24 Groundwater Flows and Velocity Measurements

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24.1 INTRODUCTION

Various data, although relatively unpublicized, exist in support of the quantitative importance of groundwater relative to other components of the hydrologic cycle on the earth. With reference to Table 24.1, excluding the large amount of the earth's water resting in the oceans and seas at high levels of salinity, groundwater accounts for about one-third of the freshwater resources of the world. If we limit our consideration to the liquid-phase freshwater, groundwater will account for almost the total volume available for use. If we consider only the most active groundwater regimes, for example, in subsurface reservoirs of good hydraulic permeability, water quantity will be reduced just to about two-thirds of the total amount. Considering this, the freshwater breakdown comes to 95% of subsurface groundwater; 3.5% of surface water such as lakes, swamps, reservoirs, and river channels; and 1.5% of soil moisture. From the usability point of view, however, this volumetric superiority of subsurface groundwater should be somewhat moderated by the average residence times listed in the right column of the table. River water has a turnover time on

TABLE 24.1
Water Balance on the Earth

Parameter	Volume Percentage (%)	Residence Time
Oceans and seas	97.5	~4,000 years
Lakes and reservoir	<0.01	~10 years
River channels	<0.01	~2 weeks
Groundwater	0.70	2 weeks to 10,000 years
Icecaps and glaciers	1.70	10–1,000 years
Atmospheric water	<0.01	~10 days

Source: Data are taken from Freeze, R.A. and Cherry, J.A., *Groundwater*, Prentice Hall, Upper Saddle River, NJ, 1979; Shiklomanov, I.A. (ed.), *World Water Resources: A New Appraisal and Assessment for the 21st Century*, UNESCO, Paris, France, 1998.

the order of 2 weeks in average. On the other hand, groundwater moves at much slower speeds, with residence times spanning from tens to thousands of years [1–4].

In the field of hydrology, the continuous circulation of water among ocean, atmosphere, and land is known as the *hydrologic cycle*, and groundwater flows play an important role in order to close the cycle as shown in Figure 24.1. Focusing on the land-based portion of the cycle, inflow arrives as *precipitation*, in the form of rainfall or snowmelt. Outflow takes place as runoff and as *evapotranspiration*; the latter is a combination of evaporation from open bodies of water, evaporation from ground surfaces, and transpiration from the subsurface soils by plants. Precipitation delivers water to such streams as *surface runoff* or *overland flow*, and eventually to rivers and channels on the land surface, and by subsurface flow routes, as groundwater *base flow* following *infiltration* into the permeable soil. The figure of the hydrologic cycle makes it clear that a mass balance in a watershed must be considered as a combination of both the surface drainage area and the parcel of subsurface soils and geological formations that underlie it. Therefore, the

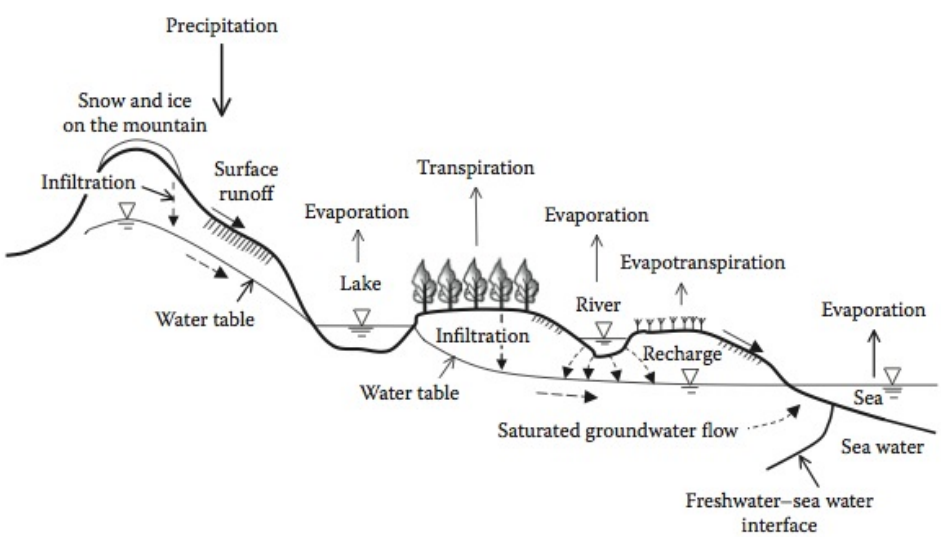

FIGURE 24.1 Hydrologic cycle in land. (Redrawn from Bear, J., *Hydraulics of Groundwater*, McGraw-Hill, New York, 1979.)