across them. The extra evaporation occurs over areas where there are basic irrigated land areas and reservoirs but additional precipitation and runoff may be expected in other parts of continents, as a rule in mountain areas along the main tracks followed by air masses.

A similar picture can be seen in major natural-economic regions. To judge by the figures in Table 37, for different regions of the world the additional runoff generated by economic activity may be 30–40 per cent of the water consumption for that purpose.

Thus, any change in the evaporation regime resulting from economic activity may subsequently change the relationship between the components of the water balance in various parts of different continents and major regions. A qualitative assessment of such phenomena over wide areas may be of great interest in long-term planning of large-scale activities to foster a rational worldwide use of water resources.

The figures in tables 36 and 37 for ΔP and ΔR for continents and regions may be somewhat overvalued because of the following assumptions:

- Additional evaporation from economic activities does not affect natural evaporation in a given region;
- Water consumption for economic needs are considered equivalent to additional evaporation.

The first assumption needs to be backed up. In reality, for example, in an endorheic basin, overall evaporation scarcely alters, so a rise in water losses in such a basin for economic needs would mean an equivalent cutback in natural losses and no extra moisture being released into the atmosphere.

For some rivers that flow into the ocean, there can also be some loss in total natural evaporation through man-made causes, for example by regulating runoff and reducing the scale and duration of flooding. In such cases, up to a certain level of water resources use, non-return losses for economic needs can to some extent be offset by lower non-productive evaporation in the basin (Shiklomanov, 1989).

The situation described may be of great importance in assessing water balance in individual river basins. However, it can be completely passed over when considering possible future changes to runoff characteristics for continents and major areas.

The second assumption is not likely to introduce major errors into the calculations either. When water is used for industry and agriculture, water consumption consist of two parts: water going into additional evaporation and water forming part of the finished product or crop. However, the second is insignificant by comparison with the first. In community water use, the bulk of non-return losses (more than 80 per cent) are due to evaporation between the source and the consumer and back again (see 5.2 and 5.3 above).

On the other hand, when calculating ΔP and ΔR, it is presumed that the effect of additional runoff is to some extent played down, namely that when calculating figures for ΔR, the mean long-term effect of additional runoff is adopted, whereas the runoff coefficient from extra precipitation is evidently higher than the mean.

The data in tables 36 and 37 are therefore fairly realistic, particularly if the inaccuracy of long-term forecast water use assessments by global regions is borne in mind.

The values in Table 36 for additional precipitation and runoff are fairly significant in relation to continental water use. It is of interest to consider, if only as a first approximation, the possible changes in the natural components of the moisture cycle over whole continents resulting from the use of water for economic needs. Such assessments at the SHI are also given for each continent in Drozdov et al. (1976). The data suggest that the rise in mean long-term precipitation expected from water use by the end of the twentieth century would be generally not significant, amounting to 1 per cent for Africa, 2 per cent for Europe and North America and 6 per cent for Asia. At the same time, no significant change should be expected in the general atmospheric circulation or the speed of water vapour transport. The main ingredient of the moisture cycle intensity for entire continents, the water vapour coefficient, will stay more or less the same, since the seeding effect of additional evaporation will show up through a rise in both the components involved in the genesis of atmospheric components, advective precipitation and precipitation from water vapour of local origin. The possible rise in continental water resources is 0.7–3 per cent (Table 36), and that of natural-economic regions of the world with developed irrigation systems, is 0.6–14 per cent (Table 37).

In this way, increasing use of fresh water calls for some change in the ratios between separate components of the water balance of continents and major regions, though even in the future it is unlikely to engender any noticeable global climate changes.

Possible changes in hydrological cycle characteristics for continents and regions are eminently suited to calculations and can be taken into account, for example, when designing large-scale water management facilities. The changes identified are fairly arbitrary, not very clear-cut, and an understanding of them is open only to experts who alone can use them in their work.

In terms of scale, evidently, an incomparably greater impact on the characteristics of the hydrological cycle and water resources should be expected from world climate change as a result of man's influence on the gas content of the atmosphere.

8.2 THE INFLUENCE OF MAN-MADE CHANGES IN ATMOSPHERIC GASES ON CLIMATE AND WATER RESOURCES

The gravest disquiet over possible future man-made world climate changes is the concern raised by the constantly rising concentrations of carbon dioxide and minor gases present in the Earth's atmosphere (freons, nitrous compounds, etc.), and also atmospheric aerosols. It is unanimously held by climatologists that rising carbon dioxide concentrations are the most crucial man-made factor, the one that is liable to have the greatest effect on the world climate, particularly in the next few decades. Carbon dioxide is a gas that is almost transparent to short-wave solar radiation, but one that also greatly weakens its long-wave equivalent, creating the so-called greenhouse effect in the atmosphere, and contributing considerably to higher temperatures in the lower layer of the air. The increasing amounts of carbon dioxide in the Earth's atmosphere are therefore bound to lead to global warming. The same effect is happening as a result of rising concentrations of minor gas components in the atmosphere.

The amounts of carbon dioxide in the atmosphere are not constant but change under the impact of natural and man-made factors. Direct measurements and various oblique methods showed that in the early 1880s, the

Table 36—Changes in precipitation and water resources of the continents due to water consumption

Continent	*Mean renewable water resources R (km³/year)*	*Water consumption, U (km³/year)*		*Sum of additional precipitation (km³/year)*		*Runoff coefficient (α)*	*Volume of additional water resources, ΔR (km³/year)*		$\frac{\Delta R}{U} \times 100\%$		$\frac{\Delta R}{R} \times 100\%$	
		1995	*2025*	*1995*	*2025*		*1995*	*2025*	*1995*	*2025*	*1995*	*2025*
Europe	2 900	189	256	132	200	0.32	42	64	22.2	25.0	1.4	2.2
North America	7 890	237	269	160	278	0.31	50	86	21.1	32.0	0.6	1.1
Africa	4 047	160	220	208	248	0.12	25	30	15.6	13.6	0.6	0.7
Asia	13 510	1 381	1 876	830	1 210	0.39	324	472	23.5	25.1	2.4	3.5
South America	1 203	89.4	120	0.0	0.0	0.41	0.0	0.0	0.0	0.0	0.0	0.0
Australia & Oceania	2 400	175	22.3	0.0	0.0	0.34	0.0	0.0	0.0	0.0	0.0	0.0

Table 37—Possible changes in precipitation and water resources by natural-economic regions of the world with developed irrigation under the influence of water consumption (by 2025)

Continent	*Region no. in Table 22*	*Area of region (km² x 10⁶)*	*Total water resources, R (km³/year)*	*Water consumption by 2025 U (km³/year)*	*Additional precipitation ΔP (km³/year)*	*Runoff coefficient (α)*	*Additional water resources ΔR (km³/year)*	$\frac{\Delta R}{U} \times 100\%$	$\frac{\Delta R}{R} \times 100\%$
Southern Europe	3	1.79	655	117	88	0.33	29	25	4.4
South of European part of former USSR, including Transcaucasia	5, 20	2.97	646	97	46	0.26	12	12	1.9
North China & Mongolia	14	8.29	1 029	187	151	0.32	48	26	4.7
South Asia	15	6.95	2 288	856	607	0.48	291	34	12.7
Western Asia	16	6.82	490	248	227	0.28	64	26	13.0
North Africa	9	8.78	181	97	75	0.08	6	6	3.3
West Africa	12	6.96	1 118	32	50	0.24	12	38	1.1
East Africa	11	5.17	775	56	123	0.18	22	39	2.8
South Africa	10	5.11	485	31	31	0.11	3	10	0.6
Central America & Caribbean	8	2.67	1 110	77	89	0.34	30	39	2.7

levels of carbon dioxide in the atmosphere stood at 285 ppm (0.0285 per cent, or a 285 millionth part of the volume of atmospheric air). In 1958, the figure was 315 ppm, in 1985 the level was 343 ppm, and by the year 2000 it had reached 370 ppm. Thus, in the space of 120 years, the concentration had risen by 30 per cent, while in the past 16 years the rise has been three times higher than it used to be, i.e. the rate of increase is climbing steeply.

The main cause behind increasing levels of carbon dioxide is man's economic activity, i.e. the combustion of fossil fuels (oil, gas, coal) and cement production, as well as the felling of tropical forests, which means that the take-up of carbon dioxide by vegetation through photosynthesis is lower. Along with carbon dioxide, other gases enter the atmosphere through economic activity, and they too behave in the same way as carbon dioxide, exacerbating the greenhouse effect. The most important of these gases are the so-called freons, widely used in making refrigerators and different kinds of paints, but methane is also important.

Despite the rapid introduction of measures in recent years to limit atmospheric emissions of greenhouse gases, their levels in the atmosphere will increase, according to all available forecasts, at least throughout the twenty-first century. According to findings from the International Panel on Climate Change (IPCC, 1995, 2001), by the year 2020, levels of greenhouse gases in the atmosphere will already be 400–410 ppm, by 2050 they will be 460–550 ppm, and by 2100 they will reach 540–940 ppm; i.e. present levels can really be expected to double more or less by the end of the present century.

Human activity contributes not only to the release of different gases into the atmosphere but also of tiny particles of various substances or aerosols, increasing the natural levels of atmospheric aerosols. Available assessments indicate that the mass of aerosols of human origin entering the atmosphere annually in the last few decades amounts to approximately 200–400 million tonnes, 10–20 per cent of its total emissions into the atmosphere (particularly large amounts of aerosols are released into the atmosphere through volcanic activity).

The effect of man-made aerosols on climate is extremely complex and so far not adequately studied. It is obvious, however, that rising aerosols levels in the atmosphere weaken solar radiation and help lower air temperatures in the surface layers of the atmosphere, i.e. the effect of aerosols on climate is the direct converse of the effect of greenhouse gases.

One of the key questions in modern climatology is how rising atmospheric concentrations of carbon dioxide, greenhouse gases, and aerosols influence our present-day climate and what we can expect in the future. Though instrumental meteorological observations have been made in different parts of the world for almost 200 years, it is hard to answer this question, given the wide natural range of climatic characteristics.

According to research findings (Jones, 1988, 1994; IPCC, 1996, 2001), since the end of the nineteenth century the global air temperature has risen by 0.3–0.6°C, 0.2–0.3°C of it during the last 30–40 years, while the 1980s and 1990s were the warmest for the entire observation period (which began in 1860). The mean annual temperature changes for the northern hemisphere are given in Figure 24. Comparison of empirical and theoretical temperature change assessments for the last 100 years provides grounds for assuming that the main cause of the warming is the increasing carbon dioxide levels in the atmosphere and other greenhouse gases caused by the economic activities of man.

An observable warming of the global climate, naturally, does not mean that air temperatures have risen everywhere at one and the same rate; the trend in the changes varies very strongly from one region to another; in many regions changes have gone practically unobserved, and there are even areas where annual air temperatures have fallen slightly in the last few decades (Anisimov and Polyakov, 1999; IPCC, 2001).

Worldwide temperatures are bound to go on rising as greenhouse gases in the atmosphere increase in concentration. According to forecasts from the IPCC (1995, 2001), by comparison with the year 1990, the changes will be, for 2020–2025: 0.3–0.9°C; for 2050: 0.8–2.4°C and for 2100: 1.4–5.8°C.

Such a significant range of possible changes is the outcome of the many uncertainties involved in forecasting, uncertainties connected with the development of the world economy and greenhouse gas emissions into the atmosphere on the one hand, and those stemming from the inadequately studied effect of different factors on temperatures (aerosols, changes in vegetation cover, processes at work in the oceans, etc.).

Still greater difficulties and uncertainties set in when analysing the changes in precipitation, not just with regard to long-term forecasting, but also in monitoring on-going trends. This is due to the wide range in time and space of precipitation and the significant errors in measuring it. Despite this, during the past decade many important results have been found in studying annual precipitation dynamics (IPCC, 1995, 2001). It has also been established that there has been increasing precipitation in high latitudes and lower rainfall in the northern tropical latitudes of Africa.

According to Groisman et al. (1991), there has been an increase in precipitation across the former USSR, averaging 10 per cent over 100 years. The changes to precipitation during the last century in Europe (apart from the former USSR) depend on the latitude. In northern Europe (north of latitude 55°N), a precipitation increase has been observed since the 1960s, but in central Europe no noticeable positive trends have been observed in the last 100 years (Brazdie, 1992). In southern Europe negative trends have prevailed (Polmieri et al., 1991; Dahlstrom, 1994).

Some rise in annual aggregate precipitation has also been noted in North America since the 1950s (Karl et al., 1993). In the United States, annual precipitation has risen by 5 per cent, in Canada the figure is 10–15 per cent, while the most serious increases are observed on the East Coast and in the Atlantic Provinces (Groisman and Easerling, 1994; Findlay et al., 1994; Lettenmaier et al., 1994).

Since mid-century, lower rainfall was found in wide tropical and subtropical areas of North Africa, East and South East Asia and Indonesia (IPCC, 1995, 2001).

During the twentieth century an insignificant increase (1 per cent) in precipitation occurred over the land masses of different continents as a whole. At the same time, the connection between variations in precipitation and air temperatures also turned out to be a function of latitude. In medium and high latitudes of the northern hemisphere there was a noticeable increase in precipitation and a rise in air temperatures while in the tropics, subtropics and temperate latitudes of the southern hemisphere the rise in air temperatures was accompanied by lower rainfall. This was the chief characteristic of the rise in air temperatures that began in the mid-1970s.

There are a number of unresolved issues for long-range forecasting of precipitation changes. Generally speaking for the world as a whole, precipitation will rise to some extent. The independent approaches used lead to a generally accepted conclusion that a doubling of greenhouse gas concentrations in the atmosphere causes a considerable rise in annual precipitation at high latitudes; most forecasts extend the rise to the middle latitudes as well. The most difficulties occur when forecasting precipitation between latitudes 30°N. and 30°S. In this band, both falls and rises in precipitation are predicted, but they are generally of insignificant amounts (IPCC, 2001; Georgievsky and Shiklomanov, 2003).

The changes to the global climate expected to occur in the next few decades as a result of human activities are creating great anxieties among hydrology and water management specialists. It is primarily due to the fact that hydrological characteristics are peculiarly sensitive to climate change and react to it immediately, and secondly because changes in the water regime and water resources largely govern how much water is available to the public, irrigated cultivation, different branches of industry, transport, emergencies and the ecological status of extensive regions.

In the past decade, researchers from many countries have published an enormous amount of literature assessing the hydrological consequences of global warming, their basic results being collated in papers by the IPCC (1995, 2001), or issued in reviews and proceedings of many international conferences, symposia, and other meetings on the subject of "climate and water".

Here we give a small sample of the results and conclusions directly connected with water resources and use.

The research topics in question follow two main paths.

The first is to elucidate how major river systems in different physical geographic areas react to climate changes that have already taken place in the last few decades.

The second research line is bound up with assessments of the hydrology and water management aspects of future world climate change.

The author considers that the research work undertaken under the first of the two approaches can be used to establish real trends in water regime changes from observation data and identify practical measures for developing and carrying out adaptive measures. Interesting and important results have been obtained for different regions of the world.

The most detailed studies have been carried out for the Russian geographical area and the states bordering on it (Georgievsky et al., 1995; Georgievsky et al., 1996; Shiklomanov I.A and A.I Shiklomanov, 2002; Bruce et al., 2002). Among other things, it has been established that there has been a considerable rise in annual streamflow for the River Volga, the rivers of Siberia and Northern European Russia, river runoff outflow into the Arctic Ocean (see section 4.2) and the Caspian Sea.

In the last two decades there has been a sharp increase in runoff (20–50 per cent) across the European part of the former USSR and Western Siberia (the basins of the Volga, Dnieper, Don, Pechora, Northern Dvina and Ob rivers). A considerable increase in winter runoff has also been observed in the countries of Northern and Central Europe (Bergström and Carlsson, 1993; Schuman, 1993; Krasovskaya, 1995, etc.). Similar trends in flow have also been found for many areas of North America (Lins and Michaels, 1994). The changes in runoff for high and middle latitudes in the northern hemisphere pointed out during the last few decades were caused by the considerable rise in cold season air temperatures and some increase in annual precipitation.

South America and the Caribbean did not reveal general trends, either for a rise or a fall in runoff (Marengo, 1995; Budyko et al., 1994). A fall in runoff along the Pacific coast was noted in Colombia, beginning in the 1970s. At the same time, there was a considerable rise in precipitation and annual river runoff in the equatorial area of the continent. According to data from Singh (1997), since the early 1980s a considerable rise in air temperatures has been observed in the Southern Caribbean accompanied by a fall in rainfall, which is bound to cause a reduction in water resources.

The trend towards decreasing water resources in the last few decades has been observed on the African continent as well. According to the data (Sirculon, 1990; Olivery et al., 1993; Sirculon et al., 1999), between 1981 and 1990, river outflow into the Atlantic fell by 17 per cent as against the average for 1950–1995, with runoff in the arid part of the continent falling by 27 per cent. During the 1970s and 1980s, the driest period in the Sahel region was recorded since instrumental observations began; on average between 1970 and 1988 the fall-off reached 43 per cent (Sirculon, 1999). In recent years, across this wide region a considerable rise in the amount of precipitation has been seen, which may indicate that the low end of the long-range runoff variations is reaching its end.

The runoff trends observed during the last few decades for the arid areas of Africa are also a feature of other regions with water resources deficits. Thus, in the years 1987–1992, an exceptionally severe drought was observed in Southern California, with annual runoff being 23 per cent lower than the norm (WRI, 1994). An analysis of hydrometeorological data for Northern China (Chunzheu, 1993) showed that since 1981 was the warmest period since instrumental records began, with average temperatures in the 1980s being 0.5°C above the benchmark. During the same period precipitation was lower than the norm, causing a considerable fall in water resources.

A tendency for rainfall and runoff to decline has also been observed across a considerable swathe of the Australian continent (Thomas and Bates, 1996). In particular, in the basin of Australia's chief basin (the Murray-Darling basin), during the period 1974–1994, annual runoff fell by some 40 per cent as compared with the preceding long-term period. A fall-off in precipitation and runoff, beginning in the mid-1970s, was observed in New Zealand (Mosley, 1991).

Thus, the analysis of shifting climatic characteristics and water resources in different regions of the world in the last 20–25 years revealed an extremely unfortunate trend when viewed from the general standpoint of the state of world water resources: an increase in water resources in northern regions (where there is in any case a sufficiency of them) and a fall in regions with arid climates where, even if climatic conditions remain stationary, the strain on water resources is great and specific water availability is falling particularly steeply (see Chapter 6).

To study the future state of water resources, *inter alia*, for the period between 2020 and 2030, studies of the effect of global warming on annual runoff and its intra-annual distribution are of particularly great importance. For such studies, it is naturally not enough to have forecasts of changing global air temperatures; there must also be regional forecasts of changes to the basic climatic characteristics with the greatest effect on water resources in a region or basin (monthly and seasonal precipitation and air temperature). Given the lack of such forecasts, various different scenarios for future climatic conditions are drawn on for quantitative assessments of hydrological consequences in different regions and basins. In most cases they are based on calculations of the General Atmospheric Circulation Model (GCM), and those obtained from paleoclimatic reconstructions of past climatic periods.

Where climate scenarios exist, changes in the hydrological regime may be determined by data from hydrological models, but for assessing the consequences for water management, water use and resource management models are employed. Thus, the output data from regional climate change assessments based on the GCM and on paleoclimatic reconstructions form an entry point into hydrological models; in their turn, hydrological model outputs, along with the results of climatic assessments, make up input data for water use models, and on the use and management of water resources. The water management and environmental changes obtained lay the foundations for developing practical measures to soften possible harmful consequences and adapt water management systems to meet the new hydrometeorological circumstances.

In the last decade a wide range of GCM's have been worked out in different countries for calculating scenarios of changes to monthly air temperatures and precipitation for entire land masses at different atmospheric concentrations of carbon dioxide (most often a doubling of carbon dioxide). The scenarios indicate that, with a global warming of 2–3°C in various regions, particularly those in high latitudes, a temperature rise of up to 5–6°C or more is to be expected, while the degree of warming in the Equatorial belt may be insignificant, in the 0–1°C range (IPCC, 1995, 2001). Such general features of expected global warming are very typical of all scenarios, both those drawn from models and those based on paleoclimatic studies.

Practical use of existing scenarios to reliably assess future climate and runoff in specific regions makes for very great difficulties, since the different scenarios provide significantly different changes to climatic characteristics in one and the same region. This particularly concerns the size of changes in precipitation, where the incompatibility of various scenarios is particularly great, which is a cause of great uncertainty in calculating regional runoff and for many regions makes it more or less impossible to take runoff into account when assessing future water availability.

To assess the hydrological consequences of global warming in 1990–1998, more often than not, scenarios are used that were obtained on the basis of the following GCM's for a doubling of carbon dioxide: GFDL (USA), UKMO (United Kingdom), GISS (USA) and CCC (Canada).

In recent years new climatic scenarios developed using GCMs have come to be widely used: in Germany (the ECHAM-5 model), the USA (the GFDL-RIS model), in Canada (the CGCM1 model) and in Great Britain (different HadCM2 models), which are considerably higher in resolution and provide changes in climatic characteristics for varying degrees of global temperature change.

As well as the model scenarios, in assessing the effect of climate change on hydrological characteristics, researchers from Russia and other parts of the former USSR have made wide use of paleoclimatic scenarios for global warming such rises of 1–2°C and 3–4°C developed at the St Petersburg SHI by a team working under Professor M.V. Budyko (Budyko and Israel, ed., 1987; Budyko et al., ed., 1991).

In the last 10–15 years in many countries, an enormous number of studies have been made to obtain a quantitative assessment of the consequences of global warming in various regions of the world. They were based on the widest possible variety of scenarios and hydrological models, and cover a broad range of items: from small experimental catchments to major river systems and natural zones, continents and even the world as a whole. In so doing, not only are the characteristics of runoff studied but so are ice regimes, sediment, river-channel processes and so forth.

We give below brief conclusions from these studies, basically with regard to annual and seasonal runoff in different physical-geographical zones: cold and temperate climates, and those that are arid or semi-desert, or the humid tropics.

8.2.1 Cold and temperate climates

Characteristic of the zone is the fact that bulk of runoff originates during spring snowmelt. The zone includes the northern regions of North America, Northern and Eastern Europe, much of Russia and Canada and Kazakhstan.

A multiplicity of studies conducted in the Scandinavian and Baltic states making use of various model scenarios and hydrological models, have generally provided similar results: a considerable increase in winter runoff; a fall in the volume of spring floods and earlier onset; an insignificant changes in summer runoff; a rise in annual runoff, together with a more even distribution over the year. In general, the conclusions are confirmed by research into the effect of global warming on river outflow into the Baltic Sea.

For Poland, detailed studies are presented in the work of Kaczmarek and Napiorkowski (1996). Using the CFDL and GISS scenarios with a doubling of carbon dioxide for 31 catchments in Poland, the two authors generally reached directly conflicting conclusions. Under the GFDL, a depletion of more than 20 per cent in annual runoff, and more than 30 per cent in summer runoff, is to be expected in central Poland. Under the GISS the reverse situation is expected; annual runoff may increase by more than 20 per cent, including runoff for summer months. For the country as a whole, with a doubling of carbon dioxide for CFDL water resources will fall by 13 per cent, whereas for GISS they will rise by 11 per cent.

Highly detailed studies for various catchments and different regions have been conducted in Great Britain since the 1980s; the results of the studies were given a wide hearing by the IPCC (1995) and Arnell (1992). In one of the studies run on six neighbouring catchments in southwest England using a single scenario, relating arbitrarily to the year 2050, rather unexpected results were obtained: in four catchments, annual runoff fell by between 7.0 per cent and 30.9 per cent, while in two others it rose by between 7.4 per cent and 20.7 per cent. Such results may possibly be explained by the geological features of the catchments governing the evaporation and outflow of groundwater from aquifers.

Particularly close research attention has been paid to possible changes in the hydrological regimes of the two largest trans-frontier river basins of Europe: the Rhine and the Danube. For the Rhine basin, assessments have been made using scenarios based on the HadCM2 model for 2020, 2050, and 2100 and various hydrological models. According to the assessments, increases in winter flooding and dwindling summer runoff are to be expected, with the frequency of very high and very low water spikes increasing, and calculated draw-off maxima rising by some 25 per cent. These conclusions are very important for all countries in the basin.

Possible future changes in the hydrological regime of the Danube have been assessed, using three model scenarios down to the year 2050. Possible changes in annual and monthly runoff were not noteworthy in any of the three scenarios, averaging ±10 per cent; only in one was there a fall in August runoff, of 25 per cent; there was a rise in annual river flow of 2–5 per cent for all three scenarios. Bearing in mind the margins of error in such assessments, the hydrological regime of the Danube should be expected to remain more or less stable in the first half of the present century, even with global warming.

During the last two decades, a particularly large number of studies assessing the influence of global warming on hydrological characteristics have been carried out in the USA and Canada, the results being reported in Waggoner et al., ed. (1990); Shiklomanov and Linz, (1991); Frederick et al., ed. (1997), etc.

Using different scenarios and hydrological models for several regions of the USA, extremely varied assessments of precipitation and river flow with global warming have been obtained, so it is very hard to arrive at any general conclusions about future water resources and water availability for the whole country.

However, drawing together the results of the many studies, it can be generally stated that the following changing trends will be observed in runoff due to global warming in certain regions of the USA and Canada:

- North and northeast: an insignificant increase in annual runoff and flooding;
- California: a considerable rise in winter runoff coupled with a fall in summer flow; an insignificant rise in annual runoff;
- Great Lakes: lower flow;
- In other regions there will be still greater uncertainties in terms of changing precipitation and runoff.

The main results of research into this problem for different parts of the vast area of Russia and countries of the former USSR are published in works like those by Georgievsky et al. (1995, 1996, 1997, 1998); Shiklomanov and Georgievsky (1995); Shiklomanov I.A. and A.I. Shiklomanov (1998, 1999, 2002); and Peterson et al. (2002).

Summing up these results, the following conclusions may be drawn in relation to changes in runoff in the light of global warming:

A 10–30 per cent rise in annual runoff should be expected for almost all the major rivers of Russia and the former USSR (Volga, Dnieper and the rivers flowing into the Arctic Ocean from the European and Siberian parts of Russia);

These conclusions are based on model scenarios using a doubling of carbon dioxide and paleoclimatological scenarios with 2–3°C warming.

Particularly important changes are to be expected in the distribution of runoff by month and season: a rise in winter runoff and a fall in spring runoff;

On rivers of the mixed forest-and-steppe and steppe zones there may be radical changes in annual runoff hydrography, with a division into just two hydrological seasons: a winter-spring period with high runoff and flow, and a low-water summer-autumn season.

8.2.2 Arid and semi-arid regions

For these regions, where as a rule there is a shortage of water resources so long as the climate is stable, it is particularly important to have reliable data on the possible hydrological consequences of the global warming that is expected. At the same time, it is in the arid and semi-arid regions that assessments of future climate differ radically from one another, depending on the various climate scenarios used, to the point of producing directly contradictory results, particularly when comparing conclusions based on GCM scenarios and paleoclimatic analogy.

An assessment of the hydrological consequences of global warming in arid and semi-arid areas has been made for the southern part of European Russia and neighbouring countries, for many river basins of the USA, Australia, South America, Africa, including the Sahel region, and Asia. At the same time, the most detailed documentation using a range of variations on scenarios for future climate change and an integrated analysis of the consequences, has been obtained for river basins of the USA in arid climates (Frederiek and Major, 1997). The studies show that even relatively small changes in temperature and precipitation can bring about extremely important changes in water resources in areas where moisture is insufficient. At the same time, river runoff in these areas are more sensitive to changes in precipitation than air temperatures.

Similar conclusions were published earlier in surveys by the IPCC (Shiklomanov et al., 1990; Stakhiv et al., 1992), and in studies from various countries (Sircunlon, 1990; Shiklomanov and Linz, 1991; Chang et al., 1992; Shiklomanov I.A. and Shiklomanov A.I., 1999) and elsewhere.

Generally speaking, the research conducted in different countries showed that river catchments in arid and semi-arid areas are often sensitive to even very minor changes in climatic characteristics. Air temperature rises of 1–2°C and falls in precipitation of no more than 10 per cent can bring about 40–60 per cent falls in annual and seasonal river flow.

When considering the consequences of global warming on the hydrological conditions in arid regions, particular stress should be placed on the problems of the Sahel, where severe drought has visited a calamity on many African countries in the last few decades. There is much uncertainty over the future of water resources in the Sahel, which is created by the contradictory data on the future of the climate stemming from GCM calculations and paleoclimatic comparisons (Sirculon et al., 1999; Budyko and Israel et al., 1997). Under the latter, global warming will cause a steep increase in precipitation in this area, with almost no accompanying change to air temperatures; in this case, the most probable trend will be an increase in water resources. However, according to calculations made using the three types of GCM with the greatest degree of resolution (IPCC, 1990), at a doubling of carbon dioxide air temperatures will grow by 1–2°C, whereas precipitation during the cool season will fall by 5–10 per cent and rise in the hot season by 5 per cent; under this scenario there are no grounds for expecting any rising trend in water resources.

8.2.3 Humid tropical regions

For the humid tropics, an assessment of the impact of global warming on water resources has been made for river basins in Venezuela, for the River Plate basin in Uruguay, for the Mekong river, the largest trans-boundary river in Asia, for river basins and regions of three countries of South-East Asia: Indonesia, Malaysia and Thailand, and for some regions of Africa, India and Sri Lanka, and China (Shiklomanov I.A. and A.I. Shiklomanov, 1999; Shiklomanov and Georgievsky, 2003).

Climate scenarios from three GCMs (GISS, GFDL and UKMO) have been used to measure the Mekong River basin (Mekong Secretariat, 1990). For all three, a considerable rise in precipitation and runoff during the rainy season was noted; the fall-off in precipitation during the dry months is insignificant but the duration of the low rainfall period is increasing. All this will lead to greater unevenness in runoff during the year and a need to introduce regulatory measures.

The hydrological consequences of climate change for the catchment areas and regions of Indonesia, Malaysia and Thailand have been followed up in different studies (Parry et al., ed., 1991; Toth, 1993). Climatic scenarios were adopted for a doubling of carbon dioxide based on three types of GCM. The main conclusion of the assessment for these regions is that in the rainy seasons greater amounts of precipitation are observed, hence an increase in runoff too, whereas during the dry season there will be a more clearly accentuated shortage of rainfall.

The effect of global warming on water resources of three basins in Indonesia has also been assessed (Rozarri et al., 1990), where a considerable rise in monthly runoff is to be expected; there will be a concomitant exacerbation of erosion processes and lower soil productivity.

Turning to India, the most detailed research on the issue has been on two heavily populated city areas, Bombay and Madras, using scenarios based on three GCMs with a doubling of carbon dioxide (Leichenko, 1993). Analysis of the calculations led the author of that study to conclude that under the scenarios used there was very great uncertainty about future water resources and water availability in the huge, fast-growing megalopolises of India in the wake of global warming.

For Sri Lanka, the results of studies have been cited in the work of Nophadol and Hemantha (1992), where different GCMs are compared in relation to their capacity to reflect observation data for precipitation and air temperatures. The authors concluded that the best results for Sri Lanka could be obtained for the GISS and UKMO models. With a doubling of carbon dioxide, these models show an increase in daily and monthly precipitation during the monsoon season, but with a negligible change in total yearly precipitation. The wettest period (from April to July) will shift to September to November; at the same time, the period of lowest runoff will grow bigger, increasing the probability of drought.

An analysis of the effect of climate change on water resources along the Zambesi River in Africa has been given in work by Urhiztondo et al. (1991), using scenarios based on different GCM models. In this, radically differing conclusions were arrived at. Calculations showed that with the GFDL and GISS scenarios using a doubling of carbon dioxide, and a fall in flow from the Zambesi River was to be expected, whereas under the UKMO scenario, the flow would rise.

Equally differing conclusions for certain catchments in Africa were cited in a review of the literature (Sirculon et al., 1999), and were also obtained in a series of studies of major catchment areas in South America. For example, for the Uruguay River, studies using three models (GFDL, GISS and UKMO) showed that all three failed to assess the present-day climate sufficiently. Calculations of runoff using scenarios based on the models with a doubling of carbon dioxide led to the conclusion that under the GISS and UKMO scenarios, runoff in the Uruguay River basin would fall by 11.7 and 6.4 per cent respectively and under the GFDL model it would rise by 21.5 per cent.

Assessments using a first approximation calculation for possible changes in water resources in South America global warming were made at the SHI (Budyko et al., 1994), using climatic scenarios based on paleoclimatic reconstructions of past warm periods and a simple hydrological water balance model. These studies show that if there is a 1°C or 2°C global warming, a 8–10 per cent water resources increase must be expected, with a significant rise being possible in the Amazon river basin, even though a slight decline in water resources may occur in the Uruguay and Paraguay river basins.

The results for humid tropical regions bear out the dominant role of the forecast size of changing precipitation in alterations to annual and seasonal river flow for the region. Given this, for areas with monsoon climates, it is rather possible that increased runoff during the rainy season and lower rainfall during the dry season can be expected, along with greater risk of drought.

It should be noted that in many studies an attempt has been made to assess possible changes in water resources with a future warming of the climate, not for individual river basins but for entire continents and for the Earth as a whole. Such first-approximation assessments for continents have been conducted at the SHI (Shiklomanov and Babkin, 1992) for the world's largest river basins, and by other researchers (Miller and Russel, 1992) for the entire world (Arnell, 1999), and for Europe (Henrics et al., 2002). The global assessments are usually based on a certain single climate scenario using highly simplified hydrological models, so naturally their margin of error is much greater than with detailed studies for specific catchment areas, where there are data available from long-term observations and reliably developed models. As the analysis shows, the results of such global assessments for individual regions can differ considerably from conclusions obtained from regional studies.

Because the forecasts of global warming indicate that in many regions and countries significant changes in the size and structure of water use may occur, there can be an exacerbation of conflicts and differences between individual water users.

If there are great changes in future air temperatures and precipitation, on the one hand it may be necessary to review long-term development plans, the location of irrigated areas, the thirstier branches of industry and the building of high dams. On the other hand, problems may arise with the water availability of the existing main water users. When this happens, naturally, the changes will first affect arid and semi-arid areas where there are already problems in providing water.

The chief use of fresh water in the world is irrigation, and it is the most sensitive to changes in climatic conditions as well. It is for this reason that, in studying the effect of possible man-made climate changes, researchers focus on water use in agriculture.

Much has been written on the subject for different parts of the USA (Peterson and Keller, 1990; Frederick, 1991; Easterling et al., 1991; McCahe and Wolock, 1992; Frederick et al., 1993, and so forth); there are studies for Russia, Poland, and various countries of Southern Africa (Georgievsky et al., 1993; 1996; Kaczmarek, 1996; etc.). All the studies showed that major changes in air temperatures and precipitation (under the doubling of carbon dioxide assumption) can significantly affect irrigation in areas with irregular rainfall. In this, the rise in water use for irrigation is mostly to do with the rise in air temperature and less to do with changes in rainfall.

Research also led to the crucial conclusion that likely water use for irrigation purposes in a future subject to global warming will depend not only on changes in air temperature and precipitation, but also on the direct effect of carbon dioxide levels on plant photosynthesis processes. The rising carbon dioxide concentrations engender increasing resistance of vegetation to water vapour uptake in the leaves, which produces reduced transpiration per unit of leaf area. Certain experiments (Rosenberg et al., 1990) have shown that a doubling of carbon dioxide levels may on average halve specific transpiration. On the other hand, the rise in carbon dioxide levels stimulates plant growth which leads to a rise in the transpiring surface area and in transpiration.

In general, the direct influence of carbon dioxide levels on transpiration is a complex process and the degree to which it influences water use will depend on the type of vegetation and numerous other factors such as climate, soil type and subsurface groundwater levels. In many cases, this effect may be very considerable, not just for the water taken up by irrigated crops but also by vegetation growing in the wild, hence for water balance in a given area, runoff and water resources. It is therefore natural that allowing or failing to allow for this factor can produce the widest range of conclusions. With regard to annual runoff, the importance of taking account of the direct effect of carbon dioxide levels on the transpiration of vegetation was already demonstrated in the 1980s for river basins in the USA (the state of Arizona) and Australia (Idso and Brusel, 1984; Aston, 1987). The latter drew a conclusion conflicting with results from many other researchers: that a doubling of carbon dioxide levels would raise the annual flow of rivers studied in the USA by 40–60 per cent and of Australian rivers by 60–80 per cent.

In the opinion of the present author, allowing for the direct impact of carbon dioxide in subsequent studies is of course necessary, but can scarcely have such a significant effect on annual runoff since total evaporation from the ground is mainly determined by energy factors. However, with regard to water use for irrigated land, the direct role of carbon dioxide may be extremely significant and must be taken into account.

The results show that allowing for the direct effect of carbon dioxide concentrations on transpiration makes for additional uncertainties when assessing the effect of global warming on water take-up by vegetation, total evaporation, and therefore on runoff and water resources in a given area.

Man-made climate changes can have affect not only water requirements for irrigation but also for community and industrial use, though to a significantly lesser extent. This is borne out by the data quoted in much of the literature (e.g. Hughes et al., 1994; Herrington, 1996; Boland, 1997; Frederic et al., ed., 1997). Analysis of these works shows that man-made changes play less of a part in the dynamics of future water use in urban areas than population growth and changes in socio-economic factors.

This brief review of research findings means that the following general conclusions can be drawn on the effect on water resources of man-made climate changes:

- Possible global and regional climate changes resulting from the use of fresh water in the economy will over the next few decades have a negligible effect in scale and may be ignored in present and future assessments of water resources, water balance and availability in river basins and natural-economic regions;
  In scale, man-made climate changes caused by emissions of carbon dioxide and other greenhouse gases into the atmosphere are likely to have an immeasurably greater impact on the hydrological cycle and water resources;
- During the last 20–25 years, a trend towards a considerable rise in water resources has been observed, together with changes in their intra-annual distribution in cold and temperate climates and a fall in regions with arid climates, which is caused by the corresponding air temperatures and precipitations. It is perfectly possible to assume that the changes are the result of global warming, which has speeded up greatly since the late 1970s;
- In the absence of reliable regional forecasts of man-made climate changes, climatic scenarios are used for quantitative assessments of the hydrological consequences of global warming. The large number of scenarios developed, based on GCM's and paleoclimatic data with very small spatial resolution, agree poorly with observation data and with one another, especially in relation to precipitation, the prime factor governing the volume of water resources and water availability. All this is behind the great degree of uncertainty in the quantitative assessments of expected future changes in the characteristics of river flow in different physical-geographical conditions. The uncertainty is aggravated by using insufficiently reliable hydrological models not based on observation data;
- The vast bulk of the research in the world to assess the hydrological consequences of global warming has been based on GCM scenarios that presuppose a doubling of carbon dioxide in the atmosphere, which, so the most realistic present forecasts claim, may be reached by around the year 2100; at the same time, the global temperature rise may be expected to be 3.6°C (compared with the period to the year 1990);
- Results of the research conducted show that with a doubling of carbon dioxide there is a high chance of a rise of up to 15–30 per cent in annual river flow in cold and temperate climates and still more significant changes in seasonal runoff. For the humid tropics and particularly for arid and semi-arid regions, quantitative assessments of possible changes in water resources are riddled with uncertainties, concerned above all with the forecasting of precipitation. At the same time, it is pointed out that in areas where there is insufficient moisture, river systems are particularly sensitive even to insignificant changes in climatic characteristics;
- Bearing in mind the forecast rates of global warming (by the years 2020–2025, there will be a 0.6°C rise in global temperatures by comparison with the period to 1990), and there is a great degree of uncertainty in existing climatic scenarios, when assessing water resources and water use for continents, major natural-economic regions and river basins up to 2010–2025, the effect of man-made global climate changes can perfectly possibly be ignored. The margins of error in so doing are much lower than the forecasting errors on the development of the economy and population size, the basic factors governing the level of stress on water resources and water availability;
- For the 2040–2050 horizon, due allowance has to be made for the effect of man-made climate changes on water resources and water availability, particularly for arid and semi-arid regions.

The development of dependable regional forecasts of man-made climate changes, a comprehensive study of the hydrological and water management consequences of these changes in various regions of the world, and the taking of steps to adapt and mitigate these possible harmful phenomena are among the most burning issues of our times faced with by climatology, hydrology and water management.

Chapter 9

HOW TO DEAL WITH WATER RESOURCES DEFICITS: SOME TECHNOLOGICAL, SOCIO-ECONOMIC, FINANCIAL AND ECOLOGICAL ASPECTS

As shown in Chapters 6 and 7, the world is being subjected to fast-increasing stress on its water resources, and in many regions and countries specific water availability is falling steeply. If the future water economy continues to develop in the same way as in the past few decades, it is to be expected that by 2025 some 40 per cent of the world's population will be living in regions with a catastrophically high degree of stress on water resources. If effective measures are taken to improve the water management technology in use in the world (as projected under the SDS scenarios developed at the Russian SHI in St Petersburg), it would stabilize world water use and vastly lower the level of stress on water resources (see Tables 25 and 26). However, even in such conditions (using the SDS), the steep population increases would mean that world water availability will still remain at a very low level (see Tables 27 and 28), and 40 per cent of the world's population will continue to have access to less than 1 000 m^3 per annum per capita, a quantity that is considered as being catastrophically low. Thus, in order to increase future water availability, it is not enough to reduce the amounts of water used, rather, ways and means of finding added water resources must be sought out.

There are two groups or types of measures that can be taken to reduce the level of stress on water resources and eliminate world shortages of fresh water and stabilize or increase water availability.

A first group proposes an increase in the water resources available for using water resources by:

- long-term and seasonal regulation of river flow;
- use of secular fresh water reserves;
- desalination of salt and brackish waters;
- artificial increases in precipitation;
- geographical redistribution of water resources.

A second group proposes reducing expansion rates for prime water users and employing improved technologies to cut down freshwater use in industry, irrigation and for the community.

Below we give a brief analysis of measures taken so far.

9.1 REGULATION OF RIVER FLOW

In much of the world, water supply difficulties arise not because there are generally not enough water resources, but because of the extremely uneven distribution of intra-annual river flow, which creates water shortages during low-water dry seasons or years. To make fullest use of local water resources, beginning in the 1940s and 1950s the construction of seasonal and long-term water regulation dams became customary. The aggregate active volume of reservoirs worldwide now stands at 4 000 km^3, raising the volume of permanent runoff by an average of 25 per cent. Some regions and countries have a relatively high degree of renewable water resources control (see Tables 8 and 10) and, naturally, less difficulty in finding available water in dry seasons or drought years. However, the development of runoff regulation processes is beset by limitations, given the harm done by dams and reservoirs (see section 5.5). This has led to a steep fall in building them during the last two decades, and evidently the decline will continue.

A non-negligible factor is that the building of reservoirs in areas that are too dry causes both regional water resources to be shed by additional water losses to evaporation and considerable flooding of fertile land. Already (see section 5.7), water losses to additional evaporation from the world's reservoirs are greater than the entire water consumption by the community, industry and power stations. This is why in recent years, water losses to evaporation and the wide-scale flooding of fertile land for reservoir storage are being kept to a minimum by making every effort to build dams in mountain or thinly populated areas of the world, and suitable sites are steadily dwindling.

9.2 SECULAR FRESHWATER RESERVES

In dealing with the problem of future water availability, experts are showing steadily growing interest in the huge reserves of secular waters stored up in lake basins, in glaciers and groundwater strata deep within the Earth. The use of water from lakes is not so promising as it is not present in such large quantities (approximately 91 000 km^3) and is distributed very unevenly, and mainly in areas where there is no lack of fresh water. Moreover, use of lake water would inevitably have harmful consequences as lake levels fall and threats to water quality appear.

One tempting idea for the long-term provision of water in continental areas of the world with persistent water shortages would be partial tapping of fresh water from mountain glaciers by artificially augmenting the melting processes, thereby increasing streamflow on glacier-fed streams. Data from Table 2 (Korzun, ed., 1974) indicate that the mountain glaciers of the world store a great deal of good fresh water (approximately 40 600 km^3), much of it in river basins whose flow is used extensively for irrigation. It is proposed to increase glacier melt rates by artificially blackening mountain snow and ice.

Experiments to speed up the melting of glaciers and snowfields were conducted in the 1970s in the former USSR, USA, China, Chile and elsewhere. In work by Krenke (1980) and Kotlyakov (1981), experimental results were reported for major glacier areas. For Central Asia in particular, the potential and realistic volumes of additional water to be obtained from accelerating the melting process were assessed.

The studies were not very promising, however. It turned out that if all the glaciers of Central Asia and South-eastern Kazakhstan (containing about 1 000 km^3) were artificially blackened, the total volume of extra annual river flow would be only 6.5 km^3, whereas the overall water consumption in areas where water resources can be used from these mountain rivers could reach 80 km^3 per annum. Moreover, the technical unreality of completely blackening all glaciers is patent, and even the yield of 1–2 km^3 additional water, or about 1 per cent of natural annual river streamflow, would be unrealistic as some 2 000–3 500 km^2 of glaciers would need to be covered in dust.

Evidently, for other mountain areas the picture would be similar, i.e. it is very likely that the additional water resources from speeding up the melting of all the mountain glaciers in the world would not exceed 20–40 km^3 a year; that would not only fail to tackle the global problem, it would not even solve it at regional level. Technical difficulties apart, the use of glaciers as additional sources of fresh water could set in train the destruction of mountain ecosystems. Even preliminary assessments point to the risk of extremely unwelcome ecological consequences from resorting to such measures.

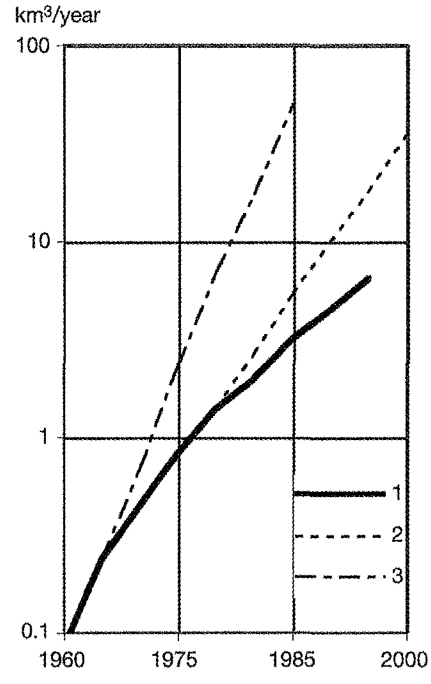
More useful would be the use of deep underground non-return secular groundwaters in arid and semi-arid areas of the planet. For example, for decades such water has been widely drawn off in the Arabian Peninsula and North Africa, India and some other countries, and has been of key importance in meeting community and farming needs in various areas, towns or cities, districts or even countries. However, the reconnoitred and easily exploitable non-return groundwater reserves are already close to exhaustion (FTGWR, 1997; Gleick, 1998, UNESCO, 1995), and do not hold out much promise of providing water for irrigation and industry on the worldwide scale.

9.3 DESALINATION OF SALINE AND BRACKISH WATERS

In assessing ways of eliminating water shortfalls, great trust is often placed in the use of desalinated saline and brackish water from lakes, groundwater and sea water, which have more or less unlimited reserves round the world. The large-scale building of desalination plants began in the 1960s. Where in 1960 the total output of all desalination plants in the world was 0.08–0.09 km^3 per annum, by 1970 it was 0.45 km^3 per annum, and by 1977 there were more than 1 500 desalination plants in service, producing 1.4 km^3 per annum of fresh water (Shiklomanov and Markova, 1987).

The dynamics of desalinated water production worldwide can be seen in Figure 53. According to Gleick's data (1996) in 1980 1.46 km^3 was being produced worldwide, and in 1996 the figure had risen to 6.5 km^3 per annum. It should be noted that in the 1960s and 1980s, it was assumed that the growth of desalination worldwide would speed up. For example, in the 1960s it was forecast that a volume of 50 km^3 per annum would be reached by 1990, but in the 1980s it was assumed that by the year 2000 desalinated water would total 33–55 km^3 per annum (Avakyan et al., 1983; Shiklomanov and Markova, 1987). It is now obvious that, as by 2000 aggregate desalinated water amounted to only some 7 km^3, a volume of 50 km^3 per annum is not likely by the year 2020.

Increases in desalination is being held up in particular by its costs and the great amount of electrical energy and fuels required to process it. The cost of 1 m^3 of water at the largest desalination stations is estimated at 0.6–1.8 dollars (i.e. from 600 to 1 800 million dollars per cubic kilometre), depending on the degree of salinity and proportion of mineral salts in the water treated. The high costs are explained by the fact that more than half the present-day world's desalination capacity is found in the Persian Gulf and Middle East with their huge water deficits but enormous oil reserves and practically limitless financial resources (Gleick, 1998).



Figure—53 Dynamics of desalinated water production in the world

1 - Actual data from 1960
2 - Predicted in 1980 before the end of the century
3 - Prognostic data in the 1960s

It is important to note that in much of the world where water reserves are in short supply, particularly those relating to endorheic basins or "no flow" catchments draining into the interior, even in the distant future the desalination of sea water is unlikely to be useful for providing irrigation water, not just because of economic considerations (the costs in Figure 3.2 are those of a single irrigation session, and do not allow for the cost of delivering water to the user), but also because the large-scale withdrawal of sea-water is not possible given the inevitable changes to the hydrological regimes of water draining into the interior. Hence, in arid areas and those where there is intensive irrigation with limited water resources, the most promising source of desalination is not salt water from the sea but relatively mildly mineralized groundwater and runoff recovered from irrigated blocks of land. There are perfectly good grounds for this. First and foremost, desalination of brackish water needs much less money than salt water (for example, the cost of desalination electrolysis is nearly proportional to the mineralization of the water), and secondly, in traditional irrigation areas, weakly mineralized waste water is nearly always enough (Shiklomanov and Markova, 1987).

It should be noted that large-scale desalination fires a need to treat and use the salts, which is crucial to desalinated water costs and the environmental impact. Another major problem is the medico-biological problems from the widespread use of desalinated water for drinking and economic needs.

In the light of all this, obviously, desalination is not able to meet long-term water needs in most countries and regions of the world, even when enough financial resources for water treatment are to hand.

9.4 PRECIPITATION ENHANCEMENT

Large-scale experiments on artificially increasing precipitation by cloud-seeding over wide areas have been conducted in many countries, especially the USA, Canada, and Australia, and were very popular in the 1960s and 1970s. A brief review of the results obtained can be seen in the 1987 work by Shiklomanov and Markova, showing that the increased rainfall obtained from large-area seeding is in practice about 5 per cent. Not only that but outright ecological, legal and political problems can arise from active interference with clouds, with their potential impact on neighbouring climates.

We should also note that even if active cloud-seeding leads to additional precipitation or runoff, it can only happen if there is a ramified system of runoff regulation across the basin in question. This has to do with the fact that the additional precipitation is mainly obtained during periods of natural rainfall, not when it is necessarily needed for economic activities.

This is evidently also why in the 1980s and 1990s the large-scale precipitation enhancement experiments dwindled sharply, and why such programmes have almost never been taken seriously any longer by water management specialists as possible sources of additional water to meet needs.

9.5 GEOGRAPHICAL DIVERSION OF WATER

The geographical diversion of river flow, practised by mankind for many centuries, has been given a considerable boost to its worldwide growth in the last few decades. Measures to divert streamflow from one place to another are based on the existing realities underlying water resources, their geographical distribution, and the purposes they are used for. Firstly, there is quite enough water in the world to meet water needs for many decades and centuries. Secondly, freshwater resources are extremely unevenly distributed across the face of the Earth; on every continent there are places where water resources are over-abundant, and others where they are in short supply. Thirdly, man's economic activities exacerbate the unevenness of geographical distribution, i.e. where water resources are too plentiful, they are used less and streamflow practically remains undiminished, while where there is too little water, as a result of the interplay of human factors, water shortages become more conspicuous with each passing year. This is clearly why mankind has striven to develop and apply measures to withdraw water from areas of plenty and divert it to areas of shortage.

In 1985 total global diverted streamflow was approximately 370 km^3 per annum (Shiklomanov and Markova. 1987), 140 km^3 in Canada, 60 km^3 in the former USSR, 50 km^3 in India, and 30 km^3 in the USA. Of this amount, the greatest amount diverted is 50 km^3 per annum. (in northern Canada), and the biggest canal carrying diverted streamflow is 1 100 km long (the Karakum Canal, running through Uzbekistan and Turkmenistan).

In the 1970s and 1980s, in different countries river diversion projects were the subject of R&D, but most of them never got off the ground because of either their ecological unsoundness, lack of financial and technical resources, and most importantly, in the author's opinion, because of the extremely unfavourable impression of gigantic water management projects in the general public's mind's eye. This attitude was hawked around by the media, pseudo nature lovers and influential but not very competent scientists and politicians, some of them simply without a conscience. For these reasons, such as in the former USSR, all project and research work was halted in 1985.

Nonetheless, the total volume of all types of major streamflow diversion has been calculated by the present author as being 500 km^3 per annum, itself a very significant amount when compared with the global volume of water use. In the last few years opinions on river diversion have begun to change; major works to divert river flow have begun in China, in Russia serious thought is being given to restarting scientific work on diverting some of the flow from Siberian rivers into the Aral Sea basin, and projects are being conducted in other countries too.

As water needs and technical and economic capacities and resources go on increasing, geographical diversion of water is bound to go on rising too. The cost of streamflow diversion depends on many factors and the literature reviews by Shiklomanov and Markova in 1987 put it at between 100 and 800 million dollars per km^3.

Under the geographical diversion of water resources heading could be included such exotic suggestions as towing Antarctic icebergs to spots along the world's desert coasts where the lack of clean fresh water is at its most acute. According to expert assessments, the cost of fresh water from towed Antarctic icebergs can vary fairly widely (taking into account the cost of bring it ashore), basically between 500 and 700 million dollars per km^3, though in some places it may be one order of magnitude less.

The use of icebergs on a large scale is hindered by a series of difficulties and limitations. Firstly, it is much more profitable to provide water to coastal areas than inland, as water transport to inland areas would require very great additional expenditure. Secondly, icebergs, with their huge bulk and great draught, cannot be towed close to shore in many areas. Studies have shown that in many places where it is proposed to moor them offshore (North and South America excepted), icebergs cannot be brought nearer inshore than 20–40 km. This sparked off the idea of fragmenting them into smaller parts and getting the residue and sediment ashore. If icebergs are widely used, not only will the economic and technical issues have to be dealt with, but also the non-negligible ecological problems (Goldman, 1978; Chamoux, 1978).

9.6 FRESHWATER SAVINGS

So far as the second group of ways to eliminate water deficits is concerned, the most important thing is the widespread application of state-of-the-art fresh-water savings technologies. In our times there are great prospects everywhere and for all types of freshwater use for reducing specific water withdrawal. In power generation and industry, this means recycling used water, and in some sectors switching over to "dry" production techniques, where fresh water drawn off and the discharge of polluted runoff into rivers and other watercourses can be considerably cut down, while effective cleansing of industrial wastewater means that the large freshwater reserves hitherto needed for diluting raw untreated runoff can also be used in other ways.

The great prospects for reducing specific water withdrawal in industry and power generation and its great effectiveness (from the water savings standpoint) is borne out by the experience of highly industrialized nations since the 1970s onwards when industrial water use diminished noticeably, despite the great rise in industrial output. At the same time, more extensive use of return water in industry and for industrial wastewater treatment is being held up by the high costs involved. For example, some data (Levin, 1973) indicate that return water supply costs 1.5–3 times its single-pass equivalent, and outlay on wastewater treatment can be from 3 to 8 times more than for freshwater supply. And here the amount spent on treating 1 cubic metre of industrial wastewater (basically depending on the contents of the wastewater) varies from 0.2 to 1.5 dollars (from 200 to 1 500 million dollars per km^3 of polluted water).

In arid areas, water savings are particularly important to irrigated farming, which is the prime world water user. In some parts of the world, specific irrigation water use is on a massive scale, with 20–50 thousand m^3 of non-return water being drawn off per hectare of irrigated land or 3–7 times what is needed by crops. This is the result of water losses in canals, and the low coefficient of efficiency for irrigation systems, in many areas amounting to 0.4–0.5; excessive sprinkling and watering standards; imperfect irrigation technology and equipment. For example, according to M. Decroix (1983), the switch from gravity irrigation to sprinkling may more than double water savings, while the drip- and micro-irrigation can be used to maximize possible savings while considerably improving harvests. Specialists are well aware of the advantages of such irrigation methods though they still have not found wide use around the world.

Progressive irrigation methods, including sprinkling, droplet and drip irrigation all need complex expensive technologies and very sophisticated irrigated farming methods. That is why even sprinkler irrigation is used only on a very limited scale, particularly in developing countries. Worldwide, sprinkler systems are at present used on only 10–12 per cent of irrigated farmland. Drip and droplet techniques cost 3–5 times more than sprinkler systems, and all three are used only on 0.7 per cent of all irrigated areas round the world (Postel, 1992). Naturally, in the long run progressive watering methods will spread more widely across the globe, but that will largely depend on the financial capacities of countries, since huge capital outlays are needed.

Apart from modernizing water delivery technology, to make water savings in traditional irrigated farming areas, it is very important to rebuild existing irrigation systems, improve the coefficient of efficiency of main canals and branch irrigation channels, in particular by eliminating filtration and diminishing unproductive evaporation. In many irrigated areas of the world there is potential for increasing water resources simply by rebuilding irrigation systems.

Thus, studies by Russian scientists back in the 1970s and 1980s (Voropayev, 1979; Kolodin, 1980) showed that if there was a thorough overhaul of old irrigation systems and if water delivery systems were improved in Central Asia, it would generate water savings of around 20 km^3 per annum in the former USSR. However, for that to happen, enormous capital expenditure would be required; the cost of saving one km^3 is 700–900 million dollars.

The ways of obtaining extra freshwater resources considered above that are either available now or in the near future are extremely wide-ranging and specific. Common to them all is the major call they make on funds, but the differences among them are also striking. Measures

Table 38—Capital investments for getting additional water resources or saving 1 km^3 of fresh water

Project	***Capital investments (mill. US$ per 1 km^3 of water***
Runoff reservoir control	50–80
Use of glaciers in mountain regions	50–100
Desalination of salt and brackish water	600–1800
Water transfers	100–800
Utilization of Antarctic icebergs	500–700
Modern technologies in industries and treatment of industrial waste	200–1000
Reconstruction of irrigation systems and technologies	700–900

belonging to the first group all have a very harmful impact on the environment in one way or another. Those from the second group (water savings methods, treatment of industrial wastewater, reconstruction of existing irrigation systems, etc.) are nearly always the best, most necessary and useful from the ecological standpoint. Table 38, compiled by the author on the basis of information from the widest possible range of publications, gives individual capital outlays per cubic kilometre of additional or saved water resources. Costs vary greatly according to different time frames and regions, and the data must be considered as no more than a rough guideline.

The cheapest ways of obtaining additional water for any given region are by regulating runoff through reservoirs or stimulating the melting of glaciers in mountain areas. River regulation is widely practised across the globe, but only allows fuller exploitation of local runoff, it does not increase overall water resources in a region but reduces them through additional evaporation. At the same time, the prospects for regulation in many places have either already been exhausted or are likely to be so in the near future. As to glaciers, the opportunities for exploiting them are very limited, both in terms of additional water resources and of geographical sites where it is feasible to do so; the ecological consequences of such techniques are enormous and hard to predict.

All other ways of obtaining additional water and making freshwater savings are generally mutually comparable in cost and potential for dealing with water availability. They will all, obviously, sooner or later be put into wide use in such parts of the world once it is worthwhile to do so economically, on physical-geographical grounds or because of the type of water use.

Of measures under the first group, the geographical diversion of water has obvious advantages; it is already a widespread practice, it is used in every physical-geographic zone, region and continent of the planet; the volume of streamflow diverted in the world today is two orders of the amount of desalinated water and is continuing to grow. In combination with a wider use of modern technologies and treatment of wastewater, geographical diversion may make it possible not only to relieve stress on water resources but even stabilize specific water availability for many regions and countries.

As shown above (chapters 6–8), the worst problems of water availability are those faced by developing countries, where steep population increases are paralleled by low incomes, implying a matching level of socio-economic development. At the same time, most developing countries lie in areas with insufficient precipitation, where even in the natural state of things, renewable water resources are not great, vary widely according to season and are sensitive even to minor man-made global climate changes.

When developing long-term projects and plans for economic progress in developing countries, a closer look should be taken (as indicated in Chapters 6, 7 and 9) at both types of undertaking to improve water availability, i.e. by looking for additional sources of water and initiating a worldwide freshwater savings campaign by introducing more effective modern technologies. In so doing, by taking as the point of departure physical-geographical conditions, technological capacity and financial resources, state of the environment and national interests, priority would be given to undertakings with the most impact for the least outlay.

It should be noted that the discovery of additional water resources is a key to developing future plans, since in situations where populations are growing steeply there are only two ways of stabilizing or increasing specific water availability, either by:

- Stabilizing population sizes, impossible in most cases for ethical, national and political considerations; or
- Finding additional sources of water in the region (country) or by importing water from neighbouring regions, naturally on the basis of mutually profitable agreements and after the possible environmental impact has been the subject of all-round study.

Effective water savings measures are also very essential, as they will act as a brake on the stress on water resources, though they do not deal with how to stabilize specific water availability. Unfortunately, that is often ignored when developing long-term sustainable water resources development plans.

Chapter 10

CONCLUSIONS

This monograph deals with just one of many aspects of the complex issue of water: a consideration of fresh water worldwide as a crucial natural resource, without which life itself would be impossible, let alone the activities of man. The role of renewable water resources in economic activity is particularly crucial; it is almost entirely represented by runoff and is the key source for meeting water needs determining water availability and shortages in different countries and regions.

The data in this monograph are mainly based on results of integrated studies done in recent years at the Russian State Hydrological Institute (SHI) in St Petersburg.

The monograph analyses the dynamics of renewable water resources over many years (1921–1985) for all natural economic regions, continents, major river basins and selected countries. It also examines the intra-annual distribution of streamflow and the long-term changes in river discharge into all the oceans of the world, including in greater detail (using data for the latest years) inflow into the Arctic Ocean, where the inflow of fresh water is of special importance.

It is the first time such detailed worldwide assessments have been made, using a uniform method on world hydrological network data for a single long-term period, which has made it possible to paint a fairly accurate picture of the share of water resources geographically and historically.

At the same time, it must be pointed out that the reliability and accuracy of water resources assessments, their dynamics historically and geographically, depend on the condition of the hydrological network and access to the hydrological information needed for scientific review purposes. Since more than half of all hydrological stations are situated along the rivers of Europe and North America, providing coverage of exceptionally long observations series, it is natural that the most detailed and trustworthy assessments are for regions and countries located in these continents. It is also important to point out that hydrological information from the countries of Europe and North America is the most easily accessed for review purposes, including for the last few years, whereas in many countries of Africa, Asia and South America it is more or less impossible to obtain the requisite hydrological data for the last 10–15 years in full.

The absence of a reliable, constantly or rapidly updated worldwide hydrological database is why a uniform long-term review period (up to 1985) was selected for the present monograph, meaning that assessments of worldwide changes to runoff have not been available for the last almost two decades since then, precisely when the steepest increase in global air temperatures occurred. This fact has hampered study of all the different components of the global hydrological cycle (under the WCRP programme).

It is also important to note that, despite the great amount of work done by the international organizations, particularly WMO and UNESCO, on preparing guidelines and recommendations for regional assessments of water resources, so far there are no reliable data on medium-term values for renewable water resources for all countries in the world, or of their dynamics in time. This hinders any realistic assessment of the state of water availability in the world and possible future changes in it.

A crucial aspect of the modern water resources situation is the need to make allowance for changes due to human activities that have already occurred or expected in the future during the next few decades to come. The monograph shows that in any assessment of the worldwide effect of economic activity on water resources, it is of prime importance to account for human activities associated with water withdrawals to meet needs of the community, industry, agriculture, and associated with the building of dams and reservoirs. These factors are encountered all over the world and may have a particularly great impact on water resources in major regions and countries. The requisite attention must also be paid to the possible impact of man-made climate changes on water resources and use.

The monograph details methodological approaches, assessments and analyses of the dynamics of domestic, industrial and agricultural water use, and also water losses through additional evaporation from reservoirs in the twentieth century for all natural-economic regions, continents and for selected countries. It also makes forecasts up to 2025 based on two widely disparate socio-economic development scenarios and the relationship to freshwater use.

The fastest expansion in water use began in the second half of the twentieth century. Whereas in the first half of the twentieth century, annual water use rose by some 800 km^3, or by 160 km^3 each decade, in the next three decades the rise shot up to 550–600 km^3 every ten years, that is, almost four times more. This was the result of the great rise in population, irrigated land areas, and the intensive development of industry as the scientific and technological revolution proceeded. After 1980, the growth rate in world water use fell back significantly as a result of slower growth in irrigated areas and more efficient industrial use of fresh water in the more developed countries of the world. Growth under both headings still remains high, however.

In Europe and North America, where most countries are highly developed, the dynamics of water use in the last few decades have been very different from that of the other continents. Beginning in 1980, aggregate water use in Europe and North America began to settle down and in some regions even fell back slightly; but on other continents the headlong growth has continued unabated throughout the entire period since 1950.

Assessments for the future have been based on two scenarios developed at the Russian SHI:

- Under the Conventional Scenario (CS), which presupposes that water use in every region in the next 25–30 years will develop exactly as on the model of preceding decades;
- Under the Sustainable Development Scenario(SDS), which assumes that future development of water use will register improved efficiency among different users that makes allowance for the capacities and interests of each region.

Under the CS, water use will rise by 10–12 per cent every 10 years until by 2025 it will be some 1.37 times more than the 1995 figure; the steepest growth is to be expected in Africa and South America (1.5–1.6 times), and the lowest in Europe and North America (1.2 times).

According to calculations under the SDS, worldwide water use should more or less settle; by the year 2010, it will be rising by 5–6 per cent but will then begin to fall, falling back to near present-day values by 2025. Industrial water use will decrease by 10 per cent by comparison with 1995 figures, and a 22–24 per cent fall in aggregate water withdrawal should occur in Europe and North America.

The greatest difficulties in assessment and analysis of the dynamics of world water use for most countries are the lack of trustworthy data on water withdrawn for economic purposes in general, and on water consumption in different sectors of the economy in particular. Moreover, there is almost no country data assessing water losses through additional reservoir evaporation.

For a general assessment of water resources use in any given region (country), two criteria are used:

- The coefficient of water resources use, as defined by the ratio of water withdrawal to available water resources;
- Specific water availability in different regions, by defining the amount of fresh water available per capita (allowing for water consumption).

The analysis we carried out used both criteria and showed that, though the world water resources situation was perfectly satisfactory (with no more than 2–10 per cent of the world population living in areas with very high levels of water stress and very low water availability) in 1950, by 1995 the situation had changed sharply for the worse. By now, some 40–50 per cent of the world population live in areas with a very high or critical level of water scarcity and exceptionally low water availability. This means that the shortfall in water resources is becoming critical for the development of the economy and community way of life. Moreover, it is important to note that at the same time on every continent there are fairly extensive areas with more water than necessary and exceptionally high water availability.

If the future freshwater use remains unchanged (CS) then, calculations show, some 60 per cent of the world's population will be in a critical water resources situation and a catastrophic one so far as water availability is concerned, i.e. there is every reason to speak of a looming global water calamity.

The development of long-term water use under the SDS would mean the level of stress on water resources could be stabilized in the next two to three decades, though it is unlikely to have a great impact on specific water availability, which will mainly be governed by population growth.

Analysis of the data for natural-economic regions and countries for 1950–2025 has shown that the rates of specific water availability depend on two main factors: the socio-economic development of countries in the given region, and climate. For industrially developed areas, the fall in individual water availability is comparatively low and, independently of climatic conditions and water available, on average amounted to 1.7 times, 70 per cent of this for the period up to 1995. For regions that include developing countries, specific water availability has fallen away much faster, and areas where there is enough or excessive precipitation, the fall in specific water availability was 4.5 times, while in arid and semi-arid climates it was as high as 7–8 times.

Thus, the world's great natural differences in the distribution of water availability are constantly widening, and doing so very fast moreover, because of human economic activities and the ways that population growth differs between developed and developing countries.

The rise in global air temperatures, particularly noteworthy in the last two decades, which are forecast to continue during the present century, is a cause of great concern among hydrology and water resources experts.

The brief analysis in this monograph on the effect on water resources of man-made climate changes, leads to the following conclusions:

- In the last 20–25 years, there has been an observable trend in cold and temperate climates towards a considerable rise in water resources and significant changes in their intra-annual distribution, matched by a fall in arid regions, brought about by the relevant changes in air temperature and precipitation. There are good grounds for supposing that the changes result from global warming, which has gathered pace since the late 1970s;
- With a doubling in the amount of atmospheric carbon dioxide, which current forecasts say will occur by the end of this century, there is very likely to be a rise (of up to 15–30 per cent) in annual runoff in cold and temperate climates, as well as more noteworthy changes in seasonal flows. For both humid tropical regions, and for arid and semi–arid zones, quantitative assessments of possible changes in water resources are highly uncertain, being

subject to the vagaries of rainfall forecasts. It is noteworthy that the river systems in regions where precipitation is low are particularly sensitive to even minor climate changes;

- Bearing in mind global warming forecasts (by 2020–2025, world temperature rises are generally expected to be 0.6°C higher than before 1990) and the high degree of uncertainty about existing climatic scenarios, when assessing water resources and availability at continental level, major natural-economic regions and river basins for 2010–2025, there are good grounds for ignoring human-induced world climate changes. The possible errors in leaving them out of account are much lower than the forecasting errors for economic development and population rises, though they are keys to determining the stress level on water resources and its availability;
- Beyond the 2040–2050 horizon, the effect of man-made climate changes on water resources and water availability has to be allowed for, however, particularly in areas where precipitation is inadequate.

To alleviate the burden on water resources and stabilize per capita water availability in given areas, as shown in various studies, two issues must be tackled simultaneously: how to reduce water use while increasing available water resources.

The technical, socio-economic and ecological aspects of possible freshwater savings and increasing water resources by the various water management measures considered in this monograph (river flow regulation, secular freshwater use, desalination, artificial rainmaking, improved water efficiency in industry and irrigation, geographical diversion of water) let us conclude the following:

All the most important and promising ways of obtaining additional water and making freshwater savings in industry and irrigation are generally comparable in costs and possible scale needed to meet water availability targets. Sooner or later they are bound to find wide application in areas and countries where it is most reasonable, ecologically safe and economically advantageous to do so, in terms of the geography, environment and type of water use contemplated.

Among ways of increasing available water resources, geographical diversion of river flow from one area to another has obvious advantages; it is generally used, is adaptable to all physical-geographic areas, regions and continents; diverted river flow worldwide is two orders of magnitude more than that obtained through desalination, and it is continuing to grow. Taken in conjunction with the extensive application of modern water use technologies and runoff treatment, it is the author's opinion that river diversions can lay true foundations not only for reducing the water resources burden but also for stabilizing individual water availability in countries and regions round the world.

The gravest water resources and availability problems are those faced by developing countries, characteristic of which are high population growth and low incomes, which also govern the associated socio-economic growth levels. Moreover, most developing countries are located in areas where precipitation is insufficient, where even in virgin conditions, renewable water resources are not plentiful, oscillate widely over time and are very sensitive even to minor anthropogenic world climate changes.

In tackling the water availability issue in places where there is too little precipitation, it is crucial to bring in a swathe of measures that will both find freshwater savings worldwide, by applying the most efficient modern technologies and looking for additional water sources. In so doing, priority should go to methods with the greatest impact, at the lowest cost and based on geographical conditions, available technical and financial resources, the environment and national interests.

It should be noted that the search for additional water resources is vital to deal with the water availability issue since, in places where the population is fast-growing, there are only two ways of stabilizing or increasing specific water availability:

- Stabilizing the population size in most cases is impossible because of ethical, national and political considerations; or
- Finding additional water sources in the region (country) or inflows from neighbouring regions, naturally where it is mutually advantageous to do so and where comprehensive allowance is made for the possible ecological impact.

The wide application of modern water savings and conservation technologies, first and foremost by using fresh water and introducing additional water resources, needs great financial inputs. Very rough expert assessments show that to stabilize the burden on water resources worldwide (the development of water use up to the year 2025 under the SDS) will need capital expenditure of 600–900 billion US dollars; more or less the same amount will be needed to stabilize individual water availability in regions of Asia and Africa where there is a looming risk of available water falling to catastrophically low levels. If the intention is not simply to stabilize the present (extremely ominous) situation but to try and reverse it, then expenditure will evidently have to be at least doubled.

The huge resources referred to will obviously be beyond the budgetary means of developing countries, especially if it is recalled that these will have to be invested within two to three decades. However, for the world community as a whole, both developed and developing countries, the issue can be resolved in the first half of the twenty-first century, given the will to do so, a general desire to secure sustainable worldwide economic development, and to conserve stocks of good quality fresh water, the basis of life.

The *sine qua non* for uniting efforts to resolve problems of world water provision is a radical change in attitude to fresh water. It must be recognized everywhere and at every level as a priceless resource, vital to human well-being and the world economy, and a key component of the environment. It is essential to reach effective international agreements, enact strict rules and regulations for water conservation, effective water use, individual rights to water, price setting, the role of the community and the private sector in dealing with water issues, and set out a strategy of water resources management as an integrated long-term action plan in every region to attain the necessary goals for regular long-term water availability.

In laying reliable scientific foundations to improve world water use and conservation, the main priorities faced by hydrometeorologists and other experts are:

- To undertake a range of research, administrative and technical work in forming a constantly updated monthly streamflow databank from selected rivers for early assessment of the world's major basins and regions' renewable water resources and freshwater inflow into the oceans;
- To draft reliable models for calculating runoff and flow from areas where no hydrological observations have been recorded;
- To work on a uniform methodology for assessing renewable water resources and their variability for all countries, and also contemporary figures for withdrawal by prime freshwater users; to establish a databank and ensure free access by all experts and the community at large;
- To work on in-depth studies on the hydrometeorological and environmental grounds for efforts to make water use more effective, and find alternative freshwater sources for various water-starved regions, including projects to divert river flow, as the most realistic way of handling the long-term prospects for water availability; and
- To make reliable regional forecasts of anthropogenic climate changes, carry out all-round studies of the hydrological and water management consequences of such changes in different parts of the world, and develop integrated activities to adapt and mitigate harmful consequences.

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