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Groundwater

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Groundwater is water that exists mainly in subsurface pore spaces but also in defined channels, such as those found in karst formations, which are created by dissolution of soluble rocks such as limestone. After the polar ice caps, groundwater is the next largest reservoir of freshwater on Earth, containing more than 100 times the volume of streams and freshwater lakes (Shiklomanov 1993). Groundwater plays an important role in the hydrologic cycle, in plant growth and soil formation, and in providing water for human activities. Since groundwater is difficult to observe and track directly, monitoring, mapping, and modeling efforts are crucial to the understanding of its storage, distribution, and patterns in flow through the subsurface, how it may be sustainably used, and how it may become contaminated. Humans have used groundwater throughout history, but the demand for it and the societal ability to consume and contaminate it have all increased exponentially over the past century. Uneven distribution of human populations combined with variations in availability and accessibility to groundwater have resulted in overexploitation of several major aquifers serving population and agricultural production centers in China, India, and the United States. Significant current and future threats to groundwater quantity and quality that require attention from policy and planning perspectives include climate change, fossil fuel exploration and extraction, natural contaminants such as radium and arsenic, underground storage tanks and industrial contaminants, and agricultural use and pollution.

Groundwater: natural and physical science perspectives

Groundwater's place in the water cycle

More than 68% of fresh water is found in polar ice caps and glaciers and is thus largely unavailable for societal use (Shiklomanov 1993). Approximately 30% of global fresh water is groundwater, whereas only 1.2% is found in streams and lakes. Geologic formations that yield a significant amount of water to wells or springs are called aquifers. An aquifer consists of two or more permeable layers in the subsurface separated at least locally by intervening layers that impede groundwater movement but do not significantly affect the regional hydraulic connectivity of the system. With the exception of fossil aquifers, groundwater is replenished mainly by precipitation falling within the recharge area of an aquifer. Precipitation on land flows horizontally across the surface or infiltrates into soil and moves either horizontally or vertically within the subsurface. Groundwater consists both of water that remains in the unsaturated or vadose zone (also often termed "soil water") and of water that reaches the saturated zone (aquifer) where pore spaces are completely filled.

Global distribution of groundwater

Groundwater may be found almost anywhere on Earth if one digs deep enough, but most accessible groundwater is generally found within 1 km of Earth's surface (Hess 2014). Beyond this depth, groundwater availability decreases gradually and quality is often poor due to high salinity and mineral concentrations. Worldwide, approximately 36% of the land surface (excluding Antarctica) is underlain by major aquifers, primarily composed of sedimentary rocks, while another 18% of the subsurface is dominated by aquifers of more complex and heterogeneous geology (Richts, Struckmeier, and Zaepke 2011, WHYMAP, Table 1). The remaining approximately 47% of the land surface is underlain by local and shallow aquifers along stream valleys and lowlands. There are significant regional variations in the distribution of aquifers. For example, shallow local aquifers dominate much of North America, whereas major regional aquifers spanning thousands of square kilometers are the predominant aquifer type throughout much of continental Europe (Table 1).

Currently, approximately 24% of global aquifers are highly overexploited; the major driving factor is irrigated agriculture for feeding human and livestock populations (Gleeson *et al.* 2012). Pumping from the most exploited aquifers (Upper Ganges, North and South Arabian, Persian, Western Mexico, and High Plains or Ogallala) is on the order of tens of times the natural recharge rate, and may also act as a limiting factor in future agricultural output (Figure 1). Although 76% of aquifers are not being significantly exploited, overexploitation of a few large aquifers has led to a

Table 1 Groundwater basins and aquifers by continent.

	Major groundwater basins		Complex hydrogeological structures		Local and shallow aquifers	
Continent	(million km^2)	(%)	(million km^2)	(%)	(million km^2)	(%)
Africa	13.5	44.9	3.3	11.0	13.2	44.1
Asia	14.5	32.0	7.8	17.3	23.0	50.7
Australia, New Zealand	2.6	32.5	2.9	36.3	2.5	31.1
Europe	5.2	53.0	1.8	18.8	2.7	28.2
Central/South America	8.4	45.0	2.0	10.9	8.2	44.1
North America	3.2	15.0	5.8	26.9	12.4	58.1
World (excl. Antarctica)	47.3	35.6	23.6	17.8	62.0	46.6

Source: Richts, Struckmeier, and Zaepke 2011. Date of the source data is 2008. With permission from WHYMAP, BGR, Stilleweg 2, 30655 Hannover, Germany.

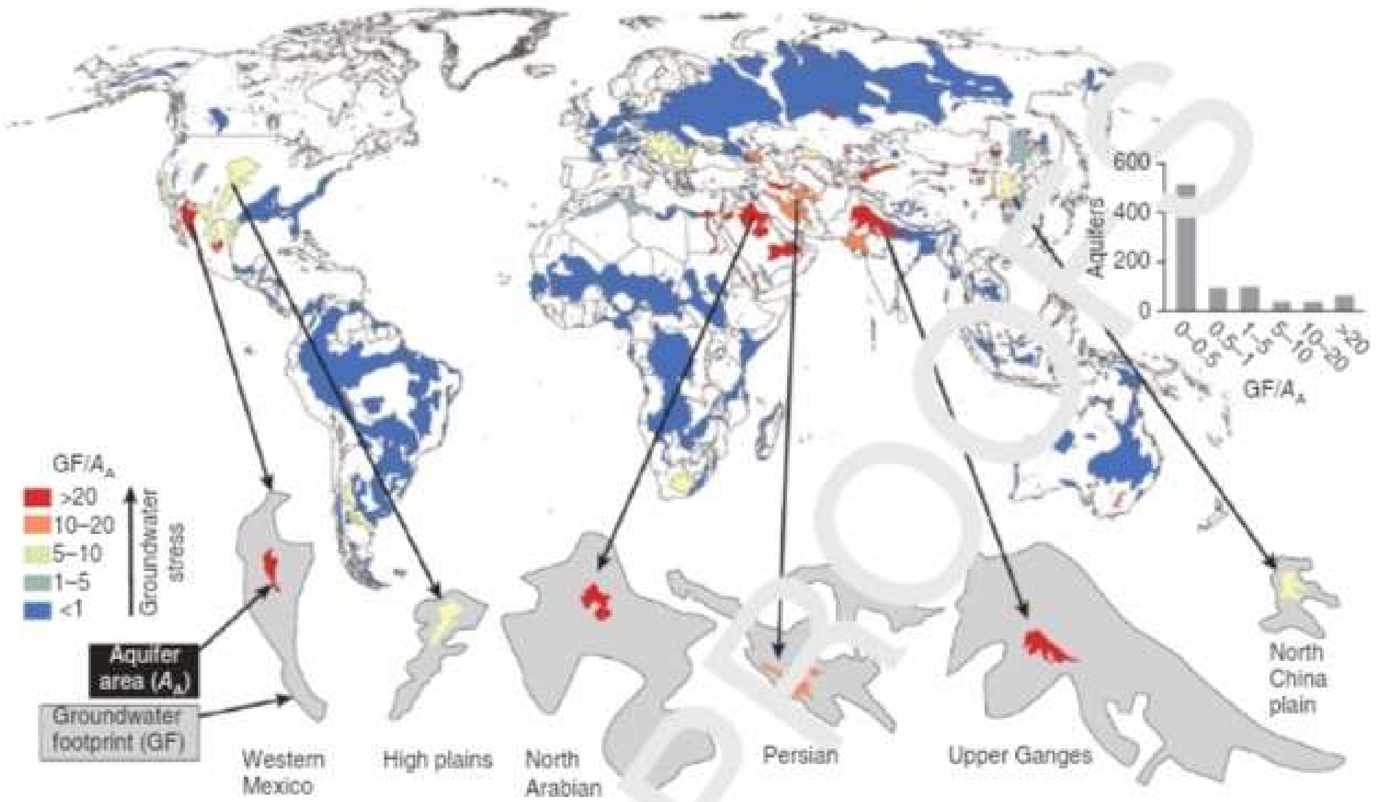


Figure 1 Groundwater footprints of aquifers. Source: Gleeson *et al.* 2012. Reproduced by permission of *Nature*.

total groundwater footprint of more than 3.4 times the global area of aquifers (Gleeson *et al.* 2012, Table 2). If 1 and 2% of the largest pristine or unexploited aquifers (7 and 15 observations from 748 considered in Table 2) are removed from consideration, the composite average of the groundwater footprint rises to 4.81 and 6.34 (39 and 84% increase, respectively) indicating that a few outlying pristine aquifers have undue influence on the composite average of the global groundwater footprint. Similarly, if 1 and 2% of the aquifers representing the largest footprints (7 and 15 observations from 748 considered in Table 2) are removed from consideration, the composite average of the groundwater footprint falls to 1.52 and 0.93 (56 and 73% decrease, respectively) indicating that a few outlying aquifers with large footprints also have undue influence on the composite average of the global groundwater footprint. In contrast, the median of the global groundwater footprint of 0.11 is robust and is not significantly impacted by the extreme outlying values of aquifer areas or groundwater footprints.

Exploitation of aquifers also varies significantly within aquifers. For example, the average water level in the High Plains (or Ogallala) aquifer of the central United States has declined by more than 4 m since before World War II. However, this includes some areas where water levels have increased by up to 20 m and others that have decreased more than 70 m (McGuire 2013). Total water storage in the High Plains aquifer has decreased by approximately 8%, but storage in 5% of the aquifer area decreased by over 50% (McGuire 2013).

silt, and clay particles. These alluvial deposits can contain large groundwater reserves that are fairly accessible and easy to withdraw. Sand and gravel aquifers of glacial origin may also have large reserves of groundwater that are fairly easy to withdraw, but hydraulic conductivity in such aquifers may be quite variable due to lack of sorting in glacial till.

Carbonate rock aquifers are comprised primarily of limestone or dolostone formed in ancient marine environments. Weak carbonic acid in rainwater dissolves carbonate rock and over thousands of years has in many areas formed karst landscapes characterized by numerous solution cavities, caverns, and sinkholes through which water can move rapidly. Where carbonate layers are exposed to the surface, runoff from precipitation or entire streams may connect directly with groundwater, resulting in significant contamination potential. Sandstone aquifers and igneous and metamorphic rock aquifers typically store and transmit water only along bedding planes, joints, and other cracks and fractures. Hydraulic conductivity in such aquifers is low, but large regional aquifers can yield high total volumes of groundwater.

Groundwater flow and wells

The geology of the aquifer influences water storage capacity as well as *hydraulic conductivity*, or the ability of aquifer materials to transmit water. Factors affecting hydraulic conductivity and storage capacity include *porosity* (proportion of pore space) and *permeability* (connectedness) of the pore spaces. Groundwater flow is down-gradient from high to low pressure, which often corresponds with moving from high to low elevation. An exception to this occurs in the case of confined aquifers contained within tilted rock formations where considerable pressure builds up in the lower reaches of the aquifer. In such cases, a well or a spring located at a point where the *potentiometric surface* (or water table) is higher than the land surface will flow freely without the need for pumping; such wells or springs are termed *artesian*.

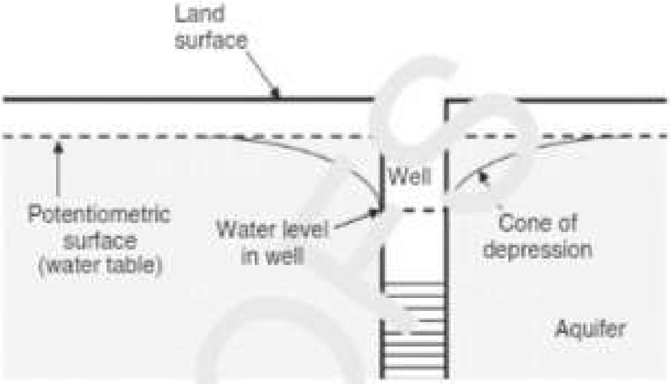


Figure 2 A schematic representation of aquifers, wells, and drawdown. Drawing by Edwin Brands.

Wells drilled into unconfined aquifers or confined aquifers with insufficient pressure to flow naturally require pumping to bring water to the surface. Some level of *drawdown* (or reduction in the height of the potentiometric surface) occurs with pumping of water from aquifers. During pumping, a *cone of depression* (Figure 2) forms around wells – the shape, size, and depth of the cone of depression as well as the rate at which the well water level recovers depend upon the pumping rate and duration, aquifer characteristics such as hydraulic conductivity, and the presence or absence of nearby wells. Pumping tests are done to determine whether the aquifer will provide an adequate yield (measured in gallons or liters per minute) for the intended purpose of the well.

Soil formation

As it moves through soil, water dissolves chemicals and sometimes deposits them at lower levels. This leaching process can deplete the topsoil of essential nutrients (Hess 2014). Fine particles such as clay are picked up by water and carried in suspension and deposited elsewhere at greater depths. Water, thus, constantly changes the physical, chemical, and biological makeup of the soil as it moves downward due to gravity, or sideways depending on available openings. When silica is removed by dissolution leaving behind the more insoluble iron compounds, reddish colored soils such as latosols are produced in tropical and subtropical regions of the world. In mid- and high latitudes, water removes minerals like oxides of aluminum and clays and forms shallow acidic soils like podzols. Gley soils are acidic and oxygen-poor and develop in waterlogged conditions in cool climates. In the more arid and semiarid regions, capillary action brings up soil moisture, which evaporates leaving behind salts like chlorides and sulfates. Soil salinization is exacerbated by inadequate drainage and low precipitation rates, resulting in calcic and other salt hardpans.

Groundwater chemistry

Groundwater quality may be affected by contaminants of both natural and human origin. Factors that determine groundwater quality include the thickness of the aquifer, aquifer structure, mineral composition of the aquifer, presence or absence of a confining layer, presence of direct conduits (e.g., abandoned wells or sinkholes) to the aquifer, and in the case of unconfined aquifers, presence of pollutants on the overlying land surface. Unconfined aquifers are more susceptible to contamination from human activities because of their proximity to pollution sources. The age or residence time of water in the aquifer is also a significant factor affecting groundwater quality as longer residence times provide more opportunity for dissolving minerals.

Many substances may be dissolved by groundwater as it moves through the subsurface. The most common chemical constituents in groundwater include sodium, calcium, magnesium, potassium, chloride, and sulfate. However, depending on mineral composition of the subsurface and on length of exposure, high levels of arsenic, fluoride, iron, manganese, or radionuclides may also be found.

Modeling and visualizing groundwater

The importance of modeling groundwater

Because of its intractability, understanding the processes associated with groundwater is more complicated relative to those associated with surface water. Hence, monitoring, mapping, and modeling efforts are crucial for this purpose. As in any area of inquiry, however, the applicability and accuracy of groundwater models is highly dependent upon (i) the quality of the input data (i.e., knowledge of initial conditions and the existence of adequate hydrogeological data) and (ii) the "fit" between the modeling approach (assumptions and equations) and the scope and purpose of the problem being explored.

Many groundwater models in one, two, or three dimensions rely at least to some degree upon *Darcy's Law* (Henry Philibert Gaspard Darcy, 1803–1858), which among other things allows for estimating water velocity in an aquifer as well as time required for water to travel between points within the aquifer, and which holds for nearly all hydrogeological conditions. In brief, Darcy's Law provides that water flows only when there is a gradient, that water flows down-gradient from high to low head (pressure), that flow velocity is proportional to head loss, and that velocity is modified by the hydraulic conductivity of the aquifer materials.

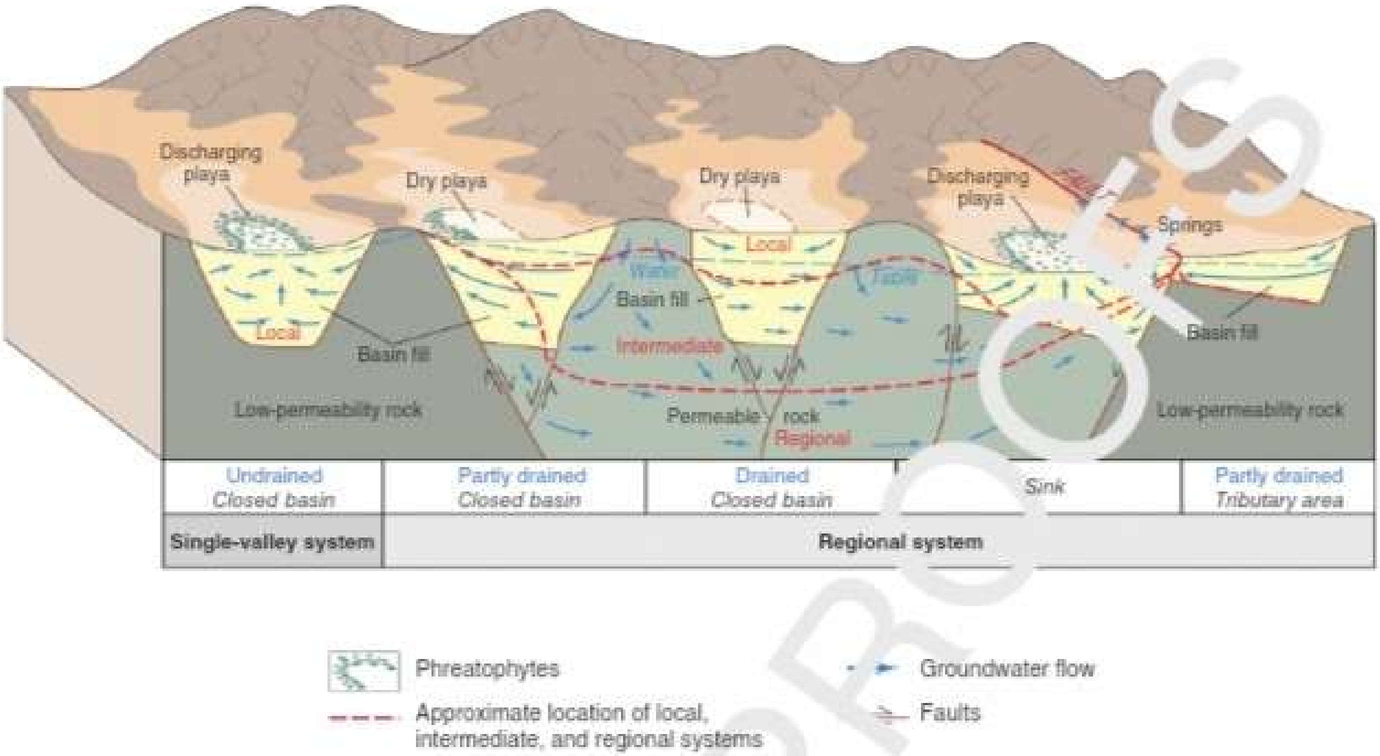


Figure 3 Schematic block diagram of Death Valley and other basins illustrating the structural relations between mountain blocks, valleys, and groundwater flow. Source: Faunt, D'Agnese, and O'Brien 2010. Reproduced by permission of USGS.

Groundwater models and geovisualization, selected examples

Hydrogeologists often use diagrammatic representations (Figure 3) to characterize and visualize the subsurface flow systems and the influence of geology and climate on such systems over time. The movement of groundwater in the subsurface of the Death Valley Regional Flow System (DVRFS) is captured and depicted in Figure 3 (Faunt, D'Agnese, and O'Brien 2010). It shows the flow paths of groundwater movement under the influence of hydraulic gradient through varying zones of permeability, from recharge to discharge areas in a regional context.

In addition to testing local aquifers to determine well or aquifer yields, and using well data to describe subsurface flow patterns, models are also used to understand groundwater both at spatial (local to regional aquifers) and temporal (e.g., tracing historical contamination to its source) scales. Two examples of 3-D groundwater modeling efforts are provided below and include predicting the migration of a uranium plume (Figure 4) and assessing risk of encountering high arsenic concentrations at various depths (Figure 5).

To construct 3-D images for visualizing concentrated plumes of contaminants such as uranium in subsurface sediments of waste sites, as shown in Figure 4, scientists at the US Department of Energy (2009) have developed groundwater models. Such models enable the prediction of movement of contaminants such as uranium over tens to hundreds of meters on temporal scales ranging from hours to years.

Arsenic contamination of shallow groundwater and its impact on the health of affected populations is one of the most serious environmental

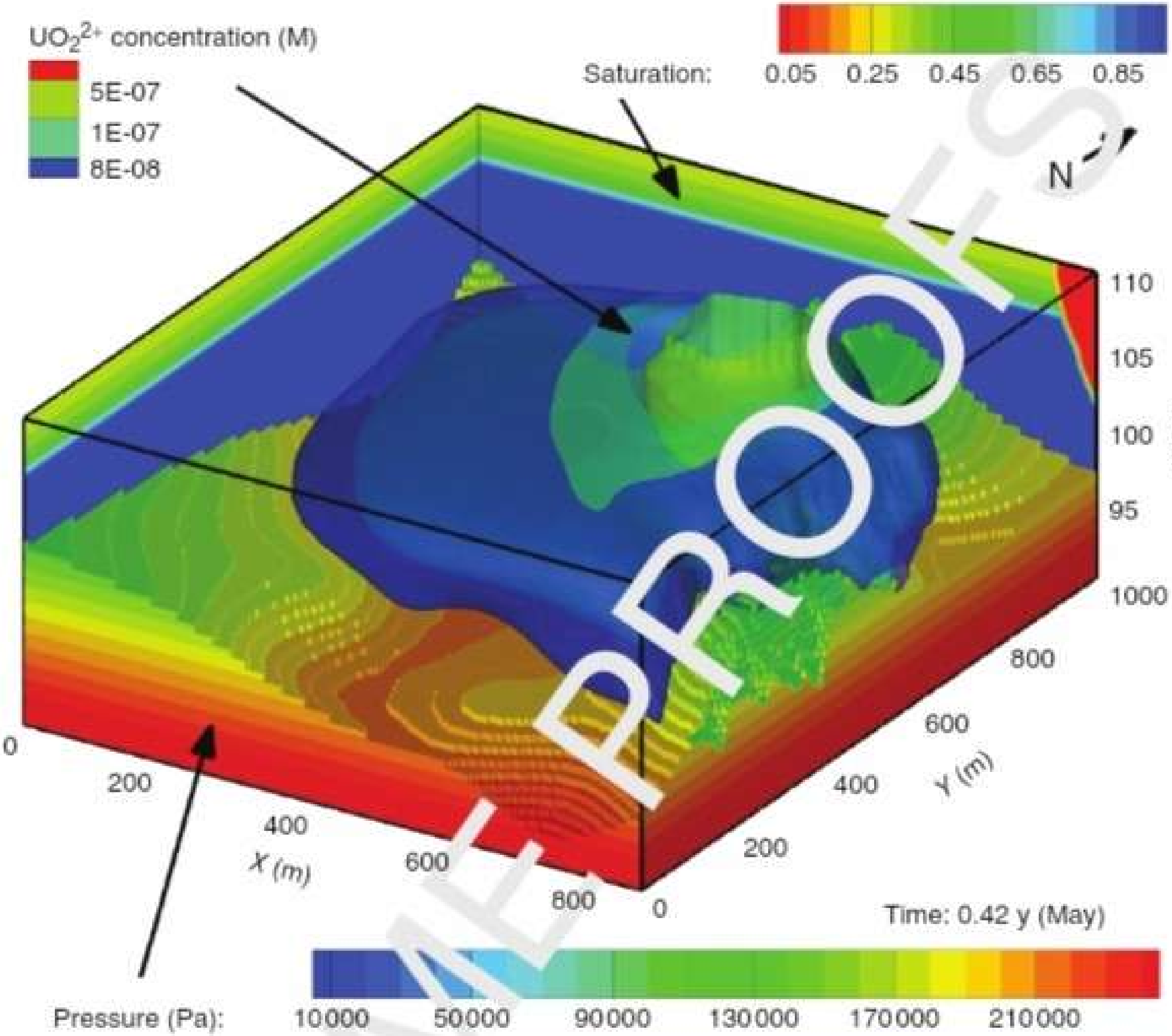


Figure 4 Three-dimensional plot of the uranium plume in groundwater beneath a portion of the Hanford 300 Area (a nuclear reservation site in Washington, USA), using PFLOTRAN model. Source: US Department of Energy 2009.

problems in developing countries. In Figure 5, the authors of a study (Winkel *et al.* 2011) on groundwater contamination of the Red River Delta in Vietnam show the probability of Arsenic (As) concentration exceeding 10 μg/l at 10 m depth intervals. Such analyses resulting from models enable us to study the connections between large-scale pumping of groundwater and the resulting vertical migration of arsenic in the subsurface.

Social, political, and planning aspects of groundwater

Historical access to and use of groundwater

Throughout history, humans have accessed groundwater in several different ways, likely beginning with locations where seeps or artesian upwellings occurred, progressing to hand-dug wells and wells accessed via windlass and bucket,

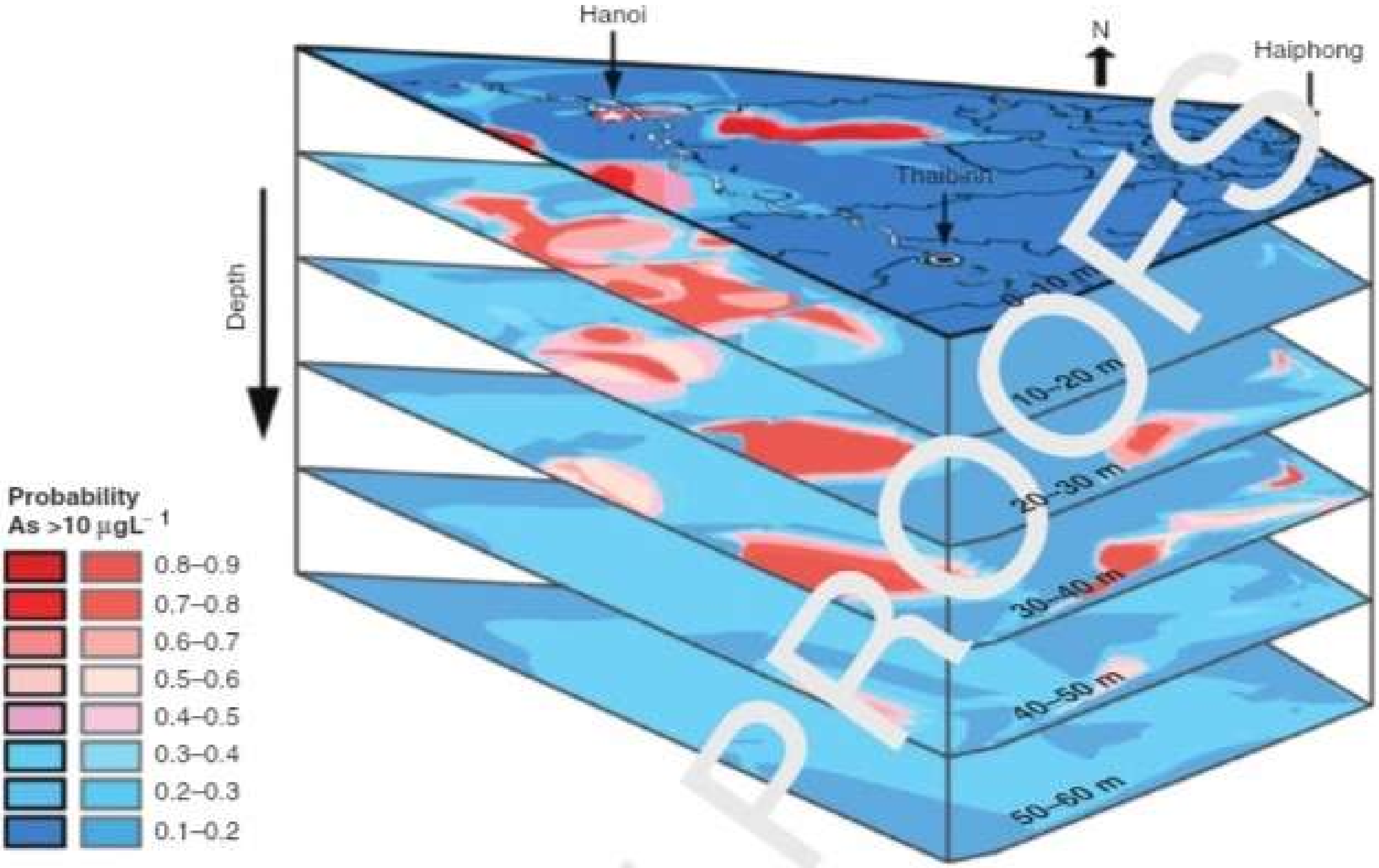
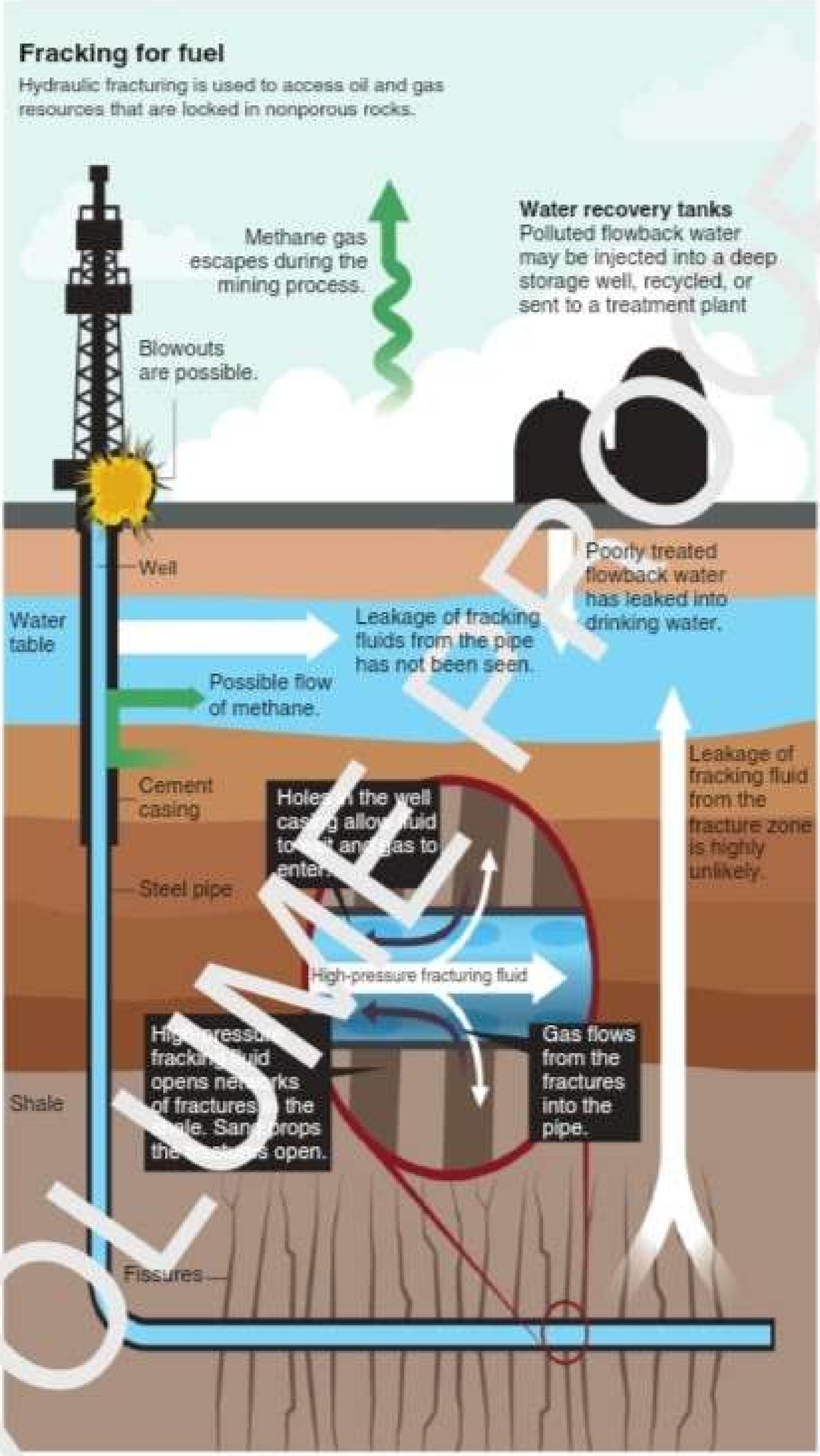


Figure 5 Risk of arsenic pollution of groundwater in Vietnam plotted in three dimensions and at 10m depth intervals. Source: Winkel *et al.* 2011. Reproduced by permission of the *Proceedings of the National Academy of Sciences*.

and finally tube wells with electric or fossil fuel-powered pumps.

Qanats, or hand-dug tunnels with numerous vertical shafts that access groundwater and deliver water by gravity for irrigation or domestic use, have been in use for more than eleven centuries throughout much of the Middle East, western Asia, southern Europe, northern Africa, and Central America. This technology is believed to have originated in Persia and spread via trade routes and expansion of Arab and Roman empires. Water from qanats was historically viewed as a community resource to be shared, and the maintenance and cleaning of qanats was also a laborious and challenging exercise. Thus the use of qanats for accessing water in effect demanded a cohesive community to successfully maintain channels. Flow in qanats varies with the level of the water table in the aquifer, which ensured sustainable use of the aquifer but also may have limited use for crops (and therefore crop yields) or other uses during periods of low recharge. Although qanats are still in use in many regions, their importance for domestic supply and irrigation has decreased due to increasing use of the same aquifers by powered pumps or other hydrological modifications that may have reduced recharge (e.g., as in the case of Morocco's Tafilalet oasis and aquifer system).

Rapidly growing urban populations with increasing water use and consumption during the twentieth and twenty-first centuries have



6 Hydraulic fracturing. Source: Howarth, Ingraffea, and Engelder 2011. Reproduced by permissi
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may allow migration of methane and fracking fluids to aquifers used for drinking and irrigation. Davies *et al.* (2014) indicate well failure rates are highly variable (1.9–75%) depending upon when and where they have been drilled. Other recent studies indicate that groundwater in close proximity to fracking operations is much more likely to be contaminated with produced water and methane, and that in some cases the chemical composition of methane found in drinking water aquifers was quite similar to the gas found in the much lower shale formations (Jackson *et al.* 2013; Gordalla, Ewers, and Frimmel 2013).

To facilitate rapid exploration and recovery of crude oil and natural gas, changes have been made to existing legislation such as the United States' Safe Drinking Water Act to exclude hydraulic fracturing from the definition of underground injection, a practice that was until the early 2000s largely prohibited or tightly regulated. Within the United States, fossil fuel exploration is mainly regulated at the state level, but the US EPA has recently undertaken a nationwide study on fracking and may issue nationwide regulations in the future. Hydraulic fracturing is already being employed or planned in Germany, the United Kingdom, India, and China (Gleick *et al.* 2012), and numerous suitable formations for exploration and extraction of resources via hydraulic fracturing exist on every populated continent.

Strategies for protecting and replenishing aquifers

At least in part due to difficulties in directly observing groundwater, efforts to conserve and protect the quality of groundwater resources have lagged behind such measures for surface water. In addition to international cases noted above, this is also true at national scales. For example, whereas the Clean Water Act is aimed at protecting surface water, there are no federal environmental laws focused on groundwater in the United States. Much of the regulation of groundwater is then left to individual states. But since aquifer and state boundaries rarely coincide, this leads or has the potential to lead to problems similar to those faced with international aquifers. One major policy need, therefore, is to "scale up" policy related to protecting and conserving aquifers.

Numerous strategies have been proposed for situations in which aquifers are stressed due to over abstraction from irrigated agriculture, including substituting dryland-adapted crops (e.g., wheat, sorghum, millet) in place of rice or maize, developing drought-tolerant strains of rice or maize, reducing tillage, reestablishing native grasslands, limiting drilling of new wells, and using moisture sensors and ultra-efficient irrigation technologies. In urban areas where aquifers are depleted, strategies such as aquifer recharge via infiltration ponds or galleries and injection of surface water or treated municipal wastewater are being increasingly employed.

SEE ALSO: Aquifers; Environmental uncertainty; Hydrologic cycle; Soil water; Waste and waste management; Water conflicts; Water: drinking; Water and human rights; Water quality; Water rights

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