Introduction

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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 composed 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, well hydraulics, groundwater chemistry, environmental isotopes, contaminant hydrogeology and techniques of groundwater remediation and aquifer management, it is the responsibility of us all to manage groundwater resources to balance environmental, economic and social requirements and achieve sustainable groundwater development (Fig. 1.1).

The eight main 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 and 3 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 4 provides an introduction to the application of environmental isotopes in hydrogeological 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, Chapter 5 provides an introduction to the range of field investigation techniques used in the assessment of catchment water

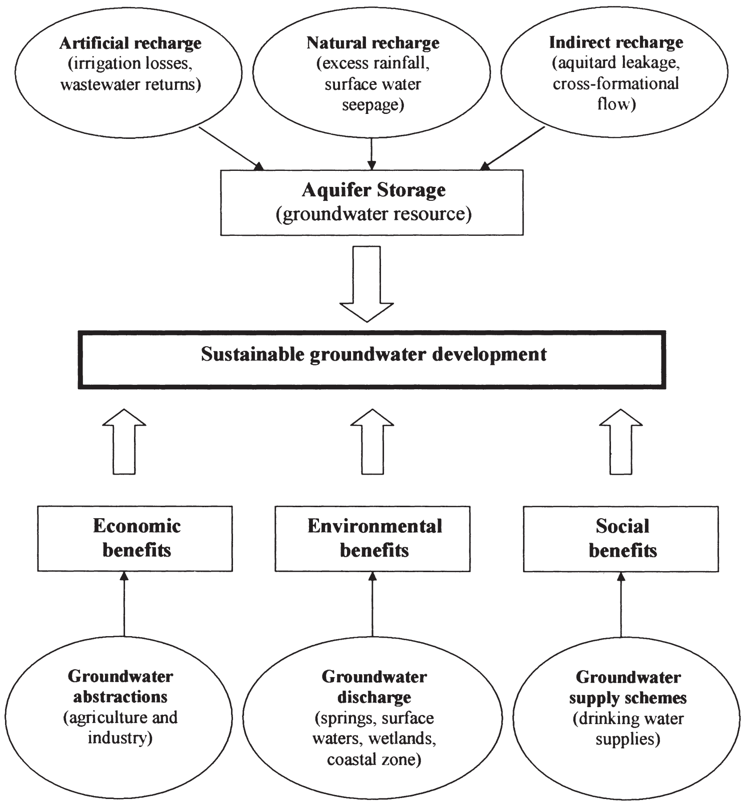

Fig. 1.1 The achievement of sustainable groundwater development through the balance of recharge inputs to aquifer storage (the groundwater resource) against discharge outputs for economic, environmental and human (social) benefits. After Hiscock et al. (2002).

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 6 introduces the principles of contaminant hydrogeology. Chapter 6 also covers water quality criteria and discusses the nature of contamination arising from a variety of urban, industrial and agricultural sources and in addition the causes and effects of saline intrusion in coastal regions. Following this Chapter 7 discusses methods of groundwater pollution remediation and protection, and includes sections that introduce risk assessment methods and spatial planning techniques. The final chapter, Chapter 8, 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 possible impact of climate change will depend largely on our ability to take a holistic view of the aquatic environment.

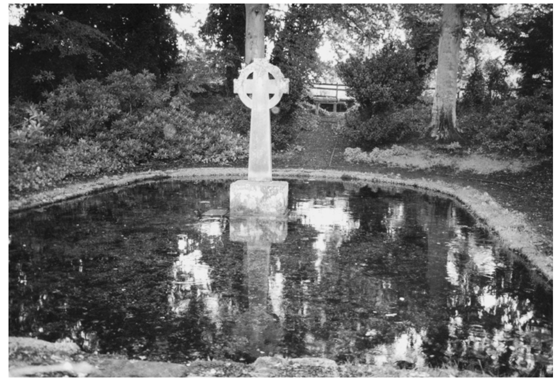

Fig. 1.2 Lady's Well in Coquetdale, northern England (National Grid Reference NT 953 028). Groundwater seeping from glacial deposits at the foot of a gently sloping hillside is contained within an ornamental pool floored with loose gravel. The site has been used since Roman times as a roadside watering place and was walled round and given its present shape in either Roman or medieval times. Anglo Saxon Saint Ninian, the fifth century apostle, is associated with the site, and with other 'wells' beside Roman roads in Northumberland, and marks the spot where Saint Paulinus supposedly baptized 3000 Celtic heathens in its holy water during Easter week, 627 AD. The name of the well, Lady's Well, was adopted in the second half of the twelfth century when the nearby village of Holystone became the home of a priory of Augustinian canonesses. The well was repaired and adorned with a cross, and the statue brought from Alnwick, in the eighteenth and nineteenth centuries. Today, groundwater overflowing from the pool supplies the village of Holystone.

1.3 Early examples of groundwater exploitation

The vast store of water beneath the ground surface has long been realized to be 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 (Fig. 1.2), and utilization of groundwater long preceded understanding of its origin, occurrence and movement.

Groundwater development 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, with 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 to feed the fountains of Rome (Box 1.1).

1.4 History of hydrogeology

As is evident from the above examples, exploitation of groundwater resources long preceded the founding of geology, let alone hydrogeology. Even as late as the seventeenth century it was generally assumed that water emerging from springs could not be derived from rainfall, for it was believed that the quantity was inadequate and the Earth too impervious to permit

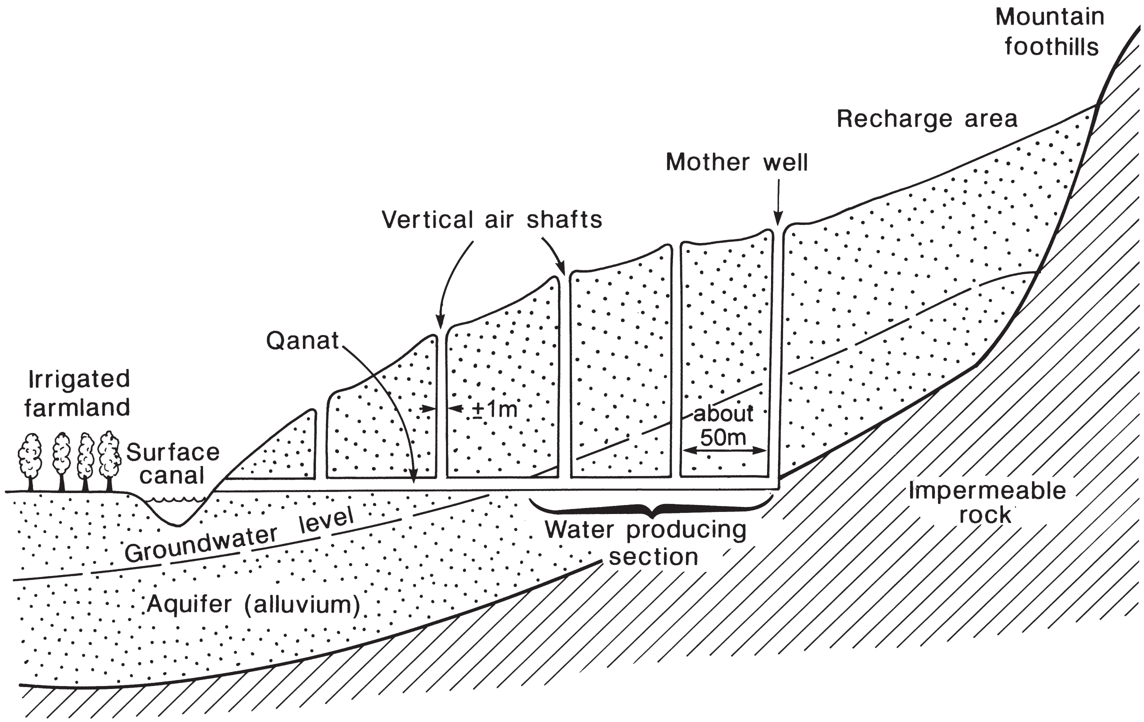

Fig. 1.3 Longitudinal section of a qanat. Based on Beaumont (1968) and Biswas (1972).

infiltration of rainwater far below the surface. 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 (c. 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 one hundred 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 & 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

Fig. 1.4 Irrigation canal supplied with water by a qanat or falaj in Oman. Photograph provided courtesy of M.R. Leeder.

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 material.

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 & 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 groundbreaking 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 programs to solve hydrogeological problems, is based on the work of these early hydrogeologists during the first half of the twentieth century.

The aqueducts of Rome

BOX 1.1

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 four hundred 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, 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 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 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). 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 indispensable 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 sestertii' which, at the time, was a very large fine. Clearly, the 'polluter pays' principle was readily adopted by the Romans! Further historical and architectural details of the ancient aqueducts of Rome are given by Bono and Boni (2001).

The Vergine aqueduct is one of only two of the original aqueducts still in use. The total discharge of the ancient aqueducts was in excess of 10 $m^3\ s^{-1}$ supplying a population at the end of the first century AD of about 0.5 million. Today, Rome is supplied with 23 $m^3\ s^{-1}$ of groundwater, mainly from karst limestone aquifers, and serving a population of 3.5 million (Bono & Boni 2001). Many of the groundwater sources are springs from the karst system of the Simbruini Mountains east of Rome.

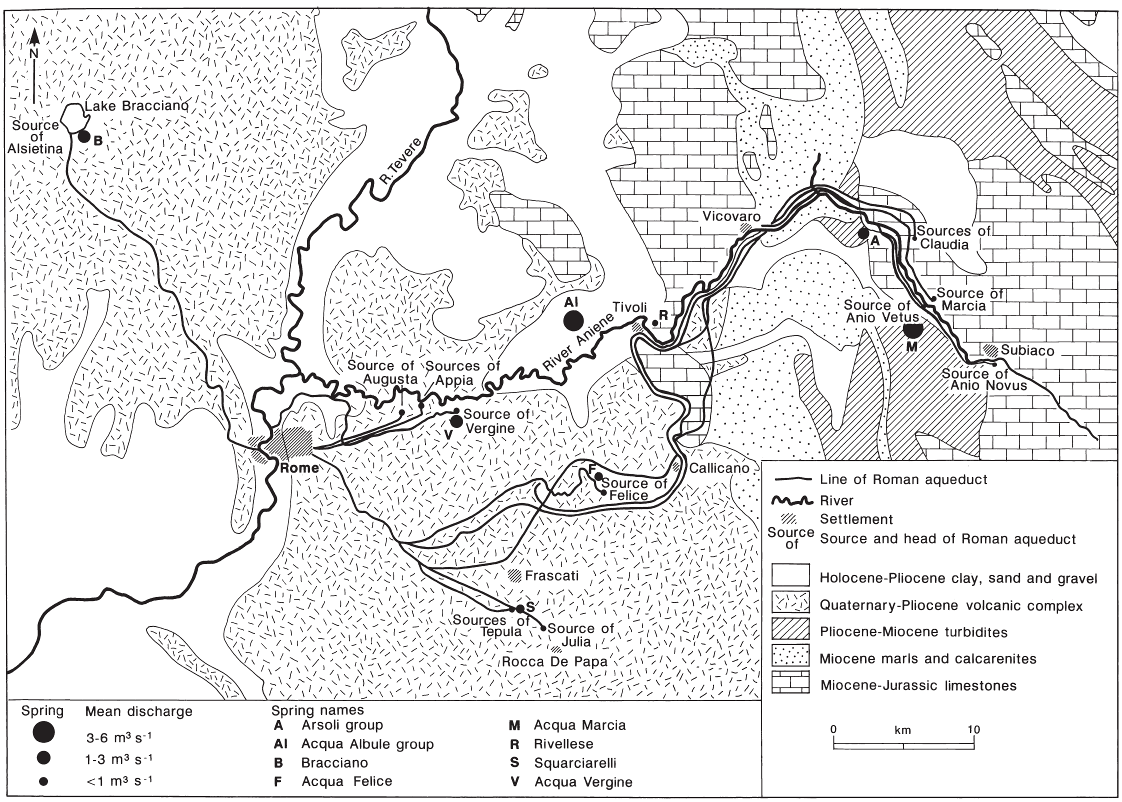

Fig. 1 Map of the general geology in the vicinity of Rome showing the location of the spring sources and routes of Roman aqueducts. Based on Bennett (1969) and Boni et al. (1986).

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 subsurface 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 multiphase systems. At the same time, environmental legislation has proliferated, and has acted as a driver in contaminant hydrogeology. Today, research efforts are directed towards understanding natural attenuation processes as part of a managed approach to restoring contaminated land and groundwater.

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.

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. 1.5, 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.

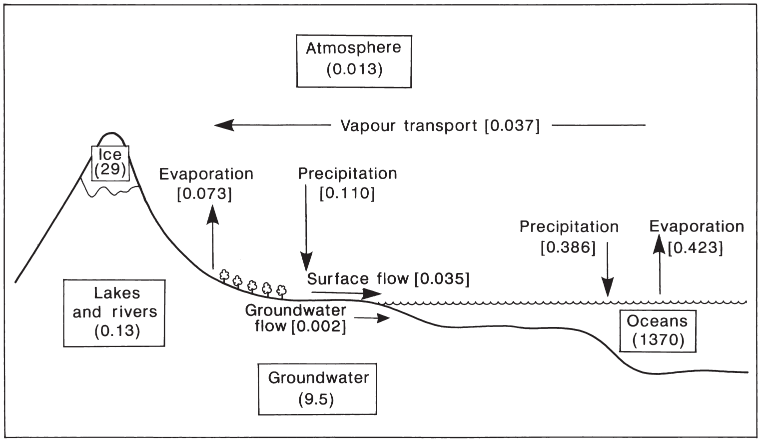

Fig. 1.5 The hydrological cycle. The global water cycle has three major pathways: precipitation, evaporation and water vapour transport. Vapour transport from sea to land is returned as runoff (surface water and groundwater flow). Numbers in () represent inventories (in 10^6 km^3) for each reservoir. Fluxes in [ ] are in 10^6 km^3 a^{-1}. After Berner and Berner (1987).

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

Reservoir	Volume ($\times 10^6$ km^3)	% of total
Oceans	1370	97.25
Ice caps and glaciers	29	2.05
Deep groundwater (750–4000 m)	5.3	0.38
Shallow groundwater (<750 m)	4.2	0.30
Lakes	0.125	0.01
Soil moisture	0.065	0.005
Atmosphere*	0.013	0.001
Rivers	0.0017	0.0001
Biosphere	0.0006	0.00004
Total	1408.7	100

* As liquid equivalent of water vapour.

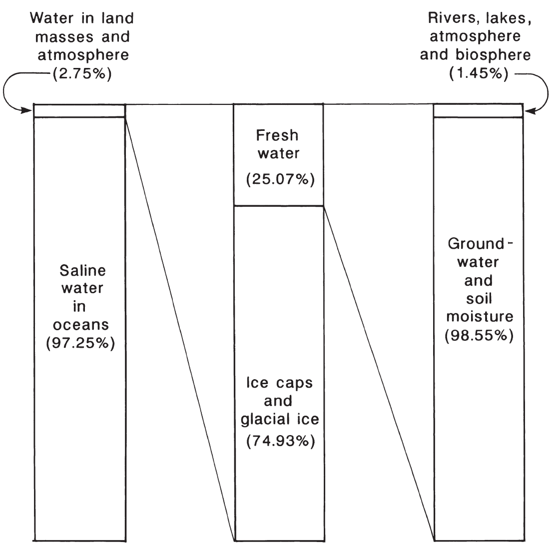

Fig. 1.6 The distribution of water at or near the Earth's surface. Only a very small amount of freshwater (<0.3% of total water) is readily available to humans and other biota. After Maurits la Riviére (1987).

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%, groundwater to a depth of 4 km accounts for 0.68%, freshwater lakes 0.01%, soil moisture 0.005% and rivers 0.0001%. About 75% of the water in land areas is locked in glacial ice or is saline (Fig. 1.6). The relative importance of groundwater can be realized when it is considered that, of the remaining quarter of water in land areas, around 98% is stored underground. In addition to the more accessible groundwater involved in the water cycle above a depth of 4 km, estimates of the volume of interstitial water in rock pores at even greater depths range from 53×10^6 km^3 (Ambroggi 1977) to 320×10^6 km^3 (Garrels et al. 1975).

Within the water cycle, and in order to conserve total water, evaporation must balance precipitation for the Earth as a whole. The average global precipitation rate, which is equal to the evaporation rate, is 496,000 km^3 a^{-1}. However, as Fig. 1.5 shows, for any one portion of the Earth, evaporation and precipitation generally do not balance. The differences comprise water transported from the oceans to the continents as atmospheric water vapour and water returned to the oceans as river runoff and a small amount (~6%) of direct groundwater discharge to the oceans (Zektser & Loáiciga 1993).

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 & Loáiciga 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 $\times 10^{-3}$ m^3 s^{-1} km^{-2}. The smallest direct groundwater discharge values of 0.2–0.5 $\times 10^{-3}$ m^3 s^{-1} km^{-2} occur in arid and arctic regions that have unfavourable recharge and permeability conditions (Zektser & Loáiciga 1993).

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. 1.5) divided by the rate of river runoff to the oceans

Table 1.2 Agents of material transport to the oceans. After Garrels et al. (1975).

Agent	% of total transport	Remarks
Rivers	89	Dissolved load 17%, suspended load 72%
Glacier ice	7	Ground rock debris plus material up to boulder size. Mainly from Antarctica and Greenland. Distributed in seas by icebergs
Groundwater	2	Dissolved materials similar to river composition. Estimate poorly constrained
Coastal erosion	1	Sediments eroded from cliffs, etc.
Volcanic	0.3(?)	Dust from explosive eruptions. Estimate poorly constrained
Wind-blown dust	0.2	Related to desert source areas and wind patterns, e.g. Sahara, major source for tropical Atlantic

(0.037×10^6 km^3 a^{-1}) gives an average time that a water molecule spends in the ocean of about 37,000 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. 1.5 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 (4.2×10^6 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 10,000 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 (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 Loáiciga (1993) indicate that globally the transport of salts via direct groundwater discharge is approximately 1.3×10^9 t a^{-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). A large proportion of the world's agriculture and irrigation is dependent on groundwater, as are a large number of industries. 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

Table 1.3 Estimated abstractions from all surface water and groundwater in England and Wales by purpose and Environment Agency region for 1996. All data are given as 10^3 m^3 day^{-1}. Source: Environment Agency for England & Wales.

Region	Public water supply	Spray irrigation	Rural*	Electricity supply	Other industry†	Total
North East	2538	55	873	5142	1871	10,479
Welsh	2051	10	411	6826	565	9863
North West	1595	6	174	6148	1124	9047
Southern	1451	23	1098	4210	365	7147
South West	1284	8	2046	3573	127	7038
Thames	4130	14	406	1715	255	6520
Midlands	2602	82	71	1681	406	4842
Anglian	1803	171	97	2001	497	4569
Total	17,454	369	5176	31,296	5210	59,505

* Category includes agricultural use (excluding spray irrigation), fish farming, public water supply (private abstractions for domestic use by individual households) and other (private domestic water supply wells and boreholes, public water supply transfer licences and frost protection use).
† Category includes industrial and mineral washing uses.

Table 1.4 Estimated abstractions from groundwaters in England and Wales by purpose and Environment Agency region for 1996. All data are given as 10^3 m^3 day^{-1}. Source: Environment Agency for England & Wales.

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

* † See Table 1.3.
‡ Groundwater supply as a percentage of the total surface water and groundwater supply (see also Table 1.5).

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 5000×10^6 m^3 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, 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 & RIZA 1991), about 75% of the inhabitants of Europe depend on groundwater for their water supply.

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

Country	Surface water ($\times 10^6$ m^3)	Groundwater ($\times 10^6$ m^3)	Total ($\times 10^6$ m^3)	% Groundwater
Denmark	9	907	916	99
Belgium	2385	4630	7015	66
Austria	1038	1322	2360	56
Luxembourg	28	29	57	51
Portugal	4233	3065	7298	42
Greece	3470	1570	5040	31
Italy	40,000	12,000	52,000	23
United Kingdom	9344	2709	12,053	22
Sweden	2121	588	2709	22
Spain	29,901	5422	35,323	15
Germany	51,151	7711	58,862	13
France	35,195	5446	40,641	13
Netherlands	10,965	1711	12,676	13
Ireland	945	125	1070	12
Finland	3011	335	3346	10
Total	193,796	47,570	241,366	20

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.

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. 1.7. The estimated total abstraction for 1995 is 1522×10^6 m^3 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 1544×10^6 m^3 day^{-1}. Estimates of abstraction by source indicate that during 1995, total fresh surface water abstractions were 996×10^6 m^3 day^{-1} and total groundwater abstractions were 293×10^6 m^3 day^{-1} (or 23% of the combined freshwater abstractions). The respective figures for 2000 are 991×10^6 m^3 day^{-1} and 316×10^6 m^3 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 163×10^6 m^3 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 (738×10^6 m^3 day^{-1} of fresh and saline water) and irrigation (518×10^6 m^3 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.

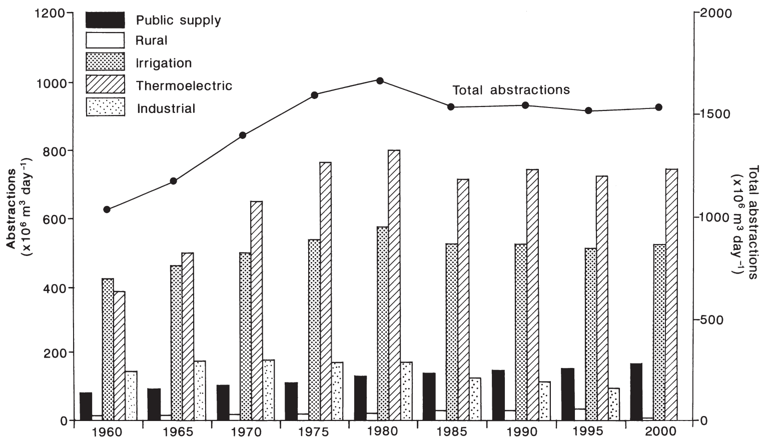

Fig. 1.7 Trends in water abstractions (fresh and saline) by water-use category and total (fresh and saline) abstractions in the United States from 1960 to 2000. After Solley et al. (1998) and Hutson et al. (2004).

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%.

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 down-gradient from the point of recharge and hazards such as ground sub-sidence 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 5.7.1). Furthermore, the application of quantitative pumping test analysis techniques (Section 5.8.2) 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 current 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 is promoting 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 new 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 (Section 8.5) 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 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 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 requires 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 introduces measures for protecting groundwater from indirect pollution (discharges of pollutants into groundwater after percolation through the ground or subsoil). In the proposed Directive, 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 proposed Directive 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 proposed Groundwater Daughter 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. In 2012, a comprehensive programme of measures to prevent or limit pollution of water, including groundwater, will become operational under the WFD. Monitoring results obtained through the application of the Groundwater Daughter Directive will be 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 (United States Environmental Protection Agency 1999).

1.10 Groundwater resources in developing countries

In the developing world, groundwater is extensively used for drinking water supplies, especially in smaller towns and rural areas, where it is 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. Shallower 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. An example of the significance of groundwater in leading the economic development in rural and expanding urban areas is the Quaternary Aquifer of the North China Plain (Box 1.2).

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. 1.8). 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.

Fig. 1.8 Collection of water for domestic use from a hand-pumped tube well drilled in Precambrian metamorphic rock in the Uda Walawe Basin, Sri Lanka.

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.

1.11 FURTHER READING

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Groundwater development of the Quaternary Aquifer of the North China Plain

BOX 1.2

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) 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. 2). 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 socioeconomic benefits in

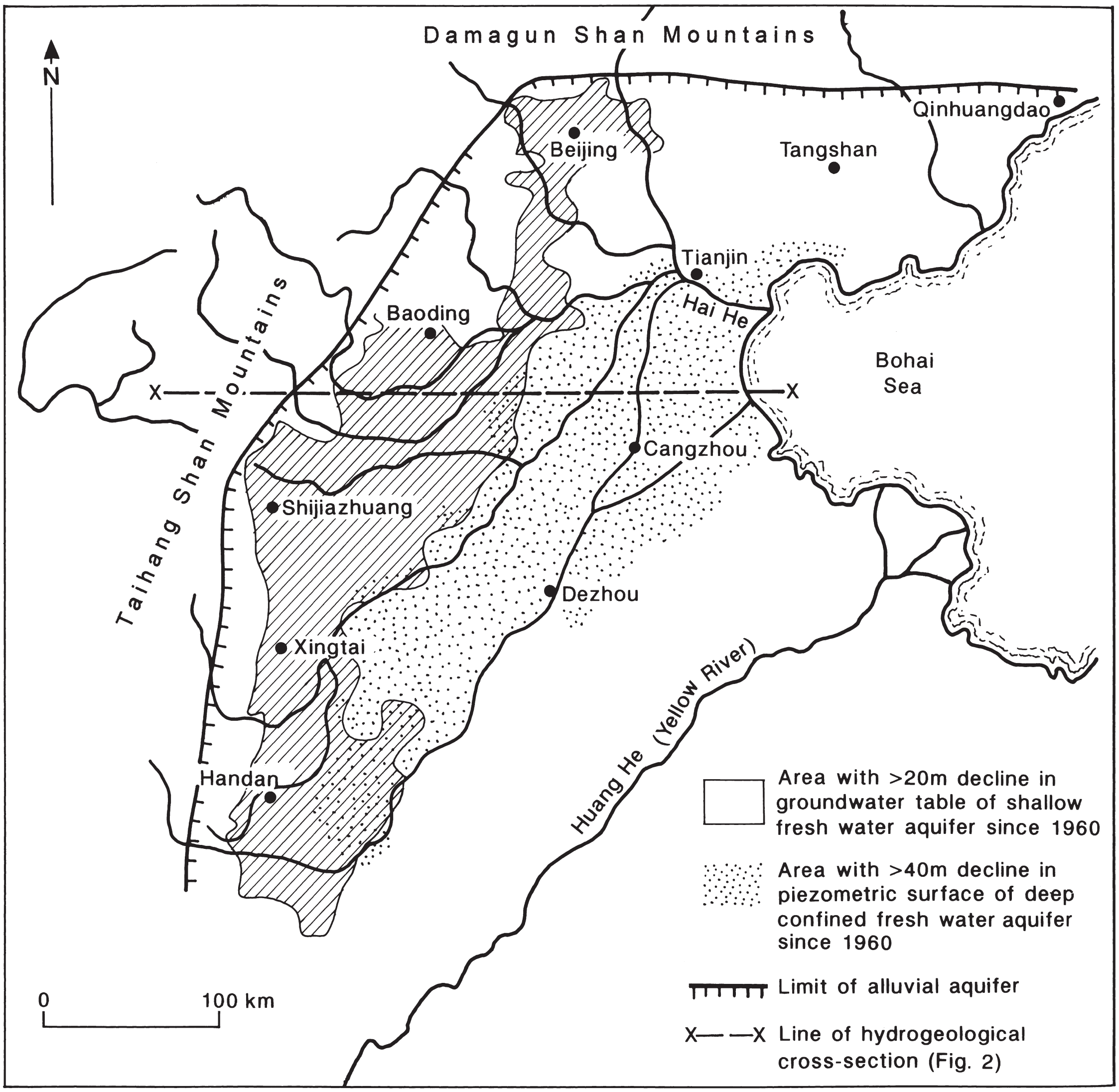

Fig. 1 Location map of the North China Plain showing the distribution of areas exhibiting marked groundwater depletion as a consequence of aquifer over-exploitation of the Quaternary aquifer system (Fig. 2). After Foster et al. (2004).

Continued

BOX 1.2

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) including a falling water table in the shallow freshwater aquifer, declining water levels in the deep freshwater aquifer, aquifer 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). 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).

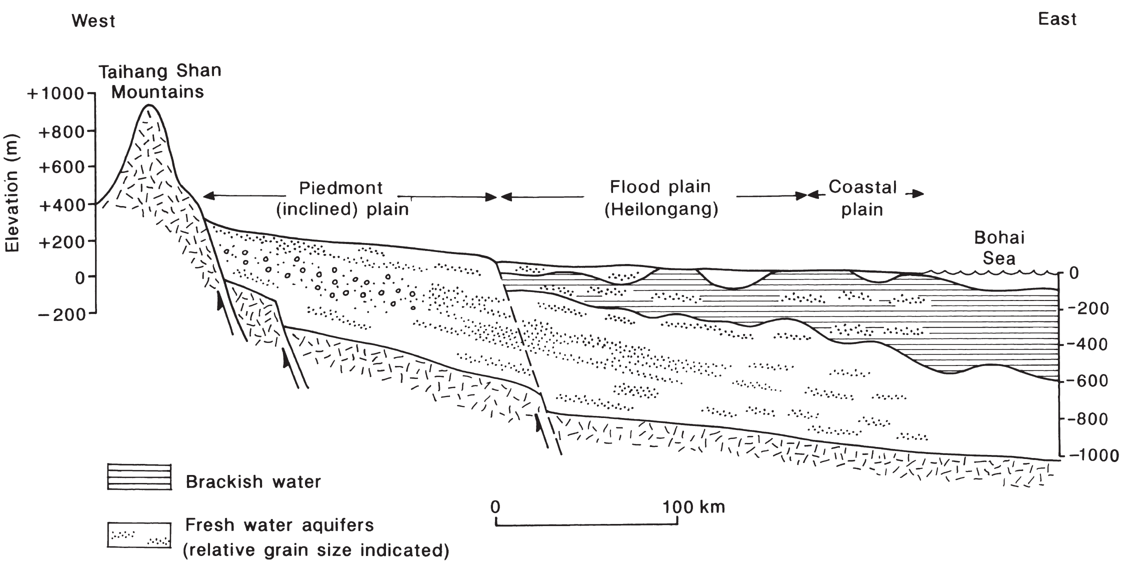

Fig. 2 Cross-section of the North China Plain showing the general hydrogeological setting of the Quaternary aquifer system which includes the gently sloping piedmont plain and associated major alluvial fans, the main alluvial plain (Heilongang) and the coastal plain around the margin of the Bohai Sea. After Foster et al. (2004).

Table 1 Key groundwater issues in the North China Plain listed according to hydrogeological setting (Fig. 2). After Foster et al. (2004).

Groundwater issue	Hydrogeological setting		
	Piedmont plain	Flood plain	Coastal plain
Falling water table of shallow freshwater aquifer	+++	+++	+
Depletion of deep freshwater aquifer	0*	+++	++
Risk of shallow aquifer and/or soil salinization	0	++	+++
Groundwater pollution from urban and industrial wastewater	+++	+	0

+++, very important; ++, important; +, minor importance; 0, not important.
* Effects of excessive abstraction may be reflected in the overlying shallow freshwater aquifer which is here in hydraulic continuity.