Distr.
LIMITED
E/ESCWA/ENR/2002/WG.1/3
14 March 2002
ORIGINAL: ENGLISH

United Nations Economic and Social Commission for Western Asia

BGR Federal Institute for Geosciences and Natural Resources

Regional Training Workshop on the Application of Groundwater Rehabilitation Techniques to Different Hydrogeological Environments in the ESCWA Region
Beirut, 18-22 March 2002

GROUNDWATER MONITORING

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02-0167

Groundwater Monitoring

Benedikt Toussaint*

1 Introduction into the problem and experience made in Germany

Until the early 1970s, measurements of groundwater levels in piezometers and the discharge of springs were in the foreground in Germany and in many other European countries. Studies focussed mainly on general hydrological phenomena, on investigations of foundation conditions and on the collection of evidence, e.g. in connection with damages through waterlogging or dying trees in dry years, or on the delineation of drinking water protection zones or well catchment areas.

Only when in the industrialized western countries the occurence of numerous groundwater contamination accidents became known and made it more and more obvious that the efficiency of the purification capacity of the subsoil had in the past been overestimated or sometimes misjudged, systematic monitoring the groundwater quality became high priority. Thus, the water agencies responded to the experience that the polluted groundwater resources may causes shortages in water supplies as well as ecological problems.

The countries in the ESCWA region nowadays have similar problems, caused by severe water scarcity resulting in climatic conditions and by adverse anthropogenic impacts on groundwater quality and quantity. Particular pollution problems of concern are: overuse of fertilizers and pesticides in the agriculture sector, discharge of industrial and domestic wastes and waste water into infiltrating rivers, dry wadi beds, sand pits and quarries, percolation from septic tanks, leakage from sewers, unfit storage facilities for oil and oil products, spills of chemicals like highly volatile halogenated hydrocarbons, seawater intrusion due to overpumping in coastal aquifers, storage of toxic wastes in aquifers, irrigation with wastewater etc. Not to forget is the careless handling with water polluting substances, partially due to ignorance, partially due to criminal energy.

Contaminated groundwater can be remedied, i.e. "repaired", often only with great effort and expenditure, if at all. That is why the environmental policy must be based on the precautionary principle, which relies on the prevention of the contamination of groundwater, our hidden tresor and in many, many countries the only source for drinking water, the food number one.

Because the groundwater pollution problem is often compounded on the lack of monitoring and control regulations, an essential precondition for the implementation of the objective of groundwater protection in qualitative and quantitative term is an efficient system of groundwater monitoring. This task is not limited to the documentation of the present state, it includes moreover the registration of negative changes and their causes, so that counteraction can be initiated in time.

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Because protection of groundwater cannot be the responsibility of the state alone, but must be a concern of everyone who either uses or impacts the groundwater in any form, this task should resp. has to be tackled in a cooperative manner.

In order to optimize the measuring services, for instance in Germany sub-networks are devoted to different tasks (fig 1). In each province ("Land") there exist the governmental basic network, which is permanent and generally wide-meshed, although higher densities are possible locally. Its technical equipment allows both the measurement of groundwater level or spring delivery and the acquisition of representative groundwater samples in the entire country. This reference network is again subdivided into the background network for yielding background information of the natural (geogenic and biogenic) status of the major hydrogeological units and the trend network for the identification of anthropogenic non-point impacts on groundwater.

With regard to the exclusive monitoring of groundwater quantity there exists the so-called hydrological bench-mark or base-line network. This should provide continuing series of consistent observations on hydrological and related climatological parameters to reflect local, regional and geographic differences of the groundwater balance.

The so-called third-party networks are mostly operated by water suppliers who transmit – either voluntarily or pursuant to legislation – the chemical data of their (groundwater-borne) raw-water and the quantitative and qualitative data of the measuring stations in the catchments of their water tappings for centralized processing and evaluation to the competent governmental agency. Further specific regional or local networks monitor selected areas or are established for specific reasons, e.g. for cases of non-point contaminations which cannot be assigned to an identifyable polluter. Separate, mostly temporary networks are the so-called emitter networks and especially networks for the surveillance of contamination damages (with „impact stations") etc.

This principle is widely approved and is therefore current practice in most European countries (OTTENS et al. 2000). Therefore, the objective of this paper is to describe relevant elements of groundwater monitoring which should result in up-to-date recommendations.

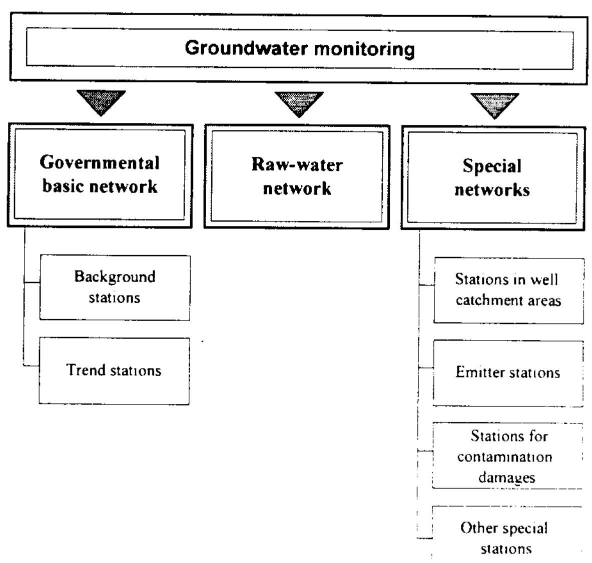

Figure 1: Components of a cooperative groundwater monitoring system with special reference to groundwater quality, example Germany (TOUSSAINT 2000).

2 Groundwater monitoring - definitions and objectives

A high population density, continously growing industrialisation and intensive agriculture have an accelerating negative effect on the natural groundwater regime (technogenic impacts such as water abstraction, melioration activities, excavation, impermeabilitization of land surface and thus increasing discharge of surface and artificial run-off, etc.) and the quality of soil and groundwater (caused by private and public waste dumps, air pollution, application of fertilizers and pesticides, use of excess manure; changes of groundwater quality are also due to disturbance of hydrodynamic balance and as consequence raising level of highly mineralized deep groundwater as well as intrusion of saline marine water, infiltration of polluted river water in the underground).

These severe problems do not only occur within countries, but can also have transboundary effects and thus eventually the consequence of international conflicts.

An effective water management has to prevent or at least to minimize the groundwater deterioration which may occur due to an increase of water mineral content such as chloride or sulphate as well as due to compounds of anthropogenic origin such as halogenated solvents. Apart from a consequent implementation of modern technologies and changes in the human behaviour the operation of a well structured and organized groundwater monitoring is one of the most important tools to obtain information needed for adequate decision-making about environmentally sound and sustainable development and the protection of the groundwater resources. The management has to be river basin-referred in accordance with the basic principle of the new EC Water Framework Directive (European Community 2000). The Directive attaches great importance to an integrated approach as surface waters and groundwater are interacting, attention is to pay to both quantity and quality aspects.

The aim of monitoring activities is to provide data for solving groundwater problems and in a much more integral and comprehensive approach environmental problems, thus ensuring the sustainability of the groundwater resources, in many countries the only source of drinking, agricultural and domestic supplies. According to the Brundtland Report of 1987, a development is sustainable when it meets the needs of the present without compromising the ability of future generations to meet their own needs.

Monitoring and assessment of groundwater must be considered as crucial tools for sustainable management of groundwater resources. A clear distinction between the two terms "monitoring" and "assessment" of groundwater is rarely made. They are frequently confused and used synonymously. Monitoring is just one of the instruments used to obtain information for the assessment of groundwater quality and quantity. It is done with the purpose to evaluate certain time dependent groundwater characteristics and has the functions to control the effectiveness of the management process and to observe the status of environment. Generally, a basic understanding and consequently a preliminary analysis or assessment of the groundwater system will first be needed to be able to define and carry out monitoring tasks. The higher the level of knowledge of the system, the more cost-effective the monitoring program can be designed and implemented. Assessment needs monitoring and monitoring needs assessment.

The process of *groundwater assessment* can be understood as "the valuation of the quantitative, physico-chemical and microbiological status of groundwaters in relation to the background conditions, human effects, and the actual and intended uses which may adversely affect human health and the environment" (OTTENS et al. 2000).

Groundwater monitoring can be defined as "the process of repetitive observing, for defined purposes on one or more elements of the environment according to prearranged schedules in space and time and using comparable methodologies for environmental sensing and data collection. It provides actual information concerning the present state and past trends in environmental behaviour" (OTTENS et al. 2000). Furthermore, the information may be used to enable the establishment of cause - effect relationships.

Groundwater monitoring can be seen as a sequence of related activities, starting with the definition of information needs and ending with the use of the information products. This cycle of activities, the "monitoring cycle" (fig. 2), is an integrative approach. It includes besides the groundwater measuring service and foregoing planning and implementation of the monitoring network also the storage and retrieval of measurements in high-performance databases as well as a reporting system that derives from these data regularly updated decision-aids for strategic and operational environmental controlling and for information of the publics, e.g. via internet.

All stages of the monitoring process should be considered because the evaluation of the obtained information may lead to new or redefined information needs, thus starting a new sequence of activities. In this way the monitoring process will be improved.

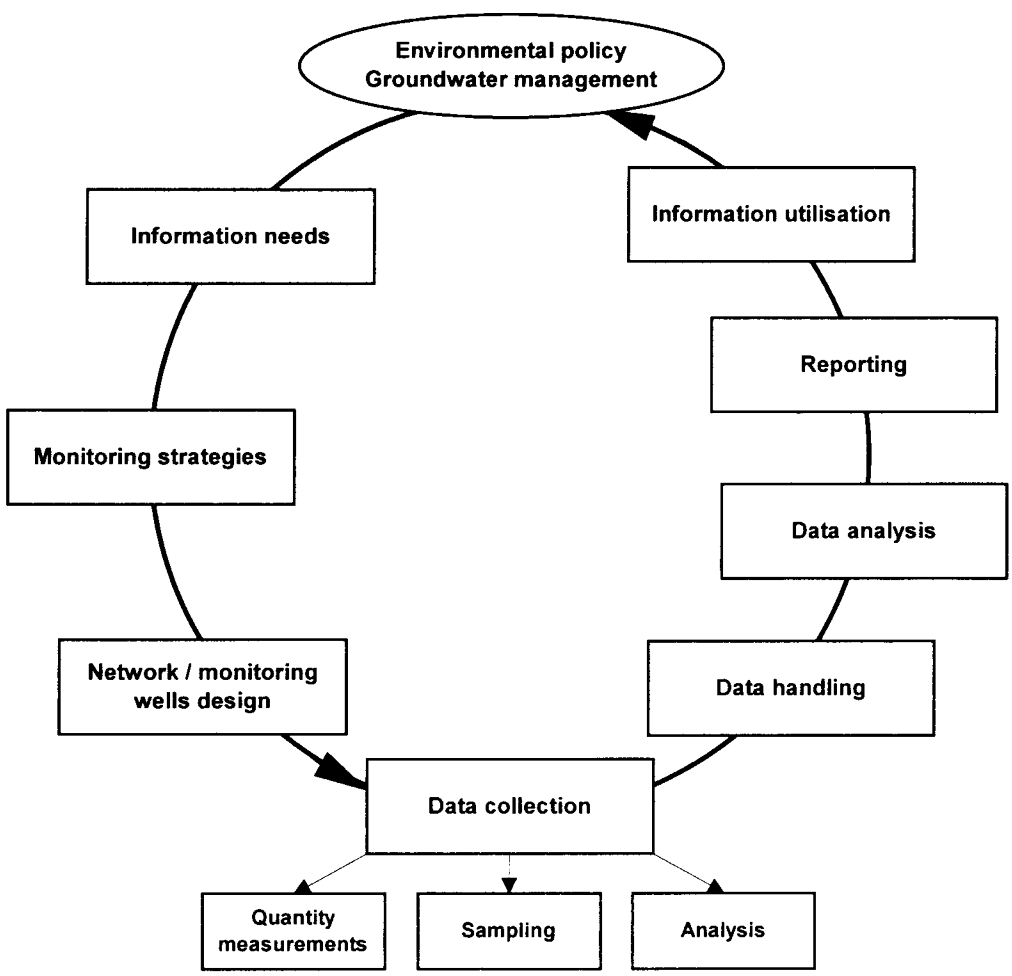

Figure 2: Monitoring cycle (after OTTENS et al. 2000).

The successive activities in this groundwater monitoring cycle are always linked to the management issues resp. to the illustration of conflicting interests and derived from this with a well designed specification of information needs, and data to be collected (fig. 3). The diagram shows the elements in water management and their interactions. The table 1 documents examples for possible functions / uses, pressures and issues.

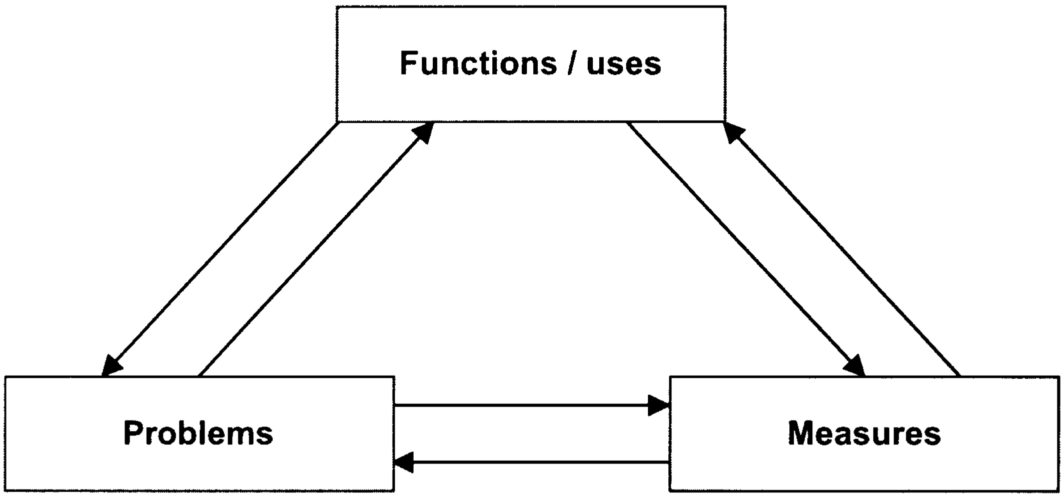

Figure 3: Core elements in water management.

Table 1: Possible functions / uses, pressures and issues

Possible functions /uses		Pressures	Issues
Ecological function			
Water supply	- drinking water - agriculture - industry	- land use (diffuse pollution: agriculture, (geo-)infrastructure, industry, urban areas) - airborne pollution - potential pollution sources	- desiccation, desertification - acidification - excess nutrients loads - salinization
Storage	- waste - geothermal energy	- point/line pollution sources - potential pollution sources	- pollution (orga-nic, heavy metals)
Transport	- soil remediation - confinement of pollution		- spreading of pollutants - public health
Miscellaneous	- prevention of land subsidence - protection of foundations		- land subsidence - foundation problems - over-abstraction

As the author is a hydrogeologist, in this paper the accent lies predominantly on specific parts of the monitoring activities labeled with "Monitoring strategy" ,"Monitoring network system design", "Establishment of the monitoring system" and „Operation of the monitoring system" in fig. 4.

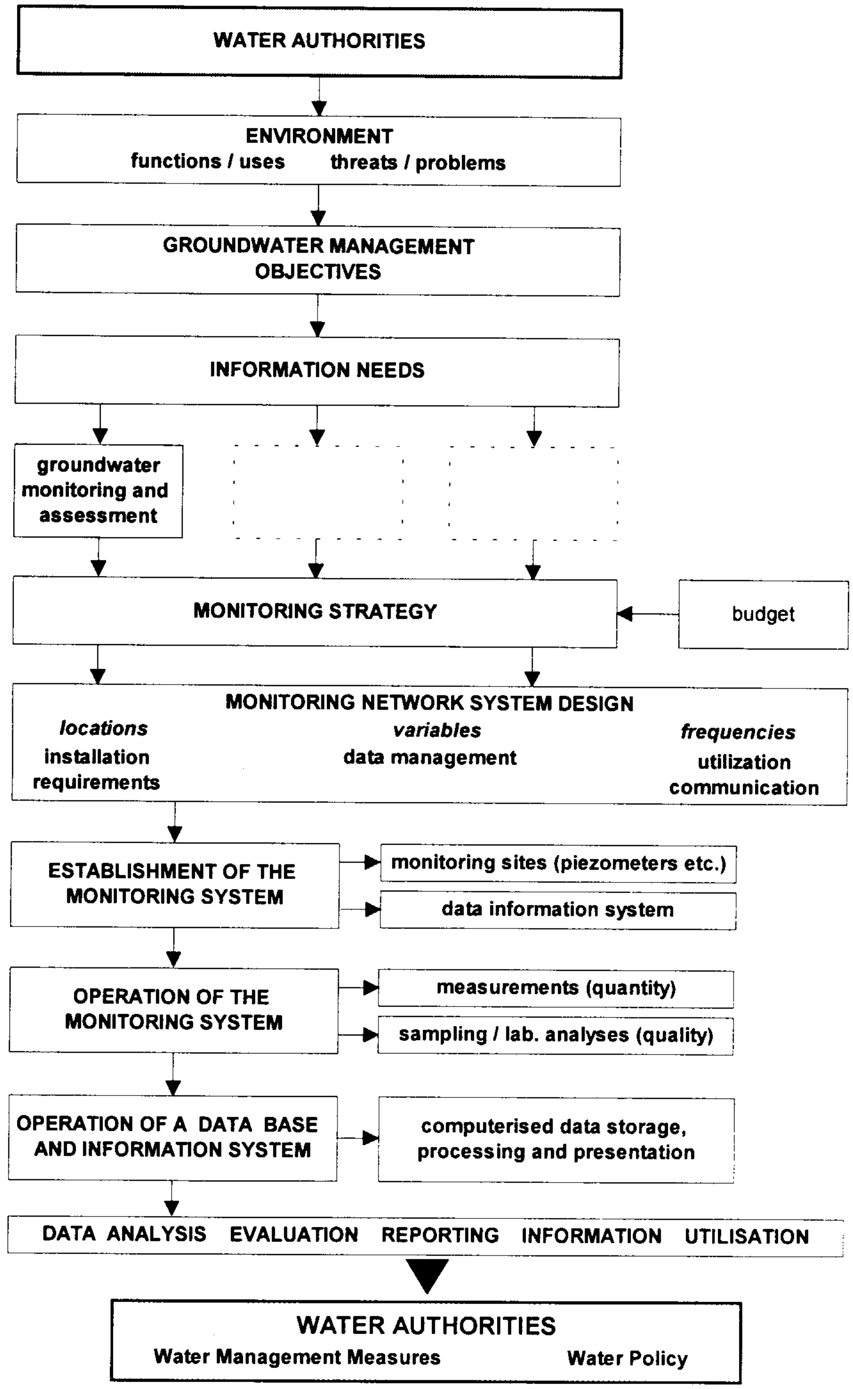

Figure 4: Implementation process of groundwater monitoring.

In this paper, quantitative aspects are subordinate to the viewpoint of groundwater quality, although many operating networks collect information on groundwater quality as well as groundwater levels or spring discharge. Superimposed influence of human activities, especially groundwater exploitation, may have impact on quality, for example intrusion of saline water into heavily exploited aquifer, and these impacts can therefore be assessed most effectively by observing groundwater quantity and quality together. That means quantity data are needed for the interpretation of quality data and vice versa. In that case, the final selection of monitoring stations and measurement frequencies will depend on an integration of both designs.

3 Criteria for monitoring network design

The design of a network may have two extreme points of departure. Firstly, a design of a network may start almost from scratch, without or with few available historical groundwater monitoring data and consequently a hydrogeological approach will be the basis of the design procedure. Secondly, a design of a network might start with the availability of sufficient historical monitoring data. In that case and if the target parameters can be sufficiently quantified, the design can be considered as an optimisation problem and might be fully supported by statistical considerations (the well known Kriging technique is often applied). However, it is expected that generally in most existing systems both the availability of hydrological data is limited and they do not comply with the modern demands of groundwater experts. Therefore, the so-called hydrogeological approach is the basis of the procedure most commonly used in practice. The network design follows from a deterministic, hydrogeological area description based on expert judgement without the use of advanced geostatistical methods.

With a less important priority, the design of a monitoring network is depending on further points of view: easy site accessibility, available personnel, sampling campaigns, organisations of institutions responsible for monitoring, financial constraints (the monitoring network is designed by balancing the information content and the monitoring effort, i.e. costs) and last, but not at least the kind of potential pollution hazard sources.

Because of the hydrogeological approach special attention is to pay to the geological and hydrogeological features of the groundwater bodies to be monitored, to stratification characteristics, to groundwater recharge (decision on a case-by-case basis which method is suitable for the regional circumstances), to groundwater flow velocity and flow direction, to hydrochemical characterisation of the groundwater including anthropogenic impacts, and to the identification and mapping of protected areas.

Non considering the necessary information means the danger of failure. The objective is to develop tailor-made criteria for the design of groundwater monitoring networks. Following the author provides some details of the different steps to be taken in performing and optimizing the network design.

3.1 Interpretation of geology and geohydrology conditions

A consistent picture of the geological conditions of the underground and a deductive hydrogeological model are the precondition for a proper design and selection of representative locations for a monitoring network and moreover for the assessment of quantitative and qualitative groundwater data. This absolutely necessary integrated interpretation of geo-scientific facts should comprise a characterisation and description of the hydrogeological units. Also, the dynamics of the groundwater flow system, such as seasonal or longer-term responses, and variations and changes in flow rate or direction caused by human activities, particularly groundwater abstraction, must be understood. Knowledge of the groundwater flow system means in particular the boundaries of hydrogeological units, the locations of groundwater recharge and discharge zones and the way groundwater flows through aquifers from zone to zone. To determine recharge and discharge conditions in some areas, the interaction between surface waters and groundwater need to be understood.

The interaction between rock material and circulating water causes the natural geohydrochemistry. Before it is possible to detect any impact of human activity, the change of background conditions over time, space and depth have to be determined. There, the evaluation of already collected groundwater quality data is indispensable.

- Origin and properties of the rocks in the underground and resulting nature of the groundwater

In order to make an assessment of the groundwater bodies, it is necessary first of all to describe the geological conditions and to establish a hydrogeological inventory. The major aquifers have to be described by reference to their various geochemical and hydraulic characteristics. In detail the study of geology and hydrogeology is complex, but the following overview of the origin and properties of the rocks in the underground and the resulting groundwater properties should be sufficient.

We can differ consolidated rocks without or with fractures, and unconsolidated, porous rocks. Depending on the types of openings and the permeability coefficients the geological bodies shall be classified into aquifers ($kf \geq 10^{-5}$ m/s), aquitards ($kf = 10^{-5}$ to $kf = 10^{-9}$ m/s) and aquicludes ($kf \leq 10^{-9}$ m/s). Commonly, the consolidated rocks with exception of sandstones and limestones or dolomites have the hydraulic function as aquiclude or as aquitard (with low values of permeability which allows some movement of water through it), act as boundaries to aquifers and may form confining strata. When there is more than one aquifer separated by aquicludes or aquitards of less permeable material, the possible pathways or connections between them need to be evaluated. In general, especially the sand and gravel media are more or less good until very good aquifers.

Nearly all of the porosity and permeability of <u>igneous rocks</u> (these are plutonic rocks such as granite or volcanic rocks such as basalt) and metamorphic rocks (e.g. gneiss, metaquartzite or marble) are the result of secondary openings, such as fractures, faults and joints, and the dissolution of certain minerals. Because the openings in igneous and especially metamorphic rocks are mostly quite small, rocks of this type are commonly poor suppliers of groundwater. Moreover, this type of rocks drains in general rapidly after a period of recharge, and because of small permeabilities and storage coefficients the yield of pumped wells is mostly negligible. Volcanic rocks can be exceptions, because fractured and thicker basalt layers, eg. in northern and northeastern Jordan or in the southern parts of Syria, are a major source of water. Unless some special circumstances, the anthropogenically not influenced groundwater is nearly always of excellent chemical quality, dissolved solids are commonly less than 100 mg/l. On the other hand, the waters circulating in igneous and metamorphic rocks are vulnerable to contamination where these rocks crop out.

Usable supplies of groundwater can be obtained from all types of <u>sedimentary rocks</u> (either clastic such as sandstone or chemical/organic such as limestone), but the fine-grained strata, such as shale, or siltstone, may only provide a few liters or cubicmeters per day and even thus can be highly mineralized. Even though fine-grained rocks may have relatively high porosities, the primary permeability is very low. On the other hand, shale is likely to contain a great number of joints that are both closely spaced and extend to depths of several ten meters. Therefore, rather than being impermeable, they can be quite transmissive. This is of considerable importance in waste disposal schemes because unsufficient attention might be paid during engineering design to the potential for flow through fractures. From another perspective, fine-grained sedimentary rocks, owing to their high porosity, can store huge quantities of water. The porosity decreases with depth because of compaction brought about by the weight of overlying sediments.

The porosity of sandstones, formed of lithified sand, ranges from less than 1 percent to a maximum of about 30 percent. The mineral cement (mostly clay, calcite, quartz, or limonite) formed during burial diagenesis can be variable both in space and time and on outcrops can differ greatly from that in subsurface.

Fractures play the most important role in the movement of groundwater through sandstones and therefore transmissivities may be much as two orders of magnitude greater in a fractured rock than in an unfractured part of the same geological formation. Commonly, they play a big role as water supplier. For instance, the Nubian sandstone of Upper Mesozoic age is in some ESCWA countries the most important aquifer, but the abstracted groundwater is fossile and sometimes highly mineralized.

Carbonate rocks are formed in different environments and the original porosity and permeability are modified rapidly after burial. In contrast to marl, marlstones or argillaceous limestones pure limestones develop high yielding carbonate aquifers of particular importance due to the presence of fractures and other tectonically induced secondary openings (e.g. joints, and fissures) thus favouring the dissolution of carbonates along fractures and bedding planes by circulating groundwater. Regions in which there has been extensive dissolution of carbonates leading to the formation of caves, underground rivers, and sinkholes, are called karst. Notable examples include for instance the Cretaceous limestones along the Jordan graben.

On the one side karst areas can provide large quantities of water to wells and springs, on the other side they are easily contaminated because the water can flow very rapidly, and there is no filtering action to degrade the pollutants. In the case of a polluted well or spring it is very difficult to trace back the pollutants to the possible release location because groundwater can flow in overcrossing conduits (karst pipes).

Most of the unconsolidated rocks owe their emplacement to running water as agent of transportation. Well sorted fluviatile sands and gravels deposited in broad valleys or in tectonical graben structures include important groundwater bodies and serve as major aquifers. On the other hand fine sands, silts or clays have the hydraulical function as aquicludes or aquitards, but only homogeneous and fine-grained porous material are hydraulically effective barriers between pollutants and groundwater.

An intergranular groundwater flow is generally slow (order of magnitude: some ten meters until a few hundred meters per year). Therefore, the potential for interaction between aquifer material and groundwater is high in space and time. Commonly, groundwater circulating in porous media is of excellent quality.

Generally, the characterisation of aquifers in porous media with intergranular primary porosity is from the standpoint of hydrodynamics less complicated than in media with secondary porosity, which is linked to joints, fissures or fractures in hard rock formations or voids formed by dissolution of limestone. Monitoring and assessment of groundwater in fractured rocks and in karstic features will therefore need special attention.

The difficulty of evaluating groundwater contaminant movement in fractured rocks is that the actual direction of movement may not in the direction of decreasing head, but rather in some different direction. The problem is further compounded by the difficulty in locating the fractures.

Because of these characteristics, evaluation of water availability, direction of movement, and velocity is exceedingly difficult.

Generally, the very difficult characterisation of such systems will compliate the set up of adequate monitoring. Therefore, samples should preferentially be taken from springs, when ever possible, since in them groundwater surfaces in a natural way (therefore groundwater samples are undisturbed), and the measurement data can usually be related to a larger area (aggregated information), whereas drilled groundwater observation wells give, as a rule, only information on point. For hydrogeological reasons, springs are more frequent in regions with hardrock underground than in unconsolidated rocks.

A prerequisite for monitoring and assessment of groundwater resources and quality is the characterisation of the condition of groundwater flows. The groundwater flows from recharge areas (in these areas the groundwater regeneration by infiltrating precipitation is higher than the surface or subsurface flow) to discharge areas. Discharge areas can be springs or rivers, in the case of groundwater abstraction production wells. Transboundary aquifers might have recharge areas on one side of the border and discharge areas on the other side (fig. 5). Activities within the recharge areas ot one side of the border might adversely effect the groundwater quality on the other side of the border.

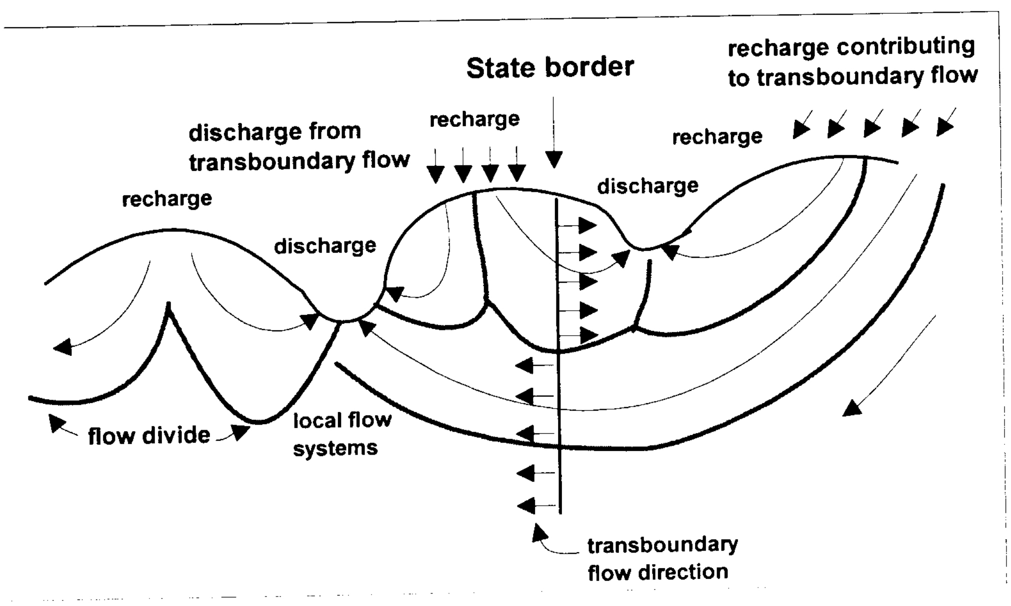

Figure 5: Transboundary groundwater flow systems.

Without anthropogenic impacts the chemistry of groundwater is governed by inorganic contents such as chloride, sulfate, hydrocarbonate (anions) and sodium, potassium, calcium and magnesium, further iron, manganese and ammonium (cations) commonly in low concentrations and heavy metals such as copper, or lead generally in traces.

Especially chloride is locally largely due to industrial activities. The intrusion of seawater caused by overpumping coastal aquifers or inter-aquifer leakage related to pressure declines brought about by withdrawals. Higher sulfate levels can result either in the given geological conditions (e.g. gypsum in sediments) or there is a direct or indirect contact with human activities (e.g. fertilizing, reduction of man-produced nitrate in the presence od sulphides such as pyrite). In humide climate, nitrate is not of geochemical nature, but is exclusively referred to processes in the biologically active soil. Nitrate contents of more than 10 – 15 mg/l derive from fertilizers or sewage. This water problem is of growing concern especially in irrigated agricultural areas and in the groundwater downstream of cities. Boron can also be abnormaly high in certain areas, it is an indicator parameter for domestic waste disposals or spread of contaminants from leaking sewers. Another problem is the flux-increase of accidifying substances, which can result in lowering pH value or in a decrease of the acid neutralising capacity of the soil.

Nevertheless, nowadays organic pollutants, generally indicated by elevated concentration of dissolved organic carbon (DOC), gain increasing attention, because halogenated solvents, BTEX hydrocarbons (benzene, toluole, ethylbenzene, xylole), PAHs (polycyclic aromatic hydrocarbons such as benzpyrene) and other synthetic organic compounds are toxic and partially carcinogenic even in µg- until ng-concentrations. This severe deterioration of groundwater quality is mostly caused by industrial activities.

- Characterisation of the groundwater cover and assessment of the vulnerability

An aquifer can be considered vulnerable when problems will occur relatively fast after a threat becomes effective and little or no time will be available to implement adequate counteracting measures. Therefore the assessment of the vulnerability provides important information to assess possible effects as a consequence of certain groundwater uses and functions or other human activities. Furthermore, this information is needed for the design and implementation of a prober groundwater monitoring system.

The vulnerability of the aquifer mainly depends on the groundwater flow situation (confined or unconfined, recharge, direction, flux, and discharge), the thickness of the unsaturated zone and its hydraulic and (bio)chemical properties (e.g. organic content, usable field capacity and composition of the top layer), and geology. An aquifer is considered highly vulnerable when high infiltration rates are combined with high permeabilities and small retardation capacities for pollutants. Consequently, highly vulnerable areas combined with high threats and high risks for health (e.g. drinking water) and environment need adequate protection measures and monitoring to evaluate the implementation and effectiveness of the measures.

The purpose of characterising overlying strata must be to assess the protective effect of the groundwater cover which shall be accorded to the categories favourable, medium, and unfavorable. Following, a simple procedure is given.

Favourable conditions occur where the cover is continuous, expansive and of great thickness (of ≥ 10 metres) and predominantly cohesive constitution of the cover (e.g. clay, silt, marl).

Medium conditions occur where there are strong variations in the thickness of groundwater cover and predominantly cohesive constitution (examples as above) or where there are very great thicknesses yet high water permeabilities and low pollutant-retention properties (e.g. silty sands, jointed claystones and marlstones).

Unfavourable conditions occur where, despite a cohesive constitution, there are low thickness or where, despite great thickness, there is predominantly high water permeability and low pollutant-retention capacity (sands, gravels, jointed and above all karstified consolidated rocks)

Since the vertical movement of substances in the unsaturated zone depends on the height of groundwater recharge, the rate of recharge - if known – must also be considered in the assessment. Thus, under "medium conditions" of groundwater cover, low groundwater recharge rates (≤

100 mm/a) can shift the outcome of the assessment into the "favourable" category, and high groundwater recharge rates ($\geq$ 200 mm/a) into the "unfavourable" category.

A favourable situation is also indicated by confined conditions, especially where the groundwater is characterised by artesian confinement.

In case of doubt, the classification should always shifted on the side of the less favourable category.

Compared with consolidated rocks and especially with karst terrains in porous media the vulnerability of groundwater to contamination is essentually lower. The reasons are a higher degree of pollutant retention by filtering in the narrow pore space and due to the mostly slow velocity and the network of hydraulically connected small voids enough residence and contact times and surface for physical, chemical, and biological reactions and processes are favouring the elimination of pollutants. Particularly in the case of a greater thickness of a less permeable layer above the groundwater table, the degree of protection is high. On the other hand, recharge areas with shallow groundwater in combination with given hazard potentials such as solvent or fuel storage facilities the groundwater is highly vulnerable to pollution. Therefore, with view to groundwater quality especially shallow aquifers are subject to monitoring, because contaminants are generally introduced from the land surface.

The highest risk of groundwater deterioration may exist if a low protection potential of the upper confining stratum coincides with potentially dangerous uses and significant replenishment of the groundwater body. This is above all the case in the face of wide-scale and long-term interference in the superficial strata (far-reaching changes in land use), extensive infrastructure measures and housing areas, or major diffuse impacts of pollutants.

3.2 Characterisation of chemical pollution by point and diffuse sources and of man-made changes of the groundwater flow system resulting in quality deterioration

The network design also has to take into consideration the real or possible existence of pollution sources. We can differ between a direct chemical impact on the groundwater (fig. 6) and an indirect man-made influence caused by changes of the groundwater dynamics.

Point sources have a significant risk potential and are frequently a result of accidents or are due to a longer term inappropriate treatment of substances that are hazardous to water. However, old deposits (landfills that are no longer in use) and abandoned sites (closed down industrial sites) have the greatest relevance to potential groundwater contamination. Where a contamination of the soil and/or of the groundwater can be demonstrated here, we shall refer to the presence of a contaminated site. Landfills, industrial installations and installations used for handling substances hazardous to water that were built using best available technology shall not be regarded as point sources.

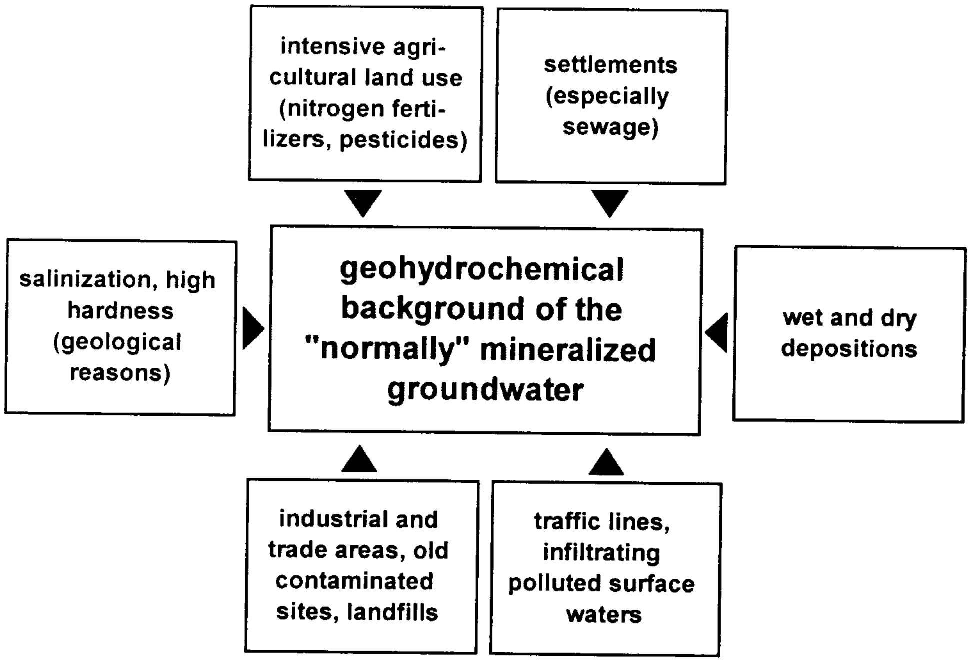

Figure 6: Groundwater pollution sources.

Via point sources, pollutants can enter the groundwater directly (discharges) or indirectly through an underground pathway (contamination focus in or on the soil surface). While the sources are confined to a small area, the polluted plume may spread over a large area in the groundwater. Characteristically, point sources can be localised well as a rule but cannot always be traced back to a single polluter, and the resulting pressure by pollutants on the groundwater is comparably large.

Diffuse sources are understood as spatial or linear substance emissions that cannot be traced back directly to a single polluter or to a point emission source. For example, land use in the shape of intensive agriculture may constitute a diffuse source, and general air pollution is also regarded as a diffuse source. In addition, traffic routes and linear installations are also assigned to the category of diffuse sources. Point source discharges into groundwater that cannot be clearly localised or quantified also lead in aggregate to diffuse pressures as a whole (e.g. leaky sewers).

Emissions from diffuse sources can result in a modification of natural groundwater quality. The types and quantities of substances that actually enter the groundwater depend on the retention and degradation processes undergone by the respective substance on its way to the groundwater.

The most widespread impact on the quantitative status of a groundwater body is from long-term groundwater abstractions. One can above all mention here: abstraction for drinking and industrial water supply, flooding measures in connection with mining/large-scale building schemes, lowering of groundwater levels when rock and earth is extracted, and abstraction for sprinkling and irrigation.

Groundwater over-abstraction results in an impairment of the quantitative status over a wide area because it upsets the quantitative balance, in some cases also in several aquifers. Excessive resource exploitation resulting in a noticeable change in pressure conditions or major interference in the flow field can lead to negative changes to groundwater quality. In coastal regions, saline intrusions may be activated, while in other places the water levels show a long-term downward trend that indicates excessive strain on the groundwater resource combined with the ascent of highly mineralised water from deeper layers (fig. 7).

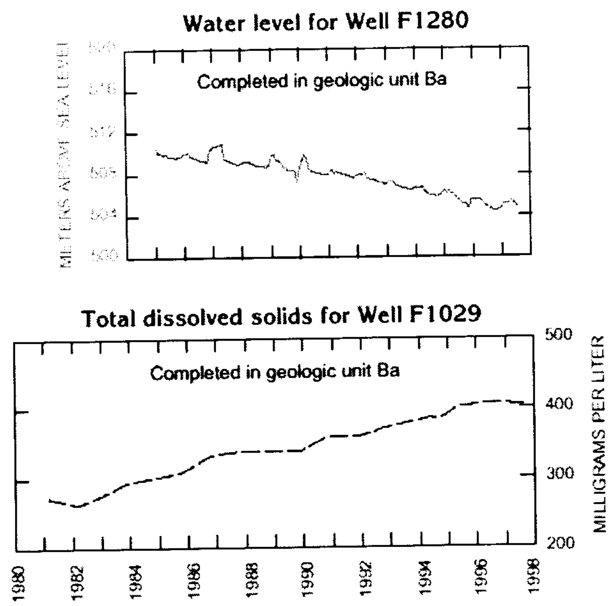

Figure 7: Hydrograph lines in the Azraq Basin, located in the Jordan Plateau (Tertiary basalts underlain by Cretaceous limestones), show a long-term decline in response to pumpage (e.g. well F1280, above) and a general increase of the dissolved solids concentrations, mostly of NaCl (e.g. well F1029, below).

In addition to impacts on the quality of groundwater from point and diffuse sources and impairments of the quantitative status by groundwater abstractions there are other pressures to be mentioned. Both quantitative and chemical aspects usually have to be taken into account for the anthropogenic influences on groundwater status.

Widespread land sealing by housing and industrial areas results in a considerable reduction of the groundwater recharge rate. Moreover, groundwater quality may also change as the groundwater temperature rises and gas exchange is inhibited.

Widespread changes in vegetation status can, by affecting water retention and evaporation conditions, lead to alterations in the water balance and thus influence the quantitative and qualitative status of the groundwater.

Open expanses of water created by flooding of underground and open-cast mines can have an impact both on the water balance and on the quality of groundwater

Water engineering work on surface waters (e.g. (building of canals, reservoirs, dam steps), straightening of water bodies and modifying their beds, result in changes in groundwater level and flow conditions in hydraulically connected aquifers. In the course of alterations to the flow field, the chemistry of the groundwater may also change.

Wastewater sprinkling and irrigation does contribute to groundwater recharge, but it can have a negative impact on groundwater quality.

In some areas, introducing (purified) wastewater into an infiltrating surface water body make a considerable contribution to groundwater recharge. If wastewater is fed into these waters, this may impair groundwater quality.

3.3 Design and density of groundwater networks

Monitoring systems must be developed as a result of national demands and management objectives, monitoring programs, geological and hydrogeological situation, land use, and naturally costs, and sometimes statistical considerations (table 2).

Table 2: Factors which determine location and density of monitoring wells

Factores
Management objectives / Information needs
Monitoring program (strategic, operational, early warning monitoring etc.)
Geology/Hydrogeology (aquifer types and distribution, flow field, groundwater cover)
Vulnerability of groundwater to pollution
Water abstractions
Land use / anthropogenic impacts
Statistical considerations
Costs

The recommendation of a hydrogeologist is that number and locations of monitoring wells should be strictly determined first by the geological/hydrogeological conditions, vulnerability assessment, mainly based on the groundwater flow situation (recharge and discharge areas), soil composition and geology, furthermore by identification of the threats to which the groundwater body is exposed, and by the problems which affect the aquifer, e.g. acidification, nutrients, salinization, pollution, etc. (table 3). Additionally to take into consideration are the spatial scale of the correlated variable, and the frequency of measurements and sampling activities.

Within a national context, monitoring networks generally have two fairly broad categories of objectives. These are basic or reference monitoring networks and specific purpose monitoring networks. The objectives of the basic networks are threefold: (1) providing data for characterising the groundwater regime und the groundwater quality, (2) providing data for detecting long-term trends in groundwater levels/spring discharges (quantity) or groundwater quality, and (3) serving as a reference network for the specific purpose networks (table 4).

Table 3: Problems in connection with drinking water supply (examples)

Problems	**Pressure**	**State**	**Impact**
excess nutrients	use of fertiliser (N, P) discharge of N and P to groundwater density of cattle type of agricultural method type of crop	BOD, DO, N, P in groundwater % of m^3 of groundwater not in compliance with drinking water standards	nitrate in drinking water effect on ecosystems vegetation change soil detoriation
acidification	deposition of acidifying substances agricultural methods	pH, SO_4, NO_3 in precipitation mobilisation of Al and heavy metals in soils	effect on ecosystems vegetation change
salinization/salt water intrusion	discharge to water type of crop agricultural use (irrigation) industrial water use domestic water use water management (over-exploitation in general) climate plant cover	water quality (salt) chloride concentration	loss of yield impairment of drinking water quality
dispersion of heavy metals		concentration of heavy metals	Pb levels in blood
hydrological change/ desiccation	desiccation	length of dry season water temperature salt content amount (m^3) water in shallow aquifers	impairment/loss of wet ecosystems
waste	production of: domestic waste industrial waste nuclear waste other hazardous waste	number of dump sites amount of waste	leakage to groundwater potability problems
dispersion of other hazardous substances	production/transport/ use/storage of hazardous substances	concentration of hazardous substances	number of water-borne diseases number of cases exceeding drinking water standards
declining groundwater tables	drinking/industrial water demand	declining groundwater tables	loss of yields

The distribution of the observation points of the network in space should enable the determination of the target parameters (e.g. groundwater table, spring discharge, groundwater contents) anywhere in the system by correlation of the measurements among different observation points with sufficient accuracy. The selected density should be made in such a way that the estimated value of a target parameter is sufficiently accurate. A greater density of the monitoring network will lead to a smaller estimation variance, but also to higher costs. Therefore, compromises seem to be inevitable, but only can be accepted if all main factors determining the design of a groundwater are considered sufficiently (see table 2) and the various types of groundwater monitoring categories and networks are well defined.

The choice of the position of monitoring stations must ensure that the variability of the groundwater table or spring discharce and of the groundwater quality over space and time can sufficiently recorded within the major hydrogeological units or in impact areas. The desirable or target density of a groundwater network is basically determined by the hydrogeological complexity and the geochemical inventory of the aquifer. In general, the characterisation of unconfined and in particular near-surface groundwater flow systems will need a denser network of observation points as deeper confinded or semi-confined aquifers. As a rule, in hydrogeological units with a high degree of homogeneity a much less dense network of monitoring wells than in systems with strong heterogeneity is sufficient. Only a few monitoring wells are required in the case of a porous aquifer, but an essentially greater number of monitoring wells is necessary in fractured aquifers.

As the groundwater surfaces naturally in springs and therefore the recorded data refer to a greater catchment area, the choice of springs as monitoring sites is recommended, especially in regions with outcropping hard rocks or with karst features and in particular for groundwater sampling purposes. With regard to representative data, one spring can replace a number of monitoring wells.

In aquifers affected by exploitation and/or anthropogenic impacts (industry, intensive agriculture, landfills, abandoned industrial sites, etc.) the network density should be higher. With regard to diffuse pollution sources, the various geohydraulic types of areas should each be covered by monitoring stations, especially the recharge areas with their possible input of contaminants dissolved in percolating waters.

Different monitoring and assessment strategies often mean different network design. With respect to the requirement that data recorded at a well have to be typical for the wider area the following matrix presents proposals for network designs depending on various scenarions (see also fig. 8). The upper aquifer is the focus of observations. Where other significant aquifers, e.g. relevant to the water supply, exist, these shall be monitored separately. Especially in consolidated rocks, which are channeled by chemical dissolution (karst aquifer), in general springs should be chosen instead of boreholes (monitoring wells).

Generally it is to differ between a large-scale basic/reference monitoring of the groundwater quantity and quality and local control resp. investigation measures referring to contaminations or a pollution potential. In the first case, the concept provides the installation of a relatively low number of „representative“ monitoring wells per hydrogeological unit. In the second case, the objectives are sectorial mostly small but dense networks, consisting of clusters or predominantly of measurement lines.

Table 4: Main types of groundwater monitoring

Types of groundwater monitoring		**Characteristics**	**Information**
State-of-the-art	Comparable types		
Strategic (state assessment and compliance)	- background stations - reference system - statuory monitoring	- beyond local anthropogenic influence - relation to diffuse anthropogenic or natural causes - international directives and conventions	- natural situation - trends (natural, diffuse pollution, hydraulic regime) - baseline (to detect human impact on groundwater), background levels - spatial distribution - compliance - reference situation
Operational (compliance, special protection areas, remediation and restoration)	- user-related monitoring - compliance monitoring - implementation monitoring - effectiveness monitoring - validation	- linked to uses and functions, regulations, laws, directives, acts, etc. - protection of functions and uses - numerical models - implementation and effectiveness	- quality standards - criteria, thresholds - health risk - environmental risk - validation - forecasting - effectiveness of measures - implementation monitoring
Surveillance/ Emergency response	- early warning monitoring - impact monitoring	- control (of management measures)	- thresholds - early warning - trends - risks - effectiveness of measures - impacts

a) Strategic networks (basic/reference monitoring)

The measuring (quantitative data) and sampling points (qualitative data) act as reference stations and are regularly monitored at moderate intervals (see chapter 4). The aim of mapping the geogenic quality and the natural groundwater flow and balance has priority. Is the aquifer homogeneous, generally a few monitoring stations are distributed more or less evenly over the aquifer. in the case of consolidated rocks their number should be greater than in porous aquifers (fig. 8 a).

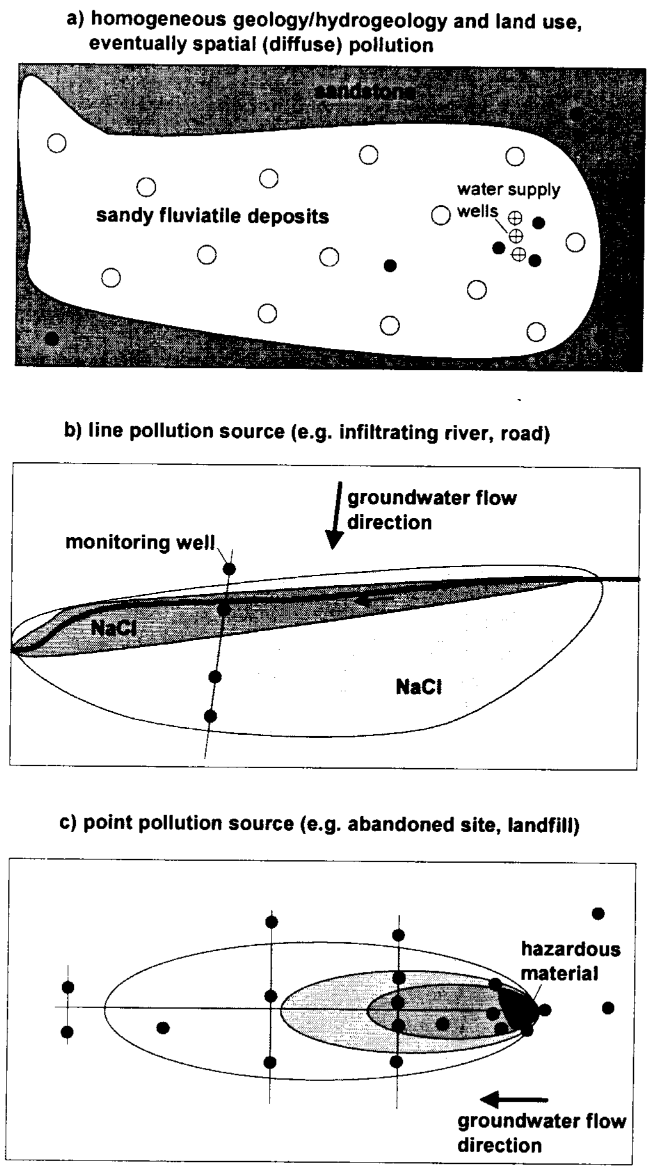

Figure 8: Types of groundwater networks – spatial distribution of the monitoring wells depending on geology/hydrogeology and kind of pollution source.

b) Operational networks (linked to functions and uses)

The density of the networks depends on the function and uses of the groundwater. One example is the early-warning or quality-assurance monitoring of drinking water supplies, involving periodic sampling of public wells to determine wether drinking water standards are met (fig. 8 a). A greater number of monitoring wells is concentrated in the catchment area/cone of depression around the drinking water pumping wells.

c) Surveillance networks

Impact monitoring activities are mostly performed at a local level and have a higher density than the strategic networks. In the case of a line pollution source, such as a road or an infiltrating surface water, usually one or more monitoring well profiles are established along the groundwater flow direction (fig. 8 b). Because there exists sometimes a more or less significant groundwater table „mound" beneath the river bed, it is correct, to sample in the up-stream sector, too. In the case of a point pollution source, it is to differ between source monitoring and plume monitoring (fig. 8 c). As a rule, there exist some monitoring wells in the groundwater up-stream and in narrow neighbourhood around the point source and a greater number of monitoring wells in the down-stream plume to define its extent and geometry. The monitoring wells are often related to profils perpendicular to the axis of the moving plume. Point source monitoring mostly becomes a part of legal proceedings to assess wether or not environmental damage has occurred and to identify the responsible party.

In all scenarios, not only the site characteristics (geology/hydrogeology, size of area under investigation, contaminants, etc.) and the number of monitoring wells are closely linked, the chemical analysis of groundwater samples from present wells can direct the placement of additional wells. Especially in view of the monitoring of line and point source contamination, without some preliminary hydrochemical data it is usually very difficult to determine the location of the most polluted zone. All aspects help to determine where and how many wells should be constructed. Certainly, the more complex the hydrogeological features and the pollution source, and the larger the area being investigated, the greater the number of monitoring wells that will be required.

4 Criteria for design and construction of monitoring wells

After the design has been completed, the system has to be established. In a first step one might want to make use of previously installed wells. In this connection it is important to know that design and construction of existing monitoring wells can include potential sources of error influencing the representativity of the measured values and the following data interpretation. Therefore, the evaluation of all existing records and following function tests of selected monitoring wells are absolutely necessary. The results must be the base for an elimination or in the case of feasibility partially for a repair of monitoring well not fulfilling the requirements.

Purposely designed and installed observation wells or piezometers tapping the groundwater body to be monitored are in general the best solution, but drilling and installation activities must meet criteria to ensure proper execution of the works and use of proper materials in order to establish an observation well which is representative for the particular situation defined for the design of the network. The design of a monitoring well must be adapted to the monitoring program, the hydrogeological situation, the parameters to be measured, the location and depth for which the parameters should be representative and the sampling techniques.

It is recommended to construct some preliminary (so-called pilot) boreholes and monitoring wells to collect and analyze geologic material samples, to measure groundwater levels, and to sample groundwater, all of which provide a guide to the detailed future placement of (additional) monitoring wells. Accurate water-level information must be obtained to determine if local groundwater flow directions and gradient differ significantly from the regional appraisal. The analysis of preliminary water-quality samples can be helpful in the vertical arrangement of monitoring wells, especially for pollutants that are denser than water. Without some preliminary chemical data, it is usually very difficult to determine the location of the most contaminated zone.

A monitoring well differs from a water supply well, because the ability to produce large amounts of water is not the primary objective. Emphasis is placed instead on a construction that will provide easily obtainable groundwater samples and thus reliable, meaningful information. Therefore, materials and techniques used for constructing a monitoring well must not materially alter the quality of the water being sampled. An understanding of the chemistry of suspected pollutants and the geological setting in which the monitoring well is to be constructed play a major role in the drilling technique and well construction materials used.

Following an overview is given of monitoring well drilling methods, and important components needed in well design such as diameter, casing and screen material, screen length and depth of placement, sealing material and procedures, development, and security. The recommendations refer to standard monitoring wells (fig. 9) with the elements casing consisting of segments of solid pipe, slotted section of pipe (well screen), annulus material (chemically inert), filter pack, bentonite seal directly over the filter pack, mixture of sand and bentonite over the impermeable bentonite plug, concrete at the ground surface, and protective steel collar at the ground surface.

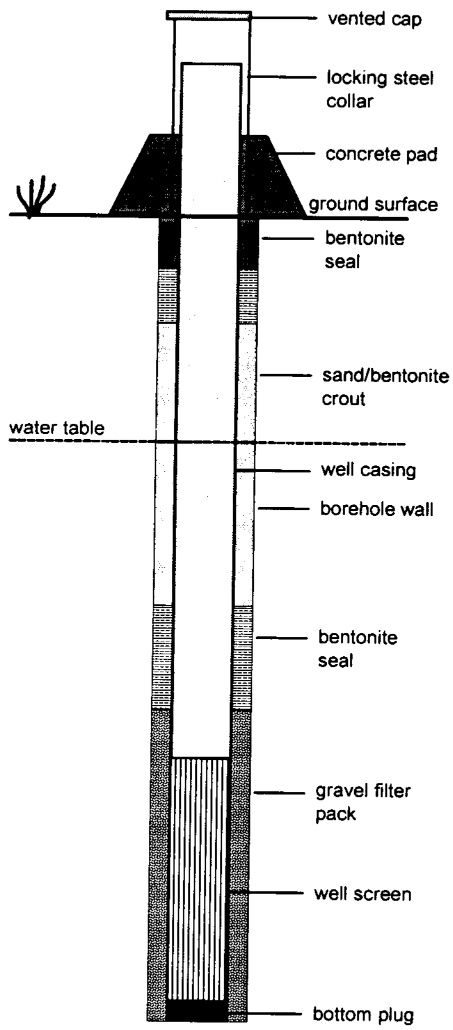

Figure 9: Standard construction design of a monitoring well.

- Monitoring well drilling methods

As might be expected, different drilling techniques can influence the quality of a groundwater sample. The criteria used to select an appropriate drilling method are the following factors: hydrogeological conditions (e.g. depth of desired screen setting below the top of the saturated zone), equipment availability, versatility of the drilling method, drilling cost, site accessibility, installation time, ability to preserve natural conditions, and ability to obtain reliable samples).

We can roughly differ several drilling methods: driven wells, hollow and solid stem auger, jetting, cable-tool (percussion), air rotary, hydraulic rotary, reverse rotary, and pneumatic rotary with downhole-hammer. All in all, hollow-stem auger will be the method of choice. Solid-stem auger, cable-tool, and pneumatic percussive hammer also offers advantages depending on the geology and contaminants of interest.

The hollow-stem auger method is frequently used to install monitoring wells. No drilling fluids are used and disturbance of the geological materials penetrated is minimal. Depths are usually limited to not more than 50 meters. Typically, auger rigs are not used when solid rock must be penetrated. A cutting head is attached to the first auger flight, and additional flights are added as the augers are rotated downward. A plug attached to a rod inside the hollow stem prevents soil from entering the interior of the stem. Cuttings are moved upward along the sides of the borehole. Periodically, the plug is removed and a sampling device is lowered down the auger to extract an undisturbed sample. Split-spoon or Shelby tube samplers are commonly used for this purpose. A split-spoon sampler is a hollow tube comprised of two halves, whereas the Shelby sampler is a one-piece hollow tube. With a hammer device, samplers are driven into the soil ahead of the bit.

Solid-stem augers in contrast to hollow-stem augers need to be removed from the borehole to collect samples and install casing. Unconsolidated deposits that lack cohesion are not amenable to the solid-stem method. Most unconsolidated and poorly consolidated deposits have a tendency to collapse when augers are removed from the saturated zone. Therefore, with the solid-stem method, undisturbed samples of unconsolidated materials cannot be collected below the water table.

Cable tool drilling is one of the oldest methods used in the water well industry. The machine operates by repeatedly lifting and dropping a heavy string of drilling tools into the borehole. The drill bit breaks and crushes consolidated rock into small fragments and loosens unconsolidated material. The reciprocating action of the tools mixes the crushed or loose particles with water to form a slurry at the bottom of the hole. Water is added if none is present in the formation. Periodically, the slurry is removed by a sand pump or bailer. With the cable-tool, excellent formation samples can be collected and the presence of thin permeable zones can be detected. As drilling processes, a casing is normally driven and this provides an ideal temporary casing within whict to construct the monitoring well.

Rotary drilling (air, hydraulic, reverse rotary) involves the use of circulating fluids to remove drill cuttings and maintain an open hole as drilling progresses. Borehole caving is a potential problem in unconsolidated formations. However, driving casing as the borehole is advanced can resolve this problem.

In the *air rotary drilling* method, air is forced down the drill pipe and back up the borehole to remove the drill cuttings. Best suited for hard rock, the air rotary method is not often used for environmental investigations because it cannot yield representative samples. Injection of air into a borehole may alter the natural properties of the subsurface.

Reverse circulation rotary drilling has limited application for monitoring well construction. Reverse circulation rotary requires large quantities of water be cirulated down the borehole and up the drill stem to remove cuttings. If permeable formations are encountered, significant quantities of water can move into the formation to be monitored, thus altering the quality of the water to be sampled.

Hydraulic or *mud rotary drilling* is probably the most popular method used in the water well industry. Hydraulic rotary involving the introduction of fluids through the drill pipe to maintain an open borehole, however, presents some disadvantages for monitoring well construction. The drilling mud (usually bentonite) circulating down the drill stem and up the borehole to remove cuttings can highly affects aquifer characteristics and groundwater quality. Filter cakes which tend to form on the sides of boreholes reduce porosity and may inhibit groundwater flow must be removed from the screened area by development procedures.

Down-hole hammer drilling is a method of drilling borehole using a pneumatic percussive hammer drill. The rock is fragmented by repeated impaction presented directly to it. This produces a medium-diameter hole, but drilling speed is relatively slow so that operating costs tend to be high. The method is often used in hard to very hard consolidated rocks. Problems with contamination and crew safety must be considered.

- Diameter

In the past, the diameter of a monitoring well was based primarily on the size of the device (bailer, pump, etc.) used to withdraw the water samples. This practice worked well in very permeable formations, where in an aquifer large volumes of water were present. However, unlike most water-supply wells, monitoring wells are quite often completed in very marginal water-producing zones. Pumping one or more well volumes of water (the amount of water stored in the well casing under nonpumping conditions) from a well built in low-yielding materials may present a serious problem, if the well has a large diameter enabling the operation of a powerful pump, thus disturbing the groundwater flow conditions. Furthermore, under low-yielding conditions, it can take considerable time to recover enough water from the well to collect a sample. Cost of well construction also is considerable. Wells less than 100 centimeters in diameter are much less expensive than large diameter wells in terms of both cost of materials and cost of drilling.

In view of hydrogeology the smaller the diameter of a borehole is, the less severe is the impact on the natural conditions of an aquifer (under other points because each hole produces a vertical drain effect, thus potentially leading to an undesired cross-flow between different water-bearing formations).

For these reasons and with the advent of a variety of commercially available small diameter-pumps capable of lifting water over 30 – 40 meters, 2-inch wells (5,1 cm) have become the standard in monitoring well technology.

Large diameter wells can be useful in situations where the monitoring well may become a remediation well to remove contaminated water for treatment. Larger diameter wells also merit consideration when monitoring is required at depths of several tens or hundreds of meters and therefore the additional strength of large diameter casing is needed.

- Casing and screen material

The type of material used for monitoring well can have a distinct effect on the quality of the water sample to be collected. The materials of choice should neither adsorb nor leach chemical constituents that would bias the representativeness of the samples.

Galvanized steel casing can impart iron, manganese, zinc, and cadmium to many waters, and steel casing may contribute iron and manganese to a sample. PVC pipe has been shown to release and adsorb trace amounts of various organic constituents to water after prolonged exposure. The presence of compounds such as these can mask the presence of other similar compounds, but that should not be a problem when stagnant water is removed in connection with sampling (see chapter 5). Teflon, glass and stainless steel are among the most inert materials considered for monitoring well construction, but they are too expensive.

A reasoned strategy for groundwater monitoring must consider the effects of contaminated water on well construction materials as well. The commonly used PVC is chemically very resistant except for ketones, aldehydes, and chlorinated solvents. Generall, as the organic content of a solution increases, direct attack on the polymer matrix or solvent absorption, adsorption, or leaching may occur. These reactions, however, are only significant near saturation concentration of the problematic substances.

Care must be taken in preparing the casing and well screen materials prior to installation. At a minimum, materials should be washed with detergent and rinsed throughly with clean water. Steam-cleaning and high pressure, hot water cleaners provide excellent cleaning of cutting oils and lubricants left on casings and screens after their manufacture (particularly for metal casing and screen materials). To ensure that these and other sampling materials are protected from contamination prior to placement down-hole, materials should be covered (with plastic sheeting or other material), and kept off the ground.

All wells should allow free entry of water. The water should be as clear and silt-free as possible. Sediment-loaden water can greatly lengthen filtering time and create chemical interference in sample analyses. It may be helpful to have several slot-sized well screens on site so that the properly manufactured screen and slots can be placed in the hole after the aquifer materials have been inspected. Gravel pack of a size compatible with the selected screen slot size will further help retain the finer fractions of material and allow free entry of water into the well by creating a zone of higher permeability around the well screen. For natural-packed wells, where relatively homogeneous, coarse materials predominate, a slot size should be selected based on the effective size and uniformity coefficient of the formation materials. The gravel-pack should be composed of clean, uniform quartz sand.

The gravel-pack should be placed carefully to avoid bridging in the hole and to allow uniform settling around the screen. A tremie pipe can be used to guide the gravel to the bottom of the hole and around the screen. The pipe should be lifted slowly as the annulus between the screen and borehole wall fills. If the depth of water standing in the annulus is not great, the gravel can be simply poured from the surface. The volume of gravel required to fill the annulus to the desired depth (usually about one meter above the top of the screen) should be calculated. Field measurements should be taken to confirm that the pack has reached this level before backfilling or sealing procedures start.

- Screen length and depth of placement

The length of screen and the depth at which it is placed depend, to a large degree, on the behaviour of the contaminant as it moves through the unsaturated and saturated zones, and on the goal of the monitoring program. In connection with getting an general overview of the groundwater quality on a regional scale, fully screened wells or cost-reducing alternations of casings and screens are common (fig. 10, Nr. 1 and 2). This screen arrangements allow depth-integrated sampling, mostly focussed on the first aquifer near the surface.

In the nearfield of a point source contaminants can tend to stratify within the saturated zone. Examples are especially halogenated hydrocarbons, which can penetrate the total thickness of an aquifer, and petroleum products which occur floating on the groundwater table in thin lenses or as film. In these cases collecting a sample integrated over a thick zone will provide little or no information on the depth and concentration that a contaminant may have reached. When specific depth intervals must be sampled at one location, several wells completed at different depth intervals (fig. 10, Nr. 3, 4, 5) are urgently recommended. In such situations screen lengts of no more than 2 to 3 meters should be used. Monitoring wells can be constructed as so-called nested wells in one larger diameter hole (fig. 10, Nr. 3) or as so-called clustered wells in individual holes placed closely together. Furthermore, only depth-differing wells provide information on the water level or potential that exists at each well screen (fig. 10, types 3, 4, and 5). These data are essential to an understanding of the vertical component of flow (see fig. 12). Nested wells will require drilling a larger diameter hole to accomodate the multiple well casings, thus reducing drilling expenses. But there is the great danger, that the sealing procedure can fail because the distance between the single casings to be sealed is very little, thus giving the possibility for vertical movement of the contaminants in the hole. Only recommended are short-screened monitoring wells in individual boreholes (fig. 10, Nr. 4). More recently, multiport sampling systems of different features have been used in increasing numbers (fig. 10, Nr. 5, fig. 11).

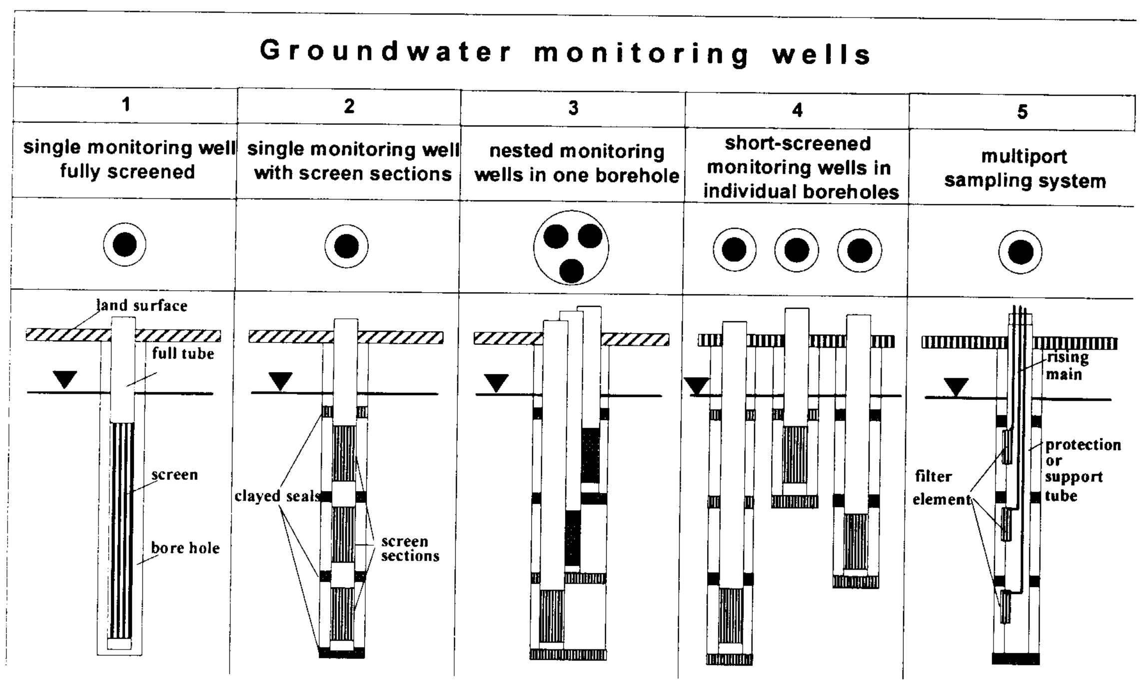

Figure 10: Selection of differently designed monitoring wells.

Consideration should be given to natural (seasonal) fluctuations, which can amount to several meters (in karst environment sometimes several tens meters) throughout the year and from one year to the next, and artificial fluctuations brought about largely by pumping, which can amount to several meters in only a few hours. Monitoring wells constructed to detect floating contaminants such as gasoline should contain screens that extent above the zone of saturation so that these lighter substances can enter the well. The thickness of floating products does not necessarily indicate the thickness of the product in the aquifer.

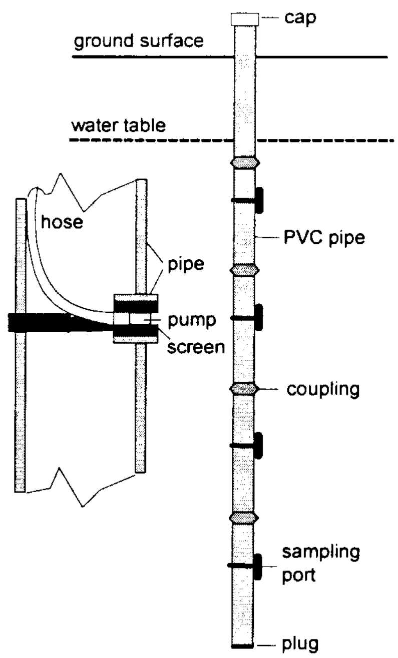

Figure 11: Multi-level sampling device.

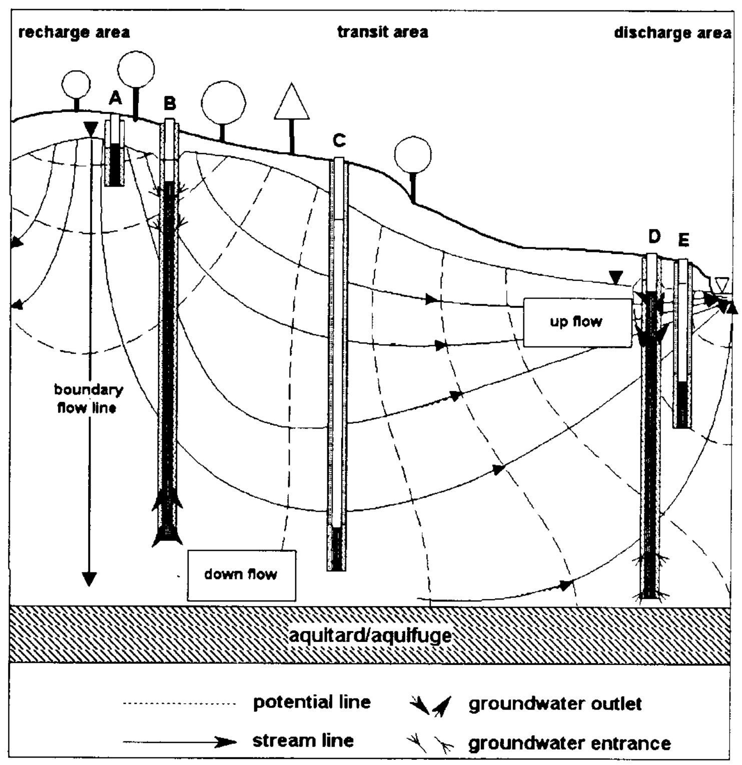

Figure 12: Groundwater flow field with vertical hydraulic gradients: the monitoring wells A, C and E with short screens at the bottom meet this hydrodynamical feature, but not the fully screened monitoring wells B and D (crossflow cannot be excluded); only in monitoring well A piezometric head and groundwater surface are identical.

In general, the exact position of the screen of an observation well between the upper and lower boundaries of the aquifer does not make much difference for the value of the hydraulic pressure (however, groundwater quality may differ). Only when the vertical flow component is considerable and the permeability of the aquifer is low, can vertical differences in hydraulic pressure be measurable (fig. 12). This might occur in recharge zones with low permeability top layers or within the capture zone of pumping stations and in the case of receiving surface waters, too.

Screening the total length of a thick aquifer is not good practice, because in this case the danger of cross flow is given, namely down flow in the recharge area and up flow in the discharge area (fig. 12, wells B and D), whereas a short filter is correct (fig. 12, well C).

If the goal should be controlling the input of diffuse contaminants in recharge areas, then shallow wells with short screens are recommended. The same recommendation is given in the case of monitoring wells located in discharge areas (fig. 12, wells A and E).

- Sealing materials and procedures

The creation of a conduit in the annulus of a monitoring well that could contribute to the spread of contamination or could produce a hydraulical crossflow between water-bearing formations is strictly to be avoided.

Monitoring wells are usually sealed with neat cement grout, dry bentonite (powdered, granulated, or pelletized), or bentonite slurry. Well seals usually are installed at two places within the annulus: one just above the screened interval and the other near the ground surface to inhibit downward leakage of surface contaminants. It is recommended that the seal plug above the screen should have a thickness of 5 meters at minimum and in accordance with the hydrogeological conditions eventually much more and the seal near the surface about 2 meters. Especially in Hesse, the home country of the author, the annulus between the two seals will be backfilled with a sand-bentonite mixture instead of the commonly used disturbed cuttings to prevent along the well casing a vertical drainage effect particularly in hard rock features producing unrepresentative samples resp. groundwater levels.

Bentonite traditionally has been considered to provide a much better seal than cement. Especially in connection with acid groundwaters, often occuring in sandstones or quarzites, a cement seal is not to be recommended, because cement grout can seriously affect the pH-value of sampled water and/or is not yet existent after some years. However, recent investigations on the use of clay liners for hazardous waste disposal have shown that some organic compounds migrate through bentonite with little or no attenuation. Therefore, in this connection cement my offer some benefits over bentonite. Furthermore, bentonite clay has appreciable ion-exchange capacity, which may interfere with the chemistry of collected water when the seal is adjacent to the screen or pump intake. But after correct well purging, i.e. removing stagnant water, before collecting the groundwater sample, this effect does not play a role all in all.

Special attention and care should be exercised during placement of a down-hole seal. Approximately 1 meter of gravel-pack should extend above the top of the well screen to ensure that too watery sealing materials do not migrate downward into the screened area and the fine materials in the seal do not penetrate the natural or artificial pack. Nowadays, a sealing clay with embedded gamma ray emitters makes it possible to determine the exact location and extent of the seal, and to estimate its continuity.

A neat cement grout is often recommended for surface sealing, but shrinkage and cracking of the cement can create an improper seal. Shrink-resistant cement and mixtures of small amounts of bentonite with neat cement have been used successfully to help prevent cracking.

- Well development

Development is a facet of monitoring well installation that often is overlooked. The proper development of monitoring wells is essential to the collection of „representative" water samples. During the drilling process, fine-grained particles are forced through the borehole wall into the formation, forming a mud cake that reduces the hydraulic conductivity of the materials in the immediate area of the borehole. To allow water from the formation being monitored to freely enter the monitoring well, this mud cake must be broken down opposite the well screen and the fine material removed from the well. This process also enhances the yield potential of the well, which is a critical factor when constructing monitoring wells in low-yielding geologic materials.

More importantly, monitoring wells must be developed to provide water free of suspended solids which may both bias the chemical analysis of the collected samples and cause frequent clogging of field filtering mechanisms. When sampling for metal ions and other dissolved inorganic constituents, water samples must be filtered and preserved at the well site in connection with sample collection. The additional time and money spent for well development will expedite sample filtration and result in samples that are more representative of water chemistry in the formation being monitored.

The basis principle behind development methods is to create reversals of flow in and out of the well and/or borehole which tend to break down the mud cake and to remove any fine sediment blocking the well screen.

In productive aquifers, over-pumping is a popular method for development. With this method, a pump is alternately turned on and off to stimulate a surging action in the well.

Pumping with air also is used effectively. Air is forced out into the formation through a jet nozzle. Air development techniques may expose field crews to hazardous constituents when highly contaminated groundwater is present.

The procedure of well development should be continued until water pumped from the well is visually free of suspended materials or sediments, partially controlled by turbidity measurements or analysis of DOC.

- Security

For most monitoring well installations, some precautions must be exercised to protect the surface positions of the well from damage. In many instances, inadvertent vehicular accidents do occur; also, monitoring wells seem particularly vulnerable to grass mowers. Vandalism is often a major concern. Several simple solutions can be employed to help minimize the damage due to accidental collisions

Where the most likely problem is one of vehicular contact, the first thing that can be done, is to make the top of the well easy to see. The well casing should also be painted a bright colour (orange or yellow are the most visible). This not only makes the well more visible, but also protects metal casing material from rusting.

The segment of the well that extends above the ground can be reinforced, particullarly if the well is constructed of PVC or teflon. The well could be constructed such, that only the portion of the well above the water table is metal. The use of well protectors is the most popular solution that involves the use of a larger diameter steel casing placed around the monitoring well at the ground surface and extending about 1 meter below ground. The protectors are usually seated in the cement surface seal to a depth below the frost line. Commonly, well protectors are equipped with a locking cap which ensures against tampering with the inside of the well.

5 Groundwater measurements and sampling including frequency

Operation of the monitoring system also involves the execution of measurements and sampling, laboratory analysis, and maintenance procedures according to the objectives and criteria set. The result of this step is the production of the groundwater raw data.

The representativity of the measured variable, given by location and depth of the well screen resp. spring site, is the most crucial monitoring aspect. Next, the period of time and frequency of measurements have to be adjusted to the monitoring objectives and the temporal fluctuations and variations of the quantitative and qualitative parameters. Generally, measurements of the water table or spring discharge and sample collection are conducted routinely over a period of many years to determine changes in the groundwater balance and/or in quality over time.

- Measuring and recording quantitative groundwater parameters

The observed parameters include groundwater level or spring discharge, additionally groundwater temperature and salinity/electric conductivity.

The general purpose of repeating measurements is to record the changes in time of the measured parameters with the aim of knowing and defining them. The following type of temporal changes and variations may occur: natural variations (diurnal, short events such as recharge from rainfall events, seasonal such as dry or wet periods, and long term trends), and anthropogenic impact variations (e.g. abstraction regimes, induced recharge, return from irrigation). To be able to define changes in time of the measured variable with a certain reliability, the frequency should be adjusted to the process and several measurements should be carried out with the period in which change of the variable occurs. It might occur that the heterogeneity especially of consolidated formations with secondary or dual permeability is high and that the water level fluctuations differ from place to place, also in temporal sense, which have to be taken into account when determining the frequency.

A wide range of frequencies is used, namely from annual to continous. A good practice, however, is to measure groundwater levels once or twice a month. Where strong fluctuations occur in groundwater levels and spring discharges, it will be necessary to set shorter monitoring frequencies, even with continual measurements. Because of high flow velocity, in general more frequent recording will be needed in fractured and especially in karstic aquifer than in porous formations. Shallow aquifers must be monitored in shorter time distances than deep aquifers because of the fast reaction of the groundwater system to impacts, such as regeneration events or man-made influences.

In most cases, manual level measuring will be an established procedure. Measurements of the pressure heads in the monitorung wells use well whistle, light plumb line (electric sounder) or wetted tape. Automatic control operations, using transducer-converter devices will be envisaged in the following situations: karstic aquifers that are subject to rapid responses to rainfall episodes, areas of difficult access, and water supply or irrigation wells integrated in operation and control systems.

- Sampling frequencies

Monitoring must be arranged to ensure that a coherent and comprehensive overview of chemical status can be given for each groundwater body. It is also necessary to register long term quality trends and to establish their causes (anthropogenic or natural).

A variety of factors controls the choice of sampling frequency. Apart from objectives, water uses, groundwater quality issues, statuary requirements, and costs, the frequency of sampling has hydrogeological and hydrological dimensions. The frequency of sampling has to be adjusted with high priority to the seasonal changes of groundwater recharge (restricted mainly to the winter months), and the temporal change in groundwater quality which is strongly related to the residence time in the unsaturated zone and the groundwater velocity in the saturated zone. The stronger the fluctuations of concentration over the period of year, the more often should be examined. Frequencies from 1 time every two years to 4 times a year are usual. Generally, in porous unconsolidated sediments the groundwater velocity is slow and consequently, the temporal change of groundwater quality is also slow. Shallow, secondary permeability features giving rise to higher velocities and subject to vulnerability need, thus, higher sampling frequencies than deeper and confined aquifers. The monitoring dates should be roughly equidistant in terms of the intervening time because that makes any future calculation of trends easier.

Additionally, some human activities (e.g. farming) are taken into account. For instance, seasonal considerations may be important in relation to parameters for which application is strongly seasonal, e.g. autumn-applied and spring-applied cereal herbicides and spring- or summer-applied non-agricultural herbicides.

- Sampling techniques

Common categories of groundwater sampling devices are bailers, suction-lift pumps, and centrifugal submersible pumps. Each sampling device has advantages and disadvantages

A bailer is essentially a hollow rigid tube that fills from the bottom when lowered into the water column. Two common styles of bailers include the single check valve or standard bailer and the dual or double check valve bailer. Groundwater experts accept only the double check valve bailer, designed for mechanically or electrically managed closing and opening in any depth of the monitoring well. It is the general view that pumping is better than bailing. The greatest disadvantage is that bailing does not remove stagnant water in a monitoring well usually found in pipes with a small diameter. There are, however, situations where the application of a bailer is advantageous, namely in the case of stratified groundwater (caused by temperature or mineralisation) resp. in the case of the presence of hydrocarbons floating on the groundwater table or existing as pools in the well sump.

Suction-lift pumps are considered inappropriate for collecting dissolved metals, pH, Eh and other gas-sensitive or volatilizing substances or measurements, because the vaccuum applied on the sample during collection may cause degassing. Additionally, because of lift restrictions (effective purging and sampling depth limit 7 - 8 meters) this kind of pumps is not recommended for groundwater sampling.

Pumping should only be done with submersible pumps (impeller and pump submersed in groundwater) or other positive displacement systems (fig 13). Manufacturers offer several models that work well for the purging and the sampling of 50 cm diameter monitoring wells; they are usually cooled and lubricated with water rather than with hydrocarbon-based coolants and lubricants that could contaminate groundwater samples. Models not capable of low-flow rates are not suited for collecting gas-sensitive samples.

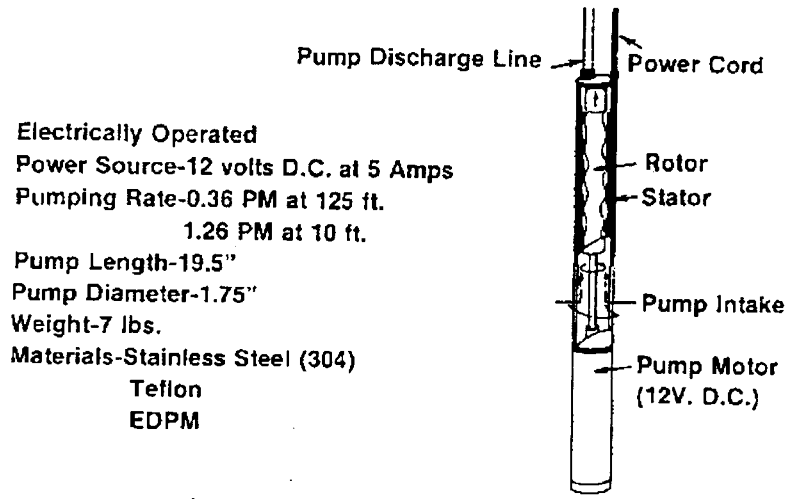

Figure 13: Submersible pump, working well for 50 cm diameter monitoring wells.

A prerequisite of collecting groundwater samples is the well purging, i.e the removal of stagnant water from the well. Stagnant water exchanges gases with the atmosphere and interacts with the well casing material. Therefore, the chemistry of water stored in the well casing is not representative of that in the aquifer and must not be collected for analysis. The goal in establishing a well purging strategy is to obtain water from the geologic formation while minimizing the disturbance of the regional groundwater flow system and the collected sample. To accomplish this goal a basic understanding of well hydraulics is necessary.

Rule-of-thumb guidelines for the volume of water to be purged (usually about 3- or 4-well volumes, but sometimes it is not enough) largely ignore the hydraulic characteristics of individual wells, and the geologic settings. Therefore, the number of well volumes to be removed should be calculated on a case-by-case basis and consider the local hydrogeological conditions (especially permeability distribution across the aquifer), the well construction design (in particular the length of the screen), anticipated groundwater quality, the pumping rate applied, and the sampling methodology to be employed.

This approach is only valid in cases where the pump intake is placed at the top of the well casing near the groundwater level (fig. 14). In hazardous environments where purged water must be contained and disposed of in a permitted facility, it is desirable to minimize the water quantity. This can be accomplished by purging the well at very low pumping rates (e.g. 100 ml/min) to minimize the drawdown in the well and maximize the percentage of aquifer water delivered to the surface in the shortest period of time. The precondition for pumping at low rates is that the pump intake is placed in the well screen.

The reasonably calculated purging requirement should be verified by measurements of pH, temperature or mostly recommended electric conductance in an in-line cell during pumping to signal quasi-stable chemistry of water being collected, thus indicating groundwater flow in the well.

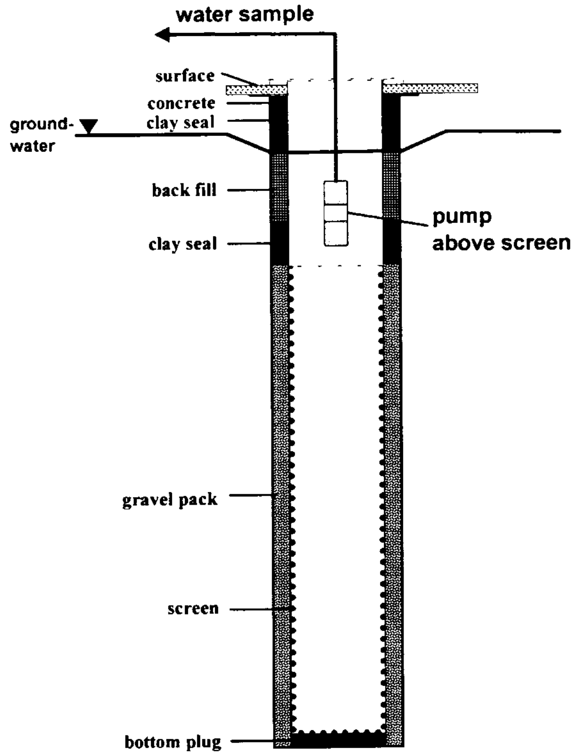

Figure 14: Groundwater sampling by pumping; the pump inlet must be above the filter.

Using packers alone in fully screened monitoring wells is not automatically a guarantee for collecting depth-dependent water samples because the gravel pack in the annulus makes possible crossflow. Nevertheless, special equipments allow groundwater sampling in existing gravel-packed wells or in uncased boreholes in such a way that only water from a specific level of the aquifer reaches the sampling port.

The new technology is represented for instance by the so-called „Separation Pump" (fig. 15). When this type is used for sampling, the groundwater flow in the well is initially separated in two partials using two additional pumps. A water divide is created in the well, its position is controlled by a thermo-flowmeter and will depend on distribution of permeabilities of the aquifer and the ratio of the two pumping rates. The trick is to pump water from the water divide between the top and the bottom pump at a rate of less than 1 % of the total rate and thus making a zone within two new water divides, created by the sampling pump. Sampling of different levels of the aquifer is done by changing the ratio of the two main pumping rates thereby moving the water divide to a new position.

Finally, sampling requires careful handling of the water itself. It should be placed into the sample container without flow turbulence in such a manner that degassing is prevented as much as possible (e.g. sample taken from a smoothly free flowing tap). In the case of higly volatile substances, 10 or 20 cm^3 glass bottles with headspace and teflon septum are often used as sample containers. Air from the headspace is then analyzed and the results are back calculated for pollutant concentration in water, using partition coefficients for water/air systems.

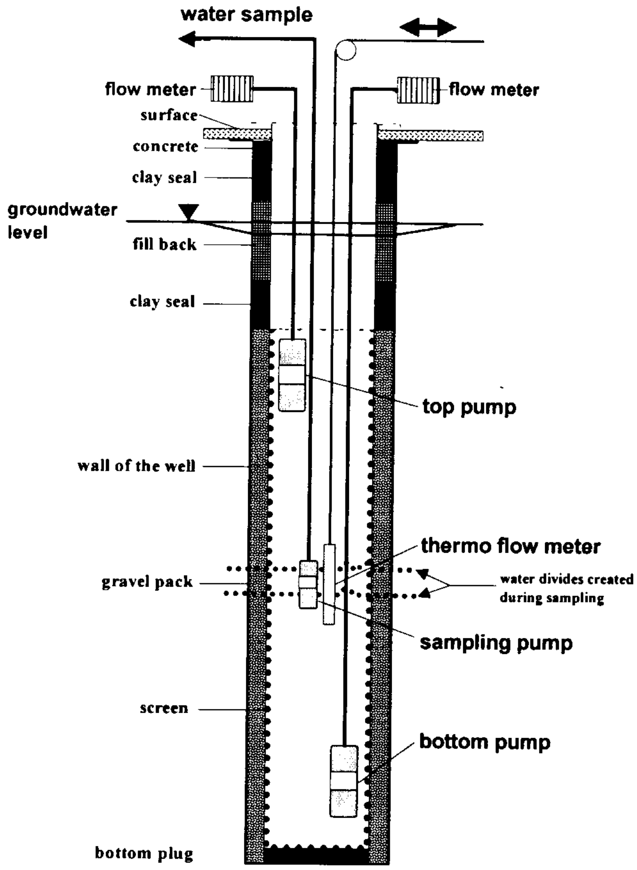

Figure 15: Schematic illustration of level-accurate groundwater sampling by ‚Separation Pumping'-technique (SP-technique).

In summary, common sampling strategy is: measuring and recording the water level in the monitoring well, removal of stagnant water, control of groundwater inflow by measurement of indicator parameters, careful handling of the pumped water without turbulence flow, prevention of degassing, chemically inert containers, and fast cooling of water.

- Chemical characterisation of water samples

The types of chemical parameters included in a monitoring program depend on the objectives of water management. Generally, the procedure of parameter choice should being depended on: characterisation of the relevant aquifers including the geochemical inventory of the water-bearing formations and the background of groundwater quality, definition of the actual functions and uses and their quality requirements, specification of the threats to which the groundwater body is exposed (e.g. generally reflected in land use), and assessment of the problems which are already experienced by the groundwater system (e.g. acidification, nutrients, salinization, etc.).

Not only with regard to sampling frequencies but still more in view of the parameter selection a tailored analytical program has to consider previous hydrochemical data.

The proposed hydrochemical parameters are documented in the table 5, they can be divided in four groups. The parameters of the group I reflect a standard program including descriptive parameters (e.g. temperature, pH, electric conductivity), major ions, and additional parameters (e.g. DOC, boron). The choice of the parameters of the special programs I through III depends partly on local or diffuse pollution sources as indicated by land-use framework. Because it is very difficult to collect representative microbiological samples from water-bearing formations (indicator parameters such as total coliforms, feacal coliforms), a special program is not documented.

Table 5: Chemical parameters

a) basic program (at minimum once a year)	
piezometric head (m)	K (mg/l)
spring discharge (m^3/s)	Fe (mg/l)
water temperature (°C)	Mn (mg/l)
pH-value (-)	Al_3 (mg/l)
electrical conductivity (mS/m)	NH_4 (mg/l)
dissolved oxygen (mg/l)	NO_2 (mg/l)
acid capacity	B (mg/l)
alkaline capacity	NO_3 (mg/l)
Ca (mg/l)	Cl (mg/l)
Mg (mg/l)	SO_4 (mg/l)
Na (mg/l)	DOC (mg C/l)
b) special program I (highly volatile halogenated hydrocarbons)	
Dichloromethane (µg/l)	Cis 1,2-Dichloroethene (µg/l)
Trichloromethane (µg/l)	Trichloroethene (µg/l)
1,1,1-Trichloroethane (µg/l)	Tetrachloroethene (µg/l)
c) special program II (pesticides)	
Atrazine (µg/l)	Bentazone (µg/l)
Desethylatrazine (µg/l)	Mecoprop (µg/l)
Desisopropylatrazine (µg/l)	Isoproturon (µg/l)
Simazine (µg/l)	Metolachlor (µg/l)
Bromacil (µg/l)	Terbutylazin (µg/l)
Hexazinon (µg/l)	Chlortoluron (µg/l)
Diuron (µg/l)	γ-HCH (γ-Hexachlorohexane) (µg/l)
Propazine (µg/l)	Dichlorprop (µg/l)
d) special program III (heavy metals)	
As (mg/l)	Cu (mg/l)
Pb (mg/l)	Ni (mg/l)
Cd (mg/l)	Zn (mg/l)
Cr (mg/l)	

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