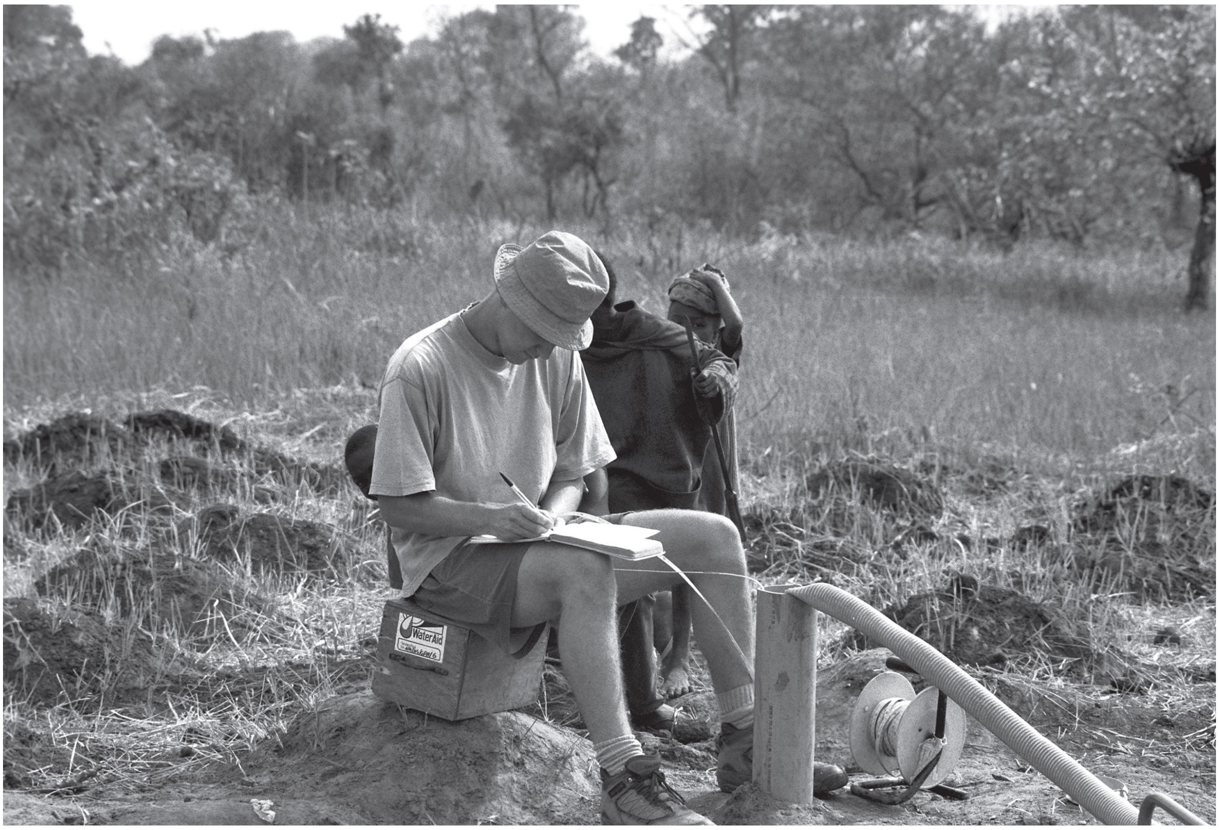

6. Groundwater Management

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6.1 Introduction

6.1.1 Importance of Groundwater Storage

Groundwater is the largest reservoir of unfrozen freshwater on our planet. If only shallow groundwater in active circulation is considered (some 8-10 million km^3), then these reserves amount to 95-97% of total freshwater stocks, with only 2-3 % being held in lakes reservoirs, rivers and swamps, and with soil-moisture storage representing about another 1%. The vast storage of many aquifer systems is their most distinctive characteristic but can result in the false impression that groundwater resources are inexhaustible. Whilst this storage provides an effective natural buffer against climatic variability, recharge is finite and controls the long-term physical sustainability of groundwater resources (Figure 6.1). As a result of being an 'invisible (or hidden) resource' the flow of groundwater is also still too widely a source of public misconception, with often mistaken ideas about underground rivers or subterranean lakes.

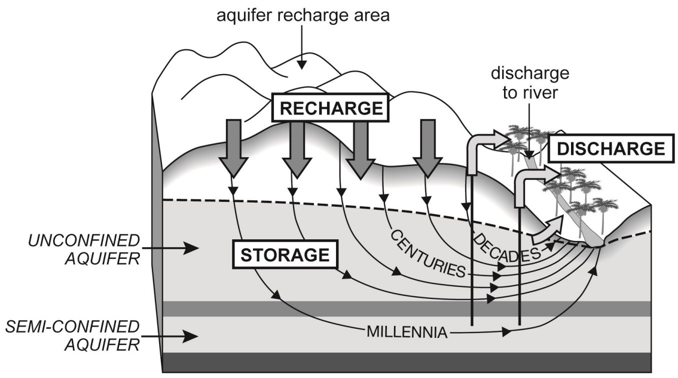


Figure 6.1 Typical groundwater flow regime and residence times.

A clear understanding of the occurrence of aquifers and the hydrogeological structure of river-basins is essential for effective catchment management. Different aquifer systems vary widely in their storage properties because of major differences in saturated thickness, spatial extent, and geology. Groundwater is generally stored in pore spaces and fractures within rocks and measured as the porosity. 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 reduces 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%. Some sedimentary rocks (such as limestones) are soluble. In these karstic systems, fractures may become enlarged as the groundwater slowly dissolves the rock to form fissures and caverns, where groundwater can flow rapidly in discrete channels. 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 often weathered to form a deep soil several tens of metres thick with groundwater stored in the resulting sands, gravels, and decomposed rock (Figure 6.2).

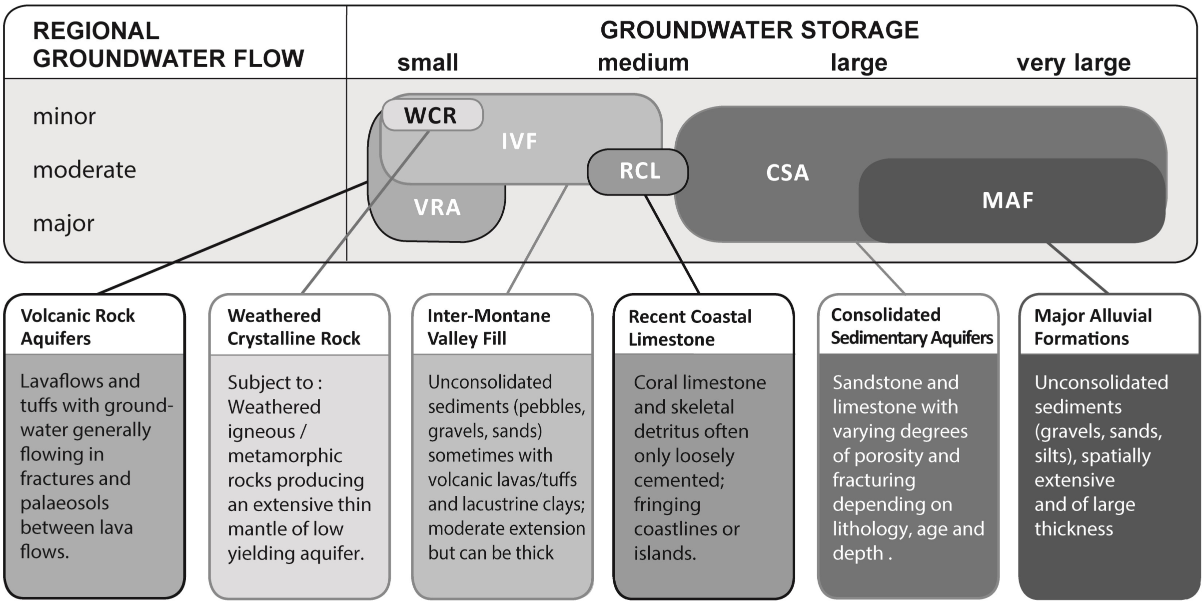


Figure 6.2 Variation of groundwater storage and flow regime with aquifer type.

6.1.2 Dynamics of Groundwater Flow Systems

Groundwater bodies are naturally recharged by rainwater or snow-melt infiltrating through the soil zone to the water-table. Tens, hundreds or even thousands of years can elapse (Figure 6.1) before eventually discharging to a spring, river, aquatic or terrestrial wetland, or directly to the coast. The rate of groundwater flow is governed by the permeability of the rocks: a measure of how connected the void spaces are. Slow flow rates and long residence times naturally transform highly variable recharge regimes into more stable discharge regimes. In dry periods the groundwater contribution to river flow (called baseflow) widely rises to 90% or more and even in hard rock mountainous areas can comprise 30% of annual flow. (Figure 6.3). Therefore, groundwater plays an important hidden role in sustaining many aquatic ecosystems (Box 6.1).

Evaluating the dynamic relationship between surface water and underlying aquifers is an important component of groundwater system characterization. In humid areas, groundwater usually discharges to rivers, however, in more arid areas, this often reverses and surface water can recharge the aquifer system. Floodplain aquifers can exhibit complex time dependent relationships where groundwater / river exchanges are dynamic depending on the flow: at low river flow groundwater flows to the river but at high river flow, the river loses water to the aquifer.

Where aquifers dip beneath much less permeable strata, their groundwater becomes confined (to varying degrees) by the overlying layers and this results in isolation from the immediately overlying land surface, but not from the aquifer system as a whole. In some hydrogeological settings, shallow unconfined and deep confined aquifers are superimposed with leakage downwards and upwards between layers according to local conditions. Past episodes of natural climate-change have transformed some large land areas (which formerly had much wetter climates) into deserts and virtually eliminated all contemporary groundwater recharge, although some discharge to oases is often still occurring. Groundwater reserves which are not being actively recharged are known as 'fossil groundwater'. These reserves can be tapped by water wells but once pumped out may never be replenished - and are thus often treated as non-renewable groundwater resources.

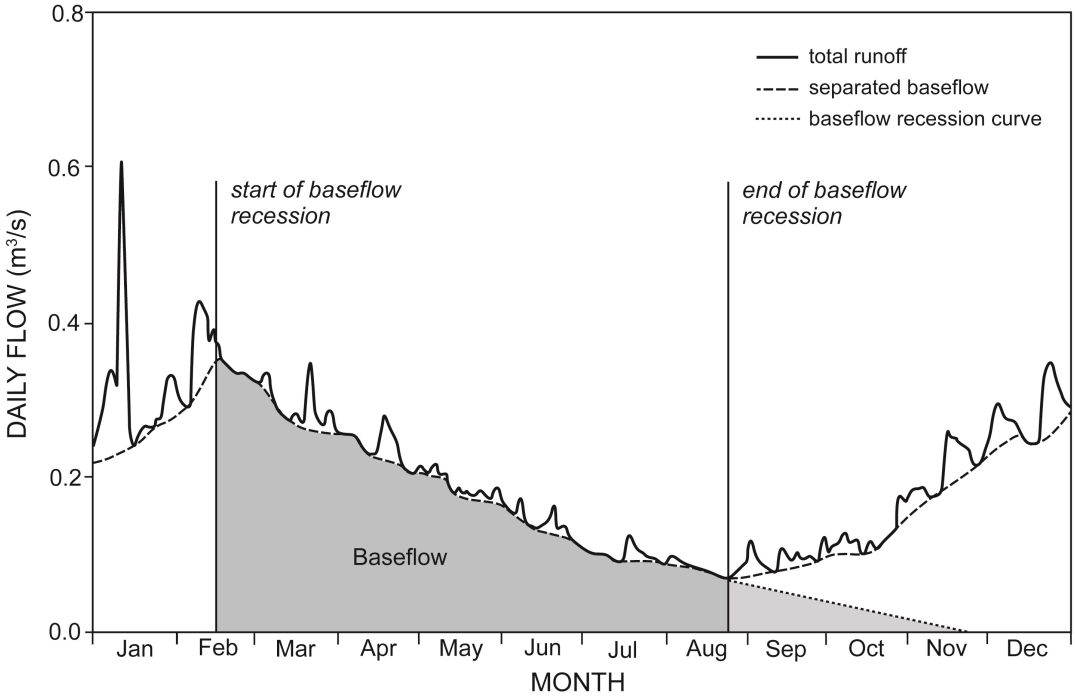
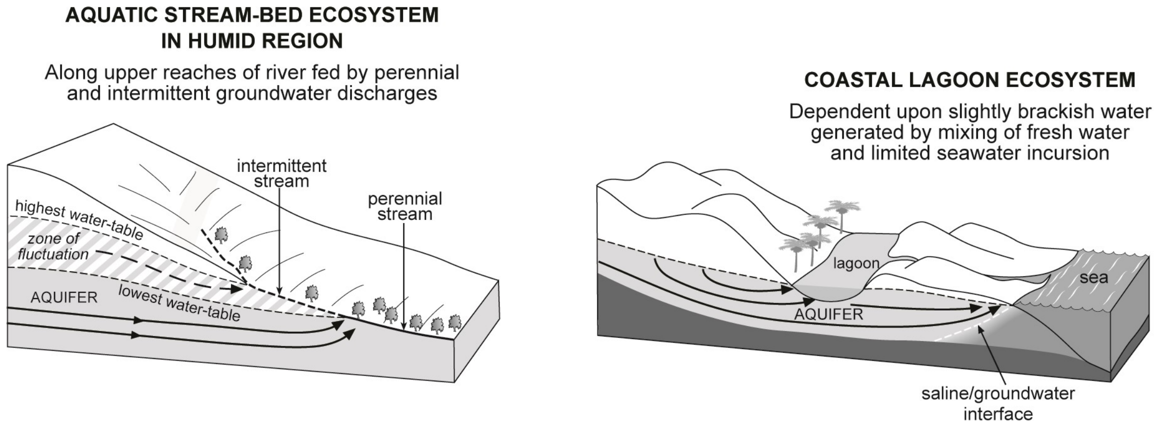


Figure 6.3 River hydrograph with large groundwater-derived baseflow component from a predominantly permeable catchment. © UKRI redrawn from: Wesselink AJ and Gustard A 1992 Groundwater Storage in Chalk aquifers - estimation from hydrographs. Institute of Hydrology, Wallingford 45pp

Box 6.1 Groundwater dependent ecosystems (GDEs)

Groundwater dependent ecosystems (GDEs) comprise a complex subset of ecosystems of major significance in the conservation of biodiversity, including many key sites covered by the RAMSAR Convention (1971). Such ecosystems are usually characterised by phreatophytic plants which derive most of their water needs from soils saturated by natural groundwater discharge. Long-term groundwater depletion will eliminate these species and their critical ecosystem functions through lowering the water-table and stopping natural groundwater discharge.

Degradation of GDEs can also result from groundwater pollution (by nutrients or pesticides) or salinization. GDEs have value directly to the human population from fish and plant production, water storage and self-purification, and indirectly in terms of landscape and habitat. However they are still poorly characterized and there is limited



6.1.3 Evaluation of Groundwater Recharge

Evaluation of contemporary aquifer recharge rates is fundamental to consideration of the sustainability of groundwater resource development. But the quantification of natural recharge, is subject to significant methodological difficulties, data deficiencies and resultant uncertainties because of both wide spatial and temporal variability of rainfall and runoff events, and of widespread lateral variation in soil profiles and hydrogeological conditions (Scanlon *et al*. 2002). Despite these uncertainties, a number of generic observations can be made about aquifer recharge processes:

- Humid areas where rainfall often exceeds evaporation on a daily, weekly or monthly basis generally have periods when the soil is saturated and further rainfall gives rise to groundwater recharge.

- Increasingly arid areas have a much lower rate and frequency of groundwater recharge, with recharge from exceptional (decadal) rainfall/runoff episodes much more significant (Cuthbert *et al*. 2019) along with incidental recharge arising from human activity and hydraulic engineering.

- Recharge is difficult to reliably measure but estimates of the direct rainfall recharge component through the soil zone are generally more reliable and easier to model and forecast than those from runoff (see Healey 2010, for a review).

Understanding the intimate linkage between rainfall, land-use and aquifer recharge is an essential basis for integrated water resources management. Rainfall volumes are the main driver of recharge, but rates can also be affected by: (1) changes in land use and vegetation cover and notably the introduction of irrigated agriculture, but also vegetation clearance and soil compaction; (2) rainfall intensity, particularly in more arid areas where intense rainfall can overcome soil moisture deficits and lead to increased recharge; (3) urbanisation processes and in particular the level of water-mains leakage, proportion of unsewered sanitation and degree of land-surface impermeabilisation; (4) widespread water-table lowering by groundwater abstraction and/or land drainage leading to increased areas and/or rates of infiltration to some aquifers; and (5) changes in surface water regime, especially diversion or canalization of river flow.

Box 6.2 Non-renewable Groundwater Resources

The large non-renewable groundwater resources of some major (and minor) aquifers can provide a very reliable source of water supply, which is completely resilient to current climatic variability. However, in the end, use of 'non-renewable groundwater resources' will be time-dependent and essentially 'one-off' and as such deserves careful consideration in terms of efficient utilisation, ecological impacts, and inter-generational equity. It should always be considered as a 'strategic development' and thus subject to specific investigation, detailed monitoring, and special management (Foster and Loucks 2006).

The Nubian Aquifer System: A Non-renewable Groundwater
The Nubian Sandstone Aquifer system (NSAS) underlies several north African countries, is widely used for agriculture and drinking water, and is not currently recharged. It is, therefore, a non-renewable water resource containing fossil groundwater and so is completely resilient to current climatic variability. The aquifer consists of highly permeable sandstones and is hundreds of metres to kilometres thick. Paleohydrology and stable isotope studies suggest that the aquifer was not only last recharged through pluvial periods 5000 and 10 000 years ago but also contains groundwater up to 1 million years old in the centre of the basin. Since it was last recharged, groundwater levels have naturally fallen and discharge through oases has gradually reduced. Pumping of the aquifer is causing local impacts but not any noticeable impacts to transboundary or regional flow (Voss and Soliman 2014).

In the medium-term, the effect of global warming on groundwater recharge rates remains somewhat uncertain (Taylor *et al*. 2013). The tendency in many areas (particularly in semi-arid regions) for more extended drought periods followed by more intense rainfall episodes could lead to increased groundwater recharge which may balance the greater evapotranspiration as a result of increased temperatures. As important as direct changes in climate will be the consequent changes in vegetation as a result of land use change. More land clearing for agriculture could increase groundwater recharge, although in many situations this will be accompanied by increased groundwater use for irrigation which could quickly overwhelm the impacts of increased recharge.

6.1.4 Processes of Groundwater Quality Degradation

Groundwater is for the most part naturally of excellent microbiological and chemical quality. The underlying reasons for this are the capacity of subsoil profiles to filter-out fecal pathogenic micro-organisms, and all suspended solids and organic matter, from percolating recharge and its long sub-surface residence time (decades to millennia) compared to the environmental survival of pathogens (usually < 50 days and rarely > 300 days). Also, the matrix material of most aquifers is generally non-toxic and poorly soluble. Nine major chemicals (sodium, calcium, magnesium, potassium, bicarbonate, chloride, sulphate, nitrate, and silicon) make up 99% of the solute content of natural groundwater. The naturally excellent quality of most groundwaters has long been a key factor in their global importance in providing potable water-supplies at a range of scales from rural villages to large cities.

There are important exceptions to this, since some aquifers exhibit natural groundwater contamination with trace elements that create a health hazard (notably from arsenic and fluoride), or nuisance (dissolved iron and/or manganese), or elevated vulnerability to pollution from the land surface (due to a thin vadose zone and/or presence of highly-preferential pathways to the water-table). Sustainable development of groundwater is thus not only constrained by resource availability but also by quality degradation.

Globally, numerous areas in semi-arid climates are experiencing serious groundwater salinization threats; for example, Pakistan and India (MacDonald *et al.* 2016) and parts of southern Africa have already been impacted. Several different processes can give rise to salinization of groundwater (Figure 6.4):

- excess infiltration causing rising groundwater tables - usually associated with inefficient irrigation using imported surface water in areas of inadequate natural drainage.
- fractionation of salinity in irrigation-water returns to aquifers – especially where groundwater is main source of irrigation.
- natural salinity being mobilised from the landscape - consequent on clearing of natural vegetation for farming development with increased groundwater recharge.
- excessive disturbance of natural groundwater salinity stratification - through uncontrolled water well construction and pumping.

The above mechanisms are in addition to the intrusion of saline water in coastal aquifers. Groundwater salinisation is very costly to remediate and often quasi-irreversible, since the saline water which invades macropores and fissures diffuses, rapidly into the matrix of porous aquifers, and then can take decades to be flushed out even after the flow of freshwater has been re-established.

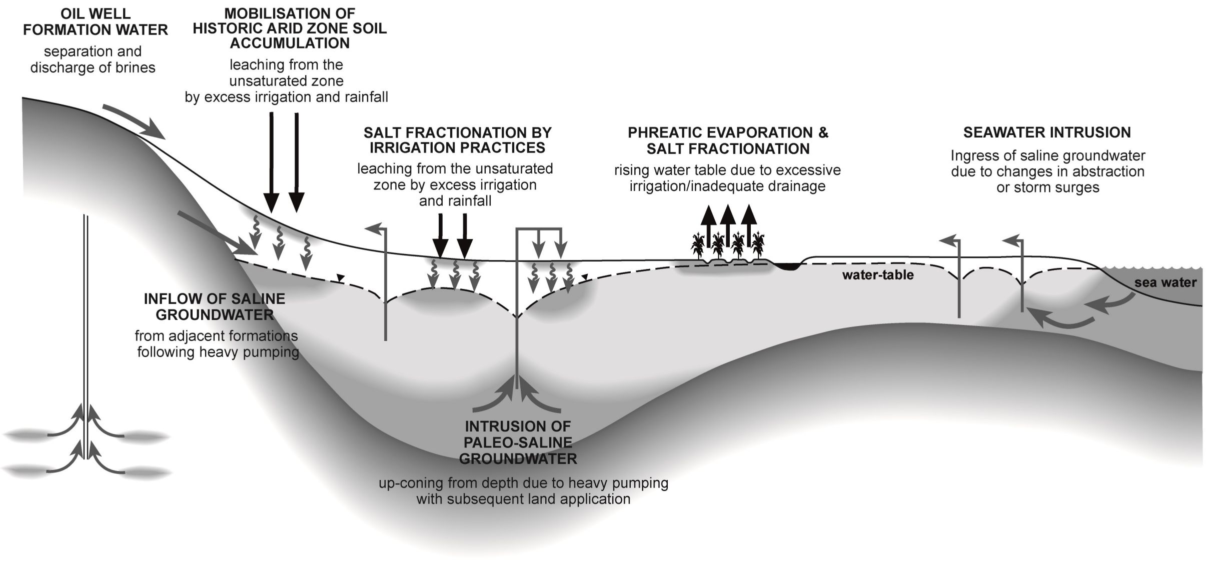


Figure 6.4 Schematic representation of processes of salinisation of groundwater recharge. Modified from Foster et al., 2018, used under Creative Commons Attribution 4.0 International License http://creativecommons.org/licenses/by/4.0/

6.1.5 Aquifer Pollution Vulnerability & Quality Protection

An important characteristic of porous soils, subsoils and rocks is the potential for natural attenuation of contaminants. This can occur through a variety of processes; adsorption, where contaminants bind to pore surfaces; retardation, where low permeability or long flow paths hinder the downward movement of contaminants; and, reaction, where the contaminants are broken down by chemical and biological processes. These different processes have been simplified into a concept called aquifer pollution vulnerability which gives a simplified measure for how vulnerable an aquifer is to polluting activity at the land surface (Box 6.3). Aquifer vulnerability can be mapped, and important water supplies protected by mapping water source protection zones around boreholes and applying appropriate controls on hazardous activities in such areas to reduce the risk of major groundwater pollution (Foster *et al.* 2002).

Box 6.3 Groundwater Pollution Vulnerability

The vulnerability of groundwater in an aquifer to pollution can be estimated (at least qualitatively) from the intrinsic properties of the vadose (unsaturated) zone, or semiconfining bed, separating the aquifer from the land surface. An important factor, especially in consolidated strata, is the possibility of downward contaminant transport via preferential pathways, which will greatly increase aquifer vulnerability to pollutants that would otherwise be retarded by adsorption and/or eliminated by biodegradation. Moreover, all aquifers are vulnerable to pollutants that are resistant to subsurface adsorption and/or biodegradation – such as nitrate, salinity, and numerous man-made organic chemicals some of which have serious ecotoxicological impacts in addition to being a serious drinking-water hazard.

Over the past 50 years or so, massive growth in urbanisation, agricultural and industrial production, together with hydrocarbon development and mining enterprises, is generating a much greater and more complex contaminant load on the subsurface. Whilst groundwater is much less vulnerable to anthropogenic pollution than surface water, once polluted, groundwater is extremely difficult to clean-up, given the large volume and inaccessibility of aquifers. In many cases a zone of groundwater contamination has just to be contained, allowing natural attenuation processes to occur over many decades. However, the location and evaluation of pollution incidents, and pollution prevention, monitoring and remediation, are all much more challenging for groundwater than for surface-water. Many pollution incidents are likely to be occurring unreported (because of inadequate groundwater monitoring) and incidents that occurred decades ago may still be threatening groundwater quality with the legacy being detectable around industrially contaminated land.

A globally recognized problem is nitrate, which has been increasing in concentrations in groundwater for the past 50 – 70 years, since the widespread adoption of chemical fertilisers. Although this is recognised in surface waters, for some parts of the world concentrations in groundwater will continue to rise due to the high load of nitrate already in the unsaturated zone which is slowly moving down to the water-table.

6.2 Groundwater Management – Needs and Approaches

6.2.1 Impacts of Groundwater Resource Development

Since earliest times humankind has met much of its need for good quality water from subterranean sources, with springs playing a key role in human development in East Africa. Early wells were rarely more than 50m deep and lifted water to the surface using manual or animal power. During the 20th century there was an enormous boom in water well construction for urban water-supply, agricultural irrigation and industrial processing. This was facilitated by major advances in drilling and pumping technology and increased geological knowledge. Deep boreholes could be drilled relatively quickly and abstract large volumes and as a result, groundwater became a key natural resource supporting social well-being and economic development.

Comprehensive statistics on groundwater pumping are not available, but global withdrawals are estimated to have reached approximately 900 km^3 $annum^{-1}$ in 2010; providing 36% of potable water-supply, 42% of water for irrigated agriculture and 24% of direct industrial water-supply (Doll *et al*. 2012). The highest groundwater withdrawals are for irrigation and occur across large areas of India, Pakistan, Bangladesh, China and Iran, and more patchily in North America, Southern Europe, North Africa and the Middle East. Dependence on groundwater for urban water-supply is intensifying, for example, 310 million urban inhabitants in the EU rely on groundwater and 105 million in the US. Groundwater’s value cannot be gauged solely by volumetric withdrawal, however, but through its widespread availability, high drought reliability, generally good quality and the ability to progressively develop the resource to meet changing demand.

Box 6.4 Groundwater: In Urban Water Supply

Groundwater is a major source of urban water supply worldwide, and aquifer storage represents a key resource for water supply security under climate change and extended drought. To achieve this, groundwater must be managed more effectively through promoting as 'best engineering practice' the establishment of more water utility wellfields outside cities, with their 'capture areas' as drinking water protection zones, and more widespread use of groundwater and surface water resources conjunctively.

Private water well construction for in situ self-supply has 'mushroomed' in many developing cities as a 'coping strategy' during periods of inadequate utility water service, and continues for years after as a 'cost-reduction strategy'. These unregulated private wells often draw water from shallow aquifers which have already been polluted by local urban or industrial waste disposal. Broad groundwater quantity, quality and economic assessments of current and likely private water well use need to be undertaken to allow the public administration responsible to formulate a balanced urban water policy (Foster et al. 2010a).

In situ sanitation practices and wastewater handling/re-use provide a significant component of urban groundwater recharge, but simultaneously pose a serious threat to shallow groundwater quality (including pathogenic micro-organisms, ammonium or nitrates, toxic synthetic community chemicals and pharmaceutical residues). The pollution risk varies widely with local hydrogeologic setting, density of population served, design of in situ sanitation units, or level of wastewater treatment. Thus, groundwater vulnerability and aquifer use for potable water supply are an important consideration in the planning of sanitation investments.

All groundwater pumping results in a decline in the water-table over a certain area. Some decline may be desirable, since it improves land drainage and maximises groundwater recharge by providing additional storage space for excess wet-season rainfall. However, over time it will result in a reduction in natural discharge to rivers or other aquatic ecosystems. While it is accepted that drawing down on aquifer storage can be a legitimate strategy during social transformation to a less water dependent economy, large overdrafts can have consequences whose implications must be weighed against the socio-economic benefits of resource development (Figure 6.5). The effects can include; water well yield reductions and/or increased pumping costs; drying up of shallower wells; degradation of groundwater-dependent ecosystems; saline water intrusion or up-coning; and, in some settings land subsidence (causing extensive damage to urban infrastructure and increased flood risk).

Aquifer overexploitation is an emotive expression with no simple rigorous scientific definition. It is however useful given its clear register at public and political level. Most take it to mean the *'long-term average rate of groundwater recharge is less than water well abstraction'* and lead to other terms such as an aquifer safe yield. However. problems arise in specifying over what period and which area the groundwater balance should be evaluated - especially in more arid climates where major recharge is a decadal episode and pumping effects may also be unevenly distributed. In practice, when speaking of aquifer exploitation, we are largely concerned about the consequences of intensive groundwater abstraction than its absolute level. Thus, the most appropriate definition is probably an economic and social one: that the *'overall negative impacts of groundwater exploitation exceed the net benefits of groundwater use'*. However, these impacts can be difficult to predict and cost, and the natural susceptibility to irreversible side-effects varying widely with aquifer type.

There are numerous examples of major groundwater depletion from use in agricultural irrigation. Cumulative resource depletion from 1900 to 2008 (but mainly since 1950) has been estimated to be 4,500 km^3 (mainly in India, USA, Saudi Arabia & China) (Konikow 2011), but estimates are subject to uncertainty over the porosity of the dewatered strata. More localised depletion occurs around many major urban conurbations such as Dhaka, Dehli, Addis Ababa and Nairobi. Aquifer depletion contributes indirectly to sea-level rise by creating a water transfer from terrestrial storage to active surface circulation with net transfer to the oceans. A volume-based assessment for depletion during 2000-08 gave an approximate estimate of 106 $km^3 annum^{-1}$, equivalent to 0.3 mm $annum^{-1}$ (or 18% of current sea-level rise).

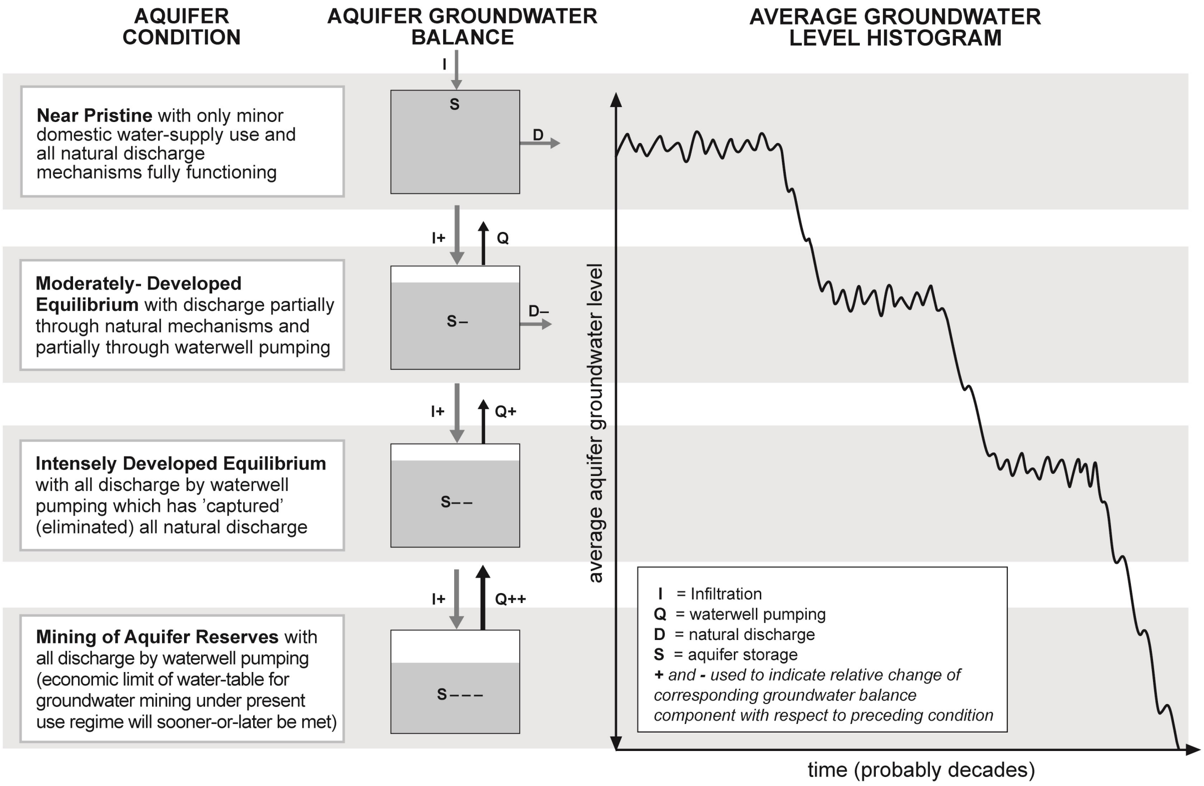


Figure 6.5 Schematic representation of the stages of groundwater resource development. Reprinted by permission from Springer: Hydrogeology Journal, Foster, S., MacDonald, A. The 'water security' dialogue: why it needs to be better informed about groundwater (2014) © Springer Nature

6.2.2 Surface-Water Impacts of Ineffective Management

Failure to manage groundwater resources at the catchment-scale results in gradual but serious impacts on river flow in aquatic ecosystems. Groundwater provides stable conditions to rivers and aquatic ecosystems, sustaining specific plants and animals that thrive in stable water regimes, such as in chalk rivers or fens (Smith *et al*. 2016). In the UK for example, groundwater generally provides more than 30% of water to rivers and often more than 50%. Groundwater tends to be at constant temperature, usually warmer than rainfall in winter and cooler in summer. Differences in groundwater chemistry, such as high pH, also support unique flora and fauna. Therefore, changes to groundwater flow or chemistry can have serious impacts to rivers. Negative impacts can occur even where some groundwater regulation has been implemented if such measures are simply restricted to reducing conflict between groundwater abstractors or protecting the quality of public drinking-water sources. A catchment-scale vision of managing groundwater systems includes the requirements for acceptable river baseflow and adequate aquifer levels to sustain groundwater-dependent ecosystems. Control over widespread (rather than just close to rivers) diffuse groundwater pollution by nutrients and pesticides or mining operations (e.g. Haunch *et al*. 2014) is also required.

6.2.3 Key Components of Groundwater Resources Management

Demand versus Supply Side Interventions:

To confront situations of excessive and unstable groundwater resource exploitation it is necessary to distinguish clearly between; demand-side management interventions, such as restricting groundwater use at certain times, making savings in consumptive use in irrigation or industry; and, in-situ supply-side engineering measures, such as enhancing aquifer recharge through land use change or engineered structures. Constraining groundwater abstraction will normally be essential for achieving a satisfactory groundwater balance, irrespective of what local supply-augmentation measures can be undertaken.

Box 6.5 Managed Aquifer Recharge (MAR)

MAR is, in effect, engineering practice aimed at maximising the enhancement of aquifer recharge from major rainfall episodes and reducing the generation of surface run-off. The engineering measures can take numerous forms (Dillon et al. 2019), according to the type of area concerned and the local hydrogeologic conditions. For example, small-scale physical impoundment of surface watercourses could be employed to reduce streamflow velocity and streambed erosion, whilst increasing streambed infiltration to groundwater. In urban areas, permeable pavement can be employed to allow infiltration and roof drainage can be directed to soak away ditches or trenches. In agricultural areas, the construction of terraces can have similar effect and routing any storm run-off to retention ponds can allow time for infiltration to groundwater to occur.

Identifying links with the rest of the water cycle:

The identification of the existence and strength of local linkages between groundwater and the wider hydrological cycle is critical. The complexity of groundwater management increases as more linkages are considered, and a pragmatic decision taken on which are most relevant to maintain a reasonable balance between the costs and benefits of management interventions. It is important to take into account the susceptibility of the system in question to degradation and the legitimate interests of water users, including ecosystems and those dependent on downstream baseflow. For many management situations, the links will be managed through defining an acceptable "aquifer yield" which, as discussed above, is usually a judgement call, rather than strict scientific limit and is based on;

- value judgements about the importance of maintaining (at least a proportion of) natural beneficial discharges from the aquifer system to the wider environment.
- distinguishing consumptive use and catchment export of extracted groundwater from non-consumptive uses which will return water to the catchment.

In most circumstances groundwater should be managed conjunctively with surface-water (Foster *et al*. 2010b), since all rivers are to some degree fed by natural groundwater discharge (with springs and seepages generating baseflow) and many rivers and lakes are also major source of groundwater recharge. The policy challenge is to define, for any given setting, the mode of conjunctive use of surface-water and groundwater use that is balanced and complementary. The level of management integration should be appropriate to local hydrogeological setting with rapidly connected systems (such a karstic limestone formations and major alluvial aquifers) requiring a different approach to deep sedimentary aquifers in arid regions.

Climate Change

Climate change (with increasing temperatures, variation of rainfall volumes and Intensity, modification of vegetation cover) will all sooner-or-later impact groundwater resources (Taylor *et al*. 2013) through changes in groundwater recharge. Graphic evidence of this exists in the palaeo-hydrologic record of aquifers containing groundwater greater than 10,000 years old, which originated as recharge in past wetter and colder millennia (e.g. the Nubian aquifers of North Africa). However, the large volume of many aquifer systems, will help to buffer the effects of climate change in the short to medium term. Aquifer systems possess their own resilience to the pressures arising from global change based on their volume, porosity and permeability. (Foster and MacDonald 2014). Therefore, each will respond differently, but predictably to climate change. Climate change will not universally reduce groundwater recharge, but in some circumstances, changes in rainfall volumes, intensity and land use may actually increase recharge (Cuthbert *et al*. 2019) and in some circumstances lead to groundwater flooding.

Irrigation

The practice of irrigated agriculture has an intimate linkage with groundwater resources (Llamas and Martinez-Santos 2005; Garrido *et al*. 2006; Foster and Cherlet 2014) although the nature of this relation varies considerably with hydrogeological setting (especially water-table depth) and whether groundwater or surface water is the main source of irrigation water-supply. Since agriculture is by far the largest consumer of groundwater, water-resource savings in irrigation is critical although real savings can only be made by either reducing consumptive use or by eliminating freshwater losses to saline water bodies. Otherwise supposed water savings are just reducing water input to another part of the catchment. The replacement of flood irrigation with precision drip or sprinkler technology can reduce the volume of groundwater applied to a crop and, therefore, reduce energy use for pumping. Moreover, precision ferti-irrigation delivers nutrients directly to the root zone, reducing weed growth and increasing crop yields. But it must be stressed that this irrigation system is not a significant water-resource saving measure (Figure 6.6) (Foster and Perry 2010), and its introduction often has negative consequences for the groundwater system as a whole. The main impacts are usually greatly reducing groundwater recharge from irrigation-water returns and increasing the build-up of soil salinity and in turn groundwater recharge salinity.

Thus, a well-informed and carefully balanced approach to irrigation is required, and the challenge (particularly in arid areas) is not only to focus on efficient water-use, but also to reconcile gross groundwater abstraction with overall average recharge and required environmental flows. It is helpful to manage Irrigation water through evapotranspiration and soil management to retain favorable moisture and salt balance. Management arrangements are required that boost crop-water productivity (net income/m^3 evaporated), whilst honoring the need for groundwater regulation to achieve resource sustainability.

Metering of irrigation water-use is a highly desirable management provision, but one that is often resisted as being logistically too complex and costly. A simpler (and usually adequate) proxy is to meter and control the energy supply for pumping which, for example, can be facilitated by using electronic smart-card technology for pump activation, with individual card allocations being chargeable and annually-variable according to aquifer water-level trends. Rural energy pricing can be used as part of an incentive framework for promoting sustainable groundwater extraction, with joint billing of pump energy consumption and groundwater resource use (with power connection depending on payment). Solar pumping complicates this picture. Although a welcome development for reducing dependence on fossil fuels, solar pumping will reduce many of the levers to manage groundwater abstraction. One possible solution is for water resources agencies to work with power companies to introduce grid buy-back tariffs that are sufficiently attractive to avoid solar energy being used for continued over-pumping of groundwater.

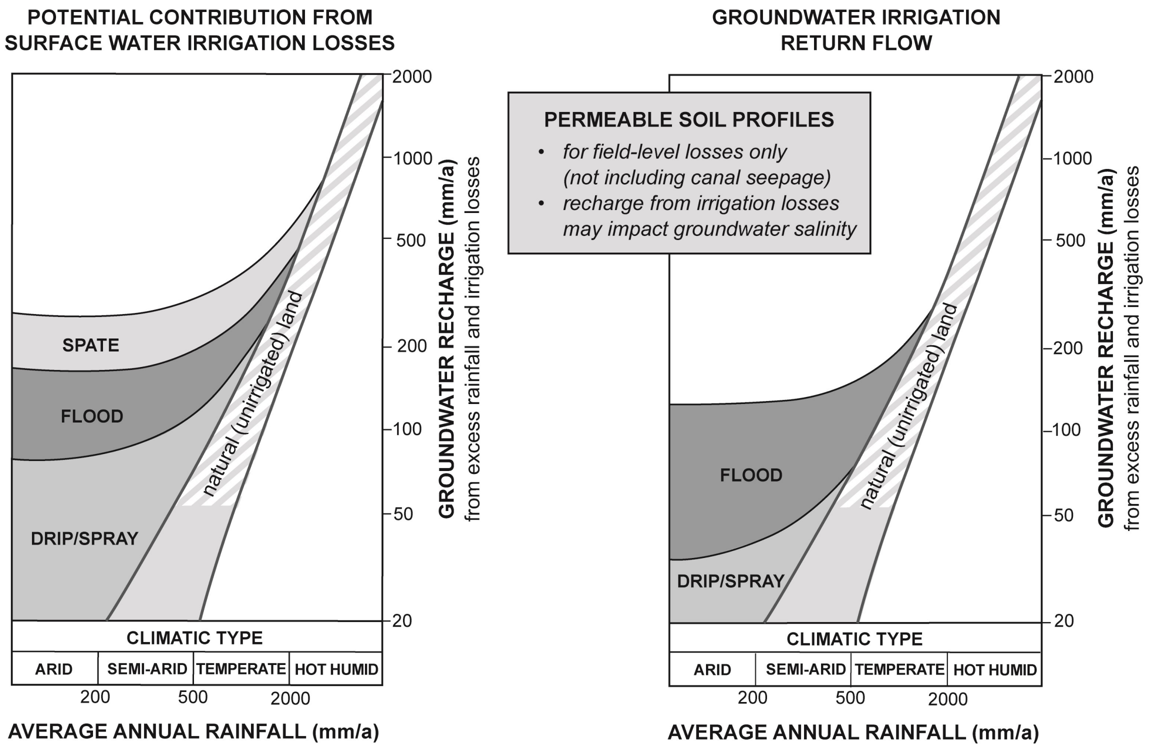


Figure 6.6 Impact of irrigated agriculture on groundwater recharge rates

6.2.4 Approaches to Groundwater Quality Protection

Potential Polluter Pays for Protection

The economic concept usually prescribed to constrain point-source water pollution is the 'polluter-pays-principle'. This principle incorporates the cost of pollution externalities into the cost of industrial production, rather than leaving them for society to pay. However, in the case of groundwater pollution, the burden of proof is often onerous, because determining who is to blame is made difficult by both the hydraulic complexity of, and the very large time-lag in, pollutant transport typical of many (if not all) aquifer systems. Thus, the above approach is not readily applicable, and would be largely ineffective as regards protection of aquifers, because of the extreme persistence of some contaminants in the subsurface and the frequent impracticability of clean-up, together with the elevated cost of some pollution episodes. Thus in the case of groundwater the 'polluter pays principle' must be interpreted as the 'potential polluter pays the cost of required aquifer protection', which will show wide variation spatially with the soil profile, underlying geology and (most importantly) be the highest in lowland groundwater recharge areas (Foster *et al*. 2002).

Groundwater-Friendly Rural Land-Use

Land-use in recharge areas has a major influence on the quality and quantity of infiltration to groundwater and thus needs to be linked systematically to groundwater management. Some of the most significant changes for underlying aquifers include clearing natural vegetation, converting forest to pasture, pasture to arable land, intensifying dryland agriculture, and reforestation/afforestation with commercial woodland. Extending irrigated agriculture with surface-water will have by far the greatest impact on groundwater as demonstrated most strikingly by the irrigation systems of the Indus and Ganges rivers (MacDonald *et al*. 2016). However, land-use decisions are usually the domain of local government, and strongly influenced by national agricultural policy, so their control is not straightforward.

Groundwater quality protection requires a consultation mechanism with the planning and investment procedures related to land-use in both rural and urban areas. Where groundwater performs a strategic municipal water-supply and/or ecological function, a useful instrument to facilitate such consultation is a regulatory provision to declare special *'groundwater protection zones'* (for highly vulnerable recharge areas and/or drinking-water capture zones) (Figure 6.7), which allows the water-resource agency to exert restrictions on land-use practices and potentially-polluting activities.

In drinking-water protection zones it will be desirable to exclude hazardous activities, through a combination of regulatory provisions and economic instruments, in preference to controlling their design and operation. It will also be preferable to introduce economic incentives for potential polluters to improve existing industrial premises and their wastewater handling, treatment, re-use and disposal facilities, and the minimisation and safe disposal of solid wastes, especially in areas where aquifer vulnerability assessments suggest high risk of groundwater pollution. The imposition of strong sanctions for non-compliance, as well as incentives for compliance, will be essential. The control of diffuse agricultural pollution from intensive cultivation using heavy applications of fertilisers and pesticides can usually only be possible through the promulgation of voluntary codes of best practice and/or the payment for ecosystem services (Foster and Cherlet 2014).

6.2.5 Need for Adaptive and Precautionary Management

The relatively high level of uncertainty resulting from limited hydrogeological data on such factors as the fracturing and permeability, temporal and spatial variation of rainfall intensity, groundwater recharge processes, actual groundwater abstraction and consumptive use etc. represents a strong argument for adopting an 'adaptive management approach'. This is one in which a 'groundwater management plan' is drawn-up on the basis of best available information, but its outcomes are subject to careful monitoring and systematic review of aquifer response, with plan adjustment after 2, 5 or 10 years according to resource status and trends. Another issue that arises is how to approach decisions on groundwater pumping and conditions of permits for potentially polluting activities as they arise. The recommended approach here is ‘precautionary’, involving the elaboration of a worst-case scenario numerical model (based on the best available data) and its use to guide decisions.

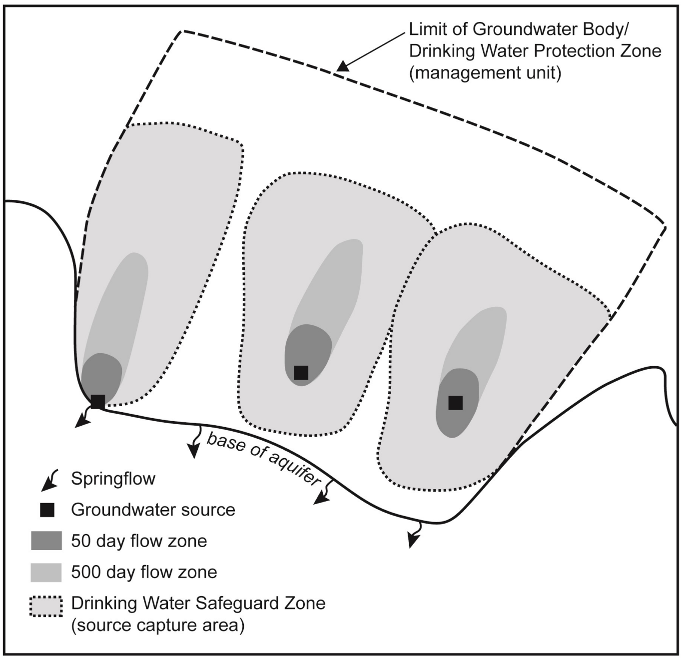


Figure 6.7 Groundwater protection zones defined on capture areas and flow time zones basis around a series of public boreholes.

6.3 New Insights

Groundwater is a classic common pool resource, which is inherently susceptible to its stakeholders acting solely in their short-term self-interest, rather than taking long-term communal requirements into account (Ostrom 1990). This is usually because of a perception that personal interests cannot be assured through communal action. Ever-increasing pressures on groundwater (from water-supply provision and from polluting activities) have led to poor outcomes, which in essence are due to inadequate governance arrangements.

6.3.1 Evolving Paradigm of Sound Governance

Important changes in the approach to groundwater governance commenced about 20 years ago in some countries and are still evolving in many others. There has been an underlying need to move the 'groundwater management target' from individual waterwells and pollution sites to entire aquifer systems. This paradigm shift has involved applying the principles of Integrated Water Resources Management (IWRM) and introducing governance concepts that will facilitate such an approach. Moreover, in recent decades there has been clearer recognition of the groundwater dependence of many aquatic, and some terrestrial, ecosystems, and the vulnerability of groundwater resources at catchment scale to extensive diffuse pollution by contaminant loads generated from agricultural intensification and urbanisation.

Effective groundwater resource management and protection, and the improved governance arrangements that facilitate them, have become a pressing need worldwide. The term 'governance' when applied to groundwater is generally understood to encompass the promotion of responsible collective action by society to ensure resource sustainability. For each defined resource unit this should include establishing the necessary institutional and participatory arrangements, agreeing the policy position and its translation into specific goals, providing procedures and finance for implementation, assuring compliance and resolving conflicts, and (most importantly) establishing appropriate monitoring and clear accountability for outcomes (FAO-UN 2016).

Groundwater management must deal with balancing the exploitation of a complex resource (in terms of quantity, quality and surface water interactions) with the increasing demands of water and land users, who can pose a threat to resource availability and quality, and the aquatic environment. Thus, it is as much about managing people, water and land users (the socio-economic dimension), as it is about scientific understanding of resource behavior under stress and how to mitigate it (the hydrogeological dimension). Groundwater governance provisions that blend these two facets require;

- the development of an effective groundwater management plan for the local aquifer system, with agreed targets, desired outcomes, a programme of measures or interventions, financial support, clear timeframe, adequate monitoring and periodic review.
- appropriate levels of integration within the overall hydrological cycle through co-management with other components of water and land resources.
- main-streaming groundwater concerns across sectors because many drivers of change in groundwater systems often arise from the socioeconomic goals outside the water sector.

The European Union has been in the vanguard of the 'integrated system approach' to groundwater governance, with the basic principles being discussed in the 1990s and enshrined in the Water Framework Directive of 2000, which was supplemented by the Groundwater Protection Directive of 2006 (EC 2008; Quevauviller 2008). Concomitantly, other programmes were pioneering a more integrated and participative approach, such as the World Bank GW-MATe Programme of 2001-11 (Foster *et al*. 2009), IWMI projects in South Asia (Mukherji *et al*. 2009) and IUCN initiatives in the Middle East. All these experiences have been brought together in the GEF Global Groundwater Governance Framework-for-Action (FAO-UN 2016).

River-basin organisations can be the most appropriate focus for local/regional groundwater management, but the given the wide variation in their function, capacity and scale (for example from the enormous transboundary Niger Basin of West Africa to the local Tana Basin in Kenya) this will not always be the case. In some situations, community groundwater management (or at least self-regulation of groundwater abstraction) maybe the only realistic option that can function effectively in small aquifers with a socially homogenous group of groundwater users.

6.3.2 Integrated Policy to Strengthen Governance

Vertical Integration within the Water Sector

When strengthening groundwater governance, the highly distributed nature of the resource needs to be appreciated. Groundwater is affected by the actions of a very large number of users and potential polluters. It thus needs to be managed at the most local scale compatible with the hydrogeological and institutional boundaries. In reality it is the local hydrogeological setting and socioeconomic circumstances that together frame groundwater resource availability and use, and in turn constrain the management measures likely to be feasible and applicable to manage aquifer degradation risks, to resolve potential conflicts and to secure catchment-scale objectives. There is no simple blueprint for integrated groundwater management, only a framework of principles for policy and planning that foster subsidiarity in the detail of local application, whilst providing clear coordination between national, provincial and local level (Figure 6.8). Fundamental to success is a clear definition of the collective responsibility for the resource, specifying who is accountable for the outcome of management measures.

Horizontal Integration beyond the Water Sector

The principal drivers of degradation of aquifer systems are often generated from outside the water-sector. Thus, incorporating groundwater resource and quality considerations into policy formulation of certain related sectors or sub-sectors (so-called horizontal policy integration) helps avoid national policies that emanate perverse signals. For example, in many countries food-production subsidies (through guaranteed prices for high water-consuming crops) or energy-use subsidies (through reduced prices for electrical energy/diesel fuel or for solar-powered pumps) (Shah *et al*. 2012) make up a significant proportion of public expenditure. As part of effective groundwater governance, the incentives provided by such subsidies, both in terms of groundwater use and excessive agrochemical applications, are at odds with sustainable groundwater management. Public finance for subsidies could be much better used to help address the problems of groundwater depletion, salinisation, ecosystem degradation and assisting those who have been adversely affected by pumping (often the poorest). The concept of paying farmers for groundwater environmental services requires more proactive promotion (Smith *et al.* 2016).

Urbanisation has a major impact on groundwater;

- quantity - with recharge simultaneously being reduced by paving and roofing, and increased by water-mains leakage and seepage from in-situ sanitation units and drainage soakaways.
- quality - from large volumes of infiltrating domestic and/or industrial wastewater and solid waste, and the hazards arising from industrial zones.

Of particular significance are in-situ sanitation practices and wastewater handling from mains sewerage systems, which provide a significant component of urban groundwater recharge in more arid climates, but simultaneously pose a serious threat of shallow groundwater pollution (including pathogenic micro-organisms, ammonium or nitrates, toxic community chemicals and pharmaceutical residues). The pollution risk varies widely with the local hydrogeological setting, density of population served, design of in-situ sanitation units or the level of wastewater treatment and re-use. It is critical, therefore, that groundwater vulnerability is taken into consideration in the planning and implementation of sanitation investments and industrial zones.

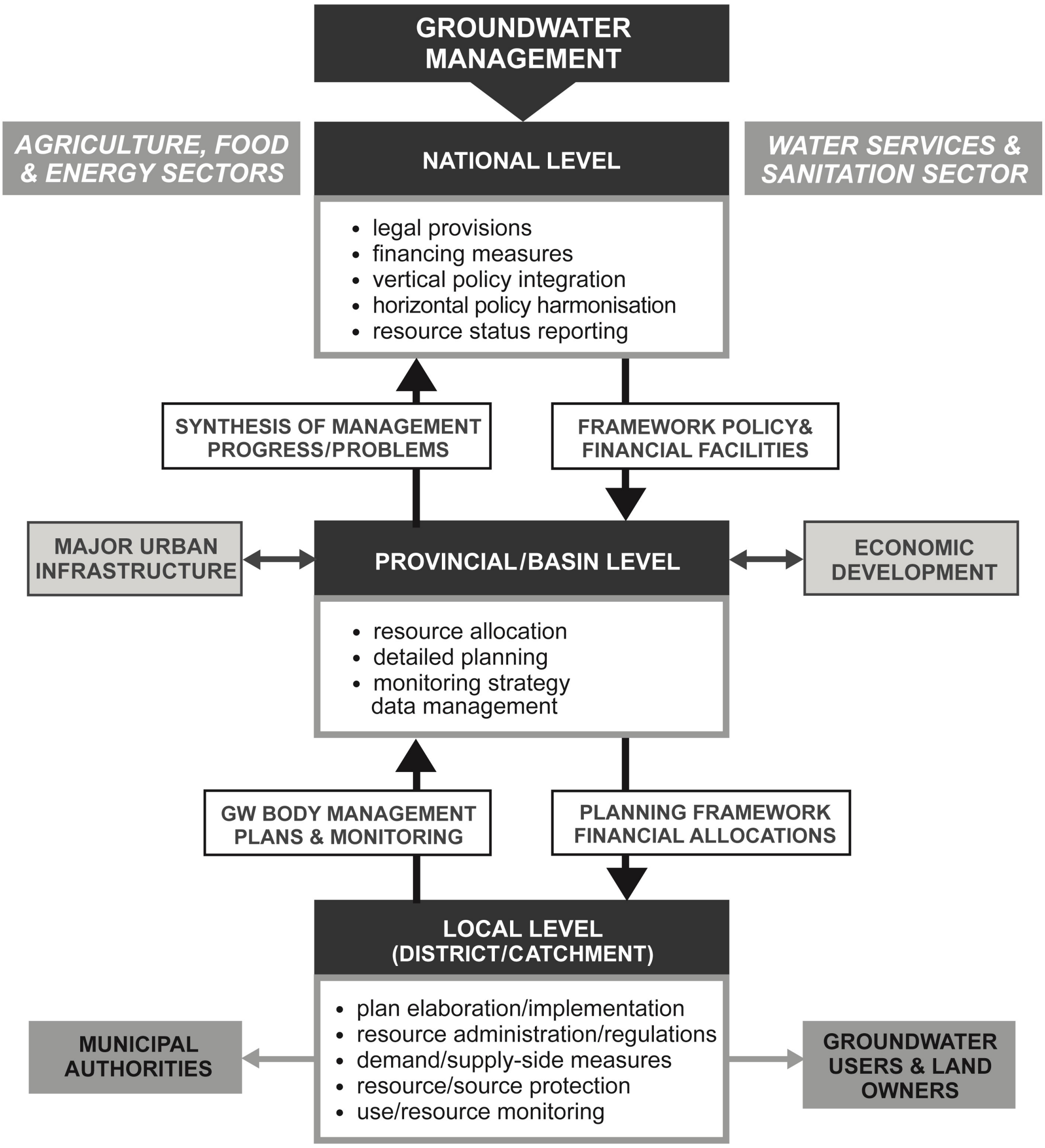


Figure 6.8 General scheme for integrated groundwater management

6.3.3 Conjunctive Use of Groundwater and Surface Water

Groundwater storage within aquifers is best managed strategically and conjunctively with surface water (Foster *et al*. 2010b). This approach increases water security and reduces the possibility of surface-water and aquatic ecosystem degradation. Conjunctive use is primarily, though not exclusively, relevant to alluvial plains, which often have important rivers and major aquifers in close juxtaposition (Figure 6.9).

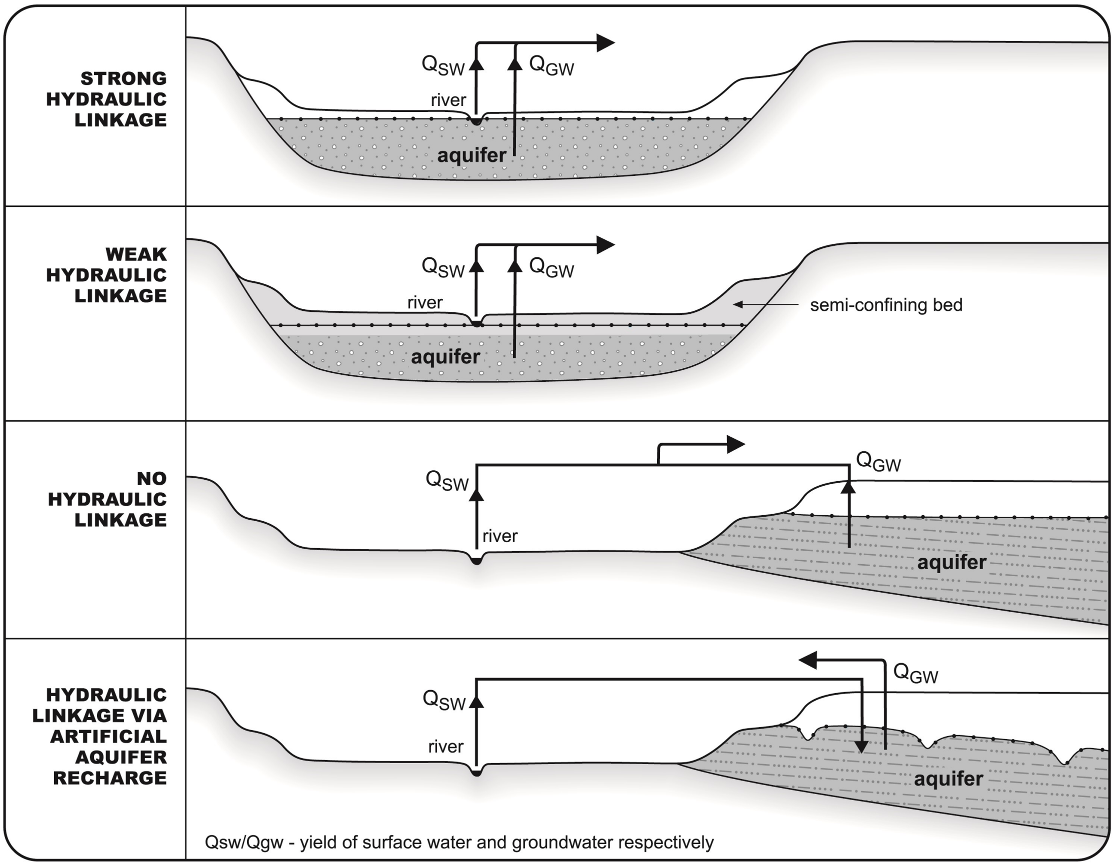


Figure 6.9 Groundwater/surface-water relations with implications for mode of conjunctive use

However, in the developing nations in particular, most current conjunctive use amounts to little more than a piecemeal coping strategy (rather than an integrated policy), and it is much more common for groundwater resources to be used continuously in irrigation and as a continuous base load for municipal supply. Urban water engineers, pressed by day-to-day problems often look for operationally simple arrangements, such as a single major water-supply source and a large water-treatment works, rather than more secure and resilient conjunctive solutions. A change in approach to consider all the water resources available to city to achieve a balance between short-term operational efficiency and long-term water-supply security. There are several good examples of conjunctive management and optimised resource use, such as in Lima-Peru and Bangkok-Thailand (Foster *et al*. 2010b), where the normal constraints have been overcome and the necessary capital investment for systematic conjunctive management mobilised.

There are significant challenges to promoting conjunctive use in established irrigation-canal command areas as a result of;

- socio-political dominance of 'head-water farmers' in irrigation canal-commands and their refusal to reduce surface-water intakes.
- a disconnect between irrigation engineers and the groundwater community.
- split institutional responsibility for surface-water and groundwater development and management.
- inadequate water resource and water-supply charging systems, with a large cost differential (as felt by users) between groundwater and surface water.

6.3.4 Groundwater Management Planning

'Good groundwater governance' requires the elaboration of an effective groundwater management plan (GW-MaP) (Box 6.6) for the local aquifer system in question, with agreed targets, desired outcomes, a programme of measures or interventions, financial support, clear time-frame, adequate monitoring, periodic review, and an appropriate level of integration within the hydrologic cycle by co-management with other components of water and land resources (Foster *et al*. 2015). GW-MaPs have another important governance function in that they help to harmonise the groundwater-related activities of all government organisations.

In many ways groundwater management planning is an art form, and a far from fashionable one. It is one, however, which is central to so-called adaptive management. The plan must be dynamic providing capacity for adaptation to change in technical knowledge and in external drivers (such as climate-change and land-use). Indicators of groundwater status (such as pre-defined water-table level or quality at a strategic monitoring site) can act as barometers of aquifer condition. It is important to emphasise that adaptive management is in no way inconsistent with groundwater planning, since a GW-MaP will on the one-hand have fixed targets (including those at catchment-scale critical for surface water and ecosystem health), which will be achieved by a programme of measures that will almost always require adjustment following periodic review of their effectiveness. The groundwater management planning process should be promoted by the responsible national groundwater ministry or agency (through provision of protocols and guidance) and undertaken by the corresponding local groundwater resource agency or office together with all relevant stakeholders. It will require co-mobilisation of financial investment for the demand management and/or pollution control measures required for plan implementation.

Whilst some types of aquifer system are relatively rapid to respond to changes in groundwater pumping and pollution load, and a response can be expected to manifest itself within 2 years, quality-related responses in thick aquifer systems can take a decade to become apparent. A carefully designed monitoring network is essential to avoid falling into a false sense of complacency when considering the initial aquifer response to newly applied pressures. Feedback from the first cycle of plan implementation should be used to up-grade the GW-MaP and, if necessary, to refine the underlying governance provisions.

Box 6.6 The Groundwater Management Planning Process

Step 1 – Characterisation of priority aquifers (also referred to as 'groundwater management units' or 'groundwater bodies')
● Physical delineation of the system considering groundwater flow regime from natural recharge to discharge zones, whilst taking account of major man-made perturbations
● Evaluating the importance of the system to socio-economic development and to ecosystem conservation
● Assessing pressures on the system and its susceptibility and vulnerability to irreversible degradation (through land subsidence, salinisation, and persistent pollution)

Step 2– Assessment of groundwater resource status
● Geographical scale of the aquifer system and size of its storage reserve, which will determine how identifiable it will be for local stakeholders
● Degree of connectivity with surface water, determining whether conjunctive management is essential to achieve improved conservation of both groundwater and surface-water resources
● Level of contemporary recharge, since if the use of non-renewable groundwater resources is likely, it should be subject to more rigorous control
● Aquifer susceptibility to degradation and groundwater vulnerability to pollution, which together will determine urgency for action and whether comprehensive regulatory provisions are essential

Step 3 – Plan consultation process
● By definition participatory process, with final decisions resting with mandated government agency
● Consultation must be fully informed on groundwater resource trends and quality status, potential consequences of 'no management action' and options as regard management measures
● Some governance provisions (and sets of management measures) will need to be specifically tailored to certain facets of the socio-economic situation conditioning groundwater use, dependence, management, and protection

Step 4– Elaboration of planning document
● Identifying regulatory measures, economic incentives, and policy changes to address groundwater management needs within the given legal and institutional framework
● Identifying a technically and economically sound array of demand-side and supply-side measures to re-balance groundwater withdrawals and avoid irreversible damage
● Definition of stakeholder roles, and specification of how these roles will be factored into planning and management and be maintained
● Recognising any dependence upon essentially non-renewable groundwater resources, requiring additional governance provisions and management strategies
● Dealing with point-source pollution (which is relatively easy once the problem has been identified)
● Addressing diffuse-source pollution threat from intensive agricultural land use through promulgation of 'best farming practices'

Step 5 – Implementing and reviewing plans
● Plan must include an operational timeframe and management monitoring network endorsed by the responsible national/local groundwater agency and all relevant stakeholders
● Implementation will often require strengthening of institutional linkages, raising substantial capital investment, improving groundwater use/protection measures and aquifer response monitoring
● Promoting more effective public information campaigns and undertaking capacity building

Foster S and MacDonald A 2021. Groundwater Management. In: RC Ferrier and A Jenkins (eds.) Handbook of Catchment Management. Second Edition. Wiley pp 125-152

A GW-MaP should be dynamic in nature and implemented as a structured, stepwise long-term (5-10 year) sequence. Indicators of resource status (for example a predefined groundwater level or quality at a strategic monitoring site) can act as barometers of aquifer condition and facilitate the adaptive management approach. The process proposed conforms in general terms with that adopted by both the EU-Water Framework Directive (EC 2000) and the GEF Groundwater Governance Programme (FAO-UN 2016), and is transparent consultative and evidence-based, thereby creating a framework for cooperation and accountability The resulting plans take the form of a formal public document with budgeted, time-bound, actions and outcomes that can be evaluated.

As discussed above, groundwater is quintessentially a local resource, and is best managed as close as possible to local stakeholders. There are, however, some exceptions to this rule, for example where a larger aquifer system extends across international frontiers and some form of transboundary cooperation will be required for its successful governance. The same applies to large aquifers extending across state boundaries in federal countries (Box 6.8).

Box 6.7 Murray–Darling Basin Plan of Australia – Key Groundwater Lessons

The Murray–Darling River Basin is a very large basin, covering over 1 000 000 km^2 of eastern Australia, spanning the jurisdiction of five semi-independent territorial authorities, and containing some 9200 irrigated agricultural enterprises. Over the last few decades, a combination of inadequately controlled land use and water abstraction for irrigated agriculture, and increasingly severe natural droughts, has led to marked degradation of the water environment, especially in the 'downstream states' (most notably South Australia).

In 2012, all levels of government agreed that a Murray–Darling Basin Plan should be defined as priority, with the aim of restoring the water environment and making provisions to support farming, industrial, and urban water use at sustainable levels. At its heart, the Basin Plan defined the amount of water that could be consumed annually, whilst leaving enough for river flow and aquatic wetlands. It was further agreed that complementary plans for individual sub-catchments and aquifer units should be implemented by state governments that included sustainable diversion limits, water environment needs, and salinity and quality management measures to ensure that, whilst meeting local requirements, the overall needs of the basin would be respected.

However, by 2018, it has becoming clear that the Basin Plan was not delivering its key objectives and the water environment remained of poor status with continuing downward trends in low river flows, increasing land and water salinity, and widespread loss of ecosystem functions. An independent judicial review has been conducted and reported in January 2018 that 'politics rather than science have driven the setting of limits on water-use for agriculture', although this has been strongly denied by the Murray–Darling Basin Authority. The Murray–Darling Basin includes 80 individual 'groundwater management units' (sub-aquifers) that required individual 'water management plans', with two specific priority issues widely needing to be addressed:

● lack of control on groundwater abstraction, use, and wastage in the northern part of the basin (Queensland and New South Wales), a large land area with low river flow reliability and major reliance on water wells for agricultural irrigation, which has led to serious groundwater-level decline (from 20–90 m) accompanied by significant nutrient pollution

● inadequate control and preparation for the impacts of land use change in the southern part of the basin (Victoria and South Australia), which has witnessed major clearing of natural vegetation to make way for surface-water irrigated agriculture resulting in a many-fold increase in groundwater recharge, rising water-table (by 5–30 m) and consequent land-drainage problems, accompanied by mobilisation of salts naturally accumulated in the vadose zone, together with soil salinisation and saline river baseflow.

Questions thus arise as to whether the Basin Plan and its implementation were in part founded upon inadequate conceptualisation of (i) the balance between ‘consumptive use’ and ‘groundwater return flows’ when so-called ‘irrigation efficiency’ is increased, and (ii) the major changes of groundwater recharge and its salinity following the clearing of natural vegetation for irrigated agriculture in semi-arid climates. The recuperation of overexploited aquifers in the north and the mitigation of rising groundwater salinity in the south will require substantial revisions to the Basin Plan, with much greater constraints in land and water use, and consistent and closely monitored implementation of policy over future decades. But the key ‘groundwater lesson’ of this important and well-documented experience is that basin-level water-resource management plans must be based on refined hydrogeologic understanding and careful attention to management detail.

Source: Based on Murray–Darling Basin Commission 2000; Grafton et al. 2018; Nogrady 2019.

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