



Sustainable Groundwater Management: Concepts and Tools

Briefing Note 9

30107 []
2004

Groundwater Monitoring Requirements for managing aquifer response and quality threats

Authors (GW•MATE Core Group)

Albert Tuinhof¹ Stephen Foster¹ Karin Kemper² Hector Garduno Marcella Nanni
(¹lead author ²main supporting author)

What are the aims, benefits and challenges of groundwater monitoring?

- Groundwater is an extensive, concealed and inaccessible resource (**Briefing Notes 1 and 2**), and (in contrast to surface water) changes in quantity and quality are often very slow processes occurring below large land areas. These changes cannot be determined by simple one-off snapshot surveys alone, and require more elaborate monitoring networks and data interpretation. The primary goal of aquifer management is to control the impacts of groundwater abstraction and contaminant loads, and monitoring aquifer response and quality trends provide key inputs for this goal.
- The evaluation of groundwater issues and the implementation of management solutions require hydrogeological data that are in part 'baseline' and in part 'time-variant' in character (Table 1)—the collection of the '*time-variant component*' is what is usually considered '*groundwater monitoring*'. Groundwater

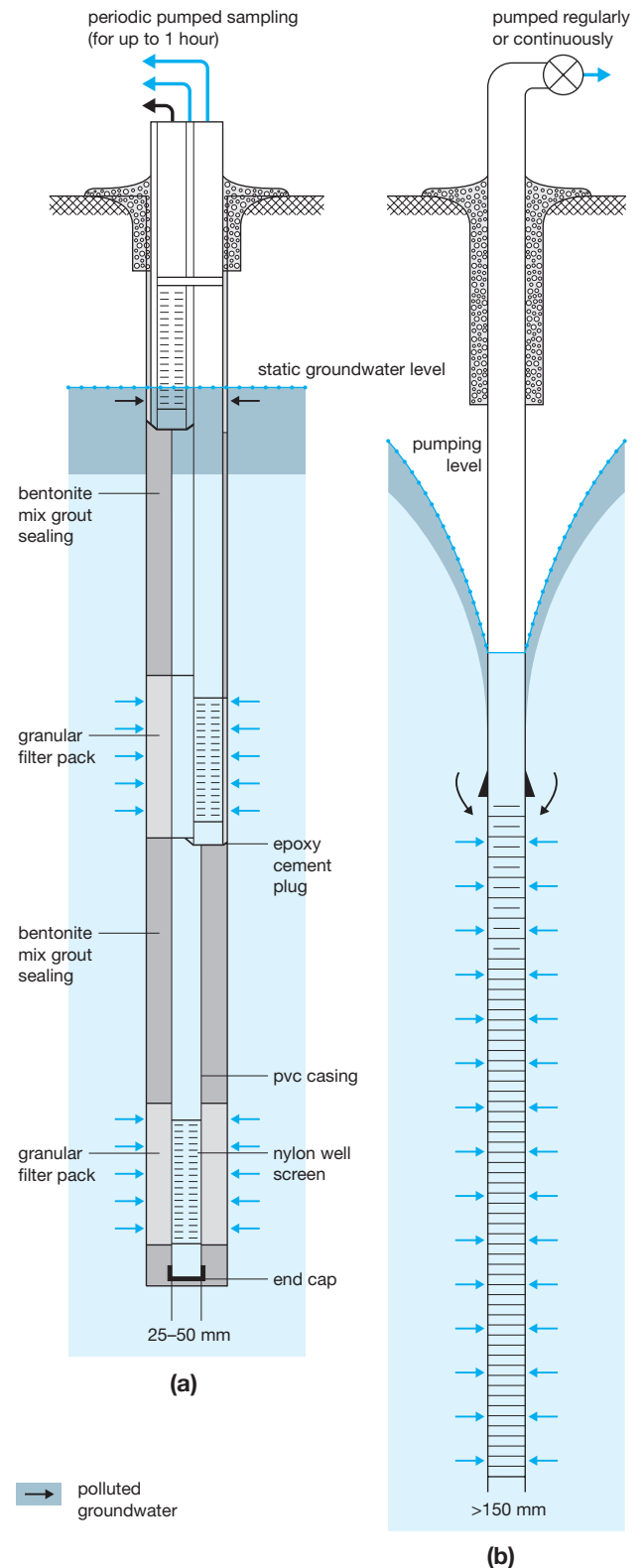
Table 1: Types of data required for groundwater management

TYPE OF DATA	BASELINE DATA (from archives)	TIME-VARIANT DATA (from field stations)
Groundwater Occurrence and Aquifer Properties	<ul style="list-style-type: none"> • water well records (hydrogeological logs, instantaneous groundwater levels and quality) • well and aquifer pumping tests 	<ul style="list-style-type: none"> • groundwater level monitoring • groundwater quality monitoring
Groundwater Use	<ul style="list-style-type: none"> • water well pump installations • water-use inventories • population registers and forecasts • energy consumption for irrigation 	<ul style="list-style-type: none"> • water well abstraction monitoring (direct or indirect) • well groundwater level variations
Supporting Information	<ul style="list-style-type: none"> • climatic data • land-use inventories • geological maps/sections 	<ul style="list-style-type: none"> • riverflow gauging • meteorological observations • satellite land-use surveys

monitoring thus comprises the collection, analysis and storage of a range of data on a regular basis according to specific circumstances and objectives. The type and volume of data required will vary considerably with the management issue being addressed, but is also inevitably dependent upon available financial resources.

- At the heart of all groundwater investigation and monitoring are wells, of the two basic types indicated below. They represent *keyholes to aquifers*, which allow groundwater pressure and quality measurements to be made and thus furnish information from which the health of the aquifer system can be judged.
- **Abstraction Wells.** When water wells are drilled they provide one-off unique *in-situ* data on the groundwater resource and its variation with depth—and data acquired during drilling (borehole logging) and initial test pumping form key baseline reference information on groundwater quantity and quality, in addition to their value for the determination of abstraction well potential. However, data collected from water wells once operational are normally more difficult to interpret, because groundwater levels are affected by the drawdown-recovery cycle and pumped-sample quality reflects the variable mixing of groundwater from a wide range of aquifer depths and residence times (Figure 1).
- **Observation Wells.** These are dedicated monitoring stations, sited and designed to detect potential changes in groundwater flow and quality—design parameters include selection of depth for the intake screen, frequency of measurement (if not continuous) and selection of quality parameters. To overcome the widespread presence of depth variation in hydraulic head and/or groundwater quality, nested piezometers (Figure 1) or well clusters can be used. Piezometer nests are more cost effective than observation well clusters, but should only be used if proper sealing can be achieved to prevent vertical flow between their screens.

Figure 1: Groundwater inflow and construction details of (a) nested monitoring piezometers with (b) production water well for comparison





- A suite of observation wells coupled with a selection of abstraction wells normally comprise a **monitoring network**, which should be designed so as to provide the required access to the groundwater resource. Monitoring networks and systems are classified into three main (but not mutually exclusive) groups (Table 2), and are specifically designed and operated to:
 - detect general changes in groundwater flow and trends in groundwater quality, and bridge gaps in scientific understanding of the groundwater resource base (**Primary Systems**)
 - assess and control the impact of specific risks to groundwater (**Secondary and Tertiary Systems**).

Table 2: Classification of groundwater monitoring systems by function

SYSTEM	BASIC FUNCTION	WELL LOCATIONS
Primary (Reference Monitoring)	evaluation of general groundwater behavior: <ul style="list-style-type: none"> • trends resulting from land-use change and climatic variation • processes such as recharge, flow and diffuse contamination 	<ul style="list-style-type: none"> • in uniform areas with respect to hydrogeology and land use
Secondary (Protection Monitoring)	protection against potential impacts of following: <ul style="list-style-type: none"> • strategic groundwater resource • wellfields/springheads for public water supply • urban infrastructure from land subsidence • archaeological sites against rising water table • groundwater-dependent ecosystems 	<ul style="list-style-type: none"> • around areas/facilities/features requiring protection
Tertiary (Pollution Containment)	early warning of groundwater impacts from: <ul style="list-style-type: none"> • intensive agricultural land use • industrial sites • solid waste landfills • land reclamation areas • quarries and mines 	<ul style="list-style-type: none"> • immediately down- and up-hydraulic gradient from hazard

How can we ensure that groundwater monitoring is cost effective?

- Effective groundwater monitoring is characterized by two key requirements:
 - it should be driven by a specific objective—*monitoring for its own sake often leads to inefficient use of manpower and budgets*
 - the data collected should be systematically stored for future use—*there are far too many cases of monitoring data being ‘lost along the way’.*
- Groundwater monitoring is often considered expensive—the main components of expenditure include the capital cost (of network installation), sampling costs (for instrumentation, personnel and logistics) and analytical costs (for laboratory, data processing and storage). Moreover, the return on initial investment is not likely to be evident immediately. Yet, in the longer run, this return can be substantial where monitoring represents an integral part of a management process and avoids loss of valuable groundwater sources, the introduction of costly treatment or the need for expensive aquifer remediation. Awareness of these factors increases if cost-benefit analysis is included in the design phase of groundwater monitoring programs.

- The effectiveness of groundwater monitoring can be considerably increased by careful attention to network design, system implementation and data interpretation (Table 3), and also by:
 - making best use of data collected by past monitoring activities
 - selecting monitoring stations that, as far as possible, are easily accessible
 - making fullest use of indicator determinands to reduce analytical cost
 - promoting complementary self-monitoring amongst water users
 - incorporating quality control and quality assurance procedures.

Table 3: Basic success rules for groundwater monitoring programs

NETWORK DESIGN	<ul style="list-style-type: none"> ● objectives must be defined and program adapted accordingly ● groundwater flow system must be understood ● sampling locations and monitoring parameters must be selected by objectives
SYSTEM IMPLEMENTATION	<ul style="list-style-type: none"> ● appropriately-constructed observation and abstraction wells must be used ● field equipment and laboratory facilities must be appropriate to objectives ● complete operational protocol and data handling system must be established ● groundwater and surface water monitoring should be integrated where applicable
DATA INTERPRETATION	<ul style="list-style-type: none"> ● data quality must be regularly checked through internal and external controls ● decision makers should be provided with interpreted management-relevant datasets ● program should be periodically evaluated and reviewed

modified after UN-ECE Task Force on Groundwater Monitoring & Assessment (2000)

How should the responsibility for groundwater monitoring be shared?

- Groundwater legislation should make provision for monitoring of groundwater use and status by assigning facets of this task to the water resources administration and to water users. To be effective this legislation should set realistic requirements that take account of existing institutional capacity (**Briefing Note 4**). A typical division of responsibilities is:
 - Central Government/National Water Authority—basic reference network
 - Regional/Basin/Aquifer Water Resource Agency—resource regulation and protection functions
 - Water well Contractors/Drilling Companies—obligations for well logs and pump testing
 - Large Groundwater Abstractors—records of metered well abstraction and water levels
 - Small Groundwater Abstractors—general feedback on well characteristics and performance
 - Potential Groundwater Polluters—defensive quality monitoring at site level.

- The storage of groundwater monitoring data (including that generated by private sector stakeholders) is an important issue, often not properly coordinated between national and local agencies involved. Clear data collection and storage protocols need to be agreed between all agencies, and a systematic database and arrangements for data sharing via the Internet established. Data storage at the lower territorial level will be more effective, although it will be useful for representative datasets to be held nationally at the Water Authority or the Geological Survey. Some data needed for groundwater management (Table 1) are usually archived by the Meteorological Service and the Geological Survey, and public access to these data systems also needs to be ensured.



It is not possible within the space available for this Briefing Note to provide a complete catalogue of groundwater monitoring techniques nor a comprehensive guide to groundwater monitoring network design (but these can be found in the Further Reading section). Two common and classic applications are provided below which will serve to illustrate the fundamentals of the approach required.

(A) MEASURING GROUNDWATER USE & AQUIFER BEHAVIOR

How can groundwater and aquifer monitoring improve the evaluation and management of groundwater resources?

- The primary goal of aquifer management is to develop groundwater resources on the basis of a policy plan, and to monitor and control the impacts of abstraction on the groundwater system. The development and evolution of policy requires good hydrogeological understanding and will benefit from a monitoring network detecting changes in aquifer water level due to groundwater abstraction. Since groundwater flow is related to groundwater levels, changes in flow regime can be determined from the observed changes in aquifer water levels. Monitoring groundwater abstraction and aquifer water levels thus provides key information for groundwater resource management.
- Groundwater is developed through drilling abstraction wells, often in groups as wellfields. Such wellfields are designed on the basis of an *acceptable predicted aquifer response* (change in groundwater levels and flow) for a certain level of abstraction. These predictions are usually made using numerical models, which simulate the aquifer response to different abstraction scenarios. Wellfield construction and abstraction licenses are issued on the basis of such predictions. Aquifer monitoring plays an important role in this context because:
 - historic data are important for the calibration of numerical aquifer models, and as such form the basis for reliable simulations of future abstraction scenarios
 - measuring (and archiving) the reference situation for new abstraction wells is important to provide baseline information for the evaluation of future changes
 - observations of groundwater levels and pumping rates during wellfield operation provide information to verify the predicted aquifer response and, if necessary, take timely action to reduce abstraction
 - the information collected can also play a key role in increasing awareness of water users, to facilitate the introduction of required groundwater demand management measures.

Which techniques are available to measure and to monitor groundwater abstraction and use?

- *Direct monitoring of groundwater abstraction* in individual water wells by means of meters normally gives accurate measurements, but (especially in developing nations) can be costly to operate and difficult to sustain without the full cooperation of water users. Water meter readings are usually made by the water user with submission to the regulatory authority. The authority also carries out periodic inspections, providing that they have adequate manpower and transport.



- It is also possible to obtain valuable data by *indirect monitoring of groundwater abstraction* through:
 - *collection of indicative data*—for example irrigation groundwater use can be estimated indirectly using hours of pump operation (from energy consumption) multiplied by average pumping rate
 - *use of remote sensing*—satellite or airborne sensors can provide objective measurements at potentially large scales, with quasi-continuous cover at low cost per km²

POTENTIAL OF REMOTE SENSING

Conventional applications include *mapping Quaternary geology, land use, crop types, soil salinization and land subsidence*. These have recently been complemented by interpretation of thermal energy sensor data to *estimate actual evaporation rates*. If sufficient frequency of adequate images is available, and land-surface relief is not too abrupt, then both *daily and total dry-season actual evaporation at farm and aquifer level* can be determined, and used for *checking data on groundwater use* and focusing efforts on ground inspection. The required images can be obtained from:

- commercial satellites (such as LandSat), with high resolution images but passing only every 16 days and may not generate sufficient datasets in regions with frequent overcast
- specialized meteo-satellites, passing more frequently but generating images that may not always be of adequate resolution.

This technique experiences increasing measurement error at low vapor fluxes, however, and thus cannot be used directly to determine *cumulative actual evaporation, soil moisture deficit and aquifer recharge rates for a natural arid-zone vegetation cover*. Nevertheless, satellite imagery and airborne surveys show much future potential to broaden the coverage and reduce the cost of groundwater investigation and monitoring.

- *estimates of change*—in regional groundwater abstraction can also be obtained through information on demographic changes and random checks on *per capita* water use.

What problems can be encountered in the monitoring of groundwater level fluctuations and trends?

- Groundwater level measurements (in observation, unused and abstraction wells) can be made manually or automatically (Figure 2). Manual water-level recorders give a visual or audio signal when their probe is immersed in water. Automatic recorders are small probes (divers) installed in observation or abstraction wells, which store water-level and temperature data at pre-set intervals, which can be downloaded to a data-logger during inspection visits or telemetrically transmitted enabling remote monitoring.
- Groundwater monitoring networks must be designed by specialists on the basis of management requirements (Table 2), but financial constraints are often a problem and require choices to be made. The inclusion of production and disused wells will help increase the number of monitoring points. But it may also be important to identify the presence of areas with marked vertical variation in groundwater head, which tend to occur below groundwater recharge or discharge areas and in layered systems.

- Operation of a monitoring network requires manpower and logistical resources, together with clear procedures to assure the continuous generation of reliable data. Lack of these resources is often a constraint in maintaining the necessary level of data collection and quality control. Delegation of monitoring responsibility to local level with self-monitoring by water users will help to overcome this problem.
- Groundwater data storage, evaluation and retrieval are essential components of effective monitoring. The flow of data from the field stations to central storage facility (database) should be assured, and qualified personnel available to review data collected. Groundwater level changes observed through monitoring may have widely differing causes and should be carefully evaluated to determine the correct management action required.

(B) DETECTING GROUNDWATER QUALITY CHANGES

Why does groundwater monitoring require special sampling procedures?

- The process of well pumping and sample handling causes major *sample modification* through such processes as air entry, degassing and volatile losses (potentially introducing more significant errors than actual sample analysis), which need to be addressed through appropriate sampling procedures (Table 4).

Table 4: Summary of sampling procedures and precautions for specific groups of groundwater quality parameters

DETERMINAND GROUP	SAMPLING PROCEDURE	PREFERRED MATERIALS	STORAGE TIME/ TEMPERATURE	OPERATIONAL DIFFICULTY/COST
Major Ions Cl, SO ₄ , F, Na, K	<ul style="list-style-type: none"> • 0.45 µm filter only • no acidification 	any	7 days/4 °C	minimal
Trace Metals Fe, Mn, As, Cu, Zn, Pb, Cr, Cd, etc.	<ul style="list-style-type: none"> • sealed 0.45 µm filter • acidify (pH <2) • avoid aeration through splashing/head space 	plastic	150 days	moderate
N Species NO ₃ , NH ₄ (NO ₂)	<ul style="list-style-type: none"> • sealed 0.45 µm filter 	any	1 day/4 °C	moderate/low
Microbiological TC, FC, FS	<ul style="list-style-type: none"> • sterile conditions • unfiltered sample • on-site analysis preferred 	dark glass	6 hours/4 °C	moderate/low
Carbonate Equilibria pH, HCO ₃ , Ca, Mg	<ul style="list-style-type: none"> • unfiltered well-sealed sample • on-site analysis (pH, HCO₃) (Ca/Mg at base laboratory on acidified sample) 	any	1 hour (150 days)	moderate
Oxygen status pE(EH), DO, T	<ul style="list-style-type: none"> • on site in measuring cell • avoid aeration • unfiltered 	any	0.1 hour	high/moderate
Organics TOC, VOC, HC, ClHC, etc.	<ul style="list-style-type: none"> • unfiltered sample • avoid volatilization • (direct absorption in cartridges preferred) 	dark glass or teflon	1–7 days (indefinite for cartridges)	high

What are the requirements and limitations of groundwater quality monitoring at mains water-supply sources?

- A primary focus for quality monitoring is the surveillance (or quality control) of water wells and spring-heads being used for public water supply via piped distribution systems, and the collection of pumped samples from such sources is the most commonly practiced groundwater sampling method. The range of determinands under analysis initially will include all those listed in the WHO potable water quality guidelines, although a reduced list of parameters will usually be monitored on a long-term basis, with fuller analytical checks being undertaken periodically and immediately after any significant change is detected. This function is essential for ‘product control’ to confirm the acceptability of raw (pumped) water and/or the effectiveness of treatment processes, and as such presents few problems specific to groundwater.
- The results of this type of monitoring do not normally correspond to the condition of groundwater *in situ*—essential for aquifer monitoring programs which have to define the subsurface distribution of groundwater of inferior quality, its variation with time and in response to management mitigation measures. This is because of **variability and uncertainty of sample origin**, given that production wells facilitate the entry of groundwater over a large depth range of the aquifer and that the proportion derived from a given depth can vary widely both with pumping rate and pumping period (Figure 1). These obstacles can be costly to overcome, and serious limitations in groundwater sampling sometimes have to be accepted. But such limitations must always be recognized in the interpretation of results, and consideration given to introducing improved sampling methods where justified economically or on public health grounds.

How can an early warning of potential threats to aquifer and groundwater supply quality be obtained?

- In many cases the critical requirement is to obtain an early warning of potential quality problems that may threaten the groundwater source and the aquifer system on which it depends. For this purpose it is necessary to design monitoring networks which relate to the three-dimensional spatial variation of groundwater flow and quality (Figure 2), so as to obtain samples representative of the quality of the more recent recharge (replenishment) to the aquifer in question. This will often be markedly different

Figure 2: Detection of groundwater quality trends in aquifer replenishment in the vicinity of a public-supply water well

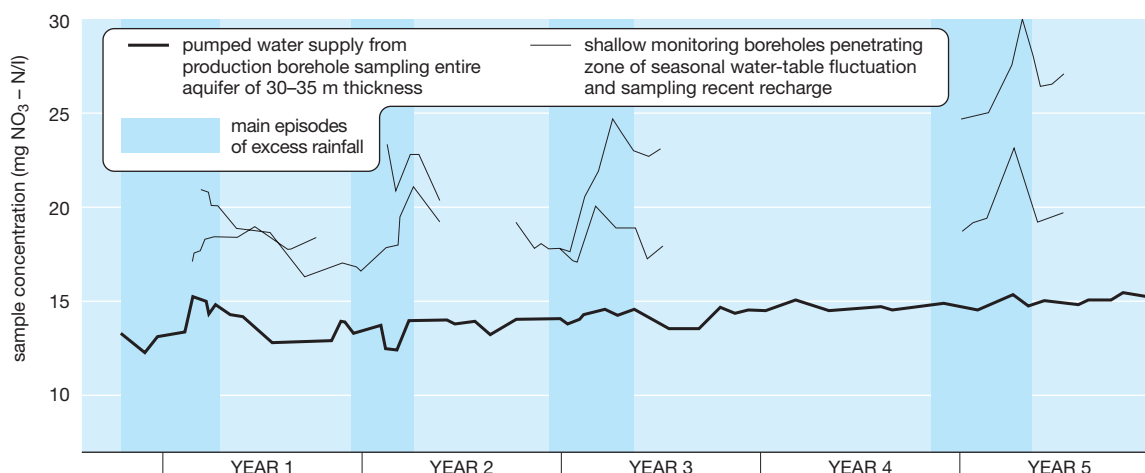
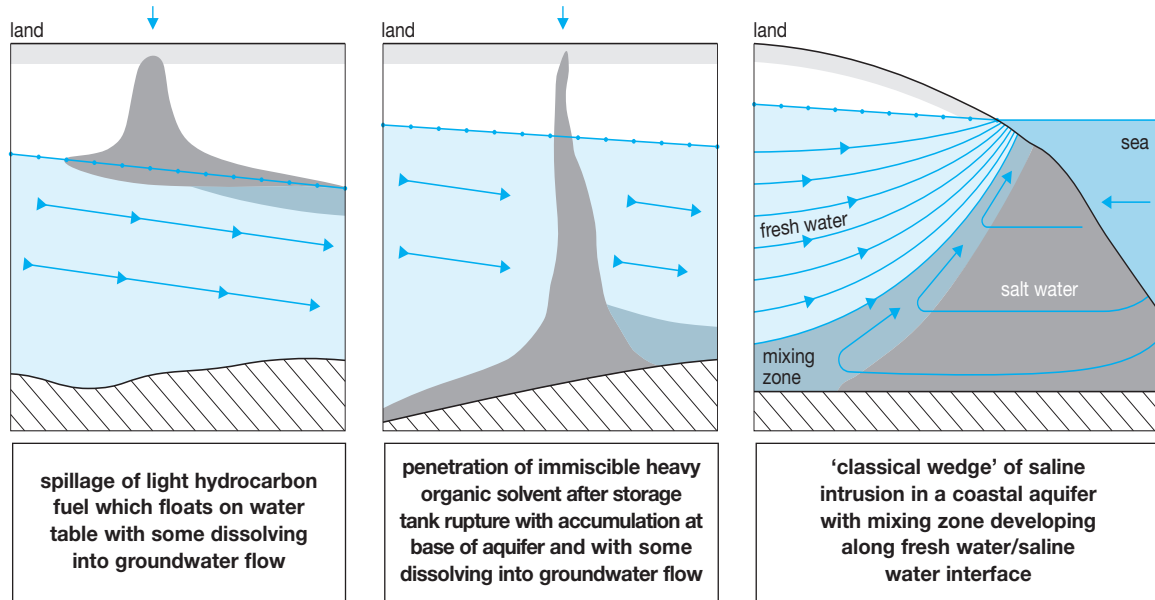


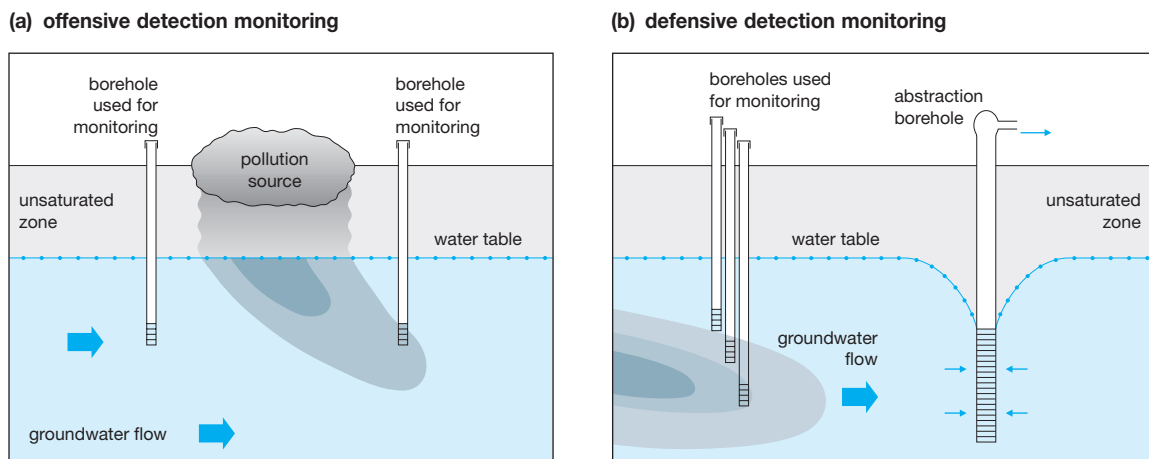
Figure 3: Processes causing major vertical variations of groundwater quality within an aquifer system which need to be detected through monitoring



from the average quality of groundwater in aquifer storage, as a result of the very large storage volumes and long residence times of many groundwater systems. Other factors which can also cause marked vertical variation in groundwater quality will require a similar monitoring approach (Figure 3).

- The rapid growth of urban and industrial waste disposal to the ground and the widespread intensification of agricultural cultivation in recent decades is necessitating a major expansion of focused groundwater quality management monitoring, using sampling piezometers designed and installed for a specific application (Figure 4) with the following types of objective:

Figure 4: Schematic representation of groundwater quality monitoring network design for specific management objectives





- to facilitate the early warning of the onset of groundwater pollution from a given activity and allow the timely introduction of any necessary control measures
- to provide advance warning of the arrival of polluted water at an important groundwater supply source and thus make provision for treatment or other mitigation
- to identify any contamination reaching an aquifer from a potential major pollution source and thus take early remedial action
- to establish evidence to determine legal liability for groundwater pollution incidents.

The complexity of groundwater flow and quality regimes is often such that specialist hydrogeological expertise will be required in many applications—both to design monitoring networks and to interpret their results.

Further Reading

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Publication Arrangements

The GW•MATE Briefing Note Series has been designed by Words and Publications, Oxford, UK, and published by the World Bank, Washington D.C., USA. It is also available in electronic form on the World Bank water resources website (www.worldbank.org/gwmate) and the Global Water Partnership website (www.gwpforum.org).

The findings, interpretations, and conclusions expressed in this paper are entirely those of the authors and should not be attributed in any manner to the World Bank, to its affiliated organizations, or to members of its Board of Executive Directors or the countries they represent.

Funding Support



GW•MATE (Groundwater Management Advisory Team) is a component of the Bank-Netherlands Water Partnership Program (BNWPP) using trust funds from the Dutch and British governments.

