6. Hydrology (수문학, 水文學)

The Dying of a sea – The Aral Sea

The Aral Sea, once the world's fourth largest lake (in area), is located in the republics of Kazakhstan and Uzbekistan. It is located in a remote desert and is fed by the Amu Dar'ya and Syr Dar'ys rivers. Unlike many other lakes, this lake has no outlet. The lake is saline and the water flowing from the two rivers had maintained a constant salinity.

Drastic increases in the abstraction of waster began in the 1950s when the former USSR first diverted water from the rivers to support the production of cotton. In the 1960s, the amount of irrigated land was more than doubled. Large dams were constructed in both rivers and a 1370 km canal was created to divert water from the rivers.

Over the next 30 years, the area became the world's fourth largest producer of cotton. The area experienced an economic boom and the population of the area increased. At the same time, the annual flow of the two rivers decreased by about 95%. As a result, the Aral Sea lost 40% of its surface area and 66% of its volume.

Today, two rivers no longer reach the Aral Sea, its waters depleted for irrigation and other uses. As the salinity increased almost 10-fold, the aquatic plants and animals suffered. Yet, the flows from the two rivers continue to be diverted for irrigation to maintain cotton production.

Results:

(1) Climate change: The Aral Sea had moderated the climate, however, reduced area loose the temperature buffering capacity. Precipitation has also decreased and desertification has progressed.

(2) Health: Winds that blow across the dried lake bed and surrounding area carry sands contaminated with heavy metals, pesticides, fertilizers, and other toxic chemicals. The public water supply is polluted. The infant mortality rate is among the highest in the world.

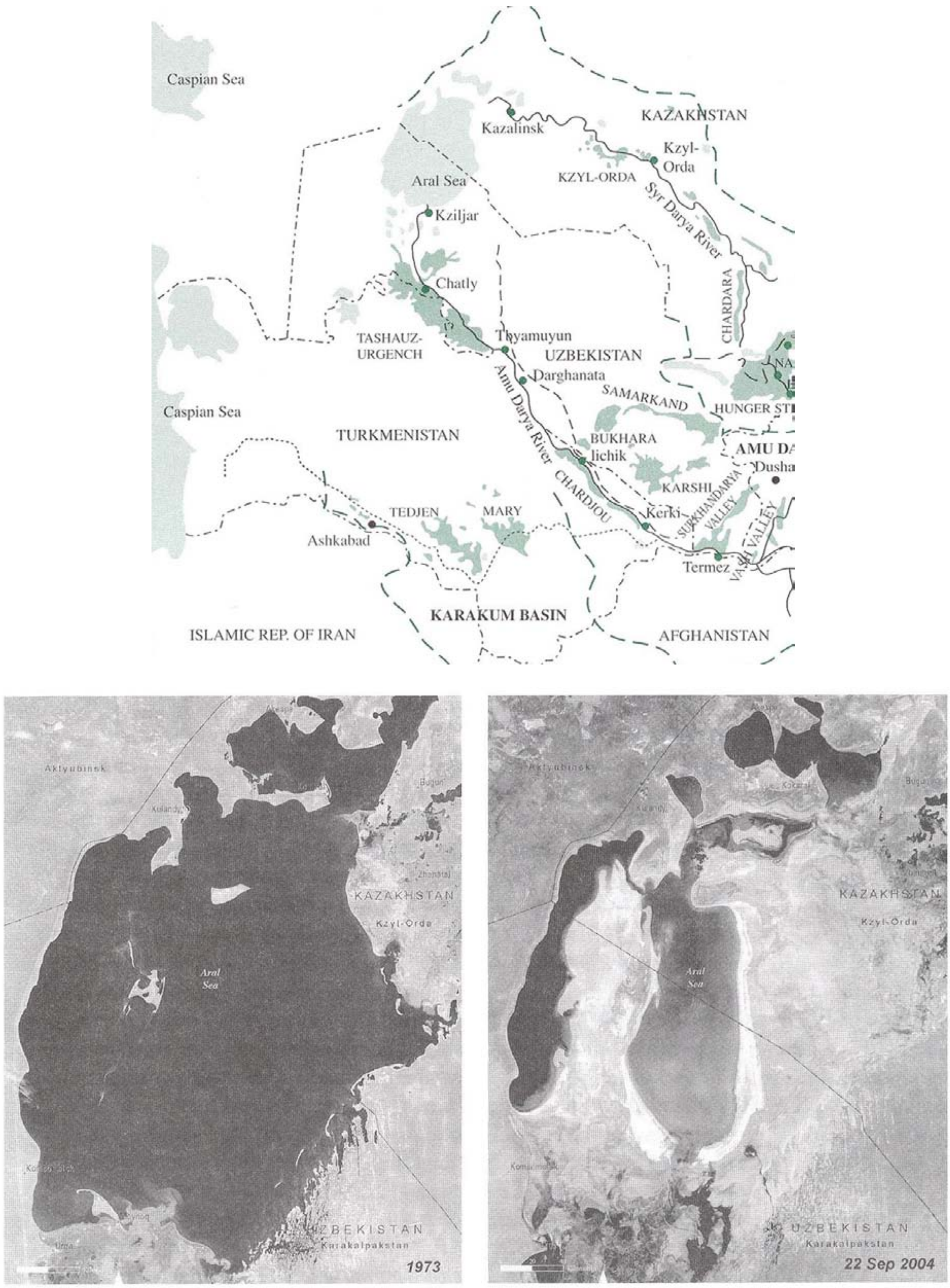


FIGURE 7–1 **(a)** Map of the Aral Sea and surrounding area. **(b)** Satellite-based images of the Aral Sea from 1960 and 2003.

Hydrosphere: The stock of water on the earth

Atmosphere: The gaseous environment surrounding the earth

Water (1) transports substances in our body

(2) plays an important role in the body's thermal regulation system

(3) functions as an important reactant in the food chain

$C_6H_{12}O_6 + 6\ O_2 \rightarrow$ 2,800 kJ of metabolic energy $+ 6\ CO_2 + 6\ H_2O$

Water Balance and Residence Time of Water

Table 1.1 Estimate of the Water Balance of the World

Parameter	Surface area $(km^2)\times10^6$	Volume $(km^3)\times10^6$	Volume (%)	Equivalent depth (m)*	Residence time
Oceans and seas	361	1370	94	2500	~4000 years
Lakes and reservoirs	1.55	0.13	<0.01	0.25	~10 years
Swamps	<0.1	<0.01	<0.01	0.007	1–10 years
River channels	<0.1	<0.01	<0.01	0.003	~2 weeks
Soil moisture	130	0.07	<0.01	0.13	2 weeks–1 year
Groundwater	130	60	4	120	2 weeks–10,000 years
Icecaps and glaciers	17,8	30	2	60	10–1000 years
Atmospheric water	504	0.01	<0.01	0.025	~10 days
Biospheric water	<0.1	<0.01	<0.01	0.001	~1 week

SOURCE: Nace, 1971.

*Computed as though storage were uniformly distributed over the entire surface of the earth.

- The dominant water stocks used by humans are (1) freshwater lakes, (2) freshwater rivers, and (3) shallow groundwater.
- These water resources constitute a very small fraction of the hydrosphere.
- According to the residence times, groundwater is a nonrenewable resource. On the other hand surface freshwater is a renewable.
- Accessible freshwater stocks and flows are irregularly distributed in space and time. To balance the temporal and spatial mismatch between supply and demand, an excessive and complex system of reservoirs, aquaducts, and pumping stations has been developed.

Physicochemical Properties of Water

- A unique material that exists in all three phases over the range of ordinary environmental conditions (e.g., temperature and pressure)
- High latent heat (잠열) and specific heat (비열)

  latent heat: the amount of energy required to cause a phase change (e.g., 334J for melting 1g of ice, and 2450J for evaporation 1g of liquid water)

  specific heat: the amount of energy needed to heat liquid water (420J for heating 1g of liquid water from 0 to 100^{o}C)

  In particular, high latent heat for evaporation is important in buffering the earth's environment against large temperature changes as shown by the smaller temperature changes of humid tropics in comparison to the arid deserts.
- The optical properties of water play an important role in affecting climate

  Since the mass of water (transparent) heated by sunlight is greater than the mass of soil (opaque), the temperature increase caused by sunlight is much lower for water than for soil.

  Incoming solar radiation may be scattered by clouds back to space, reducing the heating of the earth's surface; Both water vapor molecules and droplets absorb long-wavelength radiation that is emitted from the earth's surface, warming the earth. (Why do clouds with higher water content look gray or black? Rather than scattering, more absorb the incident visible radiation)
- For environmental purposes, water can be considered an incompressible fluid.

  The density of liquid water can be treated as constant even for wastewater streams (e.g., 1,000 kg/m^3 = 1 kg/L = 1 g/cm^3)
- more dense as a liquid than as a solid

  Lake freezes from the top.

  Freezing water bursts pipes.

  Freeze-thaw (expansion-contraction) cycle results in fractures in rocks, concrete, and asphalt.
- Movement of water alters the physical landscape.

  Glacial sculpting

Ocean surf and river scour

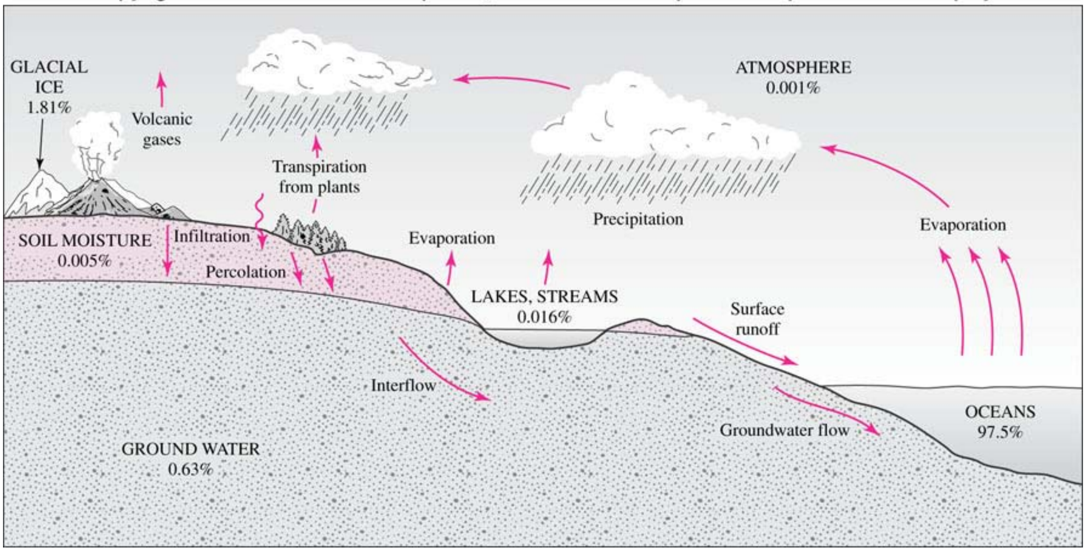
A chemical solvent (even a weak solvent)

- Viscosity of water varies by almost a factor of 3 over the typical range of liquid water temperature

Viscosity affects the rate of movement of water through pipes and through soil, and also the rate of movement of suspended particles through water.

6.1 Hydrologic Cycle

- hydrologic cycle: The movement and conservation of water on earth



- Water transfer to the atmosphere: (1) evaporation(발산) + (2) transpiration(증산) = evapotranspiration(transevaporation, 증발산)
- Water release from the atmosphere: precipitation (강수, e.g., rain, snow, etc.)
- The net amount (mass) of water that is gained or lost in a water body (e.g., lake) within a given period = "Storage problem"

  [Mass rate of accumulation] = [Mass rate in] – [Mass rate out]

For example, a lake (eq. 6-2, p.191)

Mass rate of accumulation = Flowrate of streams entering lake
+ Rate of precipitation
+ Rate of Runoff
+ Rate of seepage into lake
- Flowrate of streams exiting lake
- Rate of evaporation from water bodies
- Rate of evapotranspiration
- Rate of seepage out of the lake

For practical application, dimension conversion is necessary (eq. 6-3, p.192).

EXAMPLE 6–1 Hvarekhshaeta Lake has a surface area of 708,000 m^2. Based on collected data, Drvaspa Brook flows into the lake at an average rate of 1.5 m$^3 \cdot$ s^{-1} and the Vouruskasha River flows out of Hvarekhshaeta Lake at an average rate of 1.25 m$^3 \cdot$ s^{-1} during the month of June. The evaporation rate was measured as 19.4 cm · month^{-1}. Evapotranspiration can be ignored because there are few water plants on the shore of the lake. A total of 9.1 cm of precipitation fell this month. Seepage is negligible. Due to the dense forest and the gentle slope of the land surrounding the lake, runoff is also negligible. The average depth in the lake on June 1 was 19 m. What was the average depth on June 30th?

Solution The first step to solving this problem is to determine what we know. We know that the inputs to the lake are

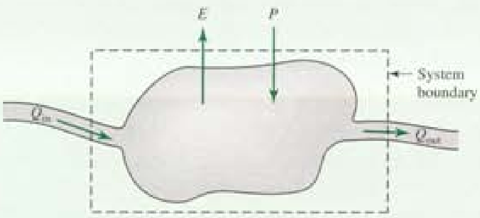
$$Q_{in} = 1.5 \text{ m}^3 \cdot \text{s}^{-1}$$
$$P = 9.1 \text{ cm} \cdot \text{month}^{-1}$$
$I_{in} = 0$ (because we were told that seepage is negligible)
$R' = 0$ (because we were told that runoff is negligible)

We also know that the outputs from the lake are

$$Q_{out} = 1.25 \text{ m}^3 \cdot \text{s}^{-1}$$
$$E = 19.4 \text{ cm} \cdot \text{month}^{-1}$$
$$E_T = 0$$

We also know that surface area of the lake is 708,000 m^2 and the average depth of the lake on June 1 is 19 m.

The following is a picture of the lake as a system



Using the average values given earlier and the most general form of the mass-balance equation (6–2), the mass-balance for this lake can be reduced to

Volumetric rate of accumulation $= Q_{in} - Q_{out} + P - E$

The volumetric rate of accumulation is often referred to as the **change in storage** (ΔS) and

$$\Delta S = Q_{in} - Q_{out} + P - E$$

Because the units for Q and P and E are different, we must ensure that the proper conversions are performed, yielding the same set of units.

Therefore,

$$\begin{aligned}\Delta S &= (1.5 \text{ m}^3 \cdot \text{s}^{-1})(86{,}400 \text{ s} \cdot \text{day}^{-1})(30 \text{ days} \cdot \text{month}^{-1}) \\ &\quad - (1.25 \text{ m}^3 \cdot \text{s}^{-1})(86{,}400 \text{ s} \cdot \text{day}^{-1})(30 \text{ days} \cdot \text{month}^{-1}) \\ &\quad + (9.1 \text{ cm} \cdot \text{month}^{-1})(\text{m} \cdot 100 \text{ cm}^{-1})(708{,}000 \text{ m}^2) \\ &\quad - (19.4 \text{ cm} \cdot \text{month}^{-1})(\text{m} \cdot 100 \text{ cm}^{-1})(708{,}000 \text{ m}^2) \\ &= 3{,}888{,}000 \text{ m}^3 \cdot \text{month}^{-1} - 3{,}240{,}000 \text{ m}^3 \cdot \text{month}^{-1} \\ &\quad + 64{,}428 \text{ m}^3 \cdot \text{month}^{-1} - 137{,}352 \text{ m}^3 \cdot \text{month}^{-1}\end{aligned}$$

Solving the preceding equation, yields

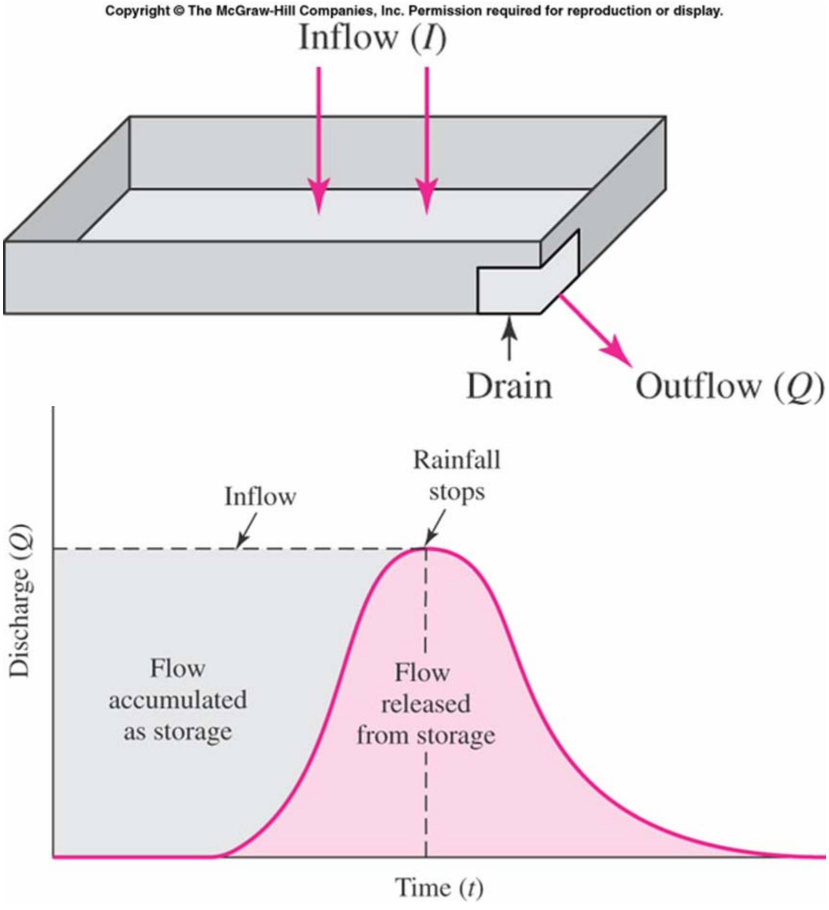
$$\Delta S = 575{,}076 \text{ m}^3 \cdot \text{month}^{-1}$$

Because $\Delta S = 575{,}076$ m$^3 \cdot$ month^{-1} and the average surface area is 708,000 m^2, the change in depth during the month of June is

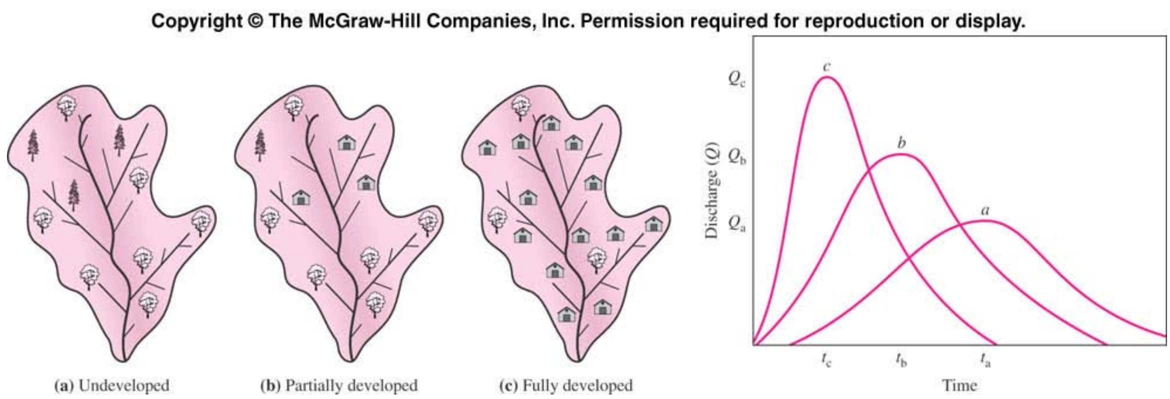
$$(575{,}076 \text{ m}^3 \cdot \text{month}^{-1})/708{,}000 \text{ m}^2 = 0.81 \text{ m}$$

Note that ΔS is positive. As such, the volume in the lake increased during June and, therefore, the depth increases. The new average depth on June 30 would be 19.81 m. Had a negative value for storage been calculated, then the depth of the lake would have decreased.

- Hydrograph(수문곡선): a chart in which flow rate is plotted versus time



- The shape of hydrograph depends on the slope of the land, density and type of ground cover, (e.g., degree of development), and time (e.g., seasonal and annual basis).



- Runoff coefficients (유출계수): [Rate of runoff] / [Rate of precipitation]

TABLE 6–1 Typical Runoff Coefficients

Description of Area or Character of Surface	Runoff Coefficient	Description of Area or Character of Surface	Runoff Coefficient
Business		Railroad yard	0.20–0.35
Downtown	0.70–0.95	Natural grassy land	0.10–0.30
Neighborhood	0.50–0.70	Pavement	
Residential		Asphalt, concrete	0.70–0.95
Single-family	0.30–0.50	Brick	0.70–0.85
Multi-units, detached	0.40–0.60	Roofs	0.75–0.95
Multi-units, attached	0.60–0.75	Lawns, sandy soil	
Residential, suburban	0.25–0.40	Flat (< 2%)	0.05–0.10
Apartment	0.50–0.70	Average (2–7%)	0.10–0.15
Industrial		Steep (> 7%)	0.15–0.20
Light	0.50–0.80	Lawns, heavy soil	
Heavy	0.60–0.90	Flat (< 2%)	0.13–0.17
Parks, cemeteries	0.10–0.25	Average (2–7%)	0.18–0.22
Playgrounds	0.20–0.35	Steep (> 7%)	0.25–0.35

Source: Joint Committee of the American Society of Civil Engineers and the Water Pollution Control Federation. *Design and Construction of Sanitary and Storm Sewers* (ASCE Manuals and Reports on Engineering Practice No. 37, or WPCF Manual of Practice No. 9), American Society of Civil Engineers, New York, (1969), p. 51.

6.2 Measurement of Precipitation, Evaporation, Infiltration, and Streamflow

(reading assignment)

When the rate of rainfall exceeds the rate of infiltration,

Horton's equation

$$f = f_c + (f_0 - f_c) \cdot e^{-kt}$$

where f = infiltration rate(침투율) [L/T];

f_c = equilibrium infiltration rate(평형 침투율) [L/T];

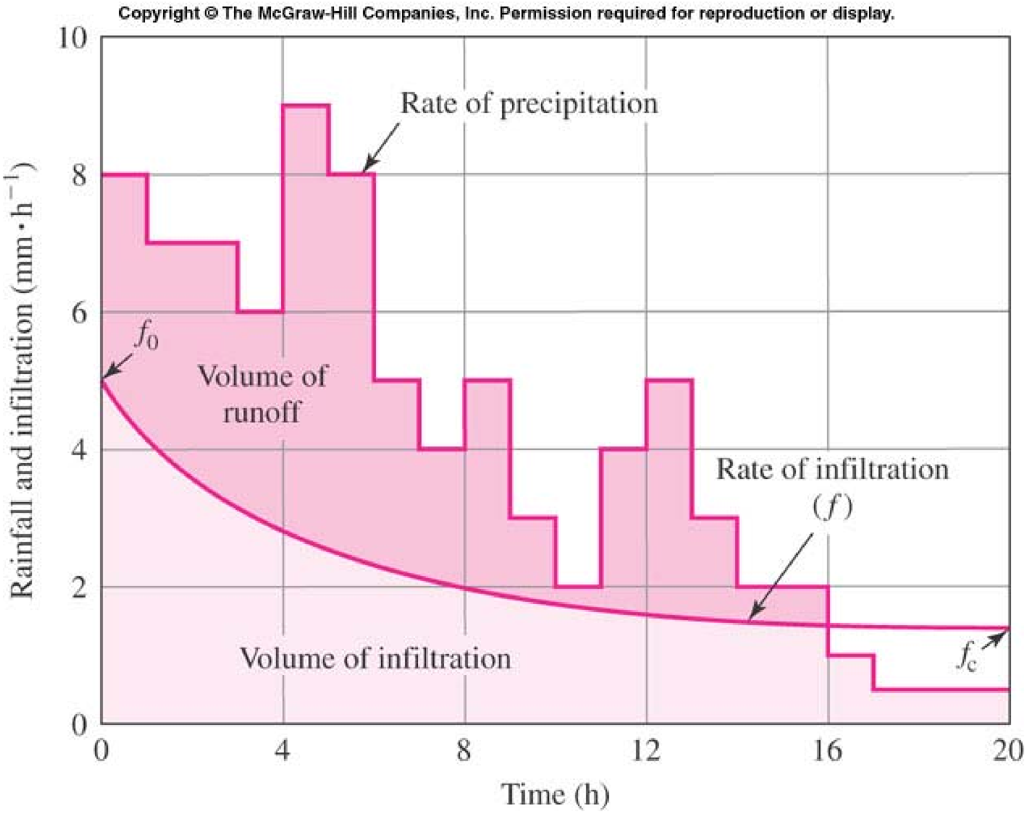
f_0 = initial infitration rate(초기 침투율) [L/T];

k = empirical constant(or decay constant, 감쇠상수) [T]; and

t = time [T].

누적침투량, $\text{Volume} = A \int f \, dt$

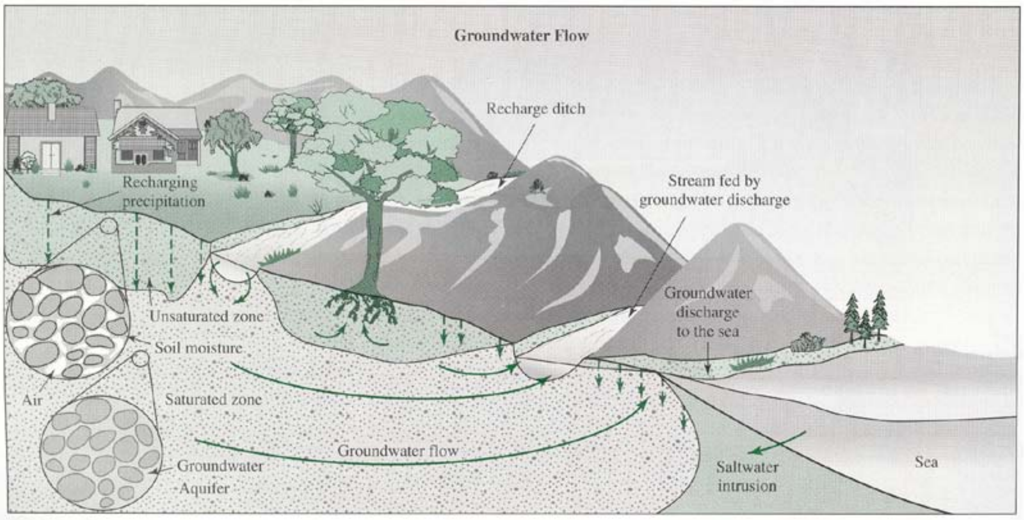
강수량 – 누적침투량 = 유출율(runoff)



6.3 Groundwater Hydrology

FIGURE 6–18

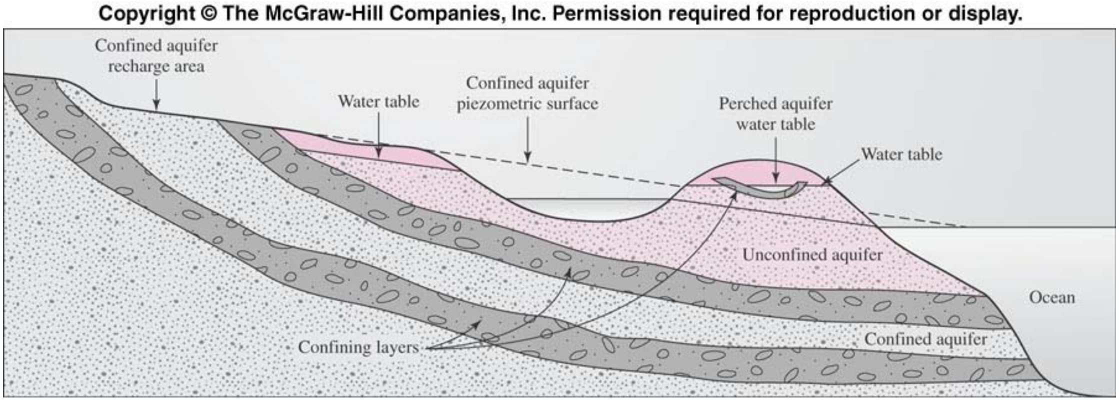
Elements of groundwater flow. (*Source: The Nature of Water, Groundwater—A Major Link in the Hydrologic Cycle*. Environment Canada, Ottawa, Canada.
site: www.ec.gc.ca/water/en/nature/grdwtr/e-link.htm
image: http://www.ec.gc.ca/water/images/nature/grdwtr/a5f2e.htm)



- Aquifers (대수층)

  Confined aquifer (피압대수층)

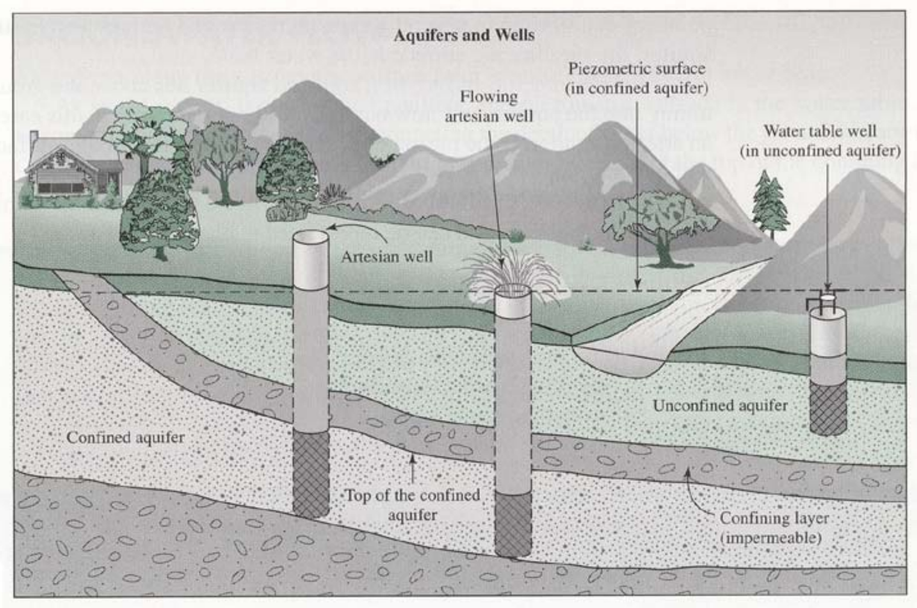
  Unconfined aquifer (자유면대수층)



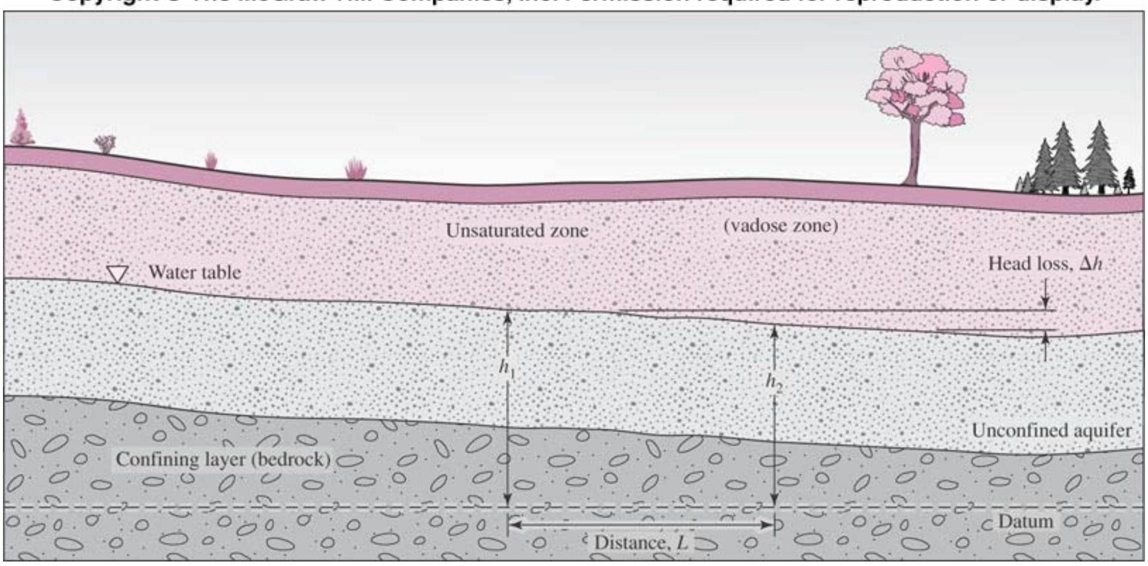
- Piezometric surface and head (piezometer)

FIGURE 6-22

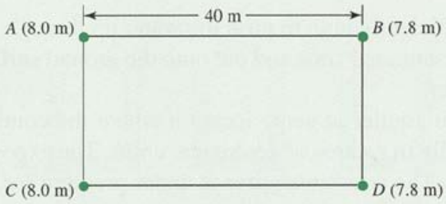
Schematic showing piezometric surface of artesian and flowing artesian wells. Note the piezometric surface for the flowing well is at ground surface. (*Source: From: Groundwater—Nature's Hidden Treasure, Environment Canada, Ottawa, Canada, 1999.* http://www.ec.gc.ca/water/en/info/pubs/FS/e_FSA5.htm image: http://www.ec.gc.ca/water/images/nature/grdwtr/a5f3e.jpg



- Groundwater flow



EXAMPLE 6–6 The head in an unconfined aquifer (Figure 6–23) has been measured at four locations as shown in the following schematic.



Using this information, determine the hydraulic gradient.

Solution The direction of flow is from AC to BD. The hydraulic gradient can be calculated using Equation 6–11

$$\frac{\Delta h}{L} = \frac{h_2 - h_1}{L} = \frac{8.0 - 7.8\text{ m}}{40\text{ m}} = 0.005\text{ m}\cdot\text{m}^{-1}$$

EXAMPLE 6–8 Let's assume that in the previous example, the aquifer is coarse sand and that the cross-sectional area of the aquifer, through which water flows is 925 m^2. What is the Darcy velocity of groundwater in this aquifer? What is the specific discharge?

Solution Using Table 6–4, we find that coarse sand has a hydraulic conductivity, K, of $6.9 \times 10^{-4}\text{ m}\cdot\text{s}^{-1}$. Because the hydraulic gradient was determined to be $0.005\text{ m}\cdot\text{m}^{-1}$, the Darcy velocity of groundwater flow can be calculated as

$$v = K\left(\frac{\Delta h}{L}\right) = (6.9 \times 10^{-4}\text{ m}\cdot\text{s}^{-1})(0.005\text{ m}\cdot\text{m}^{-1})(86{,}400\text{ s}\cdot\text{day}^{-1})$$

$$= 0.298\text{ m}\cdot\text{day}^{-1}$$

The specific discharge is equal to vA or

$$0.298\text{ m}\cdot\text{day}^{-1} \times 925\text{ m}^2 = 275.65\text{ m}^3\cdot\text{day}^{-1}$$

EXAMPLE 6–9 The geological material in the column shown in Figure 6–25 is coarse sand. The piezometric surfaces, $h_1 = 10$ cm and $h_2 = 8.0$ cm. The distance between the two points where h_1 and h_2 were measured is 10.0 cm. The cross-sectional area is 10 cm^2. What is the linear velocity of the water flowing through the column?

Solution The hydraulic gradient can be calculated as

$$\frac{\Delta h}{L} = \frac{h_2 - h_1}{L} = \frac{10.0 - 8.0\text{ cm}}{10.0\text{ cm}} = \frac{2\text{ cm}}{10.0\text{ cm}} = 0.2\text{ cm}\cdot\text{cm}^{-1}$$

From Table 6–4, we see that the hydraulic conductivity, K, of coarse sand is equal to $6.9 \times 10^{-4}\text{ m}\cdot\text{s}^{-1}$. The Darcy velocity can be calculated as

$$v = K\frac{\Delta h}{L} = (6.9 \times 10^{-4}\text{ m}\cdot\text{s}^{-1})(0.2\text{ cm}\cdot\text{cm}^{-1}) = 1.38 \times 10^{-4}\text{ m}\cdot\text{s}^{-1}$$

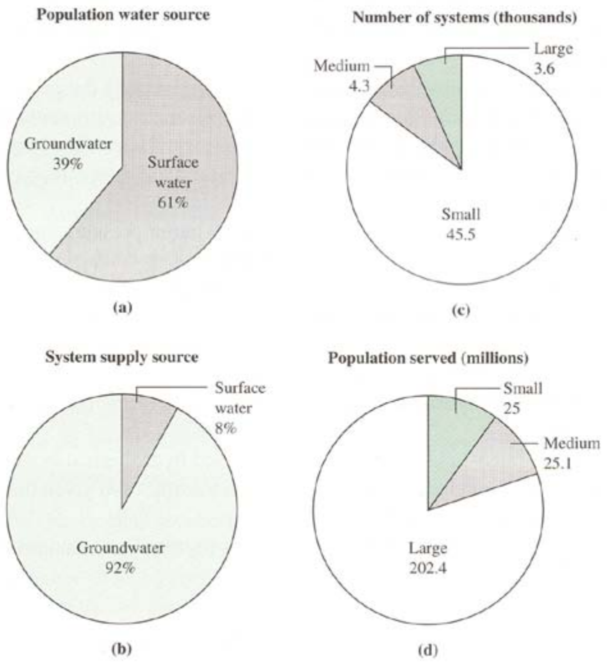
Assuming that the porosity is 0.3 (as given in Table 6–4), then the linear velocity would be

$$v'_{\text{water}} = \frac{v}{\eta} = \frac{1.38 \times 10^{-4}\text{ m}\cdot\text{s}^{-1}}{0.3} = 4.6 \times 10^{-4}\text{ m}\cdot\text{s}^{-1}$$

6.5 Surface water and Groundwater as a Water supply

FIGURE 6–27

(a) Percentage of the population served by drinking-water system source. **(b)** Percentage of drinking-water systems by supply source. **(c)** Number of drinking-water systems (in thousands) by size. **(d)** Population served (in millions of people) by drinking-water system size. (*Source: 1997 National Public Water Systems Compliance Report.* U.S. EPA, Office of Water. Washington, D.C. 20460. (EPA-305-R-99-002). (*Note: Small systems serve 25–3300 people; medium systems serve 3301–10,000 people; large systems serve 10,000+ people.*)



The Stream of Consciousness – Cheong-Gye-Cheon Restoration Project in Seoul
http://vimeo.com/2898463