

Groundwater: the Big Picture

1.1 Introduction

This book is about water in the pore spaces of the subsurface. Most of that water flows quite slowly and is usually hidden from view, but it occasionally makes a spectacular display in a geyser, cave, or large spring. Prehistoric man probably only knew of groundwater by seeing it at these prominent features. People tended to settle near springs and eventually they learned to dig wells and find water where it was not so apparent on the surface.

In the early part of the first millennium B.C., Persians built elaborate tunnel systems called *qanats* for extracting groundwater in the dry mountain basins of present-day Iran (Figure 1.1). Qanat tunnels were hand-dug, just large enough to fit the person doing the digging. Along the length of a qanat, which can be several kilometers, many vertical shafts were dug to remove excavated material and to provide ventilation and access for repairs. The main qanat tunnel sloped gently down to an outlet at a village. From there, canals would distribute water to fields for irrigation. These amazing structures allowed Persian farmers to succeed despite long dry periods when there was no surface water to be had. Many qanats are still in use in Iran, Oman, and Syria (Lightfoot, 2000).

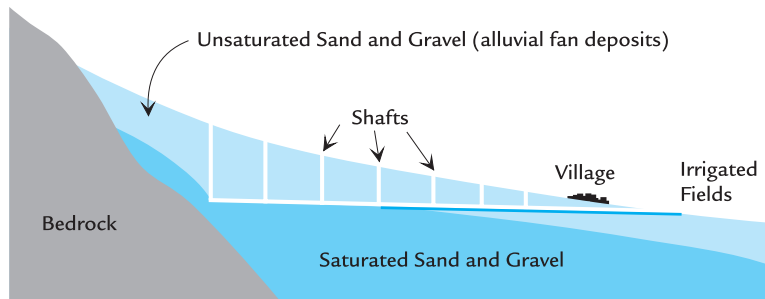
From ancient times until the 1900s, the main focus of groundwater science has been finding and developing groundwater resources. Groundwater is still a key resource and it always will be. In some places, it is the only source of fresh water (Nantucket Island, Massachusetts and parts of Saharan Africa, for example).

In the past century, engineering and environmental aspects of groundwater have also become important. With more irrigation, industry, and larger engineered projects came the need for industrial-size water supplies and the need to understand how groundwater affects structures like tunnels, dams, and deep excavations.

Environmental chemistry and contamination issues have come to the forefront of groundwater science just in the past several decades. Subsurface contamination became more widespread as nations industrialized, using and disposing of more petroleum-based fuels and metals. During the chemical revolution in the mid-1900s, the use of thousands of petroleum distillates and synthetic chemicals bloomed. Before the 1960s there were few regulations governing the storage and disposal of industrial wastes, fuels, and chemicals.



Figure 1.1 Vertical shafts of a qanat in Tafilat Oasis, Morocco (top; photo courtesy of Dale R. Lightfoot). Schematic vertical cross-section of a qanat (bottom). Water flows from saturated alluvium into the qanat at its uphill end, and then flows downhill to an exit canal near a village.



Unregulated releases silently took their toll beneath thousands of sites in the U.S. and other industrialized nations. Chemicals migrated deep into the subsurface, dissolving into passing groundwater. The contaminated groundwater often flowed far, transporting dissolved contaminants to distant wells or surface waters. Subsurface contamination went largely undetected until the environmental movement sparked investigations of sites in the 1970s and 1980s.

The Love Canal site in Niagara Falls is a notorious U.S. waste site uncovered during this era, and serves as a good introduction to the environmental side of groundwater

science. Love Canal was dug in the 1890s, part of a shipping/hydropower canal that never was completed. From 1942 to 1953, Hooker Chemical Company dumped an estimated 22,000 tons of chemical wastes, drummed and uncontained, into the canal excavation (EPA, 2001). The wastes contained hundreds of different organic chemicals, including dioxin, PCBs, and pesticides. The wastes were covered with soil, the site was sold, and a school and residential neighborhood were built on and around the former canal (Figure 1.2).

In 1975–1976, heavy precipitation raised the water table and eroded the soil cover, exposing chemicals and contaminated waters at the surface. Liquid wastes and contaminated groundwater also seeped underground through permeable sands and a fractured clay layer, migrating laterally to basements and sewer lines. Contamination from the site spread far into streams where these storm sewer lines discharged. Thankfully, the liquid wastes, which are denser than water, were unable to penetrate the soft clay under the canal and migrate into the more permeable Lockport dolomite aquifer. This was not the case at several other chemical landfill sites in Niagara Falls.

The scope of the contamination and health risks became known and publicized in 1978, the year President Carter declared the Love Canal site a federal emergency. Eventually, the school was closed and about 950 families were evacuated from the immediate 10-block neighborhood (EPA, 2001).

Cleaning up and containing the wastes at Love Canal has cost plenty. The parent company of Hooker Chemical Co. reimbursed the federal government 139 million dollars for clean-up costs, which were only part of the total costs at this site (EPA, 2001). Residents have sued for property and health damages, claiming a variety of ailments including birth defects and miscarriages. Remediation at the site includes a perimeter drain system to intercept groundwater and liquid wastes in the sands and fractured clay, an on-site water treatment plant that handles about 3 million gallons per year, a 40 acre clay and synthetic membrane cap over the wastes to limit infiltration, and removal of contaminated sediments from sewer lines and nearby creeks. The remediation efforts have dramatically improved environmental conditions in the neighborhood. Now hundreds of the abandoned homes have been rehabilitated and are occupied.

The past several decades up through the present have been a time of scientific revolution in the groundwater field. Great strides have been made in our understanding of

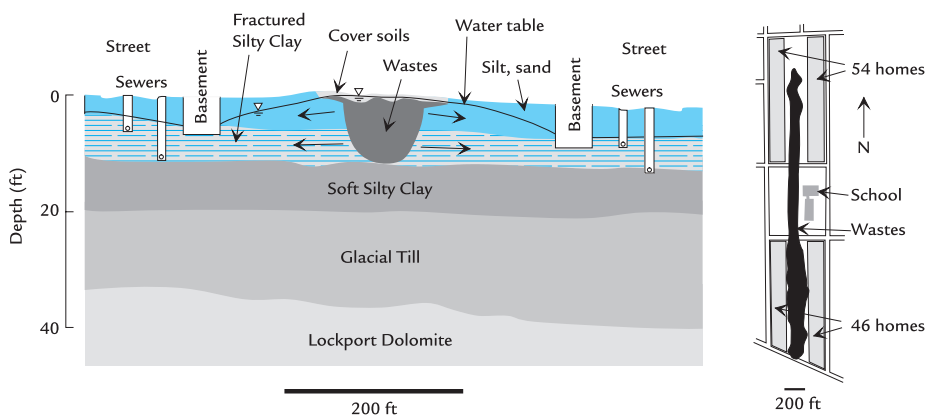


Figure 1.2 East-west cross-section through Love Canal, Niagara Falls, New York (left). Map showing the extent of wastes and nearby land uses (right). Adapted from the figures of Cohen and Mercer (1993) with permission from CRC Press.

physical and chemical processes affecting groundwater, both at the small scale of environmental and engineering problems and at the large scale of geologic processes like faulting, sedimentation, and petroleum formation. Like all sciences, there is still plenty to discover and learn. Groundwater science bridges a number of traditional disciplines including geology, physics, chemistry, biology, environmental science, soil science, mathematics, and civil engineering.

Because groundwater processes are hidden and difficult to measure, all studies involve a good deal of uncertainty and inference. This mystery and complexity help to make groundwater science fascinating and challenging.

This book provides an overview of the current “state of the art” in groundwater science, aimed at the college textbook level. In general, the book covers physical aspects first and then concludes with chemistry and contamination issues. We begin in this chapter with large-scale physical processes, looking at how groundwater relates to other reservoirs of water on earth, and man’s use of these waters.

1.2 Global Water Reservoirs and Fluxes

Water exists in virtually every accessible environment on or near the earth’s surface. It’s in blood, trees, air, glaciers, streams, lakes, oceans, rocks, and soil. The total amount of water on the planet is about $1.4 \times 10^9 \text{ km}^3$, and its distribution among the main reservoirs is listed in Table 1.1 (Maidment, 1993). Of the fresh water reservoirs, glacial ice and groundwater are by far the largest. Groundwater and surface water are the two reservoirs most used by humans because of their accessibility. Fresh groundwater is about 100 times more plentiful than fresh surface water, but we use more surface water because it is so easy to find and use. Much of the total groundwater volume is deep in the crust and too saline for most uses.

Fueled by energy from solar radiation, water changes phase and cycles continuously among these reservoirs in the hydrologic cycle (Figure 1.3). Solar energy drives evaporation, transpiration, atmospheric circulation, and precipitation. Gravity pulls precipitation down to earth and pulls surface water and groundwater down to lower elevations and ultimately back to the ocean reservoir. Evaporation and transpiration are difficult to measure

Reservoir	Percent of All Water	Percent of Fresh Water
Oceans	96.5	
Ice and snow	1.8	69.6
Groundwater:		
Fresh	0.76	30.1
Saline	0.93	
Surface water:		
Fresh lakes	0.007	0.26
Saline lakes	0.006	
Marshes	0.0008	0.03
Rivers	0.0002	0.006
Soil moisture	0.0012	0.05
Atmosphere	0.001	0.04
Biosphere	0.0001	0.003

Source: Maidment (1993).

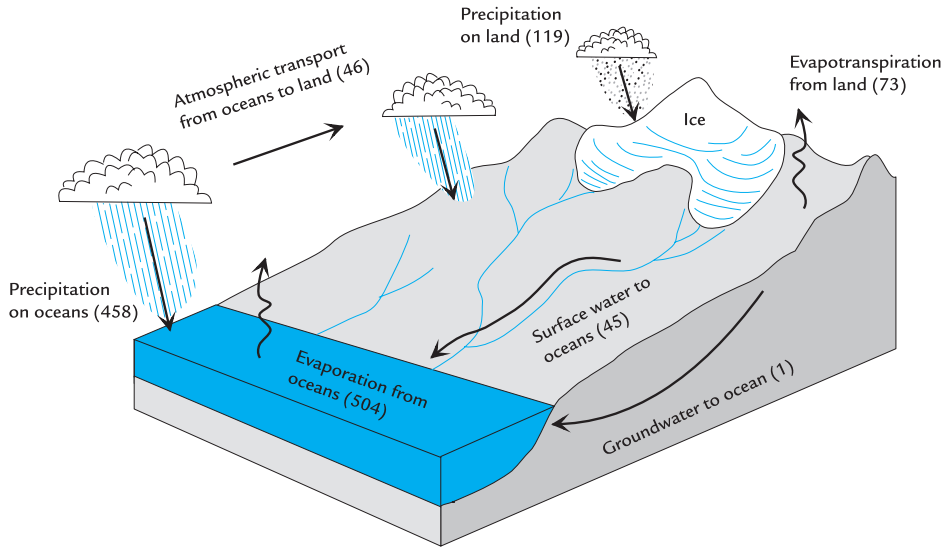


Figure 1.3 Global hydrologic cycle. Numbers in parentheses are total global fluxes in thousands of km³/yr. Data from Maidment (1993).

separately, so their combined effects are usually lumped together and called **evapotranspiration**.

Over land areas, average precipitation exceeds average evapotranspiration. The opposite is true over the oceans. On average, more atmospheric water moves from the ocean areas to the land areas than vice versa, creating a net flux of atmospheric water from ocean areas to land areas. The flux of surface water and groundwater from the land back to the oceans maintains a balance so that the volumes in each reservoir remain roughly constant over time. The hydrologic cycle represents only global averages; the actual fluxes in smaller regions and smaller time frames deviate significantly from the average. Deserts, for example, are continental areas where evaporation exceeds precipitation. On the other hand, at a cold, rainy coastline like the northwest Pacific, precipitation exceeds evaporation.

In a given region, the fluxes are distributed irregularly in time due to specific storm events or seasonal variations such as monsoons. With these transient fluxes, the reservoir volumes fluctuate; groundwater and surface water levels rise and fall, glaciers grow and shrink, and sea level rises and falls slightly.

The **residence time** is the average amount of time that a water molecule resides in a particular reservoir before transferring to another reservoir. The residence time T_r is calculated as the volume of a reservoir V [length³ or L³] divided by the total flux in or out of the reservoir Q [length³ per time or L³/T],

$$T_r = \frac{V}{Q} \quad (1.1)$$

The atmosphere is a relatively small reservoir with a large flux moving through it, so the average residence time is short, on the order of days. The ocean is an enormous reservoir with an average residence time on the order of thousands of years. The average residence time for groundwater, including very deep and saline waters, is approximately 20,000 years. Actual residence times are quite variable. Shallow fresh groundwater would have much shorter residence times than the average, more like years to hundreds of years.