# GROUNDWATER IN KARST

extract from pages 394-397 of:

Gunn, J., (editor) *Encyclopedia of Caves and Karst Science*, Fitzroy Dearborn, NY.

## Definition of Groundwater: Aquifers and Aquicludes

Groundwater is the water present beneath the Earth's surface, stored in voids in bedrock and unconsolidated deposits. A body of rock containing and able to transmit significant quantities of water is termed an "aquifer"; an "aquiclude" is unable to transmit significant quantities of water, and generally acts as a barrier to the flow of groundwater. Aquifers are generally associated with particular geological formations or sequences, and generally adopt the respective formation name or stratigraphic age designation. The strong association between groundwater and geology has led the study of groundwater to be termed hydrogeology. Groundwater is replenished by "recharge", generally the deep percolation of soil water and (in karst aquifers) the inflow of sinking streams. The shallow subsurface and soil are commonly undersaturated; water coexists with air, and not all the openings in the rock are occupied by water. In soil-covered carbonate rocks dissolution is usually at a maximum immediately below the soil–bedrock interface forming a subcutaneous or "epikarstic" zone at the top of an unsaturated zone that eventually grades into a saturated zone where all voids are occupied by water. In karst hydrogeology, the terms "vadose" and "phreatic" are commonly used instead of unsaturated and saturated. The interface between these zones is the water table. Recharge water descends more or less vertically from the surface to the water table, travels sub-horizontally through the aquifer, and emerges as groundwater discharge in the form of seeps and springs where the water table reaches the surface. Many natural wetland areas are sustained by groundwater discharge.

## Groundwater as a Reservoir: Resource and Water Balance

Groundwater is ubiquitous in favourable geological settings, and modest quantities may be readily obtained as the primary water supply for smaller communities and agricultural use. Only exceptionally productive aquifers can be exploited for large municipal supplies, because there is a limit to the quantity of water that can be withdrawn from an area.

An aquifer may be conceived as a reservoir or distinct body of water defined by its geological boundaries and quality. When the recharge and discharge are in balance, the aquifer is in equilibrium and its long-term volume does not change. If groundwater extraction causes the balance to go into deficit, aquifer water levels will decline. Computation of aquifer water balances is therefore a fundamental, but difficult aspect of groundwater management.

Natural water quality in an aquifer reflects the geological context, the solutes depending on the solubility of the minerals composing the aquifer. Many subsurface chemical processes are very slow, so the age of the water has a profound impact on quality, with older water becoming increasingly mineralized, depleted in oxygen, and soured by the presence of odorous hydrogen sulfide. Offsetting this deterioration with age is a decreasing risk of anthropogenic contamination in older waters. The age of groundwater is therefore of considerable interest, as it indicates the general position in an aquifer flow system, and the risk of pollution. It is common to determine the residence time of groundwater, perhaps based on the level of radioactive tritium or carbon, or by a simple ratio between aquifer volume and recharge or discharge rates. However, the average residence time is not a very useful concept in karst aquifers since they contain a mixture of waters of very different ages. Recharge through dolines or sinking streams directly enters the conduit network and may travel to springs at rates exceeding 1 km $d^{-1}$. Conversely, much of the recharge through thick soils or fine-grained sediments overlying the bedrock may take years to travel a few metres, and flow through the matrix of the rock can be exceedingly slow. Consequently, residence times in any karst aquifer will vary considerably with the flow path(s) that the water has followed.

**Ground-water Dynamics**

The flow of groundwater is energy-driven, with a progressive loss of energy from recharge to discharge. Rather than determining energies directly, it is more useful to describe energy indirectly as "hydraulic head", expressed in metres of elevation. The hydraulic head of any water surface is its elevation above datum. The head throughout a static water body is uniform; in a lake it is the surface elevation. This is because hydraulic head at a point is the sum of two components: elevation and pressure. The former is simply height above datum. The latter is a reflection of the force exerted by overlying water, and is represented by the height to which water would rise in a stand pipe. The balance of elevation and pressure head at any point in an aquifer can vary; as water goes deeper, pressure rises and elevation is lost. In this way, groundwater can descend to considerable depths, and yet still rise to discharge at the surface. The total hydraulic head, however, must always decline along a flow route.

The rate of loss of head along a flow route is termed the hydraulic gradient; it is a reflection of the rate of consumption of energy in driving the flow. Increased flow requires a greater hydraulic gradient, obtained by increasing water levels at the upstream end of the system. Counteracting the hydraulic gradient is the resistance to flow arising from fluid properties and rock form. In granular media such as sand or sandstone, the flow route follows the voids between the individual grains, and the ease of flow is termed the "hydraulic conductivity". All rocks have an inherent hydraulic conductivity ranging from 1 to $10^{-13}$ m $s^{-1}$ for coarse gravel to marine clays respectively. The exceptional range of values of hydraulic conductivity has profound implications. First, strong contrast between hydraulic conductivities makes the distinction between aquifers and aquicludes realistic, but relative; silt in sand is an aquiclude, but in clay would be an aquifer. Second, it makes the actual flow route taken by water extremely sensitive to almost imperceptible geological variations. Third, it makes it practically impossible to accurately characterize the hydraulic properties of any aquifer in general and karst aquifers in particular.

The effects of hydraulic gradient and hydraulic conductivity on groundwater flow in porous media are summarized in Darcy's Law, which states that the flow per unit area is the product of the two factors, hydraulic gradient and hydraulic conductivity. Darcy's Law has seen widespread application, not least in the development of popular computer models designed to simulate groundwater flow based on interpolations of observations of hydraulic head and hydraulic conductivity (see Groundwater in Karst: Mathematical Models). Such simulations are very cost-effective ways of defining aquifer flow patterns, and exploring the impact of possible environmental change or resource use and abuse. However, groundwater may follow routes other than the pores in the rock matrix, most notably through fractures and solutionally enlarged karst openings. Hydraulic head in such aquifers remains the primary driving force for groundwater movement, but the medium can no longer be characterized by a hydraulic conductivity (a bulk property), but requires definition of the size, orientation, and linkage of openings. These data are seldom available, although explorable cave passages provide a sample of the upper end of the spectrum of openings. Flow in mapped cave streams can be described by a range of generalized open or closed conduit laws (e.g. Manning, Chèzy, and Darcy-Weisbach) that show flow to depend strongly on the aperture of the conduit. Flow routes intermediate between matrix flow and cave streams are tackled either by applying Darcy's law to an assumed "equivalent" hydraulic conductivity, or more recently by attempts at direct simulation of conduits networks to obtain a matching to observations of hydraulic head. While the Darcy approximation may provide an acceptable match to observations of hydraulic head, it is not known how realistic the flow pattern might be. In particular, Darcy simulations of karst aquifers significantly underestimate flow velocities, making the transmission of contaminants appear slower and more manageable than is really the case.

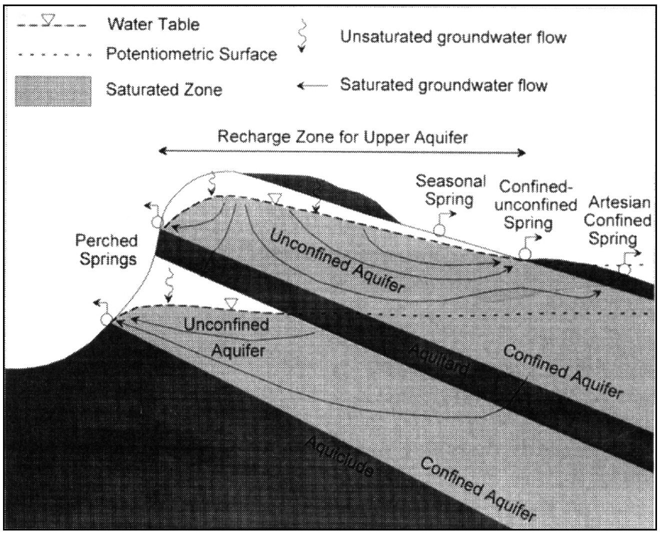
**Hydraulic Head: Landscape Controls and Flow Systems**

The correspondence between elevation and energy provides a simple rule of thumb for groundwater flow: recharge takes place at high ground, and discharge at lower elevations. In this sense groundwater flow can be viewed as obeying the same topographic rules as surface streams with corresponding divides and discharge along the axis of valleys. Strictly this rule applies to the topography of the water table, not the land surface, but the former can be provisionally considered a subdued analogue of the latter. The water table reaches the surface in discharge zones, but lies at greater depth elsewhere in recharge zones. Although there may be a number of natural features indicative of water-table level such as lakes, rivers, and springs, in many landscapes the thickness of the unsaturated zone is indeterminate, but may be many tens of metres in some karst areas. The water level in shallow wells provides the best indication of water-table elevation and the compilation of a water-table database using existing and custom wells is a primary task in hydrogeology. However, only shallow groundwater flow follows the local topography. At increasing depth, groundwater flow is influenced by wider scale topography up to regional scales of thousands of kilometres. The result may be multi-level flow systems at local, intermediate, and regional scales with frequent inconsistency of groundwater flow trajectories at different depths.

**Hydraulic Conductivity: Geological Controls**

Topographically directed flow systems develop in completely uniform porous media, and arise from consideration of only hydraulic gradient. The extreme natural variability of hydraulic conductivity often exerts greater control, especially in local redirection of groundwater. If the ground is considered to be composed of aquifers and aquicludes, then the geological extent of the aquifer dictates the storage and routing of groundwater.

Figure 1 is an idealized example of groundwater occupation of two porous medium aquifer units sandwiched between three aquicludes in an escarpment setting typical of moderately deformed sedimentary rocks. Geological exposure dictates the extent of the recharge area across the crest of the escarpment. Springs have developed at the lowest topographic points of each aquifer. The upper aquifer has filled beneath the overlying or




**Groundwater in Karst: Figure 1.** A simple escarpment composed of two aquifers sandwiched between three aquicludes. Recharge occurs at the surface exposures of the aquifers, and water is routed to respective springs or well based on the pattern of hydraulic head reflected in the water table in the unconfined aquifer, and the potentiometric surface in the confined aquifer.

confining aquiclude. An unconfined aquifer has a water table for its upper boundary; a confined aquifer has an aquiclude as its upper boundary. As a result, the water in a confined aquifer is pressurized and the hydraulic head is greater than the elevation of the upper boundary of the aquifer. It is convenient to consider a virtual water table termed a "potentiometric surface", the level to which water would rise if a well were drilled into the aquifer. It is quite possible for the potentiometric surface to be above the ground surface, in which case, artesian springs and flowing wells may occur. If recharge is highly seasonal, then the water table and potentiometric surface may also oscillate. The upper spring on the gentle dip slope may therefore be seasonal, only flowing when the water table reaches that elevation. The lower aquifer in Figure 1 is isolated from surface recharge and protected from surface-derived contamination. Recharge may occur by slow seepage from the upper aquifer, but the water would be expected to have a long residence time. Flow from the lower perched spring might be more steady, and the water more mineralized than for the upper perched spring.

**Heterogeneity and Anisotropy**

Much hydrogeological theory assumes a homogeneous aquifer in which hydraulic conductivity is uniform throughout. However, most aquifers are heterogeneous and geological contrasts result in variations in hydraulic conductivity. Groundwater is redirected or refracted when it encounters subtle changes in hydraulic conductivity. As a general rule, groundwater is focused through areas of high conductivity and away from areas of low conductivity. Some aquifers exhibit anisotropy (directional differences in hydraulic conductivity), for example in response to layering of the constituent rock materials, or the presence of fractures. In these cases, the groundwater trajectory tends to follow the higher hydraulic conductivity, rather than the direction of the steepest hydraulic gradient.

**Fracture Aquifers**

Intact igneous and metamorphic rocks are often heterogeneous and anisotropic. The intact rock has very low hydraulic conductivity, but fractures arising from tectonic, cooling, and decompression stresses may be present. Joints and bedding planes may similarly dominate the conductivity of some sedimentary rocks such as quartzites and massive limestones. The pathway taken by groundwater in such rocks depends on the relationship between the fracture pattern and hydraulic gradient. The latter is driven by topography, as expected. It is possible to simulate the flow of groundwater in fracture aquifers, but it is almost impossible to determine critical features of the fracture system such as the orientation, extent, connectivity, and aperture. In most circumstances, fracture aquifers are simulated with an equivalent porous-medium model.

**Karst Aquifers**

In rock types favouring dissolution by groundwater, the most active flow routes become enlarged over time, resulting in a highly heterogeneous and anisotropic karst aquifer. The process is particularly effective in fracture aquifers where groundwater flow is concentrated, but even porous soluble aquifers show development of solutional openings. Karst aquifers exhibit a more or less organized system of solutionally enlarged openings, typically directed and convergent towards a spring or springs. The hydraulics of enlarged openings favour water movement, so that the majority of flow may become concentrated in very few conduits, giving a dendritic (branching) network. Nevertheless, the pathways followed by karst groundwater are still directed by hydraulics, conveying higher elevation recharge to lower elevation springs. However, karst development leads to some hydro-geological peculiarities, and has evolved a distinctive terminology.

**Karst Recharge**

Where karst rocks are exposed at the surface, excess rain and snowmelt infiltrate through the soil and down into the bedrock to produce "autogenic" recharge. Surficial karst rocks become highly eroded by solution, producing many flow routes, and considerable water storage capacity, in the epikarst aquifer. The karst surface is commonly moulded into closed depressions that act to funnel recharge into more highly developed conduits. Passage through the epikarst tends to produce a steady flow of chemically enriched water. The general absence of surface rivers on karst demonstrates that autogenic karst recharge is much greater in magnitude than in other aquifers.

Less permeable materials such as shale, glacial till, or sandstone develop surface stream networks. Where such rocks are juxtaposed to, or overlie, karst, streams running onto the karst are prone to sink into the ground, constituting concentrated (focused) "allogenic" recharge. Typically, allogenic flow is variable, chemically dilute, and carries sediment, reflecting the properties of the corresponding surface catchment. Where the volume of water running onto the karst exceeds the capacity for recharge, the stream may flow for a considerable distance along an apparently conventional valley, before recharge is complete. The extent of such flow depends on the discharge of the stream, and is promoted by a common tendency for sink points to become choked by sediment and debris. In some cases, allogenic streams run completely across a karst landscape, and may have excavated a significant gorge. Where a permeable caprock overlies karst then dispersed allogenic recharge will occur, with the resulting dissolution leading to puzzling collapse dolines in the insoluble caprock.

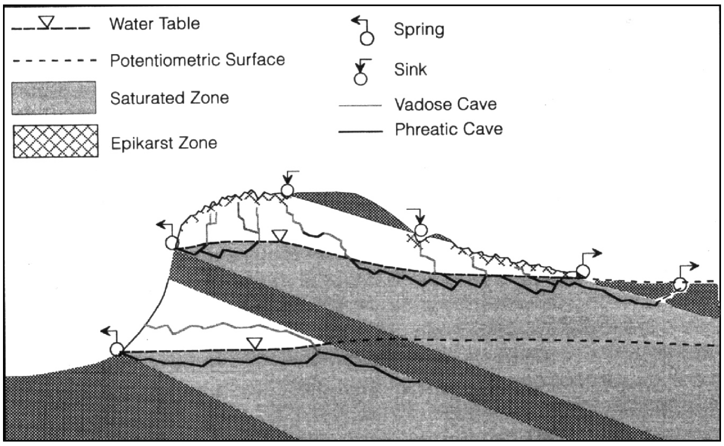
**The Karst Unsaturated or Vadose Zone**

Flow through the unsaturated zone is dominated by gravity, so flow routes tend to be directed steeply downwards. Allogenic streams tend to develop discrete cave streamways with distinctive canyon passages and vertical shafts. Autogenic water is conveyed in seeps, trickles, and a hierarchy of widely distributed flows reflecting surface conditions, the degree of focusing by closed depressions, and the magnitude of storage in the epikarst. Apart from the epikarst, there appears to be relatively little storage of water in the unsaturated zone. The traditional term for unsaturated conditions is vadose, and this term is applied to the characteristic canyon and shaft style of cave system. In contrast to porous media, there is little capillary movement of water upwards through the unsaturated zone to sustain surface evaporation; during droughts, karst surface moisture is sustained by the epikarst aquifer.

**The Karst Saturated or Phreatic Zone**

Caves filled to the roof with water are termed phreatic, have distinctive rounded cross sections, and, with flow driven by pressure, may be directed both up and down. The transition from unsaturated to saturated or phreatic conditions technically occurs at the water table. In caves, the exact elevation of this transition depends on the flow of the stream and the geometry of the channel; local and temporary phreatic conditions often develop. Sections of cave passage which become temporarily filled with water are termed epiphreatic, and exhibit a mix of vadose and phreatic features. Phreatic conduits descending to great depths below the water table are termed bathyphreatic. They develop from a combination of geological control, and the presence of hydraulic gradients at depth.

Away from primary conduits many smaller flow routes exist, a more coherent regional water table can usually be defined, and a considerable volume of water can be stored. Flow in conduits requires very low hydraulic gradient compared to flow elsewhere in the aquifer, so the water table tends to be low and flat along the line of major conduits, and relatively steep in the surrounding aquifer. Under such "normal" conditions, water drains slowly from the aquifer to the nearest conduit which then rapidly conveys the water to the surface spring. Saturated zone storage is replenished not only by autogenic seeps, but also by water driven out of conduits pressurized during floods. Under the latter conditions, the karst water table is elevated along the line of the conduit, indicating flow out of the conduit and into the surrounding aquifer.




**Groundwater in Karst: Figure 2.** The same hydrogeological setting as Figure 1, rendered for a karst aquifer. The exposures of karst where autogenic recharge occurs show rugged topography with an underlying epikarst and vadose caves. The impermeable caprock has generated allogenic streams which enter the karst as vadose streamways, descending to the phreatic zone. The water table is sketched for the phreatic conduits and has flattened considerably compared to Figure 1. The deeper aquifers may contain conduits, but function much as conventional aquifers in terms of the potentiometric surface.

Figure 2 presents a karstic version of the dual aquifers represented in Figure 1. The overall governing topography is similar, but recharge is focused by closed depressions and at the margins of impermeable cover. In response, within the unsaturated zone, many vertically directed conduits (shafts) have developed, some under closed depressions, others at stream-sinks. As the land surface changes over time and the pattern of recharge evolves, some conduits become abandoned, but nonetheless remain as potential flow routes. In the saturated zone, the flow is directed towards the springs, but is constrained by geological structure resulting in the irregular path shown. Landscape changes also alter the position of the water table and springs may find lower elevation outlets, so that multiple level conduits exist. These have been omitted from the figure for clarity. In some karst aquifers, geological controls can sustain phreatic (water-filled) passages well above the regional water table, a phenomenon which may cause confusion in hydrogeological interpretation.

**Summary**

Overall, the physical principles guiding groundwater flow in karst aquifers are those applying to all groundwater flow. However, the peculiarities of solutional development of flow routes, and the possibility of exploring the larger of these flow routes has led to a distinctive form of permeability and a quite separate terminology. The resulting separation of karst from general hydrogeology has meant that the understanding of karst water resources has been compromised.

CHRIS SMART and STEPHEN R.H. WORTHINGTON

*See also* Karst Water Resources; Springs

## Further Reading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