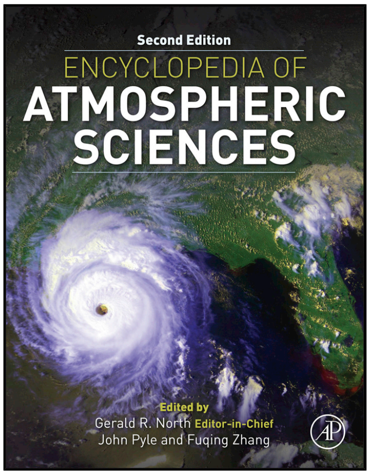

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Groundwater and Surface Water

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Synopsis

Groundwater and surface water are two important components of the hydrologic system. One objective of hydrologic studies is to understand the spatial and temporal variations of water storage and movement. This article first presents an overview of the global distribution of water, the hydrologic cycle, and the water balance concept. It then describes the physical principles governing the movement of groundwater and surface water by focusing on the hydraulic gradient as the driving force for flow: Darcy's law for groundwater and Manning's equation for streams. Finally, applied aspects of hydrology are discussed as they relate to water contamination, land subsidence, hydrothermal fluids, and hydroseismicity.

Introduction

Water is one of the most precious and indispensable natural resources. As important components of the hydrologic system on Earth, groundwater and surface water impact numerous aspects of Earth processes and many facets of daily life. Water at the Earth's surface directly interacts with the atmosphere, and water in the subsurface continuously redistributes geothermal energy and dissolved minerals in the Earth's crust at a variety of temporal and spatial scales. Hydrology encompasses the study of the occurrence and movement of water both at the land surface and in the subsurface. Although the term groundwater usually refers to the water that occurs beneath the water table in saturated soils and rocks, study of soil moisture movement in the unsaturated zone above the water table is well within the realm of groundwater studies.

Focusing on the physical dynamics of groundwater and surface water, this article first presents a brief overview of water as a resource. The discussion is then devoted to the main concepts and governing principles applied to physical processes controlling the movement of groundwater and surface water. Finally, the applied aspects of hydrology as they relate to water contamination, land subsidence, and geological processes are briefly reviewed.

Water as a Resource

The presence of abundant liquid water makes the Earth a unique planet in the solar system. This abundance has been challenged throughout human history as numerous local and regional conflicts over water resources have erupted. Evidence of early attempts to harness water for human purpose has been documented by archaeologists. For example, clever water usage for irrigation can be traced as far back as 4500 years ago in the Middle East. A remarkable water-collecting tunnel system dating from around 500 BC in Egypt has been unearthed. As world population grows, the local demand for water is expected to grow, particularly in arid developing countries. Shown in Figure 1 are the historical and anticipated global water extractions from 1900 to 2025 and how water use is partitioned among agricultural, domestic, and industrial uses. Increasing trends are observed in all three sectors and in the total extraction (bar graphs in Figure 1). The partitioning of water (pie charts in Figure 1) indicates an increased share in domestic use from 14% in 1900 to forecasted 24% in 2025 but a decreased share in agricultural use from 80% in 1900 to forecasted 60% in 2025. The increased domestic share and the decreased agricultural share may suggest food shortage problems in the future if crop production water use efficiency cannot keep up with global population growth and increased demand for food. Total freshwater withdrawal in the United States from 1950 to 2005 also followed a generally increasing trend (Figure 2). The decrease in the 1980s was primarily due to increased irrigation efficiency and reduction in water consumption by the thermoelectric power industry as a result of improved power plant technologies and efficiencies. The continual increase in domestic water use has compensated for the decrease in industrial water use.

Global Water Distribution

Figure 3 shows the water distribution in the Earth system. Of all water on the Earth, 97.33% of it is stored in the ocean and is too salty to be directly used for human consumption. Ice caps and glaciers, the next largest water reservoir, hold 2.12% of the global water and account for 79% of the total freshwater. Groundwater in the upper 800 m of the subsurface holds 0.31% of the water on the Earth. Only the portion in the upper few hundred meters of the Earth's crust is economically accessible and fresh enough for human consumption. The salinity of groundwater increases with depth and often becomes too high to be useful as a resource below 1 or 2 km. Surface waters including lakes and streams hold 0.158% of the global water, and they have served as the main water resource for people, primarily owing to their easy accessibility. The water in the atmosphere, 0.083% of total water, is much more than that occurring in all of the streams (0.003%) plus all soil moisture (0.002%) in the world.

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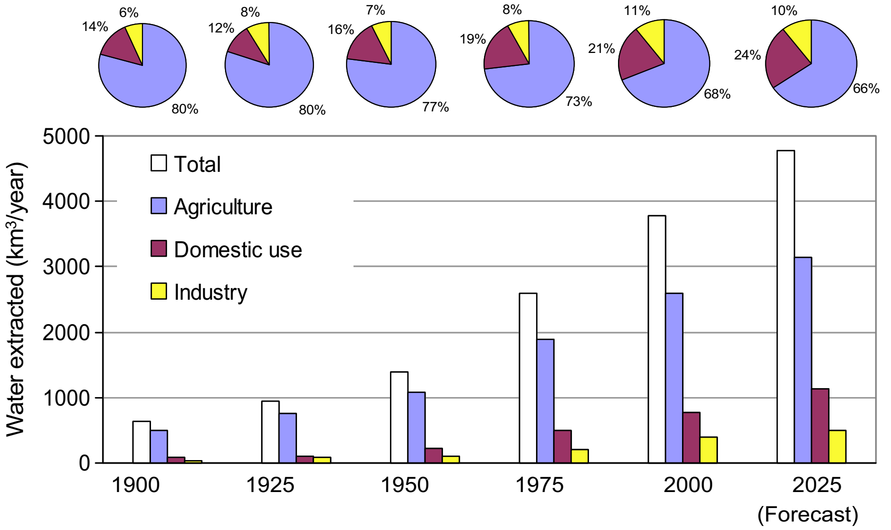

Figure 1 Global water extractions from 1900 to 2025 (bar charts) and the partition of water by different sectors (pie charts). Reproduced from UNEP, 2008. Vital Water Graphics – An Overview of the State of the World's Fresh and Marine Waters, 2nd edn. Nairobi, Kenya: UNEP, ISBN: 92-807-2236-0.

Hydrologic Cycle

Powered by solar energy, the hydrologic cycle is the endless movement of water from one part to another part in the Earth system (Figure 4). Water evaporates into the atmosphere from bare land surfaces and from open waters such as oceans and lakes. Plants also lose water to the atmosphere through transpiration. Evaporation and transpiration are collectively known as evapotranspiration. Ice and snow can lose water through sublimation, the process of changing solid water into vapor without first melting to liquid. Water falls back to the Earth's surface as precipitation in the form of snow and rain. Upon reaching the surface, water flows overland as runoff to streams or infiltrates into the subsurface. Some of that infiltrated water becomes recharge to the groundwater system. Groundwater moves through geologic media, discharging to springs and surface waters. Much of the migrating groundwater and surface waters eventually make their way to the oceans. The rates of water flow in the hydrologic cycle vary spatially and temporally. Streamflow is relatively rapid, with residence times of days to months. This is in contrast to the residence time of groundwater, the time it remains in the subsurface since recharge, which varies from months in sediments at shallow depths to tens of thousands of years in rocks several kilometers deep in the Earth's crust.

Water Budget Balance

One of the primary objectives in studying groundwater and surface water is to understand the spatial and temporal variations of water storage and movement. The basic principle

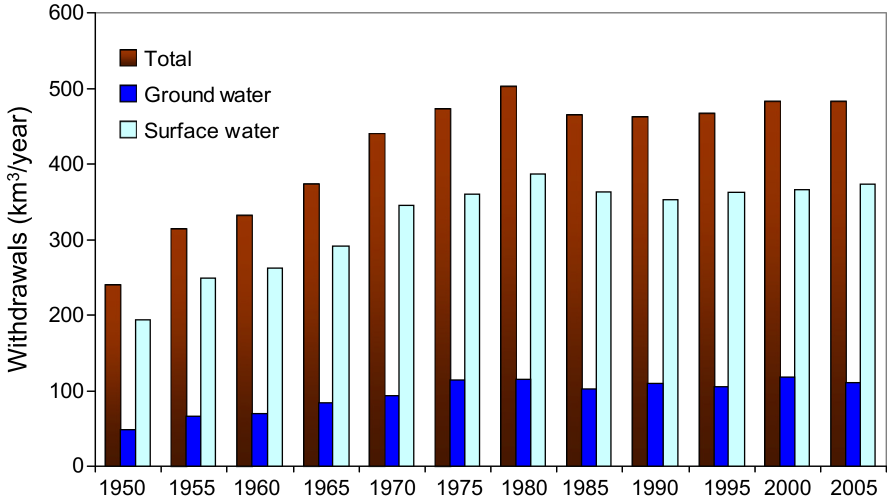

Figure 2 Freshwater withdrawals in the United States from 1950 to 2005. Reproduced from Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., Maupin, M.A., 2009. Estimated Use of Water in the United States in 2005. U.S. Geological Survey Circular 1344.

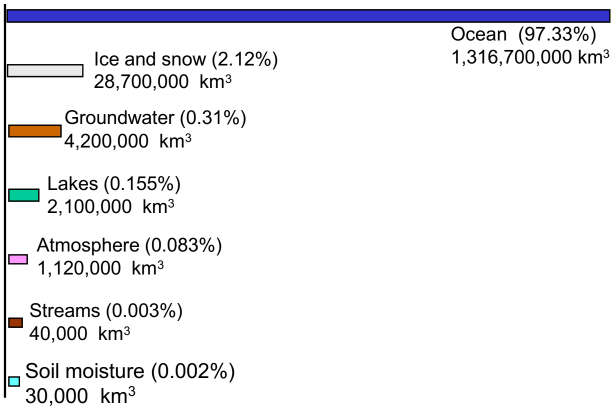

Figure 3 Global water distribution. Bar lengths are not to scale. Reproduced from Fierro, P., 2007. The Water Encyclopedia, Hydrologic Data and Internet Resources, 3rd edn. Boca Raton, FL: CRC Press. doi: 10.1201/9781420012583.ch4.

governing these variations is conservation of mass or water balance. This principle requires that the amount of water entering a control volume during a specified time period minus the amount of water exiting equals the change in storage in that volume. The principle of a water balance is often applied over a watershed, also referred to as a drainage basin, which is a geographic region where all the water flows to a common destination or an outlet. Watershed delineation is primarily based on topography where topographic divides, or ridges, form the boundaries of a watershed. Smaller watersheds or subbasins can be nested within a larger watershed. It should be noted that groundwater can flow across the boundaries of watersheds, under the topographic divides of the basin. Considering steady-state flows averaged over a long period of time, the water balance equation is:

$$P + Q_{\text{in}} + G_{\text{in}} = \text{ET} + Q_{\text{out}} + G_{\text{out}} \qquad [1]$$

where P is the precipitation, Q_{in} and Q_{out} are stream inflow and outflow, respectively, G_{in} and G_{out} are groundwater inflow and outflow, respectively, and ET includes evaporation and transpiration. All quantities have the dimension (L t^{-1}).

It is a common misconception that the amount of groundwater that can be safely extracted from the subsurface at steady state is equal to some fraction of preextraction groundwater recharge to that system. However, as suggested by the water balance shown in eqn [1], any extraction of groundwater, adding to the right side of the equation, must be balanced by increased inflows on the left side or decreased outflows on the right side of eqn [1]. In general, any extraction of groundwater during development will reduce natural groundwater discharge to springs and surface waters over the long term, which may be undesirable to people and harmful to the environment.

Physical Hydrological Processes

Surface Water Dynamics

Streams, lakes, and wetlands are the surface waters of primary interest in hydrologic studies. The following discussion focuses on streams. A stream is a body of water flowing down slope along a more or less confined course. A river is a stream with a significant amount of flow. A stream with no tributaries is designated as a first-order stream, the confluence of two first-order streams is the beginning of a second-order stream; the confluence of two second-order streams is the beginning of a third-order stream, and this pattern can continue to form higher-order streams. The branching patterns of stream orders have been studied using a fractal approach that provides a mathematical framework for treatment of similar geometric characteristics over a range of scales. Streams play vital geologic roles in incising valleys, transporting dissolved load and sediments to the sea, and reshaping the landscape over time. Stream processes are affected by a variety of factors such as the steepness of the stream, the cross-sectional area of the stream, water velocity, and sediment load. The dimensionless Reynolds

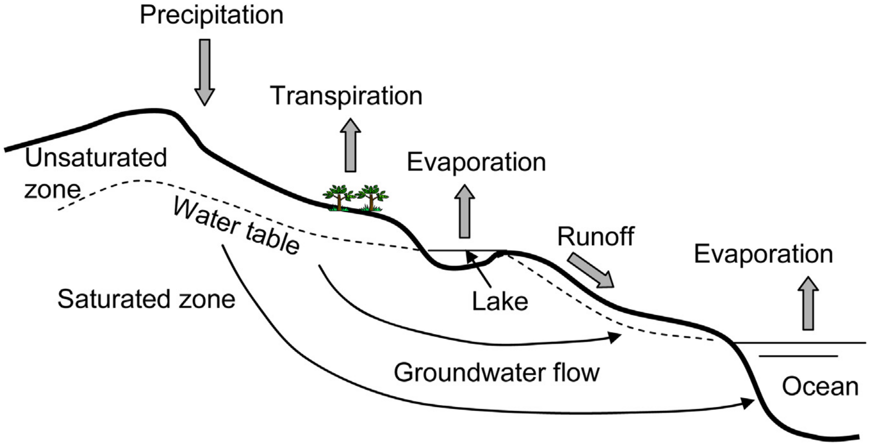

Figure 4 The hydrologic cycle: Water evaporates from open waters at the Earth's surface and transpires from vegetated lands. Upon reaching the land surface, precipitation infiltrates the soil to replenish groundwater as recharge or is removed by evapotranspiration. The remainder flows overland as runoff to open waters. Groundwater flows through the subsurface and returns to surface waters and oceans. The water table is the boundary between the unsaturated zone above and the saturated zone below. This particular diagram is most representative of humid regions where the water table is near the ground surface and streams and lakes are surface manifestations of the water table.

number, (Re), is a convenient parameter describing the state of flow as laminar or turbulent. It is defined as $(Re) = \rho v Y/\mu$, where ρ is the density of water (M L^{-3}), v is the average flow velocity (L t^{-1}), Y is the average flow depth (L), and μ is the dynamic viscosity of water (M L^{-1} t^{-1}). In streams, laminar flow occurs when (Re) is less than 500. Turbulent flow occurs when (Re) is greater than 2000 and circulating eddies form in turbulent regions. Transitional flow lies between laminar and turbulent flow regimes. Actual streamflow is seldom laminar, but when the degree of turbulence is small flow is often considered to be in the laminar range. The Manning equation is one of the most commonly used equations for computing the average flow velocity in a stream channel:

$$v = n^{-1} R^{\frac{2}{3}} S^{\frac{1}{2}} \quad [2]$$

where n is the Manning roughness coefficient, R is the hydraulic radius (L) defined as the ratio of the flow channel's cross-sectional area to its perimeter, and S is the channel slope.

Water Table

In near-surface sediments and soils, water is in the form of moisture in the unsaturated zone where void spaces are partially filled with water. At depth, void spaces are completely filled with water, which forms the saturated zone. The boundary between the unsaturated and the saturated zone marks the water table (Figure 4), although a transitional tension-saturated region called the capillary fringe occurs at the interface. The configuration of the water table in humid regions is generally a subdued replica of the topography, near the surface in low lands but deeper at high elevations. The depth of the water table varies in both space and time. In humid regions, the water table can be at or near the surface and streams and lakes are surface expressions of the water table. In drier semiarid and arid regions, the water table can be hundreds of meters below the land surface. Under natural conditions, the water table can rise in wet seasons as excess precipitation percolates through the unsaturated zone to the water table and drop in dry seasons when water is lost through evaporation and transpiration. The most reliable way to locate the water table is to drill wells. Because lateral groundwater flow follows the slope of the water table, knowledge of the water table configuration gives useful basic information about the direction of groundwater flow.

Porosity, Permeability, and Hydraulic Conductivity

The primary factors controlling groundwater occurrence and movement in the subsurface are the hydraulic properties of the geologic material and the hydrologic driving force. The most important material properties are porosity and permeability. Porosity, defined as the percentage of pore space in a unit volume, may vary from 0–5% for tight igneous and metamorphic rocks to 25–50% for sands or fractured rocks. Clay can have a porosity as high as 90%, but few of the pores are interconnected. Porosity is a measure of geologic materials' capacity for storing water. A related quantity is known as specific yield, which is used to describe the volume of water that is partially drained by gravity from a porous material as the water table declines.

Permeability is a measure of geologic materials' ability to transmit water and reflects how well pores are interconnected. In the simplest case, it is defined as follows: $k = Cd^2$, where k is the permeability (L^2), C is a proportionality constant related to grain size, sediment sorting, and packing arrangement, and d is the particle diameter for which 10% of the grains by weight are finer (L). Depending on the type of fluid flowing through a system, the ease of flow differs. One can imagine that a fluid that is sticky like honey would flow much slower than would clean water in the same medium under the same conditions. Therefore, it is necessary to consider not only the medium but also the fluid properties. The hydraulic conductivity is introduced and is defined as: $K = k\rho g/\mu$, where K is the hydraulic conductivity (L t^{-1}), ρ is the fluid density (M L^{-3}), g is the gravitational acceleration (L t^{-2}), and μ is the dynamic viscosity of the fluid (M L^{-1} t^{-1}). Values of hydraulic conductivity vary over many orders of magnitude from 10^{-13} m s^{-1} for tight rocks to over 1 m s^{-1} for sands and gravels.

The most reliable means of obtaining hydraulic conductivity values are field-scale pumping tests using sets of observation wells. When water is withdrawn from or injected into a well, the rate of water level decline and recovery in the well and in adjacent observation wells can be measured by a pressure transducer and recorded by a data logger. The rate of water level decline during pumping, and recovery after pumping is stopped, is used to compute the hydraulic conductivity of the material in the vicinity of the pumping and observation wells. Large-scale tests with many observation wells are more reliable than single well tests, known as slug tests. This is largely because local material properties near the slug test well are not necessarily representative of the regional hydraulic conditions. Laboratory tests on core samples are commonly conducted to obtain hydraulic conductivity values, but they are typically valid at the centimeter scale and not necessarily representative of larger scales because hydraulic properties typically vary over small distances in natural groundwater systems. Computer modeling is also commonly employed as an indirect means of inferring hydraulic conductivity at different scales based on changes in groundwater levels due to regional addition or removal of groundwater over time and space.

Aquifers and Aquitards

Aquifer and aquitard are terms used to characterize hydrogeologic systems. A geologic unit that is highly permeable and can store and transmit a significant amount of groundwater is called an aquifer. When an aquifer is bounded by the water table on the top, the aquifer is called an unconfined aquifer. When an aquifer is confined between two much less permeable units, it is called a confined aquifer. Water pressure in confined aquifers is usually higher than pressure in unconfined aquifers. Thus, when a well is drilled into a confined aquifer, the water level in the well will rise to above the top of the aquifer, and may even rise above the ground surface, which creates artesian flow. An aquitard, also known as a confining bed, is a much less permeable geologic unit. Because no naturally occurring porous material is completely impermeable, aquifers and aquitards are identified to distinguish their relative degree of high and low permeability, respectively. In general, gravel, sandy materials, limestone, or highly fractured rocks make good aquifers, whereas clay-rich, poorly sorted sediments, and unfractured rocks often form aquitards. The term aquiclude has been used for describing an impermeable unit, but this term has become obsolete.

Water in an Unsaturated Zone

Near the land surface at shallow depths, soils and sediments are often partially saturated, which creates a region known as an unsaturated or vadose zone. Saturation is defined as the fraction of pores that contain water, and it varies from 0 to 1, representing dry and fully saturated conditions, respectively. The water in an unsaturated zone clings onto solid particle surfaces and is sustained by capillary forces. Pore pressures in the unsaturated zone are conventionally expressed as negative values, reflecting the use of atmospheric pressure as the zero reference pressure. The pore pressure distribution and the rate of moisture movement vary spatially, depending on soil type, and temporally in response to short- and long-term climate conditions.

Infiltration is an important process in the unsaturated zone, which involves downward movement of moisture under wet conditions. The infiltration rate over a small area can be measured using a ring infiltrometer. A commonly used type of infiltrometer consists of two rings with a smaller inner ring nested inside a larger outer ring. The infiltrometer can be pushed several centimeters into the subsurface and both rings filled with water. The rate of water seepage into the ground from inside the inner ring is used to estimate the infiltration rate. The diameter of the rings of a portable infiltrometer varies from a few centimeters to 1 or 1.5 m. It is important to note that not all infiltrated water makes its way to the water table as recharge because some is temporarily stored in the near-surface sediments and subject to evapotranspiration.

In contrast to infiltration, evaporation and transpiration draw moisture upward. Evaporation not only causes water loss from surface waters, such as lakes and rivers, but also from near-surface soils and sediments. Water evaporates as a vapor diffusion process that is largely controlled by the energy exchange between radiation, or sensible heat from the atmosphere or ground, and the heat energy change in the evaporating body. A direct method to determine the evaporation rate is known as the pan evaporation approach. It involves exposing a cylindrical pan of water to the atmosphere in clearings where precipitation also can be monitored. The standard U.S. National Weather Service Class-A pan is 1.22 m in diameter and 25.4 cm deep. Transpiration is a process where water is lost to the atmosphere through the vascular systems of plants. The transpiration process works by absorption of water by plant roots, translocation of liquid through plant vascular systems, and transpiration into the atmosphere through stomata or openings in leaf surfaces. Although transpiration is considered a diffusion process, water is first pulled through the plant by a potential energy gradient, before diffusing into the air in response to a vapor pressure difference. There are a variety of methods to estimate transpiration. One is based on direct measurement using a lysimeter, a tank of soil, water, and plants in which the water loss due to transpiration can be assessed. Another general approach is based on a surface energy balance that relies on a set of measurements to compute the latent heat flux, which is proportional to transpiration.

Groundwater in a Saturated Zone

Below the water table, the movement of groundwater occurs as slow-moving seepage through the pore spaces in sediments and rocks or as relatively fast flow through rock fractures and dissolution channels. Groundwater velocities are generally much slower than streamflow rates, and may be as low as 1 mm day^{-1}. Under natural conditions, a groundwater velocity on the order of centimeters per day would be considered typical and 1 m day^{-1} or more would be considered high. The low velocity of groundwater has important implications for geological processes like metamorphisms and ore formation as well as contaminant movement because it leads to long residence times. The extent of groundwater flow systems varies from local meter-scale hill slopes to multikilometer-scale regional basins. Groundwater velocities are typically faster in shallow, local flow regimes and slower in deeper, regional flow systems. As a result, the residence time of groundwater varies significantly, ranging from days in shallow, small systems to tens of thousands of years when considering deep flow in large sedimentary basins. Quantitative descriptions of groundwater flow require a depiction of the hydraulic head field and application of Darcy's law, which are discussed in the following subsections.

Hydraulic Head

Hydraulic head is one of the key variables in describing a groundwater system. It represents the mechanical energy per unit weight of fluid in the system. Hydraulic head, h, is defined as: $h = h_\text{p} + h_\text{z}$, where h_p is the pressure head and h_z is the elevation head. All three quantities have the dimension (L). The pressure head represents the energy due to pore fluid pressure, and the elevation head represents the gravitational potential energy arising from elevation. Because groundwater velocities are so slow, kinetic energy is typically negligible. Water flows from high to low hydraulic heads along a hydraulic gradient (discussed presently). *In situ* measurement of hydraulic head is accomplished by measuring the water level elevations in wells. First, the depth to groundwater is measured with the aid of a manual tape, electric sounding instrument, pressure transducer, or similar devices. Next, water level elevations are obtained by subtracting the measured depth to water from the land surface elevation. In regions where spatial hydraulic head differences are slight, typically in areas of gentle topography, water level measurements require accuracies of millimeters.

Darcy's Law

The basic equation governing groundwater movement is Darcy's law. In 1856, Henry Darcy, a French engineer in Dijon, France, performed an experiment involving water flow through a cylindrical sand column. The experimental data led to an empirical relationship between water flow and the experiment setup parameters. This relationship later became well-known as

Darcy's law in groundwater studies. Darcy's law is a simple gradient–flux relation and is as common in groundwater studies as analogous laws are in other fields such as Fick's law describing solute flux, Ohm's law describing electrical current, and Fourier's law describing heat conduction. In a one-dimensional system, Darcy's law is expressed as:

$$Q = -K\frac{dh}{dx}A \qquad [3]$$

where Q is the volumetric flow rate ($L^3\ t^{-1}$), K is the hydraulic conductivity ($L\ t^{-1}$), h is the hydraulic head (L), x is the coordinate (L), A is the cross-sectional area of flow (L^2), and dh/dx is the hydraulic gradient. It is clear from eqn [3] that the hydraulic gradient is the primary driving force for groundwater flow. The negative sign in the equation denotes that groundwater flow is in the direction of decreasing hydraulic head, down the hydraulic gradient. In describing groundwater flow, groundwater velocity, V_{gw}, is commonly computed. It is defined by the following equation:

$$V_{gw} = \frac{Q}{(A)(n_{eff})} = -\frac{K}{n_{eff}}\frac{dh}{dx} \qquad [4]$$

where n_{eff} is the effective porosity, or pore space through which water flows unimpeded by stagnant, dead end zones. V_{gw} is the average rate of a parcel of water occupying a volume of many pores and grains.

It should be noted that groundwater flow can be driven by other spatial differences in potentials besides a hydraulic gradient. For example, groundwater flow also can be driven by gradients in temperature, solute concentration, or both. In the absence of these other gradients, Darcy's law is a simple and sound formula to compute groundwater flow.

Wells

The primary need for wells is to withdraw water from the subsurface. Wells also serve as a window to the subsurface in the study of groundwater. Some wells are used for monitoring hydraulic heads (water levels) and also for sampling water for chemical analyses. When a well is pumped, a cone of depression forms around the well as the water level declines; the drawdown in the depression cone is greatest near the pumping well and less severe with distance from the well. The rate of water level decline is typically quite different depending on whether the pumping occurs in a confined or in an unconfined aquifer. Under the same pumping rate in different aquifers consisting of similar geologic materials, initially, a larger water level decline is expected in a confined aquifer and a smaller decline in an unconfined aquifer. For similar declines due to pumping, the volume of water obtained from confined aquifer storage is much less than that obtained from unconfined aquifer storage. When pumping from a confined aquifer, the porous material is not drained and does not desaturate. Rather, water comes from storage by compaction of the aquifer material accompanying slight rearrangement of grains plus expansion of water when pore pressure is reduced due to pumping. When pumping from an unconfined aquifer, water comes from storage by partial draining of saturated pores as the upper portion of the aquifer is converted into an unsaturated zone.

Surface Water and Groundwater Interaction

Groundwater interacts with lakes, streams, and wetlands across the landscapes from mountains to plains to shores of bays and oceans. In managing water resources, conjunctive use of surface water and groundwater has increasingly become a common practice, particularly in arid and semiarid regions. The basic concept of conjunctive use is to utilize surface water while storing excess water in aquifers under wet climate conditions when streamflow is high, and to withdraw water from the aquifers under drier conditions when demand is high but streamflow is low. The success of a conjunctive use project depends heavily on the dynamics of the interaction between the surface water and the groundwater. Streams can either gain water from or lose water to aquifers. Many streams do both in different reaches of the stream and at different times in the same reach. The rate and direction of flow in or out of the stream can also vary as the elevation of the water table relative to the stream surface fluctuates. Pumping of groundwater near streams can decrease the quantity of flow feeding a stream as baseflow, and even change a gaining stream into a losing stream. Moreover, interactions between groundwater and surface water affect water quality. When the groundwater in shallow aquifers is contaminated (for example, from agricultural practices of applying fertilizer and pesticides), the shallow aquifers can contaminate surface water as the groundwater flows toward a stream. The opposite can occur when a stream is heavily contaminated (for example, from mine waste drainage in mountainous regions). Mixing of groundwater and surface water affects other natural environments such as wetlands and aquatic environments when acidity, temperature, nutrients, and dissolved oxygen are altered by mixing. Streams, lakes, and wetlands may become acidic as they receive atmospheric deposition of chemicals, such as sulfate and nitrate. Acidic precipitation directly affects the well-being of aquatic ecosystems. In some cases, significant groundwater flow into a stream may help neutralize and reduce the stream acidity to tolerable levels for aquatic organisms.

Applied Aspects of Hydrology

The scientific aim of hydrology is to seek understanding of the mechanisms of water movement in the Earth system and the roles that water plays in natural processes. The applied aspect of hydrology, on the other hand, relates to using scientific knowledge to guide safe and sustainable use of water resources, investigating the impact and consequences of improper water use, and evaluating means to protect water resources. Although only two areas are discussed below, applied hydrology contributes to society and the environment far beyond what is included in these subsections.

Water Contamination

Water contamination has increasingly become a concern in modern times. Application of pesticides and fertilizer is common agricultural practice and has resulted in aerial contamination of water as excess irrigation water percolates through soils and carries the chemicals into groundwater and directly or indirectly into surface waters. Contamination sources that occur over large areas are known as nonpoint sources; sources confined to small areas are called point sources. Multiple closely spaced point sources can form a nonpoint source. Landfills are major point sources of water contamination. Aging and leaking liners around landfills allow leachate, a mixture of water and dissolved chemical, to leak into groundwater. Wastes from mines, industrial disposal, nuclear reactor and weapon facilities, petroleum spills, and leaking underground storage tanks have all contributed to the contamination of groundwater and surface waters. Understanding contaminant transport is important for predicting future behavior of contaminated waters and designing effective remediation procedures.

Three major mechanisms control the transport of contaminants in water: advection, spreading, and chemical reactions resulting in retardation, decay, or degradation. Advection is the process of transporting contaminants by moving water and is often the dominant mechanism once the contaminants make their way into highly permeable aquifers. Spreading involves diffusing, dispersing, and mixing of the dissolved contaminants with clean waters. Spreading is due in part to a suite of mixing processes and dispersal mechanisms accompanying solute migration along relative preferential flow paths at multiple spatial scales. Spreading, mixing, and attenuation also occur due to the slow movement of solutes into and out of relatively stagnant zones, such as dead end pores and local immobile regions of low permeability. Advection and spreading are the physical processes of contaminant transport, while retardation, degradation, and decay result from chemical reactions occurring as the contaminated water migrates through and interacts with geologic media. Retardation, degradation, and decay are simple terms used here to express a collection of many complex chemical and biological processes. Chemical reactions can slow down the rate of migration of contaminants and even degrade or sequester certain compounds. These reactions may include sorption, precipitation, oxidation, reduction, ion exchange, and biological activity.

Land Subsidence

Extraction of groundwater plays a direct role in land subsidence. Uneven subsidence of the historic Tower of Pisa in Italy has created a tourist attraction. Subsidence has been a problem in many cities and towns as building foundations and road surfaces become cracked and tilted as the ground subsides. When a large amount of water is withdrawn from the subsurface, void spaces in rocks, and sediments collapse, which leads to compaction and subsidence. The Santa Clara Valley and nearby San Joaquin Valley in Northern California have experienced regional subsidence of several meters due to excessive groundwater pumping in order to sustain productive agriculture and water use in rapidly urbanizing areas. As Las Vegas Valley in Nevada has turned into a fast-growing metropolitan area, groundwater is being rapidly depleted and this area has also suffered problems with land subsidence and ground fissures due to horizontal movement. Subsidence may also occur from drainage of soils that are rich in organic carbon as microbial decomposition converts organic carbon to carbon dioxide gas and water. Subsidence at the rate of 20–80 mm year^{-1} has been observed as a result of the decomposition of the remains of shallow water sedges and reeds in California's Sacramento–San Joaquin Delta and in Florida's Everglades. More catastrophic subsidence takes place with the formation of sinkholes associated with localized collapse of subsurface cavities. Often triggered by a decline in the groundwater level, sinkholes typically form in areas underlain by carbonates (e.g., limestone and dolomites) and evaporites consisting of easily dissolved minerals such as salt, gypsum, and anhydrite.

Role of Groundwater in Geologic Processes

Water exists in pore spaces in sediments and rocks to a depth of more than 10 km. The degree of pore water decreases with depth in response to a general decrease of porosity with depth. Groundwater plays an essential role in mineral dissolution and precipitation, and impacts metamorphic processes by altering rocks' mineral compositions over geologic time. As water flows through deep sections of the crust or passes through thermally active regions, such as in the vicinity of a cooling magma, the heated waters become hydrothermal. Hot springs emerge at the locations of hydrothermal water discharge. Groundwater carries dissolved minerals and transports them to ore-forming locations. Petroleum forms, as natural gas or crude oil, at significant depths of burial of marine organism and sediments. Groundwater then transports the petroleum to shallower locations, a process known as secondary migration in petroleum system studies.

The mechanical interaction between groundwater and rock deformation has been thought to contribute to triggering earthquakes. As pore pressures in faults and the surrounding area increase, faults become lubricated and weakened, setting the stage for an earthquake. The best-known example is the documented earthquakes between 1962 and 1972 in the Denver area when liquid waste was injected underground into fractured granites a few kilometers deep at the Rocky Mountain Arsenal. The time and frequency of the earthquakes were correlated strongly with the time and volumetric rate of waste injection. Interest in fluid-induced seismicity is on the rise as fluid injection activities associated with carbon dioxide sequestration in geologic formations and hydrothermal exploration are expected to intensify in coming years.

See also: **Hydrology, Floods and Droughts:** Overview; Soil Moisture; Modeling and Prediction.

Further Reading

Alley, W.M., Reilly, T.E., Franke, O.L., 1999. Sustainability of Ground-Water Resources. U.S. Geological Survey Circular 1186.

Black, M., King, J., 2009. The Atlas of Water. University of California Press, Berkeley, CA.

Bredehoeft, J.D., Papadopulos, S.S., Cooper, H.H., 1982. Groundwater: The water-budget myth. In: Scientific Basis of Water-Resource Management, Studies in Geophysics. National Academy Press, Washington, DC, pp. 51–57.

Encyclopedia of Atmospheric Sciences, Second Edition, 2015, 209–216

Dingman, S.L., 2002. Physical Hydrology. Prentice Hall, Upper Saddle River, NJ.

Domenico, P.A., Schwartz, F.W., 2008. Physical and Chemical Hydrogeology. John Wiley & Sons, Inc., New York, NY.

Fetter, C.W., 1999. Contaminant Hydrogeology. Prentice Hall, Upper Saddle River, NJ.

Fetter, C.W., 2001. Applied Hydrogeology. Prentice Hall, Upper Saddle River, NJ.

Fierro, P., 2007. In: The Water Encyclopedia, Hydrologic Data and Internet Resources, third ed. CRC Press, Boca Raton, FL DOI: 10.1201/9781420012583.ch4.

Freeze, A.R., Cherry, J., 1979. Groundwater. Prentice-Hall, Englewood Cliff, NJ.

Gleeson, T., Marklund, L., Smith, L., Manning, A., 2011. Classifying the water table at regional and continental scales. Geophysical Research Letters 38, L05401. doi:10.1029/2010GL046427.

Gleick, P.H., 2001. Making every drop count. Scientific American February, 41.

Haggerty, R., Gorelick, S.M., 1995. Multiple-rate mass-transfer for modeling diffusion and surface-reactions in media with pore-scale heterogeneity. Water Resources Research 31 (10), 2383–2400.

Hornberger, G.M., Raffensperger, J.P., Wiberg, P.L., Eshleman, K.N., 1998. Elements of Physical Hydrology. The Johns Hopkins University Press.

Kenny, J.F., Barber, N.L., Hutson, S.S., Linsey, K.S., Lovelace, J.K., Maupin M.A., 2009. Estimated Use of Water in the United States in 2005. U.S. Geological Survey Circular 1344.

RodrPguez-Iturbe, I., Rinaldo, A., 2001. Fractal River Basins. Cambridge University Press, Cambridge, UK.

The World's Water Series, http://www.worldwater.org/books.html

Tindall, J.A., Kunkel, J.R., 1999. Unsaturated Zone Hydrology. Prentice Hall, Englewood Cliffs, NJ.

UNEP., 2008. Vital Water Graphics – An Overview of the State of the World's Fresh and Marine Waters, second ed. UNEP, Nairobi, Kenya. ISBN: 92-807-2236-0.

Vorosmarty, C.J., Green, P., Salisbury, J., Lammers, R.B., 2000. Global water resources: vulnerability from climate change and population growth. Science 289, 284–288.

Winter, T., 1998. Groundwater and Surface Water, a Single Resource. U.S. Geological Survey Circular 1139.