Subject	Geology
Paper No and Title	**Hydrogeology and Engineering Geology**
Module No and Title	Introduction to Hydrology and Hydrogeology
Module Tag	HG & EG I

Principal Investigator	Co-Principal Investigator	Co-Principal Investigator
Prof. Talat Ahmad ***Vice-Chancellor*** Jamia Millia Islamia Delhi	**Prof. Devesh K Sinha** Department of Geology University of Delhi Delhi	**Prof. P. P. Chakraborty** Department of Geology University of Delhi Delhi
Paper Coordinator	**Content Writer**	**Reviewer**
Dr. Shashank Shekhar Department of Geology University of Delhi Delhi	**Dr. Tajdarul Hassan Syed** Department of Applied Geology, IIT, Dhanbad	**Dr. D. C. Singhal** Emeritus Professor Department of Hydrology, IIT, Roorkee

Table of Content

1. Learning Outcomes
2. Water
3. The Hydrologic Cycle
4. Elements of the Hydrologic Cycle
    3.1 Evaporation
    3.2 Transpiration
    3.3 Precipitation
    3.4 Runoff
5. The Hydrologic Budget Equation

1. Water

Water is certainly the most important molecule on the planet Earth, even though it is not the most common. Water exists in three phases, i.e., liquid, solid, and vapor. Each of these phases makes significant contribution to the way our Earth behaves. Life on Earth is hypothesized to have started in water and it continues to flourish because of it. Approximately, 60% of all animal tissue and 90% of plant tissue is made up of water. Water vapor is also the most abundant and important greenhouse gas in the atmosphere. In the absence of water vapor, Earth's average surface temperature would be significantly lower than its current value of about 300K. The continuous cycling of water between land, atmosphere and ocean sustains the flow of water over land and also determines the evolution of landscapes. Further, the ability of water to store large amounts of energy, in the form of latent heat or because of its high thermal capacity, also capacitates moving water vapor to transport large quantities of energy around the globe. The presence of frozen water on land as snow/ice also has a major impact on the energy balance of the Earth. Frozen water or ice has the highest albedo amongst all natural objects and hence it has the ability to reflect incoming solar insolation back to space, which would have been otherwise absorbed by the land surface causing increase in land surface temperature.

Hydrology is study of water in the broadest sense. It encompasses the occurrence, distribution and circulation of water, its physical and chemical properties and its relation to living things. All natural occurring subsurface materials possess some ability to hold water. The water holding capacity of subsurface materials is defined by its porosity. These porous spaces are filled by either water or air. Near the surface, the pore spaces are filled by air and water, but with depth these pores spaces become progressively saturated with respect to water. The water present in the unsaturated portion of the subsurface is known as **soil moisture** and those in the saturated portions of the subsurface is known as **groundwater**. **Hydrogeology** is the study of groundwater in terms of its quality, quantity and movement. Although used loosely as a term synonymous with hydrogeology, **Geohydrology** is more precisely an engineering field of study involving subsurface fluid flow.

Water exists in three phases: liquid, solid, and vapor. On the phase diagram (Figure 1), the point at which vapor, solid, and liquid all exist in equilibrium is called the **triple point** of water (T = 273.16 °K or 0.01 °C and P = 611.21 Pa or 4.58 torr). The maximum density of liquid water is near 4°C, not the freezing point. Therefore, water expands upon freezing, and ice floats on water. This is also known as the anomalous behavior of water.

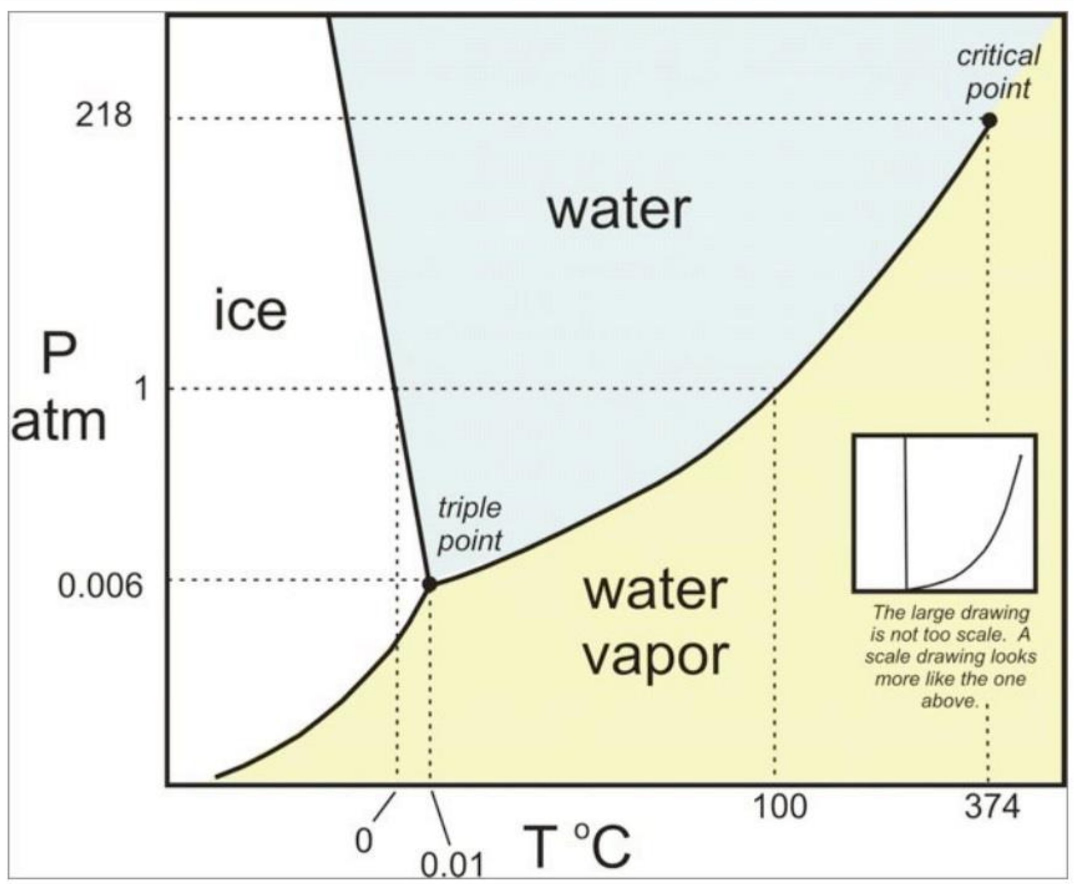

Fig. 1 Phase diagram of water.

As water changes its physical phase (e.g., from liquid to vapor or from liquid to solid), heat is either absorbed or released. The heat associated with a phase change of a substance is called the **latent heat**. The latent heat values of water during phase changes are tabulated in Table 1.

Table 1: Latent heat values of Water.

Temperature	Vaporization/ Condensation	Freezing/ Melting	Sublimation/ Deposition
0°C	2.5×10^{6} J/Kg	3.34×10^{5} J/Kg	2.83×10^{6} J/Kg
100°C	2.25×10^{6} J/Kg		

Water vapor may serve as a vehicle for transferring heat from the point of evaporation to the point of condensation. For example, when water in the tropics is evaporated by intense solar radiation it uses about $2.4\text{x}10^{6}$ J per kilogram of water evaporated. The water vapor may then move toward the mid-latitudes and be re-condensed to liquid in the form of cloud. The condensation process releases $2.4\text{x}10^{6}$ J of sensible heat per kilogram of water condensed.

2. The Hydrologic Cycle

The continuous movement of water between the Earth's biosphere, atmosphere, lithosphere, and hydrosphere is called the hydrologic cycle. Water on the Earth is stored in various reservoirs including atmosphere, oceans, lakes, rivers, soils, vegetation, swamps, glaciers, snowfields, and groundwater. This water is continuously transferred from one reservoir to another through processes like evaporation, transpiration, condensation, precipitation, runoff, infiltration, groundwater flow, sublimation, and melting (Figure 2).

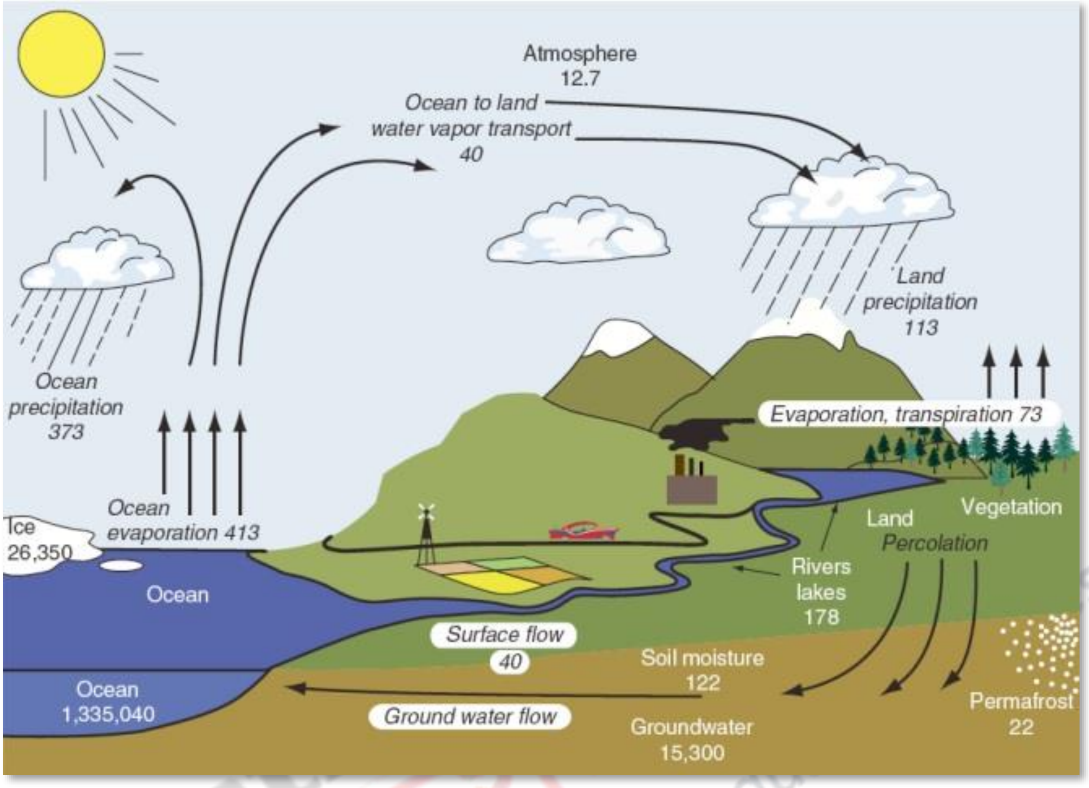

Fig. 2 The global annual average hydrological cycle including estimates of the main water reservoirs (in plain font in units of 103 km3) and of the flow of moisture between stores (in italics in units of 10^3 km^3 yr^{-1} (From Trenberth et al., 2007).

Distribution of Water

The Earth's hydrosphere contains a tremendous amount of water (~ 1.4 billion km^3). However, about 97% of this amount is saline water, and only about 3% is fresh water (Table 2). Within this 3% freshwater, the vast majority of it is in the form of ice and permanent snow cover (69%) or groundwater (30%). Only 0.3% of the total amount of fresh water on the Earth's hydrosphere is stored in lakes, reservoirs and river systems where it can be easily accessed for our daily life. The water present in the atmosphere is very small indeed, only about 0.001%. However, the water exchanged between the stores of atmosphere and the land and ocean, through precipitation or rainfall, is comparatively large, about 113 km^3/yr. and ~370 km^3/yr. respectively. Consequently, there is rapid turnover water in the atmosphere and hence the residence time of water in the atmosphere is low.

Table 2: Estimated sizes of the main water reservoirs in the Earth system, the approximate percentage of water stored in them and turnover time of each reservoir (Source: Gleick, 1996).

Natural Storages of water	Volume (10^6 km^3)	Percent of total water	Percent of freshwater	Approximate residence times
Oceans (including saline inland seas)	~1340	~96.5		1000 - 10000 years
Polar Ice, glaciers & permanent	~24	1.8	68.7	10 - 1000 years
Groundwater	~23	1.7	30.1	15 days - 10000 years
Lakes, swamps, marshes	0.19	0.014	0.29	~10 years
Soil moisture	~0.017	0.001	0.05	~50 days
Atmosphere	~0.013	-0.001	0.04	~10 days
Rivers	~0.002	-0.0002	0.006	~15 days
Biological water	-0.0011	-0.0001	0.003	~10 days

Water is continually cycled between its various reservoirs. Table 2 summarizes the approximate residence times of water in the major reservoirs. The residence time of water in the atmosphere and in rivers is fairly short (e.g., days to weeks), whereas the residence time for water in large lakes, glaciers, ocean bodies and groundwater are much longer, typically in the range of tens to thousands of years (Table 2).

3. Elements of the Hydrologic Cycle

3.1 Evaporation

Evaporation is the process by which liquid water is converted to its gaseous form. This process requires large amounts of energy, e.g., $2.4x10^6$J ($5.7x10^5$ calories) of heat energy is required to convert 1 kilogram of liquid water to the vapor phase. At any given temperature, the air can only hold a certain amount of moisture, which is referred to as the **saturation humidity**. The saturation humidity increases exponentially with increase in air temperature (Figure 3). This relationship is popularly known as Clausius-Clayperon relationship. The **relative humidity** (expressed as %) is the ratio of the measured humidity (gm$_{water}$/m$^{3}_{air}$) to the saturation humidity. Evaporation ceases when 100% relative humidity is reached.

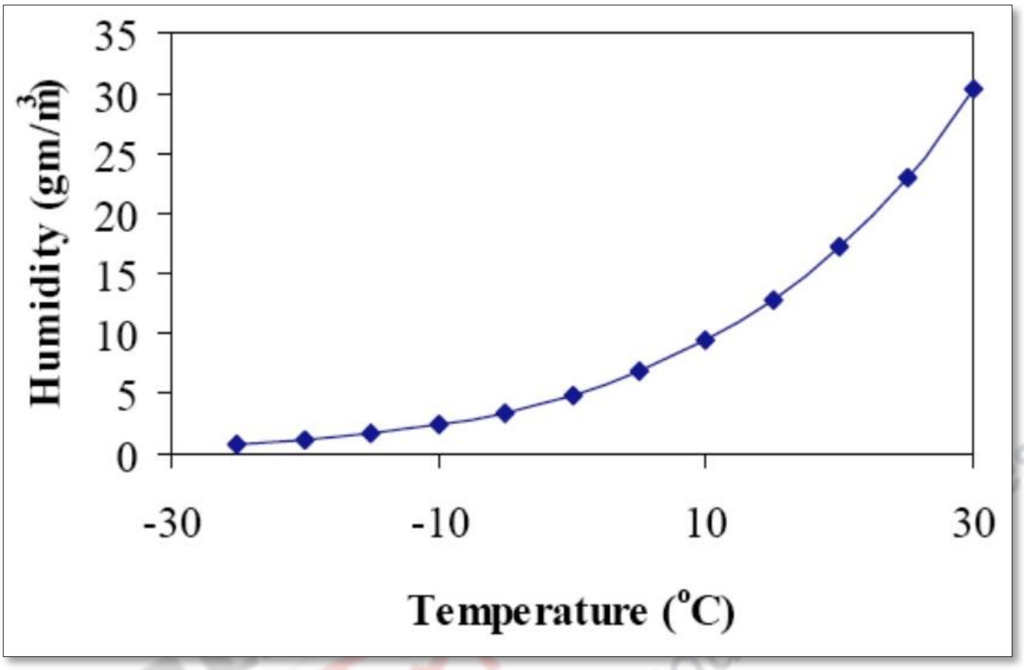

Fig. 3 Variation of saturation humidity of air at various temperatures.

While incoming solar radiation provides the energy required for the transformation from liquid to gaseous state, wind drives evaporation by maintaining the vapor pressure deficit between the water surface and the overlying air. Wind removes water vapor from the water surface, thus keeping the absolute humidity low above the water surface. By keeping the absolute humidity low, the driving force for evaporation remains strong.

Evaporation is measured using a **land pan**. Land pans are 4 feet in diameter and 10 inches deep, and are made of unpainted galvanized metal. Wind speed and precipitation are simultaneously gathered at the land pan site to determine pan evaporation rates. Due to differences in the depth of water in a pan versus a water body, the pan may gain or lose heat differently than a water body; a pan coefficient is used to account for this discrepancy.

3.2 Transpiration

Plants extract water from the ground and transfer it to the atmosphere through a process called transpiration. Transpiration increases with size and density of vegetation, but is also controlled by incoming solar radiation (transpiration is only important during the growing season) and available soil moisture. When the soil moisture drops to level, at which even the plants cannot extract moisture it is said to have reached its **wilting point**.

The combined loss of water to the atmosphere via the processes of evaporation from free water or soil moisture and transpiration (total water loss) is called **evapotranspiration**. Hence, evapotranspiration is the collective term used to group a set of processes, which lead to the transfer of water from the land or ocean surface into the atmosphere. The term **potential evapotranspiration** is used to quantify the upper limit of evapotranspiration under a given set of meteorological conditions with continuous availability of soil water. Therefore, at no point of time evapotranspiration ceases due to non-availability of water. In reality, the process of evaporation or transpiration is limited by the availability of soil moisture. Hence, the term **actual evapotranspiration** is used to define the amount of water lost under normal field conditions, which is always less than that of potential evapotranspiration.

Evapotranspiration includes:

a) Evaporation from open water bodies (ocean, lakes, rivers, and ponds).
b) Evaporation from bare soil.
c) Transpiration from vegetation (aquatic, terrestrial, riparian).

Evapotranspiration is an important process in the hydrologic cycle that can account for a large proportion of the rainfall received within a region. In semi-arid and arid regions, evapotranspiration potential is high and will lead to a large proportion of water loss from watersheds (equal to or exceeding rainfall).

3.3 Precipitation

As an air mass cools, its saturation humidity decreases, and relative humidity of the air mass increases. If relative humidity exceeds 100% it leads to condensation (precipitation), which occurs usually due to cooling of the air mass. Cooling of the air mass occurs due to increase in altitude, since temperature in the troposphere decreases with altitude. Precipitation depends, among other things, on the condensation of atmospheric moisture. A parcel of air rising will undergo changes in temperature due to the ambient temperature distribution. This will affect the parcel pressure and volume.

For rainfall to occur at significant rates, four processes must occur:

a) Cooling of moist air parcel to dew point.
b) Condensation (phase change).
c) Droplet growth.
d) Importation of water vapor.

The cooling of moist air and condensation typically occurs when a parcel of moist air rises (upliftment) as a result of frontal convergence, orographic uplift or convective uplift. Temperature reductions during the ascent of an air mass lead to condensation. However, the uplift of air parcels due to frontal convergence, orography, or thermal convection does not guarantee precipitation. In order to form clouds, the presence of Cloud Condensation Nuclei (CCN) is absolutely essential. CCN provides the surface on which condensation occurs. The CCN usually comprises of numerous small particles, called *aerosols*, suspended in the atmosphere. Usually, the concentration of aerosols decreases with altitude and in the troposphere, its average concentration is on the order of 10^{12} per cubic meter. While aerosols can originate from natural as well as human activities, on an average natural sources are dominant. Locally, aerosol concentration can be greatly enhanced by industrial activity and agricultural practice, including the burning of agricultural crops and forests. Additional requirements include significant growth in water droplet size so that it is large enough to have a terminal velocity such that they fall through the cloud despite upliftment of air and also withstand the effects of evaporation as it fall through the atmosphere.

In estimating water budgets, one needs to determine an effective uniform depth (EUD) of precipitation over the control area. If the rain-gauge network is of uniform density, then a simple arithmetic average of the rainfall data is sufficient to determine the EUD. However, more often than not gauging networks are not uniform and hence require certain adjustments. The most accurate method is to draw a precipitation contour map with lines of equal rainfall (**isohyets**). In drawing isohyets, influences such as the effect of topography on precipitation can be taken into account. The area bounded by adjacent isohyets can be measured using a planimeter, and the average depth of precipitation over the area is the mean of the bounding isohyets. Isohyets follow the same rules as topographic contours, that is, they never split, meet, cross, and so on (Figure 4).

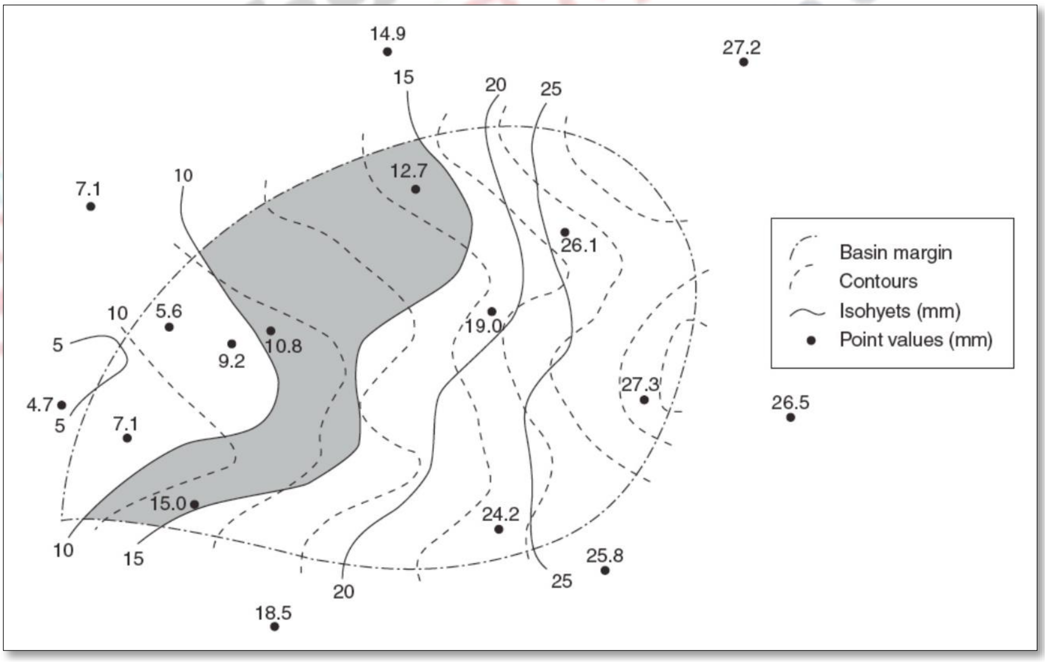

Fig. 4 Calculation of area-average precipitation using the Isohyetal Method (Shuttleworth, 2012).

A simpler method is the Theissen polygon method, which uses a weighting factor for each rain gauge. This factor is based on the area of a polygon, within the drainage basin, that is representative of the area influence of a certain rain gauge. To compute the polygons, the closest stations are joined by lines to form triangles. Then a perpendicular line is then drawn at the midpoint of each line between two stations. These bisectors are then extended to form polygons around each station. The area of each polygon is measured to determine the weighted average for each station (Figure 5).

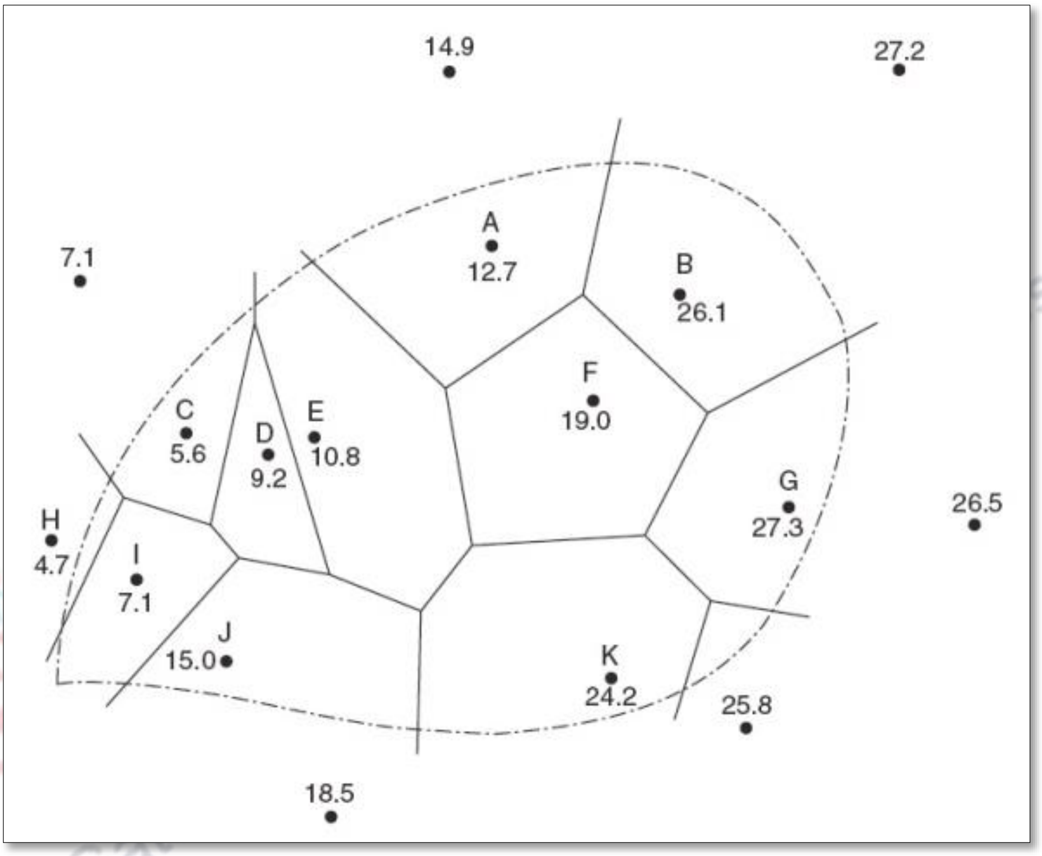

Fig. 5 Calculation of area-average precipitation using the Theissen Polygon Method (Shuttleworth, 2012).

3.4 Runoff

Runoff is the total flow (that includes overland flow, interflow, and baseflow flow) in a stream. The initial response of rainfall over porous surface soil is the downward movement of water into the soil layer, which is termed as **infiltration**. Infiltration into soil varies with soil type and depends on rate of precipitation and on ambient soil moisture. When the precipitation rate exceeds the infiltration rate, some of the precipitated water will drain across the land to a stream channel, and such topographic movement of a thin film of water on land surface is called **overland flow**. While, most of the infiltrated water will percolate more or less vertically through the unsaturated zone, some of the infiltrated water may move horizontally in the unsaturated zone where layers of soil with a low permeability exist beneath the surface. The horizontal movement of water in the unsaturated zone is referred to as **interflow**. Flow of water in the saturated portions of the subsurface, under the influence of gravity as well as hydraulic gradient is known as **groundwater flow**. A part of the groundwater flow discharges into streams as **baseflow**. In other words, baseflow is the groundwater contribution to streamflow. If infiltration into the ground causes groundwater levels to rise then baseflow also increases. The amount of baseflow to a stream is directly proportional to the hydraulic gradient toward the stream (Figure 6).

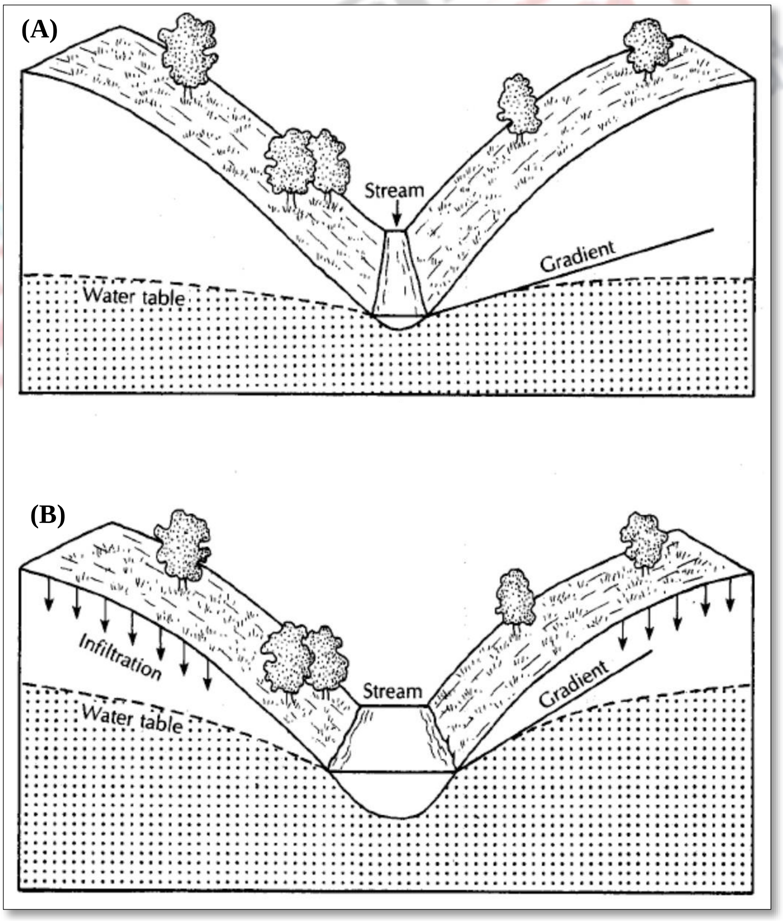

Fig. 6 Groundwater contribution to stream flow is (A) low due to low hydraulic gradient and (B) high due to increased hydraulic gradient. (Source: Fetter, 2007).

During periods of no precipitation, the streamflow represents only contributions from the groundwater and flow from tributaries. As the water table drops due to groundwater extraction, the gradient between the groundwater table and stream decreases and so is the discharge to the stream. Hence, based on the relative height between the bottom of the stream channel and groundwater level, streams gain/lose water from/to the surrounding aquifer. In humid regions, a typical stream receives groundwater discharge and the stream discharge increases as one travels downstream, even if no tributaries occur. This is a **gaining stream**, or an **effluent stream**. For a gaining stream, the hydraulic gradient of the surrounding aquifer is toward the stream (Figure 7A). On the contrary, in arid regions, a typical stream receives water from overland flow, interflow, and baseflow at high elevations. At lower elevations, the bottom of the stream channel is at a higher elevation than the local water table, and as a result, water drains away from the stream into the ground (Figure 7B). Such a stream is called a **losing stream**, or an **influent stream**.

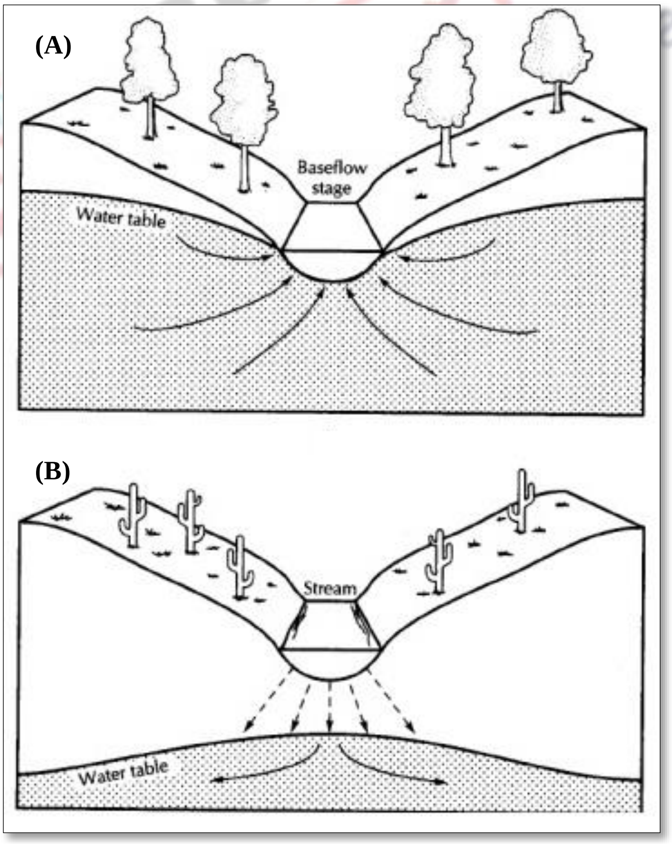

Fig. 7 Cross sections of gaining (A) and loosing stream (B) (Source: Fetter, 2007).

The streamflow or river discharge can be determined by various ways. One of the most common techniques involves the measurement of the velocity of the stream at a series of locations across the width of the stream. Each measurement is made to represent the velocity for a cross-sectional area of the stream extending midway between each measurement. Measuring velocity requires recognition of the fact that water velocity increases to a maximum toward the surface. Studies show that measurements made at 60% of the depth from surface represent the average velocity for the water column. Discharge can also be estimated by measuring the stage or height of the free surface of water in a river or stream with respect to a recognized datum such as the global mean sea level. Discharge is commonly expressed in cubic meters per second (m^3/s or cumec). The discharge at a site is a function of the cross-section area, which is a function of river stage, and flow velocity. The measurement of discharge at a gauging station is both costly and manpower intensive, therefore, usually discharge is not measured. The measurement of river stage is much easier and therefore, observations of river stage are commonly taken. Fortunately, there exists a relation between river stage and discharge at a cross-section and this relation is known as **rating curve** or **stage-discharge curve**. A rating curve is developed by using the concurrent data of stage and discharge observed over a lengthy period of time. It is important that the data covers the range of stages that are likely to occur at the gauging station. Hence, streamflow measurement normally involves: 1) obtaining a continuous record of river stage (water level) above a datum, 2) establishing the relationship between stage and discharge and 3) transforming the record of stage into a record of discharge.

4. The Hydrologic Budget Equation

A hydrologic budget is based on the principle of conservation of water mass within a control volume, which can vary from small watersheds to the earth as a whole, and is valid for time intervals ranging from instantaneous to decadal scales. In general, a hydrologic budget equation is expressed as follows:

Change in Storage (with respect to time) = Inflow - Outflow (1)

A control volume is a selected region over which the components of inflow and outflow are computed. A watershed is a natural hydrologic unit, typically selected as a control volume, which is separated from other watersheds by a divide. The watershed surface has three-dimensional topography drained by a stream network.

Since the control volume can vary significantly in size and location, the respective inflows and outflows will vary accordingly. For example, precipitation is considered as a dominant inflow when the control volume is a watershed. However, in the case of a groundwater aquifer, precipitation cannot be considered as a direct inflow in to the system. Therefore, depending on the control volume, the inflows and outflows may vary among the following fluxes:

Sources of inflow:	**Sources of outflow:**
Precipitation	Evapotranspiration
Overland flow	Evaporation of surface water
Surface water inflow	Surface water outflow
Groundwater inflow	Groundwater outflow
Anthropogenic inputs (e.g. pipes)	Anthropogenic outputs

When a system is at a **steady state**, the inflow equals the outflow, and hence the accumulation is zero. A steady state does not refer to the condition when the flows have stopped. When a system is in a **transient** state, the difference between inflow and outflow leads to accumulation or depletion, which is represented as positive or negative changes in storage.

Changes in **storage** due to positive or negative accumulation occur as changes in the mass of water in the following components of land water storage:

Surface water
Soil moisture
Ice and snow
Plant moisture
Groundwater

While the hydrologic budget equation determines the amount of change in storage, it does not identify the component in which the change has taken place. Hence, equation (1) only provides a column integrated estimated of storage change. It is important to note that, the dominant components of land water storage are primarily dependent on the subsurface geology and the climate of the concerned area. For example, in high latitude river basins snow and ice may be the most dominant component influencing changes in total storage. Whereas, storage change in tropical river basins may be primarily attributed to changes in groundwater and soil moisture.

So in total: **Inputs** (precipitation, surface water inflow, groundwater inflow, injection) - **Outputs** (evapotranspiration, surface water outflow, groundwater outflow, pumping) = **Accumulation** (changes in storage in surface water, soil moisture, ice, snow, plant moisture, and groundwater).

Hence, on a basin-wide scale one can determine the amount of recharge to the groundwater aquifer using the hydrologic budget equation for the aquifer. If all the groundwater inflows, outflows, and storage processes are understood, then one could balance all these known estimates to calculate the amount of recharge. However, it is important to note that the practical applications of the hydrologic budget equation often involve certain assumption. For example, groundwater inflows and outflows along the boundary of a watershed are extremely difficult to quantify, hence it is best to ignore them for practical purposes. It is also important to compare the magnitudes of fluxes on the right hand side of equation (1). Inflows and/or outflows significantly smaller in magnitude can also be ignored on the basis that they make insignificant contribution to the magnitude of storage change.

As an example, the hydrologic budget for the surface and groundwater system of an open system (Figure 8) can be expressed as follows:

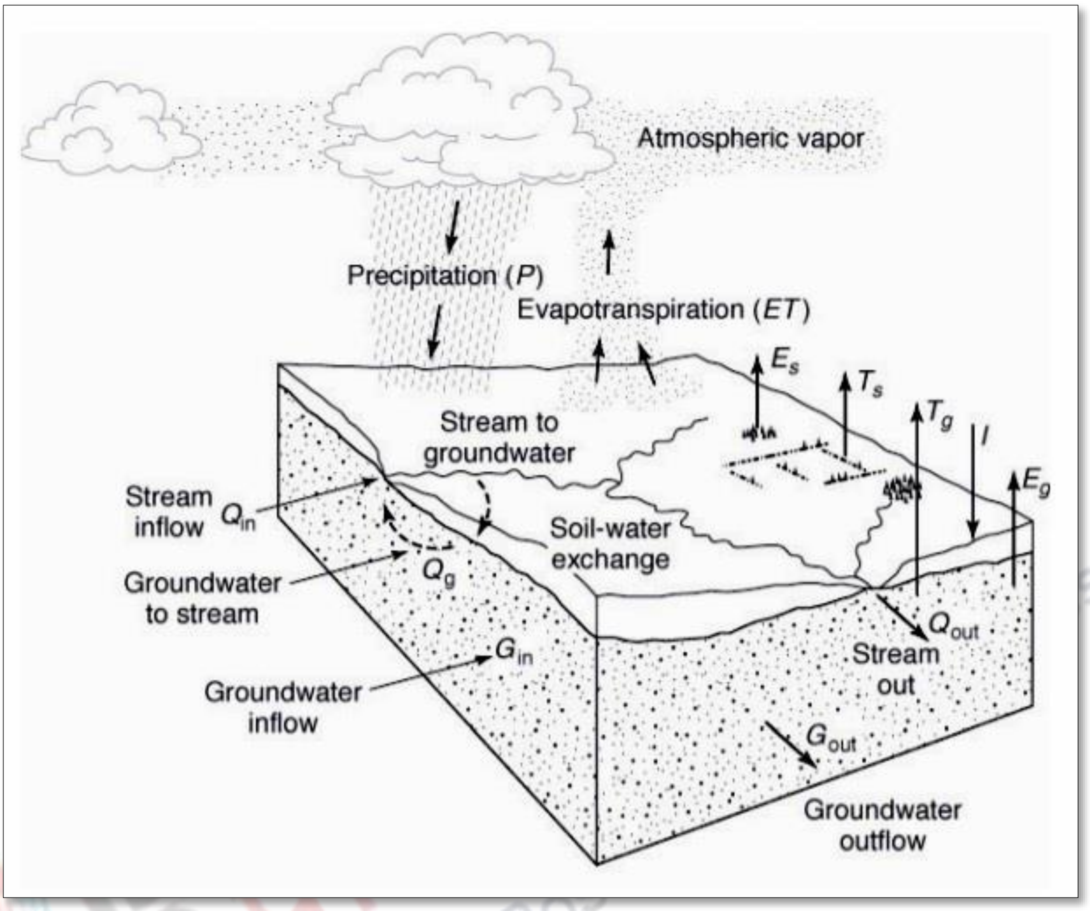

Fig. 8 Components of hydrologic budget in an open system (Source: Todd and Mays, 2011).

Surface water system:

$$P + Q_{in} - Q_{out} + Q_g + E_s - T_s - I = \Delta S_s \qquad (2)$$

Groundwater system:

$$I + G_{in} - G_{out} - Q_g - E_g - T_g = \Delta S_g \qquad (3)$$

Total system:

$$P - (Q_{out} - Q_{in}) - (E_s + E_g) - (T_s + T_g) - (G_{out} - G_{in}) = \Delta(S_s + S_g) \qquad (4)$$

Simplifying the above result using net mass exchanges, the hydrologic budget is given as:

$$P - Q - G - ET = \Delta S \qquad (5)$$

where P is precipitation, Q is surface runoff, G is subsurface runoff, ET is evapotranspiration, and S is storage in the control volume. Closing a water budget entails measurements or estimates of all the components, which seems like a simple task. However, large uncertainties still exist in many water balance computations owing to the following:

- **a)** Defining control volume boundaries.
- **b)** Estimating fluxes at boundaries over time and space.
- **c)** Knowledge of system storage capacity.
- **d)** Internal redistribution within control volume.

Frequently Asked Questions-

Q1. Why are pan measurements multiplied with a factor (pan coefficient)?

Ans. Pan evaporation estimates are multiplied by some factor less than one, in order to compensate for the fact that water evaporates faster from pans than from natural water bodies.

Q2. Why uplift of air is required for precipitation?

Ans. Since the saturation humidity decreases with decrease in temperature, moist air will start condensing as it moves up in the atmosphere.

Q3. What is a watershed?

Ans. An area that topographically appears to contribute all the water that passes through a given cross section of a stream. More simply, an area of land, which drains to a common point.

Q4. What is the source of subsurface water?

Ans. Almost all the water found within the subsurface material of the earth originates on the surface and is subsequently transferred to the subsurface.

Q5. What is vapor pressure?

Ans. In the atmosphere, water vapor is always present in varying proportions. The water vapor in the air exerts a partial pressure independent of the presence of other gases. This pressure exerted by the water vapor is called the vapor pressure and is the most useful measure of the water content of the atmosphere.

Q6. Why does temperature decrease with height in the atmosphere?

Ans. The amount of water vapor that air can hold before becoming saturated is less at lower temperatures and hence water is precipitated out as water droplets or ice particles in clouds. The very fact that water vapor content falls quickly with height is strongly related to the fall in temperature with height.

Q7. What is meant by anomalous behavior of water?

Ans. Water exhibits anomalous behavior when its temperature increases from 0°C to 4°C (it contracts) and when its temperature is decreased from 4°C to 0°C (it expands). However, in most liquids density increase with decrease in temperature of a liquid. But, as water goes below 4°C, there is a phase transition, which reduces the average density of water. Since, other liquids do not show this property hence the term anomalous.

Multiple Choice Questions-

1. Warming produced by greenhouses gases are due to trapping of

(a) Ultraviolet radiation
(b) Solar radiation
(c) Terrestrial radiation

2. The global average of precipitation over the ocean is

(a) Greater than evaporation from ocean
(b) Lesser than evaporation from ocean
(c) Equal to evaporation from ocean

3. Increase in temperature of moist air will lead to

(a) More precipitation
(b) No precipitation
(c) None of the above

4. Under a steady state assumption, precipitation minus evapotranspiration in a watershed is

(a) Equal to runoff
(b) Equal to zero
(c) Greater than runoff

5. Downdraft of air will never lead to condensation because

(a) Saturation humidity decreases
(b) Saturation humidity increases
(c) Saturation humidity remains the same

6. Wind blowing over a free surface of water leads to

(a) Increased evaporation rate
(b) Decreased evaporation rate
(c) Does not affect evaporation rate

Suggested Readings:

1. Fetter, C. W., (2001). Applied Hydrogeology, 4th Edn., Prentice-Hall Inc. (Pearson), New Jersey, USA.
2. Gleick, P. H., (1996). Water resources. In Encyclopedia of Climate and Weather, Ed. by S. H. Schneider, Oxford University Press, New York, Vol. 2, pp.817-823.
3. Shuttleworth, James W. (2012), Terrestrial Hydrometeorology, 1st Edn., Wiley-Blackwell Publications, USA.
4. Todd, David Keith and Mays, Larry W., (2011), Groundwater Hydrology, 3rd Edn., Wiley India Pvt. Ltd., New Delhi.
5. Trenberth, K. E., Smith, L., Qian, T., Dai, A., & Fasullo, J. (2007). Estimates of the global water budget and its annual cycle using observational and model data. Journal of Hydrometeorology, 8(4), 758-769.