



Chapter 2

The hydrological cycle

The hydrologic cycle is a conceptual model that describes the storage and movement of water between the biosphere, atmosphere, lithosphere, and the hydrosphere (see Figure 2.1). Water on this planet can be stored in any one of the following reservoirs: atmosphere, oceans, lakes, rivers, soils, glaciers, snowfields, and groundwater.

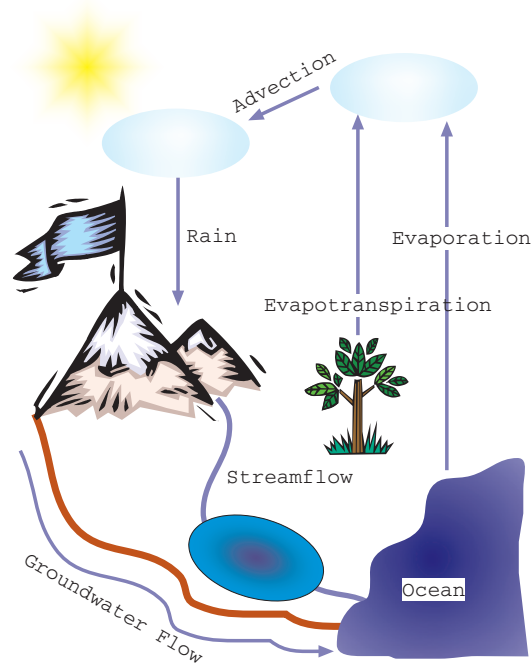
Water moves from one reservoir to another by way of processes like evaporation, condensation, precipitation, deposition, runoff, infiltration, sublimation, transpiration, melting, and groundwater flow. The oceans supply most of the evaporated water found in the atmosphere. Of this evaporated water, only 91% of it is returned to the ocean basins by way of precipitation. The remaining 9% is transported to areas over landmasses where climatological factors induce the formation of precipitation. The resulting imbalance between rates of evaporation and precipitation over land and ocean is corrected by runoff and groundwater flow to the oceans.

Water is continually cycled between its various reservoirs. This cycling occurs through the processes of evaporation, condensation, precipitation, deposition, runoff, infiltration, sublimation, transpiration, melting, and groundwater flow. Table 1.3 describes the approximate residence times of water in the major reservoirs. On average water is renewed in rivers once every 16 days. Water in the atmosphere is completely replaced once every 8 days. Slower rates of replacement occur in large lakes, glaciers, ocean bodies and groundwater. Replacement in these reservoirs can take from hundreds to thousands of years. One of the oldest groundwater is found beneath the Sahara desert in Egypt (Nubian aquifer), where the water ages range from about 200 ka to 1 million years old, depending on location [18].

Some of these resources (especially groundwater) are being used by humans at rates that far exceed their renewal times. This type of resource use is making this type of water effectively nonrenewable.

Every year the turnover of water on Earth involves $577,000 \text{ km}^3$ of water. This is water that evaporates from the oceanic surface ($502,800 \text{ km}^3$) and from land ($74,200 \text{ km}^3$). The same amount of water falls as atmospheric precipitation, $458,000 \text{ km}^3$ on the ocean and $119,000 \text{ km}^3$ on land. The difference between precipitation and evaporation from the land surface ($119,000 - 74,200 = 44,800 \text{ km}^3/\text{year}$) represents the total runoff of the Earth's rivers ($42,700 \text{ km}^3/\text{year}$) and direct groundwater runoff

Fig. 2.1 Schematic of the hydrological cycle.



to the ocean ($2100 \text{ km}^3/\text{year}$). These are the principal sources of fresh water to support life necessities and man's economic activities.

The hydrologic cycle is a model of the movement of water through the Earth system. It also is a pathway through which energy is transferred between the surface of the earth and the atmosphere. The unequal distribution of water leaves its imprint on the surface of the earth through the mosaic of biomes and landforms sculpted by the power of moving water and ice. Human survival requires adequate and safe water resources. The future of those resources hinge on our understanding of the delicate balance of water in our earth system.

The water balance is an accounting of the inputs and outputs of water. The water balance of a place, whether it is an agricultural field, region, or continent, can be determined by calculating the input and output of water. The major input of water is from precipitation and output is evapotranspiration. The geographer C. W. Thornthwaite (1899-1963) pioneered the water balance approach to water resource analysis. He and his team used the water-balance methodology to assess water needs for irrigation and other water-related issues.

Water is constantly moving within and above the earth in a cycle called the hydrologic cycle. Not only is the hydrologic cycle a cycle of water, it is a cycle of energy as well. There are six major components of this cycle: evapotranspiration, condensation, precipitation, infiltration, percolation and runoff.

Nature recycles the earth's water supply through a process known as the water cycle or hydrologic cycle. This cycle operates continuously and receives energy from the sun.

The hydrologic cycle consists of inflows, outflows, and storage. Inflows add water to the different parts of the hydrologic system, while outflows remove water. Storage is the retention of water by parts of the system. Because water movement is cyclical, an inflow for one part of the system is an outflow for another.

Looking at an aquifer as an example, percolation of water into the ground is an inflow to the aquifer. Discharge of ground water from the aquifer to a stream is an outflow (also an inflow for the stream). Over time, if inflows to the aquifer are greater than its outflows, the amount of water stored in the aquifer will increase. Conversely, if the inflows to the aquifer are less than the outflows, the amount of water stored decreases.

Inflows and outflows can occur naturally or result from human activity.

2.1 Condensation

Definition 2.1. Condensation is the cooling of water vapor until it becomes a liquid.

As the dew point is reached, water vapor forms tiny visible water droplets. When these droplets form in the sky and other atmospheric conditions are present, clouds will form. As the droplets collide, they merge and form larger droplets and eventually, precipitation will occur.

Condensation generally occurs in the atmosphere when warm air rises, cools and loses its capacity to hold water vapor. As a result, excess water vapor condenses to form cloud droplets. The upward motions that generate clouds can be produced by convection in unstable air, convergence associated with cyclones, lifting of air by fronts and lifting over elevated topography such as mountains.

Precipitation

Definition 2.2. The moisture that falls from the atmosphere as rain, snow, sleet, or hail.

Precipitation varies in amount, intensity, and form by season and geographic location. These factors impact whether water will flow into streams or infiltrate into the ground. In most parts of the world, records are kept of snow and rainfall. This allows scientists to determine average rainfall for a location as well as classify rain storms based on duration, intensity and average return period. This information is crucial for crop management as well as the engineering design of water control structures and flood control.

The water vapor may condense back into a liquid and in so doing, releases latent heat which is converted into sensible heat that warms the surrounding air. This warming fuels the uplift of air to help promote adiabatic cooling and further condensation. As droplets of water coalesce into larger droplets they attain a size big enough to fall towards the earth's surface as precipitation. Located high in the troposphere they possess a high degree of potential energy that is converted into kinetic energy once they begin to fall toward the surface. Impacting the surface they convert this kinetic energy into work done on the surface (erosion for example). Rather than condensing and precipitating directly back into the ocean, water vapor may be transported to some other location where it condenses and precipitates out.

2.2 Evaporation

Definition 2.3. Evaporation is the phase change of liquid water into a vapor.

Evaporation is an important means of transferring energy between the surface and the air above. The energy used to evaporate water is called "latent energy". Latent energy is "locked up" in the water molecule when water undergoes the phase change from a liquid to a gas. Eighty-eight percent of all water entering the atmosphere originates from the ocean between 60 degrees north and 60 degrees south latitude. Most of the water evaporated from the ocean returns directly back to the ocean. Some water is transported over land before it is precipitated out.

The conversion of water from a liquid into a gas. Approximately 80% of all evaporation is from the oceans, with the remaining 20% coming from inland water and vegetation. Winds transport the evaporated water around the globe, influencing the humidity of the air throughout the world.

Most evaporated water exists as a gas outside of clouds and evaporation is more intense in the presence of warmer temperatures. This is shown in the image above, where the strongest evaporation was occurring over the oceans and near the equator (indicated by shades of red and yellow).

2.3 Evapotranspiration

Definition 2.4. Evapotranspiration is the combined net effect of evaporation and transpiration.

Evapotranspiration uses a larger portion of precipitation than the other processes associated with the hydrologic cycle.

Evaporation is the process of returning moisture to the atmosphere. Water on any surface, especially the surfaces of mudholes, ponds, streams, rivers, lakes, and oceans, is warmed by the sun's heat until it reaches the point at which water turns into the vapor, or gaseous, form. The water vapor then rises into the atmosphere.

Transpiration is the process by which plants return moisture to the air. Plants take up water through their roots and then lose some of the water through pores in their leaves. As hot air passes over the surface of the leaves, the moisture absorbs the heat and evaporates into the air.

Transpiration is the evaporation of water into the atmosphere from the leaves and stems of plants. Plants absorb soilwater through their roots and this water can originate from deep in the soil. (For example, corn plants have roots that are 2.5 meters deep, while some desert plants have roots that extend 20 meters into the ground). Plants pump the water up from the soil to deliver nutrients to their leaves. This pumping is driven by the evaporation of water through small pores called "stomates", which are found on the undersides of leaves. Transpiration accounts for approximately 10% of all evaporating water.

Evapotranspiration is the combination of water released to the atmosphere by evaporation and transpiration. Actual evapotranspiration is the amount of water delivered to the air from these two processes. Actual evapotranspiration is an output of water that is dependent on moisture available at the surface, temperature and humidity. Think of actual evapotranspiration as water use, that is, water is actually evaporating and transpiring given the environmental conditions of a place. Actual evapotranspiration increases as temperatures increase, so long as there is water to evaporate and for plants to transpire. The amount of evapotranspiration also depends on how much water is available, which depends on the field capacity of soils.

Potential evapotranspiration (PE). Potential evapotranspiration is the amount of water that would be evaporated under an optimal set of conditions, among which is an unlimited supply of water. Think of potential evapotranspiration of water need or demand. In other words, it would be the water demand for evaporation and transpiration given the local environmental conditions. One of the most important factors that determines water demand is solar radiation. As energy input increases the demand for water, especially from plants increases. Regardless if there is, or isn't, any water in the soil, a plant still demands water. If it doesn't have access to water, the plant will likely wither and die.

2.4 Infiltration and percolation

Definition 2.5. Infiltration is the entry of water into the soil surface.

Infiltration constitutes the sole source of water to sustain the growth of vegetation and it helps to sustain the ground water supply to wells, springs and streams. The rate of infiltration is influenced by the physical characteristics of the soil, soil cover (i.e. plants), water content of the soil, soil temperature and rainfall intensity. The terms infiltration and percolation are often used interchangeably.

As water reaches the surface in various forms of precipitation, it is intercepted by plants or falls directly to the surface. Precipitation that collects on the leaves or stems of plants is known as interception. The amount of water intercepted by a plant largely depends on plant form. Water is held on the leaf surface until it either

drips off as through fall or trickles down the leaf stem finally reaching the ground as stem flow. Interception of falling rain buffers the surface against erosion. Coniferous trees tend to intercept more water than deciduous trees on an annual basis because deciduous trees drop their leaves for a period of time.

Upon reaching the ground, some water infiltrates into the soil, possibly percolating down to the groundwater zone or it may run across the surface as runoff. Infiltration refers to water that penetrates into the surface of soil. Infiltration is controlled by soil texture, soil structure, vegetation and soil moisture status. High infiltration rates occur in dry soils, with infiltration slowing as the soil becomes wet. Coarse textured soils with large well-connected pore spaces tend to have higher infiltration rates than fine textured soils. However, coarse textured soils fill more quickly than fine textured soils due to a smaller amount of total pore space in a unit volume of soil. Runoff is then generated quicker than one might have with a finer textured soil.

Vegetation also affects infiltration, see Figure 2.2. For instance, infiltration is higher for soils under forest vegetation than bare soils. Tree roots loosen and provide conduits through which water can enter the soil. Foliage and surface litter reduce the impact of falling rain keeping soil passages from becoming sealed.



Fig. 2.2 Droplets of water intercepted by tree leaf (photo: M. Marzot (FAO)).

Definition 2.6. Percolation is the downward movement of water through soil and rock.

Percolation occurs beneath the root zone. Ground water percolates through the soil much as water fills a sponge, and moves from space to space along fractures in rock, through sand and gravel, or through channels in formations such as cavernous limestone. The terms infiltration and percolation are often used interchangeably.

Soil Moisture Storage (ST). Soil moisture storage refers to the amount of water held in the soil at any particular time. The amount of water in the soil depends soil properties like soil texture and organic matter content. The maximum amount of water the soil can hold is called the field capacity. Fine grain soils have large field capacities than coarse grain soils. Thus, more water is available for actual evapotranspiration than fine soils than coarse (sandy), soils. Soil moisture storage falls between 0 and the field capacity.

Change in Soil Moisture Storage (DST). The change in soil moisture storage is the amount of water that is being added to or removed from what is stored. The change in soil moisture storage falls between 0 and the field capacity.

2.5 Runoff

Definition 2.7. Runoff is the movement of water, usually from precipitation, across the earth's surface towards stream channels, lakes, oceans, or depressions or low points on the earth's surface.

The characteristics that affect the rate of runoff include rainfall duration and intensity as well as the ground's slope, soil type and ground cover.

Precipitation may fall directly to the surface or be intercepted by plants, ultimately reaching the ground. Once on the ground, water can infiltrate into the soil or move across the surface as runoff. Surface runoff generally occurs when the rainfall intensity exceeds the rate of infiltration, or if the soil is at its water holding capacity. Infiltration and water holding capacity are both a function of soil texture and structure. Soils composed of high percentages of sand allow water to infiltrate through them quite rapidly because they have large, well-connected pore spaces. Clay soils have low infiltration rates due to their smaller sized pore spaces. However, there is actually a smaller total amount of pore space in a unit volume of coarse, sandy soil than that of soil composed mostly of clay. As a result, sandy soils fill rapidly and generally generate runoff sooner than clay soils.

If the rainfall intensity exceeds the infiltration capacity of the soil, or if the soil has reached its field capacity, surface runoff occurs. Water runs across the surface as either confined or unconfined flow. Unconfined flow moves across the surface in broad sheets of water often creating sheet erosion. Confined flow refers to water confined to channels. Stream flow is a form of confined flow.

Water that runs along the surface may become trapped in depressions and held as depression storage. Here water may either evaporate back into the air, infiltrate into the ground or, spill out of the depression as it fills.

Stream flow is measured in a variety of ways, one of which is stream discharge. Stream discharge is the volume of water passing through a particular cross-section of a stream in a unit of time. Stream discharge is measure in cubic feet per second or cubic meters per second. The "normal" or base flow a stream is provided by seepage of groundwater into the stream channel. This seepage is what keeps perennial flowing streams going all year. When precipitation from a storm occurs, the stream discharge increases as water is added to the stream, either from direct precipitation into the channel or runoff.

Runoff is the movement of landwater to the oceans, chiefly in the form of rivers, lakes, and streams. Runoff consists of precipitation that neither evaporates, transpires nor penetrates the surface to become groundwater. Even the smallest streams are connected to larger rivers that carry billions of gallons of water into oceans worldwide. Excess runoff can lead to flooding, which occurs when there is too much precipitation.

2.6 Transport

Definition 2.8. Transport is the movement of water through the atmosphere, specifically from over the oceans to over land.

Some of the earth's moisture transport is visible as clouds, which themselves consist of ice crystals and/or tiny water droplets. Clouds are propelled from one place to another by either the jet stream, surface-based circulations like land and sea breezes, or other mechanisms. However, a typical 1 kilometer thick cloud contains only enough water for a millimeter of rainfall, whereas the amount of moisture in the atmosphere is usually 10-50 times greater.

Most water is transported in the form of water vapor, which is actually the third most abundant gas in the atmosphere. Water vapor may be invisible to us, but not to satellites, which are capable of collecting data about the moisture content of the atmosphere. From this data, visualizations like this water vapor image are generated, providing a visual picture of moisture transport in the atmosphere.

