# Hydrogeological environments

This resource reviews some key characteristics of aquifers and shows how different geological settings will vary in their response to the pressures of water abstraction and pollution. Boxes 1 and 2 describe the role of groundwater in the Earth's water cycle, how it occurs and the main types of flow system.

**Box 1 How groundwater occurs**

Groundwater is part of the Earth's water or *hydrological* cycle. When rain falls, a part infiltrates the soil and the remainder evaporates or runs off into rivers. The roots of plants will take up a proportion of this moisture and then lose it through transpiration to the atmosphere, but some will infiltrate more deeply, eventually accumulating above an impermeable bed, saturating available pore space and forming an underground reservoir. Underground strata that can both store and transmit accumulated groundwater to outlets in rivers, springs and the sea are termed *aquifers.*

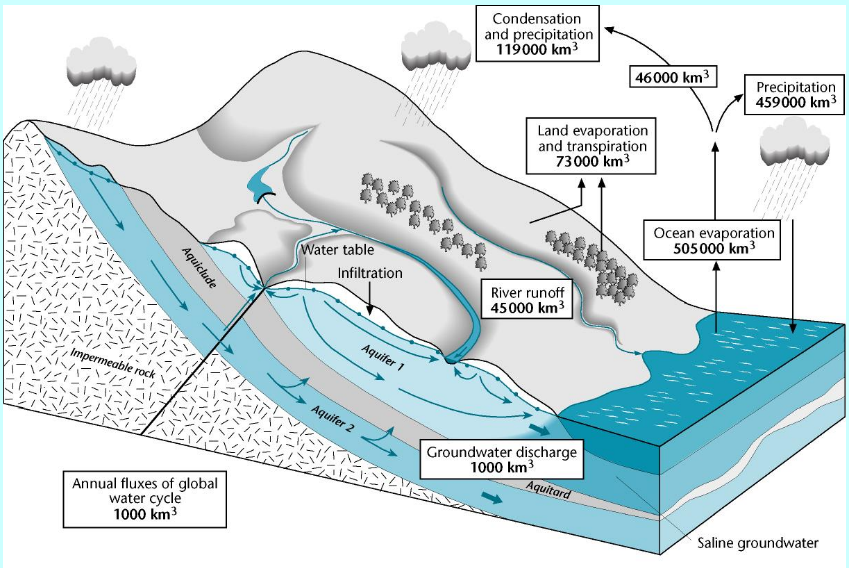


**Figure A Groundwater in the hydrological cycle**

The *water table* marks the level to which the ground is fully saturated (*saturated zone*) and reaches the surface at most rivers and all groundwater-fed lakes. Above the water table the ground is known as the *unsaturated zone.*

The productivity of an aquifer depends on its ability to store and transmit water, and these qualities may vary (see Figure A). Unconsolidated granular sediments (Figure Ba below), such as sand or gravel contain pore space between the grains and thus the water content can exceed 30 per cent of the volume. This is reduced progressively as the proportion of finer materials such as silt or clay increases and as consolidation occurs, typically accompanied by cementation of the grains (Bb below). In highly consolidated rocks (Bc below) groundwater is found only in fractures and rarely exceeds 1 per cent of the volume of the rock mass. However, in the case of limestones (Bd below), these fractures may become enlarged, by solution and preferential flow to form fissures and caverns. Even then, the total storage is relatively small compared with unconsolidated aquifers; one result is that there is less water available to dilute contaminated water that finds its way into the system.

## IMPORTANCE OF DIFFERENT AQUIFER PROPERTIES

### Intergranular and fracture flow

The productivity of an aquifer depends on the characteristics of the strata of which it is composed. The most important of these properties is whether the porosity is primary (or *intergranular)*, so that water is stored in the interstices between the grains, or secondary, where water is stored in and flows through *fractures.* The different ways that water is stored and flows through the rock control both the volume of storage and its relative mobility.

In an intergranular aquifer, the volume of water that can drain under gravity (*specific yield*) may exceed 30 per cent, for example in a medium to coarse-grained sand or gravel that is well sorted (the grains are of a uniform size) and uncemented. This represents a very large volume of storage, and it acts as an important buffer to sudden change, both in water levels and in water quality.

**Box 1 contd**

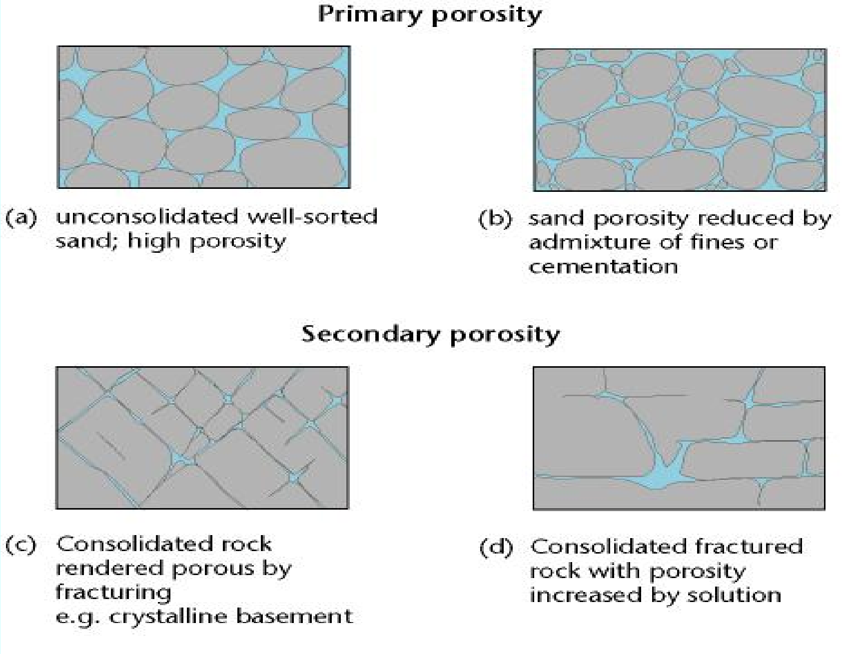


**Figure B Rock texture and porosity of typical aquifer materials (modified from Meinzer, 1923)**

In the major aquifers, the rock matrix provides a certain proportion of the total storage capacity of the system, while the fractures provide the dominant flow-path.

The most widespread aquifers combine these features and are known as *dual permeability aquifers*, where some regional flow can occur through the matrix and some through structural features such as joints or fault planes. This situation is common in many sandstones. The effect can be enhanced during aquifer development where individual boreholes/well fields may become extra productive after prolonged pumping through preferential near-well development of local fracture systems. This effect has been observed in some Permo-Triassic sandstone aquifers of north-west Europe. Another combination is the *dual porosity aquifer*, such as the important Chalk aquifer of north-west Europe, where the microporous nature of the limestone provides very large but relatively immobile storage, and practically all lateral flow is through fractures. This arrangement greatly modifies pollutant movement, as the water in the matrix is relatively immobile compared with that in the fissures.

For instance, in a 100-hectare (1 km$^2$) area of an aquifer comprised of well-sorted coarse sand, each metre of saturated strata would contain 250 000 to 300 000 m$^3$ of water. Yet quite a heavy rainstorm depositing 50 mm of rain would cause the water table in such an aquifer to rise by no more than 0.2 m, even if all the rain entered the aquifer and none is lost as evaporation or runoff. This large volume of storage means that there is much potential for the dilution of contaminants entering with new recharge.

Much of this water in the interstices is relatively immobile, and flows only very slowly through the matrix. The average linear velocities under natural groundwater gradients are measured typically in metres or tens of metres a year.

As Henri Darcy demonstrated more than 150 years ago, one can predict the rate and volume of flow in an intergranular aquifer with the quite limited information of groundwater gradient, the rock hydraulic properties and some knowledge of the cross-sectional area and aquifer geometry. This makes it easier to predict effects on the productivity of the aquifer, and also how it will respond to different modes of contamination.

In contrast the storage in even highly fractured aquifers is much smaller, and typically does not exceed a few per cent. Thus, the volume of water available for dilution is much smaller.

## Box 2 How groundwater moves

All freshwater found underground must have had a source of *recharge*. This is normally precipitation (rainfall/snow-melt), but can also sometimes be seepage from rivers, lakes or canals. The recharge typically travels downwards through the unsaturated zone and the aquifer fills up until water reaches the land surface, where it flows from the ground as springs or seepages, providing the dry-weather flow (or *baseflow*) of lowland rivers. Thus the aquifer becomes saturated to a level where the outflow matches recharge.

Shallow aquifers in recharge areas are generally *unconfined,* but elsewhere, and at greater depths, groundwater is often *partially confined* by low permeability strata (an *aquitard*) or fully *confined* by overlying impermeable strata (an *aquiclude*). In confined conditions water may be encountered under pressure, and when wells are drilled, rises above the top of the aquifer, even as far as ground surface, to a level called the *potentiometric surface* (see Figure A).

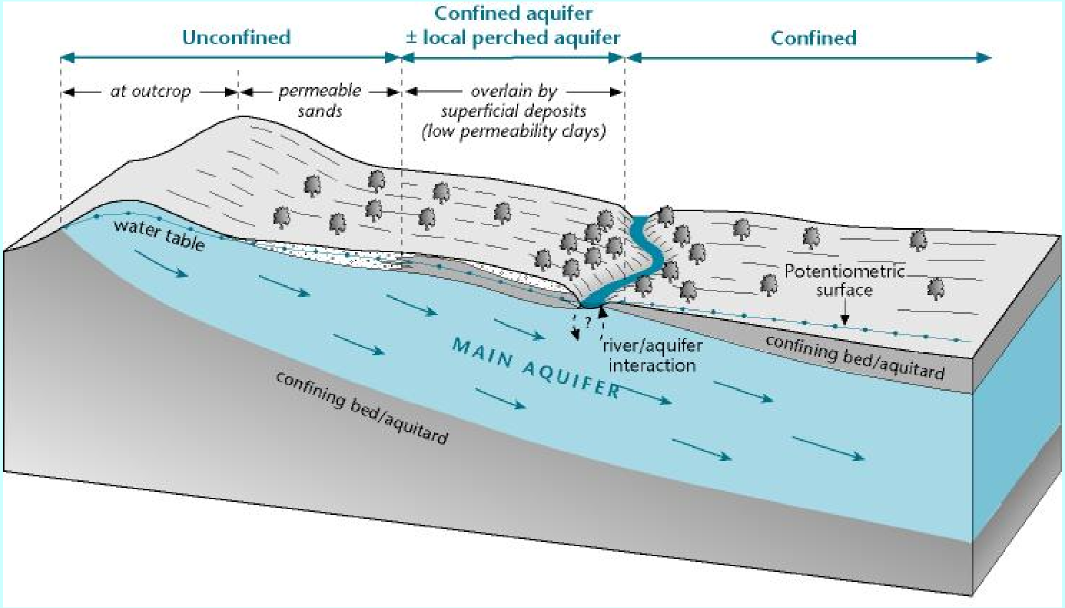


**Figure A Schematic of a common aquifer situation**

Groundwater systems are dynamic and water is continuously in slow motion down gradient from areas of recharge to areas of discharge. In large aquifer systems, tens or even hundreds of years may elapse in the passage of water through this subterranean part of the hydrological cycle (Figure B). Such flow rates do not normally exceed a few metres per day and compare with rates of up to 1 metre per second for riverflow. Velocities can be much higher where flow is through fracture systems, dependent on factors like aperture or fracture network density. In limestones with well-developed solution or *karst* or in some volcanic aquifers with extensive lava tubes or cooling cracks, velocities can be measured in km/day. Thus supplies located in different aquifers, or in different parts of the same aquifer, can tap water of widely different residence time. This is an important factor for contaminants that degrade over time and in the control of disease-causing micro-organisms such as some bacteria, viruses and protozoa.

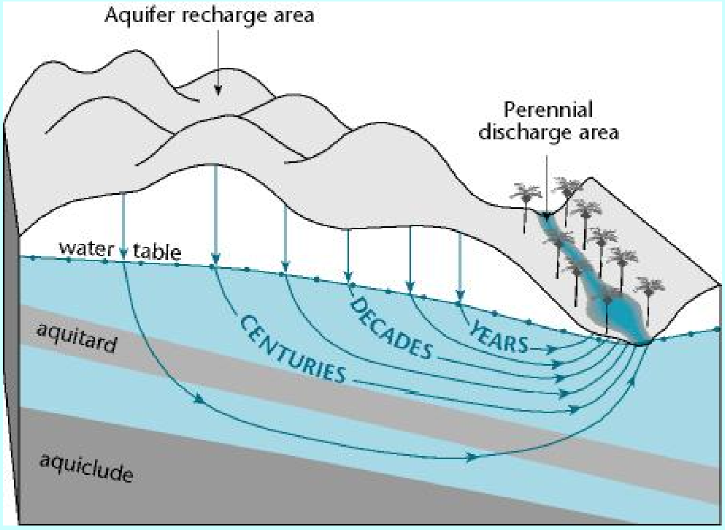


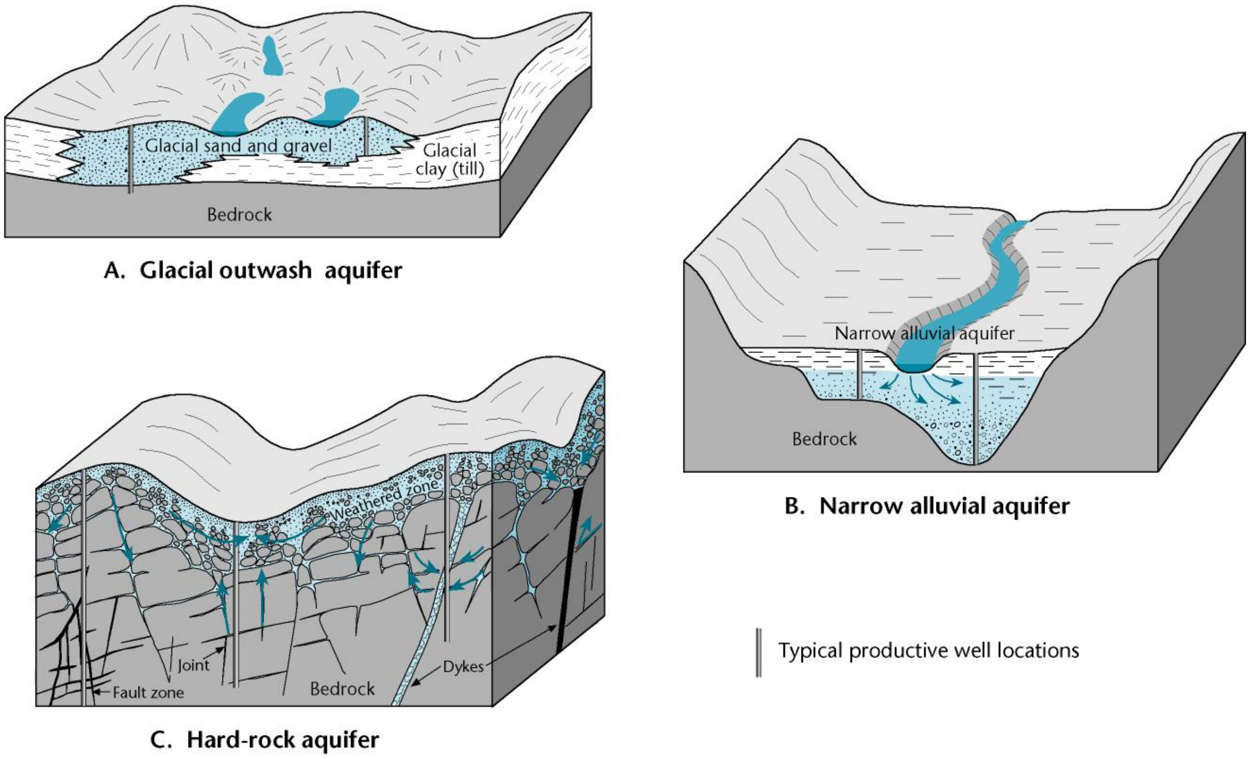
**Figure B Groundwater flow system in large aquifer**

Moreover, the aperture range and degree of interconnection control the availability of the water and the speed with which it flows. Groundwater velocities can be much higher, and may be measured in km/day in some limestone and volcanic lava aquifers, but are also much more variable. It is also technically much more difficult to characterise the fracture density and pattern. This makes for uncertainty in productivity forecasts, in the prediction of the rate and extent of contaminant plume migration, and in the extent to which remediation techniques can be effective.

## Layering

Groundwater is found in a wide range of rock types, from ancient crystalline basement rocks that store minor quantities of water in shallow weathered and jointed layers, to alluvial plain sediments that may extend to depths of several hundred metres and contain enormous volumes of groundwater. Sedimentary rocks, in particular, commonly have a strong primary stratification that influences the aquifer system (see Box 5). This layering is hydraulically important because the presence of strata with different permeabilities affects the rate at which contaminants can move into an underlying aquifer. These factors determine the yield, design and depth of the wells that tap such systems.

Layering can also occur in crystalline rocks and metamorphic rocks even though the primary bedding is obscured. It occurs because weathering processes enlarge fractures and introduce interstices near to the ground surface in rocks of otherwise very low permeability. Such rocks may also be overlain by a thin superficial layer of much more recent alluvial or glacial deposits which, if permeable, can provide a temporary storage medium for rainfall recharge, thereby increasing the productivity and apparent storage of the underlying hard rock formation. It results in much more localised flow systems because the aquifer is limited in vertical or lateral extent (Figure 1) as in the case of relatively recent glacial (A) or alluvial (B) sediments, or because the bedrock is highly consolidated and usable water only occurs either in certain fracture systems or in a thin weathered zone near the ground surface (C).



**A. Glacial outwash aquifer**

**B. Narrow alluvial aquifer**

**C. Hard-rock aquifer**

**Figure 1A,B,C Localised groundwater flow systems in minor aquifers (adapted from Freeze and Cherry 1979, Davis and De Wiest, 1966)**

Residence times in such aquifers are much less predictable either because the degree of interconnection with nearby rivers or lakes is uncertain or there is more scope for rapid by-pass flow along fracture networks. Typically the shortest residence times (hours→days→weeks) occur in karstic limestones or in some lavas and tuffs.

## HYDROGEOLOGICAL SETTINGS

Aquifers can be grouped into broad types that encompass the types of rock, the environments in which they were formed and the effect of subsequent geological processes. All of these factors influence how aquifers respond to the effects of resource degradation. For instance, different settings can:

- permit (or make unlikely) significant stratification of water quality
- allow the development of major vertical components of flow within the system
- produce wide variation in the response time or lag between an event, such as pumping or disposal of waste at the ground surface, and the observed response in the aquifer

The broad classification, based principally on their geological characteristics, genesis and extent is summarised in Table 1 and discussed briefly below, while Plate 1 (see separate .pdf file) shows the extent of some of the larger aquifer systems.

### Unconsolidated aquifers

#### THICK SEDIMENTS ASSOCIATED WITH RIVERS AND COASTAL REGIONS

These unconsolidated sediments include many of the world's most important aquifers because very large volumes of groundwater are stored in them and large quantities are pumped from them for water supply and irrigation. They supply water to enormous tracts of irrigated land (for example the Indo-Gangetic Plain of Northern India and Pakistan and the Huang-Hai-Hai Plain of eastern China) and to many urban areas, including the major cities of Bangkok, Jakarta, Calcutta, Dhaka, Hanoi and Shanghai.

These aquifers are almost invariably stratified, with permeable layers of sand or gravel separated by less permeable silty or clayey strata, some in discontinuous layers or lenses. Both the aquifers and intervening aquitards in these systems have high porosities (typically 10 to 30 per cent), providing much potential for dilution. Once pumped, these aquifers can have complex flow patterns because the stratification can produce significant vertical head gradients, facilitating movement from one layer to another. Nevertheless, flow velocities both laterally and vertically are typically low so microbiological quality is generally excellent except at very shallow depths and where the contaminant load is very high, as beneath cities. However, the slow travel times also imply a long contact time with the sediment and in some aquifers this can result in significant dissolution of the rock matrix, resulting in mineralisation of the water. The solute content is variable and depends on residence time, the composition of the aquifer matrix and the physicochemical processes. These formations may however be susceptible to subsidence problems caused by pumping.

#### MOUNTAIN VALLEY, UPLAND AND VOLCANIC SYSTEMS

Aquifers in this setting result from rapid infilling of troughs and basins within mountain regions. Interlayering of volcanic ash and lava may occur, together with reworked erupted material as volcanosedimentary strata. There are numerous examples of these systems in Central America (such as the aquifers that underlie Mexico City, Chihuahua, León and Guatemala City), and beneath Kathmandu (Nepal) and Sana'a (Yemen). Aquifer permeabilities and porosities are generally high although variable. When combined with above-average rainfall, typical of the climatic regimes where many of these environments are found, valuable aquifers occur and are capable of substantial well yields. Additional recharge to groundwater often occurs where surface water flows from the surrounding mountains and infiltrates the highly permeable valley-fill deposits, especially through alluvial fans and colluvial deposits found on valley margins.

## Table 1 Characteristics of the principal hydrogeological environments

| Type | Hydrogeological Environment | Lithology | Description/genesis | Extent/dimension |
|---|---|---|---|---|
| Unconsolidated aquifers | Major alluvial and coastal plain sediments | Gravel, sand, silt and clay | Unconsolidated sediments deposited by major rivers, deltas and shallow seas; primary porosity and permeability usually high | Usually extensive in area and of significant thickness |
| | Intermontane colluvial and volcanic systems | Pebbles, gravel, sand, clay, and interbedded lavas and tuffs or ash | Rapid infilling of faulted troughs and basins in mountain regions; deposits are unconsolidated, primary porosity and/or permeability is usually high for colluvium and coarse alluvium, modern lavas and ashes, but older volcanic rocks are generally poor aquifers | Much less extensive than alluvial and coastal plain sediments but can be very thick |
| | Glacial and minor alluvial formations | Boulders, pebbles, gravel, sand, silt, clay | Ice-transported sediments are commonly unsorted and of low permeability, but water-sorted sediments such as meltwater and outwash deposits have a high porosity and permeability. Alluvial sand and gravel can also be very productive but storage is limited and resource is sensitive to recharge regime | Can comprise relatively narrow channel fills or coalesce to form thick patchy multi-aquifer along piedmont zone |
| | Loessic Plateau Deposits | Silt, fine-sand and sandy clay | Usually well-sorted windblown deposits of silt and fine sand, with some sandy clay deposits of secondary fluvial origin; low permeability generally makes subsurface more suitable as receptor than aquifer | Very extensive although deposits may form isolated systems cut by deep gullies |
| Consolidated aquifers | Consolidated sedimentary aquifers | Sandstone | Marine or continental sediments are compacted and cemented to form consolidated rocks; degree of consolidation generally increases with depth and age of deposition. Primary porosity is moderate to poor but secondary porosity from fractures of tectonic origin can be significant | Can form extensive aquifers and be of substantial thickness |
| | | Limestone | Deposited from skeletal material (shell fragments, reefs, reef detritus) in shallow sea. Solution enlargement of fractures can form well-developed cavities/conduit systems (karst features) | |
| | Recent coastal calcareous formations | Limestone and calcareous sand | Composed of coral limestones, shellbanks, chemically precipitated ooids and calcareous oozes; generally loosely cemented; porosity and permeability can be exceptionally high, especially if features are enhanced by solution | Limited area, often forming narrow aquifers that fringe coastline/form oceanic islands |
| | Extensive volcanic terrains | Lava, tuff and ash intercalations | Flows from quiet effusion of mainly basaltic lavas or large explosive eruptions of ash. Primary (interconnected) porosity of thick flows is often neglible but flow junctions and chilled margins can be very permeable if rubbly or degassed. Extremely variable potential; permeability tends to decrease with age | Flood basalts and some ashes are extensive and thick |
| | Weathered basement complex | Crystalline rocks | Decomposition of ancient igneous or metamorphic rocks produces a weathered mantle of variable thickness, with moderate porosity but generally low permeability; underlain by fresher rock, which may be fractured. The combination results in a low-potential, but regionally important, aquifer system | Very extensive, but aquifers are often restricted to upper 30 m or less |

The interlayering of volcanic and sedimentary rocks can also generate productive spring systems, as occur widely at sandstone/lava junctions in the Rift Valley basalts of Ethiopia.

### GLACIAL, MINOR ALLUVIAL AND WINDBLOWN DEPOSITS

Deposits of glacial and fluvioglacial origin form important aquifers not only in temperate zones of the world but also at altitude in mountain ranges of the Andes and Himalayas. Ice-transported sediments are commonly unsorted mixtures of all grain sizes from clay to boulders; typically, they have low permeabilities, acting as aquitards or aquicludes. Their geographical distribution is usually limited, as they tend to occur in regions of active erosion. In contrast, water-sorted sediments, laid down from glacial melt-water, include sands and gravels that form highly productive aquifer systems. These can be extensive, as in the coalescing gravel outwash plains of North America, the eastern Andes and the Himalayas–Pamir–Tienshan cordilleras, or quite narrow and sinuous, as in the glacial channels of the North German Plain and the Great Lakes. Deposition from meltwater streams and the upper reaches of braided rivers produces very variable lithologies, forming complex systems in which lenses of highly permeable sands and gravels are partly separated vertically and laterally from each other by less permeable fine sand, silt and clay. Lenticular multi-aquifers are typical of this environment, and the resultant ‘patchy’ aquifer can be very productive, but hydraulic continuity between different lenses means that mobile persistent contaminants are able to penetrate to significant depths by leakage induced by head differences due to large-scale pumping. On the edge of large mountain ranges they grade into extensive alluvial deposits more characteristic of large river systems, as in the plains east of the Andes and Rocky Mountains and north of the Himalayas.

These aquifers are very widely used for urban supply, either directly by means of boreholes, or as prefilters for high volume riverbank intakes via infiltration galleries or collector wells. A few of the many examples include Cincinnati and Lincoln (USA), Dusseldorf (Germany), Vilnius (Lithuania) and Bishkek (Kyrghyzstan).

Loess, a fine-grained wind-blown deposit, forms an important aquifer in China, and is found elsewhere, for example in Argentina and north of the Black Sea. Thick deposits are almost entirely restricted to north central China where they form vast plateaux covering an area in excess of 600 000 $km^2$; about three-quarters of this area consists of a continuous sheet of loess with a thickness of between 100 and 300 m. The deposits are of low permeability and the presence of ancient soils produces a layered aquifer; the deeper zones are partly confined. The water table is commonly quite deep, 30 to 50 m below surface, but the loess is a key source of domestic water in this semi-arid region of China.

At tropical and equatorial latitudes, minor river systems lay down deposits that, although quite narrow, can provide a water resource of importance out of all proportion to the land area occupied, as in the case of wadi (seasonal river) deposits in desert areas of North Africa and Arabia or ribbons of alluvium on basement rocks in Central Africa.

## Consolidated aquifers (potentially fractured)

### CONSOLIDATED SEDIMENTARY AQUIFERS

Important aquifers occur worldwide within consolidated sedimentary strata, principally sandstone and limestone. Some sandstones retain a primary porosity (porosity between the grains) and are typically of low to moderate permeability. In cemented sandstones (usually found in older formations), the primary porosity is highly variable and, depending on the degree of cementation, the rocks can range from friable to highly indurated. In the latter, it is the secondary (fracture) porosity that provides the aquifer permeability and storage. Sandstone aquifers are important sources of water in Western Europe and North America, in North Africa (Nubian Sandstone), Southern Africa (Karroo Sandstone), in northern India (Tertiary sandstones), in eastern South America (Guarani Complex) and in Australia (Great Artesian Basin).

Even poorly permeable formations can provide a useful groundwater supply in semi-arid zones and regions with a long dry season, where they may be the only source of water. Wells producing only 1 to 2 l/s for instance can be a valuable resource for rural water supply and stock watering. Examples include the Waterberg Sandstone of South Africa and Botswana, the Voltaian sandstones and shales of Ghana, the Continental Terminal sandstones of Gambia, Senegal and tropical West Africa and the Benue shales and limestones of south-east Nigeria. In some cases the productivity of these formations comes from localised weathering rather than more widespread faulting or other structural features.

The vulnerability to pollution of consolidated sedimentary aquifers can be greatly increased where there is a highly developed secondary porosity. Typically this occurs in limestones as a result of solution enhancement of fractures (karst) that permits particularly rapid ingress of water from the surface and movement along enlarged fractures. The resulting aquifers can be prolific, although well yields are highly variable in time and space. Such aquifers are found worldwide, but are important in China, southern and western Europe, in the Middle East and in Zambia. In China alone, karst occupies an area of 2 200 000 km$^2$. The limestones are typically several hundred metres thick, and the groundwater resources are estimated at more than 200 000 MCM /a.

### RECENT COASTAL CALCAREOUS FORMATIONS

Examples of recent calcareous formations can be found in Jamaica, Cuba, Hispaniola and numerous other islands in the Caribbean, the Yucatán peninsula of Mexico, the Cebu limestone of the Philippines, the Jaffna limestone in Sri Lanka, and some low-lying coral islands of the Indian oceans (such as the Maldives). These formations can form important local aquifers and provide sources of water for cities and for irrigation. Permeability is high to very high and derives both from the initially high primary porosities of the sedimentary rocks and from solution enhancement of fractures. This can produce rapid groundwater movement with velocities frequently in excess of 100 m/d. The high infiltration capacity of these strata means that there are few streams or rivers, and groundwater may be the only available source of water supply in these areas.

These characteristics have important implications for groundwater quality. Soils overlying these formations can be thin, and water movement from the soil to the water table via fractures is often so rapid that even filtration and removal of micro-organisms within the unsaturated zone is not effective. Consequently, these formations are vulnerable to widespread pollution. In addition, as these coastal aquifers are usually in hydraulic continuity with marine water, excessive abstraction with a consequent lowering of the water table may induce sea water up-coning and contamination of the fresh water.

### EXTENSIVE VOLCANIC TERRAINS

Extensive lava flows occur in west-central India, where the Deccan basalts occupy an area of more than 500 000 km$^2$. Other extensive volcanic terrains occur in North and Central America, Central Africa, and many islands are entirely or predominantly of volcanic origin, such as Hawaii, Iceland and the Canaries. Some of the older, more massive lavas can be practically impermeable (such as the Deccan) as are the dykes, sills and plugs which intrude them, and the thick beds of air-fall ashes that may also be extensive in some volcanic areas. However, younger basic lavas provide some of the world’s most prolific onshore and offshore springs (Snake River Basalts, Idaho and Hawaii). Individual lava flows can be up to 100 m in thickness. The more massive flows are generally impermeable, although the junctions of many flows can be highly productive, as they may contain shrinkage cracks and rubbly zones caused by the covering over of the rough surfaces of the lava by the chilled bottoms of the next flows. In some terrains, extensive lava tubes may be formed as low viscosity lava drains out beneath a cooled congealed upper surface. The viscosity and gas content of lavas and incandescent ash clouds (welded tuffs or ignimbrites) control not only the compactness, thickness and lateral extent of a flow but also how rubbly it is likely to be once extruded. These factors in turn dictate the likely storage and water transmitting capacity of a volcanic sequence.

In volcanic terrains where lavas alternate with air-fall ash, productive two-part aquifer systems can be encountered. Highly permeable but relatively thin rubbly or fractured lavas act as excellent conduits but have themselves only limited storage. Leakage from overlying thick, porous but poorly permeable, volcanic ash may compensate for this by acting as aquitards, and are the storage medium for the system. The prolific aquifer systems of the Valle Central of Costa Rica and of Nicaragua and El Salvador are examples of such systems.

### WEATHERED BASEMENT COMPLEX

Over large parts of Africa and in parts of Asia and South America, groundwater occurs in basement aquifers. These are ancient crystalline rocks with little or no primary porosity but groundwater is present in fractures and near-surface weathered layers. In some cases the bedrock has disintegrated into an extensive and relatively thick layer of unconsolidated highly weathered rock with a clayey residue of low permeability. Below this zone, the rock becomes progressively less weathered and more consolidated until fresh fractured bedrock is reached. The zone of weathering is generally only a few tens of metres deep, but in areas of low relief can reach up to 70 m in depth. There are other areas, generally of high relief, where the weathered layer is very variable in thickness and bedrock can occur at the ground surface. As a consequence, groundwater velocities in the weathered and fractured bedrock aquifers can be very variable, as is the pollution vulnerability. Near surface laterite zones for instance can be quite transmissive. Permeabilities even in deeply weathered areas are typically low, but can be sufficient for rural water supplies or small-scale irrigation.

Crystalline basement rocks are commonly used as a source of groundwater because of their wide extent but yields are typically small and the low storage makes boreholes prone to drying up during drought. The disposal of waste water on site to the subsurface in an unsanitary manner can also be a problem for cities. Kampala, Uganda has this problem, where the fractured aquifer occurs at shallow depths, and springs with very localised catchments are easily contaminated. The shallow location of aquifers, the low available storage, localised flow systems and the short residence times for urban recharge all contribute to a setting of high pollution hazard.

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