Chapter 2

Groundwater Systems

2.1 Groundwater Knowledge: The Starting Point for Management Solutions

Groundwater is a vulnerable resource. As schemes are developed to pump out huge quantities of water, and with the advent of particularly persistent contaminants, the resource needs to be protected and managed (see Table 2.1). Despite groundwater's pivotal role in sustaining ecosystems and providing water supply, the resource is still poorly understood, and hence poorly managed, in many parts of the world. When things go wrong, the damage can be lasting or even permanent. For example, over-pumping and continuous long-term contamination by urban effluents and agricultural practices in the Gaza Strip has led to some groundwater becoming unfit for drinking or agricultural use. Even if pumping and contamination stopped today, it would take hundreds of years for the contaminants and intruding saline water to be flushed out of the groundwater system. Some groundwater resources were accumulated aeons ago and are no longer replenished (e.g. many of the sandstone aquifers of North Africa), thus using them is similar to mining non-renewable minerals.

If groundwater systems were all alike, their management would be simple. However, groundwater systems vary tremendously, which means they respond differently to pressures and, therefore, require different management solutions.

A vital starting point for improving management of groundwater is to develop a technical understanding of how groundwater systems work. For example:

- what types of rocks make good aquifers
- why some aquifers are naturally recharged while others are not
- how to determine how much water can be sustainably taken from an aquifer, and
- which types of aquifers are at most risk of pollution.

With this type of knowledge, and supported by effective monitoring, communities and groundwater managers can develop reasonable visions and plans for groundwater management and identify management actions needed.

Table 2.1 Advantages and limitations of using groundwater for water supply[13]

Advantages of groundwater	Limitations
• Groundwater is often available close to where it is required	• Groundwater is not ubiquitous and considerable effort may be needed in some situations to locate suitable sites for boreholes
• Groundwater can be developed relatively cheaply and progressively to meet demand with lower capital investment than many surface water schemes	• As overall coverage increases, the more difficult areas which are left can become more costly to supply
• Groundwater generally has excellent natural quality, and is usually adequate for potable supply with little or no treatment	• Natural quality constraints such as high fluoride and arsenic occur in some areas
• Groundwater generally has a protective cover provided by the soil and unsaturated zone	• As development increases more rapidly, pollution can exceed the capacity of the soil to attenuate contaminants
• Groundwater is generally available during times of surface water drought	• As demand for groundwater increases overexploitation of the resource can occur; climate change may reduce recharge in some areas

2.1 How Groundwater Works

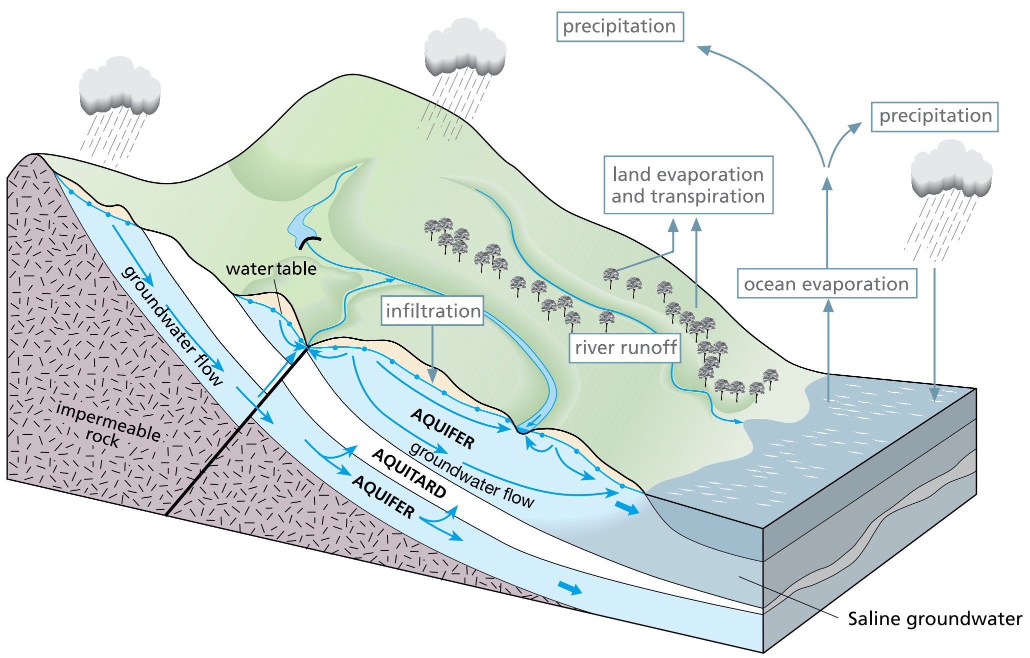
2.1.1 Groundwater systems

Understanding how to identify and diagnose groundwater problems requires a basic understanding of the Earth's natural hydrological cycle, of which groundwater is an integral, but often neglected, part (see Figure 2.1). The cycle, driven by the energy of the sun, takes water from the land and the oceans and transfers it through the atmosphere back to the oceans through various routes. When rain falls onto the land surface, some of it infiltrates into the soil with the remainder evaporating or running off into rivers. Most water stored as soil moisture is either taken up by plant roots and moved up through their leaves where it transpires back into the atmosphere, or it flows quickly (a few days to years) into a river.

> "GROUNDWATER HAS A VITAL ROLE IN SUSTAINING AQUATIC ECOSYSTEMS."

However, some of the water infiltrates the soil more deeply, eventually accumulating above an impermeable layer, saturating any available porous space in rocks and forming an underground aquifer. An *aquifer* is a saturated underground layer of water-bearing permeable rock or unconsolidated materials (gravel, sand, or silt). The groundwater flows slowly (years, decades, even millennia) by gravity through pores and fractures in the rock to eventually discharge into springs, rivers, lakes, or the sea. Figure 2.1 shows a shallow aquifer above a semi-permeable layer (an aquitard) and a deeper aquifer between the aquitard and a layer of impermeable rock.

Figure 2.1 Groundwater's place in the wider hydrological system[14]

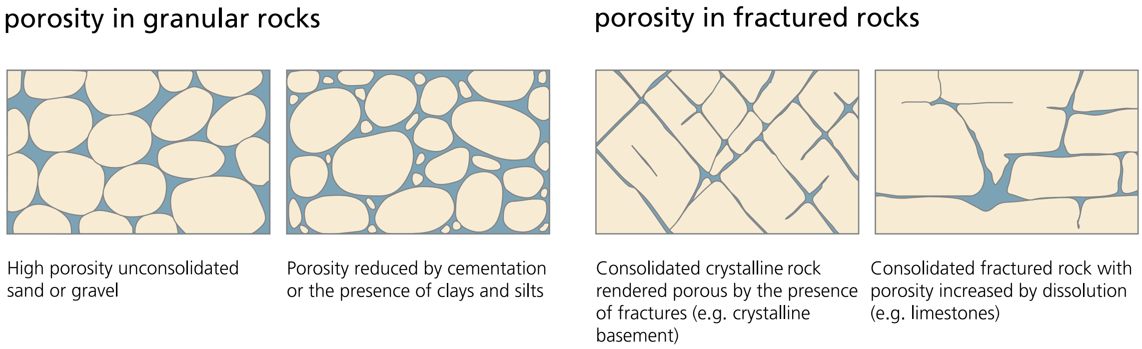


Groundwater has a vital role in sustaining aquatic ecosystems. It provides a reliable year-round discharge to streams, rivers, and wetlands sustaining flows through dry seasons and droughts. In some lowland catchments, groundwater can account for more than 90% of river flow during dry periods. Even in upland catchments, where groundwater storage is limited, 30% of the river flow may have passed through rocks as groundwater.

2.1.2 Aquifers and groundwater storage

Although some groundwater can occur in underground lakes in caves or major cavities, the vast majority is stored within pore spaces and fractures in rocks. The rock characteristics (see Figure 2.2) determine the storage capacity and productivity of an aquifer. Rocks with many voids that can hold water are said to be *porous* and if the pores and fractures are joined so water can flow easily, the rocks are said to be *permeable*. Unconsolidated granular sediments, such as sands or gravels are highly porous and the water content in these aquifers can exceed 30% of their volume. Porosity progressively reduces both with the proportion of finer materials (such as silt or clay) and with consolidation of sediments into solid rock under pressure. In highly consolidated sedimentary rocks, the porosity may be less than 10%. The least permeable sedimentary rocks are clays, which generally do not allow groundwater to move through them, and therefore act as barriers to groundwater movement. Some sedimentary rocks (such as limestones) are soluble. In soluble rocks, fractures may become enlarged as the groundwater slowly dissolves the rock to form fissures and caverns, where groundwater can flow rapidly in discrete 'underground rivers'.

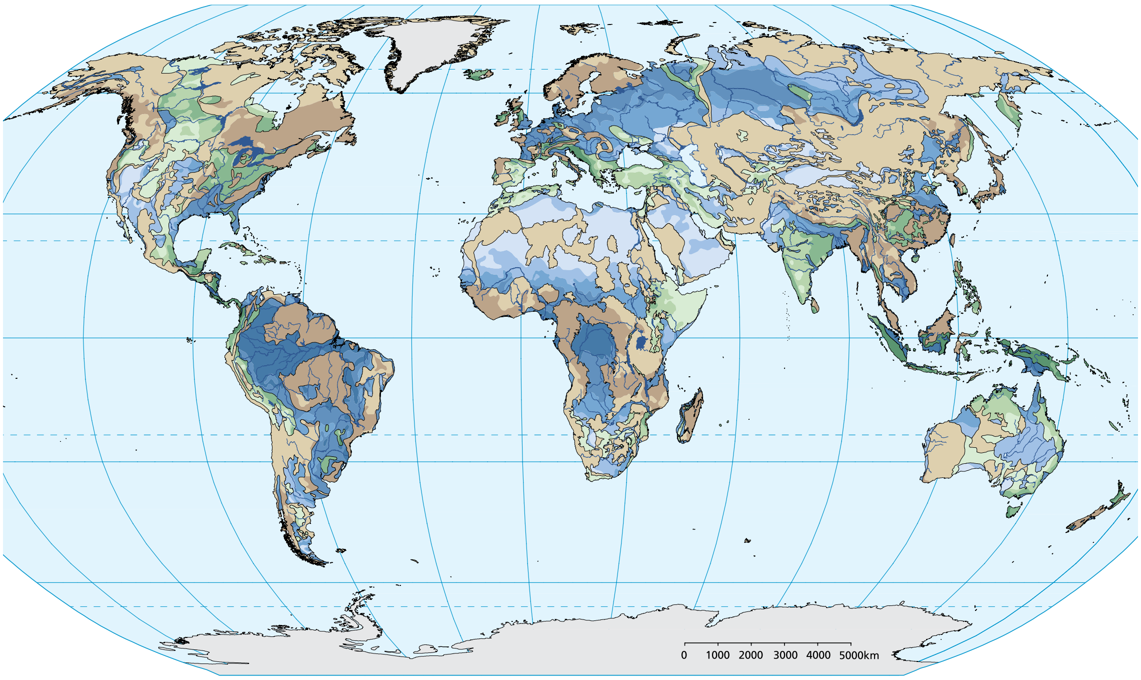
Figure 2.2 Rock texture and porosity for typical aquifers[15]



In crystalline rocks, such as igneous and metamorphic rocks, groundwater is found only in fractures and rarely exceeds 1% of the volume of the rock mass. These rocks are common; for example, they cover approximately 34% of the land area of Africa. Fortunately, these rocks are often weathered to a depth of 20 meters or more to form a deep soil with groundwater stored in the resulting sands, gravels, and decomposed rock. In unweathered crystalline rocks, groundwater will be found only in areas that are fractured.

The deeper they are in the Earth, the more compression rocks undergo from the weight of the rocks and soil above them and the more their pores and fractures close up. It is not known how deep usable groundwater can be found, but it is thought that about 1 km is the usual limit. For most uses, only shallow groundwater is exploited, but increasingly there are examples of its extraction for high-value uses to depths of 150-500 m. A global map of the major aquifer types is shown in Figure 2.3.

Figure 2.3 Map of groundwater resources of the world showing major groundwater basins (blue), areas with complex hydrogeological structures (green) and local and shallow aquifers (brown)[16]



"RECHARGE WATER TYPICALLY TRAVELS VERTICALLY DOWNWARD THROUGH THE UNSATURATED ZONE TO THE WATER TABLE"

2.1.3 Recharge and renewability

Groundwater is normally recharged by precipitation (i.e. rainfall and snow-melt), but in some topographic settings it can also be recharged by seepage from rivers, lakes, or canals. In arid climates, recharge from precipitation becomes less significant than seepage from riverbeds and ephemeral streams. The recharge water typically travels vertically downward through the unsaturated zone to the water table, the level at which the groundwater pressure head is equal to atmospheric pressure. Once below the water table, groundwater flow is predominantly horizontal, according to pressure gradients, and eventually reaches depressions in the land surface (see Figure 2.4), where it discharges, usually into a stream, spring, or wetland. In effect, the aquifer becomes saturated to a level at which the outflow matches the recharge.

Figure 2.4a shows groundwater recharge, flow, and residence times for a typical sedimentary aquifer in a region with a humid-temperate climate, where rainfall above 700 mm ensures significant annual recharge. The groundwater has a relatively rapid shallow circulation and discharges into rivers as well as into a deeper level of groundwater, which is under pressure. This lower portion of the aquifer system is geologically confined and isolated from the surface, and contains much older, essentially non-renewable, groundwater.

Figure 2.4 Groundwater flow regimes in present-day (a) humid and (b) arid regions[17]

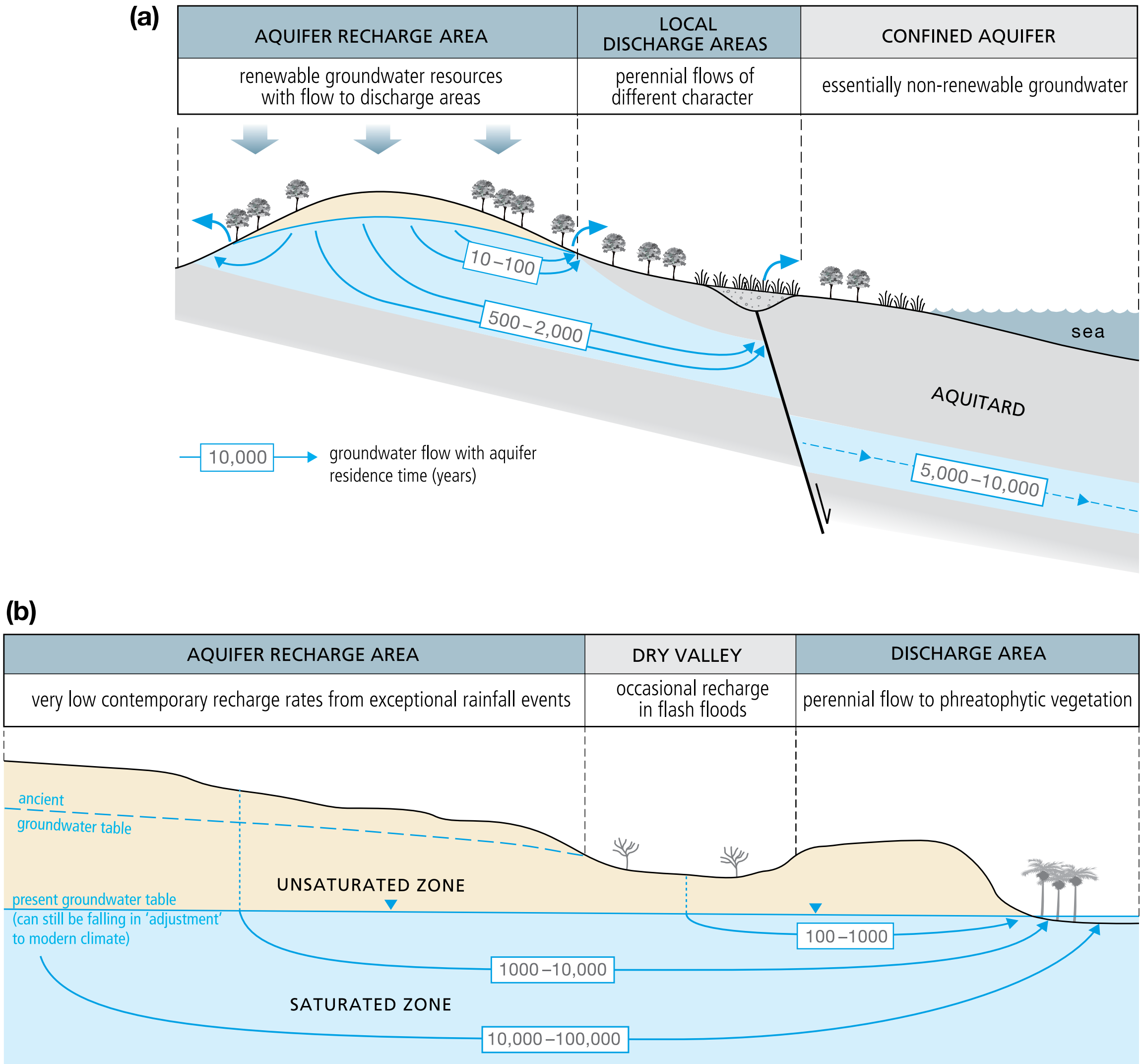


Figure 2.4b shows the corresponding situation in a region with a hyper-arid climate (rainfall below 200 mm per year). Most groundwater (except a very small local component originating in a dry valley) is extremely old (having infiltrated in past episodes of much wetter climate), but is still slowly flowing to an oasis discharge area. Note that the groundwater has been lowered from the ancient groundwater level to the present level by natural discharge of groundwater, which is not now replaced by rainfall. Note that at the higher ancient groundwater level, the dry valley was an oasis.

The proportion of rainfall that becomes groundwater recharge is determined by the soil characteristics and vegetation. Where the soil is poorly permeable or the vegetation requires much water, groundwater recharge is limited. The intensity of the rainfall can also have an effect. Recent evidence indicates that infrequent but large, high-intensity rainfall events are important for recharging aquifers, particularly in semi-arid areas.

In some cases the relationship between groundwater and surface water bodies can change. Historically, Las Tablas de Daimiel wetlands in central Spain were supplied with water by upwelling from the underlying aquifer. Following major groundwater pumping to support irrigated agriculture, the water table fell and water reaching the wetlands from rainfall and river flow percolated downwards to the aquifer, thus altering the interaction from one of groundwater discharge to groundwater recharge.

"AS WATER IS ABSTRACTED, USUALLY BY PUMPING, GROUNDWATER LEVELS FALL."

As noted earlier, most groundwater is actively recharged, thus it is a renewable resource. The manager's task is to figure out a way to 'harvest' it sustainably. However, some aquifers have little or no recharge. Their current groundwater is from rainfall from a wetter period – maybe 5,000 or 10,000 years ago (see Figure 2.4). Such groundwater – sometimes called 'fossil groundwater' – is not renewable under current conditions. Major areas of he world with essentially non-renewable groundwater include much of northern Saharan Africa, the Middle East and Central Asia. In the Sahara desert, for example, deep groundwater was formed when rainfall was higher during high-latitude glaciations.

As water is abstracted, usually by pumping, groundwater levels fall, making room in the aquifer for recharge. If abstraction is less than recharge, natural discharge to springs and rivers will achieve a new equilibrium. The time taken for this transition depends on a number of factors and may be

Photo 2.1 Groundwater, seen down a well.

decades or hundreds of years. If abstraction is greater than recharge, water levels will continue to decline as the volume of stored groundwater is diminished. Thus a good knowledge of the aquifer recharge rate, water level variations, and abstraction regime is fundamental to any management of groundwater resources.

Groundwater in aquifers can be under pressure. When a well is drilled in an aquifer under pressure, water will rise above the top of the aquifer and sometime even above the ground surface, so that no pumping is needed (these are called artesian wells). Pressurised water is usually found in aquifers *confined* between semi-permeable or impermeable layers. Shallow aquifers in recharge areas are generally *unconfined*, and the groundwater is at atmospheric pressure. An unconfined aquifer recharges more quickly. A confined aquifer has a longer recharge time. It may be less prone to pollution, but if polluted, especially with long-lived contaminants, it may not be able to recover in the foreseeable future.

2.1.4 Groundwater, rivers, and ecosystems

Groundwater is intimately linked to rivers, wetlands, and lakes and helps sustain many important aquatic ecosystems. In humid areas, groundwater generally discharges to rivers, sustaining their baseflow and aquatic ecosystems (see Figure 2.6). In more arid areas, the relationship is more complex and rivers often lose their water to the groundwater system. This loss can occur in many ways, for example: seepage through the base of large perennial rivers, the periodic infiltration of water from ephemeral rivers or wadis, or flood events recharging floodplain aquifers.

"GROUNDWATER-FED AQUATIC ECOSYSTEMS CAN BE GOOD INDICATORS OF THE HEALTH OF AN AQUIFER."

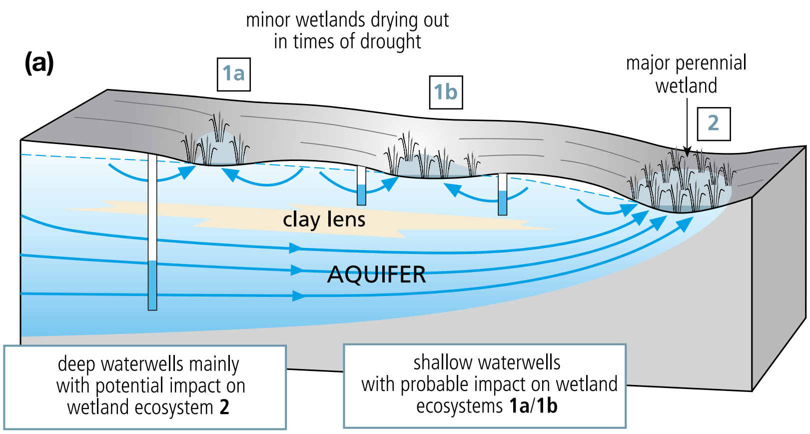
Groundwater-fed ecosystems tend to exhibit slow changes in flow or water level, called the hydroperiod, giving rise to specific plants and animals that thrive in stable water regimes, such as in chalk rivers or fens. In these ecosystems, groundwater tends to be at constant temperature (e.g. 10-11°C), usually warmer than surface fed rivers in winter and cooler in summer. Thus, lowland groundwater-fed rivers can support fish, such as salmon, normally found in cooler mountain rivers. Differences in groundwater chemistry, such as high pH in chalk rivers, also support unique flora and fauna. Groundwater-fed aquatic ecosystems can also be good indicators of the health of the aquifer in terms of both water quantity and quality. In particular circumstances, groundwater supports unique or endemic species such as stygobites (e.g. *Niphargus glenniei* - small shrimp-like crustaceans) and Blind Cave Fish (*Astyanax mexicanus*) in Mexico. In desert environments, groundwater may be the only source of water and groundwater-fed oases often include highly productive aquatic ecosystems that provide crucial natural resources and ecosystem services for people, such as fish and grazing lands, within surrounding arid environments. Evaporation is often very high from these areas, but the overall volume of water tends to be low because of their small spatial extent.

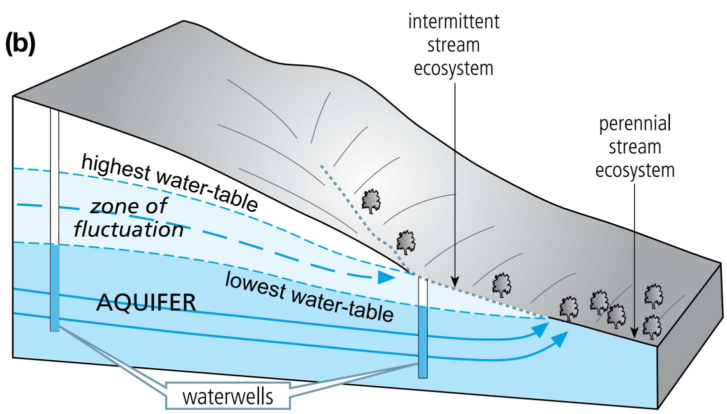
Wetland ecosystems can depend on groundwater that flows from different depths, and thus the depth of a well from which water is pumped can determine the impact on a wetland. Figure 2.5a shows how shallow wells might pump water away from minor wetlands in surface depressions, whereas over-abstraction from a deep well, even far from a major perennial wetland, could seriously affect the water levels in that wetland. Figure 2.5b shows how pumping from deep wells, again far from the ecosystem, can cause a fluctuation in the water table that causes part of the stream to dry up periodically.

Irrigation can enhance groundwater and surface water interaction: surplus water from irrigated fields leaches into the groundwater; leaky canals or pipes can also recharge aquifers. This leakage is not always beneficial to groundwater as it can lead to an increase in groundwater salinity, which, if not diagnosed and controlled, will result in a serious decline in agricultural productivity. There are several distinct mechanisms by which irrigation water can affect groundwater: (1) canal seepage can cause the water table to rise (this can also occur from rivers); (2) irrigation water can leach through the soil picking up salts, which increases the salinity of groundwater; and (3) over-abstraction can lower the water table and allow saline water from an estuary or ocean to flow 'backwards' into the aquifer.

Figure 2.5 Ecosystem dependence on groundwater for (a) wetlands associated with a multi-layered aquifer in a humid area and (b) a stream in an arid area.[18]

In (a) the potential impact of waterwell abstraction depends on the depth and level of water intake. In (b), with the upper stream fed in part by intermittent groundwater flow and the lower stream by perennial discharge, the impact of waterwell abstraction will depend on distance from the stream, period of pumping and aquifer characteristics.

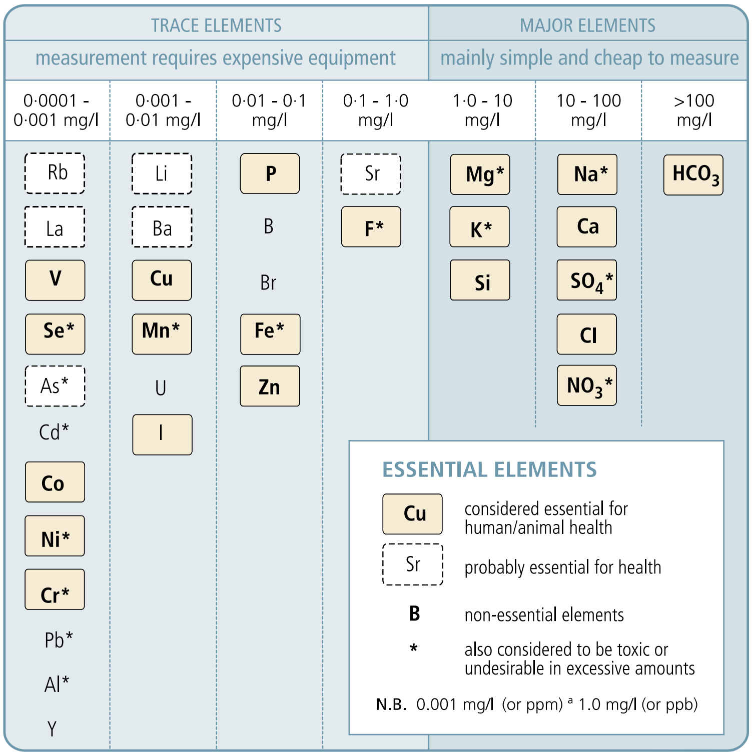




2.1.5 Groundwater chemistry

Most groundwater has excellent natural microbiological quality and adequate chemical quality for most uses. Indeed many people buy (at great expense) bottled water from natural groundwater sources in preference to public supplies, which may be treated river water. Nine major chemicals (sodium, calcium, magnesium, potassium, bicarbonate, chloride, sulphate, nitrate, and silicon) make up 99% of the solute content of natural groundwater. The proportion of these chemical constituents in the groundwater reflects the geology and history of the groundwater flow. Minor and trace constituents make up the remaining 1%, and their presence (or absence) locally can give rise to serious health problems or make the water unacceptable for human or animal use (Figure 2.6).

Figure 2.6 Chemical constituents naturally found in groundwater[19]



"PROBLEMS OCCUR WHERE RECHARGE WATER CARRIES CHEMICAL POLLUTANTS."

Groundwater can become contaminated if protective measures at wells, boreholes, or springs are not soundly constructed and maintained. Further problems occur where recharge water carries chemical pollutants from agriculture, waste disposal, or industry. Thus, it is essential to assess these risks and also test groundwater supplies used for drinking to make sure they meet health standards. It is also essential for water managers to appreciate that groundwater quality in an aquifer is not uniform, and important variations in both natural quality and levels of contamination occur vertically as well as horizontally (see Figure 2.7).

Two natural constituents — arsenic and fluoride — are of particular concern to health. One of the most dramatic demonstrations of this is the arsenic crisis in South Asia (notably Bangladesh, India-Bengal and the Nepal terai), where shallow boreholes constructed to supply safe drinking water often provided water with naturally high arsenic concentrations (see Figure 2.7). Arsenic is a poison that can cause skin cancers and gangrene among other ailments. Natural fluoride in groundwater is of growing concern with more than 200 million people at risk of drinking water with elevated concentrations. High exposure to fluoride can lead to severe dental problems, and even higher concentrations can cause skeletal fluorosis, which limits mobility and can be crippling.

Figure 2.7 Stratification of groundwater and arsenic (As) contamination in the alluvial flood plains of Ganges-Brahmaputra delta in Bangladesh and terai of Nepal[20]

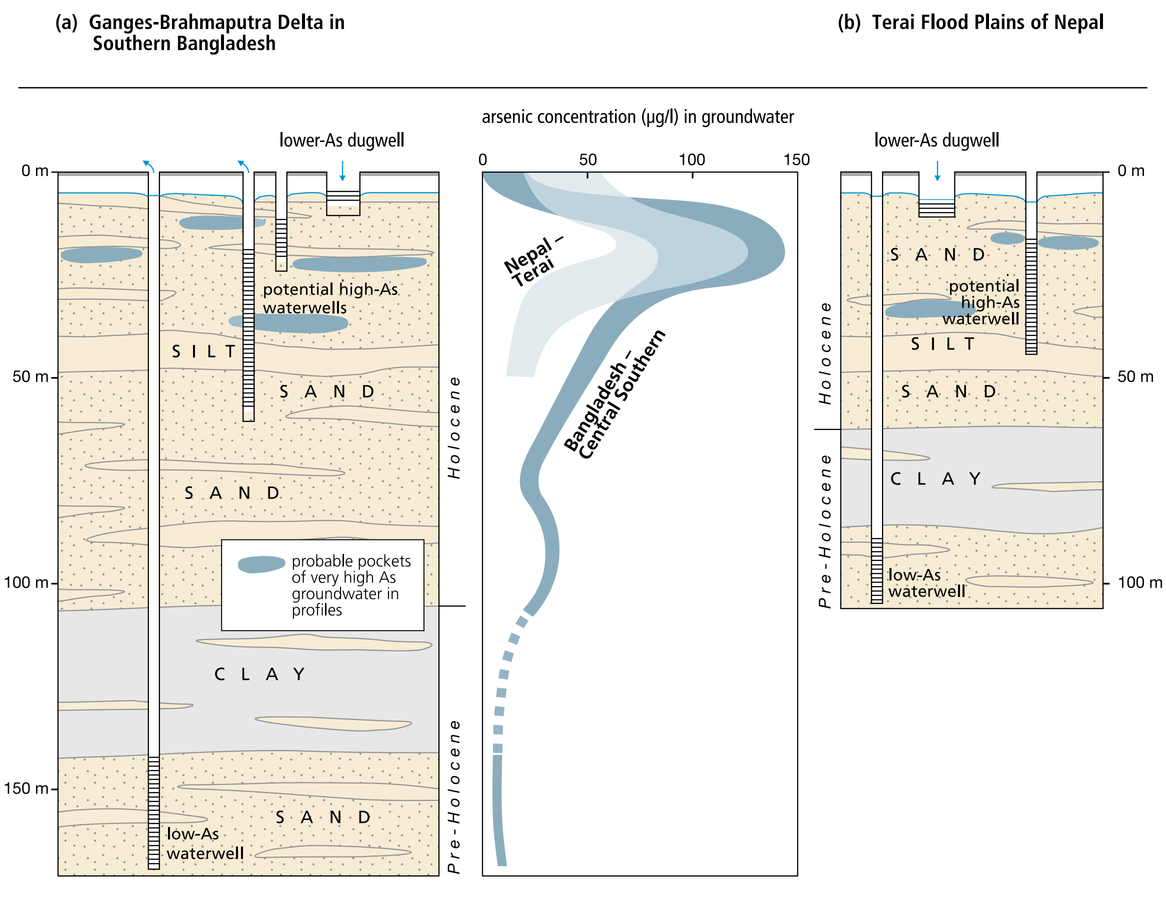


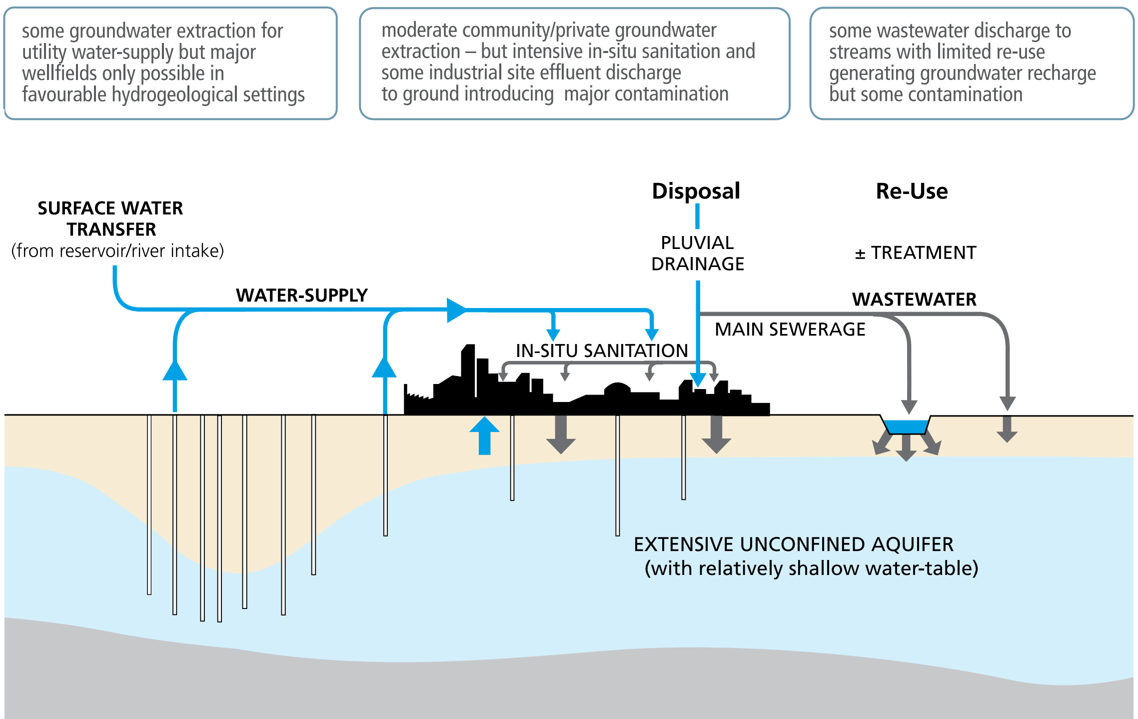
Figure 2.7 shows high concentrations of soluble arsenic occurring at a depth of 5 to 30-40 meters below ground level as a result of natural variations in the hydrochemistry in the aquifer. Drilling deeper wells bypasses the pockets of arsenic-laden water and provides safe drinking water (at greater expense). However, over time, arsenic contaminated water may be drawn down to the deeper layers by pumping.

2.2 Threats to Groundwater: Overuse and Pollution

2.2.1 Drivers of groundwater degradation

The two major threats to groundwater are overuse and pollution. Urbanisation, industrialisation and intensification of farming practices have led to an escalating demand for groundwater as a reliable source of water supply. This situation has been complicated by rapid population growth and climate-change pressures. These practices can also produce a high contaminant load, which is often released into the natural environment and ultimately contaminates groundwater. The scale of perturbation to the natural groundwater system under a large urban area is illustrated in Figure 2.8. Different groundwater systems react differently to these threats. Managers need to know not only the threats, but the susceptibility and vulnerability of the groundwater system in question. Figure 2.9 shows a city in which some groundwater is used in conjunction with surface water for the water supply. Discharge of some wastewater and industrial chemicals cause contamination of both groundwater and streams. Intensive on-site sanitation, with waste discharged to ground can cause major groundwater contamination.

Figure 2.8 The close relationship between groundwater and urbanisation[21]



2.2.2 Impacts of overuse

Intensive abstraction can deplete the groundwater in an aquifer. A lower water level increases pumping costs at the very least, and can cause serious damage by allowing intrusion of saline water into the freshwater system or even land subsidence if the tiny voids previously filled with groundwater are compressed and cave in. These effects can take several decades to manifest themselves and can be irreversible. Falling water tables can reduce the yield of shallow wells, or even cause them to fail, if the groundwater level falls below the bottom of the well. In some susceptible systems, even a small drop in the groundwater level can have a major impact on the flow of springs or the health of wetlands, as the natural discharge of groundwater reduces to accommodate the abstraction.

"INTENSIVE ABSTRACTION CAN DEPLETE THE GROUNDWATER IN AN AQUIFER."

These effects sometimes happen in a limited area (for example around a well) even when overall abstraction is less than overall recharge, because as groundwater flows toward the depression caused by abstraction the hydraulic gradient in the surrounding aquifer is changed. If surrounding (including overlying and underlying) aquifers contain saline or brackish water, this water can flow into the depression, degrading the fresh groundwater. Saline intrusion is most common in coastal aquifers, where salty water from the sea flows inland in response to pumping (Case 2.1). Saline waters can also be found deep in some aquifers, or in arid areas with shallow water tables as a result of direct evaporation.

Case 2.1 Sea water invades Cyprus aquifer[22]

The development of the coastal limestone of south-eastern Cyprus is typical of many islands and coastal areas with highly permeable aquifers. The groundwater table was naturally higher than sea level. However, uncontrolled pumping for irrigation plus the construction of dams that reduced recharge led to a major reduction in the level of the water table. Between 1960 and 1980, water levels in wells had widely fallen to more than 25 m below sea level. Saline water near the sea flowed 'backwards' into the depression leading to major landward intrusion of sea water into the aquifer for several kilometres from the shoreline.

The long-lasting effects can be observed today by many abandoned wind pumps and uncultivated fields close to the shore. One report estimated that it would take 12 years of no pumping to restore the groundwater to its previous levels and then longer to rid the groundwater of nitrate pollution caused by irrigation, which makes most of the groundwater unfit for drinking. Decreased rainfall has caused a reduction in the flow of rivers and aquifer recharge, which combined with over-pumping, has negatively impacted groundwater resources, stretching sustainable extraction levels to the limit.

The country has developed a participatory action plan for river basin management focused on a drastic reduction of pumping to sustainable levels and increasing the recharge with natural and artificial methods, but it will take decades of discipline to restore the resource.

"HOW RAPIDLY A GROUNDWATER SYSTEM WILL DEPLETE DEPENDS ON ITS HYDROGEOLOGY."

Groundwater abstraction reduces the pressure in the aquifer's pore spaces. If the rock is compressible, it can collapse and its ability to hold water, even after recharge, can be permanently reduced. If thick clay layers are present, either as interlayers or as overlying beds, compression can be significant and lead to land subsidence, which, in heavily developed urban or coastal areas, can have severe impacts on infrastructure.

2.2.3 Susceptibility to side-effects of overuse

How rapidly a groundwater system will deplete or how susceptible it is to secondary degradation, such as saline intrusion or land subsidence, depends on its hydrogeology. Table 2.2 details the impacts of excessive abstraction and which hydrogeological factors determine the susceptibility of different aquifers to experiencing these effects.

If symptoms, such as a decline in water quality and well yields, or a deterioration in a dependent ecosystem, have started to appear (see Table 2.2), the hydrogeology must be quickly assessed to predict future deterioration and assess which management options will be most effective. The more quickly a diagnosis can be made, the better. Routine monitoring of water quality, water levels, and ecosystem health are important for early detection of problems.

Table 2.2 Hydrogeological factors affecting the susceptibility of an aquifer to overexploitation

Symptoms of Excessive Abstraction	Hydrogeological Factors Affecting Susceptibility of the System to Excessive Abstraction
• Falling water levels: increased pumping costs; declining borehole yields; drying up of shallow wells; reduction in spring and baseflow	• Aquifer properties: transmissivity and storage coefficient • Annual recharge • Aquifer volume
• Vegetation stress: as groundwater levels fall, some dependant vegetation will become stressed, appearing to wilt or die; wetlands may also begin to dry out leading to significant stresses on the dependant ecosystem	• As above, plus the depth of the groundwater
• Saline water: falling water levels can cause poor quality water to flow into the aquifer – often from the sea, but also from other sources – with symptoms such as change in taste, reduction in crop yields, and increased corrosion, easily measured as change in salt content or electrical conductivity of pumped water	• Proximity of saline or polluted water • Presence of physical and hydraulic barriers
• Loss of aquifer capacity: overuse can cause loss of pressure and compaction of the porous rocks, thus reducing their capacity to hold water, which can lead to reduced well yields	• Aquifer compressibility
• Land subsidence: as groundwater levels fall, some aquifers compress significantly causing land subsidence with corresponding damage to infrastructure	• Aquifer compressibility • Compressibility of overlying and interbedded aquitards • Thickness of aquitards

2.2.4 Pollution processes

Urbanisation, industrialisation, and agricultural intensification can lead to serious groundwater pollution. Some major sources of groundwater pollution are shown in Figure 2.9. Agricultural pollution tends to be widespread across areas with intensive agriculture. It can produce elevated nitrate concentrations from fertilisers and animal waste as well as more exotic compounds from pesticides. Industries can give rise to different pollutants including many different kinds of hydrocarbons and heavy metals. Mining can lead to severe water pollution with elevated concentrations of iron and other metals, acidic water, and a high level of sulphates. Human wastewater can also be a major source of pollution, especially through seepage from on-site sanitation such as latrines and septic tanks, or where sewers exist, through application of the collected wastewater directly to irrigation of crops, which can result in elevated nitrate, chloride, and organic carbon concentration and, in some cases, to faecal contamination of groundwater and even the crops.

"POLLUTION OF GROUNDWATER MAY NOT BE DETECTABLE UNTIL YEARS AFTER THE APPLICATION OF FERTILISERS."

Conceptually, groundwater is at risk of pollution if the natural capacity of the soil, unsaturated zone, or confining layers of an aquifer are not sufficient to contain and attenuate the contaminant load or the pressure applied. Because the movement of water in the ground is often very slow, pollution of groundwater may not be detectable until years after the application of fertilisers or disposal of effluent and it may last well beyond any cessation of the pollution.

Figure 2.9 The range of activities that can generate a subsurface contaminant load and pollution of the underlying aquifer. The blue line represents the water table and the dark grey shading below ground shows the type of groundwater pollution plume that can result in a granular aquifer system.[23]

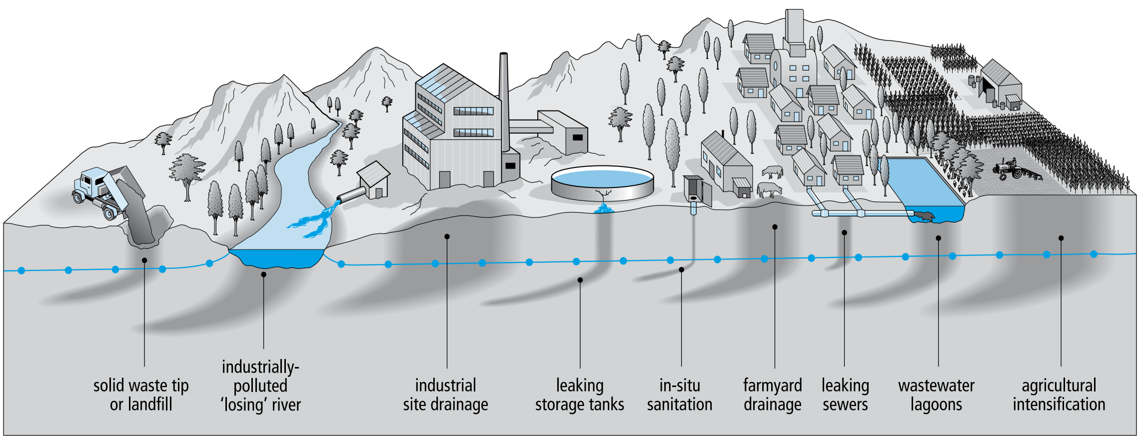


Figure 2.9 shows the range of activities that can pollute groundwater in a shallow aquifer. The figure illustrates the type of groundwater pollution plume that can result in a granular aquifer. If these activities are contemplated, or already exist, in areas with vulnerable aquifer types (see next section), or if the groundwater extracted is used for potable water-supplies, selected pollution control measures should be identified and implemented.

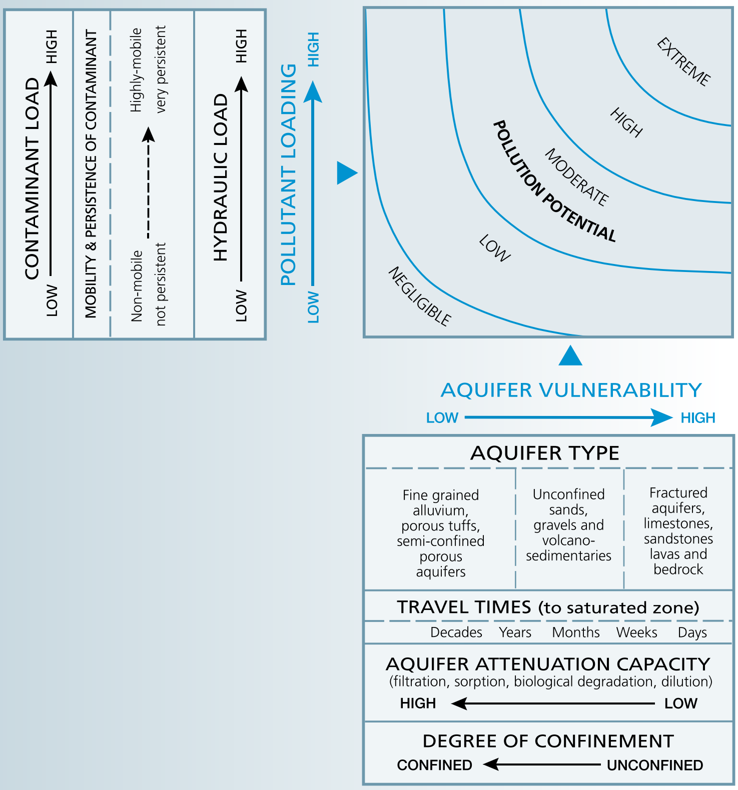
Box 2.1 Determining the vulnerability of an aquifer to pollution

How seriously groundwater is polluted depends on two things: the nature of the pollution and the nature of the aquifer. Figure 2.10 shows how one might consider each on a scale of low to high. The chart "pollution loading" considers three characteristics of pollutants (a) the amount of pollution (level of contaminant load), (b) the mobility and persistence of the pollutant, and (c) the hydraulic load. In general a contaminant load that is at a high level, mobile, persistent, and flushed into the ground is more serious than pollutants that are at a low level, not easily mobilised, not persistent and not driven by a strong hydraulic gradient.

Mobility is governed by geochemical reactions; the prevailing groundwater environment influences which pollutants are mobilised. Mobile contaminants are generally those that are readily soluble in water, such as nitrate, solvents and some light oils. The mobility of metals (e.g. lead, chromium) depends on the pH and redox state of groundwater. Heavy oils are generally not very mobile, and pesticides can be difficult to predict with some types more mobile than others.

Four characteristics impact an aquifer's vulnerability to pollution (Figure 2.10): (a) type of soil and rock, (b) travel time of water through the aquifer, (c) the aquifer's ability to adsorb pollutants, and (d) its degree of confinement. In general, the most vulnerable aquifers are fractured bedrock, with a short travel time (days), show a low ability to filter out pollutants, and are unconfined by semipermeable layers. Aquifers are better able to deal with pollutants if they are made of fine grained materials, have travel times measured in decades, have a high filtration capacity, and are confined by semipermeable layers or aquitards.

Figure 2.10 Influence of pollutant loading and aquifer vulnerability on potential for pollution of groundwater[24]



2.2.5 Vulnerability to pollution

Some groundwater systems are intrinsically more vulnerable to pollution than others. Shallow unconfined aquifers are more at risk of pollution because there are fewer layers to filter out contaminants. For deeper aquifers, the natural subsoil profiles afford protection, and can actively attenuate many water pollutants through biochemical degradation and chemical reactions, as well as retard contaminants that can adhere to the surfaces of clay minerals and/or organic matter (see Box 2.1).

The properties of the strata separating a saturated aquifer from the land surface generally determine the sensitivity of the aquifer to pollution from the land surface. For land management purposes, an intrinsic vulnerability of different aquifer types can be defined and matched with land uses (see Section 2.4.2, below). Some hydrogeologists advocate the use of 'specific vulnerability maps' for individual contaminants (such as nitrates or a pesticides group), but there are rarely adequate data or sufficient human resources to adopt this approach on a routine basis.

2.3 Information Needs for Improving Groundwater Management

Getting good information on groundwater resources is vital for improving groundwater management. This requires using appropriate scientific tools to diagnose and monitor the status of the aquifer system. The best methods for characterizing groundwater systems are described below, followed by an introduction to some technical tools for management, such as groundwater modelling to foresee potential problems, land zoning to help limit pollution, and a range of engineering solutions to mitigate damage that has already occurred.

2.3.1 Groundwater balance

The *water balance* is estimated by comparing the recharge into the aquifer with the natural discharge and abstraction. Unfortunately, this is not a straightforward process, as there can be many discharges and abstraction points, and recharge cannot be directly measured. As a short cut, it is worth trying to put together a history of groundwater level variations, ideally from data obtained by monitoring boreholes over time, which can indicate if groundwater is being steadily depleted over the long term. If historical data are not available, some general information on the state of groundwater resources can be gained from discussions with a variety of groundwater users about their recollections of past situations. Only with some history can a picture be developed of how the system responds to different events over time.

The methods required to develop and test the groundwater balance in an aquifer are shown in Table 2.3. One of the most important steps is to make an inventory of all groundwater abstractions. Without this information, it will be difficult to define and implement effective groundwater management measures. Measuring recharge, the input side of the equation, is complex and data intensive. Recharge can come from diffuse infiltration of excess water through the soil, or in episodic events such as high-intensity rainfall, and can also result from human activities such as excess agricultural irrigation or seepage from water infrastructure in urban areas.

One of the best methods of testing the water balance of an aquifer is to construct a numerical groundwater model (see Section 2.3.3). Creating this model involves applying the recharge and pumped discharge to the *aquifer geometry* with known aquifer properties, and then comparing model-predicted and field-measured groundwater levels and natural discharges. Numerical models are an excellent tool for understanding and prioritising what additional information needs to be collected.

Table 2.3 Methods for assessing groundwater conditions

Purpose	Method	Requirements
• Estimate discharge	• Inventory of boreholes/wells/springs • River gauging	• Locate every major abstraction and gain current abstraction details and pumping patterns. Search for historical information • Analyse existing stream gauge data to assess groundwater baseflow. If none exists, use ungauged catchments methods and consider installing monitoring
• Estimate recharge	• Soil moisture balance, or threshold methods for more arid areas • Chloride balance method • Residence time indicators	• Daily rainfall, evapotranspiration and soil and vegetation information • Measure chloride in uncontaminated groundwater and compare with rainfall (particularly effective in arid areas) • Stable isotopes or dissolved gases used to indicate the residence time of groundwater
• Assess water levels	• Measure groundwater levels in unpumped wells	• Monitoring of water levels in the aquifer, not in individual pumped boreholes
• Test water balance	• Analytical equations • Groundwater model	• Water balance assessed simply by balancing discharge, recharge and changes in storage • Much more robust assessment of aquifer understanding and water balance, but time, and data intensive
• Assess water quality	• Water quality survey	• Survey of the groundwater quality from boreholes, wells and springs, with rigorous sampling and analysis to distinguish pollution or saline intrusion from natural geochemical changes

2.3.2 Groundwater quality

Characterising groundwater quality is more straightforward than estimating the water balance, but requires detailed and systematic sampling. A survey of pumping boreholes, shallow wells, and springs can be carried out relatively quickly, but must be undertaken in a systematic manner and the samples analysed by a reputable laboratory. Monitoring data can be interpreted to distinguish contamination or saline intrusion from the natural geochemical evolution of the groundwater. Historical information on groundwater chemistry is invaluable to determine how quality has evolved or pollution advanced. The World Health Organisation publishes *Guidelines for Drinking-Water-Quality.*[25] Certain contaminants can be compared against these guidelines or the baseline conditions expected in a natural system.

Case 2.2 Arsenic in groundwater in Bangladesh[26]

A detailed and systematic survey of groundwater quality in Bangladesh carried out by the British Geological Survey and the Bangladesh Government shed light on the nature, scale and causes of arsenic contamination in drinking water.

The study mapped the distribution of arsenic in groundwater on a national scale and showed that problems with arsenic contamination lay in groundwater from a young, shallow (Holocene age) aquifer. Of the groundwater samples tested from this aquifer, around a quarter had arsenic concentrations above the national standard for arsenic of 50 µg/L and almost half exceeded the WHO guideline value of 10 µg/L. A deeper (Pleistocene age) aquifer beneath contained groundwater with concentrations almost invariably below the WHO guideline value (Figure 2.7). The study showed that the source of the arsenic was likely to be naturally-occurring iron oxides residing in the Holocene aquifer and concluded that the arsenic release would have been taking place over thousands of years. The mapping indicated that up to 35 million people in Bangladesh could be drinking water with arsenic concentrations exceeding the national standard and up to 57 million people drinking water exceeding the WHO guideline value.

The national arsenic map identified priority areas for mitigation, patient identification and treatment, awareness campaigns and further testing. The findings also provided a framework for defining national policy on water supply and have provided background data and information for many scientific groups working subsequently on the arsenic problem in the Bengal Basin and elsewhere.

2.3.3 Determining aquifer characteristics: data, mapping and modelling

Moving from diagnosing groundwater problems to managing them requires an understanding of the nature of the aquifers. The first requirement is to know where the aquifers are. Next, the characteristics of their soils, sediments, and rocks need to be assessed to give information on the aquifer's capacity and vulnerability. Table 2.4 lists methods used to determine the nature of an aquifer.

Although aquifers may initially be envisioned on a flat map, they must ultimately be understood in three dimensions and over time as a functioning system. With sufficient information, a numerical groundwater model can be constructed, which can be a useful step in both identifying the knowledge gaps of a groundwater system, and forecasting potential outcomes from management strategies.

Geological maps are the basis of any hydrogeological understanding of an area. Most countries will at least have a national geological map at some scale. However maps are not always available at the more useful scale of less than 1:250,000. Fortunately new geological mapping techniques using a combination of satellite information and targeted field studies are making geological mapping more rapid and less expensive. With the addition of information about the aquifer properties of the different rock types, the groundwater levels, and sometimes groundwater chemistry, these maps can be transformed into hydrogeological maps. They can be printed or developed in a digital geographic information system (GIS). Ultimately, their utility depends on the reliability of the data.

"DIAGNOSING GROUNDWATER PROBLEMS REQUIRES AN UNDERSTANDING OF THE NATURE OF THE AQUIFERS."

Transforming a two-dimensional map into three dimensions requires information on the thickness of the geological strata. Data from deep boreholes drilled through the aquifers can reveal information on the rock variations. Where the aquifers are very deep, other methods, such as geophysics, can be used.

Table 2.4 Methods for characterising aquifers[27]

Purpose	Method	Requirements
• Locate aquifers	• Hydrogeological mapping	• Good geological information and maps. Information on the hydrogeological properties of various rock formations. Information on the aquifers, boreholes and water-levels
• Understand aquifers in 3-dimensions	• Interpret existing borehole information • Geophysical surveys • Drill exploration boreholes • Geophysical logging	• Detailed interpretation of drilling logs from borehole records if they exist • Geophysical surveys to provide information on aquifer thickness and structure • Purpose-drilled exploration boreholes If there is insufficient information on the aquifer • Downhole geophysical logging to help characterise aquifer structure and identify the main flow horizons.
• Quantify aquifer properties	• Review available pumping test data • Detailed pumping tests in boreholes across the aquifer • Laboratory tests to measure porosity and permeability	• Collate existing information from disparate institutions • Pumping at a controlled rate for a period of several days to several weeks, and monitoring the response in other boreholes • Analysis of core samples from boreholes for further aquifer properties

To understand how a groundwater system will respond over time to pumping or pollution, one must determine the aquifer's capacity to store water ('storage coefficient') and the rate at which the water flows through the aquifer ('transmissivity'). These terms, and two related terms for aquifer properties: 'hydraulic conductivity' and 'porosity', are defined in Box 2.2. If information is not available on these important parameters,[28] a series of investigations can be undertaken. The storage coefficient and transmissivity can be measured by carrying out controlled pumping tests at boreholes and measuring the response of the water table. These aquifer properties can vary by many orders of magnitude across the same rock type, therefore tests at a sufficient number of boreholes must be carried out to provide confidence in the results. Hydraulic conductivity and porosity are generally measured by taking core samples of rocks and performing tests in the laboratory.

Specialised tools, such as geophysical tools and tracer tests, are sometimes used to help characterise aquifers. Borehole geophysics can identify how groundwater flows in the aquifer – whether through single fractures or diffusely through many pore spaces. For example, this technique was used successfully in the south of England to map seasonal variations in salinity in individual fractures in a major chalk aquifer, which led to improved management of the aquifer to control saline intrusion. In Africa, electrical currents passed through the ground are used to indicate types of rock layers that might bear water as good locations to drill boreholes (Case 2.3).

Case 2.3 Geophysical techniques used to locate groundwater in Africa[29]

Throughout Africa, where rural people usually depend on groundwater from wells, geophysical techniques are often used to locate the best sites for boreholes wherever the geology is complex, such as in crystalline basement aquifers. Two techniques that measure the electrical properties of the rocks are often used: resistivity and electromagnetic surveying. Electrical currents are passed through the ground and instruments measure how easily the ground conducts electricity. Solid rock generally does not conduct electricity, so higher measurements are usually associated with increased porosity of the rock and thus some water content. Using this technique reduces the chance of drilling a dry borehole, thus helps reduce the overall cost of a project.

Tracer tests, which involve introducing a dye into the water, are used in highly fractured aquifers and karstic limestones to trace connections between boreholes and the ground surface or rivers.[30]

Box 2.2 Four aquifer properties needed to predict groundwater behaviour

Porosity - the total void space within the rock, which therefore usually defines the total amount of groundwater stored in an aquifer.

Storage coefficient - a truer measure of the amount of groundwater available within an aquifer; it is defined as the amount of groundwater released from storage within the aquifer when the water table falls by 1 m.

Hydraulic conductivity - the velocity (measured in m/day) that groundwater would flow through rock if there were a pressure gradient of 1 m over a distance of 1 m.

Transmissivity - the ability of an aquifer to transmit volumes of groundwater (measured in m^2/day), calculated by multiplying the hydraulic conductivity by the aquifer thickness.

2.4 Technical Framework for Management

2.4.1 Groundwater monitoring

Once a database and map of the aquifers is developed, both groundwater levels and groundwater quality must be regularly monitored across the aquifer to determine trends. Are the water levels rising or falling? Are nitrate concentrations increasing dramatically? Effective groundwater monitoring should be driven by a specific objective and the data collected should be systematically stored for future use.

Acceptable levels of abstraction and of pollution in different areas should be determined at the policy level based on national or international health guidelines. Monitoring reveals how the actual situation measures up to these yardsticks. Contaminant levels can be compared to the World Health Organisation guidelines for groundwater quality.[31]

For best results in monitoring groundwater levels, boreholes should be constructed specifically for that purpose, with their locations carefully chosen to ensure they are monitoring what is specifically required for management (e.g. natural water level in the aquifer or levels affected by well-field pumping). To sample baseline water chemistry, it is best to use abstraction boreholes that are pumped regularly, and to sample a large part of the aquifer. However, for targeted pollution sampling, it is best to construct boreholes in the area of pollution. Sufficient investment should be given to continue monitoring over the long term, and to construct a robust and usable database to store and report data easily.

When a problem is found, action should be taken to correct it. For example, in Scotland, careful monitoring identified rising nitrate concentrations in several major aquifers. Although still below the WHO health guidelines, the data showed that continued agricultural practices would lead to the groundwater eventually exceeding these limits. As a precautionary measure, these areas were designated as nitrate-vulnerable zones and special measures introduced to restrict the quantity and timing of nitrogen application and the disposal of slurry.[32]

2.4.2 Land zoning for groundwater protection

Accurate maps of the location and types of aquifers can be used to create land-use zoning maps that allow only land uses compatible with the capacity of the underlying aquifer. Many countries have policies that combine land surface zoning with a code of practice that advises what activities are acceptable in the different zones. Land surface zoning usually has two elements:

- *resource protection* based on the vulnerability of a groundwater system to pollution and,
- *source protection* around individual groundwater sources, such as boreholes or springs, to especially protect them from pollution.

In zoning, the land is divided into areas ranging from extreme to negligible groundwater vulnerability to contamination. Extreme vulnerability is associated with highly-fractured aquifers with a shallow water table, and negligible vulnerability is assumed if the aquifer is separated from surface activity by impermeable layers (see Table 2.5). Vulnerability maps have proved to be a simple and effective tool in many countries easily fitting into a land-use planning system. In some countries, the maps are used to determine the level of site investigation required before development, rather than prohibiting certain land activities altogether.

Source protection zones are capture areas around an abstraction borehole, well or spring, either determined by numerical modelling or by using standard analytical shapes, which serve to avoid contamination of the water supply. For readily degradable contaminants (e.g. pathogens) a basic strategy is to reduce the risk of their entering the ground in areas where the groundwater travel times from the pollution source to abstraction sites is insufficient for them to be eliminated through filtration or adsorption. For more persistent contaminants (e.g. industrial chlorinated hydrocarbons and certain pesticides) the best strategy is to prevent their discharge into the ground.

Table 2.5 Broad classification of aquifer vulnerability

• Extreme	Vulnerable to most water pollutants with relatively rapid impact in many pollution scenarios
• High	Vulnerable to many pollutants, except those highly adsorbed and/or readily transformed, in many pollution scenarios
• Moderate	Vulnerable to some pollutants, but only when continuously discharged or leached
• Low	Only vulnerable to the most persistent pollutants in the long-term, when continuously and widely discharged or leached
• Negligible	As demand for groundwater increases overexploitation of the resource can occur; climate change may reduce recharge in some areas

2.4.3 Groundwater numerical modelling

A dynamic groundwater model for an aquifer is an excellent tool for managing abstraction, and can also be used to help assess saline intrusion and the movement of pollutants. A groundwater model is a numerical representation of an aquifer system that can be run using computer packages on a standard PC.[33] A reliable model requires a considerable amount of data: the geometry of the aquifer, the river network, location of boreholes, distributed recharge and the aquifer properties. Various computer modelling packages such as MODFLOW or ZOOM, can be used. It is useful to have a dedicated groundwater modeller carrying out the work in tandem with hydrogeologists. To help refine a model, reliable and time-variant data on groundwater levels, river flows, rainfall and recharge are necessary. However, even with limited data, a preliminary model can help confirm understanding of an aquifer behaviour, indicate the magnitude of likely responses, and determine priorities for data collection.

With a well-constructed and calibrated groundwater model, questions can be asked and future scenarios can be investigated. For example: what would be the effect of continuing abstraction at current or increased rates on the aquifer and dependant ecosystems? The model can also estimate the time needed for physical changes to be observed or for management policies to take effect. Despite the resources required to set up a groundwater model, the results can be cost effective because a model allows potential future options to be investigated without the financial, political, and economic risks of actual implementing any scheme (see Cases 2.4 and 2.5).

Case 2.4 Modelling groundwater in Death Valley[34]

The USA's the Death Valley in southern Nevada and eastern California is an area of complex hydrogeology with controversial groundwater management issues. In addition to ongoing groundwater abstraction, there is a legacy of contamination from historical underground nuclear testing, and also a reoccurring proposal to construct a repository for high-level nuclear waste at Yucca Mountain. An understanding of groundwater movement is crucial to knowing how contamination might spread.

A numerical three-dimensional (3D) transient groundwater flow model of the Death Valley region has been developed by the U.S. Geological Survey for the U.S. Department of Energy. Decades of study of the groundwater flow system, investigations of the hydraulic properties of the rocks and conceptualizations of flow were evaluated together to develop the complex, digital model.

The groundwater flow model MODFLOW-2000, a 3D finite-difference modular groundwater flow model was constructed for the region using all available geological and hydrogeological data and calibrated against water level monitoring data and spring flows for the period 1913-1998. The model represents the large and complex groundwater flow system of the Death Valley region with a greater resolution and accuracy than has been possible previously. The model is now being used to help simulate the effects of pumping on water availability, contamination migration, and water-dependent ecosystems.

Case 2.5 Groundwater modelling of the Nubian Aquifer System, eastern Sahara[35]

The Nubian Aquifer System (NAS) in the eastern Sahara is the largest groundwater system in Africa, extending over more than 2 million km^2 and providing water for much of the population in this area outside the Nile valley, for domestic, agricultural, and industrial uses. The NAS is formed by four basins (a) the Kufra Basin, of south-eastern Libya, north-eastern Chad and north-western Sudan; (b) the Dakhla Basin of Egypt; (c) the north-western basin of Egypt; and (d) the Sudan Platform. In the centre and north of the system, average precipitation is low (50 mm/year) and consequently, there is no current groundwater recharge in most parts of the system and most of the available resources were recharged during wetter periods in Saharan history.

To improve existing groundwater modelling of NAS, GIS databases were developed for both regional and local scales, and a database was created that comprises all the available hydrogeological information from the previous studies and incorporated hydrogeological data from the newly drilled water wells in Egypt and Libya up to year 2001. Telescoping meshes were developed in this regional model for the inclusion of local details. Building on the GIS database, an integrated GIS-based numerical time-dependent three-dimensional transient groundwater flow model was developed using MODFLOW. This was used to simulate the response of the aquifer to the climatic changes that occurred in the last 25,000 years. The model calibration relied on simulating palaeolakes that existed in this period to estimate and calibrate the groundwater recharge throughout the duration of this time period.

Results of the study showed that the groundwater reserves of the Nubian Sandstone Aquifer in Egypt and Libya are currently being mined. The model showed that by expanding the presently established well fields to their full capacity by year 2020, the water-levels will continuously decline and may fall below economic levels of abstraction.

2.5 Management Interventions for Groundwater Protection and Remediation

Sustainable management of groundwater should aim to prevent groundwater from becoming severely depleted or highly polluted, since prevention is always less expensive than trying to remediate problems once they have occurred. However, sometimes groundwater degradation may have to be mitigated with technical measures, either because the aquifer will not recover on its own, or because other pressures mean that groundwater will continue to be exploited from an increasingly degraded system. Numerous measures have been used globally with various rates of success.

Several measures can be used to maintain a supply of groundwater:

- optimising the location of wells and boreholes to limit overall aquifer drawdown at the same abstraction rate
- control of pumping regimes to minimize drawdown or reduce saline intrusion
- use of standby boreholes, in extreme cases, to sustain sensitive ecosystems or river flows for periods when natural discharge of groundwater is lost, and
- scavenger wells in coastal areas to protect productive areas of the aquifer by pumping out saline water (although this exacerbates the overall water balance deficiency so must be managed carefully).

Management of aquifer recharge to increase groundwater recharge rates is growing in popularity and several methods are being used: (1) constructing infiltration ponds and basins (see Case 2.6), (2) modifying surface water channels and building small dams; (3) directly injecting groundwater through boreholes, and (4) constructing small-scale structures in agricultural fields.

Case 2.6 Managed aquifer recharge in Mexico[36]

More than half of Mexico is dominated by arid and semi-arid climatic conditions, making groundwater an essential resource for national development. Total groundwater abstraction has been estimated at of 28,000 million m^3/year with agriculture using 71% and urban and industrial areas consuming 26%. Currently, over 100 regional aquifers are considered to be over-exploited. To respond to this, a pilot aquifer recharge project was carried out in the Comarca Lagunera Region of northern Mexico, a major agricultural area. Water for irrigation purposes, domestic and industrial use is abstracted from the Nazas and Aguanaval rivers and from 3500 boreholes drawing groundwater from the Comarca Lagunera aquifer. At present, it is estimated that abstraction is at least three times greater than recharge, resulting in a significant decline in the groundwater level and deterioration in groundwater quality.

The pilot scheme aimed to manage aquifer recharge as a means of replenishing groundwater supplies. The scheme used an adapted recharge sand basin near to the Nazas River Bed, in Torreon City, covering an area of 13 ha with a storage capacity of about 197,000 m^3. Waterworks were implemented to transport surface water from the Zarco dam to the recharge basin. A trial period between May and August 2000 saw a total volume of 5.2 million m^3 transported to the recharge basin. Of this volume, 0.2 million m^3 was lost to evaporation and 5.0 million m^3 infiltrated into the subsurface.

Recommendations from this pilot scheme include building new structures to control delivery of the water to the basins, to release only 0.5 million m^3 per week to avoid basin spills, to construct parallel sedimentation basins to reduce clogging and to construct adsorption wells 20 m deep and >0.3 m in diameter to avoid low conductivity horizons.

"PREVENTION IS ALWAYS LESS EXPENSIVE THAN TRYING TO REMEDIATE PROBLEMS."

Even more important, measures can be taken to reduce abstraction by controlling demand for water. Over the past 15 years or so, there has been much progress on engineering designs that make more efficient use of water. In agriculture for example, drip irrigation (in which crops are only given the volume of water required for optimum growth) can result in major decreases in the amount of water applied and pumping energy consumed per unit area of crop cultivated, whilst maintaining or increasing yields. However, it is conceptually a mistake to associate 'improving irrigation water-use efficiency' with 'real groundwater resource saving' – the latter will only follow when parallel action is taken to reduce groundwater pumping, since most of the so-called efficiency improvements result from eliminating previous excess irrigation which was already being returned to the aquifer by infiltration.

At the municipality level, physical measures aimed at reducing domestic water consumption and supplementary use of rainwater in gardens can reduce demand on aquifers. Of greater significance: (a) the reduction of frequently high rates of urban water main leakage, bearing in mind that, in some cases, leaky water mains can recharge groundwater, and (b) appropriate handling and treatment of urban wastewater to allow its reuse for agricultural and/or amenity irrigation as a substitute for fresh groundwater, bearing in mind that such reuse can generate a contaminant load to aquifers.

"MEASURES CAN BE TAKEN TO REDUCE ABSTRACTION BY CONTROLLING DEMAND FOR WATER."

Many methods have been developed to remediate groundwater that has been contaminated, initially as a consequence of litigation in the USA or under the implementation of the EC Water Framework Directive. Most methods are specific to the contaminant and the hydrogeological conditions, may be only partially successful, and are expensive to implement. A key aspect of any remediation programme is clear agreement on the targeted end point and on how it will be monitored and measured. Remediation measures can be done in situ (introducing oxygen, nano particles, or bacteria to help speed up natural biogeochemical processes) or ex-situ (commonly pumping contaminated groundwater to the surface and treating it or erecting barriers to contain contaminated groundwater.

2.6 Checklist: Application of Technical Knowledge and Information to Groundwater Management and Protection

Build knowledge of hydrogeology and groundwater resources

- Promote improved understanding of how groundwater systems work among groundwater users, technical agencies, policy makers and legislators.
- Communicate knowledge of threats to groundwater including excessive abstraction and pollution. Explain the implications of groundwater degradation to the general public, groundwater users and policy makers in terms of risks to the economy, health, food and water security, biodiversity and the environment.
- Build technical knowledge among stakeholders and technical agencies including of how aquifer characteristics and chemistry determine how groundwater can be used sustainably and priorities for groundwater management and protection.

Generate and make available information needed for improving groundwater management

- Build technical capacities for diagnostic analysis and monitoring of groundwater systems.
- Assess aquifer characteristics using geological information on rocks, sediments and soils and through scientific studies of transmissivity and the capacity of aquifers to store water.
- Gather information on long-term variations in groundwater levels or, if not available, start monitoring as a priority.
- Make an inventory of all groundwater abstractions and estimate the water balance of aquifers by comparing natural recharge with discharge and abstraction.
- Characterise groundwater quality by implementing a systematic programme for sampling of boreholes. Establish baselines to enable monitoring of changes relative to water quality standards.
- Develop national hydrogeological maps to show the locations of aquifers and national databases to systematically store aquifer and groundwater data for use in groundwater management.
- Assess the vulnerability of aquifers to pollution and develop vulnerability maps for use in land-use planning.
- Develop dynamic numerical models of aquifers where the needed resources and skills are available. Apply the model to assess the implications of alternate management options and scenarios for future exploitation of aquifers.

Identify management interventions

- Put in place a national system for regularly monitoring groundwater levels and groundwater quality, including a network of monitoring boreholes.
- Create a system for land-use zoning that only allows land uses that are compatible with the capacity of the underlying aquifer. Use vulnerability maps to identify where conditionalities need to be in place before development proceeds and to delineate source protection zones where restrictions on land-use are needed to avoid contamination of groundwater.
- Identify and implement controls needed to limit groundwater pumping to sustainable levels. Complement these with measures designed to control water demand.
- Implement managed aquifer recharge where increased recharge rates are needed, though for example construction of infiltration ponds or direct aquifer injection.
- Assess the need for and appropriateness of alternate remediation methods where groundwater has become contaminated.