## UN/ECE Task Force on Monitoring & Assessment

under the Convention on the Protection and Use of Transboundary Watercourses and International Lakes (Helsinki, 1992)

Working Programme 1996/1999

*Volume 4:*

# State of the art on monitoring and assessment of groundwaters

ISBN 9036952778

Authors:
H. Uil (NITG-TNO)
F.C. van Geer (NITG-TNO)
J.C. Gehrels (NITG-TNO)
F.H. Kloosterman (NITG-TNO)

Netherlands Institute of Applied Geoscience TNO,
Delft, The Netherlands

Lelystad, September 1999

# Colofon

**Lay-out:**
Grafisch bedrijf ve&es

**Cover design:**
Ph. Hogeboom (Panthera BNO)
G.E. Arnold (RIZA)

**Cover pictures:**
KNMI
NITG-TNO
Leon Lamers, KUN
Srećko Božičević

**Printed by:**
Grafisch bedrijf ve&es

**English corrections:**
M.T. Villars (Delft Hydraulics)
I. Záborszky

Reproduction permitted only when quoting is evident.

Additional copies of the following 4 volumes can be ordered from RIZA, Institute for Inland Water Management and Waste Water Treatment, ECE Task Force project-secretariat, P.O. box 17, 8200 AA Lelystad, The Netherlands. Fax: +31 (0)320 249218.

- Volume 1: Inventory of transboundary groundwaters (ISBN 9036952743)
- Volume 2: Problem-oriented approach and the use of indicators (ISBN 9036952751)
- Volume 3: Application of models (ISBN 903695276X)
- Volume 4: State of the art on monitoring and assessment of groundwaters (ISBN 9036952778)

NOTE:
The designations employed and the presentation of the material in this publication do not imply the expression of any opinion whatsoever on the part of the Secretariat of the United Nations concerning the legal status of any country, territory, city or area, or its authorities, or concerning the delimitation of its frontiers or boundaries.

# Preface

This report "State of the art in Monitoring and Assessment of Groundwaters" is one of the four background documents to be used for the drafting of Guidelines on monitoring and assessment of transboundary groundwaters. This report has been prepared by H. Uil, F.C. van Geer, J.C. Gehrels and F.H. Kloosterman in close co-operation with G.E. Arnold. Designated advisors for this sub-project were J. Chilton and M. Varela.

For the execution of the overall groundwater program, a core group was established, which also provided guidance in the preparation of these guidelines. The core group was made up of:

| | | |
|---|---|---|
| G.E. Arnold | project leader groundwater program and sub-project leader State of the Art | Institute for Inland Water Management and Waste Water Treatment (RIZA), Ministry of Transport, Public Works and Water Management, The Netherlands |
| Zs. Buzás | sub-project leader Inventory | Ministry of Transport, Communication and Water Management, Hungary |
| R.A. Bebris | | Ministry of Environmental Protection and Regional Development, Latvia |
| J.J. Ottens | sub-project leader Indicators | RIZA, The Netherlands |
| P. Rončak | sub-project leader Models | Slovak Hydrometeorological Institute, Slovak Republic |
| R. Enderlein | secretary to the ECE Water Convention | ECE Secretariat, Switzerland |
| J. Chilton | advisor | British Geological Survey/ UK-World Health Organisation (BGS-UK/WHO), United Kingdom |
| O. Tarasova | advisor | Ministry of Environmental Protection and Nuclear Safety, The Ukraine |
| M. Varela | advisor | Ministry of Environment, Spain |

This report was discussed and accepted by the Core Group on Groundwater, established by the ECE Task Force on Monitoring and Assessment under the Convention on the Protection and Use of Transboundary Watercourses and International Lakes.

# Contents


| | | |
|---|---|---|
| Preface | | 3 |
| **1.** | **Introduction** | **7** |
| 1.1 | General | 7 |
| 1.2 | Objectives | 8 |
| 1.3 | Definitions | 8 |
| 1.4 | Main sources of information | 9 |
| 1.5 | Outline of the report | 10 |
| **2.** | **Groundwater systems and assessment** | **11** |
| 2.1 | Need for transboundary assessment | 11 |
| 2.2 | Characterisation of the groundwater systems | 11 |
| 2.3 | Groundwater assessment and groundwater management issues | 14 |
| 2.3.1 | Functions/uses | 15 |
| 2.3.2 | Vulnerability | 15 |
| 2.3.3 | Threats | 16 |
| 2.3.4 | Problems | 16 |
| 2.3.5 | Measures | 17 |
| 2.4 | The Monitoring Cycle | 17 |
| **3.** | **Groundwater management** | **19** |
| 3.1 | Problem definition | 19 |
| 3.2 | Groundwater management objectives | 20 |
| 3.3 | Information needs and technical objectives | 20 |
| 3.3.1 | Chacterisation of the groundwater system (threats and problems) | 21 |
| **4.** | **Current monitoring and assessment practices** | **25** |
| 4.1 | Current groundwater monitoring practices in ECE countries | 25 |
| 4.1.1 | Discussion of the UN/ECE questionnaire responses | 25 |
| 4.1.2 | Groundwater monitoring in EEA countries | 28 |
| **5.** | **Design of groundwater monitoring and assessment systems** | **33** |
| 5.1 | Introduction | 33 |
| 5.1.1 | The step-wise process of the design | 33 |
| 5.1.2 | Statistical versus hydrogeologic approach | 36 |
| 5.1.3 | Monitoring effort and acquired information | 38 |
| 5.2 | Monitoring strategy | 38 |
| 5.3 | Main types of monitoring | 40 |
| 5.4 | Primary aspects in network design | 40 |
| 5.4.1 | Groundwater quantity | 41 |
| 5.4.2 | Groundwater quality | 45 |
| 5.4.3 | Integration of groundwater quantity and groundwater quality networks | 46 |
| 5.5 | Data flow and data management | 46 |
| 5.5.1 | Monitoring of groundwater levels | 47 |
| 5.5.2 | Monitoring of groundwater quality | 47 |
| 5.5.3 | Processing of groundwater data | 49 |
| 5.5.4 | Data bases and geo-information systems | 50 |
| 5.5.5 | Data quality control | 50 |
| 5.5.6 | Database security | 51 |
| 5.6 | Scale aspects | 52 |

5.6.1 Process scale 52
5.6.2 Information scale 53
5.6.3 Measurement scale 53
5.6.4 Examples to illustrate the different scale types 54
5.6.5 Scale constraints in network design 55

**6. Key points 57**

**7. References 61**

**Annexes**
I Questionnaire on transboundary groundwaters 67
II Statistical approach to monitoring network design 73
III Description of REGIS 79

# 1. Introduction

### 1.1 General

The Convention on the Protection and Use of Transboundary Watercourses and International Lakes was drawn up under the auspices of the Economic Commission for Europe (ECE) and adopted in Helsinki on 17 March 1992. The Convention entered into force in October 1996 and covers, amongst others, the monitoring and assessment of transboundary waters, the assessment of the effectiveness of measures taken to prevent, control and reduce transboundary impact, the exchange of information between riparian countries and provision of public information on the results of water and effluent sampling. Riparian Parties shall also harmonise rules for setting up and operating monitoring programs, including measurement systems and devices, analytical techniques, data processing and evaluation procedures.

In 1994, the ECE Working Party on Water Problems established the Task Force on Monitoring and Assessment of Transboundary Waters. At its eighth session in March 1995, the Working Party agreed on a phased approach to the drafting of guidelines on monitoring and assessment of transboundary waters. This phased approach means that guidelines will be drafted for rivers, groundwater, lakes and estuaries successively. After finishing the guidelines for transboundary rivers, the Working Party requested the Task Force on Monitoring & Assessment to draw up - as a second step of its activities - draft guidelines on monitoring and assessment of transboundary groundwaters.

At the first meeting of the Parties to the Convention on the Protection and Use of Transboundary Watercourses and International Lakes in Helsinki (Finland) in July 1997, an overall work-plan was agreed upon. The drafting of guidelines on monitoring and assessing transboundary groundwaters (including background documentation) was formulated as one of the activities of program area 3 "Integrated management of water and related ecosystems". These guidelines will be considered at the second meeting of the Parties in the year 2000.

Groundwater supports various important functions. Some functions, like nature and agriculture, are directly related with the occurrence of groundwater. In other areas, like drinking water and industrial water supply, groundwater is used as a production factor, because of its normally good and constant quality. However, a high population density, continuously growing industrialisation and intensive agriculture will have a negative effect on the quality of soil and groundwater. In recent times, the soil has become polluted more and more by private and public waste dumps, air pollution, fertilisers and use of excess manure. In shallow groundwaters this pollution can easily be transported to locations where it may be harmful to other interests. These problems do not only occur within countries, but can also have transboundary impacts, which demand accountable monitoring and assessment activities. Furthermore, measures should be taken to avoid these undesired developments, within, as well as between countries with joint groundwater bodies. The integral basin area approach, or ecosystem approach, which was adopted as a basic principle in the Convention is also the basis for structuring the guidelines on monitoring and assessment of transboundary groundwaters.

As with the Guidelines on Water-quality Monitoring and Assessment of Transboundary Rivers, these guidelines are brief and concise and supported by supplementary documentation. An inventory was made of monitoring and assessment practices in ECE countries, which includes an examination and evaluation of these practices. Prior to the drafting of the guidelines, additional activities were launched to identify indicators for groundwater assessment and review the use of models. In addition, an overview of transboundary groundwaters in the ECE region was drawn up.

Co-operation has been sought with various international organisations and institutions to make the best use of existing programs and link on-going activities in the field of monitoring and assessment.

The Guidelines on Transboundary Groundwater Monitoring and Assessment are supported by a series of 4 background documents dealing with the following themes:

1. Inventory of transboundary groundwaters
2. Problem-oriented approach and the use of indicators
3. Application of models
4. State of the art on monitoring and assessment of groundwaters

The present report is the result of the activities under item number 4: State of the art on monitoring and assessment of groundwaters.

### 1.2 Objectives

The objective of this report is to describe the state of the art of relevant elements of groundwater monitoring and assessment which should result in up-to-date recommendations that can be used for formulation of guidelines. The report is based on a review of recent literature and the responses to a questionnaire with the aim of collecting information about the on-going activities with regard to monitoring and assessment of transboundary groundwaters within the ECE countries.

### 1.3 Definitions

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. 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.

- The process of *groundwater assessment* is an evaluation of the physical and chemical state of groundwater in relation to (i) natural situation, (ii) human intervention and (iii) actual and intended functions and uses.

- *Groundwater monitoring* is the collection of data, generally at set locations and depths and at regular time intervals in order to provide information which may be used (i) to determine the state of groundwater both in quantitative and qualitative sense, (ii) to provide the basis for detecting trends in space and time and (iii) to enable the establishment of cause-effect relationships.

Monitoring and assessment of groundwater can be considered as crucial tools for proper management of groundwater resources.

### 1.4 Main sources of information

To collect information specifically about the present practices of transboundary monitoring and assessment of groundwater, questionnaires were sent to the ECE member states. The responses received are evaluated in Chapter 4. In recent years, many inventories and studies related to the subject of monitoring and assessment of groundwater resources have been carried out. The main sources consulted for information about monitoring and assessment practices are listed below.

- The UN/ECE study of Transboundary Watercourses and Lakes is the precursor of the present study of transboundary groundwaters. In particular the volume 5 "State of the Art on Monitoring and Assessment of Rivers" (Niederländer et. al., 1996) gives an overview about the principles of monitoring network design. This report also contains information about chemical analysis and treatment of samples according to international standards.
- The European Network of Fresh Water Research Organisations (EurAqua) dedicated its second technical review to "Optimizing Freshwater Data Monitoring Networks including Links with Modelling" (EurAqua, 1996). This technical review contains reports of 14 European countries about their monitoring networks, for both surface water and groundwater. The report gives an impression about the dimensions of the existing national networks (including organisational structure), the underlying objectives and statements about the necessity of future research for monitoring.
- The report "Groundwater Monitoring in Europe" (Koreimann et al. 1996) is the result of an inventory conducted by the European Topic Centre on Inland Waters (ETC/IW) of the European Environmental Agency. It is specifically focused on groundwater monitoring, quality as well as quantity. It is an inventory of existing networks of the EEA member states (EU countries, Norway and Iceland) and contains a lot of technical detail.
- Based on the previous inventory of Groundwater Monitoring in Europe, the ETC/IW of the EEA has made a proposal for the design of a groundwater monitoring network in the EEA countries that is presented in the report "European Freshwater Monitoring Network Design" (Nixon, 1996). The proposed design procedure is based on an overview and evaluation of the present monitoring practices.
- Two conferences "Monitoring Tailor Made I" and "Monitoring Tailor Made II" have taken place in respectively 1994 and 1996. The proceedings of both conferences, respectively Adriaanse et al. (1994) and Ottens et al. (1997) contain new developments in monitoring and assessment, both in surface water and groundwater.
- In addition to the aforementioned main sources, some other publications have been consulted in the scientific literature (see Chapter 7: "References").

### 1.5 Outline of the report

The present report on the state of the art in monitoring and assessment is focused on those aspects that are typical for (transboundary) groundwaters. Aspects that are already described in other reports will be mentioned only briefly. In particular, this counts for the treatment and chemical analysis of water samples, that is described by Niederländer et al. (1996) and by international standards. Examples of aspects that are typical for groundwater are well construction and conservation of anoxic conditions. General procedures for the design and optimisation of monitoring and assessment are described in relation to surface water in Niederländer et al. (1996) and the edited Guidelines on Water-Quality Monitoring and Assessment of Transboundary Rivers (UN/ECE, 1996). Special attention will be paid to the aspects that differ from the surface water monitoring and assessment. In particular, these aspects are related to the spatial and temporal variability and the generally slow rate of groundwater movement. Furthermore, differences between the monitoring and assessment of groundwater in unconsolidated formations with primary permeability and in consolidated formations with secondary permeability are dealt with.

In Chapter 2, the need for a characterisation of the transboundary groundwater systems and the link between groundwater and groundwater management issues has been addressed. The monitoring cycle is presented in this chapter. Chapter 3 deals with groundwater management, which forms a basis for groundwater monitoring and assessment. It describes the management objectives, tasks, information needs and the link to the assessment and technical objectives. Current practices in monitoring and assessment of groundwater are summarised in Chapter 4. The general process for setting up a system for groundwater monitoring and assessment and the different steps to be considered for the design of such a system have been addressed in Chapter 5. Descriptions of different types of scales are given in the last section of this chapter. For the description of the design, not only the selection of parameters, locations and frequencies are dealt with but also the installation requirements, the organisational aspects, the quality control and the data flow management from sample collection to presentation and communication are addressed. Finally, key points for drafting guidelines have been given in Chapter 6 and a list of references in Chapter 7.

# 2. Groundwater systems and assessment

### 2.1 Need for transboundary assessment

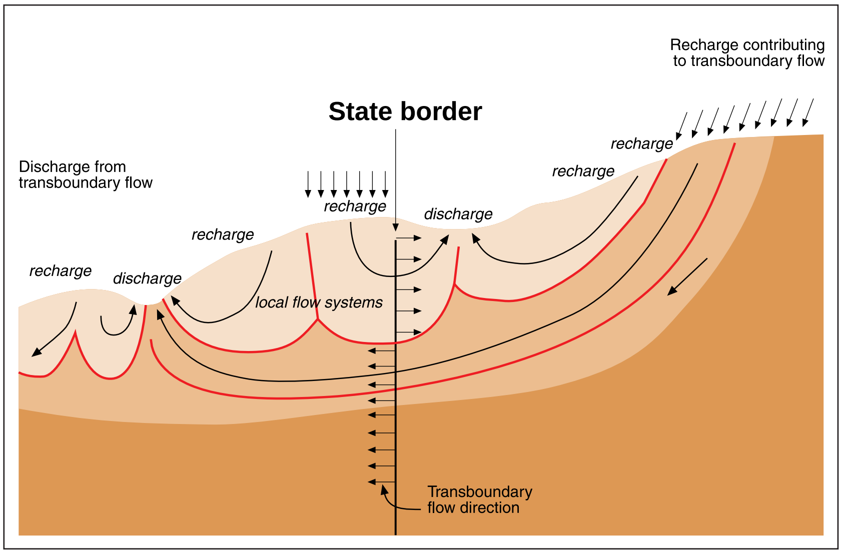
Because the borders between riparian countries do not necessarily coincide with the natural boundaries of groundwater aquifers, groundwater may flow from one state to another. Moreover, abstractions or other activities on one side of the border may adversely affect groundwater functions on the other side. To be able to distinguish natural characteristics from anthropogenic effects, information will be required about the aquifer and flow conditions on both sides of the border. However, in practice, it is often difficult to obtain consistent pictures of the subsoil and groundwater characteristics. Based on the information originating from riparian countries, the pictures might show abrupt and unrealistic changes in geology and groundwater characteristics at the border crossings. Furthermore, the possible existing monitoring networks may have been set up with different objectives, the measurement locations, times and frequencies might not match and the assessment and presentation may be different. Moreover, it is often very difficult to obtain the required data because of logistical difficulties. Consequently, without proper establishment of cross-border groundwater monitoring and assessment, errors may occur in aquifer characterisation and in the prediction and evaluation of changes in groundwater flow and quality.

To develop and evaluate strategic policies for groundwater management it is a prerequisite that the monitoring and assessment of groundwater in the riparian countries is performed in a comparable way. This means, for example, in order to assess trends in groundwater quality, the definition of trends, the sampling procedures and chemical and numerical analysis should be comparable on both sides of the border.

### 2.2 Characterisation of the groundwater systems

A prerequisite for monitoring and assessment of groundwater resources in general and for transboundary groundwater bodies in particular is the preliminary characterisation of the relevant aquifer systems and the actual condition of groundwater flows. At the border between two countries, different flow systems might be superimposed and even opposite flow directions might occur (Figure 2.1). Recharge- and discharge areas should be identified including the interaction between surface water and groundwater. Transboundary aquifers might have recharge areas on one side of the border and discharge areas on the other side. Activities within the recharge areas at one side of the border might adversely effect the groundwater quality on the other side of the border.

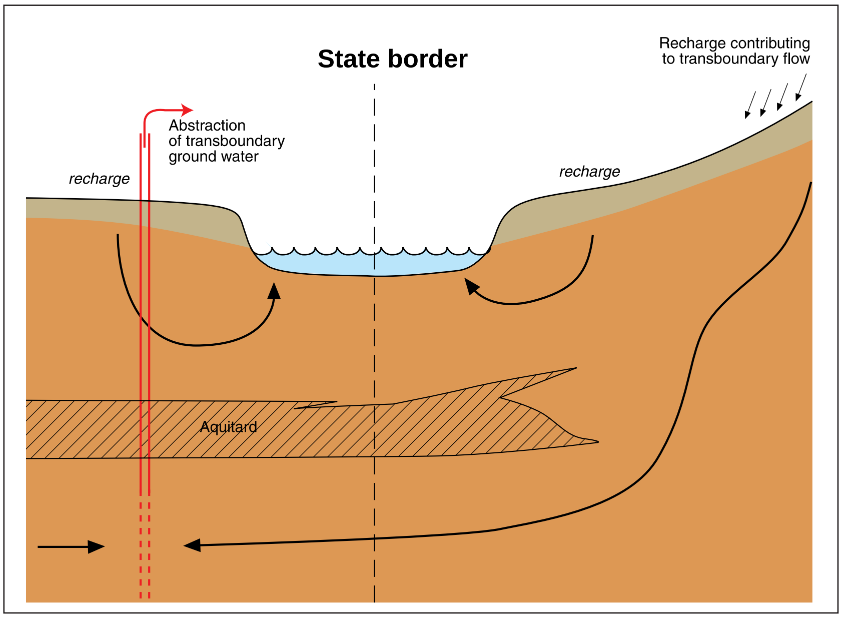
**Figure 2.1**
Transboundary groundwater flow systems




Furthermore, transboundary water transmitting layers, zones or structures have to be characterised in order to be able to produce a consistent picture of the geometry of these layers, zones or structures (Figure 2.2). This will be needed for a proper assessment of possible transboundary phenomena. Therefore, an integrated interpretation of transboundary information on geology, geophysics and geo-hydrology will be necessary. Information on the extent of the different layers is also needed for a proper design and selection of representative locations for a transboundary monitoring network for groundwater and moreover for the assessment of the data on groundwater levels and groundwater quality.

Generally, the characterisation of aquifers in porous media with intergranular primary porosity is much less complicated than in media with secondary porosity, such as fractured and fissured consolidated rock formations or in limestone with karst features. An intergranular groundwater flow is generally slow (order of magnitude: 30 m/year), while secondary porosity features might give rise to much higher velocities

**Figure 2.2**
Effect of a transboundary aquitard on groundwater flow



of water masses and constituents in certain karst formations on one hand or to very small fluxes of flow by fractures, fissures and joints in certain hard rock formations on the other hand. Moreover, the characterisation of such systems is generally much more difficult to assess which will complicate the set up of adequate monitoring.

After a preliminary characterisation of the groundwater systems, further monitoring should provide information about the aquifer dynamics such as seasonal variations and changes of the groundwater flow system and about the effects of measures and other anthropogenic influences. Therefore, groundwater quality, groundwater levels and groundwater abstractions have to be monitored as well as the surface water systems which form the boundaries of the groundwater flow systems. Hence, an integrated evaluation of the results of groundwater and surface water monitoring is needed and in certain cases integration of the monitoring activities of groundwater and surface water is recommended. The application of groundwater flow modelling may be very useful to provide three dimensional pictures of the flow systems and to get indications of the groundwater fluxes.

The pre-assessment of the transboundary groundwater system and flow conditions may imply a considerable investigation effort, preliminary to the actual set up and implementation of monitoring and assessment procedures. In "Hydrological Systems Analysis, Methods and Applications" (Engelen and Kloosterman, 1996), an introduction to flow system analysis, the use of groundwater modelling as well as the application of flow analysis in many case studies has been given. This methodology has been applied for the design of several groundwater monitoring networks for provincial authorities in The Netherlands. The first step is to compile and evaluate the existing information such as geological-, geo-hydrological-, topographical-, geo-morphological- and soil maps and the available groundwater quantity and quality data. Aerial photographs and satellite images may provide important additional information. To fill gaps, additional geological, geo-hydrological and/or geophysical research might be needed. The application of GIS-techniques is very useful for preparing composite maps and overlays of different thematic maps. Furthermore, the GIS-programs are very helpful for the presentation of the appropriate figures and maps.

A three-dimensional picture of the transboundary aquifers and the actual groundwater flow from recharge- to discharge areas should be obtained. Recharge sources might be infiltration from precipitation or from surface water bodies and discharge is generally represented by surface water and abstraction points. Hence, also information about the interaction surface-groundwater should be presented. Besides the geometry of the groundwater flow system, additional information about the different quantity and quality aspects e.g. precipitation, evapo-transpiration, abstractions, base flows of streams, water balances etc., should be collected and presented.

The results of the preliminary assessment should include: the identification of the possibly dynamic boundaries of the transboundary groundwater flow systems, the characterisation of the transboundary aquifers, aquitards and aquicludes, a description of the relevant groundwater quantity and quality characteristics and the identification of the respective water management authorities involved. Gaps in knowledge and uncertainties should be specified.

### 2.3 Groundwater assessment and groundwater management issues

The groundwater issues which should be considered for the assessment have to be specified first to enable the definition of the information that should be provided by monitoring. Groundwater issues are linked to the groundwater management issues. The groundwater management issues are based on the core elements in water management as presented in UN/ECE TFMA (1996). These elements in water management and their interactions are shown in the diagram of Figure 2.3.

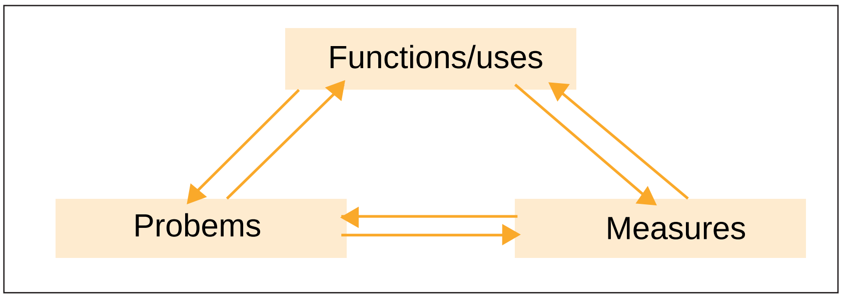



**Figure 2.3**
Core elements in water management

The groundwater issues ascertained are as follows:

- the actual and potential uses and/or functions which are or can be assigned to the inherent quantity and quality features of the groundwater system;
- the external threats (pressures) from pollution sources and other human activities;
- the actual and potential groundwater quantity and quality problems, which occur or may occur when a threat becomes effective;
- the inherent vulnerability of the groundwater system, and
- the identification of measures and their impact on the overall functioning of the groundwater system.

In Table 2.1 a summary is given of possible functions/uses, threats (pressures) and problems (issues).

**Table: 2.1**
Possible functions/uses, pressures and issues

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

### 2.3.1 Functions/uses

After the characterisation of the aquifer, one of the first issues to be addressed by the management authorities involved will be the assessment of the actual and possible future functions and uses, which is based on the quantity and quality features of the groundwater system concerned. Possible functions and uses of groundwater are: drinking water supply, agriculture use, industrial use, geothermal use. Further, the maintenance of certain groundwater levels and/or groundwater quality may sustain ecological values, base flow of streams, well abstractions, foundation protection and/or prevention of land subsidence. On a local scale, groundwater flows might be used and/or manipulated for the purpose of confinement or remediation of contaminated sites. For example, if groundwater abstractions on one side of the border affect groundwater levels, the groundwater flow and/or groundwater quality on the other side of the border, the assignment of the function will need a transboundary approach.

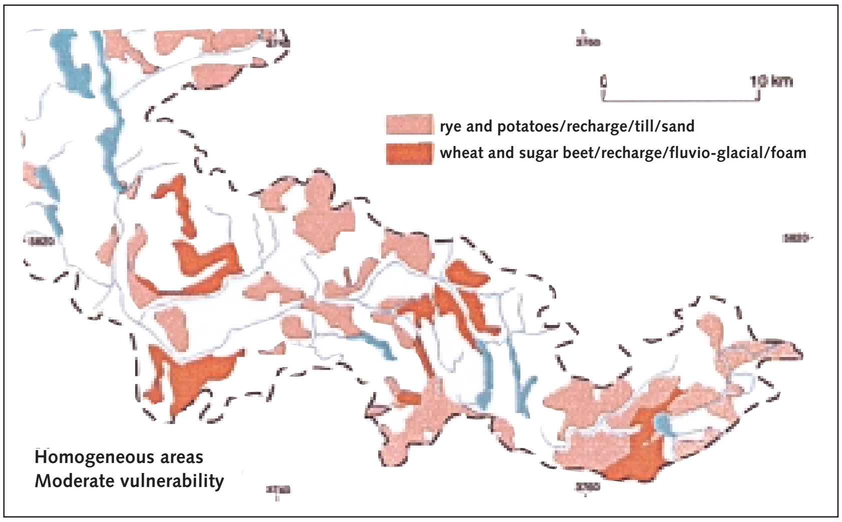
### 2.3.2 Vulnerability

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 of a transboundary groundwater system provides important information for the groundwater manager to assess possible transboundary 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 proper transboundary groundwater monitoring and assessment 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, the hydraulic and (bio)chemical soil properties (e.g. organic content, hydraulic properties 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. In that case, if the aquifer becomes polluted by contaminated infiltration water, the pollutants will be transported rapidly which makes it difficult to undertake effective remediation measures. 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 use of Geographic Information Systems (GIS) is extremely helpful in performing an integrated assessment of aquifer vulnerability. Overlay techniques can be used to combine different thematic maps (e.g. soil type, hydraulic conductivity, geology, thickness of the unsaturated zone) with the aim of defining homogeneous areas in terms of vulnerability. The resulting integrated map can be combined with others that represent actual or expected threats (e.g. land use) to produce maps depicting the risk of aquifer pollution (Figure 2.4).

Figure 2.4
Homogeneous area types of vulnerability (from: "A Pilot Monitoring Network System for Groundwater Quality and Quantity in the Upper Notec Catchment (Poland)", Uil et al., 1996)




### 2.3.3 Threats

A threat is an activity or situation which might cause groundwater quality or quantity problems. In particular, when the threat and the connected problem are separated by a national boundary, a transboundary approach to groundwater management is required. Threats may include potential pollution sources such as agriculture areas, urban areas, industrial areas, infrastructure and also subsoil use and airborne pollution. Besides threats which may cause adverse quality effects, undesired quantity effects may also occur due to abstractions, improved drainage, construction of dams, etc. Hence, potential threats can generally be assessed from the actual and historical land use and subsoil use. If relevant, agricultural areas can be differentiated by type of crops depending on the amount of fertilisers and pesticides used.

Over-exploitation of groundwater resources is an example of one of the threats which might endanger the sustainability of the abstractions and certain ecological values and which may cause problems like saltwater intrusion, land subsidence etc. Groundwater quality may be threatened by pollution from diffuse and point sources and by undesired effects of the seepage/infiltration fluxes. Known pollution sources such as agricultural activities and waste disposal sites can be counteracted by adequate measures and monitoring systems. However, in densely populated areas also many other known and unknown potential (historical) pollution sources might endanger groundwater quality.

Other activities which change or control groundwater and surface water levels such as the construction of dams, river regulation, the use of irrigation canals, abstractions around open mining pits, etc. affect groundwater levels and flow direction and may cause groundwater quantity problems.

### 2.3.4 Problems

Groundwater problems are defined as undesired situations with respect to man and the environment which are related to groundwater use and/or functions. For example, abstractions may result in increasing salinization, over-abstraction may give rise to mining of the groundwater resources and falling groundwater levels may give rise to problems like desiccation, land subsidence and foundation problems. Intensive agricultural practices and emission from other pollution sources have resulted in problems like acidification and excess nutrients. Land subsidence is possible in areas with falling groundwater levels within peat formations.

Groundwater budgeting and determination of trends will be needed to identify over-abstraction. Groundwater level observation, surface water monitoring and vegetation cover monitoring are needed for the identification of desiccation.

#### 2.3.5 Measures

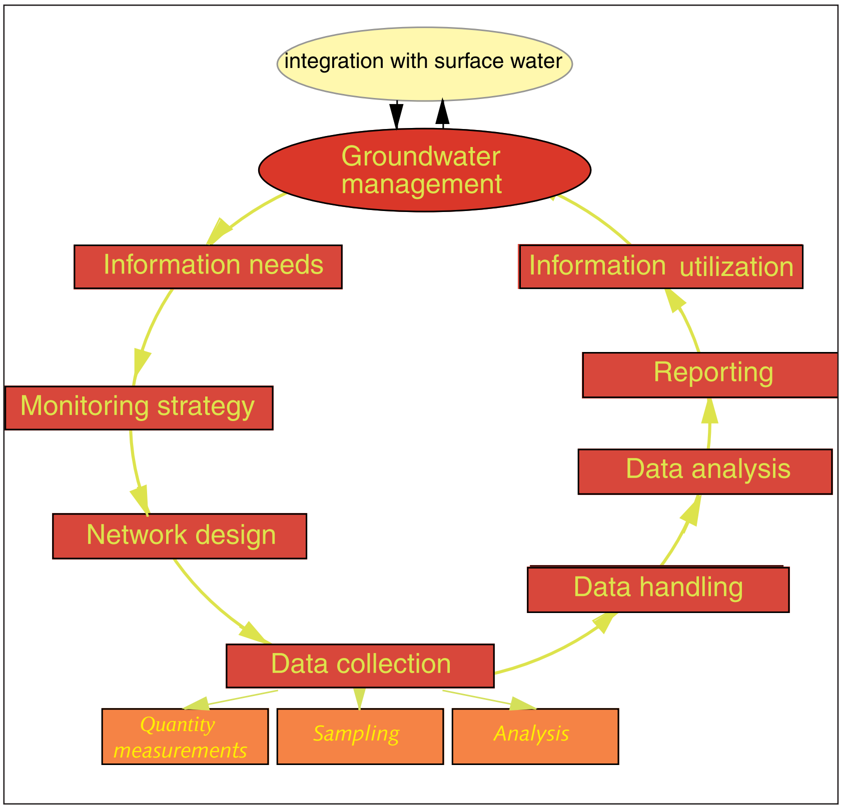
After identification of the functions, uses, problems and threats of the groundwater resources, often alternative measures will be defined from the side of the water managers and water policy makers to protect and/or re-establish and/or guarantee the functions and uses of the groundwater. The final selection of measures should be the result of an evaluation of the different measures and their environmental, economical and social impact, in the framework of an integrated and comprehensive approach of environmental management.

### 2.4 The Monitoring Cycle

Monitoring of groundwater is one of the tools used in groundwater management to obtain the information which is required for the assessment of the groundwater system and the groundwater management issues. To establish an effective monitoring system, a proper design procedure should be applied that starts with the specification of the information needs. For setting up monitoring and assessment of groundwater, the monitoring cycle as given in the Guidelines on Water-Quality Monitoring and Assessment of Transboundary Rivers (UN/ECE Task Force on Monitoring and Assessment, 1996) may also be adopted. This suggests that the process of monitoring and assessment should principally be seen as a sequence of related activities that starts with the definition of information needs, and ends with the use of the information product. Since quantity aspects are very important, the step "Laboratory analysis" has been substituted by "data collection" which comprises "quantity measurements (levels, discharge)", "sampling" and "laboratory analysis". This adapted cycle of activities is shown in Figure 2.5.

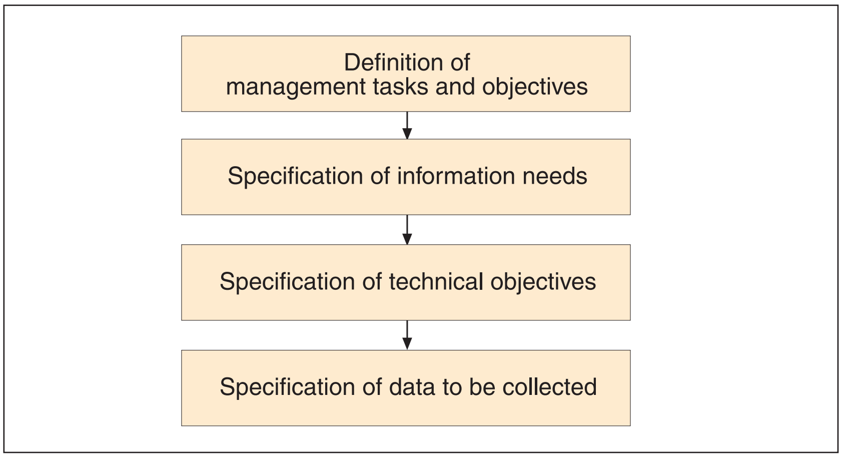
Successive activities in this monitoring cycle should be specified and designed based on the required information product as well as the preceding part of the chain. In drawing up programs for the monitoring and assessment of groundwater systems, riparian countries should jointly consider all stages of the monitoring process. 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. This should enhance one of the major objectives of most monitoring programs, i.e. the accurate identification of long-term trends in groundwater characteristics (UN/ECE TFMA,1996).

Figure 2.5
The monitoring cycle adapted for groundwater (quantity measurements as discharge and levels)




The initial monitoring design stage that finally should arrive at the specification of the data to be collected contains the steps which are depicted in Figure 2.6.
The different steps will be dealt with in the next chapter, where the management objectives and tasks, the needed information and the general technical objectives have been specified.

Figure 2.6
The initial steps of designing a groundwater monitoring system



# 3. Groundwater management

### 3.1 Problem definition

Groundwater supports different functions and uses. Available groundwater resources are being exploited at a large scale for urban, industrial and agricultural uses. During the last decades, the demand for groundwater of good quality has grown rapidly and consequently a continuously increasing quantity of the groundwater resources is exploited. One result is that many groundwater resources are being *over-exploited* with water being abstracted at unsustainable rates. Furthermore, falling groundwater levels may result in *ecological deterioration* and in land subsidence which could damage foundations and buildings in certain urban areas.

At the same time, in many coastal areas in the world, over-pumping has caused groundwater quality problems due to saltwater intrusion. *Groundwater pollution* has increased as a result of human activities, the consequences of high population density, continuously growing industrialisation and intensive agriculture. The soil and groundwater have become polluted by private and public waste dumps, airborne pollution, use of fertilisers, deposition of excess manure, etc. Furthermore, groundwater acts as the transport medium for the mobile contaminants by which public health, the environment or other interests might be threatened even at distances far from the pollution sources. The threats, due to the high pollution levels may even necessitate remedial actions or other counteracting measures. However, once polluted, groundwater is extremely difficult to purify on account of its inaccessibility, its huge volume and its slow flow rates (Helmer, 1997).

**Conflicting interests**

As a result of the developments as described above, the demands of the different groundwater functions (e.g. drinking water supply, industry, agriculture and nature reserve), of public health, physical planning and environment show more and more conflicting interests which may be transboundary as well. Also, the geographical extent of groundwater management and groundwater pollution has been increased, partly due to the fact that the management actions affect larger areas, and partly due to the subsurface transport of groundwater and contaminants.

Until recently, the interests in groundwater were mostly focused on exploitation of the available resources and on counteracting the possible spread of contaminants in those aquifers with moderate to high permeability, allowing reasonable flow rates and large discharges. However, in the last decades, the possibility of having (nuclear) waste sites in low permeability zones also induced an interest in the control and monitoring of the groundwater quality in those areas. Therefore, groundwater hydraulics in low permeability zones (including salt domes and hard rock areas) become more and more important, in particular when transboundary aspects are involved.

To balance the demands of the different groundwater user groups with the potential groundwater functions and uses and with the interests and demands of the other sectors of society, an integrated approach of groundwater management will be needed. Management objectives and information needs have to be defined. Monitoring and assessment of the groundwater resources have to provide the needed information.

### 3.2 Groundwater management objectives

Generally, groundwater management is aimed at an environmentally and economically sound and sustainable development of groundwater resources, which is socially accepted. The definition of the general groundwater management objectives should be derived for the different management issues: functions and uses, threats, problems and measures (Paragraph 2.3).

Groundwater management is performed at different administrative levels: national, regional and local. Going from the national to the local level, the tasks of the groundwater manager tend to change from generic and strategic to specific and operational. This implies that in most cases national water management deals with long-term planning at large spatial scales, whereas local water management deals with short term operations at small spatial scales. For transboundary water management, local as well as regional and national scales might be appropriate depending on the geographical extend of the transboundary aquifers.

To fulfil the management tasks at the different levels, information about the groundwater quantity and quality aspects at the right scale is required. Therefore water managers formulate the "*assessment objectives*". Often these objectives are formulated in general terms, like "to detect a change in groundwater quality over time". To enable the specification of data to be collected, the assessment objectives should be translated into "*technical objectives*". Unlike the assessment objective, the technical objective is formulated quantitatively. In the example of the change in quality, this could be "to detect a change of 10% over 5 years in the annual average of the nitrate concentration with a confidence level of 95%". Unfortunately it is not always possible to quantify the technical objective exactly. Examples where this is difficult, or even impossible, are monitoring networks that are set up for "general reference" and "calibration of a numerical groundwater flow model". Often management objectives are expressed technically in relation to standards i.e. "change in percent compliance with standard", especially if managers at local, regional or national level are trying to control pollution to improve groundwater quality (e.g. EC Nitrate Directive).

### 3.3 Information needs and technical objectives

The technical objectives for the design of a monitoring network should be derived from a specification of the information needs with respect to the management stages given in the previous section. In this section, the assessment objectives and the information needed from the groundwater system are described in general terms. To enable the design of a monitoring and assessment system, these objectives have to be translated into technical objectives, which should be quantified descriptions of the information needs which are to be assessed from the data to be collected.

There is a large variety of technical objectives, each related to specific groundwater management tasks at different administrative levels. In this paragraph, an attempt is made to describe the most important technical objectives with respect to transboundary networks. If possible, reference will be made to current practices in monitoring and assessment of groundwater. Therefore, information is used from the UN/ECE questionnaire and the EEA reports: "Groundwater monitoring in Europe" and "European Freshwater Monitoring Network Design" (Paragraph 1.4).

Technical objectives can be divided into two groups. The first group consists of "*characteristics*". The information needed is the final product of data analysis, where the data are interpreted, aggregated or integrated to provide information on a higher level. For many purposes, the information needed is in terms of general characteristics with respect to the status of the groundwater resources in both qualitative and quantitative senses, like spatial or annual averages, extremes, natural variability, etc. The second group consists of "*continuous representations*". Determination of spatial and temporal trends is often one of the most important objectives of a monitoring system. These trends may indicate undesired or desired changes in the groundwater conditions.

### 3.3.1 Characterisation of the groundwater system (threats and problems)

**Characterisation of the groundwater flow systems**

The aim is to obtain a three-dimensional picture of the groundwater flow systems and in particular to identify the transboundary systems. For the characterisation of the flow systems, information is needed about different aspects and with different levels of detail. A summary is depicted in Table 3.2 at the end of this Sub-paragraph. The question is which technical objectives can be defined and which data should be collected to provide the needed information. In this report, only the technical objectives with respect to the monitoring of groundwater are considered. Some examples of the linkage between information needs, technical objectives and data to be collected, defined up to a certain level of detail, have been depicted in Table 3.1.

**Table 3.1**
Examples of technical objectives for the characterisation of the groundwater flow system

| Information needs | Technical Objectives | | Data to be collected |
|---|---|---|---|
| Characterisation of groundwater flow systems | Groundwater contours/levels for the different aquifers | - temporal trend<br>- annual average<br>- average wet season<br>- average dry season | -> several years groundwater levels<br>-> at least one year, frequently<br>-> at least one year, frequently<br>-> at least one year, frequently |
| | Groundwater quality distribution not disturbed by point pollution | - Distribution of macro parameters within groundwaters | -> e.g. Ca, Mg, K, Na, Cl, SO4, HCO3, NO3, at least one sample and analysis campaign |
| | Abstractions from the different aquifers | - annual abstractions<br>- variation in abstraction | -> location, depth and e.g. monthly abstractions |

**Extent of aquifers, aquitards and aquicludes**

The aim is to produce a consistent picture of the geometry and hydraulic characteristics of the different layers. An information need is the degree of inter-connection between aquifers. The technical objectives are to define the groundwater contours and head distribution and the horizontal and vertical flow components. Furthermore, the information on the extent of the different layers is needed for a proper selection of representative locations and depth of observation for a transboundary groundwater monitoring network and also for a proper assessment of the data on groundwater levels and groundwater quality. Transboundary information on geology, geophysics and geohydrology will be necessary to produce the picture of the transboundary layers.

**Identification of the potential for groundwater use**

The identification of the potential for groundwater abstractions and consequently the assignment of functions and uses to the groundwater system need a transboundary approach. Water balance considerations, including the present abstractions, and the aquifer conditions will give indications for possible quantities of abstractions. The current groundwater quality conditions have to be compared with the requirements for the different uses. The additional information needs have been given in Table 3.2 at the end of this section.

The evaluation of historical groundwater monitoring data might be opportune for assessing the potential for groundwater abstraction. After the implementation of management measures, monitoring and assessment of groundwater is needed to enable the evaluation of the effect of measures taken and to adjust the measures if needed.

**Assessment of the vulnerability of the groundwater system to pollution**

A vulnerable groundwater system may need more intensive monitoring, in particular in combination with high pollution hazards e.g. in agriculture areas with use of high amounts of fertilisers and pesticides.

*The vulnerability* has to be assessed and classified, mainly on the basis of the following information: groundwater flow situation (e.g. confined or unconfined, infiltration, discharge, flux), thickness of unsaturated zone, depth to water table, soil composition (e.g. organic content, hydraulic properties and composition of the top layer) and geology.

**Assessment of the threats from actual and potential pollution sources**

One of the main objectives of a monitoring and assessment system is the evaluation of the groundwater situation in relation to human effects. Therefore, for interpretation purposes as well as for the design of a monitoring system it is necessary to combine the actual threats and the past threats with the vulnerability of the system and the current problems with respect to the groundwater situation.

**Assessment of the problems of the groundwater system**

Generally, one of the main objectives of a monitoring and assessment system is to assess the current problems of the groundwater system which are closely linked to the threats. To enable the evaluation of these problems, suitable technical objectives should be identified. Groundwater budgetting and determination of trends will be needed to identify over-abstraction. Groundwater level observation, surface water monitoring and vegetation cover monitoring is needed for the identification of desiccation.

**Assessment of the reference values for the concentrations of chemical constituents**

Different definitions are used for reference values or reference situations. A reference situation can be defined as the natural situation without anthropogenic influences. Sometimes the reference situation is defined as the background situation which might already be affected by anthropogenic activities. A reference monitoring network for groundwater may consist of stations which represent certain hydro-geological units. Hence, a clear definition of reference values or the reference situation is very important. In regional monitoring and assessment in which the purpose is to assess regional phenomena of the groundwater resources, it is important to avoid local phenomena like the impact of local pollution sources or abstractions.

**Table 3.2**
Linkage between management objective and technical objectives for groundwater monitoring

| **Management objective, task** | **Information needs** | **Technical objectives** | **Data type (or specific technical objective). Some examples with respect to groundwater monitoring** |
|---|---|---|---|
| Characterisation of the groundwater flow system, threats and problems, needed for defining of the potential functions and uses | 1 Characterisation of groundwater flow system, (three dimensional picture) | - surface water system<br>- groundwater level contours<br>- horizontal and vertical flow components<br>- groundwater quality distribution<br>- groundwater abstractions<br>- geology<br>- soil<br>- geomorphology<br>- climate data | - groundwater levels<br><br>- macro parameters<br>- annual / monthly abstractions |
| | 2 Aquifers, aquitards and aquicludes, (geometry, degree of interconnection) | 1 and additionally:<br>- lithology<br>- hydraulic parameters | - selection of monitoring locations representative for certain aquifers |
| | 3 Identification of groundwater potential (groundwater availability) | - 1 + 2 and additionally:<br>- trends of groundwater quality and groundwater level<br>- effects of current abstractions<br>- current groundwater budgets<br>- quality standards for uses and functions | - groundwater level measurements and calculations<br>- macro parameters, diffuse pollution |
| | 4 Vulnerability of groundwater | - groundwater flow situation<br>- soil properties<br>- geology | - discharge/recharge<br>- TOC |
| | 5 Threats of the groundwater | - land use<br>- airborne pollution<br>- abstraction<br>- drainage<br>- point/line pollution<br>- potential pollution sources | - fertilizers, pesticides |
| | 6 Problems (Groundwater quantity) | - over abstraction<br>- desiccation, desertification<br>- land subsidence<br>- foundation problems | - groundwater levels, trends<br>- groundwater balances |
| | 7 Problems (Groundwater quality) | - acidification<br>- excess nutrients<br>- salinization<br>- pollution (spreading) | - specific parameters |
| | 8 Reference values (for natural situation or background situation) | - local phenomena to be avoided<br>- natural situation<br>- diffuse anthropogenic effects | - thematic parameters e.g. which are representing acidification, excess nutrients, salinization or pesticides |

# 4. Current monitoring and assessment practices

### 4.1 Current groundwater monitoring practices in ECE countries

In this section, a summary of the current groundwater monitoring practices in some of the ECE countries is presented. This summary is based on the returned questionnaires with regard to the state of the art of transboundary monitoring and assessment and on two reports of the European Environmental Agency (EEA) dealing with the preparation of an European Freshwater Monitoring Network.

Questionnaires were sent to the 37 ECE countries on the initiative of the UN/ECE Task Force on Monitoring & Assessment, with the aim of collecting information on the actual practices with regard to monitoring and assessment of transboundary groundwaters (Table 4.1). Specific questions with regard to the state of the art in monitoring and assessment were included in the third part of the questionnaire (Form C). The respondents were requested to answer ten questions. During the preparation of this report twenty two questionnaires containing different levels of detail were returned. The answers have been summarised in Annex A and they have been evaluated in the next Sub-paragraph.

Partly, parallel to the activities of the UN/ECE Task Force on Monitoring & Assessment, the European Topic Centre on Inland Waters of the European Environmental Agency (EEA) presented a report with an overview of the current groundwater quality and groundwater quantity monitoring procedures and practices on national or federal scales within the EEA area (EU countries, Norway and Iceland) (Koreimann et al., 1996). The information obtained from the EEA area, also by means of a questionnaire, is more or less complementary to the information obtained by the UN/ECE questionnaires, because several EEA countries did not respond to the questionnaire of the UN/ECE. The EEA inventory forms the basis for the design of a European wide freshwater monitoring network which is presented in an EEA report edited by Nixon (1996). Relevant results of both activities have been presented here.

#### 4.1.1 Discussion of the UN/ECE questionnaire responses

The UN/ECE members were requested to answer the following questions with regard to the State of the Art in monitoring and assessment of groundwaters:

1. Is information about transboundary groundwaters collected?
   a) ad hoc; b) systematically
2. What kind of information is collected ?
   a) groundwater heads/piezometric levels;
   b) groundwater quality (sampling);
   c) hydraulic parameters (k, T, S); d) soil quality samples; e) others
3. For which purposes are the data collected ?
   a) strategic; b) operational; c) evaluation; d) others
4. For which purposes are the information actually used ?
5. Is there a network in operation ?
6. Which network design procedure has been used ?
7. How is the monitoring frequency designed ?

8. Are the data stored and is there a digital system (data base) ?
9. What kind of standards (quality samples) and quality control are used ?
10. Who is responsible (owner) of the network and the data collection, data storage and data handling ?

**Purposes and uses of existing monitoring and assessment of transboundary groundwaters**

Most of the responding countries stated that information about transboundary groundwaters is collected in a systematic way or on an ad hoc basis (question 1). According to the answers to question 5, monitoring networks are functioning in nineteen of the twenty-two responding countries. From the answers to question 3, it can be concluded that the monitoring networks have been established for strategic (14) and/or operational (13) purposes and/or for the purpose of evaluation of the groundwater situation (17) and/or for research purposes (2). Various purposes for the actual use of monitoring information have been given in the answers to question 4 (see Annex I).

**Table 4.1**
Countries and respondants to the questionnaire

| countries involved | questionnaire circulated by: | | answers received by lead country | forms received |
|---|---|---|---|---|
| | lead country (Hungary) | ECE secretariat | | |
| Albania | | x | | |
| Armenia | | x | | |
| Austria | x | | x | A,B,C |
| Azerbaijan | | x | x | A |
| Belarus | x | | x | A,B,C |
| Belgium[1] | | x | x | A,B,C |
| Bulgaria | x | | x | A,B,C |
| Croatia | x | | x | A,B,C |
| Czech Republic | x | | x | A,B,C |
| Estonia | x | | x | A,B,C |
| Finland | x | | x | A,C |
| France | | x | | |
| Georgia | | x | | |
| Germany[2] | x | | x | A,B,C |
| Greece | x | | | |
| Hungary | x | | x | A,B,C |
| Italy | | x | | |
| Kazakstan | | x | | |
| Kyrgystan | | x | | |
| Latvia | x | | x | A,B,C |
| Lithuania | x | | x | A,B,C |
| The Netherlands | x | | x | A,B,C |
| Norway | | | x | A,B |
| Poland | x | | x | A,B,C |
| Portugal | x | | x | A,B,C |
| Republic of Moldova | | x | x | A,B,C |
| Romania | x | | x | A,B,C |
| Russian Federation | x | | | |
| Slovak Republic | x | | x | A,B,C |
| Slovenia | x | | x | A,B,C |
| Spain | x | | x | A,B |
| Switzerland | | x | x | A,B,C |
| Tajikistan | | x | | |
| Turkmenistan | | x | | |
| The Ukraine | x | | x | A,B,C |
| United Kingdom | x | | x | A,B,C |
| Uzbekistan | | x | | |

1) Flandres, treated as Region
2) Germany is treated in this report according to the provinces (Länder):
Germany-I (Schleswig-Holstein), Germany-II (Bayern), Germany-III (Rheinland-Pfalz), Germany-IV (Brandenburg), Germany-V (Baden-Württemberg) and Germany-VI (Lower Saxony) where necessary due to the differences amongst the provinces in their administrative and institutional structure.

Two main uses can be distinguished, namely:
- use for protection, management and planning of the groundwater resources and
- use for assessment of the state of the groundwater resources and for the detection of trends in the quality and quantity of the groundwater.

**Information collected**

Most operating networks collect information on groundwater quality as well as groundwater levels. This is the outcome of question 2 of the questionnaire. Additionally, in 15 countries information on the hydraulic parameters such as hydraulic conductivity k, transmissivity T and/or storage coefficient S is also collected. The groundwater quality is monitored in 6 of the 19 operative monitoring networks.

For the storage and processing of the collected data, computerised data bases are used in most responding countries, at least for some of the monitoring networks maintained (question 8).

**Design aspects**

The application of certain specific systematic methodologies for the design of the existing monitoring could not be discerned from the answers given to question 6. A few respondents have indicated that the groundwater regime or hydrogeological conditions and geostatistics form the basis for the design of the networks and that e.g. uniform coverage and representativity of the aquifer considered should be aimed at. One respondent has stated that special attention is paid to the transboundary conditions and that suitable existing wells have been selected for the network (question 6).

Various frequencies are used for the measurement of groundwater levels and the groundwater quality (question 7). The frequencies used for quality measurements are rather comparable and vary from 1 to 4 times a year. They are linked to the seasonal hydrological regime. Only in one country higher frequencies, up to 12 times a year, are applied. A wide range of frequencies is used for the measurements of the groundwater levels, namely from continuously recording, to hourly, daily, weekly, bi-weekly, monthly, quarterly or annually, depending on the purpose of the monitoring and on the expected groundwater fluctuations. Specific design procedures for the frequencies of measurement or sampling have not been described in the questionnaires. In the former USSR member states, the former USSR directives are sometimes still in use. Furthermore, some respondents have given some general reasons for the frequency applied, such as purpose of monitoring, hydrogeological conditions, groundwater level fluctuations, abstractions and vulnerability of the aquifer.

**Standards and quality control (QC) applied**

Different kind of standards and quality control methods are applied by the responding UN/ECE member state countries (question 9). The impression is gained that in most countries national standards, guidelines and quality control methods are applied. The former USSR standards are still used in some former USSR countries. EU (or EC) standards, recommendations and directives are applied in six countries according to the returned questionnaires. Furthermore, the use of both ISO and WHO standards and regulations have been mentioned by one respondent.

**Conclusions**

The questionnaires have been returned from only 22 of the 37 ECE countries, hence the conclusions are only based on the situation in these responding countries. Only very general conclusions can be given because of the limited questionnaire answers given. Probably a better overview of the current monitoring and assessment practices can be given when the questionnaires of all the sub-projects are evaluated in an integrated way.

Based on the returned questionnaires, it is concluded that apparently in most responding countries, some attention is paid to transboundary monitoring and assessment of groundwater. However, it is surprising that the assessment of transboundary flows of groundwater and transport of dissolved constituents have not been mentioned at all, neither as one of the main purposes for the establishment of the networks, nor as one of the main uses of the information obtained. Therefore, the impression is gained that actual transboundary monitoring and assessment of groundwater on national basis hardly exist.

Monitoring networks are mostly operated and maintained with application of national standards and quality control procedures. The questionnaires give only very limited insight into the applied monitoring design methodologies, the different network set ups and the transboundary aspects and extent of the existing monitoring networks. Harmonisation of network design, measurement frequency, standards, quality control and data storage and processing will be needed for setting up transboundary monitoring and assessment of groundwater.

Computerised data processing seems to be in use in most responding UN/ECE member states. Different data base systems are used. Data formats developed will be different, which will complicate the exchange of information. A universally agreed data transfer format, like e.g. ASCII, will be needed to simplify the exchange of data between the riparian countries.

In the questionnaire, no special attention has been paid to the effect of the different aquifer types on monitoring and assessment. Generally, the occurrence and characteristics of groundwater in porous media (primary porosity) can be described and understood much more easily than the occurrence and transport of groundwater in rock types with secondary porosity which is linked to joints, fractures and voids formed by dissolution of limestone. Monitoring and assessment of groundwater in these rock types of secondary or mixed porosity is complicated and will need special attention.

### 4.1.2 Groundwater monitoring in EEA countries

In the report on Groundwater Monitoring in Europe (Koreimann et al., 1996), the results of questionnaires returned by the EEA member states (EU countries plus Norway and Iceland), have been presented and evaluated. Some relevant aspects are presented here under (for list of EEA countries, see Table 4.1).

**Groundwater characteristics**

In the questionnaire, different types of aquifers have been distinguished for the description of the groundwater characteristics, namely groundwater in porous media, karst groundwater and other. Most countries have given a short description of the aquifer types. Besides the occurrence of groundwater in porous formations with inter granular permeability (primary porosity) and in karst formations with secondary permeability features, groundwater occurs also in fractures, fissures and joints of other hard rock formations in some other countries. However, no specific linkage has been given between the different types of aquifer and the monitoring and assessment methodologies, activities or other aspects.

**Monitoring objectives**

The networks described are in principal national in extent with the exception of regional or federal networks in Germany and France. However, in certain countries groundwater monitoring, and in particular the quality monitoring, is only conducted in certain areas. Monitoring has been developed as a result of national demands and objectives, geological and hydrogeological situation and, in case of quality monitoring, land use. Therefore, the monitoring objectives and consequently the different network set ups show considerable differences for groundwater quality monitoring in the various states (spatial density, frequency of measurements and type of parameters). Only general surveillance purpose and water quality trend identification are mentioned as widespread common goals. Furthermore, the following monitoring objectives were mentioned: assessment of compliance with national or EC legislation (e.g. control of drinking water quality, EC Nitrate Directive), detection of sea water intrusion, detection of impacts caused by airborne pollutants (in relation to acidification problems) and detection of impact of fertilisation and use of pesticides.

For groundwater quantity monitoring, more similar objectives between the EU countries, such as the collection of basic groundwater data, the management of groundwater resources, water supply control, control of impact areas and the support of hydrogeological science, have been mentioned. In some countries, monitoring is undertaken to assess compliance with national and/or EC legislation, even though there is no current EC Directive for groundwater quantity monitoring.

**Monitoring network density**

The quality network sample density shows wide ranges from 0.003 to 0.57 sites/km2 and the quantity network from 0.004 in Norway to 7.3 sites/km2 in Finland. Within the different aquifer types, the majority of sampling sites are distributed evenly within the whole groundwater area. Furthermore, many are concentrated around pumping stations for drinking water. In Germany and Portugal impact areas are also investigated.

**Measured parameters and frequency**

The measured water quality parameters vary considerably between the networks and apparently are adapted to national circumstances. In the report, it is stated that at present they cannot be readily compared at a European level. It is concluded that the majority of countries have national standardised sampling and analytical methods as well as standardised regulations for precision and accuracy. The observed parameters can be divided into the following groups: the descriptive parameters (e.g. pH, EC, etc.) and the major ions (e.g. Ca, Mg, Na, K, NO3, NO2, NH4, Cl, SO4, HCO3, etc.) are the most analysed, then additional parameters (e.g. DOC, boron, fluoride, cyanide, hydrocarbon benzene), heavy metals (Pb, Zn, Cd, Ni, Hg, Cr, etc.), organic substances including chlorinated solvents (e.g. trichlorethene, tetrachlorethene, etc.) and pesticides (herbicides, insecticides). Sampling varies from once every two years to 12 times per year for basic program parameters.

The quantity parameters are observed at a range of frequencies. The observed parameters include groundwater levels for all countries, temperature in most countries and sometimes spring level and spring discharge.

**Organisation**

The majority of monitoring programs are co-ordinated by a single national institution which mostly collaborates with (sometimes many) regional or provincial organisations. In the different countries, sampling and analysing is carried out from 1 up to more than 200 institutions which are mostly public ones. Sampling and analysing methods as well as regulations for precision and accuracy are often standardised on national level.

**Data Bases**

Data bases used are e.g. Oracle, VAX/Rdb, Ingres and Informix. Different operating systems like VMS, UNIX, WINDOWS, DOS and different languages and software tools are used. Interfaces have to be designed to facilitate data transfer between the different data bases. In most countries, dissemination of data are not subject to restriction or fees.

**Conclusions**

It was concluded that in the EEA area monitoring networks have very different purposes and objectives. Therefore, structure and design of the networks are different. However, it was difficult to establish the representativeness of the networks. It is stated that at present there is not enough comparable information on monitoring and assessment of groundwater resources in Europe. A full analysis of gaps in existing monitoring programs is not yet available because the information from the questionnaires has been insufficient for this purpose. In particular, more interpretative information is needed on the objectives of each monitoring program to explain differences in sampling density and sampling frequency and how these aspects are linked up with the hydrogeological characteristics of each groundwater region and the type of impacted areas.

Based on information obtained from the above mentioned report, a European Freshwater Monitoring Network Design, has been proposed (Nixon, 1996). In the report, a design of a groundwater monitoring network is given, which will be a general surveillance network and which will comprise representative stations in all nationally important aquifers; groundwater in porous media, karstic groundwater and other should be covered. The overall objective of the groundwater monitoring network is: "to obtain timely, quantitative and comparable information on the status of groundwaters from all EEA Member States, so that valid temporal and spatial comparisons can be made and so that key environmental problems associated with Europe's groundwaters can be defined, quantified and monitored".

Three main categories or types of monitoring have been distinguished:

- statutory monitoring to meet legal obligations;
- surveillance monitoring to assess the state of groundwater quality and quantity and to make spatial and temporal comparisons possible;
- operational monitoring (e.g. water supply, soil remediation, pollution control).

Overlaps between the categories may exist. The type of information required by the EEA is for surveillance purposes. The EEA must take into account in its descriptions and assessments of the environment, the quality, sensivity and pressures on the environment.

For the groundwater quality monitoring, the following three types of networks are distinguished:

- *Basic networks*
  For the assessment of the general state of the groundwater quality in

the entire country. Reference stations yielding background information of the natural situation can be part of the network. The basic networks are permanent.

- *Specific networks*
  Regional or local networks. They monitor selected areas or are established for specific reasons (e.g landfills). They act as "impact stations" and can be separate networks or extensions of a basic network.
- *Temporary networks*
  They are operational during project periods and will normally be impact stations.

For the monitoring of groundwater quantity, an additional type of network has been identified, the 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.

In the report, the purposes and objectives of groundwater quality and quantity monitoring have been listed and the framework of the proposed groundwater monitoring networks has been given. Furthermore, the conditions for the different aspects of the EEA groundwater monitoring network have been described. Although the general objectives of the EEA monitoring network will be different from transboundary groundwater monitoring, quite some overlap may be expected and harmonisation of the different monitoring and assessment aspects of the two systems is necessary.

# 5. Design of groundwater monitoring and assessment systems

## 5.1 Introduction

The operation of a groundwater monitoring program is one of the most important tools to obtain the information needed for adequate decision-making about environmentally sound and sustainable development and the protection of the groundwater resources.

It is assumed that the *technical basis of a network* for groundwater monitoring generally consists of a network of observation points which are either existing wells, boreholes and springs or are purposely designed and installed observation wells or observation piezometers tapping the groundwater body which has to be monitored.

### 5.1.1 The step-wise process of the design

The entire monitoring cycle as presented in Figure 2.5 constitutes the framework for the design process of a monitoring network system for groundwater. In principle, all successive stages presented in this cycle should be considered, described, designed and documented. The different steps and aspects of this sequence are depicted in the generalised scheme of Figure 5.1 and described briefly below. The numbers of the steps given below refer to the numbers in the flow chart of Figure 5.1.

**Information needs**

The design of a monitoring and assessment system depends on the information which is required for the execution of proper groundwater resources management. The information needs should be assessed on the basis of the management objectives, which should be translated into technical monitoring and assessment objectives for which the required monitoring efforts (e.g. measurements and data analysis) should be defined (Paragraph 3.4).
The chart in Figure 5.1 shows that groundwater monitoring and assessment provides only a part of the required information.

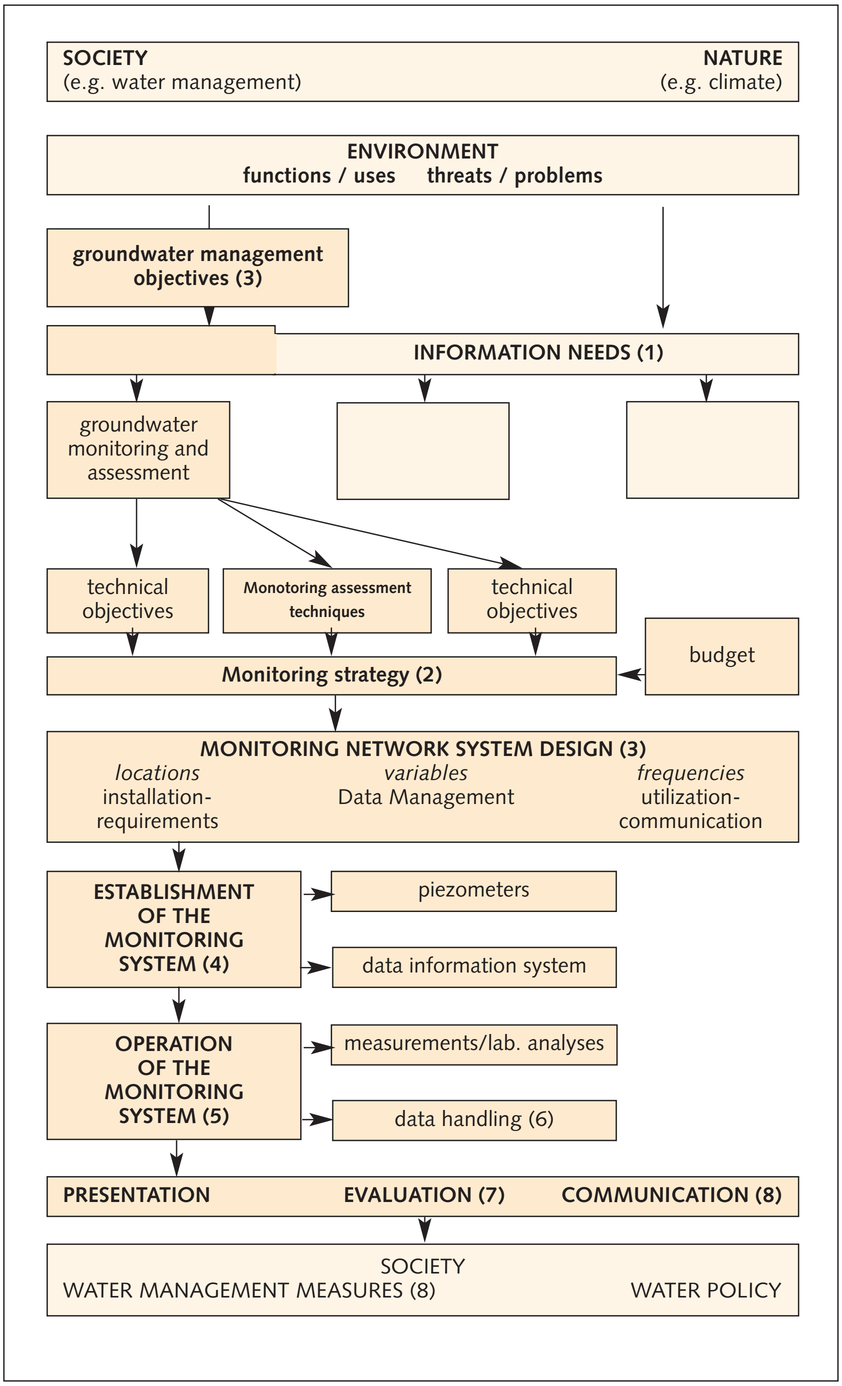
**Monitoring and assessment strategy**

A monitoring strategy defines the approach and the criteria needed for a proper design of the monitoring and assessment program (UN/ECE TFMA, 1996). Defining the strategy is aimed at optimising the use of available technical, legal, financial and human resources to meet the information requirements. A further elaboration is given in Paragraph 5.2.

**Design of the monitoring and assessment system**

If the existing information and monitoring- and assessment systems do not comply with the demands, a monitoring- and assessment system has to be designed according to the strategy and techniques outlined in the previous step. This may also include the improvement or optimisation of existing systems. When a monitoring network has to be established, the design is not only restricted to (i) the selection of the type and density of the network stations, (ii) the parameters of measurement and (iii) the frequency of measurements. An appropriate design also considers the

**Figure 5.1**
Design and implementation process of a monitoring network for groundwater




necessary activities for the establishment of the network stations, the technical design of the measurement points and the materials used and further the operational procedures for the measurement- and sample campaigns, laboratory analysis and data handling. And moreover, a user-friendly easy accessible computerised data base management system should constitute the nucleus for appropriate data storage, processing and presentation. Factors which determine the main components in network design for groundwater quality have been given in Table 5.1.

**Table 5.1**
Factors which determine the main components in network design (Chilton et al., 1996)

| Sampling point | | Sampling frequency | Choice of parameters |
|---|---|---|---|
| Type | Location/Density | | |
| Primary assessment objectives<br>Hydrogeology (complexity)<br><br><br><br><br><br>Costs | Primary assessment objectives<br>Hydrogeology (complexity)<br>Geology (aquifer distribution)<br>Land-use<br>Statistical considerations<br>Costs | Primary assessment objectives<br>Hydrogeology (residence time)<br><br><br>Statistical considerations<br>Costs | Primary assessment objectives<br>Water uses<br><br>Water quality issues<br>Statutory requirements<br><br>Costs |

**Establishment of the monitoring and assessment system**

After the design has been completed, the system has to be established. In case of new network stations, the points of observation have to be selected in the field according to the criteria set. Drilling- and installation activities should meet criteria to ensure proper execution of the works and use of proper materials in order to establish an observation point which is representative for the particular situation defined for the design of the network. Furthermore, the organisations responsible for the maintenance and operation of the network and for the data handling, data analysis and reporting should be made operative. Data entry, control- and management procedures should be set up and documented. Data storage, processing, exchange and presentation procedures have to be agreed upon between the parties involved.

**Operation and maintenance of the monitoring and assessment system**

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

**Data base and Information system**

Data handling after the production of the raw data is included in the operation of a data base and information system. Application of GIS computer programs is recommended to facilitate the data processing, analysis and presentation.

**Data analysis and Reporting**

Data analysis and reporting are needed to provide the different owners, user groups and authorities with the requested information. It should be clear which agencies are responsible and to whom and when reports have to be delivered. The acquired information should be utilised for the fulfillment of the objectives which should include the determination of the target parameters, the technical objectives and the management objectives. Formats for standard reporting procedures should be produced.

**Information utilisation, communication**

Finally, the information produced will be used by the user groups and the groundwater management authorities. The acquired information should be compared with the expectations and the standards and when necessary management measures have to be taken or changed. Communication to the general public for raising general awareness is important to get support for the measures taken. Water management is not an isolated activity for specialists only. The state and changes of the environment are of concern to the general public and therefore of the governmental authorities, which should be aware of the threats, problems and management alternatives.

**Additional information needs**

Groundwater monitoring cannot provide all the needed information on the water resources for the execution of adequate groundwater management. Additionally, meteorological and surface water data are needed for the analysis of the information obtained from the groundwater network. Moreover, a proper knowledge of the lithological and bio-chemical composition of the subsoil is a prerequisite, not only for the analysis of the data but also for the design of the monitoring system. Groundwater management cannot be performed on its own; on the contrary, it will be a part of a comprehensive and integrated policy on the use and protection of the environment and the natural resources. Consequently, information about the possible impact on the water resources from activities beyond the scope of the water management may be needed. This is also depicted in the flow chart of Figure 5.1.

### 5.1.2 Statistical versus hydrogeological approach

This sub-paragraph describes the process of the design of a groundwater monitoring network subsequent to the specification of the technical objectives. The monitoring network should provide data which fulfils the technical objectives and the defined information needs which have been derived from the groundwater management objectives. From the point of view of the groundwater manager, the objective of the monitoring network is preferably defined in terms of target parameters. In some cases, the target parameter can be a property of the groundwater, e.g. concentration of nitrate, however, in most cases the target parameter is some function of the measured properties. Some examples, increasing in complexity are:

- the average concentration of a constituent over an area;
- the rate of change of a concentration over time (temporal trend);
- an indicator for the effectiveness of groundwater management (see also background document 2: "Problem-oriented approach and the use on indicators");
- response characteristics of the groundwater system based on geohydrological modelling (see also background document 3: "Application of models").

Obviously, many target parameters exist. It is important that, in principle, target parameters are quantifiable in terms of scalar characteristics (mean value, indicator), a surface in space, a trend in time, levels of exceeding, etc.

**Estimated value**

In principle, a basic property of a network will be the existence of a correlation of parameters among different observation points. The distribution of the observation points of the network should enable the determination of the target parameter anywhere in the system by interpolation of the measurements at the observation points with sufficient accuracy. Consequently, the derived value for the target parameter is referred to as the estimated value. The selection of density and frequency should be made in such a way that the estimated value of the target parameter is sufficiently accurate. The difference between the estimated and the real value is called the estimation error. Quite similar to the design of the monitoring network in space, the monitoring in time, in other words, the sampling frequency should be based on the quantification of the relationship between the desired accuracy and the frequency. For example, a greater number of samples will lead to a smaller estimation variance. Suppose a particular criterion is defined in terms of desired accuracy, being similar to the estimation variance, the number of samples may be iteratively increased to meet the sample variance that was chosen initially.

In order to characterise the behaviour of a variable in space and/or time, a clear distinction can be made between characterisation in terms of (1) general characteristics, and (2) continuous interpolations. General characteristics are numbers, independent of space and time, which are – to some extent – representative for the variable in question, for example, arithmetic mean, median, standard error or variance, percentiles, all kinds of indicators, etc. Continuous representations are quantitative or intuitive interpolations or extrapolations describing the target parameter as a function of space and time.

Loaiciga et al. (1992) identify the main approaches to groundwater monitoring network design as (1) the hydrogeological and (2) the statistical approaches.

**Statistical approach**

If the estimation error is explicitly calculated in one form or another, the quantification will always involve some sort of statistical criterion. In this approach, a variety of criteria is known. Dependent on these criteria, the statistical approach can be further divided into (1) classical statistics, (2) geostatistics, and (3) time series analysis. The advantages and disadvantages of each of these approaches depend on such factors as the objective of the monitoring program, the scale of the program, available data, nature of the investigated processes, resources available, etc. A more detailed description of the statistical approaches is given in Annex II.

**Hydrogeological approach**

The hydrogeological approach is the basis of the procedure most commonly used in practice. In the hydrogeological approach, no explicit quantification of the uncertainty is given. Instead, the network design follows from a deterministic, hydrogeological, area description based on expert judgement. Loaiciga et al. (1992) define this approach as the case where the network is designed based on the calculations and judgement of the hydrologist without the use of advanced geo-statistical methods. The hydrogeological approach is better suited for site-specific studies where there is, for example, a well-delimited source of contamination. The number and locations of sampling sites are strictly determined by the hydrogeological conditions (i.e. scale of hydrogeological variability) near the source of contamination, such as a waste impoundment. The approach relies heavily on descriptive information about the aquifers of interest, and often does not fully utilise the available quantitative hydrogeological information.

*Hence, in areas where relevant hydrological data are limited or even absent – in so-called scarce data areas – this approach may be the only possible technique.*

Just as the hydrogeological approach can provide information on the spatial layout of the network design, it can also help determine the sampling frequency in time. This is typically done by taking into account the seasonal changes for some objectives and some human activities e.g.

farming and by application of Darcy's law to describe groundwater velocity. For example, by estimating hydraulic conductivity and porosity (or by determining the type of sediment) in the near surroundings of a groundwater abstraction well, the flow velocity can be calculated and related to, say, the groundwater quality sampling interval. In general, more frequent sampling will be needed in shallow, high velocity aquifers with a more vulnerable, while less frequent sampling is needed in deeper and in confined aquifers.

Finally, a combination of the statistical approach and the hydrogeological approach can be applied to design a network. In this approach, a deterministic, hydrological model simulation is used in combination with the statistical interpolation techniques to quantify the estimation errors.

### 5.1.3 Monitoring effort and acquired information

The basic idea behind monitoring network design is that there should be a relation between the monitoring effort, which consists of the number of sample points and frequency, and the order of magnitude of the estimation error. Increasing the monitoring effort will result in a decreasing estimation error. After having selected the appropriate target parameter to meet the management objective, the optimal monitoring effort should be determined on the basis of this relationship and the subsequent benefits for the groundwater management. However, in most cases, it is difficult or even impossible to define this relationship and often the "information content" is used as a substitute objective. The reason behind this is that the information obtained from the monitoring network (information content) increases with an increasing monitoring effort. The monitoring network is designed by balancing the information content and the monitoring effort (cost). The information content is a function of the estimation error. The smaller the estimation error, the more information is obtained from the network.

*Regardless of which objective or target parameter has to be monitored, the design of the monitoring network should be based on the relationship between the measurement effort and the estimation error.*

The fact that monitoring network design is based on the relation between an estimation error and the monitoring effort, does not necessarily mean that the estimation error is quantified in statistical terms. In some cases, the error can also be taken into account intuitively by professional judgement.

## 5.2 Monitoring strategy

After the technical objectives have been derived, a more specific strategy has to be developed before starting the actual design of a monitoring network. The following questions and aspects are involved in the development of a proper strategy (see also UN/ECE Task Force on Monitoring & Assessment, 1996):

1. *Existing information.* Is needed information already available from other sources (e.g. existing monitoring systems, specific surveys, models, other data suppliers, etc.)?

2. *Required assessments.* What kind of assessments have to be carried

out (e.g. natural situation, background situation, compliance with requirements of uses and functions, pollution levels, risk assessments with regard to public health and/or environment, early warning assessment etc.)?

3. *Monitoring techniques.* What are the available and suitable monitoring techniques (e.g. surface water monitoring, meteorological monitoring, remote sensing techniques, early assessment monitoring (e.g. use of pesticides, etc.), water use, geo-physical methods, (phreatic) groundwater monitoring network system, continuous recording monitoring system, etc.)?

4. *Existing monitoring and information systems.* Can existing monitoring and information systems provide the needed information by adjusting the operation of these systems? Is it possible to use the existing data base information system? What does this require from a possible new monitoring system?

5. *Type of monitoring.* If monitoring is needed, what type of monitoring will be required? Will a single survey be sufficient or is more extended monitoring necessary?

6. *Step-wise approach.* Is a step-wise approach of developing a monitoring network system, leading from coarse to fine assessments, worthwhile?

7. *Responsibilities.* Who will be responsible for the organisation of the monitoring system (for the design, implementation, operation and evaluation)?

8. *Financial and human resources.* And last but not least, what is the available budget and consequently which human resources can be made available? The responsible authorities should realise that most often monitoring of groundwater should be guaranteed for a long time. The needed financial input may be guaranteed by charging water users and miss-users of the groundwater resources.

According to the guidelines on water-quality monitoring and assessment of transboundary rivers (UN/ECE, 1996), the integration of monitoring activities for reasons of cost-effectiveness in an early stage of the monitoring cycle may cause an over- or under- dimensioning of monitoring networks. Therefore, it is recommended to develop an information strategy per monitoring objective or information need. Integration of monitoring efforts may be considered in the implementation phase.

The outcome of the development of the monitoring strategy should be the specification of one or more monitoring options for which a system should be designed. In the next sections, the design of the different components of a monitoring system is dealt with. Only monitoring network systems consisting of groundwater observation points (e.g. purpose constructed wells, existing wells, boreholes, springs etc.) have been considered because this type of monitoring combined with surface water monitoring and meteorological monitoring is the only widespread type of groundwater monitoring applied (other types may be geophysical methods, drainage systems, springs etc.).

## 5.3 Main types of monitoring

Various types of groundwater monitoring categories and networks are distinguished in the different consulted reports. In Table 5.2, a distinction is made between monitoring for strategic management and policy, for operational water management and surveillance purposes. Operational monitoring and surveillance will be linked to respectively functions/uses and problems/threats, the so-called core elements in water management. Other monitoring types and networks can often be linked to one of these three categories. Some general characteristics and objectives of the different types of monitoring have been summarised in this table.

**Table 5.2**
Main types of monitoring

| **Types of groundwater monitoring**<br>State-of-the art | <br>Transboundary context | <br>Comparable types | **Characteristics** | **Information** |
|---|---|---|---|---|
| Strategic | Basic/reference for status assessment and compliance | - background stations<br>- reference system<br>- statutory monitoring | - beyond local anthropogenic influence<br>- relation to (diffuse) anthropogenic or natural causes<br>- international directives and conventions | - natural situation<br>- trends (natural, diffuse pollution, hydraulic regime)<br>- baseline (to detect human impact), background levels<br>- spatial distribution<br>- early warning<br>- compliance |
| Operational | Monitoring linked to function/use monitoring for specific purposes compliance special protection areas remediation and restoration | - user related monitoring<br>- compliance monitoring<br>- implementation monitoring<br>- effectiveness monitoring<br>- validation | - linked to uses and functions , regulations, laws, directives, acts etc.<br>- protection of functions and uses<br>- models<br>- implementation and effectiveness | - quality standards<br>- criteria, tresholds<br>- health risk<br>- environmental risk<br>- validation<br>- forecasting<br>- effectiveness of measures |
| Surveillance | Early warning and surveillance emergency response | - early warning monitoring<br>- impact monitoring | control (of management measures) | - tresholds<br>- early warning<br>- risks<br>- effectiveness of measures |

## 5.4 Primary aspects in network design

The design of a groundwater monitoring network includes primarily the determination of:

- the *parameters* to be measured;
- the *locations and depths* for which the parameters should be representative;
- the *period of time* for which monitoring is required and the frequency of the measurements within this period of time.

The essence of a monitoring network system is the choice of parameters to be measured or analysed. Then the representativity of the measured variable, given by location and depth, is the most crucial monitoring aspect. Without knowing the representativity, the knowledge of the variable would be worthless. 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 parameters.

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 the 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. However, it is expected that generally in most transboundary groundwater resource systems the availability of hydrological data is limited and that a so-called hydrogeological approach will prevail. Particularly this will be the case for the design of monitoring systems in consolidated formations (hard rock formations).

**Integration of groundwater quantity and quality networks**

In the next sections, groundwater quality and quantity are dealt with separately. However, in most cases groundwater quantity as well as groundwater quality have to be monitored and then integration of both monitoring efforts will be needed from a technical as well as from an economical point of view. Groundwater quantity data are needed for the interpretation of groundwater 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 in which the overlapping criteria will be combined to reach the most effective and economical groundwater monitoring system. Often this also implies integration in organisational sense when monitoring of groundwater quantity and quality is the responsibility of different organisations.

### 5.4.1 Groundwater quantity

**Parameters**

The general objectives of groundwater quantity monitoring will be the acquisition of information about groundwater levels (hydraulic pressures), the direction and quantity of groundwater flows, including recharge- and discharge areas, and about groundwater balances. Information will be needed from recharge areas towards the discharge zones of the groundwater system. The needed information must be acquired from different sources and not only from a groundwater quantity network system.

Possible parameters of groundwater quantity are primarily:

a) water level *measurements* within an observation well;
b) *discharge* of abstractions and springs;
c) *induced recharge* (disposal of effluent, infiltration of surface water for purification and storage of drinking water etc.);
d) *leakage* of distribution and sewerage systems;

Further the following information will also be needed:

e) *the surface water system* (levels and flows); interaction with groundwater (discharge, recharge); in particular base flow of rivers and streams.

Then, for balancing recharge, storage and discharge of the groundwater resources, data will be needed on:

f) the *climatological conditions* (e.g. precipitation, evapotranspiration);

g) *soil moisture*;

h) *return flow* from irrigation;

i) possible interaction (drainage or leakage) between sewerage systems and groundwater.

Quantified parameters which can be measured directly are mentioned under (a) through (d). It is recommended that a groundwater quantity network system should include these parameters or it should be guaranteed that these data can be easily obtained, for example by integration with other monitoring systems. The central storage of all the relevant data in an easy accessible data base is a prerequisite for an efficient evaluation of the groundwater situation.

A uniform reference level (e.g. MSL) for the water levels has to be decided upon. This aspect needs particular attention in transboundary monitoring.

Principally, there is no difference between the type of quantity parameters to be measured in the complex groundwater flow systems of consolidated, indurated formations which are entirely or partly linked to the occurrence of joints, fractures and/or voids and the groundwater flow systems in unconsolidated sediments with intergranular porous permeability. However, the evaluation of the results will be more difficult for the hard rock formations which will generally need more additional information (e.g. geology).

**Locations**

Probably the most crucial monitoring design aspect is the specification of the measurement positions in a spatial sense, because this defines an important feature of the observation point, namely its representativity. Technically, the positioning of the observation points and the number of observation points, which determines the density of the network, is governed by two criteria, namely (i) the specified representativity of the observation points and (ii) the possibility to determine the spatial trend of the groundwater levels or hydraulic head pressures on the required scale. The first criterion means in general a specification of the groundwater flow system or unit for which a network should be established. The second depends primarily on the defined technical objectives. For example, for a regional network, a strategic type of monitoring, the objective could be to enable the determination of a regional trend based on the average groundwater levels for a certain period or on the groundwater levels for a specific date. In case of the operational and surveillance type of monitoring, the periods to be considered for trend detection will generally be much shorter and require a higher density of observation points compared to regional monitoring. Continuous interpretations for describing the groundwater levels and hydraulic pressures in space will also be needed for monitoring of transboundary groundwater systems, which may include strategic as well as operational or surveillance monitoring.

**Representativity**

After the definition of the monitoring objectives, the following aspects have to be taken into account to determine the groundwater domains for which the network stations should be representative:

**(i) The characterisation of the relevant groundwater flow systems.**

This aspect has already been mentioned in Chapter 2. In principle only those flow systems will be considered which have been specified during the definition of the objectives. A further specification might be needed. The aim is to define the boundaries of all the groundwater flow systems which may have transboundary flow components.

The characterisation of the flow systems is primary needed to establish the distribution of the measuring points in a lateral sense within the boundaries of the transboundary systems identified and to some extent beyond these boundaries.
For positioning the measurement points in a vertical sense, more information will be needed on the lithological composition of the subsoil for which the following aspects have to be considered.

**(ii) The extent of aquifers, aquitards and aquicludes or the characterisation of geohydrological units.**

Besides the positioning within a particular groundwater flow system, a more precise positioning of the measuring or sample point is needed. It can be given by taking into account the permeability distribution of the subsoil and therefore the geometry of different lithological layers which may delineate aquifers, aquitards and aquicludes. The measuring points should be positioned within the aquifers or a geohydrological unit. Geohydrological units may be considered as aquifer systems with strongly correlated hydrological responses (e.g. groundwater level variations) to natural (e.g. precipitation, evaporation, surface water systems, recharge) or anthropogenic stresses (abstractions, canals etc.).

In general, the exact position of an observation point 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. This might occur in recharge zones with low permeability top layers or within the capture zones of pumping stations.

In general, the characterisation of local phreatic flow systems will need a relatively dense network of observation points while for the deeper confined or semi-confined aquifers a much less dense network is sufficient.

**(iii) Additional information.**

Depending on the objectives, additional information has to be taken into account. The impact zones due to human activities like watershed management measures, abstractions, operation of dams, canals, weirs, drainage systems, etc. have to be avoided for the establishment of reference networks, while for certain operational and surveillance purposes the observation points should deliberately be located within those impact areas (e.g. to monitor over-abstraction). Hence, for the selection of measurement locations all the information on those anthropogenic "threats" should be collected in order to take them into account for the design of the network.

The above outlined general considerations can be applied to groundwater resources within unconsolidated sediments with primary permeability. For groundwater resources within consolidated and indurated rock types with secondary or dual permeability features, the selection of proper measurement locations is generally more difficult due to the complex groundwater regime. In principal, the aspects to be considered remain the same; much attention has to be paid to the characterisation of the groundwater flow systems, the extension of the water bearing formations and to the recharge and discharge areas in particular. However, more intensive input of geological expertise will be needed and even then the specification of the representativity of the measuring points will often remain difficult.

**Network density**

Despite economical constraints, the density of the network has to fulfil the defined monitoring objectives (as far as possible). Further, the required spatial distribution will depend on aspects like:

- the characteristics of the identified zones which should be represented;
- the spatial scale of the correlated variable, often a spatial trend should be detectable;
- the magnitude and frequency of the variations of the measured variable in space and time;
- the frequency of measurements.

Statistics may be applied in case sufficient historical data are available and the effectiveness of a network is quantified as a certain accuracy of the spatial interpolation of the variable considered (i.e. the standard deviation of the spatial interpolation error). Therefore, the well known Kriging technique is often applied. In Annex II a more detailed explanation of the statistical techniques is given. Some actual applied monitoring densities are given in Sub-paragraph 4.1.2.

**Frequencies**

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 or being able to eliminate them in a sufficiently accurate manner. The following type of temporal changes and variations may occur:

- natural variations, such as (i) diurnal, (ii) short events like recharge from rainfall events or discharge changes due to natural changes at the outlet of the system, (iii) seasonal (dry and wet periods), (iv) long term trends;
- anthropogenic impact variations e.g. abstraction regimes, induced recharge, return flow from irrigation, etc.

To be able to define certain 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 within the period in which the change of the variable occurs. If measurement series are available, statistical techniques offer possibilities for extrapolating an optimal frequency.

The same basic approach has to be adopted for the determination of the frequencies of measurement in consolidated formations with secondary or dual permeability. However, it might occur that the heterogeneity of the system 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. In practice, a wide range of frequencies is used, namely from continuous to annual.

### 5.4.2 Groundwater quality

**Parameters**

Possible parameters to be measured can be linked to the core-elements of water management and their interaction as presented in Paragraph 2.3. The parameters to be measured will depend on (i) the requirements of the defined functions and uses of the groundwater system, (ii) the threats to which the groundwater system is exposed and, (iii) the problems which are already effective. Within the background report 2 "Problem-oriented approach and the use of indicators", this concept has been defined with a proposal for Pressure-State-Impact and Response indicators (PSIR-indicators). In the background report, different indicators have been established for some combinations of functions and issues (problems and threats). For the description of the relevant parameters, reference should be made to the extensive discussion in that report. Generally, the following procedure should be followed to define the parameters to be measured:

- characterisation of the relevant aquifers (including chemical composition of the soil matrix and background groundwater quality);
- definition of the actual functions and uses and their quality requirements, eventually stipulated in international or national standards, directives or regulations (e.g. ecological function, water supply for drinking water, agriculture and industry, etc.);
- specification of the threats to which the groundwater system is exposed (e.g. generally reflected in land-use: agriculture, industry, waste sites, military sites etc.). Then specification of the relevant parameters and indicators;
- specification of the problems which are already experienced by the groundwater system (e.g. acidification, nutrients, salinization, pollution, etc.). Then specification of the relevant parameters and indicators.

**Locations**

In general, the locations should be representative for the defined objectives which often reflect one or more of the issues mentioned above in Sub-paragraph 5.4.2 (a). The approach to be followed is similar to that for groundwater quantity with incorporation of the above mentioned issues. In fact this has been worked out already in Sub-paragraph 3.3.1. The aim of the recommended approach is that the positioning of the observation points should be based on the vulnerability of the groundwater flow system, combined with the functions/uses, threats and problems and the core-elements of water management. The different activities to be carried out for a specification of a location are summarised below:

- characterisation of the groundwater systems and the geometry of the principal water bearing formations;
- vulnerability assessment, mainly based on the groundwater flow situation (discharge and recharge areas), soil composition and geology;
- identification of the threats to which the groundwater system is exposed (in particular reflected in land use: agriculture, industry, waste sites, military sites, etc.);
- identification of the problems which affect the aquifer (e.g. acidification, nutrients, salinization, pollution, etc.).

The combination of the vulnerability classification with the identified threats and problems gives the opportunity to concentrate the monitoring effort within the most urgent areas. The vertical position of the observation points should be adjusted to the groundwater flow velocity and the eventual movement of pollution fronts, which is generally very slow in porous unconsolidated formations. However, in consolidated formations with secondary permeability much higher velocities may occur.

**Frequencies**

The frequency of measurement has to be adjusted to the temporal change in water quality which is related to the groundwater velocity. Generally, in porous unconsolidated sediments the groundwater velocity is slow, in the order of centimetres to some tens of meters per year and consequently the temporal change of groundwater quality is also slow. This is reflected in the applied frequencies in the UN/ECE countries which varies in general from 1 to 4 times a year. Depending on the functions/uses and threats/problems (e.g. health risk) higher sample frequencies might be needed. Also, secondary permeability features may give rise to higher velocities and to higher sample frequencies.

### 5.4.3 Integration of groundwater quantity and groundwater quality networks

The idea of integrating both groundwater quantity and groundwater quality networks seems to be obvious because of the strong relationship between groundwater flow and groundwater quality processes. However, a number of aspects complicates this idea (Jousma and Willems, 1996):
- differences in the regimes of flow and quality processes;
- groundwater levels have a relatively strong spatial coherence, but relatively large fluctuations. Whereas groundwater quality has much less spatial coherence and is generally less variable in time;
- differences in technical specifications for monitoring groundwater quantity and groundwater quality.

The technical specifications for monitoring groundwater quality are much stricter than those for monitoring groundwater levels. Doubts about the method of drilling and construction of the wells have been the reason for disqualifying many existing wells for monitoring groundwater quality. Special skills and experienced people are required to meet the high standards demanded for groundwater quality measurements, whereas groundwater level measurements is a relatively simple exercise.
Another aspect is the difference between point sampling and non-point sampling. In many cases, there will not be a substancial difference in hydraulic head values measured in an aquifer using point and non-point sampling procedures. In relation with groundwater quality measurements, concentrations of contaminants can change considerable over relatively small vertical distances (Domenico and Schwartz, 1990).

These aspects must be considered when integration of groundwater level and groundwater quality networks is taken into consideration. The success of integrating monitoring networks largely depends on the objectives of monitoring.

## 5.5 Data flow and data management

The flow of data, from sampling or measurement in the field up to the presentation and evaluation of the needed information, follows different stages which all need thorough attention. Protocols for data collection, data handling, data storage and data processing are needed and to be followed to guarantee the required quality of the obtained information. Also for the installation and use of materials of purposely installed groundwater measurement points certain criteria should be met.

### 5.5.1 Monitoring of groundwater levels

Measurement and sampling of observation wells for groundwater depends not only on the objectives of the monitoring network for groundwater and temporal variations, but also on aspects like site accessibility, available personnel or volunteers, sampling campaigns, organisations or institutions responsible for monitoring, financial constraints, etc. A good practice, however, is to measure groundwater levels once or twice a month.
In most cases, manual level measuring will be an established procedure. Automatic control operations, using transducer-converter devices, will be envisaged in the following situations (Sánchez and Varela, 1996):

- karstic aquifers, subject to rapid responses to rainfall episodes;
- areas of difficult access;
- water supply or irrigation wells integrated in operation and control systems.

### 5.5.2 Monitoring of groundwater quality

Sampling of groundwater for quality is carried out by qualified technicians using standard methods of sampling. This may include regular monitoring programs or ad hoc sampling campaigns.
For groundwater qualities frequencies of 1 time every two years to 4 times a year appear to be satisfactorily. (Chilton and Milne, 1994; Sánchez and Varela, 1996).
Often a small group of parameters is used at every sampling interval, supplemented by an extended, more comprehensive group once a year. The chemical analyses is performed by licensed laboratories. In most cases, the analyses concentrates on the major ion species.

The quality parameters on which information might be required can be divided into seven groups:

1. descriptive parameters
2. major ions
3. additional parameters
4. heavy metals
5. organic substances
6. pesticides
7. microbes

The first three groups are, at present, measured in all EEA countries (i.e. those countries which are Member States of the European Environmental Agency) with an observation network (Nixon, 1996). Groups 4, 5 and 6 are only measured in a few of the EEA countries. The types of parameters included in a program depend on the purpose of the monitoring network. Heavy metals and organic substances are important in monitoring programs on point pollution as landfills and contaminated sites. On the other hand, heavy metals and pesticides are more important for diffuse pollution from farming. The number of analysed compounds within each group depends on the purpose of the network and on the economy. Table 5.4 shows a list of parameters for the seven groups.

**Table 5.4**
List of suggested parameters required for a groundwater quality monitoring network (Nixon, 1996)

| Group | Parameters |
|---|---|
| 1 Descriptive parameters | Temperature, pH, DO, (EC) |
| 2 Major ions | Ca, Mg, Na, K, HCO3, Cl, SO4, PO4, NH4, NO3, NO2, Total organic carbon |
| 3 Additional parameters | Choice depends partly on local pollution source as indicated by land-use framework. |
| 4 Heavy metals | Hg, Cd, Pb, Zn, Cu, Cr. Choice depends partly on local pollution sources as indicated by land-use framework. |
| 5 Organic substances | Aromatic hydrocarbons, halogenated hydrocarbons, phenols, chlorophenols. Choice depend partly on local pollution sources as indicated by land-use framework. |
| 6 Pesticides | Choice depends in part on local usage, land-use framework and existing observed occurrences in groundwater. |
| 7 Microbes | Total coliforms, feacal coliforms |

**Sampling procedures in the field**

A standard protocol has been defined as so-called SOP's (Standard Operating Procedure). Before sampling, the riser pipes are pumped by using a special small-diameter electrical pump (Grundfoss, Denmark). The pump is lowered into the riser pipe down to the screen and three times the volume of the riser pipe is pumped. Sampling takes place under anaerobic conditions using a vacuum technique. The samples are filtered under Nitrogen gas. pH and K20 and the oxygen content is measured by lowering electrodes into the riser pipe down to the screen.

A standard sampling technique is used when the groundwater level in the riser pipe is not more than 7 m below ground surface. Using a PE tube groundwater is sucked by a vacuum pump into a PTFE vessel with a filtration unit. The filtration unit is flushed twice with the sample and then filtered using cellulose-nitrate filters of 0.45 µm. The first filtered water is used to flush the sampling bottles (one litre PE bottles) in which everything takes place under an over-pressure with Nitrogen gas to prevent any contact of the sample with oxygen in the atmosphere. The number of bottles to be filled depends on the analysis package and the type of laboratory. The bottle for micro parameters is the last one to be filled and is acidified to a pH = 2. After sampling, the equipment (bottles, tube, filtration unit, etc.) is flushed with demineralised water and filled with demi water with a pH = 2. All samples are transported in cool boxes and stored in refrigerators (dark conditions and 4O Celsius. Blanco or dummy samples are taken to verify the flushing procedures. The samples are kept during a maximum of $^1/_2$ week in a refrigerator.

In many cases, there may not be a substantial difference in hydraulic head values measured in an aquifer using point and non-point sampling procedures. However, in relation with groundwater quality aspects, concentrations of contaminants can change markedly over relatively small vertical distances. In that case non-point sampling will yield concentrations that can differ a lot from the true concentration (Domenico and Schwartz, 1990).

### 5.5.3 Processing of groundwater data

**Groundwater Level Data**

The following protocol summarises the phases of data entry and processing in the Netherlands:

**Phase 1: Data entry**

*Manual data entry from forms sent by well owners/observers:*
- one data entry typists controls and checks the entered data of another typist. After these checks, the data is given a first quality flag;
- the entered data is first stored in a shadow database.

*Data (digital) from magnetic data carriers or sent by modem:*
- standard checks on trivial errors like typing errors, missing values, empty records, values out of range, incorrect lettres in strings/numbers, are applied on the data before the shadow databases are generated.

Every week, all shadow databases are added to the main database, after passing the standard quality checks and controls, amongst others:
1. well location, depth of screens, etc. must be known;
2. each date must be accompanied by a groundwater level measurement or a remark/comment;
3. groundwater levels must be above bottom of screen;
4. etc.

Data which are rejected by the conversion from shadow to main database is corrected and checked again and every entered record receives a quality label providing information on how the data was entered.

**Phase 2: Preliminary data validation**

The entered groundwater level time series are checked by using routines to detect unrealistic extreme values and interchanged screens:
- time series with extreme values are visually controlled by plotting the hydrographs;
- the well owners/observers are then confronted with the extreme (unrealistic) values.

**Phase 3: Control of extreme values**

Detection of extreme values by applying statistical tests (confidence limits, auto-correlation coefficient, etc.) and correlation with neighbouring well locations.

**Groundwater Quality Data**

**Phase 1: Data entry**

*Manual data entry and digital data entry:*
- location, screens, etc. must be known;
- correct data format;
- chemical analysis data already existing and what type of components have been stored;

- correct conversion to standard units;
- chemical analysis values within known and natural limits.

**Phase 2: Data validation**

*Conversion of shadow database to the main database:*
- calculation ion balance;
- difference between measured and calculated Electrical Conductivities;
- detection of extreme unrealistic values;
- unrealistic chemical relationships (CO2-HCO3-Ca-pH, pH and high metal concentrations, oxic-anoxic settings, etc.);
- unrealistic hydrochemical typologies (Stuyfzand classification);
- every record is assigned with a quality label;
- the well owners/observers, samplers or the laboratories are then confronted with the extreme (unrealistic) values.

**Borehole Drilling Data**

**Phase 1 and 2: Data entry and validation**

- drilling data are converted to litho-codes. After entry in the shadow database, the litho-codes are translated back to drilling log descriptions and the generated litholog is compared with the field data;
- drilling log and generated lithologs are correlated with geophysical well logging data;
- generated lithologs are compared with neighbouring boreholes;
- etc.

**Misellaneous Data**
- half-yearly control of administrative data by using look-up tables with addresses, etc.

### 5.5.4 Data bases and geo-information systems

The huge amount of data collected from monitoring networks is stored in modern relational databases using modern software packages like Oracle, MS Access, Informix, Ingres, etc. A database is in fact only the cornerstone of a total integrated geo-information system. Although it is orderly stored in a well designed database, most of the data is practically inaccessible to most of the common users. One needs an information system to manage, retrieve and visualise the stored data in the form maps, graphs, diagrams, reports, etc. The database should be "invisible" to the user; he or she only has to deal a user-friendly (graphical interfaces) information system to disclose the stored data without knowing the physical structure of the database. The user interface is the geo-information system acting as a shell around the database as the core of the system. As an example of a database in Annex III, a description is given of REGIS (Regional Geographic Information System) which was developed in The Netherlands.

### 5.5.5 Data quality control

The following protocol is used in The Netherlands to perform quality control:

*Automatic quality control checks are made for data entered manually or from magnetic data carriers into the national database, e.g. check on:*
- correct new identification numbers;
- correct sequence of data input and type (strings, numbers, reals/integers; etc.); conversion, location, screen depths/types/diameters, administrative data, technical construction, etc.;
- geographical coordinates in accordance with the map sheet;
- surface altitudes within the range -10,00 to 330,00 m AMSL;
- top of the screen above bottom;
- etc.

*Every six months, automatic quality control checks are made (about 200) on the complete data set, e.g. checks on:*
- coordinates in accordance with map sheet identification;
- surface altitudes within the range -10.00 to 330.00 m AMSL;
- date in correct format;
- correct well type codes (A, B, E, L, M, P, R, S, W);
- checks on presence of location data when screen data are found;
- correct sequence numbers of screens;
- top of screen above bottom of screen (standard lengths 2m);
- total well depth greater than bottom of deepest screen;
- length riser pipe + screen length = well collar altitude - bottom screen;
- bottom screen below surface;
- no groundwater levels below bottom screen;
- geological marker horizons labeled with correct sequence number;
- etc.

### 5.5.6 Database security

An element of paramount importance is the security protocol for the database. The system manager is the only person to have write and edit permissions for the database and is given the responsibility for the data integrity. For REGIS the following guidelines are used:

**System**

The database can only be accessed by using a user-name and password. Every user has his own user-environment. Authorization is given by the system manager. Only the system manager is permitted to update and change the database. The system is menu-driven. In case of a system failure or fatal error, all users are disconnected from the database. Only the system manager may access the database at operating system level.

**Embargoes**

Data sets from certain owners (e.g. water supply companies, industries, etc.) are secured by embargoes. Only with a written permission of the owner can data sets be accessed by third parties.

**Backups**

Every week a double backup of the entire database is made. One backup is stored in the office of the system manager and the other backup is stored in another building in a fireproof vault. Daily incremental backups are made.

**Calamities**

An emergency plan and protocol is available in case of severe calamities. With this plan, a spare system is operational within a few days.

## 5.6 Scale aspects

Scales of spatial and temporal variability play an important role in monitoring and assessment of groundwater. The scale aspects have to be taken into account, for the formulation of the technical objectives and for the design of the monitoring network. In this report, three types of scales have been distinguished:

1. process scale,
2. information scale and
3. measurement scale

Note: scale means "the relative size or extent of something"

### 5.6.1 Process scale

Groundwater processes show variations at a large number of scales, in space as well as in time. This is due to heterogeneity of the soil and aquifer properties like transmissivity and reactivity, and variation in driving forces, such as recharge from precipitation. The groundwater heads and concentrations of constituents can be considered as a sum of components, each representing variation at a particular scale in space and time. For example, the groundwater head can show a day-to-day reaction to the precipitation excess, a seasonal variation and a long term change (Figure 5.2). The latter is often referred to as trend.

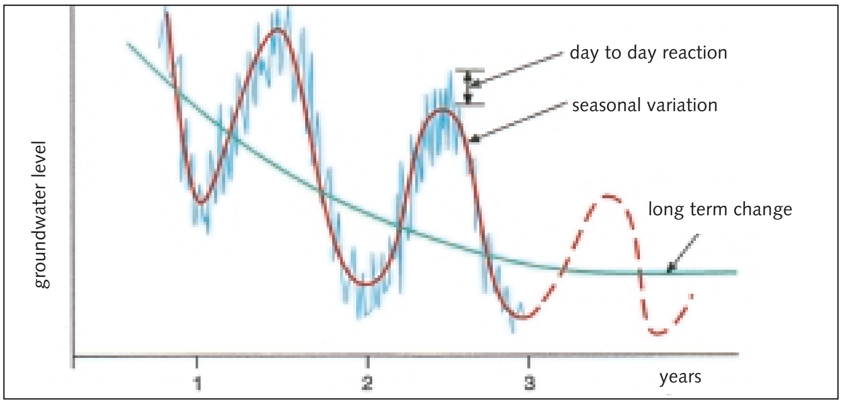
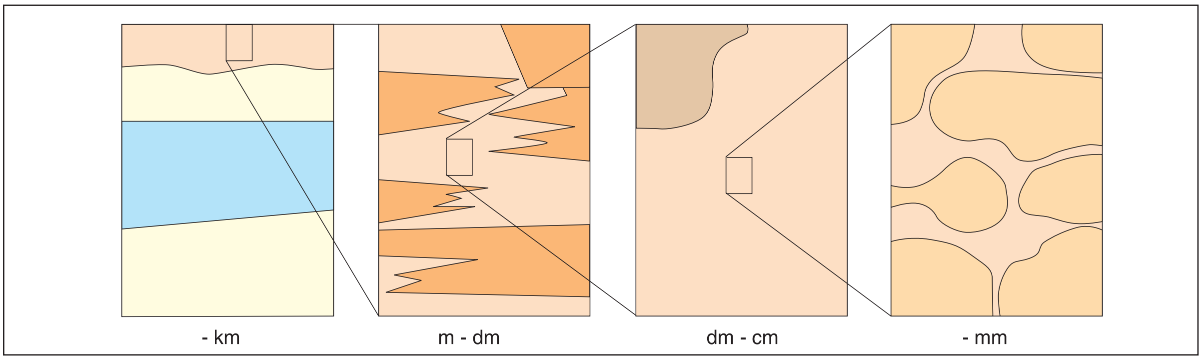



**Figure 5.2**
Groundwater head split into three different components

Another example is a particular soil type that can be highly variable spatially at a scale of grains, whereas the same soil can be homogeneous at scales of hectares and finally heterogeneous again at a scale of kilometres (Figure 5.3).
The type of scale belonging to the physical groundwater processes is referred to as the process scale. The process scale varies continuously from micro scale to global scale. However, the various process scales are not equally important. In most cases, a limited number of process scales dominates the groundwater behaviour. Often a dominant time scale is the seasonal period of one year. In space, the dominant scales are related to the geometry of the geology (grain size, clay lenses, basins, etc.). For monitoring network design, the process scales are given and can not be changed.

**Figure 5.3**
Different spatial scales




### 5.6.2 Information scale

The information required is directly related to the tasks of the groundwater manager. Therefore, the information needs are dependent on the level of water management. For example, the spatial extent of the decisions of water managers at a provincial or national level is significantly larger than that of a local water manager. Also the time period of interest is, in general, much larger at national than at local level. The information provided to managers for utilisation, generally does not equal the direct measured data. Often some analysis technique is applied, such as interpolation or averaging.

Each water manager likes to extract only that information from the observations that is relevant for his tasks. Therefore, for each management task a limited range of scales of the whole groundwater system is relevant. The variation at higher scales is not relevant and variations at smaller scale appear as noise. For example, if information is needed about the long term trend in the concentration of a specific solute in groundwater, the scale of interest is years. The day to day changes are noise. In contrast, if, for operational water management, the reaction of the groundwater system to dry or wet periods is required, the relevant scale is days or weeks. In this case, the long term changes appear as trends. The type of scale at which the information is needed is referred to as: the information scale. The information scale is determined by groundwater management requirements and is considered to be given in monitoring network design.

### 5.6.3 Measurement scale

A third type of scale is important for monitoring network design; the scale at which the groundwater is observed or sampled. This scale type is referred to as the measurement scale and can be considered at the scale of the individual measurements and at the scale of a monitoring network. A short description of both scales has been given below.

**At the scale of individual measurements**

The first part of the measurement scale is related to the individual measurements. For groundwater head measurements, this scale is almost one point. The scale of concentration measurements is most often related to a volume of up to several cubic metres. Pump tests for evaluation of transmissivities can have scales of tens of metres. All variations at smaller scales than the sample scale are smoothed out and cannot be recalled. In some cases, this smoothing effect is created by purpose, in particular with mixed samples of groundwater to analyse concentrations.

**At network scale**

The second part is the scale of the network design. This scale is determined by the number of sample locations, the lay-out of the monitoring network and the measurement frequency.

The measurement scale is up to certain limitations a free choice of the network designer. Generally, it can be stated that for an adequately designed monitoring network the measurements scales are chosen in such a way that the information needed at the information scale is obtained at the minimum cost, accounting for the relevant process scales.

### 5.6.4 Examples to illustrate the different scale types

The different scale types are illustrated with the following two examples.

1. **Small process scale and large information scale.** In the first example the objective is to have a reference value of the concentration of a chemical component in a district of a city. Therefore, the spatial average of the concentration has to be estimated within acceptable uncertainty margins. The concentration of the chemical component is highly variable spatially at a distance of tens of metres, resulting in a dominant process scale in space of ca 50 m. The area of district of the city is about 6 $km^2$, resulting in an information scale of 2 to 3 km. In this case, the dominant process scale (< 50 m) is much smaller than the information scale (>1 km). This situation is indicated in Figure 5.4. The small variation of the process is not relevant for the assessment objective and is considered as "noise" around the spatial average. Initially, the small scale variations should be measured in order to understand the processes themselves and to assess the order of magnitude of the variations. Once these properties of the process are known, the network design is based on the relation between the uncertainty of the spatial average and the number of observation points to be determined.

2. **Large process scale and small information scale.** In the second example, the objective is to have an interpolation of the groundwater head in an area of 10 km by 10 km. The distance between the observation wells is in the order of a few kilometres. Let the dominant process scale be in the order of more than 20 km. In

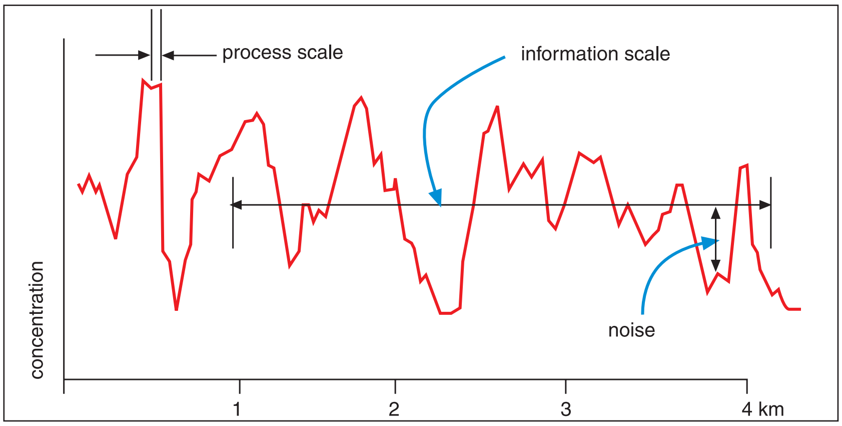



**Figure 5.4**
Cross section of a situation with small process scale and large information scale

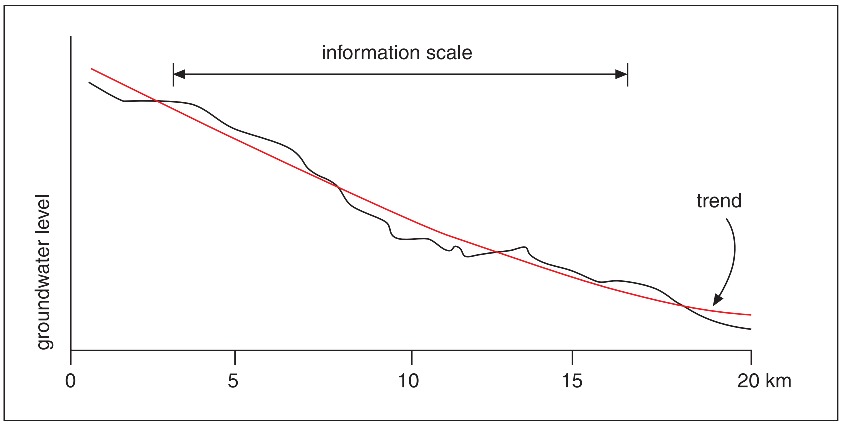



**Figure 5.5**
Cross section of a situation with large process scale and small information scale

this case, the process scale is larger than the information scale and the large scale variation of the groundwater level appears as a trend in space. This situation is indicated in Figure 5.5.

### 5.6.5 Scale constraints in network design

In practice, the three types of scales will not always match. In some cases, it is even impossible to choose the measurement scales as such that the required information is obtained. Two examples of impossibilities are given below.

In the first example, the information and measurement scales are much larger than the dominant process scales. This can occur when at a regional or national level a continuous interpolation of the groundwater quality is desired. The dominant process scales are in the order of a few kilometres maximum, whereas for budgetary reasons the distance between the measurement locations is in the order of 5 to 10 kilometres. Since a single measurement contains information about the spatial variability up to a distance of 1 kilometre, in large parts of the domain only the general characteristics (spatial mean and variance) can be estimated. It is not possible to perform a meaningful interpolation of the concentrations as a continuous function of space. In this case, contour plots made in a GIS environment are misleading.

In the second example, the dominant process is much larger than the information scale. For example, in areas where we have a thick unsaturated zone and a phreatic aquifer, the dominant time scales of the groundwater process (function of the groundwater head in time) are in the order of many years, and the natural variation of the groundwater level is about 6 metres. Measures are taken to raise the average groundwater level by 1 metre, and the water manager may like to evaluate the effect of this measure within a period of say four years. Whatever measurement frequency we choose such an evaluation is impossible, because it will take a longer period to distinguish the average rise of the groundwater level from the natural variation.

# 6. Key points

.

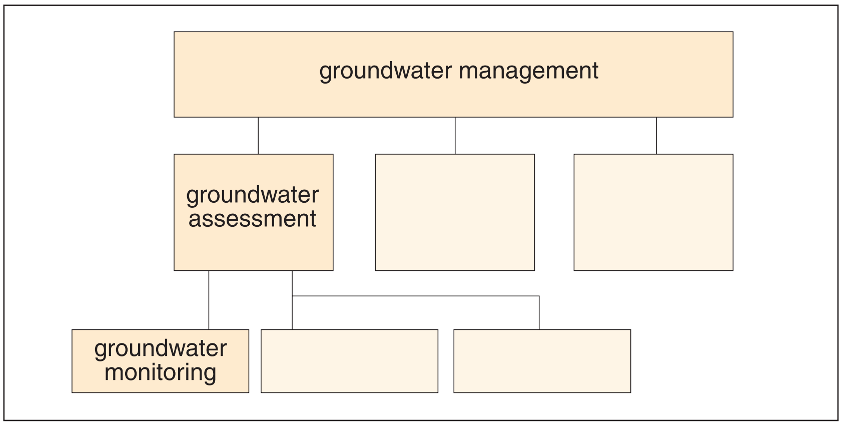
Based on the state-of-the art review of groundwater monitoring and assessment, a number of key points (conclusions and recommendations) which assist in the drafting the guidelines can be made.

1. Monitoring and assessment of transboundary groundwaters is still in its infancy. Therefore assessments of transboundary impact have hardly been carried out and consequently the extent of adverse effects resulting from transboundary groundwater flow is unknown.

2. The primary goal of monitoring and assessment of transboundary groundwaters and of groundwater in general is to support water management or more specifically groundwater management. However, developments in formulating water policy, physical planning and environmental protection have emerged into a much more integrated and comprehensive approach to the management and development of natural resources and of water resources in particular. The water sector cannot be considered as an isolated entity; on the contrary its interaction with the whole of society and the environment has to be taken into account. This context must be understood and taken of account in the establishment of transboundary monitoring and assessment and this should eliminate discrepancies in approaches applied in neighbouring countries.

3. There is a need for clear definition of and distinction between the terms "monitoring" and "assessment" of groundwater. They are frequently confused and used synonymously. In Figure 6.1 a scheme representing the link between groundwater monitoring, groundwater assessment and groundwater management is given. The link follows the flow of information. Effective management of the groundwater resources will be based on information. An important part of the information comes from the groundwater assessment. Generally information from groundwater monitoring is needed to enable an appropriate assessment. The scheme illustrates that information from beyond the groundwater sector is needed to establish groundwater management.

**Figure 6.1**
Linkage between groundwater management, assessment and monitoring follows the flow of information



4. The results from the questionnaire have been of very limited benefit to this sub-project. The questionnaires have been returned from only 22 of the total number of 52 ECE countries. Hence, the conclusions are only based on the situation in these responding countries.

5. Monitoring networks are mostly operated and maintained with application of national standards and quality control procedures. The questionnaires give only very limited insight into the applied monitoring design methodologies, the different network set ups, and the transboundary aspects and extent of the existing monitoring networks.

6. No specific linkage has been given between the different types of aquifer and the monitoring and assessment methodologies. Generally, the occurrence and characteristics of groundwater in porous media (primary porosity) can be described and understood much more easily than the occurrence and transport of groundwater in rock types with secondary porosity which is linked to joints, fractures and voids formed by dissolution of limestone. Monitoring and assessment of groundwater in these rock types of secondary or mixed porosity is complicated and will need special attention.

7. General surveillance and water quality trend identification are mentioned as widespread common goals. Furthermore, compliance with national or EC legislation (e.g. control of drinking water quality, EC Nitrate Directive), detection of sea water intrusion, detection of impacts caused by airborne pollutants (in relation to acidification problems) and detection of the impact of fertilisation and use of pesticides are mentioned as monitoring goals.

8. Computerised data processing seems to be in use in most responding UN/ECE member states. Different data base systems are used. Data formats developed will be different, which will complicate the exchange of information. A universally agreed data transfer format, such as ASCII, will be needed to simplify the exchange of data between riparian countries.

9. The characterisation of transboundary aquifers - boundaries, lithology, recharge and discharge, flow conditions, water quality - is a basic prerequisite in monitoring network design. A three dimensional picture of the groundwater flow system and its dynamics from recharge to discharge areas should be obtained.

10. For the design of a monitoring network it is important that the measurement scale will be adjusted to the information scale and the process scale in order to obtain the required information. Despite the first impression that monitoring and assessment of transboundary groundwaters would refer to large scales, e.g. regional, national or international scale, it is expected that many phenomena with possible adverse transboundary effects occur at a local scale.

11. Groundwater management is generally the starting point for monitoring and assessment of groundwater. The elaboration of the core elements of groundwater management (functions/uses, threats/problems and management measures) and their interaction form the basis for the monitoring and assessment of groundwater.

12. The definition of the information needs based on the management tasks and objectives is the first step to come to a specification of the technical objectives and finally to the specification of the data to be collected.

13. For the design of a monitoring and assessment system a step-wise approach is proposed including:
    - identification of information needs;
    - definition of monitoring and assessment strategy;
    - design of the monitoring and assessment system (locations, variables and frequency);
    - establishment of the system;
    - operation and maintenance;
    - data flow and data management;
    - data analysis and reporting;
    - information utilisation, evaluation, communication;
    - identification of additional information needs.

# 7. References


- Adamowski, K., 1971. Spectral density of a river flow time series. Hydrol., J., 14: pages 43-52.
- Adamowski, K. and Hamory, T., 1983. A stochastic systems model of groundwater level fluctuations. Hydrol., J., 62: pages 129-141.
- Aelmans, F., 1997. Digital Waterway Vechte; Netherlands Institute of Applied Geoscience TNO, Delft, The Netherlands. Report NITG 97-283-B.
- Ahlfeld, D.P. and Pinder, G.F., 1988. A groundwater monitoring network design algorithm. Report 87-WR-4, Dep. Civil Eng. and Operations Res., Princeton Univ., Princetion, N.J.
- Bastin, G., Lorent, B., Duque, C. and Gevers, M., 1984. Optima estimation of the average areal rainfall and optimal selection of raingauge locations. Water Resources Research, 20(4): pages 463-470.
- Ben-Zvi, M. and Kesler, S., 1986. Spatial approach to estimation of missing data. Hydrol, J., 88: pages 69-78.
- Box, G.E.P. and Jenkins, G.M., 1976. Time series analysis; forecasting and control. Prentice Hall, New Jersey, page 575.
- Bras, R.L. and Rodriguez-Iturbe, I., 1976a. Network design for the estimation of areal mean of rainfall events. Variables, 12(6): pages 1185-1196.
- Bras, R.L. and Rodriguez-Iturbe, I., 1976b. Rainfall network design for runoff prediction. Water Resources Research, 12(6): pages 1197-1208.
- British Geological Survey, A national strategy for the NRA. Final Report, November 1994. Technical report WD/94/40C. National Environment Research Council. Technical Report, Hydrogeology Series.
- Broers, H.P. and Buijs, E.A., 1996. Trends in de grondwaterkwaliteit van Drenthe; analyse van 12 jaar meetgegevens van landelijke meetpunten in de provincie Drenthe. TNO Grondwater en Geo-Energie, rapport GG R 96-80(A). (in Dutch)
- Broers, H.P. and Griffioen, J., 1992. Het grondwaterkwaliteitsmeetnet van de provincie Noord-Brabant; opzet en eerste resultaten. H2O (25), pages 728-735.
- Carrera, J., Usunoff, E. and Szidarovski, F., 1984. A method for optimal observation network design for ground-water management. Hydrol., J., 73: pages 147-163.

- Chilton, P.J. and Milne, C.J., 1994. Groundwater quality assessment: A national strategy for the NRA. Final report, November 1994. Technical report WD/94/40C. British Geological Survey, National Environment Research Council. Technical Report, Hydrogeology Series.

- Christiakos, G. and Olea, R.A., 1988. A multiple-objective optimal exploration strategy. Math. Compu. Modeling, 11(4): pages 413-418.

- Davis, J.C., 1986. Statistics and data analysis in geology. John Wiley, New York, page 646.

- Domenico, P.A. and Schwartz, F.W., 1990. Design and quality Assurance Issues in Water Sampling. Physical and chemical Hydrogeology. John Wiley and Sons, New York.

- Engelen, G.B. and Kloosterman, F.H., 1996. Hydrological Systems Analysis.

- EurAqua, 1995. Proceedings: Optimizing Freshwater Data Monitoring Networks including Links with Modelling. Second technical review. European Network of Fresh Water Research Organisations. Paris, La Defense, October 18 - 20, 1995.

- Fiering, M., 1965. An optimizaton scheme for gaging. Water Resources Research, 1(4): pages 463-470.

- Frapporti, G., Hoogendoorn, J.H., and Vriend, S.P., 1995. Detailed hydrochemical studies as a useful extension of national ground-water monitoring networks. Ground Water 33(5): pages 817-828.

- Gehrels, J.C., Geer, F.C. van, and Vries, J.J. de, 1994. Decomposition of groundwater level fluctuations using transfer modelling in an area with shallow to deep unsaturated zones. J. Hydrol., 157: pages 105-138.

- Georgakakos, A.P., Kitanidis, P.K., Loaiciga, H.A., Olea, R.A. and Yates, S.R., 1990. Review of geostatistics and geohydrology: II. Applications. ASCE Task Committee on Geostatistical Techniques in Geohydrology, J. Hydraul. Eng., 116(5): pages 633-658.

- Graham, W. and McLaughlin, D., 1989a. Stochastic analysis of nonstationary subsurface solute transport, 1. Unconditional moments. Water Resources Research, 25(2): pages 215-232.

- Graham, W. and McLaughlin, D., 1989b. Stochastic analysis of nonstationary subsurface solute transport, 1. Conditional moments. Water Resources Research, 25(11): pages 2331-2356.

- Grift, B., van der and Dael, J.G.F., van, 1997. Problem-oriented approach and the use of indicators, final draft sub-project 4. UN/ECE Task Force on Monitoring & Assessment. Project-secretariat, RIZA, Lelystad, The Netherlands.

- Helmer, R., 1997. Ground water quality monitoring strategies. WHO Geneva

- Helsel, D.R. and Hirsch, R.M., 1995. Statistical methods in water resources. Studies in Environmental Science 49. USGS, Elsevier, page 529.

- Hipel, K.W., McLeod, A.I. and Lennox, W.C., 1977. Advances in Box-Jenkins modeling; 1. Model construction. Water Resources Research, 13(1): pages 567-575.

- Hsu, N.S. and Yeh, W., 1989. Optimum experimental design for parameter identification in ground-water hydrology. Water Resources Research.

- IAHS Publ. No. 158, 1986. Integrated design of hydrological networks.

- Journel, A.G. and Huijbregts, Ch. J. (1978); Mining geostatistics. Academic Press, London, page 600.

- Jousma, G. and Willems, J.W., 1996. Groundwater monitoring networks. European Water Pollution Control, Vol. 6, no. 5, 1996.

- Knopman, D.S. and Voss, C.I., 1988. Discriminaton among one-dimensional models of solute transport in porous media: implications for samplig design. Water Resources Research, 24(11): pages 1859-1876.

- Koreimann, C., Grath, J., Winklerm, G., Nagy, W. and Vogel, W.R., 1996. Groundwater Monitoring in Europe. European Topic centre on Inland Waters, European Environment Agency. Copenhagen, Denmark.

- Loaiciga, H.A., 1988. Groundwater monitoring network design. In: Computational Methods in Water Resources Vol. 2: Numerical Methods for Transport and Hydrologic Processes, Elsevier, New York, 1988, pages 371-376.

- Loaiciga, H.A., 1989. An optimization approach for ground-water quality monitoring network design. Water Resources Research, 25(4): pages 1771-1780.

- Loaiciga, H.M. and Hudak, P.F., 1989. Correlated versus uncorrelated hydrologic samples. J. Water Resources Planning and Management Vol. 115(5): pages 699-705.

- Loaiciga, H.M. and Marino, M.A., 1987. Parameter estimation in groundwater: Classical, Bayesian, and deterministic assumptions and their impact on managament policies. Water Resources Research, 23(6): pages 1027-1035.

- Loaiciga, H.A., Charbeneau, R.J., Everett, L.G., Fogg, G.E., Hobbs, B.F. and Rouhani, S., 1992. Review of ground-water quality monitoring network design. ASCE Task Force Committee on Ground Water Monitoring Network Design. Hydraul., J., Eng. 118(1): pages 11-37.

- MacDonnell, L.J. and Guy, D.J., 1991. Approaches to groundwater quality protection in the western United States. Water Resources Research, 27(3): pages 259-265.

- Massman, J. and Freeze, R.A., 1987a. Groundwater contamination from waste management sites: the interaction between risk-based engineering design and regulatory policy, 1. Methodology. Water Resources Research, 23(2): pages 351-367.

- Massman, J. and Freeze, R.A., 1987b. Groundwater contamination from waste management sites: the interaction between risk-based engineering design and regulatory policy, 1. Results. Water Resources Research, 23(2): pages 368-380.

- Matheron, G., 1971. The theory of regionalized variables and its applications. Les Cahiers du Centre de Morphologie Mathematique de Fontainebleau No. 5, Fontainebleau.

- McLeod, A.I, Hipel, K.W. and Lennox, W.C., 1977. Advances in Box-Jenkins modeling; 2. Applications. Water Resources Research, 13(3): pages 577-586.

- Meyer, P.D. and Brill, E.D., 1988. Method for locating wells in a groundwater monitoring network under conditions of uncertainty. Water Resources Research, 24(8): pages 1277-1282.

- Niederländer, H.A.G., Dogterom, J., Buijs, P.H.L., Hupkes R. and Adriaanse, M., 1996. State of the Art on Monitoring and Assessment of Rivers. UN/ECE Task Force on Monitoring & Assessment Volume 5. Project-secretariat, RIZA, Lelystad, The Netherlands.

- Nixon, S.C., 1996. European Freshwater Monitoring Network Design.

- Olea, R., 1984. Sampling design optimization for spatial functions. Math. Geol., 16(4): pages 365-391.

- Ottens, J.J., Claessen, F.A.M., Stoks, P.G., Timmerman, J.G. and Ward, R.C., 1997. Proceedings Monitoring Tailor-made II, An international workshop on information strategies in water management in Nunspeet, The Netherlands (1996). Lelystad, The Netherlands, Nieuwegein, The Netherlands, Fort Collins, Colorado, USA.

- Quinlan, J.F., Davies, G.J. and Worthington, S.R.H., 1993. Discussion of review of groundwater monitoring network design. Hydraul., J., Eng.,119(12): pages 1436-1441.

- Rouhani, S., 1985. Variance reduction analysis. Water Resources Research, 21(6): pages 837-846.

- Rouhani, S. and Hall, T.J., 1988. Geostatistical schemes for groundwater sampling Hydrol., J., 81(1): pages 85-102.

- Sanchez, A. and Varela, M.,1996. Groundwater monitoring networks in Spain. Proceedings of the international workshop Monitoring Tailor-made II, September 1996, Nunspeet, The Netherlands.

- Sophocleous, M., Paschetto, J.E. and Olea, R.A., 1982. Ground-water network design for northwest Kansas, using the theory of regionalized variables. Ground Water 20(1): pages 48-58.

- Timmerman, J.G., Gardner, M.J. and Ravenscroft, J.E., 1996. Quality Assurance, UN/ECE Task Force on Monitoring & Assessment Volume 4. Project-secretariat, RIZA, Lelystad, The Netherlands

- Uil, H., Kloosterman, F.H., Pijewska, I., Plenzler, W., Rapackiand, L., Broers, H.P., 1996. A Pilot Monitoring NetworkSystem for Groundwater Quality and Quantity in the Upper-Notec Catchment (Poland). Phase 2B: Final design of the Groundwater Monitoring Network. TNO, Institute of Applied Geoscience, Delft, The Netherlands; Institute of Meteorology and Water Management, Poznan, Poland; Institute of Environmental Engineering Systems, Warsaw University of Technology, Poland.

- UN/ECE Task Force Monitoring & Assessment, 1997. Working program on the drafting of guidelines on groundwater monitoring and assessment. TF 5.03, CGG 5.02. RIZA, Lelystad, The Netherlands.

- UN/ECE Task Force Monitoring & Assessment, 1996. Guidelines on Water-Quality Monitoring and Assessment of Transboundary Rivers. ECE Task Force project-secretariat, RIZA, Lelystad, The Netherlands.

- Wagner, B.J. and Gorelick, S.M., 1987. Optimal groundwater management under parameter uncertainty. Water Resources Research, 23(7): pages 1162-1174.

- Wagner, B.J. and Gorelick, S.M., 1989. Reliable aquifer remediation in the presence of spatially variable hydraulic conductivity: from data to design. Water Resources Research, 25(10): pages 2211-2225.

- World Meteorological Organization, 1989. Management of Groundwater

- Yangxiao, Z. 1992. Design and Analysis of Groundwater Monitoring Networks. International Institute for Infrastructural, Hydraulic and Environmental Engineering (IHE), Delft, The Netherlands.

- Yfantis, E.A., Flatman, G.T. and Behar, J.V., 1987. Efficiency of Kriging estimation for square, triangular and hexagonal grids. Math. Geol., 19(3): pages 183-205.

# ANNEX I Questionnaire on transboundary groundwaters

**Questionnaire, concerning transboundary groundwater issues**
**Form C**

1. Is information about transboundary groundwaters collected ?
2. a) ad hoc; b) systematic
3. What kind of information is collected ?
4. a) groundwater heads/piezometric levels; b) groundwater quality (sampling); c) hydraulic variables (k, T, S); soil quality samples; others
5. For which purposes is the data collected ?
6. a) strategic; b) operational; c) evaluation; d) others
7. For which purposes is the information actually used ?
8. Is there a network in operation ?
9. Which network design procedure has been used ?
10. How is the monitoring frequency designed ?
11. Are the data stored and is there a digital system (data base) ?
12. What kind of standards (quality samples) and quality control is used ?
13. Who is responsible (owner) of the network and the data collection and data storage and handling ?

| Country | 1. Collection | | 2. Information collected | | | | | 3. Purposes | | | | 5. Oper net-work | 8. Digital Data Base |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | ad hoc | system. | gw levels | gw. qual. | k, T, S | soil qual. | others | stra-tegic | opera-tional | evalu-ation | others | | |
| Austria | | X | X | X | X | X | | X | X | | | Yes | Yes |
| Belgium, Flandres | X | | X | X | X | | | X | X | X | | Yes | Yes |
| Bulgaria | | X | X | X | X | X | X | X | X | X | | Yes | Yes |
| Croatia | X | | X | X | X | | | | | X | | No | Y (partly) |
| Czech Rep. | X | X | X | X | X | | | X | | X | Resch | Yes | Yes |
| Estonia | | X | X | X | X | | | X | | X | | Yes | Yes |
| Finland | | | X | X | X | X | | | X | X | Resch | Yes | |
| Germ., Bavaria | X | X | X | X | X | | X | X | | X | | partly | Yes |
| Germ, Badenbr.b. | | X | X | | | | | X | X | X | | Yes | Yes |
| Germ. Baden Wurt. | | X | X | X | X | | X | X | | | | Yes | Yes |
| Germ., Rhineland P | | X | X | X | X | | | X | | X | | Yes | Yes |
| Germ., Schlesw.H. | | X | X | X | X | | | | X | X | | No | No |
| Hungary | X | X | X | X | X | | | X | X | X | | Yes | Yes |
| Latvia | X? | | X | X | X | X | | | | X? | | Yes | Y(partly) |
| Lithuania | | X* | | X | | | | | | X | | Yes | Yes |
| The Netherlands | | X | X | X | | | | X | X | X | | Yes | Yes |
| Northern Ireland | X | | X | | | | | | X | | | No | Yes |
| Portugal | n | X** | X | X | X | | | | | X | | Yes | Yes |
| Rep. of Belarus | X | | X | X | X | | | X | X | X | | Yes | Yes |
| Rep. of Moldova | X | X (to '90) | X | X | | | | X | X | X | | Yes | No |
| Romania | n | | X | X | X | | | X | X | X | | Yes | Yes |
| Slovenia | | X | X | X | | | | X | | | | Yes | Yes |
| Spain | n | n | | | | | | | | | | No | |
| Switzerland | | X | X | | | | | | X | | | Yes | |
| The Slovak Rep. | | X | X | X | X | X | | X | | X | | Yes | Yes |
| The Ukraine | | X | X | X | X | X | | X | X | X | | Yes | GIS |

| | 4. For which purposes is the information actually used ? |
|---|---|
| Austria | Water management goals |
| Belgium, Flandres | |
| Bulgaria | Water management: Assessment of quantity and quality of groundwaters, trend identification. |
| Croatia | Hydrogeological map of Rep. of Croatia |
| Czech Rep. | Water resources protection. Research projects on improvement of water protection and water use, state water balance. |
| Estonia | Water permits (limits) |
| Finland | see 3 |
| Germ., Bavaria | see 3 |
| Germ, Badenbr.b. | Monitoring of water quantity (levels) |
| Germ. Baden Wurt. | see 3 |
| Germ., Rhineland P | Groundwater management |
| Germ., Schlesw.H. | Control of groundwater abstraction for water works |
| Hungary | Regulary evaluation of status of groundwater system. Assessment of local problems |
| Latvia | Strategy of water supply |
| Lithuania | Int. project: Groundwater monitoring on Lithuanian - Polish border; evaluation of trends in water quality and in water levels. |
| The Netherlands | Trend detection, model input, analysis of characteristics |
| Northern Ireland | Operational use |
| Portugal | Evaluation of ground water levels |
| Rep. of Belarus | see 3 |
| Rep. of Moldova | Problem solving of water supply at local and regional scales |
| Romania | Assessment, sustainable development and protection of groundwater resources |
| Slovenia | Control of GW level regime; longterm water quality monitoring; water management |
| Spain | |
| Switzerland | Management of the recharge |
| The Slovak Rep. | Water policy making: evaluation of water quality and quantity changes. |
| The Ukraine | Planning and management of environmental protection and ground water consumption. |

| | 6. Which network design procedure has been used |
|---|---|
| Austria | Basic and specific network |
| Belgium, Flandres | No specific procedure, minimum density per aquifer |
| Bulgaria | |
| Croatia | |
| Czech Rep. | Historical and representative one |
| Estonia | |
| Finland | Integrated system |
| Germ., Bavaria | No defined design procedure |
| Germ, Badenbr.b. | Groundwater monitoring network (quantity, quality) |
| Germ. Baden Wurt. | Experience, use of historical data |
| Germ., Rhineland P | |
| Germ., Schlesw.H. | |
| Hungary | Optimalisation of existing networks |
| Latvia | |
| Lithuania | None |
| The Netherlands | 1) heads / piezometric level: spatial kriging interpolation; 2) groundwater quality: estimation spatial characteristics |
| Northern Ireland | None |
| Portugal | Monitoring network ? (Algarve) |
| Rep. of Belarus | Groundwater regime, balance and quality |
| Rep. of Moldova | Uniform coverage of aquifer; systematic supervision at the exploration sites |
| Romania | Representativeness for groundwater systems |
| Slovenia | To cover aquifer with special attention paid to trandsboundary conditions; Use of existing wells etc. |
| Spain | Hydrogeologic criteria, geostatistics |
| Switzerland | |
| The Slovak Rep. | ISO, national standards and guidelines |
| The Ukraine | Groundwater regime: recharge, discharge and transit |

| | 7. How is the monitoring frequency designed ? |
|---|---|
| Austria | Levels: 1 to 2 times/week; quality: 4 times/per year |
| Belgium, Flandres | No specific procedure, levels: monthly, quality: irregular, in near future yearly |
| Bulgaria | Frequency depends on purpose and on vulnerabilty of the aquifer |
| Croatia | |
| Czech Rep. | Levels: daily or weekly; quality once or twice |
| Estonia | 4 times/year (once per season) |
| Finland | Levels: 2 times/month at 500 locations, automatic recording at 54 stations; quality: 6 times/year |
| Germ., Bavaria | Continuous recording gw. table/piezometric level |
| Germ, Badenbr.b. | 2 times a year |
| Germ. Baden Wurt. | Surveys within 5-7 years, operational/experience/statistical for state networks |
| Germ., Rhineland P | Depending demands. quantity: 52 times/year; quality: 2 times/year |
| Germ., Schlesw.H. | According to the possibility of relevant changing |
| Hungary | see 6 |
| Latvia | 1-12 times/year |
| Lithuania | Groundwater monitoring on Lithuanian - Polish border: quality: 2/year, levels: 3-5 times/month |
| The Netherlands | Expert judgement and statistical 4-24 times/year |
| Northern Ireland | Varies, see report |
| Portugal | Quantity: daily, hourly, periodical, seasonal; Quality: (Algarve): ? |
| Rep. of Belarus | Quantity: 60-120/year; quality: 1-2/year |
| Rep. of Moldova | To 1990 according USSR decisions; at present: according possibilities |
| Romania | According int. recommendations |
| Slovenia | According gw level fluctuations; continuous close to rivers and boundary of the aquifer. Quality: 2 times/year |
| Spain | Hydrogeological conditions; abstraction conditions |
| Switzerland | |
| The Slovak Rep. | Levels: 53 or 365 times/year'; quality: 2,4,6, or 12 times/year; |
| The Ukraine | Levels: 5 times/month; quality: 2 times/year |

| | 9. What kind of standards (quality samples) and quality control is used ? |
|---|---|
| Austria | Austrian and German standards. spiked samples; auditing laboratories, inter laboratory comparison |
| Belgium, Flandres | Laboratories approved |
| Bulgaria | QC procedure: blank, duplicate and spiked samples; before storage: data validation, double input, limits of measurements |
| Croatia | Regulations pursuant to WHO |
| Czech Rep. | See Annex 2, part B ? |
| Estonia | Accredited laboratories assess compliance with water standards (EU standards) |
| Finland | ISO; CEU |
| Germ., Bavaria | Analysis for water quality management |
| Germ, Badenbr.b. | Statistical |
| Germ. Baden Wurt. | AQS sampling procedures and control, data plausibility, multiple analysis etc. (Sum = approx. 15% oftotal effort) |
| Germ., Rhineland P | AQS (Analyseverfahren nach DIN und DEV); ringtests |
| Germ., Schlesw.H. | AQS |
| Hungary | Nat. standards for sampling and quality control; additional EC standards |
| Latvia | Standard former USSR, WHO guidelines, EC recommendations |
| Lithuania | No standardization |
| The Netherlands | |
| Northern Ireland | Varies, see monitoring report |
| Portugal | Parameters have been mentioned in the questionnaire |
| Rep. of Belarus | State certified methods |
| Rep. of Moldova | Ex-USSR standards, int. (EU) standards |
| Romania | Int. recommendations |
| Slovenia | Reference materials and internal standards (not for all parameters); control cards QA/QC in progress |
| Spain | EU Directive and water act standards |
| Switzerland | |
| The Slovak Rep. | Slovak standard: STN 757111; QC: control samples (6% parallel samples); control of 2 or 3 standard dev. |
| The Ukraine | Drinking w. stand. (USSR), QC by MoH.Centr. Analyt. Laboratory (State Committee of Geology) is responsible for QC of labs. |

| | 10. Responsible organisations |
|---|---|
| Austria | Quantity: Hydrographic Service (Min. of Agr. and Forestry, MoAF); quality: MoAF and the Federal Env. Agency |
| Belgium, Flandres | AMINAL, Dep. Water, Belliardstraat 4-6, 1040 Brussel |
| Bulgaria | Nat. Centre for Env. and Sustainable Dev. (MIn. of Env.), Comm. of Geology and Mineral Res., Nat. Inst. of Met. and Hydrology |
| Croatia | Data collection and data storage is different: Croation waters, State Hydrometeorological Survey, Institute of geology and PH |
| Czech Rep. | Czech Hydrometeorological Institute |
| Estonia | Centre of Geology |
| Finland | Finnish Environmental Institute |
| Germ., Bavaria | Landesamt fur Wasserwirtschaft |
| Germ, Badenbr.b. | Landesumweltamt Brandenburg, Inselstrasse 26, D-03046 Cottbus, +49(0) 355-6350, fax. +49(0) 355-635300 |
| Germ. Baden Wurt. | Landesanstalt fur Umweltschutz, Griefbachstr 1-3, D-76185 Karlsruhe, +49(0) 721 983 1364, fax+49(0) 721 983 1514 |
| Germ., Rhineland P | Landesamt für Wasserwirtschaft |
| Germ., Schlesw.H. | Water supply companies for network operation and data storage and handling; water authorities for data storage and handling |
| Hungary | Nat. Water Authority and Reg. Water Auth. Supervision by Wat. Res. Res. Centre Plc/Vituki, Inst. of Hydrology |
| Latvia | Geological Survey concerning hydrailic parameters, Data collected by regional groundwater monitoring network. |
| Lithuania | Geological Survey of Lithuania |
| The Netherlands | Owner: provinces, RIZA; for data storage and handling: RIVM and NITG-TNO |
| Northern Ireland | Environment agency, no national system |
| Portugal | INAG, Instituto oa Agua |
| Rep. of Belarus | Min. of Natural Resources and Env. Prot.; Min. of Housing and Communications; Min. for PH Care of the Rep. of Belarus |
| Rep. of Moldova | State Ass. Geologia Moldovei, State Concern Apele Moldovei, Nat. Res. and Practical. Centre for Hygiene and Epidemiology |
| Romania | Reg Water Authorities (11 entities) for data collection: Nat. Inst. of Meteorology and Hydrology for storage and handling |
| Slovenia | Min. for Env. and Physical PLanning: Hydrometeorological Inst. responsible for operation of the network and info centre |
| Spain | Min. of Environment |
| Switzerland | Service de geologie du Canton de Geneve |
| The Slovak Rep. | Slovak Hydrometeorological Institute, Bratislava |
| The Ukraine | State Committee of Geology and Nat. Resources Use of Ukraine |

| ADDRESSES OF RESPONDENTS | |
|---|---|
| Austria | Mr. Karl Schwaiger, Federal Ministry of Agriculture and Forestry Department IV A 1, Marxergasse 2, A-1030 Wien, Tel: 43 1 714 09 50 24, Fax: 50 30. |
| Belgium, Flandres | Marleen van Damme, AMINAL, Dep. Water, Elfjulistraat 43, 9000 Gent, 09-2448337, fax.: 2448300; marleensm.vandamme@lin.vlaanderen.be |
| Bulgaria | Nikola matev, Min. of Environment (MoE), 67, W. Gladstone str. 1000 Sofia, Bulgaria. Tel: 359-2 810386, Fax: 800425. |
| Croatia | Zeljka Brkic, Institute of Geology, Sachgova 2, Tel: +385 1 61 523 00, Fax.: 50571, E-mail brkic@magi.igi.hr |
| Czech Rep. | J.A. Plainer, Czech Hydrometeorological Institute, Na Sabatce 17, 149 06 Prague 4. Tel: 420-2-4403 2327, Fax: 2357. e-mail: plainer@chmi.cz |
| Estonia | Veikko Taal, Min. of Environment, Toompuiestee 24, Tallinn, Estonia. Tel: 372 62 62 857, Fax: 801. e-mail:veiko@ekm.enir.ee |
| Finland | Jouko Soveri, Finnish Environment Inst., P.O.Box 140, Fin-00251 Helsinki, Finland. Tel: 358940300237, Fax: 291. e-mail:jouko.soveri@vyh.fi |
| Germ., Bavaria | B.D. Haug, Bayer. Landesamt für Wasserwirtschaft (LfW), Lazarettstr. 67, 80636 München, tel: 089/1210-0, fax.: 089/1210-1435 |
| Germ, Badenbr.b. | Mr. P. Schultze, Landesumweltamt Brandenburg, Inselstrasse 26, D-03046 Cottbus, +49(0) 355-6350, fax. +49(0) 355-635300 |
| Germ. Baden Wurt. | Dr. Grimm Strele, Landesanstalt fur Umweltschutz, Griefbachstr 1-3, D-76185 Karlsruhe, tel: 49(0) 721 983 1364, fax+49(0) 721 983 1514, e-mail: josl.grimm-strele@x400.efuka.um.bwl.de |
| Germ., Rhineland P | LBD Dr. Ing. Dieter Prellberg, Landesamt für Wasserwirtschaft, Am tollhafen 9, 55118 Mainz, tel: +49 (0)6131 630150, fgax:..148 |
| Germ., Schlesw.H. | Dr. Holthusen, Landesamt Für Natur und Umwelt des Landes Schleswig-Holstein. Hamburger Chaussee 25, D-24220 Flintbek tel: +49 (0) 4347 / 704-472; fax:...402; hholthus@lanu.landsh.de |
| Hungary | |
| Latvia | |
| Lithuania | Dr. Algirdas Domasevicius, Geological Survey of Luthuania, Tel: 3702635605, Fax: 3706706376, e-mail: Algirdas.Domasevicius@lgt.lt |
| The Netherlands | |
| Northern Ireland | |
| Portugal | Dr. Carlos WPETO, INAG, Instituto Ncional de Agua, Avenida almirante gago coutiniao, 30 -1000 Lisboa, Tel: 351-1-8409218, Fax: 8473023, e-mail: wpeto@tote.inag.pt |
| Rep. of Belarus | M.M. Chrepansky, Central Res. Inst. for Complex Development of water Resources, Min. of Nat. Res. and Env. Prot., 220086 Minsk, Slavinsky St. 1. Tel: 375 17 263 59 06. Fax: 264 27 34. E-mail:wri@wri.belpak.minsk.by |
| Rep. of Moldova | Dr. Petru Cocirta, Dep. ofEnvironmental Protection, Nat. Inst. of Ecology. Bd. Dacia 58, 2060 Chisinau. Tel: 373-2 761964 |
| Romania | Gabriel Constantin Tomescu, Nat. Int. of Meteorology and Hydrology, Groundwater Division. SOS. Bucuresti, Ploiesti 97, sector 1, Bucharest, 71552. Tel: 40-1-2303240/164. Fax: 4013129843 |
| Slovenia | Martina Zupan, Hydrometeorological Institute of Slovenia, Vojkova 1b, 1000 Lubljana, Tel: 386 61 1784102, Fax: 1784102, e-mail: martina.zupan@rzs-hm.si |
| Spain | |
| Switzerland | Paul Buttet, Swiss national hydrological and geological Survey. CH-3003-Berne. Tel. ++ 41 31 324 77 64, Fax. 76 81, e-mail: paul.buttet@buwal.admin.ch |
| The Slovak Rep. | Boris Minarik, Slovak Hydrometeorological Inst. (SHMI), Ieseniova 17, 833 15 Bratislava, Tel:421-7-373602, Fax: 421-7--373602. e-mail roncak@shmurax.shmu.sk |
| The Ukraine | Yegeiy Yakovlev, State Committee on Geology and Natural resource Use of Ukraine, 34 Volodymyrska Sr., Kyiv, 252003 Ukraine, Tel: 380 044 228 3394, fax: 380 44 228 6221 |

# ANNEX II Statistical approach to monitoring network design

## 1. Introduction

The aim of a monitoring network is to estimate a target parameter from measurements. Examples of target parameters are a spatial average, a trend in time and a spatial interpolation. The difference between the true value of the target parameter and its estimate is the estimation error. If more measurements are taken, the smaller the estimation error will be. Because, in practice, the true value of the target parameter is unknown, the estimation error is also unknown. In the hydrological approach to monitoring network design, the estimation error is dealt with intuitively. In the statistical approach, the estimation error is quantified by its statistical characteristics, in most cases the variance. This variance is dependent on the monitoring network design (network density and measurement frequency) and the statistical properties of the measured parameters. In order to calculate the error variance the statistical properties have to be evaluated from available measurements, or estimated as a initial guess. If there is insufficient data to do so, one has to relay on the hydrological approach.

Dependent on the target parameter, the statistical methods for monitoring network design can be divised into three classes.

1. Classical statistics is applied in case the target parameter is formulated in terms of general characteristics. Such as a reference value in space or an average value in time.
2. Geostatistics is applied when the target parameter is formulated as a function or space, in particular a spatial interpolation. The monitoring network design is focused on the network density and the locations of the sample points
3. Time series statistics is applied if the target parameter is formulated as a function of time, for example a trend in time. Here, the design is focused on the measurement frequency and the length of the monitoring period.

## 2. Classical Statistics

Classical statistics is so commonly used in all sorts of applications that it is perhaps not even recognised as a separate technique. The term classical statistics for application of a number of summary statistics such as the population mean, variance, etc., but also for parametric and non-parametric hypothesis testing. It is applied to spatial as well as temporal characteristics. These general characteristics provide for the concise description of a data set in terms of:

1. Measures of the centre of the data.
   The sample mean is probably the most common measure representing the centre of a data set. Several variations exist, such as the arithmetic, geometric and harmonic mean. The median, or 50th percentile, is the central value of a distribution when the data are ranked in order of magnitude. An important property is that the median, in contrast to the mean, is only minimally affected by the magnitude of a single observation (it is more robust or ‘resistant’),

being determined solely by the relative order of the observations (Helsel and Hirsch, 1995). For example, when a summary value is desired of a small set of concentration values of a chemical constituent containing an extreme value, the outlier will have hardly any influence on the median, while the mean will be strongly pulled towards the outlier.

2. Measures of the spread or variability.
   The sample variance (or its square root, the sample standard deviation) is the most common measure of spread. It is of paramount importance, as it is directly linked to the uncertainty or accuracy of the estimation. Like the mean, the variance is strongly influenced by outlying values. A more robust measure of variation is the interquartile range (IQR). It measures the range of the central 50% of the data and it is therefore not influenced at all by the 25% on either end of the data set (Helsel and Hirsch, 1995).
3. Measures of the symmetry of the data distribution.
4. Measures for extremes in the data set (Helsel and Hirsch, 1995).

For monitoring network design, the relation between the number of samples and the estimation error variance is required. This relation can be found in many statistical textbooks.

In addition, statistical measures as serial correlation functions, semi-variograms, etc. can be considered as general characteristics too. These functions may be regarded as a more precise quantification of the relation between sampling frequency and estimation variance. With these functions one can define a measure for what changes will have to be included in the measurements.

## 3. Geostatistics

In geostatistics, the variable property is viewed as a spatial random function. Such a function has been called a regionalised variable by Matheron (1971) and Journel and Huijbregts (1978). A regionalised variable is seen as one of many possible realisations of a spatial random field. The variable in this random field is not a classical random variable without any spatial structure, but is assumed to exhibit a spatial statistical dependence. Values of samples at neighbouring locations tend to be more alike than those values collected at distant locations. These correlation structures are usually represented by covariance and/or semivariogram functions. The incorporation of the spatial correlation structure is an important characteristic of geostatistical analyses.

Geostatistical techniques for groundwater monitoring network design that may be grouped into three classes:
1. simulation;
2. variance-based, and
3. risk-based approaches.

### 3.1 Simulation Approach

The conceptual backbone of the simulation approach is that by generating multiple synthetic fields of the variable to be measured. From these synthetic fields, the statistical properties are derived. With these statistical properties and the relationship between the number and locations of sample points and the reliability of estimate of the target, the variable is determined. With this relationship the monitoring network effectiveness is evaluated. For example, for any given arrangement of monitoring wells, the simulation approach yields quantities such as the probability that a contaminant plume might miss all of the sampling points and go undetected. By careful experimental design of the simulation, various network configurations can be examined for their adequacy in contaminant detection. Examples of simulation applications in groundwater quality monitoring network design can be found in Massman and Freeze (1987a, 1987b), Meyer and Brill (1988) and Ahlfeld and Pinder (1988).

### 3.2 Variance-Based Approach

The basis of the second group of statistical techniques is the estimation variance. Geostatistics offers various estimation algorithms, notably Kriging, which provide a spatial interpolation including the corresponding estimation error variance. This estimation variance may be regarded as a measure of the accuracy of the estimated value. The objective in this method is to minimise the estimation variance. As noted by Georgakakos et al., (1990), each sampling alternative can be evaluated before any new measurements are actually conducted. This is due to the fact that the uncertainty-reducing effectiveness of any sampling scheme depends only on the number and location of measurements sites, and not on the magnitude of measured values at those sites. Variance-based techniques have been used for the design of meteorological and hydrological networks. Examples are given by Fiering (1965), Bras and Rodrigues-Iturbe (1976a, 1976b), and Bastin et al. (1984).

Among variance-based approaches are the following:

**Global Method**

The aim of this method is to identify the best pattern (e.g., square, triangular, or other geometric arrangement) and the best density (the number of points per unit area) of the sampling sites. Authors as Olea (1984), Yfantis et al. (1987), and Christiakos and Olea (1988) present some global (i.e., regional-scale) indices for the performance of a monitoring program. Such global performance standards do not seem to be appropriate for groundwater quality monitoring, where interest is commonly directed to more localised performance.

**Variance-Reduction Analysis**

This approach (Rouhani, 1985) uses a methodical search for the number and locations of sampling sites that would minimise the variance or estimation error of the variable of interest. The search for a groundwater monitoring network configuration starts with a number of existing sample wells to which additional wells from a pool of potential sites are added, one at a time. The site of each additional well is chosen to produce the largest reduction in variance of estimation error. The statistical nature of the variance-reduction approach limits its capability to incorporate complex hydrogeologic settings. Previous applications indicate that the variance-reduction analysis is best suited for the determination of additional sampling sites (Georgakakos et al., 1990).

**Optimisation Approach**

In this approach, the groundwater quality monitoring network design is posed as a mathematical programming problem with a clearly defined objective function, such as minimising the estimation variance of groundwater quality properties (Knopman and Voss, 1988; Loaiciga, 1989). The optimisation approach is appealing because, in principle at least, it yields optimal sampling locations and sampling times while considering a variety of restrictions on the sampling plan. However, some of the most advanced applications reported to date have obvious limitations, concerning mainly the required simplifications of the hydrogeologic setting. Another shortcoming of many optimisation-based methods is their static nature. Sequential procedures seem to be the most likely new generation of optimisation methods (e.g., Graham and McLaughlin, 1989a; 1989b).

### 3.3 Probability-Based Approach

In the probability-based approach the selection criterion not only includes the estimation variance, but also the magnitude of the estimated values. The variance-based approaches give more priority to points with high estimation variance, regardless of their estimated values. Such criteria are not suitable for a typical groundwater quality monitoring activity, where information is required about areas where the variable of concern exhibits critical values. Rouhani and Hall (1988) propose a network design that incorporates the level of the variable in question and its estimation variance by introducing the probability of exceedance of a certain level of the variable as a criterion to be controlled in the network design problem. The exceedance probability depends on both the level and the estimation variance and, thus, these two parameters influence the selection of the sampling sites.

## 4. Time series analysis and sampling frequency

In the classical statistics approach the observations or samples are considered as a random number of measurements. The essential difference in the time series approach is that the measurements show an ordering in time and they may have a serial correlation. Typical objectives related to time series are trend detection, input response functions, decomposition of the series in component. For monitoring the mean issue is to derive the requirement measurement frequency and the observation period. To reach the measurement frequency, the relationship between the estimation uncertainty and the measurement frequency is to be evaluated. This relationship depend heavily on the variance and the serial correlation of the series.
Three categories of analysis methods are distinguished:

1. Regression analysis and other trend detection techniques
2. Auto-regressive integrated moving average (ARIMA) models
3. Spectral analysis

### 4.1 Regression analysis and other trend detection techniques

Many parametric and non parametric statistical trend detection techniques have been developed for time series. These detection techniques give the most likely estimate of the change over time and the corresponding confidence interval, which is dependent on the number of measurements and the monitoring period. This dependency is used to design the measurement frequency.
Helsel and Hirsch (1995) classify a number of trend tests for use in water resources, of which the ordinary least squares, usually referred to as linear

regression, is probably the best known. If a linear relationship exists and the residuals are Gaussian, then regression analysis is a technique providing optimal significance (Helsel and Hirsch, 1995). When testing for trends, the null-hypothesis is no apparent trend, which is rejected when a significant change over time of the variable is found.

A drawback of regression analysis is that it makes fairly strong assumptions about the distribution of the variable over time. Alternatively non parametric procedures can be used.  A very robust and a simple non parametric trend test is the Mann-Kendall test. For example, Broers and Buijs (1996) successfully applied it to the data of the National Groundwater Monitoring Network of the Netherlands in a regional study to assess the possible changes in groundwater quality of the province of Drenthe.

### 4.2 Auto-regressive integrated moving average (ARIMA) models and transfer noise models

Starting point in this class of methods is the description of the time series behaviour over time in terms of input response functions. With these functions, the forecasts can be made or decomposition of the series can be performed. The parameters in the input response functions are estimated statistically from the time series. The uncertainty in the parameter estimates and the forecasts are dependent on the measurement frequency, and hence it provides a relationship where the  measurement frequency can be evaluated with. The basic theoretical considerations behind time series analysis by means of autoregressive integrated moving average (ARIMA) models have been extensively described by Box and Jenkins (1970). Others have later extended the concepts and the practicality of the modelling (e.g., Hipel et al., 1977; McLeod et al., 1977). ARIMA models describe the time series behaviour by the history of the series itself. In transfer-function/noise models,also information from other measured time series is taken into account. For example, Gehrels et al. (1994) applied a transfer-function/noise model for groundwater level fluctuations to quantify the impact of groundwater abstraction and reclamation of a large polder area in the central Netherlands. In addition to the time series of the groundwater level they used time series of precipitation, surface water levels and groundwater abstraction as additional information.

### 4.3 Spectral analysis

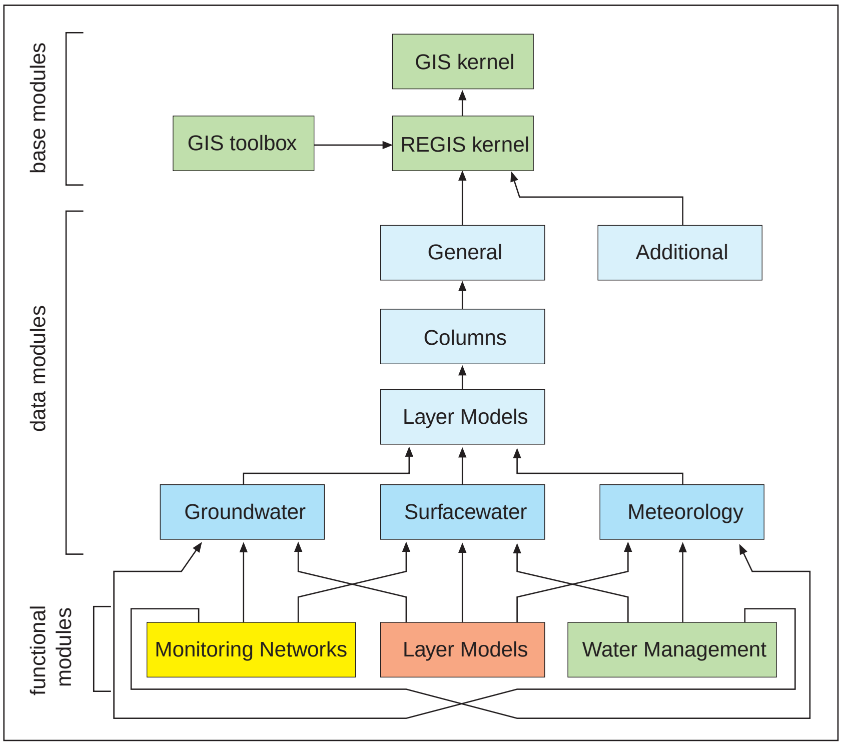
Spectral analysis is the partitioning of the time series into components according to the duration or length of the intervals within which the variation occurs (Davis, 1986). Spectral analysis is also known as harmonic analysis, Fourier analysis, and frequency analysis. The technique is based on the Fourier theory that states that any continuous, single-valued function can be represented by a series of sinusoids of differing amplitudes, wavelengths, and starting points. The time series is decomposed into its constituents parts, called harmonics. These harmonics have amplitudes which can be expressed in terms of variance, and since the decomposed time series can be regarded as the sum of many sinusoidal functions, the variance of the time series is composed of the sum of variance of these harmonics. The variances of the successive harmonics can be plotted in a periodogram or a line power spectrum. The periodogram can be used to determine the dominant frequencies in the time series and, also, which fraction of the total variance is explained by these frequencies. Hence, the periodogram offers a quantification of the relationship between measurement frequency and the degree to which the variance of the actual time series is captured with the measurements. The highest frequency that is to be captured by the measurements determines the minimum acceptable sampling frequency. A well-known criterion in this respect is the Nyquist frequency saying that the highest frequency that can be estimated is the frequency whose wavelength is exactly twice the distance between the successive observations (Davis, 1986).

# ANNEX III Description of REGIS

**Database characteristics**

Figure 1 refers to the database of a REgional Geohydrological Information System, REGIS which was developed in the Netherlands. In 1990 the development of REGIS was initiated and supported by the Netherlands Ministries of Transport, Public Works and Water Management and the provincial governments. The aim of the system is to offer a wide range of tools for governments at regional and local levels to assist them in performing their tasks in managing water resources, soil/subsurface and groundwater/surface water domains and managing the huge flows of data collected from various monitoring networks in the Dutch settings. REGIS actually covers a family of geo-information systems, each developed for a specific type of user. In a later stage of the development, water supply companies and local water boards joined forces to support the further enhancement and expansion of products from the REGIS family to a wider group of users. REGIS is based on the concept of geo-information systems capable of both storing huge quantities of data (time-dependent, point data, map data, etc.) and processing data in one coherent user-friendly system to evaluate (geo)hydrological conditions on national, regional and local scales. More specifically, REGIS is a combination of a Geographical Information

**Figure 1**
Diagram of the modules and links in a modern database for (geo)-hydrological data.



System (GIS) and a Database Management System (DBMS), moulded into one user-friendly Windows-driven system. The integration of a database and GIS allows the user to select objects on a map and instantly display the relevant data from this object. The user is exposed to only the Graphical User Interface and does not have to deal with intricate DBMS or GIS technology. Even the physical locations where data are stored remain immaterial to the user.

**Overview of Data Sets and Items stored in REGIS**

REGIS has the functionalities to store point data, spatial data, time-series, etc. The following sets of data can be stored in REGIS:

**3D Geohydrological Subsurface Model**

REGIS has the capability to store a 3D -model of the subsurface comprising data on lateral extent, depth, thickness and hydraulic properties of individual layers in the subsoil. Data such as bore hole data, geophysical well logging data, geo-electrical soundings, well tests and pumping tests can be used to generate the 3D-model.

**Groundwater levels**

Level data (piezometric heads) from groundwater monitoring networks (observation wells and pumped wells) can be stored in REGIS as well as contour maps of piezometric heads in aquifers.

**Groundwater Quality**

REGIS allows the storage of the chemical composition of water samples (macro and minor components, micro-pollutants, organic compounds, pesticides, etc.) and information on the depth of fresh/brackish/salt interfaces.

**Groundwater Abstraction**

Technical and administrative information on groundwater production in the form of time-series of the pumped amounts. The locations of the protection zones are also stored in the system.

**Surface Water**

REGIS uses a data model for surface water adopted from the Dutch water boards. Items such as location of water courses, regulating structures, drainage basins and areas with artificially fixed groundwater levels can be stored, as well as relevant hydrological properties such as dimensions, water levels, drainage resistances, fixed levels, pumping capacities, etc.

**Ground Surface Level**

Various sets of surface level data can be stored and displayed.

**Topographic Maps**

Topographic maps, maps from drawing applications and satellite imagery in the form of grid files can be stored in REGIS.

**Additional Data or Thematic Maps**

Heterogeneous thematic map data such as land use, infiltration and discharge areas, information on soil pollution sites, waste disposal sites, etc. can be stored.

## Overview of REGIS Special Facilities

### Database

Both point or non-spatial data and spatial data can be stored in the REGIS database (non-spatial data in the Oracle database and spatial data in ArcView). For the user, these two data types are fully inter linked and transparent. All types of data can be stored, processed, modified and visualised. A variety of pre-defined database forms are available to enter, select, check, modify and view data in a systematic fashion. Built-in controls offer quality assurance checks on the data.

### Catalogue

In REGIS, a new catalogue is used to access and represent spatial data. With the catalogue the user gets an easy overview of available datasets. From the catalogue the users easily selects themes to be displayed in the GIS window.

### Data Exchange

Functions are available to import and export data in low-level formats like ASCII or CSV (Comma Separated Value) formats which are accepted by practically any commercial software package. Data can also be exchanged with other information systems like HYMOS for surface water.

### Subsurface Layer Models

A variety of layer models can be stored in REGIS. Geological layering, geohydrological layering, electrical resistivity layering, etc. can be compiled from basic data. Vertical cross-sections displaying the pile of strata, are easily prepared on the screen by simply selecting an arbitrary line.

### Development Potential and User Customisation Potential

An additional toolkit has been developed for REGIS for software developers. The toolkit enables users or developers, who have to be familiar with the underlying software, to implement their own functionalities within REGIS.

## Overview of REGIS Modules

Several modules are available in REGIS and others can be added. As the development of REGIS will be continued at least for the next five years, more modules will become available. An overview of the current modules is as follows:

### General and Additional Data Modules

Topographic and additional data are contained in these modules. Functionalities include creating and maintaining a catalogue, the help functions and the project manager functions for authorising, creating, deleting and managing projects, databases and users.

### Column and Layer Model Modules

Basic bore hole data, geophysical logging data, geo-hydrological and fresh/salt water interface layer models are stored in this module. The module has the functionalities to generate vertical cross-sections through layer models.

**Groundwater Module**

The groundwater module is made up of three parts:

1. Groundwater level data;
2. Groundwater quality data;
3. Groundwater abstraction data.

The functionality covers many data management features, display and visualisation functions and data exchange.

**Surface Water Module**

This module contains the basic data of surface water systems and enables linking with other information systems like HYMOS.

**Meteo Module**

Storage and presentation of meteorological data on precipitation, evaporation, air pressure, humidity, etc. is handled by this module.

**Water Level Management Module**

This module was specially made for the situation in the Netherlands, enabling water boards to implement active water level management for both surface and groundwater data.

**Numerical Modelling Coupling Module**

This module presently under development is aimed at the exchange of data (layer configuration, hydraulic parameters, groundwater abstractions, etc.) to numerical groundwater flow models like USGS MODFLOW and MT3D (transport).

**Functional Description**

**Forms for entering, editing and viewing of data**

REGIS uses Oracle forms to enter, edit and view non-spatial time-dependent or time-independent data. Any type of data can be stored as long as there is a table defined in the database to store a particular data set. Forms are made by standard Oracle tools and can be easily modified and tailor-made created to specific needs.

**Data import from standard database software and spreadsheets**

Import and export of data to spreadsheets and databases is accomplished by using the common and well-known CSV (Comma Separated Value) format, which is essentially an ASCII file with the numerical parameters separated by commas and a text strings additionally surrounded by quotes. This format can be read by any modern commercial spreadsheet (like EXCEL, LOTUS, QUATRO PRO, etc.) and maintains the original structure in columns and rows. The same applies to database software. Native formats are not being produced by REGIS because of the rapid obsoleteness due to frequent new version releases.

**Data validation**

A "Primary Validation" (Integrity/consistency checks) is carried out when data is entered through Oracle forms or through direct import. A "Secondary Validation" can be performed based on site-specific criteria and requirements.

**Generation of location and contour maps, hydrographs, X-Y plots, borehole logs, well constructions and water quality presentations**

Automatic generation of maps and graphs forms one of the major pillars of the REGIS information system. Through various settings screens/windows the user may customise the graphical output which is sent to the screen or to the printer/plotter. The Spatial Analyst offers all the functionalities to edit the grid values hence indirectly the generated contours.

**Statistics**

From the statistical functions, the following are included in REGIS:

1. basic statistics (mean, variance, standard deviation: built-in ArcView functionalities);
2. Moving averages;
3. Kriging and C-Kriging (built-in ArcView functionalities for grids only);
4. Trend surface analysis (built-in ArcView functionalities).

**Generation of periodic customised yearbook reports**

Report formats and layouts can be easily created using the tools included in the Oracle software package. A standard package is available.

**Import and export of maps and cross-sections**

Preparation of contour maps and manual editing capabilities
Manipulation of layer-wise information from original/manually edited contour and thematic maps and database
Well log presentation along specified cross-section lines
Integrated map generation by posting information on basemaps
Preparation and manipulation of spatial and layer-wise information for modelling software

The coupling with numerical models like MODFLOW and MT3D is still under development. The objective is to generate all the necessary input files for the models and have the output viewed within REGIS.