Groundwater flow and quality

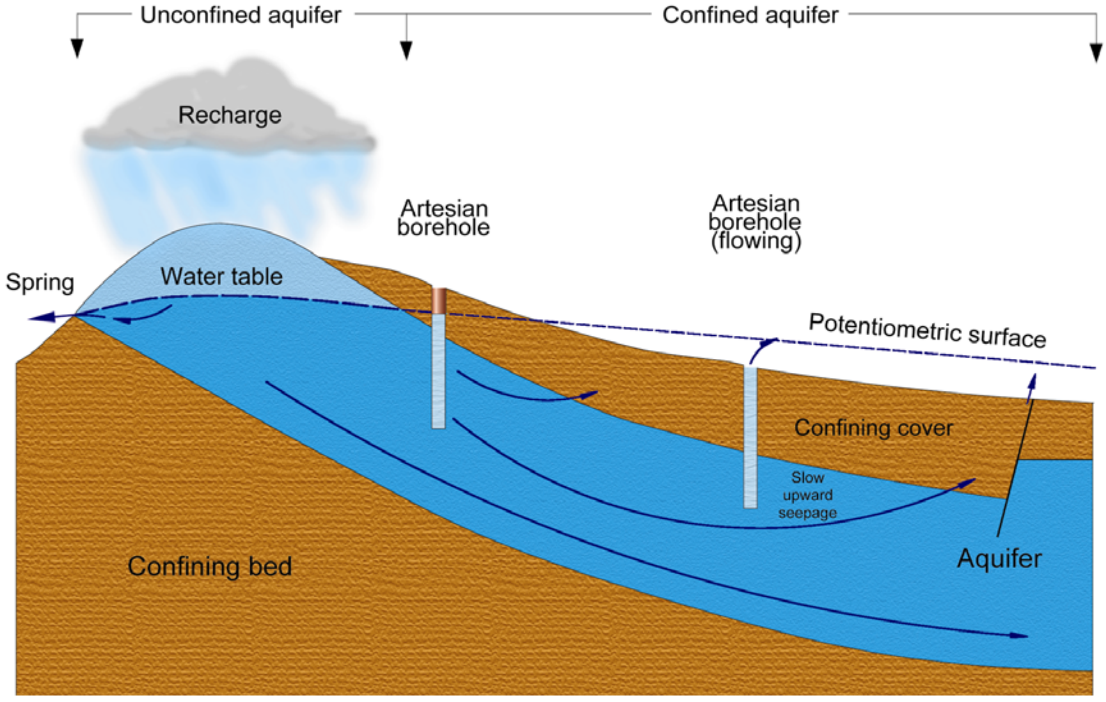
Groundwater flow

The direction of groundwater flow follows a curved path through an aquifer from areas of high water levels to areas where water levels are low; that is from below high ground, which are recharge areas, to groundwater discharge points in valleys or the sea. The direction of flow is indicated by the slope of the water table which is called the hydraulic gradient.

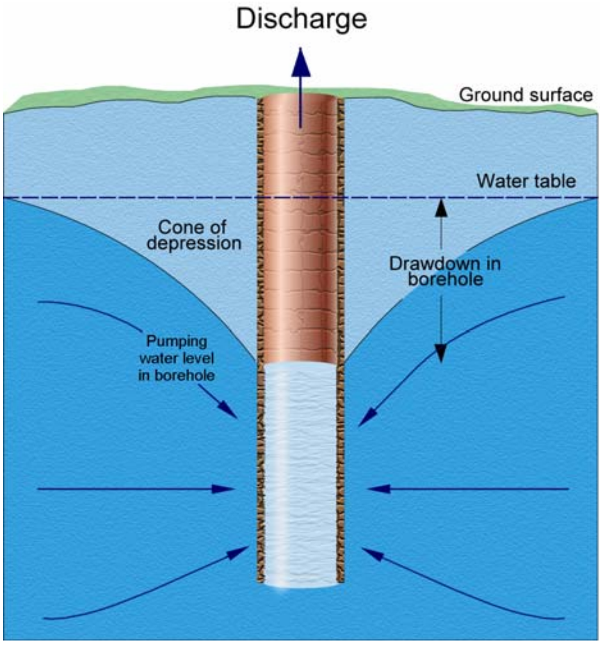
An aquifer that crops out (i.e. is exposed at the surface) is said to be unconfined. Because of earth movements in the past, many aquifers dip below younger strata of impermeable clay. As the thickness of the clay increases the aquifer becomes saturated throughout its entire thickness and the pressure of the water it contains increases. The water rises above the top of the aquifer and may overflow at the surface from a borehole that penetrates into the aquifer; it is said to be under artesian pressure. Such aquifers are called confined aquifers. The level to which the water rises in boreholes that penetrate into confined aquifers is known as the potentiometric surface.

Water flows through confined aquifers to discharge points some distance down-gradient at a spring or possibly offshore into the sea. The isolated oases in deserts exist because groundwater is issuing from a confined aquifer which may have locally intersected the ground surface, or where the water is rising up a fracture in the overlying confining rocks. Where such outlets do not exist the water discharges from confined aquifers by slow upward seepage through the overlying clays. The velocity of flow under confined conditions is much slower than that in unconfined aquifers.

When groundwater is pumped from a borehole, the water level is lowered in the surrounding



Unconfined and confined aquifers. Aquifers are recharged by rainfall where they are unconfined. The water overflows from springs. Large volumes of water are stored below the level of these 'overflow points'. An aquifer confined by relatively impermeable strata is fully saturated. In a confined aquifer, the water pressure is greater than atmospheric pressure. Water rises in a borehole that penetrates a confined aquifer until the column of water balances the water pressure in the aquifer. Where the potentiometric surface is above the ground surface, water overflows from boreholes. Generally groundwater discharges naturally from a confined aquifer by slow upward seepage but water may be released under pressure as a spring where the confining bed is intersected by a fracture that extends into the aquifer.



The drawdown of the water table around a pumping borehole to form a cone of depression. The shape and extent of the cone of depression depends upon the rate of abstraction, the duration of the abstraction and the hydraulic properties of the aquifer.

area. An hydraulic gradient is created in the aquifer which allows water to flow towards the borehole. The difference between the original water level and the pumping level is the drawdown, which is equivalent to the head of water necessary to produce a flow through the aquifer to the borehole — the greater the yield from the borehole, the greater the drawdown. The drawdown decreases with increasing distance from the borehole until a point is reached where the water level is unaffected. The surface of the pumping level is in the form of an inverted cone and is referred to as a cone of depression.

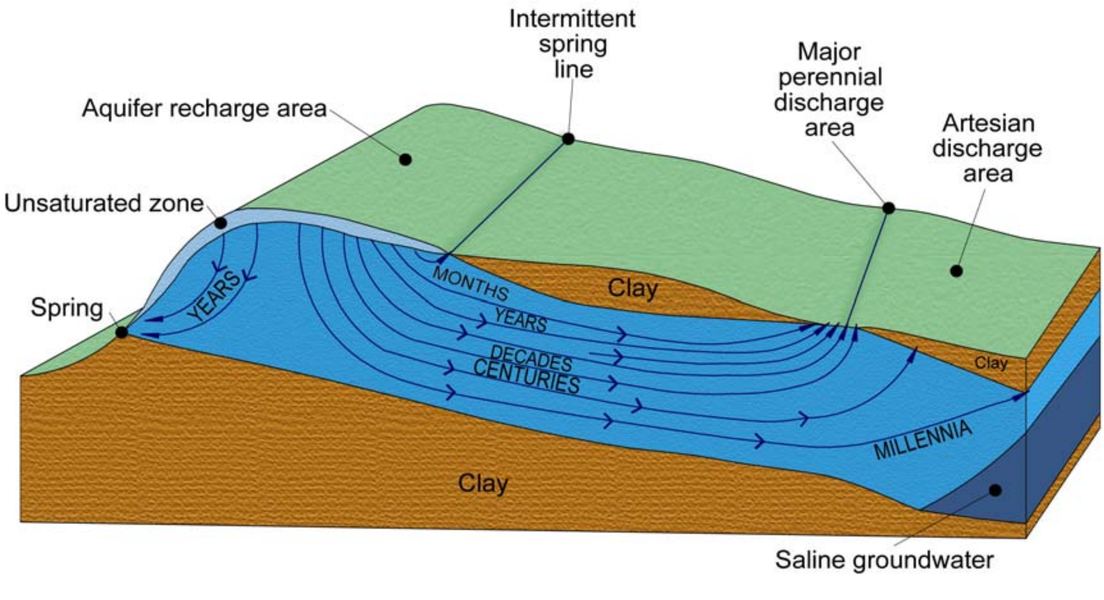
Water flows into a borehole from all directions in response to pumping and, as it is flowing through a decreasing cylindrical area, the velocity increases as it converges towards the borehole.

The age of groundwater

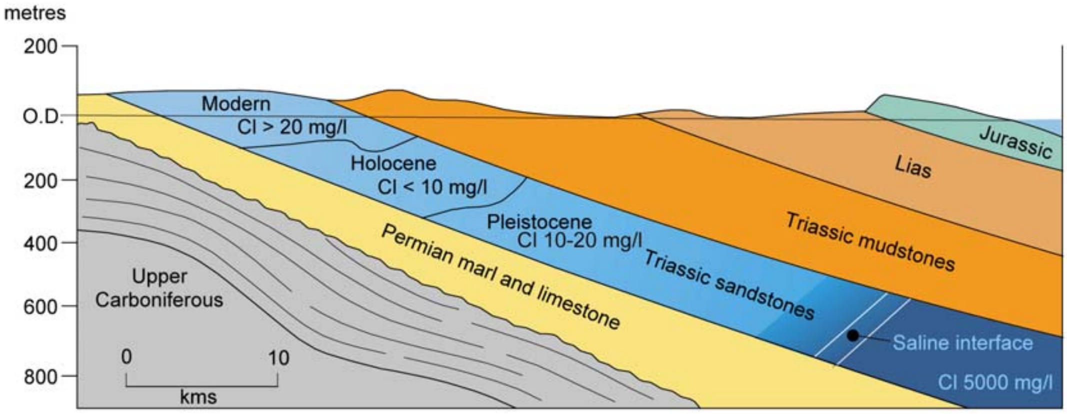
Water remains in rivers for a relatively short time, a matter of days or weeks. In contrast, the age of groundwater is measured in decades, or even millennia, because the water flows so slowly through the ground.

The age of groundwater can be measured from the rate of decay of radioactive elements present in the water at very low concentrations. Tritium, an isotope of hydrogen, and carbon-14 are most commonly used. Tritium and carbon-14 were formed in the atmosphere by the tests of thermonuclear bombs in the 1950s and 1960s, but carbon-14 is also formed naturally by the bombardment of nitrogen by cosmic rays.

Analysis for tritium in the late 1960s revealed that water infiltrates through the matrix of the Chalk in the unsaturated zone at a rate of about 1 metre per year. Thus, where the unsaturated zone is 50 metres thick, water is some 50 years old when it reaches the water table. However, in such a fractured limestone, some water also travels rapidly through the fractures in the unsaturated



Age of groundwaters. Groundwater in the upper part of the unconfined zone generally varies in age from months to years. As water penetrates to greater depths the age increases to decades, centuries or even millennia. The very saline water lying in aquifers below the zone of active freshwater circulation can be millions of years old.



Stratification of groundwaters of different ages in the Triassic sandstones of the East Midlands of England. Fresh groundwater has penetrated to a depth of about 500 metres during the Holocene and late Pleistocene. Holocene water is up to 10,000 years old and Pleistocene water from 10,000 to over 30,000 years. The higher chloride value in the modern water compared to that in the Holocene reflects human contamination. (The Holocene and Pleistocene form the Quaternary).

zone at velocities of the order of 50 metres per day. About 10 to 15% of the infiltration to the Chalk flows through fractures in the unsaturated zone to the water table.

Groundwater is actually a mixture of waters from many sources of different ages. The age of a particular sample is the average age of all the constituent components. In general the age of groundwater increases with depth.

Analysis for carbon-14 has shown that groundwater in the Chalk in the centre of the London Basin contains a component that is some 20,000 years old and fell as rain during the late stages of the Ice Age. Many saline groundwaters flowing at great depths are believed to be millions of years old and many may contain a component derived from the pore waters that were in the rocks when they were deposited.

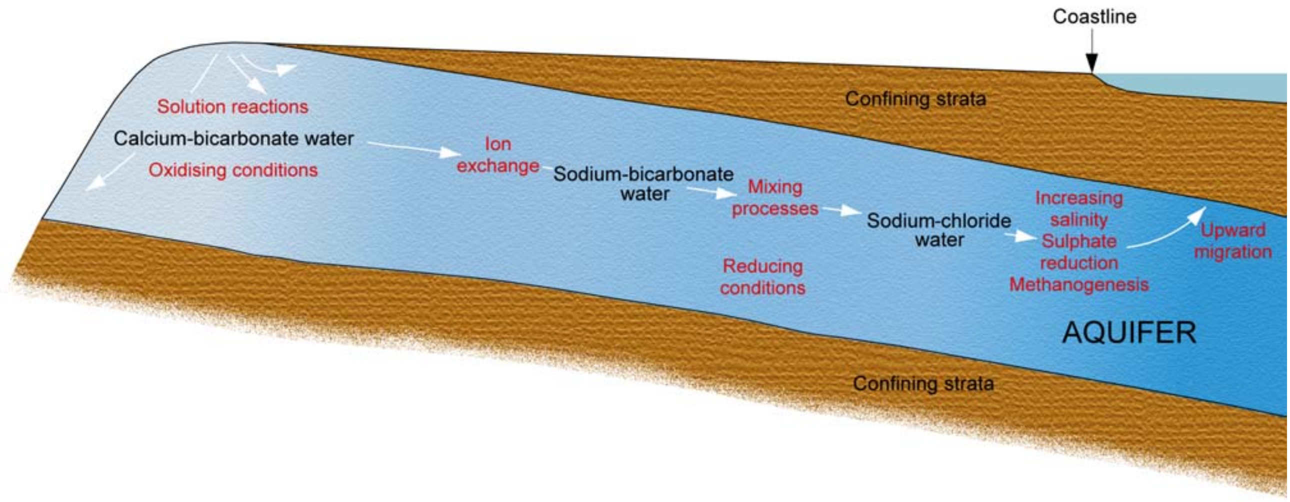
Groundwater quality

Groundwater in its natural state is generally of excellent quality. This is because rocks act as filters. Any bacterial contamination from surface sources or the soil is removed after groundwater has passed through some 30 metres of saturated sand or unfissured rock; in the unsaturated zone no more than 3 metres may be necessary to purify water percolating through the zone.

Groundwater is actually a complex, generally dilute, chemical solution. The chemical composition is derived mainly from the dissolution of minerals in the soil and the rocks with which it is or has been in contact. Rainfall itself is a dilute chemical solution and contributes significant proportions of some constituents in groundwater, especially in regions with little soil cover where hard compact rocks occur at or near the surface.

As water flows through the ground the dissolution of minerals continues and the concentration of dissolved constituents tends to increase with the length of the flow path. At great depths, where the rate of flow is extremely slow, groundwater is saline, with concentrations ranging up to ten times the salinity of the sea.

Before the industrial revolution, the main risk to groundwater quality was from bacteria and viruses. Generally groundwater was free from contamination because the physical properties and the mineral constituents of rocks have a remarkable facility for purifying water. The principal action is filtration but other processes are also involved. The velocity of water flow in the small intergranular pore spaces of the unsaturated zone of a sandstone is very low. Organic compounds, bacteria and viruses, tend to be retained or absorbed on the matrix and may be degraded by microbial activity. Metals and other inorganic compounds may also be absorbed, diluted by mixing, or may be modified or broken down into simpler products by chemical reactions. These processes delay the transport of contaminants through an aquifer and may reduce their concentrations. However, in a fractured aquifer, contaminants can rapidly pass through the unsaturated zone to the water table and the effect of the purifying processes is significantly reduced. This is particularly likely after a period of intense or prolonged rainfall. As water flows through the saturated zone, contaminants are diluted by the mixing of waters in different flow-paths, flowing at different speeds in the complex, tortuous pore passages in the aquifer.



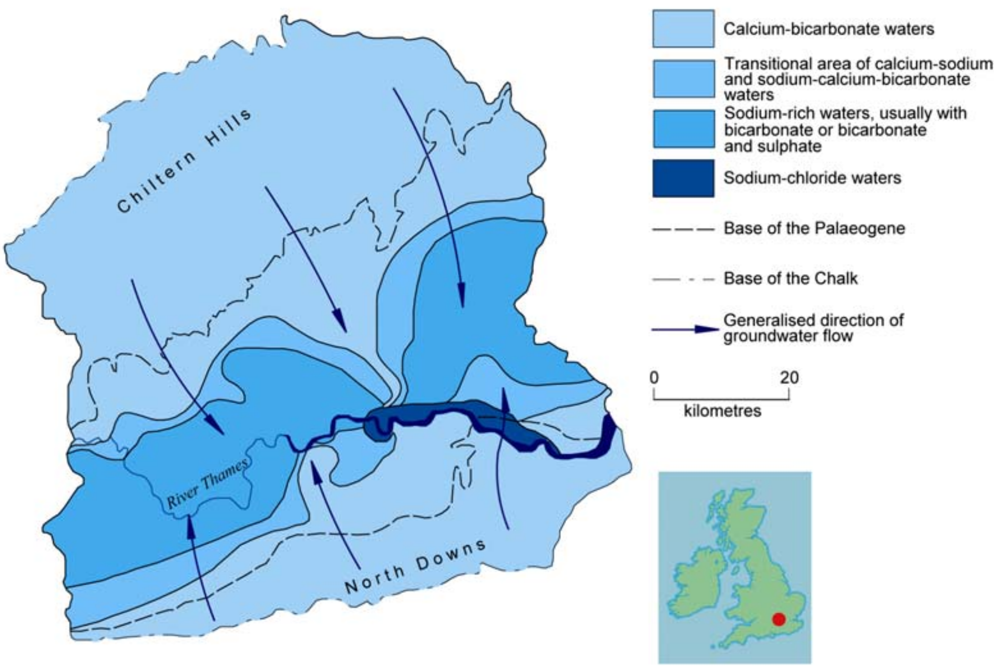
Schematic diagram of down-gradient chemical changes in groundwater. A 'hard' calcium-bicarbonate water at outcrop gradually passes into a 'soft' sodium-bicarbonate water which in turn passes into a saline sodium-chloride water.

Although the purifying capacities of rocks improve the quality of groundwater, aquifers do not have an infinite capacity for purifying contaminated water and dilution is not a reliable remedy for pollution.

Chemical changes in groundwater

The principal dissolved constituents in groundwater are calcium, magnesium, sodium, bicarbonate, sulphate and chloride. They occur in the form of electrically charged ions. Many other minor constituents may be present, for example fluoride which helps to prevent dental caries when present in drinking water at a concentration of about 1 milligram per litre (mg/l).

As rain infiltrates through the soil it dissolves carbon dioxide, which is in the soil 'air' at a much greater concentration than in the atmosphere. The acidic solution formed reacts with carbonates in the rocks giving solutions of calcium, and to a lesser extent magnesium, bicarbonates. This is the dominant reaction in limestones and in sandstones in which the quartz grains are held together by a carbonate cement. In rocks that do



The chemical composition of groundwater in the Chalk of the London Basin.

not contain carbonates, as for example sands, groundwater tends to be slightly acidic and corrosive because the carbon dioxide in solution forms carbonic acid and reacts only slowly with silicate minerals. Such waters are said to be ‘soft’ whereas those containing calcium or magnesium bicarbonates are ‘hard’. Soap easily makes a lather in ‘soft’ water and ‘hard’ water causes ‘fur’ in kettles.

An important source of sulphate in groundwater is the oxidation of pyrite (ferrous sulphide) which is widely distributed in sedimentary rocks. Sulphuric acid is a product of the reaction and this reacts with any carbonate present to form calcium and magnesium sulphates. The reaction may be promoted by sulphur-oxidising bacteria.

Most of the chloride found in groundwaters that are actively circulating at relatively shallow depths is derived from rain or, near coastlines, from sea spray.

The dominant chemical reaction in aquifers where they outcrop is the solution of minerals in the aquifer’s matrix. The water in limestones and calcareous sandstones contains calcium and magnesium balanced with bicarbonate and sulphate. As these groundwaters flow down the hydraulic gradient below confining clays they are modified by ion exchange, the calcium and magnesium in the water being replaced by sodium from minerals in the aquifer’s matrix. The water is thereby converted from a ‘hard’ water to a ‘soft’ sodium bicarbonate or sodium sulphate water.

Groundwater in aquifers where they outcrop contains dissolved oxygen. As the water flows down-gradient this decreases as organic matter and ferrous iron in the aquifer’s matrix are oxidised. When the oxygen has been used up, other ions, such as nitrate and sulphate, provide oxygen. These ions are converted to nitrogen and sulphide by reactions promoted mainly by anaerobic bacteria. A final stage in some deep aquifers is the reduction of carbon dioxide to methane.

The very saline groundwaters found at depths below the actively circulating zone, are formed by the gradual solution of soluble constituents in aquifers and also by the modification, concentration and migration of the sea water that was in many rocks when they formed. Some hydrogeologists believe some groundwaters have been concentrated by the filtering action of clays which act as semi-permeable membranes.