1 Introduction

1.1 Scope of this book

This book is about the study of hydrogeology and the significance of groundwater in the terrestrial aquatic environment. Water is a precious natural resource, without which there would be no life on Earth. We, ourselves, are comprised of two-thirds water by body weight. Our everyday lives depend on the availability of inexpensive, clean water and safe ways to dispose of it after use. Water supplies are also essential in supporting food production and industrial activity. As a source of water, groundwater obtained from beneath the Earth’s surface is often cheaper, more convenient and less vulnerable to pollution than surface water.

Groundwater, because it is unnoticed underground, is often unacknowledged and undervalued resulting in adverse environmental, economic and social consequences. The over-exploitation of groundwater by uncontrolled pumping can cause detrimental effects on neighbouring boreholes and wells, land subsidence, saline water intrusion and the drying out of surface waters and wetlands. Without proper consideration for groundwater resources, groundwater pollution from uncontrolled uses of chemicals and the careless disposal of wastes on land cause serious impacts requiring difficult and expensive remediation over long periods of time. Major sources of contamination include agrochemicals, industrial and municipal wastes, tailings and process wastewater from mines, oil field brine pits, leaking underground storage tanks and pipelines, and sewage sludge and septic systems.

Achieving sustainable development of groundwater resources by the future avoidance of over-exploitation and contamination is an underlying theme of this book. By studying topics such as the properties of porous material, groundwater flow theory and geological processes, well hydraulics, groundwater chemistry, environmental isotopes, contaminant hydrogeology and techniques of groundwater remediation and aquifer management, it is our responsibility to manage groundwater resources to balance environmental, economic and social requirements and achieve sustainable groundwater development (Fig. 1.1).

The 10 chapters of this book aim to provide an introduction to the principles and practice of hydrogeology and to explain the role of groundwater in the aquatic environment. Chapter 1 provides a definition of hydrogeology and charts the history of the development of hydrogeology as a science. The water cycle is described and the importance of groundwater as a natural resource is explained. The legislative framework for the protection of groundwater resources is introduced with reference to industrialized and developing countries. Chapters 2–4 discuss the principles of physical and chemical hydrogeology that are fundamental to an understanding of the occurrence, movement and chemistry of groundwater in the Earth’s crust. The relationships between geology and aquifer conditions are demonstrated both in terms of flow through porous material and rock-water interactions. Chapter 5 provides an introduction to the application of environmental isotopes in hydro geological investigations for assessing the age of groundwater recharge and includes a section on noble gases to illustrate the identification of palaeowaters and aquifer evolution.

In the second half of this book, Chapters 6 and 7 provide an introduction to the range of field investigation techniques used in the assessment of
catchment water resources and includes stream gauging methods, well hydraulics and tracer techniques. The protection of groundwater from surface contamination requires knowledge of solute transport processes and Chapter 8 introduces the principles of contaminant hydrogeology. Chapter 8 also covers water quality criteria and discusses the nature of contamination arising from a variety of urban, industrial and agricultural sources and also the causes and effects of saline intrusion in coastal regions. The following Chapter 9 discusses methods of groundwater pollution remediation and protection, and includes sections that introduce risk assessment methods and spatial planning techniques. The final chapter, Chapter 10, returns to the topic of catchment water resources and demonstrates integrated methods for aquifer management together with consideration of groundwater interactions with rivers and wetlands, as well as the potential impacts of climate change on groundwater.

Each chapter in this book concludes with recommended further reading to help extend the reader’s knowledge of hydrogeology. In addition, for students of hydrogeology, a set of discursive and numerical exercises is provided in Appendix 10 to provide practice in solving groundwater problems. The remaining appendices include data and information in support of the main chapters of this book and will be of wider application in Earth and environmental sciences.

1.2 What is hydrogeology?

Typical definitions of hydrogeology emphasize the occurrence, distribution, movement and geological interaction of water in the Earth’s crust. Hydrogeology
is an interdisciplinary subject and also encompasses aspects of hydrology. Hydrology has been defined as the study of the occurrence and movement of water on and over the Earth’s surface independent of the seepage of groundwater and springs which sustain river flows during seasonal dry periods. However, too strict a division between the two subjects is unhelpful, particularly when trying to decipher the impact of human activities on the aquatic environment. How well we respond to the challenges of pollution of surface water and groundwater, the impacts of over-exploitation of water resources, and the potential impact of climate change will depend largely on our ability to take a holistic view of the aquatic environment.

1.3 Early examples of groundwater exploitation

The vast store of water beneath the ground surface has long been realized as an invaluable source of water for human consumption and use. Throughout the world, springs fed by groundwater are revered for their life-giving or curative properties (see Fig. 1.2), and utilization of groundwater long preceded understanding of its origin, occurrence and movement.

Evidence for some of the first wells to be used by modern humans is found in the far west of the Levant on the island of Cyprus. It is likely that Cyprus was first colonized by farming communities in the Neolithic, probably sailing from the Syrian coast about 9000 BC (Mithen 2012). Several Neolithic wells have been excavated from known settlements in the region of Mylouthkia on the west coast of Cyprus (Peltenberg et al. 2000). The wells are 2 m in diameter and had been sunk at least 8 m through sediment to reach groundwater in the bedrock. The wells lacked any internal structures or linings other than small niches within the walls, interpreted as hand- and foot-holds to allow access during construction and for cleaning. When abandoned, the wells were filled with domestic rubbish which dates from 8300 BC, indicating that the wells had been built at or just before this date (Mithen 2012).

Wells from the Neolithic period are also recorded in China, a notable example being the wooden Hemudu well in Yuyao County, Zhejiang Province, in the lower Yangtze River coastal plain. Based on carbon-14 dating of the well wood, it is inferred that the well was built in 3710 ± 125 BC (Zhou et al. 2011). The depth of the well was only 1.35 m with over 200 wooden components used in its construction comprising an outer part of 28 piles surrounding a pond, and an inner part, the wooden well itself, in the centre of the pond. The walls of the well were lined with close-set timber piles reinforced by a square wooden frame. The 28 piles in the outer part of the site may have been part of a shelter for the well, suggesting awareness by the people of the Hemudu culture that their water source required protection (Zhou et al. 2011).

Evidence for the appearance of dams, wells and terraced walls, three methods of water management, is widespread by the Early Bronze Age from 3600 BC, as part of what has been termed a ‘Water Revolution’ (Mithen 2012). The recognisable
development of groundwater as part of a water management system also dates from ancient times, as manifest by the wells and horizontal tunnels known as qanats (ghanats) or aflaj (singular, falaj), both Arabic terms describing a small, artificial channel excavated as part of a water distribution system, which appear to have originated in Persia about 3000 years ago. Examples of such systems are found in a band across the arid regions extending from Afghanistan to Morocco. In Oman, the rural villages and aflaj-supplied oases lie at the heart of Omani culture and tradition. The system of participatory management of communal aflaj is an ancient tradition in Oman by which common-property flows are channelled and distributed to irrigation plots on a time-based system, under the management of a local community (Young 2002).

Figure 1.3 shows a cross-section along a qanat with its typical horizontal or gently sloping gallery laboriously dug through alluvial material, occasionally up to 30 km in length, and with vertical shafts dug at closely spaced intervals to provide access to the tunnel. Groundwater recharging the alluvium in the mountain foothills is fed by gravity flow from beneath the water table at the upper end of the qanat to a ground surface outlet and irrigation canal on the arid plain at its lower end (Fig. 1.4). The depth of the mother well (Fig. 1.3) is normally less than 50 m. Discharges, which vary seasonally with water table fluctuations, seldom exceeding 3 m\(^3\)s\(^{-1}\).

Such early exploitation of groundwater as part of a sophisticated engineered system is also evident in the supply of water that fed the fountains of Rome (see Box 1.1). Less sophisticated but none the less significant, hand-operated pumps installed in wells and boreholes have been used for centuries to obtain water supplies from groundwater found in surface geological deposits. The fundamental design of hand pumps of a plunger (or piston) in a barrel (or cylinder) is recorded in evidence from Greece in about 250 BC (Williams 2009). It is assumed that wooden pumps were in continuous use after the end of the Roman period, although examples are difficult to find given that wooden components perish in time. In Britain, the majority of existing hand-operated pumps are cast iron, dating from the latter part of

![Fig. 1.3 Longitudinal section of a qanat. (Based on Beaumont 1968 and Biswas 1972.)](image-url)
the nineteenth century (see Plate 1.1). Although entirely redundant now due to issues of unreliability in dry weather and the risk of surface-derived pollution, private and domestic pumps were once widely used for supplying houses, farms, inns, almshouses, hospitals, schools and other institutions in cities, towns and villages. Ultimately, as mains water was introduced across Britain from the nineteenth century onwards following the Public Health (Water) Act of 1878, the village pump was superseded by the communal outdoor tap or water pillar, itself made redundant when piped water was provided to individual houses.

### 1.4 History of hydrogeology

It is evident from the examples mentioned previously that exploitation of groundwater resources long preceded the founding of geology, let alone hydrogeology. Western science was very slow in achieving an understanding of the Earth’s hydrological cycle. Even as late as the seventeenth century it was generally assumed that water emerging from springs could not be derived from rainfall, in that it was believed that the quantity was inadequate and the Earth too impervious to permit infiltration of rain water far below the surface. In contrast, Eastern philosophical writings had long considered that the Earth’s water flowed as part of a great cycle involving the atmosphere. About 3000 years ago, the sacred

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**Box 1.1 The aqueducts of Rome**

The remarkable organization and engineering skills of the Roman civilization are demonstrated in the book written by Sextus Julius Frontinus and translated into English by C.E. Bennett (1969). In the year 97 AD, Frontinus was appointed to the post of water commissioner, during the tenure of which he wrote the *De Aquis*. The work is of a technical nature, written partly for his own instruction, and partly for the benefit of others. In it, Frontinus painstakingly details every aspect of the construction and maintenance of the aqueducts existing in his day.

For more than 400 years, the city of Rome was supplied with water drawn from the River Tiber, and from wells and springs. Springs were held in high esteem, and treated with veneration. Many were believed to have healing properties, such as the springs of Juturna, part of a fountain known from the south side of the Roman Forum. As shown in Fig. 1.5 and illustrated in Plate 1.2, by the time of Frontinus, these supplies were augmented by several aqueducts, presumably giving a reliable supply of good quality water, in many cases dependent on

*continued on p. 6*
groundwater. For example, the Vergine aqueduct brought water from the estate of Lucullus where soldiers, out hunting for water, were shown springs which, when dug out, yielded a copious supply. Frontinus records that the intake of Vergine is located in a marshy spot, surrounded by a concrete enclosure for the purpose of confining the gushing waters. The length of the water course was 14 105 paces (20.9 km). For 19.1 km of this distance the water was carried in an underground channel, and for 1.8 km above ground, of which 0.8 km was on substructures at various points, and 1.0 km on arches. The source of the Vergine spring, located approximately 13 km east of Rome in the small town of Salone, is shown on a modern hydrogeological map (Boni et al. 1986) as issuing from permeable volcanic rocks with a mean discharge of 1.0 m$^3$s$^{-1}$ (Fig. 1.5). Frontinus also describes the Marcia aqueduct with its intake issuing from a tranquil pool of deep green hue. The length of the water-carrying conduit is 61 710½ paces (91.5 km), with 10.3 km on arches. Today, the source of the Marcia spring is known to issue from extensively fractured limestone rocks with a copious mean discharge of 5.4 m$^3$s$^{-1}$.

After enumerating the lengths and courses of the several aqueducts, Frontinus enthuses: ‘with such an array of indispensible structures carrying so many waters, compare, if you will, the idle Pyramids or the useless, though famous, works of the Greeks!’ To protect the aqueducts from wilful pollution, a law was introduced such that: ‘No one shall with malice pollute the waters where they issue publicly. Should any one pollute them, his fine shall be 10 000 sesterces’ which, at the time, was a very large fine. Clearly, the ‘polluter pays’ principle was readily

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**Fig. 1.5** Map of the general geology in the vicinity of Rome showing the location of the spring sources and routes of Roman aqueducts. (Based on Bennett 1969 and Boni et al. 1986.)
Hindu Vedas texts of India explained the Earth’s water movements in terms of cyclical processes of evaporation, condensation, cloud formation, rainfall, river flow and water storage (Chandra 1990).

A clear understanding of the hydrological cycle was achieved by the end of the seventeenth century. The French experimentalists Pierre Perrault (1611–1680) and Edme Mariotte (ca. 1620–1684) made measurements of rainfall and runoff in the River Seine drainage basin, and the English astronomer Edmond Halley (1656–1742) demonstrated that evaporation of seawater was sufficient to account for all springs and stream flow (Halley 1691). Over 100 years later, the famous chemist John Dalton (1766–1844) made further observations of the water cycle, including a consideration of the origin of springs (Dalton 1799).

One of the earliest applications of the principles of geology to the solution of hydrological problems was made by the Englishman William Smith (1769–1839), the ‘father of English geology’ and originator of the epoch-making Map of England (1815). During his work as a canal and colliery workings surveyor in the west of England, Smith noted the various soils and the character of the rocks from which they were derived and used his knowledge of rock succession to locate groundwater resources to feed the summit levels of canals and supply individual houses and towns (Mather 1998).

In Britain, the industrial revolution led to a huge demand for water resources to supply new towns and cities, with Nottingham, Liverpool, Sunderland and parts of London all relying on groundwater. This explosion in demand for water gave impetus to the study of the economic aspects of geology. It was at this time that Lucas (1874) introduced the term ‘hydrogeology’ and produced the first real hydrogeological map (Lucas 1877). Towards the end of the nineteenth century, William Whitaker, sometimes described as the ‘father of English hydrogeology’, and an avid collector of well records, produced the first water supply memoir of the Geological Survey (Whitaker and Reid 1899) in which the water supply of Sussex is systematically recorded.

The drilling of many artesian wells stimulated parallel activity in France during the first half of the nineteenth century. The French municipal hydraulic engineer Henry Darcy (1803–1858) studied the movement of water through sand and from empirical observations defined the basic equation, universally known as Darcy’s Law that governs groundwater flow in most alluvial and sedimentary formations. Darcy’s Law is the foundation of the theoretical aspects of groundwater flow and his work was extended by another Frenchman, Arsène Dupuit (1804–1866), whose name is synonymous with the equation for axially-symmetric flow towards a well in a permeable, porous medium.

The pioneering work of Darcy and Dupuit was followed by the German civil engineer, Adolph Thiem (1836–1908), who made theoretical analyses of problems concerning groundwater flow towards wells and galleries, and by the Austrian Philip Forchheimer (1852–1933) who, for the first time, applied advanced mathematics to the study of hydraulics. One of his major contributions was
a determination of the relationship between equipotential surfaces and flow lines. Inspired by earlier techniques used to understand heat flow problems, and starting with Darcy’s Law and Dupuit’s assumptions, Forchheimer derived a partial differential equation, the Laplace equation, for steady groundwater flow. Forchheimer was also the first to apply the method of mirror images to groundwater flow problems; for example, the case of a pumping well located adjacent to a river.

Much of Forchheimer’s work was duplicated in the United States by Charles Slichter (1864–1946), apparently oblivious of Forchheimer’s existence. However, Slichter’s theoretical approach was vital to the advancement of groundwater hydrology in America at a time when the emphasis was on exploration and understanding the occurrence of groundwater. This era was consolidated by Meinzer (1923) in his book on the occurrence of groundwater in the United States. Meinzer (1928) was also the first to recognize the elastic storage behaviour of artesian aquifers. From his study of the Dakota sandstone (Meinzer and Hard 1925, it appeared that more water was pumped from the region than could be explained by the quantity of recharge at outcrop, such that the water-bearing formation must possess some elastic behaviour in releasing water contained in storage. Seven years later, Theis (1935), again using the analogy between heat flow and water flow, presented the ground-breaking mathematical solution that describes the transient behaviour of water levels in the vicinity of a pumping well.

Two additional major contributions in the advancement of physical hydrogeology were made by Hubbert and Jacob in their 1940 publications. Hubbert (1940) detailed work on the theory of natural groundwater flow in large sedimentary basins, while Jacob (1940) derived a general partial differential equation describing transient groundwater flow. Significantly, the equation described the elastic behaviour of porous rocks introduced by Meinzer over a decade earlier. Today, much of the training in groundwater flow theory and well hydraulics, and the use of computer programmes to solve hydrogeological problems, is based on the work of these early hydrogeologists during the first half of the twentieth century.

The development of the chemical aspects of hydrogeology stemmed from the need to provide good quality water for drinking and agricultural purposes. The objective description of the hydrochemical properties of groundwater was assisted by Piper (1944) and Stiff (1951) who presented graphical procedures for the interpretation of water analyses. Later, notable contributions were made by Chebotarev (1955), who described the natural chemical evolution of groundwater in the direction of groundwater flow, and Hem (1959), who provided extensive guidance on the study and interpretation of the chemical characteristics of natural waters. Later texts by Garrels and Christ (1965) and Stumm and Morgan (1981) provided thorough, theoretical treatments of aquatic chemistry. By the end of the twentieth century, the previous separation of hydrogeology into physical and chemical fields of study had merged with the need to understand the fate of contaminants in the sub-surface environment. Contaminants are advected and dispersed by groundwater movement and can simultaneously undergo chemical processes that act to reduce pollutant concentrations. More recently, the introduction of immiscible pollutants, such as petroleum products and organic solvents into aquifers, has led to intensive research and technical advances in the theoretical description, modelling and field investigation of multi-phase systems. At the same time, environmental legislation has proliferated, and has acted as a driver in contaminant hydrogeology and in the protection of groundwater-dependent ecosystems. Today, research efforts are directed towards understanding natural attenuation processes as part of a managed approach to restoring contaminated land and groundwater and also in developing approaches to manage groundwater resources in the face of global environmental change.

Hence, hydrogeology has now developed into a truly interdisciplinary subject, and students who aim to become hydrogeologists require a firm foundation in Earth sciences, physics, chemistry, biology, mathematics, statistics and computer science, together with an adequate understanding of environmental economics and law, and government policy. Indeed, the principles of hydrogeology can be extended to the exploration of water on other planetary systems. Finding water on other planets is of great interest to the scientific community, second only to, and as a prerequisite for, detecting evidence for extraterrestrial life. As an example, a discussion of the evidence for water on Mars is given in Box 1.2.
Box 1.2 Groundwater on Mars?

Significant amounts of global surface hydrogen as well as seasonally transient water and carbon dioxide ice at both the North and South Polar Regions of Mars have been detected and studied for several years. The presently observable cryosphere, with volumes of 1.2–1.7 and 2–3 \times 10^6 \text{km}^3, respectively at the north and south poles, contains an equivalent global layer of water (EGL), if melted, of a few tens of metres deep (Smith et al. 1999; Farrell et al. 2009). Surface conditions on Mars are currently cold and dry, with water ice unstable at the surface except near the poles. Geologically recent, glacier-like landforms have been identified in the tropics and the mid-latitudes of Mars and are thought to be the result of obliquity-driven climate change (Forget et al. 2006). The relatively low volume of the EGL, coupled with widespread indications of chemical and geological landforms shaped by extensive palaeohydrological activity (Andrews-Hanna et al. 2010; Michalski et al. 2013), has resulted in an extensive search for other extant water resources, as well as evidence of how much water, hydrogen and oxygen was stripped from the Martian atmosphere about 4 Ga.

The most likely reservoir for extensive storage of water on Mars is groundwater and a global Martian aquifer was long been assumed to exist beneath the permafrost at a depth where crustal temperatures maintained by geothermal heating may support liquid water. Depending on latitude, this melting isotherm is tentatively estimated to be located between depths of 5–9 km and to be overlain by a layer of mixed soil and ice (Farrell et al. 2009; Harrison and Grimm 2009). It is thought that topographic and temperature gradients act to create a significant and prolonged difference in hydraulic head between the melt water-fed, polar groundwater ‘mound’ and the equatorial aquifer and this is assumed to facilitate significant subsurface flow over geological timescales to establish a global equilibrium depth to the melting isotherm (Baker et al. 1991; Clifford 1993).

Martian groundwater research advanced greatly in the 1980s and early 1990s when the currently accepted ideas regarding subterranean dynamics and subsurface structure were hypothesized. Contemporary investigations are examining these assumptions using the imagery and data now collected by the extensive array of Martian orbiters, landers and rovers, notably NASA’s Mars Odyssey satellite, launched in 2001, and the ESA Mars Express, in orbit since 2003. As Mars has a very thin atmosphere and no planetary magnetic field, solar cosmic rays reach the planet’s surface unimpeded where they interact with nuclei in subsurface layers up to 2 m in depth, producing gamma rays and neutrons of differing kinetic energies that leak from the surface. Instruments on board the Mars Odyssey orbiter can detect this nuclear radiation and use it to calculate the spatial and vertical distribution of soil water and ice in the upper permafrost layer (Plate 1.4) (Mitrofanov et al. 2004; Feldman et al. 2008). The results indicate water ice content ranging from 10 to 55% by mass, depending on latitude, with the highest concentrations in and around the southern subpolar region (Mitrofanov et al. 2004).

The Mars Advanced Radar for Subsurface and Ionospheric Sounding (MARSIS) instrument mounted on the Mars Express satellite analyses the reflection of active, low frequency radio waves to identify aquifers containing liquid water, since these have a significantly different radar signature to the surrounding rock. The initial findings of the MARSIS sensor effectively identified the basal interface of the ice-rich layered deposits in the South Polar Region with a maximum measured thickness of 3.7 km, with an estimated total volume of 1.6 \times 10^4 \text{km}^3, equivalent to a global water layer of approximately 11 m thick (Plaut et al. 2007). However, more recent studies using the MARSIS instrument presented a lack of direct evidence for the

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existence of subsurface water resources on Mars, possibly as a result of the high conductivity of the overlying crustal material (a mix of water ice and rock) resulting in a radar echo below the detectable limit of the MARSIS sensor (Farrell et al. 2009).

Other studies based on groundwater modelling approaches to explain various topographic features on Mars, such as chaotic terrains thought to have formed owing to disruptions of a cryosphere under high aquifer pore pressure, have concluded that a global confined aquifer system is unlikely to exist and, instead, regionally or locally compartmentalized groundwater flow is more probable (Harrison and Grimm 2009).

1.5 The water cycle

A useful start in promoting a holistic approach to linking ground and surface waters is to adopt the hydrological cycle as a basic framework. The hydrological cycle, as depicted in Fig. 1.6, can be thought of as the continuous circulation of water near the surface of the Earth from the ocean to the atmosphere and then via precipitation, surface runoff and groundwater flow back to the ocean. Warming of the ocean by solar radiation causes water to be evaporated into the atmosphere and transported by winds to the land masses where the vapour condenses and falls as precipitation. The precipitation is either returned directly to the ocean, intercepted by vegetated surfaces and returned to the atmosphere by evapotranspiration, collected to form surface runoff, or infiltrated into the soil and underlying rocks to form groundwater. The surface runoff and groundwater flow contribute to surface streams and rivers that flow to the ocean, with pools and lakes providing temporary surface storage.

### Table 1.1 Inventory of water at or near the Earth's surface.
(Adapted from Berner and Berner 1987.)

<table>
<thead>
<tr>
<th>Reservoir</th>
<th>Volume (x10^6 km^3)</th>
<th>Percentage of total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oceans</td>
<td>1370</td>
<td>97.25</td>
</tr>
<tr>
<td>Ice caps and glaciers</td>
<td>2.9</td>
<td>2.05</td>
</tr>
<tr>
<td>Deep groundwater (750–4000 m)</td>
<td>5.3</td>
<td>0.38</td>
</tr>
<tr>
<td>Shallow groundwater (&lt;750 m)</td>
<td>4.2</td>
<td>0.30</td>
</tr>
<tr>
<td>Lakes</td>
<td>0.125</td>
<td>0.01</td>
</tr>
<tr>
<td>Soil moisture</td>
<td>0.065</td>
<td>0.005</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.013</td>
<td>0.001</td>
</tr>
<tr>
<td>Rivers</td>
<td>0.0017</td>
<td>0.0001</td>
</tr>
<tr>
<td>Biosphere</td>
<td>0.0006</td>
<td>0.00004</td>
</tr>
<tr>
<td>Total</td>
<td>1408.7</td>
<td>100</td>
</tr>
</tbody>
</table>

Note:

1 As liquid equivalent of water vapour

Of the total water in the global cycle, Table 1.1 shows that saline water in the oceans accounts for 97.25%. Land masses and the atmosphere therefore contain 2.75%. Ice caps and glaciers hold 2.05%,
The approximate breakdown of direct groundwater discharge from continents to adjacent oceans and seas is estimated as follows: Australia 24 km$^3$ a$^{-1}$; Europe 153 km$^3$ a$^{-1}$; Africa 236 km$^3$ a$^{-1}$; Asia 328 km$^3$ a$^{-1}$; the Americas 729 km$^3$ a$^{-1}$; and major islands 914 km$^3$ a$^{-1}$ (Zektser and Loaiciga 1993). The low contribution from the Australian continent of direct groundwater discharge, despite its relatively large territory, is attributed to the widespread occurrence of low-permeability surface rocks that cover the continent. At the other extreme, the overall proximity of recharge areas to discharge areas is the reason why major islands of the world contribute over one-third of the world’s direct groundwater discharge to the oceans. The largest direct groundwater flows to oceans are found in mountainous areas of tropical and humid zones and can reach 10–15 x 10$^{-3}$ m$^3$ s$^{-1}$ km$^{-2}$. The smallest direct groundwater discharge values of 0.2–0.5 x 10$^{-3}$ m$^3$ s$^{-1}$ km$^{-2}$ occur in arid and arctic regions that have unfavourable recharge and permeability conditions (Zektser and Loaiciga 1993). For further discussion of groundwater discharge to the oceans, see Section 2.16.

Using a global hydrological model, Wada et al. (2010) assessed the amount of groundwater depletion, defined as the excess of abstraction over recharge replenishment, and estimated that for sub-humid and arid areas the rate of total global groundwater depletion has increased from 126 ± 32 km$^3$ a$^{-1}$ in 1960 to 283 ± 40 km$^3$ a$^{-1}$ in 2000. Groundwater depletion in 2000 equalled about 40% of the global annual groundwater abstraction, about 2% of the global annual groundwater recharge and about 1% of the global annual continental runoff, contributing a considerable amount (about 25%) of 0.8 ± 0.1 mm a$^{-1}$ to current sea level rise. Using a similar approach in which groundwater depletion was directly calculated using calibrated groundwater models, analytical approaches or volumetric budget analyses for multiple aquifer systems, Konikow (2011) estimated an average global groundwater depletion rate of 145 km$^3$ a$^{-1}$ during the period 2000–2008, equivalent to 0.4 mm a$^{-1}$ of sea-level rise, or 13% of the reported rise of 3.1 mm a$^{-1}$ during this period. Using an integrated water resources assessment model to simulate global terrestrial water stocks and flows, Pokhrel et al. (2012) estimated that the sum of unsustainable groundwater use, artificial reservoir water impoundment, climate-driven
changes in terrestrial water storage and the loss of water in closed basins, principally the Aral Sea, has contributed a sea-level rise of about 0.77 mm a\(^{-1}\) between 1961 and 2003, or about 42% of the observed sea-level rise. Considering a simulated mean annual unsustainable groundwater use during 1951–2000 of about 359 km\(^3\) a\(^{-1}\), Pokhrel et al. (2012) estimated, using the assumption of Wada et al. (2010) that 97% of unsustainable groundwater use ends up in the oceans, a cumulative sea-level rise due to groundwater over-abstraction during this period of 48 mm or about 1 mm a\(^{-1}\).

Taking the constant volume of water in a given reservoir and dividing by the rate of addition (or loss) of water to (from) it enables the calculation of a residence time for that reservoir. For the oceans, the volume of water present (1370 × 10\(^6\) km\(^3\); see Fig. 1.6) divided by the rate of river runoff to the oceans (0.037 × 10\(^6\) km\(^3\) a\(^{-1}\)) gives an average time that a water molecule spends in the ocean of about 37000 years. Lakes, rivers, glaciers and shallow groundwater have residence times ranging between days and thousands of years. Because of extreme variability in volumes and precipitation and evaporation rates, no simple average residence time can be given for each of these reservoirs. As a rough calculation, and with reference to Fig. 1.6 and Table 1.1, if about 6% (2220 km\(^3\) a\(^{-1}\)) of runoff from land is taken as active groundwater circulation, then the time taken to replenish the volume (4.2 × 10\(^4\) km\(^3\)) of shallow groundwater stored below the Earth’s surface is of the order of 2000 years. In reality, groundwater residence times vary from about 2 weeks to 10000 years (Nace 1971), and longer (Edmunds 2001). A similar estimation for rivers provides a value of about 20 days. These estimates, although a gross simplification of the natural variability, do serve to emphasize the potential longevity of groundwater pollution compared to more rapid flushing of contaminants from river systems.

As an agent of material transport to the oceans of products of weathering processes, groundwater probably represents only a small fraction of the total transport (see Table 1.2). Rivers (89% of total transport) represent an important pathway while groundwater accounts for a poorly constrained estimate of 2% of total transport in the form of dissolved materials (Garrels et al. 1975). More recent estimates by Zektser and Loaiciga (1993) indicate that globally the transport of salts via direct groundwater discharge is approximately 1.3 × 10\(^9\) ta\(^{-1}\), roughly equal to half of the quantity contributed by rivers to the oceans. Given a volumetric rate of direct groundwater discharge to the oceans of 2220 km\(^3\) a\(^{-1}\), the average dissolved solids concentration is about 585 mg L\(^{-1}\). This calculation illustrates the long residence time of groundwater in the Earth’s crust where its mineral content is concentrated by dissolution.

### 1.6 Groundwater as a natural resource

Groundwater is an important natural resource. Worldwide, more than 2 billion people depend on groundwater for their daily supply (Kemper 2004). Total global fresh water use is estimated at about 4000 km\(^3\) a\(^{-1}\) (Margat and Andréassian 2008) with

<table>
<thead>
<tr>
<th>Agent or Ocean</th>
<th>% of total material transport (Remarks)</th>
<th>% of total dissolved salts transport</th>
<th>Subsurface dissolved salts discharge (10(^9) t a(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface runoff</td>
<td>89 (Dissolved load 19%, suspended load 81%)</td>
<td>66</td>
<td>–</td>
</tr>
<tr>
<td>Glacier ice, coastal erosion, volcanic and wind-blown dust</td>
<td>–9 (Ice-ground rock debris, cliff erosion sediments, volcanic and desert-source dust)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Groundwater</td>
<td>2 (Dissolved salts similar to river water composition)</td>
<td>34</td>
<td>–</td>
</tr>
<tr>
<td>Pacific</td>
<td>–</td>
<td>520.5</td>
<td></td>
</tr>
<tr>
<td>Atlantic</td>
<td>–</td>
<td>427.8</td>
<td></td>
</tr>
<tr>
<td>Mediterranean Sea</td>
<td>–</td>
<td>42.5</td>
<td></td>
</tr>
<tr>
<td>Indian</td>
<td>–</td>
<td>295.5</td>
<td></td>
</tr>
<tr>
<td>Arctic</td>
<td>–</td>
<td>7.2</td>
<td></td>
</tr>
<tr>
<td>All oceans</td>
<td>–</td>
<td>1293.5</td>
<td></td>
</tr>
</tbody>
</table>
99% of the irrigation, domestic, industrial and energy use met by abstractions from renewable sources, either surface water or groundwater. Less than 1% (currently estimated at 30 km$^3$ a$^{-1}$) is obtained from non-renewable (fossil groundwater) sources mainly in three countries: Algeria, Libya and Saudi Arabia. With rapid population growth, groundwater abstractions have tripled over the last 40 years (Fig. 1.8), largely explained by the rapid increase in irrigation development stimulated by food demand in the 1970s and by the continued growth of agriculture-based economies (World Bank 2007). Emerging market economies such as China, India and Turkey, which still have an important rural population dependent on water supply for food production, are also experiencing rapid growth in domestic and industrial demands linked to urbanization. Urbanized and industrial economies such as the European Union and the United States import increasing amounts of ‘virtual water’ (Allan 1998, 2003) in food and manufactured products, while water use in industrial processes and urban environments has been declining, due to both technological changes in production processes and pollution mitigation efforts (WWAP 2009).

The increase in groundwater exploitation has been stimulated by the development of low-cost, power-driven pumps and by individual investment for irrigation and urban uses. Currently, aquifers supply approximately 20% of total water used globally, with this share rising rapidly, particularly in dry areas (IWMI 2007). Globally, 65% of groundwater utilization is devoted to irrigation, 25% to the supply of drinking water and 10% to industry. Groundwater resources account for more than 70% of the water used in the European Union, and are often the only source of supply in arid and semi-arid zones (100% in Saudi Arabia and Malta, 95% in Tunisia and 75% in Morocco). As demonstrated for the case of the Northwest Sahara Aquifer System (Box 1.3), irrigated

**Fig. 1.8** 1960–2000 trends in total global water demand (right axis, indexed for the year 2000), global groundwater abstraction (left axis, km$^3$ a$^{-1}$) and global groundwater depletion (left axis, defined as groundwater abstraction in excess of groundwater recharge in km$^3$ a$^{-1}$) for sub-humid and arid areas. (Adapted from Wada et al. 2010. Reproduced with permission from John Wiley & Sons.)
Box 1.3 The Northwest Sahara Aquifer System and the Ouargla Oasis, Algeria

The Sahara Basin covers an area of about 780,000 km² and includes two sub-basins separated by the M’zab High. The western sub-basin occupies about 280,000 km² and is covered by sand dunes of the Grand Erg Occidental and the eastern sub-basin extends over about 500,000 km² and is covered by the desert of the Grand Erg Oriental. The Sahara Basin is underlain by two major aquifers that comprise the Northwest Sahara Aquifer System (NWSAS) of Cretaceous age that extends below Algeria, Tunisia and Libya in North Africa (see Plate 2.7). The Lower Aquifer (the Continental Intercalaire) is composed of continental sandstone alternating with argillaceous layers and the Upper Aquifer (the Complex Terminal) is a multilayered aquifer consisting of sandstones and limestones. The thickness of the thicker, more extensive Lower Aquifer ranges between 200 and 1000 m, decreasing northeastwards to 125 m. The lower confining unit consists of argillaceous and marly formations of Devonian-Triassic age while the upper confining units consist of evaporites and clays of Upper Cretaceous age (Zektser and Everett 2004).

In western Algeria, the Lower and Upper Aquifers are almost independent but towards the Mediterranean coast the aquifers become interconnected or merge to form one aquifer system. Groundwater movement in the NWSAS is towards the south and southwest in the western sub-basin. In the eastern sub-basin, where the Complex Terminal aquifer is heavily exploited in Algeria and Tunisia, groundwater flows towards discharge areas, mainly desert depressions or oases known as ‘chotts’. The chotts supply irrigation water through traditional qanat systems (foggaras), with some 570 foggaras discharging about 90 × 10⁶ m³ a⁻¹ (Zektser and Everett 2004).

In the western sub-basin, the total dissolved solids content of groundwater in the Lower Aquifer ranges from 0.5 to 1 g L⁻¹. In the eastern sub-basin, salinity increases to 5 g L⁻¹. The concentration of total dissolved solids in the Upper Aquifer is about 2 g L⁻¹ in southern areas of the Grand Erg Oriental, increasing in concentration northeastwards from 2 to 5 g L⁻¹ at Tozeur in Tunisia. At Ouargla in Algeria, concentrations reach 8 g L⁻¹ in discharge areas (Zektser and Everett 2004).

Groundwater reserves in the NWSAS are estimated to be 60,000 km³ although, given the low rainfall amount, the aquifer system is generally considered a non-renewable aquifer system. Use of the superficial water table of the NWSAS extends back to ancient times and, from the middle of the nineteenth century, boreholes were drilled to access deeper parts of the aquifer. In Algeria, exploitation of groundwater from the aquifer system was about 150 × 10⁶ m³ until 1940 since when pumping has increased to about 260 × 10⁶ m³ a⁻¹ (Zektser and Everett 2004). By the 1970s, in the Ouargla Oasis of northern Algeria, there were approximately 2000 boreholes developed in the NWSAS in order to irrigate date palms (see Plate 1.5). In southern Tunisia, exploitation of the Complex Terminal aquifer increased from 9 × 10⁶ m³ a⁻¹ in 1900 to about 190 × 10⁶ m³ a⁻¹ in 1995. The impact of this intensive development on the aquifer system has been observed in discharge areas. In Algeria, the flow of springs decreased from 200 L s⁻¹ in 1900 to 6 L s⁻¹ in 1970, whereas in Tunisia the flow from springs decreased from 2500 L s⁻¹ in 1900 to virtually nil (less than 30 L s⁻¹) in 1990 (Zektser and Everett 2004). Traditional irrigation methods in the region used sustainable quantities of water but the more intensive modern irrigation methods used at present have led to a degraded water quality, decreased water levels and loss of artesian pressure, as well as salinization of the superficial water table and soil zone due to the drainage conditions. This salinized water is typically at a depth of 0.5 to 1.5 m below the soil surface and is detrimental to date palms (UNEP 2008).
agriculture is the principal user of groundwater from the major sedimentary aquifers of the Middle East, North Africa, North America and the Asian alluvial plains of the Punjab and Terai (WWAP 2009).

In regions of the world where the rate of groundwater abstraction exceeds the rate of natural groundwater recharge over extensive areas and for long time periods, over-exploitation or persistent groundwater depletion is the consequence. As shown by the global overview of Wada et al. (2010), in the year 2000 the rate of total global groundwater depletion is estimated to have increased to 283 km³ a⁻¹ (Fig. 1.8). Groundwater depletion rates were found to be highest in some of the world’s major agricultural regions including: northeast Pakistan and northwest India, northeast China, the Ogallala aquifer in the central United States (see Section 10.2.1), the San Joaquin aquifer in the Central Valley of California (see Box 2.7 in the next chapter), Iran, Yemen and south-east Spain.

Whether groundwater or surface water is exploited for water supply is largely dependent on the location of aquifers relative to the point of demand. A large urban population with a high demand for water would only be able to exploit groundwater if the aquifer, typically a sedimentary rock, has favourable storage and transmission properties, whereas in a sparsely populated rural district more limited but essential water supplies might be found in poor aquifers, such as weathered basement rock.

The relationship between population and geology can be inferred from Tables 1.3 and 1.4 which give a breakdown of water use by purpose and type (surface water and groundwater) for regions of England and Wales. Surface water abstraction for electricity generation is the largest category, but most of the freshwater abstracted for cooling purposes is returned to rivers and can be used again downstream. In terms of public water supply abstractions, groundwater is especially significant in the Southern (73% dependence on groundwater), Anglian (41%), Midlands (39%) and Thames (33%) regions and accounts for 42% of the total public water supply in these four regions. In these densely populated regions of south-east England and the English Midlands, good quality groundwater is obtained from the high-yielding Cretaceous Chalk and Triassic sandstone aquifers.

At the European level, groundwater is again a significant economic resource. As Table 1.5 reveals, large quantities of groundwater are abstracted in France, Germany, Italy and Spain (all in excess of 5000 × 10⁶ m³ a⁻¹) comprising 16% of the total water abstracted in these four countries. Overall, average annual water abstraction from groundwater accounts for 20% of the total, ranging from in excess of 50% for Austria, Belgium, Denmark and Luxembourg to,
Table 1.4 Estimated abstractions from groundwaters in England and Wales by purpose and Environment Agency region for 1996. All data are given as $10^6\text{m}^3\text{day}^{-1}$. (Reproduced from Environment Agency for England and Wales.)

<table>
<thead>
<tr>
<th>Region</th>
<th>Public water supply</th>
<th>Spray irrigation</th>
<th>Rural$^1$</th>
<th>Electricity supply</th>
<th>Other industry$^2$</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thames</td>
<td>1378 (33)$^4$</td>
<td>8</td>
<td>63</td>
<td>0</td>
<td>176</td>
<td>1625</td>
</tr>
<tr>
<td>Southern</td>
<td>1056 (73)</td>
<td>10</td>
<td>202</td>
<td>0</td>
<td>155</td>
<td>1423</td>
</tr>
<tr>
<td>Midlands</td>
<td>1024 (39)</td>
<td>34</td>
<td>14</td>
<td>9</td>
<td>138</td>
<td>1219</td>
</tr>
<tr>
<td>Anglian</td>
<td>735 (41)</td>
<td>68</td>
<td>51</td>
<td>0</td>
<td>218</td>
<td>1072</td>
</tr>
<tr>
<td>North East</td>
<td>441 (17)</td>
<td>40</td>
<td>97</td>
<td>0</td>
<td>135</td>
<td>713</td>
</tr>
<tr>
<td>South West</td>
<td>407 (32)</td>
<td>3</td>
<td>185</td>
<td>2</td>
<td>31</td>
<td>628</td>
</tr>
<tr>
<td>North West</td>
<td>262 (16)</td>
<td>2</td>
<td>9</td>
<td>0</td>
<td>121</td>
<td>394</td>
</tr>
<tr>
<td>Welsh</td>
<td>113 (6)</td>
<td>2</td>
<td>9</td>
<td>3</td>
<td>28</td>
<td>155</td>
</tr>
<tr>
<td>Total</td>
<td>5416 (31)</td>
<td>167</td>
<td>630</td>
<td>14</td>
<td>1002</td>
<td>7229</td>
</tr>
</tbody>
</table>

Notes:
1$^\text{and}^4$ See Table 1.3
3$^\text{Groundwater supply as a percentage of the total surface water and groundwater supply (see Table 1.5)}$

Table 1.5 Average annual water abstractions in European Union member states by source for the period 1980–1995. The data are ordered in terms of the percentage groundwater contributes to the total abstraction. (Reproduced from European Environment Agency Data Service.)

<table>
<thead>
<tr>
<th>Country</th>
<th>Surface water ($\times10^6\text{m}^3$)</th>
<th>Groundwater ($\times10^6\text{m}^3$)</th>
<th>Total</th>
<th>% Groundwater</th>
</tr>
</thead>
<tbody>
<tr>
<td>Denmark</td>
<td>9</td>
<td>907</td>
<td>916</td>
<td>99</td>
</tr>
<tr>
<td>Belgium</td>
<td>2385</td>
<td>4630</td>
<td>7015</td>
<td>66</td>
</tr>
<tr>
<td>Austria</td>
<td>1038</td>
<td>1322</td>
<td>2360</td>
<td>56</td>
</tr>
<tr>
<td>Luxembourg</td>
<td>28</td>
<td>29</td>
<td>57</td>
<td>51</td>
</tr>
<tr>
<td>Portugal</td>
<td>4243</td>
<td>3065</td>
<td>7308</td>
<td>42</td>
</tr>
<tr>
<td>Greece</td>
<td>3470</td>
<td>1570</td>
<td>5040</td>
<td>31</td>
</tr>
<tr>
<td>Italy</td>
<td>40000</td>
<td>12000</td>
<td>52000</td>
<td>23</td>
</tr>
<tr>
<td>United Kingdom</td>
<td>9344</td>
<td>2709</td>
<td>12053</td>
<td>22</td>
</tr>
<tr>
<td>Sweden</td>
<td>2121</td>
<td>588</td>
<td>2709</td>
<td>22</td>
</tr>
<tr>
<td>Spain</td>
<td>29901</td>
<td>5422</td>
<td>35323</td>
<td>15</td>
</tr>
<tr>
<td>Germany</td>
<td>51151</td>
<td>7711</td>
<td>58862</td>
<td>13</td>
</tr>
<tr>
<td>France</td>
<td>35195</td>
<td>5446</td>
<td>40641</td>
<td>13</td>
</tr>
<tr>
<td>Netherlands</td>
<td>10965</td>
<td>1111</td>
<td>12676</td>
<td>13</td>
</tr>
<tr>
<td>Ireland</td>
<td>945</td>
<td>125</td>
<td>1070</td>
<td>12</td>
</tr>
<tr>
<td>Finland</td>
<td>3011</td>
<td>335</td>
<td>3346</td>
<td>10</td>
</tr>
<tr>
<td>Total</td>
<td>193796</td>
<td>47570</td>
<td>241366</td>
<td>20</td>
</tr>
</tbody>
</table>

Note: The data given in this table should be considered with some reservation due to the lack of a common European procedure to estimate water resources.

respectively, only 10% and 12% for Finland and Ireland. The data given in Table 1.5 should be treated with caution given the lack of a common European procedure for estimating water resources and the fact that the data probably underestimate the contribution made by groundwater to municipal water supplies. According to a report commissioned for the European Commission (RIVM and RIZA 1991), about 75% of the inhabitants of Europe depend on groundwater for their water supply.

A similar picture emerges of the importance of groundwater for the population of North America. In Canada, almost 8 million people, or 26% of the population, rely on groundwater for domestic use. Five million of these users live in rural areas where groundwater is a reliable and cheap water supply.
that can be conveniently abstracted close to the point of use. The remaining groundwater users are located primarily in smaller municipalities. For example, 100% of the population of Prince Edward Island and over 60% of the populations of New Brunswick and the Yukon Territory rely on groundwater for domestic supplies. In Ontario, a province where groundwater is also used predominantly for supplying municipalities, 22% of the population are reliant on groundwater.

The abstraction of fresh and saline water in the United States from 1960 to 2000 as reported by Solley et al. (1998) and Hutson et al. (2004) is shown in Fig. 1.9. The estimated total abstraction for 1995 is $1.52 \times 10^6 \text{ m}^3 \text{ day}^{-1}$ for all offstream uses (all uses except water used instream for hydroelectric power generation) and is 10% less than the 1980 peak estimate. This total has varied by less than 3% since 1985. In 2000, the estimated total water use in the United States is $1.544 \times 10^6 \text{ m}^3 \text{ day}^{-1}$. Estimates of abstraction by source indicate that during 1995, total fresh surface water abstractions were $996 \times 10^6 \text{ m}^3 \text{ day}^{-1}$ and total groundwater abstractions were $293 \times 10^6 \text{ m}^3 \text{ day}^{-1}$ (or 23% of the combined freshwater abstractions). The respective figures for 2000 are $991 \times 10^6 \text{ m}^3 \text{ day}^{-1}$ and $316 \times 10^6 \text{ m}^3 \text{ day}^{-1}$, with 24% of freshwater abstractions from groundwater.

Total water abstraction for public water supply in the United States in 2000 is estimated to have been $1.63 \times 10^6 \text{ m}^3 \text{ day}^{-1}$, an 8% increase since 1995. This increase compares with a 7% growth in the population for the same period. Per capita public water supply use increased from about 678 L day$^{-1}$ in 1995 to 683 L day$^{-1}$ in 2000, but is still less than the per capita consumption of 696 L day$^{-1}$ recorded for 1990.

The two largest water use categories in 2000 were cooling water for thermoelectric power generation ($738 \times 10^6 \text{ m}^3 \text{ day}^{-1}$ of fresh and saline water) and irrigation ($518 \times 10^6 \text{ m}^3 \text{ day}^{-1}$ of freshwater). Of these two categories, irrigation accounts for the greater abstraction of freshwater. The area of irrigated land increased nearly 7% between 1995 and 2000 with an increase in freshwater abstraction of 2% for this water use category. The area irrigated with sprinkler and micro-irrigation systems has continued to rise and now comprises more than half of the total. In 2000, surface water was the primary source of irrigation water in the arid West and the Mountain States and groundwater was the primary source in the Central States. California, Idaho, Colorado and Nebraska combined accounted for one-half of the total irrigation water abstractions. California and Idaho accounted for 40% of surface water abstractions and California and Nebraska accounted for one-third of groundwater abstractions. In general,
groundwater abstractions for irrigation have increased significantly. In 1950, groundwater accounted for 23% of total irrigation water, while in 2000 it accounted for 42%.

The rapidly growing economy of China, with about 20% of the world’s population but only about 5–7% of global freshwater resources, has a high demand for groundwater. Groundwater is used to irrigate more than 40% of China’s farmland and supplies about 70% of drinking water in the dry northern and northwestern regions, with the past few decades having seen groundwater extraction increase by about 2.5 × 10^7 m^3 a^-1 to meet these needs. Consequently, groundwater levels below the arid North China Plain have dropped by as much as 1 m a^-1 between 1974 and 2000 (Qiu 2010). Further discussion of the significance of groundwater leading to economic development in the rural and expanding urban areas underlain by the Quaternary Aquifer of the North China Plain is presented in Box 1.4.

Currently, the largest threat to sustainable water supplies in China is the growing geographical mismatch between agricultural development and water resources. The centre of grain production in China has moved from the humid south to the water-scarce north over the past 30 years, as southern cropland is urbanized and more land is irrigated further north. As the north has become drier, increased food production in this region has largely relied on unsustainable overuse of local water resources, especially groundwater. Wasteful irrigation infrastructure, poorly managed water use, as well as fast industrialization and urbanization, have led to a serious depletion of groundwater aquifers, loss of natural habitats and water pollution (Yu 2011).

To provide more sustainable management of groundwater resources, China needs to build an integrated network to monitor surface water and groundwater, and use it to assess and set water policies through an integrated water-resource management system, backed up by legislation that sets out clear policies on data sharing, and penalties for those who do not comply (Yu 2011). Arguably, the biggest improvement could come in the agriculture sector, which already uses 70% of the China’s fresh water. For instance, to boost grain production and help maintain food security, China has a double-cropping system of growing wheat in winter and maize in summer, an unsustainable system that needs reconsidering. Meanwhile, the Chinese government hopes that a massive system of canals and pipes, to

Box 1.4 Groundwater Development of the Quaternary Aquifer of the North China Plain

The Quaternary Aquifer of the North China Plain represents one of the world’s largest aquifer systems and underlies extensive tracts of the Hai river basin and the catchments of the adjacent Huai and Huang (Yellow) river systems (Fig. 1.10) and beyond. This densely populated area comprises a number of extensive plains, known collectively as the North China Plain, and includes three distinct hydrogeological settings within the Quaternary aquifer system (Fig. 1.11). The semi-arid climate of north-eastern China is characterized by cold, dry winters (December–March) and hot, humid summers (July–September).

The Quaternary Aquifer supports an enormous exploitation of groundwater which has lead to large socio-economic benefits in terms of irrigated grain production, farming employment and rural poverty alleviation, together with urban and industrial water supply provision. An estimated water supply of 27 × 10^9 m^3 a^-1 in the Hai river basin alone was derived from wells and boreholes in 1988 (MWR 1992) but such large exploitation of groundwater has led to increasing difficulties in the last few years.

Given the heavy dependence on groundwater resources in the North China Plain, a number of concerns have been identified in recent years (Fig. 1.10) including a falling water table in the shallow freshwater aquifer, declining water levels in the deep freshwater aquifer, aquifer

continued
Salinization as a result of inadequately controlled pumping, and aquifer pollution from uncontrolled urban and industrial wastewater discharges. These issues are interlinked but do not affect the three main hydrogeological settings equally (Table 1.6). A range of water resources management strategies are considered by Foster et al. (2004) that could contribute to reducing and eventually eliminating the current aquifer depletion and include agricultural water-saving measures, changes in land use and crop regimes, artificial aquifer recharge of excess surface runoff, re-use of treated urban wastewater, and improved institutional arrangements that deliver these water savings and technologies while at the same time limiting further exploitation of groundwater for irrigated agriculture and industrial production (Foster et al. 2004).
Transfer $45 \times 10^9 \text{ m}^3 \text{ a}^{-1}$ from China’s wetter south to its arid north, will alleviate groundwater depletion once completed in 2050 (Qiu 2010).

### 1.7 Management and protection of groundwater resources in the United Kingdom

Approaches to the management and protection of groundwater resources have developed in parallel with our understanding of the economic and environmental implications of groundwater exploitation. In the United Kingdom, it is interesting to follow the introduction of relevant legislation, and how this has increased hydrogeological knowledge.

Hydrogeological experience prior to 1945 rested on a general awareness of sites likely to provide favourable yields, changes in chemistry downgradient from the point of recharge and hazards such as ground subsidence from groundwater over-exploitation. The Water Act 1945 provided legal control on water abstractions and this prompted an...
era of water resources assessment that included surveys of groundwater resources, the development of methods to assess recharge amounts (Section 5.5), and the initiation of groundwater studies. Increased abstraction from the Chalk aquifer during the 1950s and a drought in 1959 highlighted the effect of groundwater abstractions upon Chalk streams and stimulated the need for river baseflow studies (Section 6.7.1). Furthermore, the application of quantitative pumping test analysis techniques (Section 6.8.2) during this period revealed spatial variations in aquifer transmissivity and an association between transmissivity and topography.

The Water Resources Act 1963 led to the formation of 27 catchment-based authorities responsible for pollution prevention, fisheries, land drainage and water resources. The Act ushered in a decade of groundwater resources management that required the licensing of all abstractions in England and Wales. Under Section 14 of the Act, each authority was required to undertake a survey of resources and the Water Resources Board (abolished 1974) was established with the task of resource planning on a national scale. Regional groundwater schemes were developed in the context of river basin analysis for the purposes of river augmentation by groundwater, seasonal abstraction and artificial recharge. Scientific advancement in the application of numerical models to solve non-linear equations of groundwater flow permitted the prediction of future groundwater abstraction regimes.

The Water Act 1973 reflected the importance of water quality aspects and heralded the developing interest in groundwater quality. The Act led to the formation of 10 catchment-based regional water authorities with responsibility for all water and sewerage services and for all parts of the water cycle. The Control of Pollution Act 1974 extended the powers of the regional water authorities in controlling effluent discharge to underground strata and limited certain activities that could lead to polluting discharges. The first aquifer protection policies were developed at this time.

The Water Act 1989 separated the water supply and regulatory functions of the regional water authorities, and the new National Rivers Authority was set-up to manage water resources planning, abstraction control, pollution prevention and aquifer protection. A number of other Acts of Parliament followed including the Environmental Protection Act 1990 and the Water Resources Act 1991 that control the direct and indirect discharge of harmful substances into groundwater and are, in part, an enactment of the European Communities Directive on the Protection of Groundwater Against Certain Dangerous Substances (80/68/EEC). Further controls on discharges were implemented under the Groundwater Regulations 1998. In addition, the Water Resources Act 1991 consolidated all the provisions of the Water Resources Act 1963 in respect of the control of groundwater abstractions. In pursuing a strategy to protect both individual borehole sources and wider groundwater resources, the National Rivers Authority (1992) developed its practice and policy for the protection of groundwater with the aim of raising awareness of the vulnerability of groundwater to surface-derived pollution. Following the establishment of the Environment Agency under the Environment Act 1995 (when the National Rivers Authority, Her Majesty’s Inspectorate of Pollution and the Waste Regulatory Authorities were brought together) the practice and policy document for the protection of groundwater was updated (Environment Agency 1998).

Currently, the Environment Agency for England and Wales promotes a national framework for water resources protection in the context of emerging European initiatives, principally the Water Framework Directive (Section 1.8). The Water Act 2003 is one example of legislation to further the sustainable use of water resources and protect the environment. The Act links water abstraction licensing to local water resource availability and moves from a licensing system based on purpose of use to one based on volume consumed. The Act also introduces time-limited licences to give flexibility in making changes to abstraction rights in the face of climate change and increased demand. From 2012, licences without a time limit will be revoked, without a right to compensation, if an abstraction causes significant environmental damage.

### 1.8 European Union Water Framework Directive

The Water Framework Directive (WFD) establishing a framework for Community action in the field of water policy is a far-reaching piece of legislation
governing water resources management and protection in the European Union (Council of the European Communities 2000). The Directive (2000/60/EC) was adopted in December 2000 and requires Member States to enforce appropriate measures to achieve good ecological and chemical status of all water bodies by the end of the first, six-year cycle in 2015. The purpose of the Directive is to establish a framework for the protection of inland surface waters, transitional waters (estuaries), coastal waters and groundwater to prevent further deterioration of aquatic ecosystems and, with regard to their water needs, terrestrial ecosystems and wetlands. In its implementation, the WFD requires an integrated approach to river basin management and promotes sustainable water use based on long-term protection of available water resources. A specific purpose of the WFD is to ensure the progressive reduction of pollution of groundwater and prevent its further pollution.

Article 17 of the WFD required a proposal (2003/0210(COD)) from the Commission for a Groundwater Daughter Directive leading to the adoption of specific measures to prevent and control groundwater pollution and achieve good groundwater chemical status (Commission of the European Communities 2003). In addition, the proposal introduced measures for protecting groundwater from indirect pollution (discharges of pollutants into groundwater after percolation through the ground or subsoil). In the Groundwater Directive (Council of the European Union 2006), compliance with good chemical status is based on a comparison of monitoring data with quality standards existing in EU legislation on nitrates and plant protection and biocidal products which set threshold values (maximum permissible concentrations) in groundwater for a number of pollutants. With regard to pollutants that are not covered by EU legislation, the Directive (2006/118/EC) requires Member States to establish threshold values defined at the national, river basin or groundwater body levels, thus taking into account the great diversity of groundwater characteristics across the EU.

The Groundwater Directive sets out specific criteria for the identification of significant and sustained upward trends in pollutant concentrations, and for the definition of starting points for when action must be taken to reverse these trends. In this respect, significance is defined both on the basis of time series and environmental significance. Time series are periods of time during which a trend is detected through regular monitoring. Environmental significance describes the point at which the concentration of a pollutant starts to threaten to worsen the quality of groundwater. This point is set at 75% of the quality standard or the threshold value defined by Member States. Under the WFD, a comprehensive programme of measures to prevent or limit pollution of water, including groundwater, became operational. Monitoring results obtained through the application of the Groundwater Directive are used to design the measures to prevent or limit pollution of groundwater.

1.9 Management and protection of groundwater resources in the United States

Groundwater management in the United States is highly fragmented, with responsibilities shared among a large number of federal, state and local programmes. At each level of government, unique legal authorities allow for the control of one or more threats to groundwater, such as groundwater contamination arising from municipal, industrial, mining and agricultural activities.

Beginning with the 1972 amendments to the federal Water Pollution Control Act, and followed by the Safe Drinking Water Act 1974, the federal government’s role in groundwater management has increased. The introduction of the Resource Conservation and Recovery Act (RCRA) 1976 and the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) 1980, established the federal government’s current focus on groundwater remediation. With these acts, the federal government has directed billions of dollars in public and private resources towards cleaning up contaminated groundwater at ‘Superfund’ sites, RCRA corrective action facilities, and leaking underground storage tanks. In 1994, the National Academy of Sciences estimated that over a trillion dollars, or approximately $4000 per person in the United States, will be spent in the next 30 years on remediating contaminated soil and groundwater.

The approach to groundwater protection at the federal level has left the management of many
contaminant threats, for example hazardous materials used by light industries (such as dry cleaners, printers or car maintenance workshops), to state and local government authorities. Other groundwater threats, such as over-abstraction, are not generally addressed under federal law, but left to states and local governments to manage.

In 1984, the US Environmental Protection Agency (USEPA) created the Office of Ground Water Protection to initiate a more comprehensive groundwater resource protection approach and to lead programmes aimed at resource protection. Such programmes include the Wellhead Protection and Sole Source Aquifer Programs, which were established by Amendments to the Safe Drinking Water Act 1986. The Wellhead Protection Program (WHPP) encourages communities to protect their groundwater resources used for drinking water. The Sole Source Aquifer Program limits federal activities that could contaminate important sources of groundwater.

State groundwater management programmes are seen as critical to the future achievement of effective and sustainable protection of groundwater resources. In 1991, the USEPA established a Ground Water Strategy to place greater emphasis on comprehensive state management of groundwater as a resource through the promotion of Comprehensive State Ground Water Protection Programs (CSGWPPs) together with better alignment of federal programmes with state groundwater resource protection priorities (USEPA 1999).

1.10 Groundwater resources in developing countries

It remains one of the greatest challenges for the future to provide the basic amenity of a safe and reliable supply of drinking water to the entire world's population. Despite the efforts of governments, charities and aid agencies, many villagers have to walk hundreds of metres to obtain drinking water from sources that may be unprotected from contamination (Fig. 1.12). Pollution sources include unsewered pit latrines to dispose of human wastes, inorganic fertilizers and pesticides used in an effort to secure self-sufficiency in food production, and industrial wastes in urban areas.

In the developing world, groundwater is extensively used for drinking water supplies, especially in smaller towns and rural areas, where it is often the cheapest source. Groundwater schemes consist typically of large numbers of boreholes, often drilled on an uncontrolled basis, providing untreated, unmonitored and often unconnected supplies. Shallow dug wells continue to be constructed in some cases. Better yielding boreholes (100 L s⁻¹) are quite widely developed in larger towns to provide piped supplies. Even in these cases, raw water monitoring and treatment are often limited and intermittent. As an example of the significance of groundwater in leading the economic development of rural and expanding urban areas in developing countries, Box 1.5 provides a description of the groundwater potential of the African continent.

The Third World Water Forum held in Osaka, Japan, in March 2003 emphasized issues relating to the development and management of groundwater and recommended that many developing nations need to appreciate their social and economic dependency on groundwater and to invest in strengthening institutional provisions and building institutional capacity for its improved management. International development agencies and banks are urged to give higher priority to supporting realistic initiatives to strengthen governance of groundwater resources and local aquifer management. For the future, sustainable livelihoods, food security and key ecological systems will be dependent on such initiatives.
Box 1.5 Groundwater resources potential in Africa

Currently, there are more than 300 million people in Africa without access to safe drinking water, many of whom are amongst the poorest and most vulnerable in the world (JMP 2010; Hunter et al. 2010). Even for those with access to improved water sources, there is growing evidence that domestic water use will need to increase substantially to help lift people out of poverty (Grey and Sadoff 2007; Hunter et al. 2010). In Africa, groundwater is the major source of drinking water and its use for irrigation is forecast to increase substantially to counter growing food insecurity. At present, only 5% of arable land is irrigated (Siebert et al. 2010) and there is discussion of the need to increase irrigation to help meet rising demands for food production in the context of future, less reliable rainfall (UNEP 2010, Pfister et al. 2011).

Increasing reliable water supplies throughout Africa will depend on the development of groundwater (Giordano 2009; MacDonald and Calow 2009). However, quantitative, spatially explicit information on groundwater in Africa is required to characterize this resource in order to inform strategies to adapt to growing water demand associated not only with population growth but also climate variability and change. To address this significant knowledge gap, MacDonald et al. (2011, 2012) have developed the first quantitative continent-scale maps of groundwater storage and potential yields in Africa based on an extensive review of available maps, publications and data. From this analysis, MacDonald et al. (2012) estimated total groundwater storage in Africa to be \(0.66 \times 10^8\) km\(^3\) (range \(0.36–1.75 \times 10^8\) km\(^3\)). Not all of this groundwater storage is available for abstraction, but the estimated volume is more than 100 times estimates of annual renewable freshwater resources in Africa.

Groundwater resources are unevenly distributed in Africa. The largest groundwater volumes are found in the large sedimentary aquifers in the North African countries of Libya, Algeria, Egypt and Sudan (see Box 1.3). Crystalline basement rocks have the lowest yields, generally less than 0.5 L s\(^{-1}\), though a significant minority of areas has yields that are in excess of 1 L s\(^{-1}\). Highest borehole yields (>20 L s\(^{-1}\)) can be found in thick sedimentary aquifers, particularly in unconsolidated or poorly consolidated sediments. Depth to groundwater (Plate 1.6) is another important factor controlling accessibility and cost of developing groundwater resources. Water levels deeper than 50 m are not easily accessible by a hand pump. At depths >100 m the cost of borehole drilling increases significantly due to the requirement for more advanced drilling equipment.

The aquifer productivity map (Plate 1.7) shows that for many African countries, appropriately sited and constructed boreholes will be able to sustain community hand pumps (yields of 0.1–0.3 L s\(^{-1}\)) and, for most of the populated areas of Africa, groundwater levels are likely to be sufficiently shallow to be accessed using a hand pump. The majority of large groundwater stores in the sedimentary basins which can accommodate high yielding boreholes are in northern Africa. These are often far from population centres and have deep water levels and are therefore costly to develop. Away from the large sedimentary aquifers, the potential for borehole yields exceeding 5 L s\(^{-1}\) is not widespread, though higher yielding boreholes may be successful in some areas if accompanied by detailed hydrogeological investigation. The potential for intermediate boreholes yields of 0.5–5 L s\(^{-1}\), which could be suitable for small-scale household and community irrigation, or multiple-use water supply systems, is much higher, but will again require effective hydrogeological investigation and borehole siting. According to MacDonald et al. (2012), strategies for increasing the use of groundwater throughout Africa for irrigation and urban water supplies should not be based on the widespread expectation of high yielding boreholes but recognize that high borehole yields may occasionally be realized where a detailed knowledge of the local groundwater conditions has been developed.
1.11 Future challenges for groundwater management

Three aquifer characteristics determine whether groundwater resources will ultimately prove sustainable: vulnerability to pollution under contaminant pressure from the land surface; susceptibility to irreversible degradation from excessive exploitation; and renewability of storage reserves under current and future climate regimes. These characteristics vary widely by aquifer type and hydrogeologic setting. Vulnerability to pollution is generally linked to the accessibility of an aquifer. Aquifers that are shallow and readily recharged are more likely to suffer pollution from agrochemicals and urbanization (in particular, from low-cost wastewater disposal and careless disposal of industrial chemicals). Groundwater development and effluent disposal for urban water supply have far-reaching implications for public health, municipal planning and resource sustainability. In Europe, land use zoning is now used to protect vulnerable key aquifers that provide municipal water supply, as well as developing deeper, confined groundwater sources that are naturally protected from urban pollution (WWAP 2009).

The tension between private and public services derived from aquifers remains. More convergent and sustainable resource use will be achieved only through substantial investment in management operations on the ground, working primarily through community consultation and cross-sectoral policy dialogue (WWAP 2009). Such dialogue is supported by shared knowledge and common understanding of the current situation and future options. Good and reliable groundwater information is crucial to facilitate co-operation among stakeholders. All stakeholders should have easy access to reliable data on abstractions, water quality and groundwater levels. Adopting an adaptive management approach (Fig. 1.13) it should be possible to establish mutually acceptable regulations, adopted by all parties, based on a holistic definition of the aquifer system and understanding of the impacts of abstraction and contamination.

A significant challenge for the future development of groundwater sources is to raise political awareness of the issues involved. Unfortunately, increased scientific understanding of groundwater has not yet made a significant influence on resource policy-making or featured prominently in global or national water policy dialogues, with discussion too often on groundwater development rather than groundwater management. Also, governance and practical management are not well funded and, as a consequence, opportunities for utilizing groundwater resources sustainably and conjunctively are being lost and insufficient attention is being paid to the inter-relationship between groundwater and land-use planning (IAH 2006). Often, decisions on groundwater development and management objectives, and the allocation of human, financial and environmental resources to meet these objectives, are made by leaders in government, the private sector and civil society, not by groundwater professionals alone. Therefore, hydrogeologists must help inform the decisions of these leaders outside the water domain on such issues as spatial and development planning, demographic planning, health, education, agriculture, industry, energy, economic development and the environment (WWAP 2009).

Finally, water resources management has a clear and rapidly developing association with many other policy areas such as energy, land use and nature conservation. In this context, groundwater is part of an emerging integrated water resources management
approach that recognizes society’s views, reshapes planning processes, co-ordinates land and water resources management, recognizes water quantity and quality linkages, manages surface water and groundwater resources conjunctively and protects and restores natural systems while considering climate change.

Further reading


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