Chapter 1

The Hydrosphere — An Overview

"Water, water, every where, — nor any drop to drink" (Samuel Taylor Coleridge, "The Rime of the Ancient Mariner") aptly sums up the overall picture of the hydrosphere — that part of planet Earth made up of water. The oceans, covering 71% of the surface of the globe, make up 97.25% of the mass of water. Most of the freshwaters, whose volume is estimated to be $39{\cdot}10^6\,\mathrm{km}^3$, are also not immediately accessible: $29{\cdot}10^6\,\mathrm{km}^3$ is ice accumulated on mountain glaciers and on the ice caps of the poles; $9.5{\cdot}10^6\,\mathrm{km}^3$ constitute groundwaters and only about $0.13{\cdot}10^6\,\mathrm{km}^3$ are surface waters, mainly lakes and rivers. The amount of water held up in the biosphere is estimated to be $0.6{\cdot}10^3\,\mathrm{km}^3$. The atmospheric moisture amounts to just $13{\cdot}10^3\,\mathrm{km}^3$ — less than 10^{-5} of the total amount of water — but this small amount is the one which actuates the hydrologic cycle by virtue of its dynamic nature.

Figure 1.1 shows in a schematic fashion the components of the hydrologic system and the mean annual fluxes between these compartments, i.e. the evaporation, transport through the atmosphere, precipitation over sea and land surfaces, and the backflow to the ocean as surface and sub-surface runoff. Some secondary loops of water recycling from the continents to the atmosphere are also indicated. It is evident that to a first approximation, the hydrologic cycle is a closed one. However, the different reservoirs are not strictly in a steady state, on a variety of time scales. There is a marked seasonal imbalance caused by snow accumulations on large land areas in winter; soil moisture and surface reservoirs such as lakes and wetlands fill up during rainy periods, whereas they drain and dry up or are used up by the vegetation during periods of drought. On a longer time scale, much of the cryosphere and some of the deeper groundwaters are immobilised for long periods and the size of these reservoirs undergo variation on a geological

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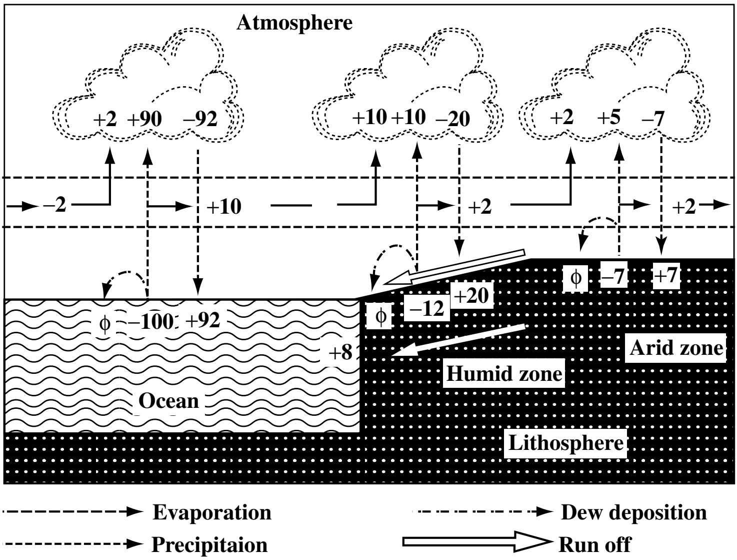

Fig. 1.1. The hydrologic cycle, showing flux units relative to the average marine evaporation rate (100 units). Θ signifies a small fraction of the flux. (Adapted from Chow, 1964).

time scale. In particular, the waxing and waning of glaciers during glacial and inter-glacial periods has resulted in sea-level changes of hundreds of metres.

The total amount of water in the hydrosphere is, however, believed to have been fairly constant throughout most of the geological record, except for the early formative years of the globe. The addition of exhaled water from the interior, by means of volcanism, is nowadays but a very minor factor. Similarly, the loss of water to space, mainly by means of the photolysis of water in the upper atmosphere and the preferred loss of hydrogen atoms, does not amount to much compared to the other fluxes. The residence times or through-flow rates in the various reservoirs are very different, however, ranging from about 10 days in the atmosphere to thousands of years in deep groundwater systems. This concept of the *Residence Time* is further elaborated in Box 1.1.

This text is concerned mainly with *meteoric* waters, i.e. those derived from precipitation, especially those actively taking part in the hydrologic cycle. Thus, the ocean water masses will not be discussed, except as far as they are the sources for the meteoric waters.

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Box 1.1 Residence and transit times in water reservoirs.

The residence time of water in a reservoir (τ) is defined as the average time a water molecule will spend in that reservoir. For a well-mixed reservoir at steady state where $F(\mathrm{in}) = F(\mathrm{out})$ so that V=constant [F being the flux and V the volume of the system], this can be expressed by a mass balance equation:

$$\tau = V/F.$$

This time is then equivalent to the one that would be needed to fill up the reservoir. It is further equal to the mean transit of an ideal solute or tracer material, assuming a “piston-flow displacement (PFD)” of the tracer through the medium.

Some average values of the residence time in compartments of the hydrologic cycle are given as follows:

The oceans	3000 yrs. (based on mean evaporation flux)
Groundwaters	500 yrs. (based on the base-flow of the continental discharge)
Rivers	4 months
Atmosphere	10 days

The range of values in each reservoir is very large, especially in groundwater and ice deposits where values can range from a few years in some to thousands of years in others.

The subject has been exhaustively discussed in a number of seminal papers and reviews, more recently in Chapters 9 and 10 in “Solute Modelling in Catchment Systems” (St. T. Trudgill, edtr), Wiley, 1995.

As can be seen in Fig. 1.1, more than 90% of the water evaporated from the oceans falls back as marine precipitation and only about 8% of the evaporated flux is advected onto the land areas. From Fig. 1.2, which shows the distribution of the atmospheric water balance over the globe, we learn that the major source regions of atmospheric moisture are in the subtropical belt. The maximum advective flux of moisture then occurs by eastward flow onto the North-American and European continents at mid-latitudes and by westward transport to the South-American and African continents in the tropical regions. Due to the vertical gradient of temperature in the atmosphere and the resultant low temperatures in the upper troposphere, which limits the amount of water held aloft (Fig. 1.3), most of the vapour is transported in the lower part of the troposphere.

As rain falls on the ground, it is partitioned at (or near) the earth surface into surface runoff and ground infiltration on the one hand, and a return flux of water into the atmosphere by means of direct evaporation or

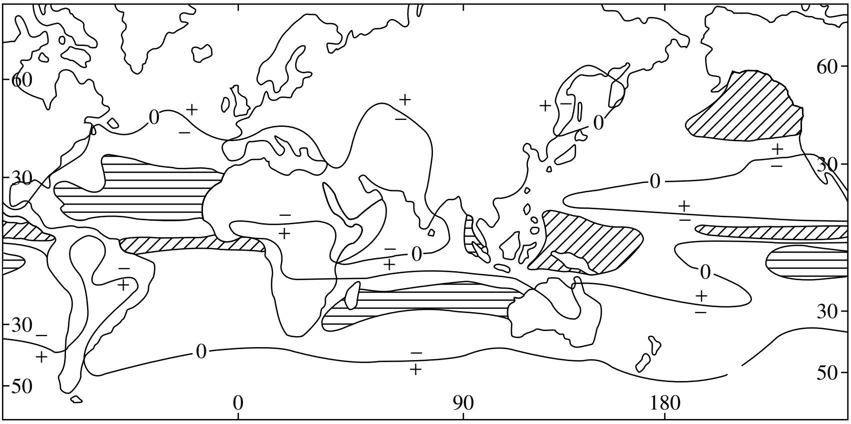

Fig. 1.2. Worldwide ratios of Precipitation/Evaporation amounts. (+) signifies ratios exceeding worldwide average and (−) below that. In stippled areas precipitation excess over evaporation exceeds 100 mm/year and in dashed areas evaporation is in excess of 100 mm/year.

evapo-transpiration through the intermediary of plants, on the other hand. Figure 1.4 schematizes these processes. The major role played by the return flux into the atmosphere is to be noted, which explains the fact that the integrated precipitation amount over the continents exceeds the vapour flux from the oceanic source regions onto the continents. The total amount of re-evaporated waters from all the terrestrial surface reservoirs accounts for more than 50% of the incoming precipitation in most cases and approaches 100% in the arid zone. Details depend on the climate, surface structure and plant cover. The holdup times in the different surface reservoirs prior to evapo-transpiration range from a scale of minutes on the canopy and bare surfaces, to days and weeks in the soil, and up to many years in large lakes.

The potential evaporation, i.e. the maximum rate of evaporation which is that of an open water surface, depends on the climatic condition, the insolation, the wind field and atmospheric humidity. However, since open water bodies occupy just a small fraction of the land surface, it is found that the largest share of the flux into the atmosphere from land is provided by the transpiration of the plant cover, mostly drawing on the waters accumulated in the soil. Evaporation from water intercepted on the canopy of plants also accounts for a surprisingly large share — for example, 35% of the incoming precipitation in the tropical rain forest (Molion, 1987) and 14.2% and 20.3%, respectively, from deciduous and coniferous trees in the

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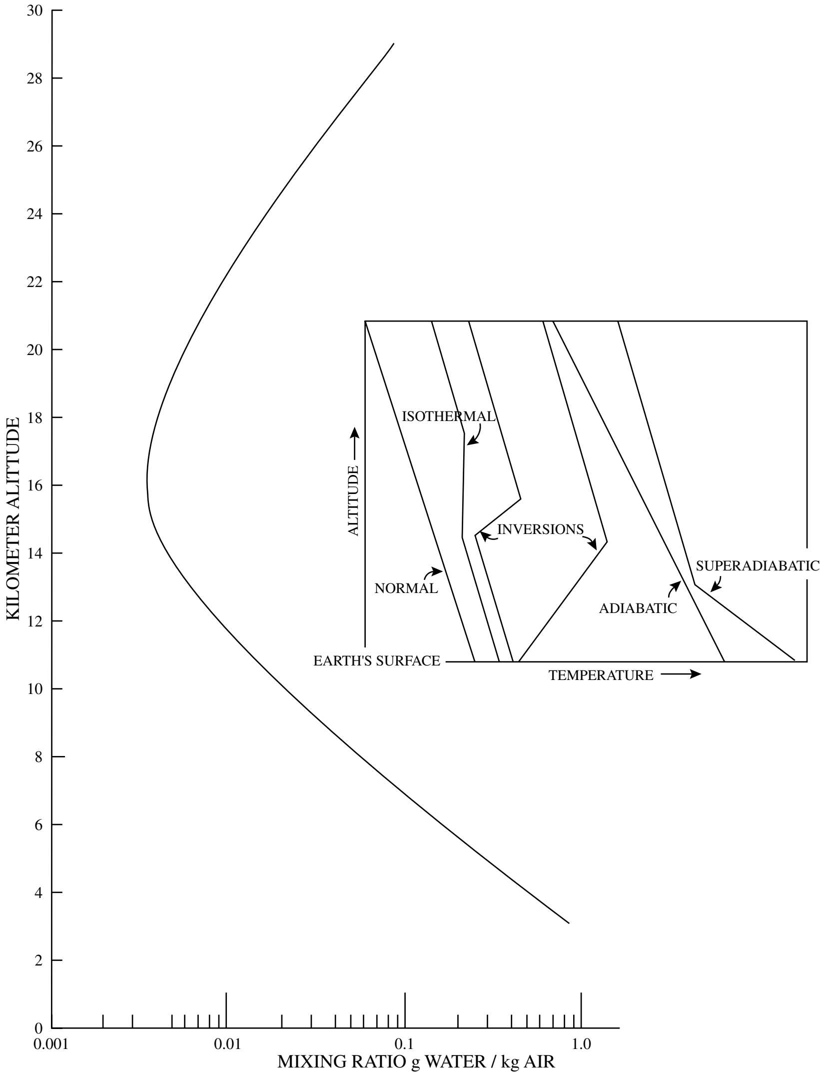

Fig. 1.3. Vertical profile of the mean water content in the troposphere and lower stratosphere. (Inset: typical vertical temperature gradients in the troposphere.)

Appalachian Mountains in Northern America (Kendall, 1993). Direct loss of water by evaporation from the soil, which makes up the balance of the water flux to the atmosphere, is not appreciable where there is an ubiquitous plant cover (Zimmermann *et al.*, 1967).

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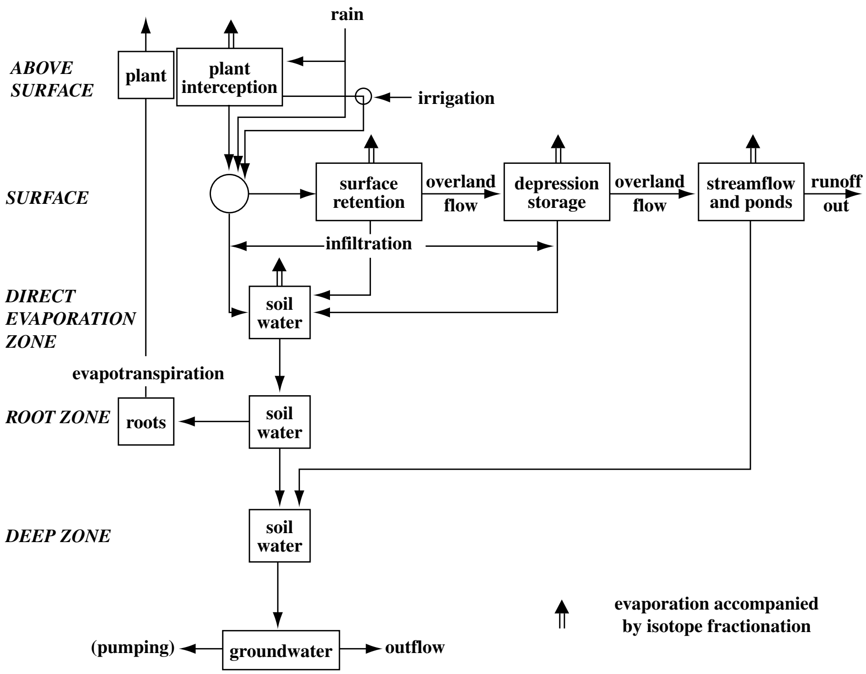

Fig. 1.4. Scheme of the water fluxes at the atmosphere/land-surface interface (adapted from Gat and Tzur, 1976).

Except for the water recycled into the atmosphere, the precipitation which falls on land ultimately drains back into the oceans, mostly as surface runoff in rivers. However, the travel time from the site of precipitation to the sea is varied, as is the interplay between surface and sub-surface runoff. The latter depends on the climate, land use, morphology and scale of the runoff system.

In the tropics, the major part of runoff takes the form of fast surface runoff, which occurs quite close to the site of precipitation. In the temperate and semi-arid zones, most of the incoming precipitation infiltrates the soil, and that part which is in excess of the water taken up by the plants moves further to recharge groundwaters or to drain to the surface. Most of the groundwater emerges as springs further afield and, as shown in Fig. 1.5, the percentage of surface waters in the total runoff increases on a continental scale. Obviously, some further evaporative water loss can then take place, especially where the surface drainage system is dammed or naturally forms lakes and wetlands. As a rule, the transit times through the sub-surface

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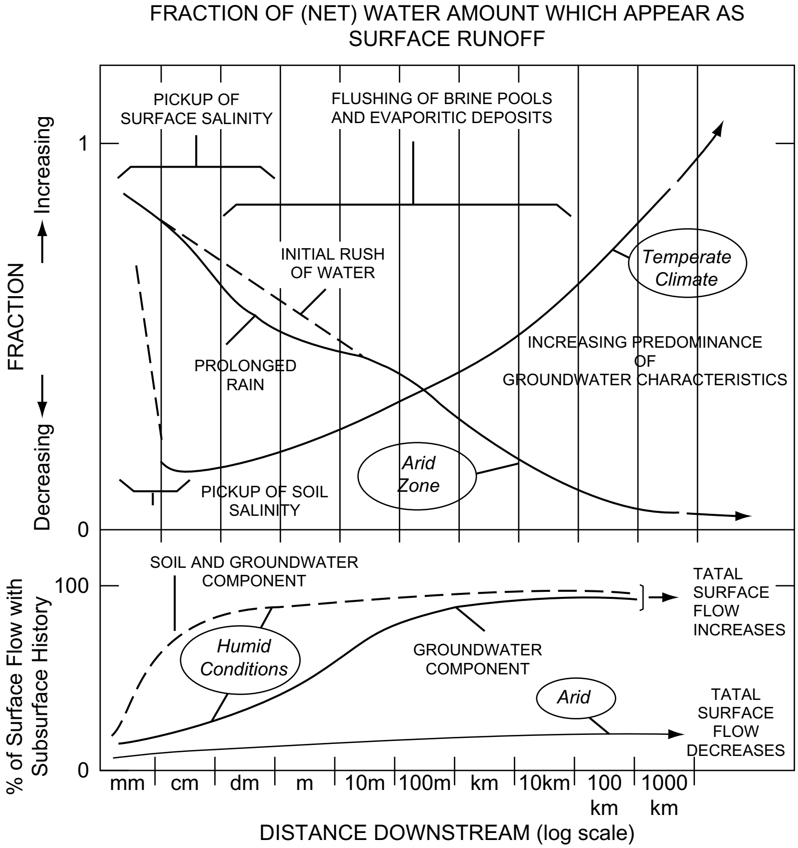

Fig. 1.5. Scheme of the partitioning of the continental runoff between surface and sub-surface flows under different climate scenarios (from Gat, 1980): Top: Fraction of the surface water runoff (corrected for evaporative water losses), scaled downstream from the site of precipitation. Bottom: Percent of the surface runoff with a sub-surface history.

systems are of the order of a few months or years, inversely correlated with the magnitude of the flux.

In contrast, in the arid zone, the largest part of the incoming precipitation is re-evaporated close to the site of precipitation. However, due to the absence of a soil or vegetation cover, even relatively small rain amounts can result in surface flows and, in extreme cases, in flashfloods; these later infiltrate the river bed recharging local desert aquifers. When these waters reappear at the surface they may then dry up completely, forming typical saltpans (locally named salinas or sabkhas). As shown in Fig. 1.5, the surface to sub-surface relationship as a function of distance from the site of precipitation in the arid zone differs considerably from that of the more temperate zones. Moreover, due to the relatively low water fluxes, the ages of some of the groundwaters of the arid zone are very large, up to the order of thousands of years.

The quantitative deconvolution of these relationships is one important task of the tracer hydrology, in general, and of isotope hydrology in particular.

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