



Groundwatergroundwater

Groundwater refers to the saturated layer of Earth's crust extending beneath the land surface to a depth where solid rock does not permit the movement or storage of water. The widespread geographical distribution of groundwater and its usually high quality for human consumption, agriculture, and other uses make this a resource of global importance; it accounts for a third of the planet's total volume of water outside the oceans, or close to 98% of all freshwater outside ice caps and glaciers. The spatial occurrence and quality of groundwater are not uniform, which is the result of geology, climate, surface water interactions, and, increasingly, human use and contamination. There is a growing recognition that a comprehensive understanding of groundwater must consider its multiple and interconnected physical, hydrogeological, and human use dimensions.

This entry is organized as follows: A brief physical characterization of groundwater in the hydrological cycle is followed by a description of its geographical distribution and importance, which leads to assessment of groundwater use, quality, and sustainability challenges. The entry concludes by outlining human organizational and institutional aspects, along with a synthesis of the human-environment dimensions of groundwater.

Groundwater Hydrology

Active groundwater is conventionally distinguished as the portion that circulates in contact and exchange with Earth's surface hydrological cycle; this accounts for approximately half of the total groundwater. The remaining *deep* groundwater portion occurs within Earth's crust and is largely inaccessible to surface hydrologic interaction or human use. Geological conditions, specifically geochemical processes and residence times, influence the quality of groundwater. Much deep groundwater is considered to be of a quality that is not suitable for ecological or human purposes; for example, it frequently has high dissolved mineral content as a result of prolonged chemical interaction or deposition from saline ocean water over geological timescales. Shallow groundwater extensively interacts with surface water over timescales that vary from days to millennia.

Aquifers are the spatial units of rock, alluvium, and other subsurface materials where groundwater occurs, and they are separated from other aquifers by nonporous geological formations that impede the subsurface flow of water. Aquifer properties include porosity, rock fractures, conductivity (groundwater movement that a pressure gradient produces), and transmissivity (conductivity over the depth of the water-bearing strata). These properties, coupled with groundwater pressure that results from elevation differences of water levels in the aquifer, determine the rates of groundwater extraction that pumping will produce. *Drawdown* and *cone of depression* refer to localized groundwater-level effects resulting from extraction.

Groundwater is recharged vertically from the surface infiltration of rainfall, other atmospheric precipitation, or water bodies, including lakes, rivers, wetlands, and estuaries. Under certain aquifer conditions, recharge may occur laterally from surface water bodies. Water occurring in the immediate near-surface, weathered soil layer, often coinciding with the depth that plant roots will penetrate, is referred to as *soil moisture*. Below this, water percolates in the unsaturated vadose zone (the area between the surface and the saturated zone) and deeper to saturated layers of the aquifer, commonly referred to as the *water table*. Alluvial deposits often result in unconfined aquifer conditions. In contrast, impervious strata, for example, solid or low-porosity rock or clay layers, can result in confined or semiconfined aquifers and, depending on the groundwater pressure, may cause water to flow freely to the surface in artesian wells.

Depending on the water levels, groundwater may reside indefinitely in aquifer storage, or it may discharge to the surface or to oceans. An important process of groundwater discharge supplies the base flow (minimum dry-season surface flow) in streams and rivers during periods of low precipitation and runoff. A special class of ocean-aquifer interactions accounts for the salinity of groundwater in near-coastal areas. Islands in the ocean often have a lens of low-salinity fresh groundwater perched above the underlying saltwater. The saline-freshwater interface is subject to disruption, for example, through pumping, which may cause salinity ingress to otherwise freshwater aquifers.

It is important to briefly summarize mathematical modeling approaches to groundwater occurrence and movement and to the fate and transport of contaminants. Early mathematical development proceeded from

hydraulics and improved on static water budgets that assumed uniform aquifer mixing. Groundwater flow models require extensive parameterization (definition and quantification of multiple variables) and data sets based on extensive monitoring of groundwater levels and flow processes. Models such as MODFLOW are based on finite-element grids that represent the aquifer in three dimensions. Additionally, these models are capable of simulating the geochemical interactions of specific contaminants. Groundwater models are developed and run for research and operational purposes, for example, by agencies charged with the management of water resources.

Geographical Distribution

The occurrence of groundwater is determined by three principal factors: (1) aquifer characteristics that permit recharge and storage of groundwater, (2) precipitation or surface water availability for recharge (bearing in mind the extended, millennial scales of storage and circulation), and (3) human use that may drive aquifer depletion if extraction is significantly in excess of recharge. Despite its recharge from precipitation, groundwater may be abundant in aquifers in low-precipitation (arid and semiarid) regions. As a result, it is a resource of critical importance in the Middle East, North Africa, South and West Asia, Australia, Western North America, and parts of South America and Europe. Due to its ease of access and temporal dependability compared with surface waters that are often prone to drought and intermittent depletion, groundwater is also extensively used in higher-precipitation humid regions.

Surveys to quantitatively estimate groundwater storage have been conducted at the national and subnational levels; however, these are based on inconsistent methods and differing assumptions of subsurface aquifer characteristics. Reporting problems similarly plague groundwater use data. It is estimated that globally, India is the largest user of groundwater (150 km₃/yr. [cubic kilometers per year]), followed by the United States (100 km₃/ yr.), China (75 km₃/yr.), Pakistan (45 km₃/yr.), Iran (45 km₃/yr.), and Mexico (28 km₃/yr.).

Groundwater Use

As indicated above, groundwater is increasingly used for human purposes, including (in order of estimated volume currently extracted) agriculture and livestock, potable water supply in urban and rural areas, power generation, and industrial uses. Historically, humans devised ingenious means to use and extract groundwater. Desert oases occur where shallow groundwater accumulates at the surface. Lift devices from shallow open wells used human and animal draft power and included the Archimedean screw, Persian wheel, and animal skin bailer. Wind-powered and water flow-powered lift devices became important with advances in mechanics and materials. *Qanats*, sloped horizontal tunnels to intercept groundwater within a hillside and convey it by gravity to the surface, were developed in Persia as early as 2,500 yrs. ago. This technique, with some innovation and under a range of names, spread in Central Asia and farther west, to North Africa, Southern Europe, and the Americas, as well as east to parts of China, Japan, and the Philippines. Functioning qanats can still be found.

The 19th-century advent of mechanized pumps, driven initially by steam power and subsequently by electrical motors or hydrocarbon-fueled engines, resulted in widespread tapping of aquifers for human use. Early examples of groundwater-based regional and economic development, particularly for urban expansion and agricultural irrigation, include the American West, Mexico, Spain, the Middle East, India, China, and Australia. Groundwater development was intricately linked with population growth in urban centers and rural areas alike, human occupation of regions previously considered uninhabitable for lack of access to reliable water supplies, and increased food production. Rural electrification programs in the early and mid 20th century, coupled with the development and reduction in costs of pumps and related irrigation technology, drove the expansion of groundwater-based agriculture, which by a large margin exerts the greatest demand on groundwater resources. In numerous locations, falling water levels resulted from extraction in excess of renewable groundwater supplies. In other aquifers with exceedingly low or nonexistent recharge, extraction is referred to as *groundwater mining*, or use of *fossil groundwater*.

Numerous regions where population growth as well as economic development and diversification away from agriculture were facilitated by reliance on intensive groundwater use began to show symptoms of aquifer depletion: rising costs of extraction (both for deepening and operating wells), declining water quality, land surface subsidence (where compaction of aquifer layers pumped dry caused nonuniform settling and often large surface cracks or sinkholes), and drying of surface streams previously fed partially or wholly by groundwater discharge, among other impacts. This has resulted in serious risk to groundwater-dependent human populations and ecosystems. Related impacts of intensive groundwater use include (a) the mobilization of geogenic sources of arsenic, resulting in often serious contamination of water supplies in some of the world's most densely populated regions, particularly the lower Ganges-Brahmaputra river basin in Bangladesh and parts of India and Nepal; (b) fluoride contamination of groundwater; and (c) salinity ingress in coastal

aquifers as well as salt buildup in intensively irrigated soils in arid regions. It is also now recognized that recharge processes can be exacerbated by climate change-driven precipitation variability coupled with human modification of the land surface, for example, compaction of agricultural soils or sealing over urban spaces through paving and roofing. Drought and flood cycles and the variability of surface water resulting from climate change processes may induce additional human reliance on groundwater as a dependable source of supply to meet a range of demands. At the same time, groundwater use may exert feedbacks on the climate system via greenhouse gas emissions resulting from the generation of power to pump the groundwater. Human use of water is extremely energy intensive; for example, India uses a third of its electrical power to pump groundwater, and Southern California uses a fifth of its power for the full cycle of water service provision.

In sum, groundwater development has been a primary driver of urban and rural growth and prosperity but has often resulted in unsustainable aquifer depletion. Regions considered emblematic of the groundwater extraction-depletion trajectory include the southwestern United States and the high plains Ogallala aquifer, Central and northwest Mexico, northeast Brazil, the Pacific coast of Northern Chile and Peru, Central Spain, most of North Africa and the Middle East, Iran, Central and northwest India, Central Asia, the North China plains, and Western Australia.

Groundwater Pollution

As indicated above, the quality of groundwater varies naturally as a result of geochemical processes, residence times, and proximity to saline water bodies. Anthropogenic sources of pollution, too, influence groundwater quality, specifically nutrients, salinity, pathogens, and inorganic and organic compounds. Groundwater pollution is exceedingly difficult to reverse or remediate, given the nonuniform mixing, long residence times, and geochemical interactions between pollutants and aquifer materials.

Agricultural fertilizers and human and animal waste are the principal source of nutrients that influence groundwater quality. Nitrogen in its soluble form as nitrate is less reactive with aquifer materials than are other nutrients and is conveyed from surface sources and land uses via percolation to the underlying aquifer. In cases where groundwater is used to supply drinking water for human settlements, high concentrations of nitrate are a particular concern due to the risk to human health. Blue baby syndrome can be fatal for infants who consume water, formula, or other food prepared using water with high nitrate levels.

Pathogenic microorganisms including bacteria, protozoa, and viruses occur in groundwater as a result of human activity and the transmission of these pathogens to the underlying aquifers. Aerobic conditions above the saturated aquifer layer and anaerobic conditions below, along with the physical properties of the aquifer (pore size and geometry) significantly influence the distribution and fate of pathogens in groundwater. In general, shallow aquifers with periodic aerobic conditions are more prone to pathogen contamination than are deep aquifers with extended groundwater residence times.

Salinity is a major concern for groundwater quality. Primary salinity may result from groundwater deposition from ocean water over geologic timescales. Secondary salinity has human causes chiefly related to irrigation using water with high dissolved mineral content. As irrigation is applied, crops consume (transpire) water, or it is evaporated from the soil surface, leaving minerals in or on the soil. Subsequent irrigation may involve an extra watering simply to flush the salts out of the root zone of the soil, which may pollute the underlying groundwater depending on the depth to the aquifer. Salinity resulting from irrigation can cause waterlogging where groundwater levels rise to the surface, a condition that is widespread and growing. Waterlogging is common where surface irrigation using canals brings water into an area with underlying saline groundwater that is unusable for irrigation or where topographic conditions make it difficult to drain excess irrigation water. A special case of salinity is presented by irrigation using groundwater that is brackish, that is, with low to medium levels of salinity that some crops may tolerate. Salinity buildup from irrigation with brackish water can be rapid, often putting such areas out of agricultural production.

Finally, a range of inorganic and organic compounds from human sources may impair groundwater quality. Persistent inorganic pollutants in groundwater may include heavy metals; however, these are usually chemically bound to particles that may not easily pass through soil or aquifer material to reach the groundwater. As indicated above, geogenic sources of arsenic represent an important groundwater pollution problem. Solvents, fuel additives, manufacturing byproducts, and other organic constituents that leach into underlying aquifers are representative of organic pollutants that are increasingly recognized as a risk to human health and the environment. The wide range of organic pollutants, some highly site specific, makes it difficult to review their occurrence; however, it should be noted that their traceability and often localized occurrence mean that such contaminants are often targeted for remediation efforts. Given the persistence of groundwater pollutants, remediation may involve physically removing (excavating) contaminated aquifer material. Other approaches, particularly for shallow contaminated layers, include phyto-remediation using plants that selectively take up and bind contaminants in their tissue. Remediation is invariably difficult and

expensive, and efforts to prevent groundwater pollution through source control are critical.

Human Organization, Management, and Policy

The use of groundwater for human purposes displays unique organizational characteristics that distinguish it from many other natural resources, including surface water. Because of its geographical distribution, groundwater is accessible to a wide range of users. Technology represents a mediating factor for groundwater use and appropriation and, in cases of aquifer depletion such as those discussed above, forms a mechanism for competition among users. In the early stages of a society's development and reliance on groundwater, access was considered to be unencumbered by formal institutional arrangements or systems of rights that applied to surface water or other natural resources. In the Western United States, for example, prior appropriation rights to surface water were only subsequently modified and applied to groundwater—often, however, in a manner disassociated from surface water, although hydrologically the two remain connected. Here, groundwater capture by users with the most powerful pumps generated strong competition among users or simply deprived others of access. In other instances, private capture was pitted against public regulation. In the absence of effective regulation, groundwater has been a prime example of the tragedy of the commons, that is, the private appropriation of publicly owned resources that leads to overuse and degradation.

In societies that historically innovated with collective action to use and manage resources, for example, canal irrigation in Asia or the Andes, the advent of groundwater use represented a marked departure from community norms for access and management of water. As a result, Tushaar Shah refers to groundwater use as atomistic, resulting from private investment even by smallholder farmers of limited economic means. In some instances, these changes have undone community institutions, rule making, and enforcement and compliance, as well as the distribution of labor, costs, and benefits. In other cases—for example, share-based group wells or aquifer-using societies—attempts have been made to bring groundwater and its use under the purview of community institutions. The role of the state in providing or withholding public investment and infrastructure and setting legal frameworks for groundwater use and dispute resolution increasingly overlaps with more localized public and private interests around groundwater.

In the context of mature institutional arrangements, groundwater use is subject to regulation based on legal provisions (e.g., limits to use, spacing of wells, and titling rights) and economic instruments (land, production, or value-added taxation). A growing body of research and case evidence holds significant promise for groundwater regulation through the water-energy nexus, or synergistic management of energy and water—for example, dual water and energy savings based on efficiency and conservation or pricing of energy to manage the demand for water.

Groundwater is no longer considered an insular resource, separate from surface water or unfettered by competing claims over its use. Aquifers are acknowledged to encompass a multitude of uses and users. Competition among agriculture, urban water supply, power generation, and ecosystem needs is increasingly evident, often across national boundaries. Transboundary aquifers are the subject of growing interest among decision makers and researchers, reflecting a trend in the increasing globalization of water issues and paradigms for its management. Transboundary aquifers of particular note include the Guarani aquifer in South America, the Ganges-Brahmaputra-Meghna aquifer system in South Asia, and the Imperial Valley-Mexicali aquifer in Western North America.

Aquifer depletion remains a principal management and policy challenge for human use of groundwater. Various groundwater augmentation and demand management strategies have been attempted at a range of scales. At the very local level, for example, individuals may harvest rainwater runoff from their roofs or fields to recharge individual wells. More concerted efforts have been made at the scale of aquifers in the river basins they underlie. Aquifer conservation plans, conjunctive surface and groundwater use, and integrated river basin management all attempt to influence groundwater use. An important strategy for sustainable aquifer management has been based on importation of surface water, often through transfer from distant river basins. In the United States, Southern California and Southern Arizona aquifers rely on massive pumped delivery of surface water from outside their respective river basins, yet neither region has reached sustainable management targets. Finally, in the sequence of expanding scale, transboundary and global initiatives increasingly address multiple, integrated aspects of groundwater.

Human-Environment Interactions Involving Groundwater

From a coupled human-environment perspective, aquifer physical processes and the attendant water quantity and quality exert mutually causal influences on human groundwater dependence, with critical economic and institutional implications. The rapid development of groundwater over relatively short timeframes of human generations must be considered along with aquifer flow and storage that occur over millennia. Climate change with human and natural drivers that are global in scale adds further complexity to local patterns of human

dependence on groundwater.

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Further Readings

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