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LECTURE NOTE
ON

HYDROLOGIC CYCLE AND WATER BALANCE

By

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HYDROLOGIC CYCLE AND WATER BALANCE

INTRODUCTION

The Hydrologic Cycle is a fundamental concept in hydrology and is amongst a number of cycles known to be operating in nature, such as the carbon cycle, the nitrogen cycle, and other biogeochemical cycles. The National Research Council (NRC, 1982) defines the hydrologic cycle as "the pathway of water as it moves in its various phases to the atmosphere, to the earth, over and through the land, to the ocean and back to the atmosphere". This cycle has no beginning or end and water is present in all the three states, viz., solid, liquid, and gas, in the cycle. A pictorial representation of the hydrological cycle is given in Fig. 1.

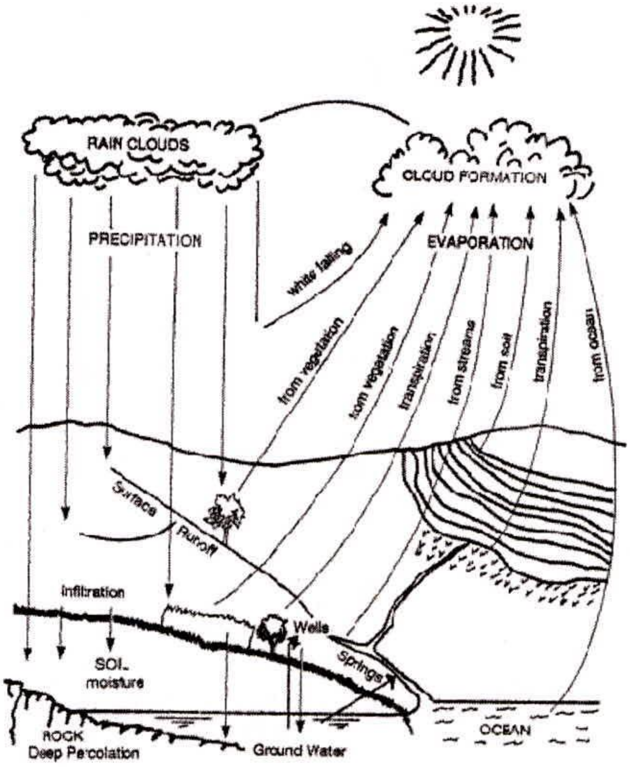

Fig. 1 Pictorial representation of the hydrological cycle (Source: Singh, 1992).

The hydrologic cycle, also known as the water cycle, is a concept which considers the processes of motion, loss, and recharge of the earth's waters. It connects the atmosphere and two storages of the earth system: the oceans, and the landshpere (lithosphere and pedosphere). The water that is evaporated from the earth and the oceans enters the atmosphere. Water leaves the atmosphere through precipitation. The oceans receive water from the atmosphere by means of precipitation and from the landsphere through streamflow and ground water flow. The only way that water goes out of oceans is through evaporation. The landsphere receives water through precipitation. The water leaves this sphere through evaporation, transpiration, evapotranspiration, streamflow, ground water flow. Evaporation and precipitation are the processes that take place in the vertical plane while streamflow and ground water flow occur mostly in the horizontal plane.

The exchange of water among the oceans, land, and the atmosphere has been termed as 'the turnover' by Shikhlomanov (1999). This turnover affects the global patterns of the movement of ocean waters and gases in the atmosphere, thereby greatly influencing climate. Besides, water is a very good solvent and hence geochemistry is an integral part of the hydrologic cycle. The hydrologic cycle is, thus, the integrating process for the fluxes of water, energy, and the chemical elements (NRC, 1991). Usually, rain and snow are considered as the purest form of water although these may also be mixed with pollutants that are present in the atmosphere. During the journey on earth, many chemical compounds are mixed with water and consequently the water quality undergoes a change.

The hydrologic cycle can also be visualized as a perpetual distillation and pumping system. In this endless circulation of water, the glaciers and snow packs are replenished, the quantity of river water is replenished and its quality restored. From the point of view of utilization of water, the land phase of the hydrologic cycle is the most important. The necessity and utility of the study of the hydrologic cycle arises from the fact that water is essential for survival of life and is an important input in many economic activities. But water of the desired quality may not be available when needed.

In view of the complexities and extensive coverage, the study of the complete hydrologic cycle is truly interdisciplinary. For instance, the atmospheric part is studied by meteorologists, the pedospheric part by soil scientists, the lithosphere part by geologists, and the part pertaining to oceans falls in the domain of oceanographers. The domain of a hydrologist is confined mainly to the land phase and this in itself is a very large domain. A host of other professionals may be interested in the study of hydrologic cycle, including the energy utility managers, chemists, agricultural engineers, public health officers, and inland navigation managers. It is hard to draw lines demarcating various domains in such an interdisciplinary subject and the boundaries are often blurred. Teams of people from various specialties often work together on a problem dealing with the components of the hydrologic cycle.

COMPONENTS OF HYDROLOGIC CYCLE

The hydrologic cycle can be subdivided into three major systems: The oceans being the major reservoir and source of water, the atmosphere functioning as the carrier and deliverer of water and the land as the user of water. The amount of water available at a particular place changes with time because of changes in the supply and delivery. On a global basis, the water movement is a closed system but on a local basis it is an open system. A systems representation of the hydrologic cycle is shown in Fig. 2.

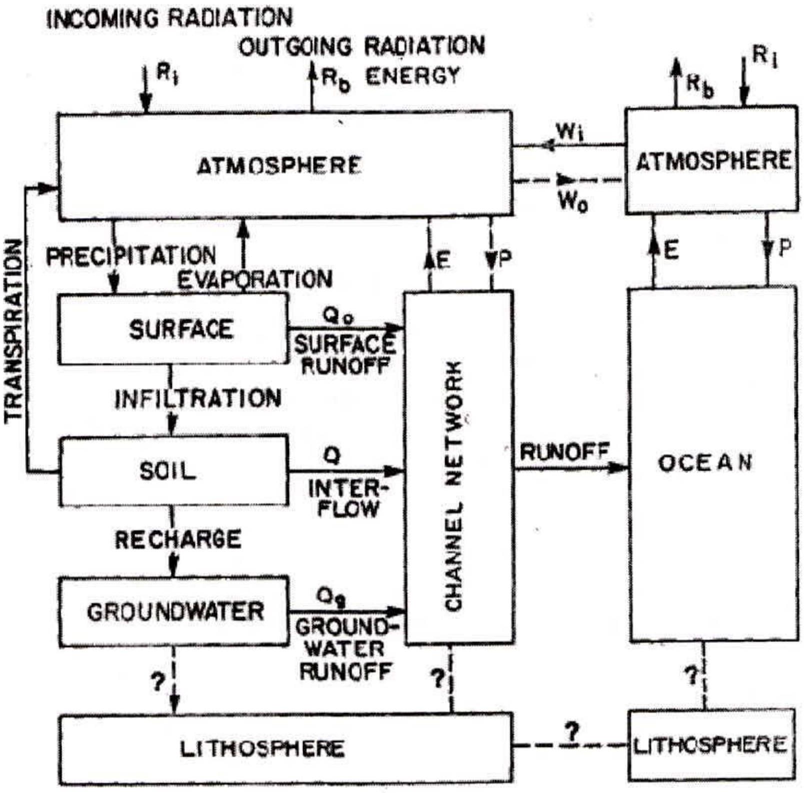

Fig. 2 The Systems Representation of Hydrologic Cycle [after Singh, 1988].

The major components of the hydrologic cycle are precipitation (rainfall, snowfall, hale, sleet, fog, dew, drizzle, etc.), interception, depression storage, evaporation, transpiration, infiltration, percolation, moisture storage in the unsaturated zone, and runoff (surface runoff, interflow, and baseflow).

Evaporation of water takes place from the oceans and the land surface mainly due to solar energy. The moisture moves in the atmosphere in the form of water vapour which precipitates on land surface or oceans in the form of rain, snow, hail, sleet, etc. A part of this precipitation is intercepted by vegetation or buildings. Of the amount reaching the land surface, a part infiltrates into the soil and the remaining water runs off the land surface to join streams. These streams finally discharge into the ocean. Some of the infiltrated water percolates deep to join groundwater and some comes back to the streams or appears on the surface as springs.

This immense movement of water is mainly driven by solar energy: the excess of incoming radiation over the outgoing radiation. Therefore, sun is the prime mover of the hydrologic cycle. The energy for evaporation of water from streams, lakes, ponds and oceans and other open water bodies comes from sun. A substantial quantity of moisture is added to the atmosphere by transpiration of water from vegetation. Living beings also supply water vapor to the atmosphere through perspiration. Gravity has an important role in the movement of water on the earth's surface and anthroprogenic activities also have an increasingly important influence on the water movement.

An interesting feature of the hydrologic cycle is that at some point in each phase, there usually occur: (a) transportation of water, (b) temporary storage, and (c) change of state. For example, in the atmospheric phase, there occurs vapor flow, vapor storage in the atmosphere and condensation or formation of precipitation created by a change from vapor to either the liquid or solid state. Moreover, in the atmosphere, water is present in the vapor form while it is mostly (saline) liquid in the oceans.

SCALES FOR STUDY OF HYDROLOGIC CYCLE

Depending on the purpose of study, the hydrologic cycle is studied at many different spatial scales. Horton (1931) clearly recognized the diversity of scales when he stated: *Any natural, exposed surface may be considered as a unit area on which the hydrologic cycle operates. This includes, for example, an isolated tree, even a single leaf or twig of a growing plant, the roof of a building, the drainage basin of a river system or any of its tributaries, an undrained glacial depression, a swamp, a glacier, a polar ice-cap, a group of sand dunes, a desert playa, a lake, an ocean, or the Earth as a whole* [Quoted in NRC, 1991]. A qualitative representation of hydrologic cycle is given in Fig. 3.

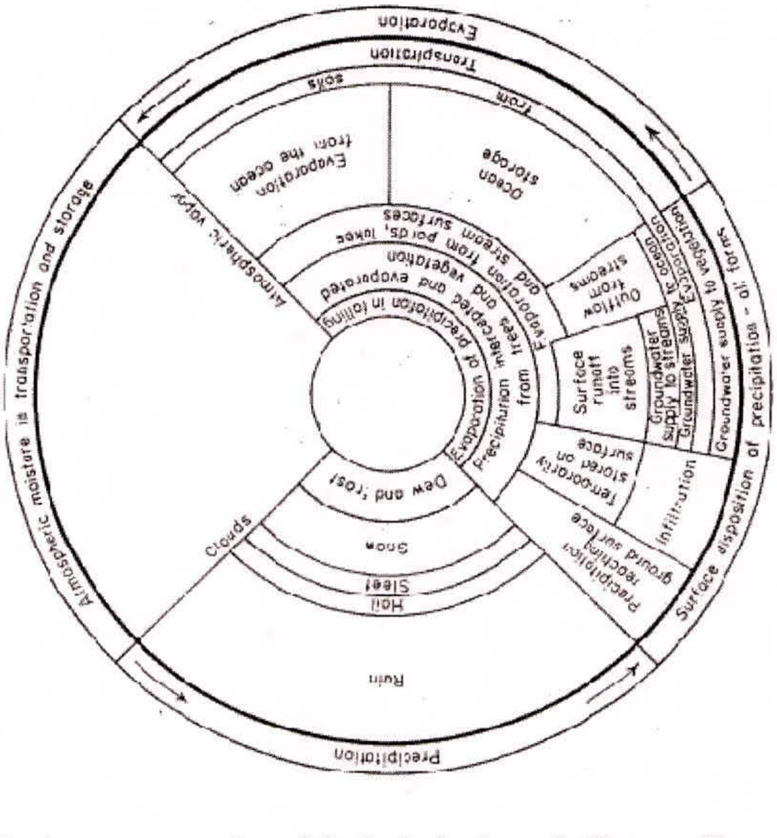

Fig. 3 Qualitative representation of the hydrologic cycle [Source: Horton, 1931].

From the point of view of hydrologic studies, two scales are readily distinct. These are the global scale and the catchment scale.

Global scale

From a global perspective, the hydrologic cycle can be considered to be comprised of three major systems; the oceans, the atmosphere, and the landsphere. Precipitation, runoff and evaporation are the principal processes that transmit water from one system to the other, as illustrated in Fig. 4. This illustration depicts a global geophysical view of the hydrologic cycle and shows the interactions between the earth (lithosphere), the oceans (hydrosphere), and the atmosphere. The study at the global scale is necessary to understand the global fluxes and global circulation patterns. The results of these studies form important inputs to water resources planning for a national, regional water resources assessment, weather forecasting, and study of climate changes. These results may also form the boundary conditions of small-scale models/applications.

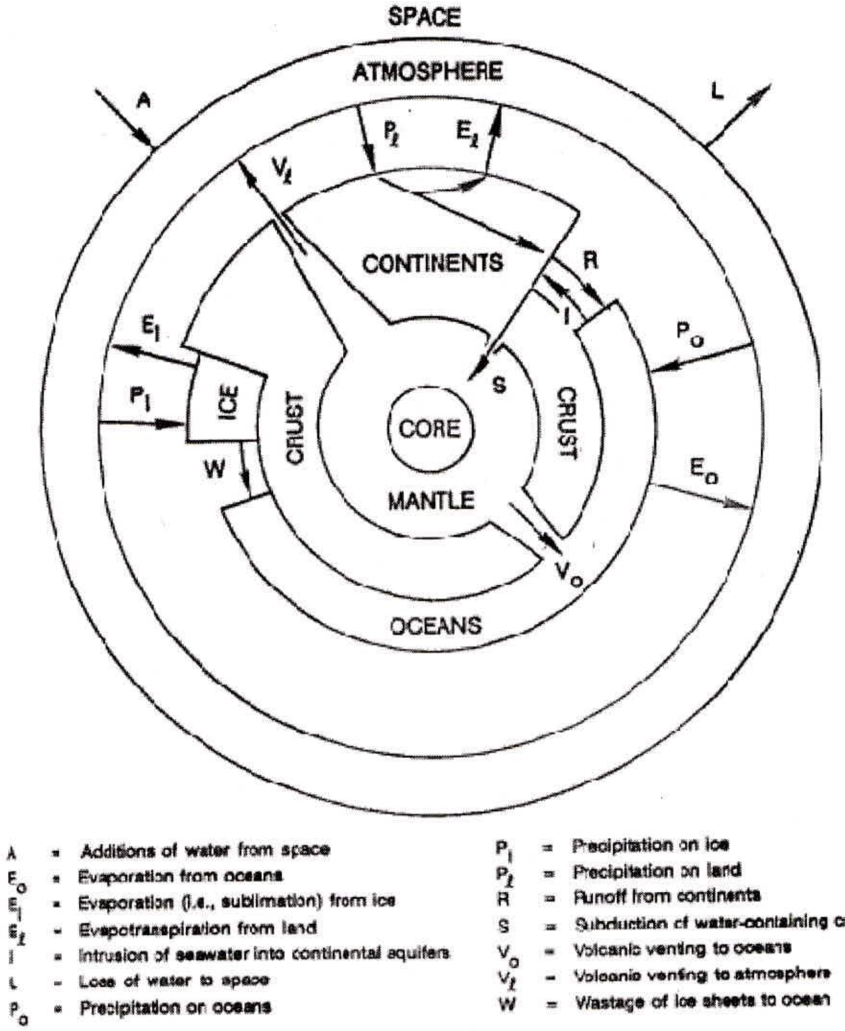

Fig. 4 The hydrologic cycle as a global geophysical process [Source: NRC, 1991].

Catchment Scale

While studying the hydrologic cycle on a catchment scale, the spatial coverage can range from a few square km to thousands of square km. The time scale could be a storm lasting for a few hours to a study spanning many years. When the water movement of the earth system is considered, three systems can be recognized: the land (surface) system, the subsurface system, and the aquifer (or geologic) system. When the attention is focused on the hydrologic cycle of the land system, the dominant processes are precipitation, evapotranspiration, infiltration, and surface runoff. The land system itself comprises of three subsystems: vegetation subsystem, structural subsystem and soil subsystem. These subsystems subtract water from precipitation through interception, depression and detention storage. This water is either lost to the atmospheric system or enters subsurface system. The exchange of water among these subsystems takes place through the processes of infiltration, exfiltration, percolation, and capillary rise.

Fig. 5 shows the schematic of the hydrologic cycle at global scale, in the earth system, and micro-scale view of the cycle in the land system.

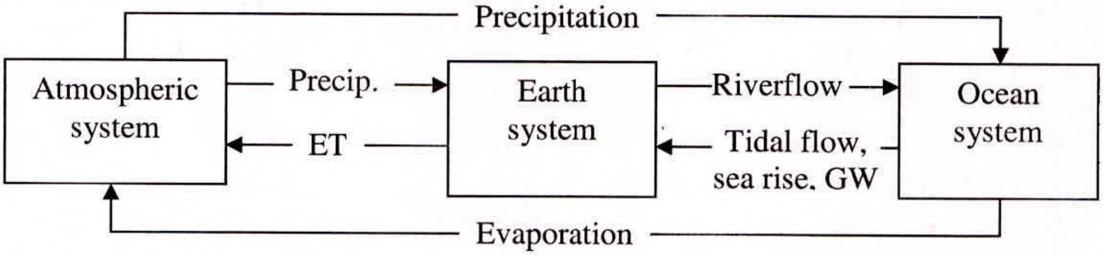

Fig. 5a A global schematic of the hydrologic cycle [Source: Singh (1992)].

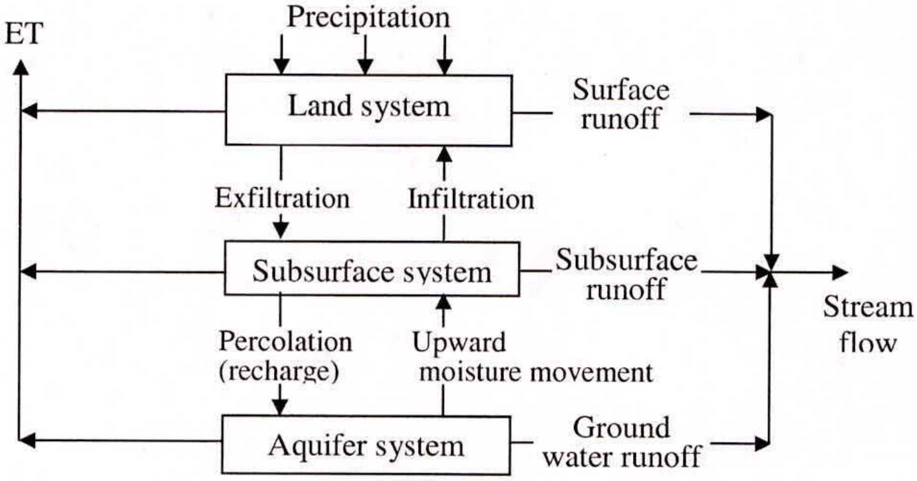

Fig. 5b A schematic of the hydrologic cycle of the earth system [Source: Singh (1992)].

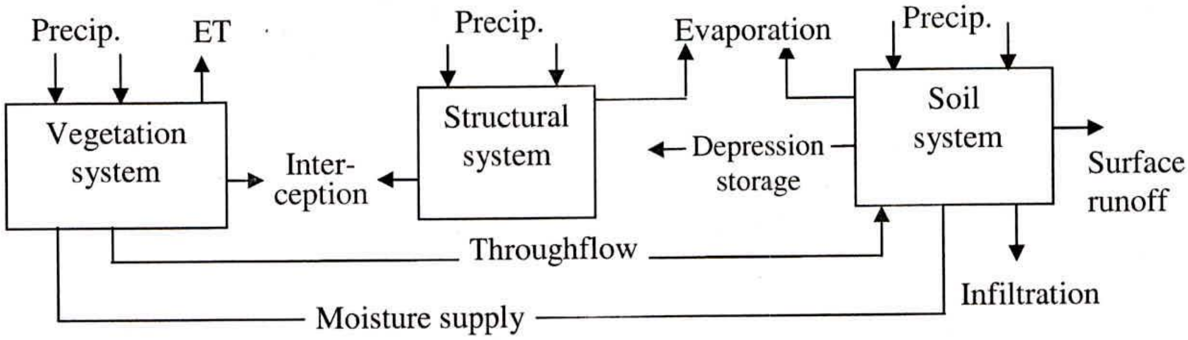

Fig. 5c A detailed schematic of the hydrologic cycle in the land system [Source: Singh (1992)].

Time scales in hydrologic cycle

The time required for the movement of water through various components of the hydrologic cycle varies considerably. The velocity of streamflow is much higher compared to the velocity of ground water. The time-step size for an analysis depends upon the purpose of study, the availability of data, and how detailed the study is. The estimated periods of renewal of water resources in water bodies on the earth is given in Table 1. The time step should be sufficiently small so that the variations in the processes can be captured in sufficient detail but at the same time, it should not put undue burden on data collection and computational efforts.

Table 1. Periods of water resources renewal on the Earth

Water of hydrosphere	**Period of renewal**
World Ocean	2500 years
Ground water	1400 years
Polar ice	9700 years
Mountain glaciers	1600 years
Ground ice of the permafrost zone	10000 years
Lakes	17 years
Bogs	5 years
Soil moisture	1 year
Channel network	16 days
Atmospheric moisture	8 days
Biological water	Several hours

Source: Shiklomanov (1999).

The range of spatial and temporal dimensions of many processes related to the hydrologic cycle is shown in Fig. 6.

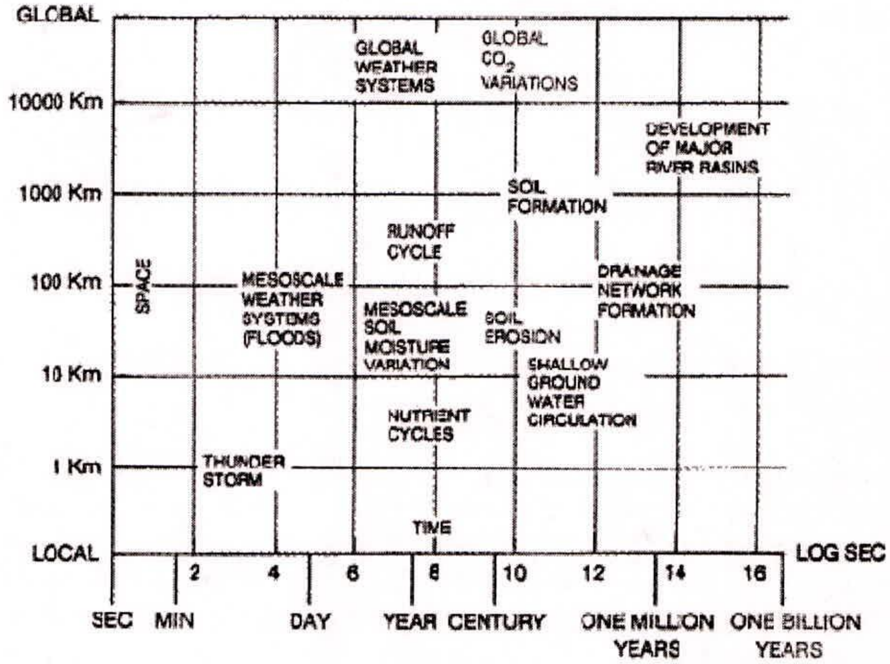

Fig. 6 Illustrative range of process scales [source: NRC, 1991].

WATER BALANCE -- MATHEMATICAL REPRESENTATION OF THE HYDROLOGIC CYCLE

The quantities of water going through the various components of the hydrologic cycle can be evaluated by the so-called hydrologic equation, which is a simple spatially-lumped continuity or water budget equation:

$$I - Q = \Delta S \tag{1}$$

where I = inflow of water to a given area during any given time period, Q = outflow of water from the area during the selected time period, and ΔS = change in storage of water in the given area during the time period. If I and Q vary continuously with time, then equation (1) can be written as

$$d\,S(t)/dt = I(t) - Q(t) \tag{2}$$

By integrating, this equation can also be written as

$$\int dS(t) = \int [I(t) - Q(t)]\, dt$$

or

$$\begin{aligned} S(t) - S(0) &= \int_0^t I(t)dt - \int_0^t Q(t)dt \\ &= V_I(t) - V_O(t) \end{aligned} \tag{3}$$

where S(0) is the initial storage at time t=0, S(t) is the storage at time t, $V_O(t)$ and $V_I(t)$ are volumes of outflow and inflow at time t. Each of the terms of this lumped equation is the result of a number of other terms. These can be sub-divided and even eliminated from the equation depending upon the temporal and spatial scale of the study. The continuity equation is one of the governing equations of almost all hydrologic problems. For a watershed, equation (1) may be written as

$$P + Q_{SI} + Q_{GI} - E - Q_{SO} - Q_{GO} - \Delta S - \varepsilon = 0 \tag{4}$$

where P is precipitation, Q_{SI} is surface inflow, Q_{GI} is ground water inflow, E is evaporation from the watershed, Q_{SO} is surface water outflow, Q_{GO} is ground water outflow, ΔS is change in the storage of water in the watershed, and ε is a discrepancy term. For large watersheds, Q_{GI} and Q_{GO} are usually negligible. The discrepancy term is included in equation (4) because the sum of all other terms may not be zero due to measurement errors and/or simplifying assumptions. However, a small value of discrepancy term does not necessarily means that all other terms have been correctly measured/estimated.

Depending on the specific problem, the terms of equation (1) may be further subdivided. For example, when applying the hydrologic equation for short time intervals, the change in the total water storage (ΔS) may be subdivided into several parts: changes of moisture storage in the soil (ΔM), in aquifers (ΔG), in lakes and reservoirs (ΔL), in river channels (ΔS_C), in glaciers (ΔS_G), and in snow cover (ΔS_S). Thus, ΔS can be expressed as:

$$\Delta S = \Delta M + \Delta G + \Delta L + \Delta S_C + \Delta S_G + \Delta S_S \tag{5}$$

The hydrologic equation may be applied for any time interval; the computation of the mean annual water balance for a basin being the simplest, since it is possible to disregard changes in water storages in the basin (ΔS), which are difficult to measure and compute. In general, the shorter the time interval, the more stringent are the requirements for measurement or computation of the components and the more subdivided are the terms of equation (1). This results in a complex equation which is difficult to close with acceptable errors.

The hydrologic equation may be applied for areas of any size, but the complexity of computation greatly depends on the extent of the area under study. The smaller is the area, the more complicated is its water balance because it is difficult to estimate components of the equation. Finally, the components of the hydrologic equation may be expressed in terms of the mean depth of water (mm), or as a volume of water (m^3), or in the form of flow rates (m^3/s or mm/s).

FORMS OF WATER BALANCE EQUATION

Many forms of the water balance equation are possible by sub-dividing, consolidating, or eliminating some of the terms, depending upon the purpose of computation. Water balance techniques are also a means of solving important theoretical and practical hydrological problems. Water balance approach makes it possible to make a quantitative evaluation of water resources and their change under the influence of man's activities.

The study of the water balance structure of lakes, river basins, and ground-water basins forms a basis for the hydrological substantiation of projects for the rational use, control and redistribution of water resources in time and space (e.g. inter-basin transfers, stream flow control, etc.). Knowledge of the water balance assists the prediction of the consequences of artificial changes in the regime of streams, lakes and ground water basins.

Current information on the water balance of river and lake basins for short time intervals (season, month, week and day) is used for operational management of reservoirs and for the compilation of hydrological forecasts for water management. An understanding of the water balance is also extremely important for studies of the hydrological cycle. With water balance data it is possible to compare individual sources of water in a system, over different periods of time, and to establish the degree of their effect on variations in the water regime. Further, the initial analysis used to compute individual water balance components, and the co-ordination of these components in the balance equation makes it possible to identify deficiencies in the distribution of observational stations, and to discover systematic errors of measurements.

Finally, water balance studies provide an indirect evaluation of an unknown water balance component from the difference between the known components (e.g. long-term evaporation from a river basin may be computed by the difference between precipitation and runoff).

GENERAL FORM OF THE WATER BALANCE EQUATION

In hydrology, the study of the water balance is the application of the principle of conservation of mass, often referred to as the continuity equation. According to this equation, for any arbitrary volume and during any period of time, the difference between total input and output will be balanced by the change of water storage within the volume. In general use of a water-balance technique implies measurement of both storage and fluxes (rates of flow) of water. By judicious selection of the volume and period of time for which the balance will be applied, some measurements can be eliminated.

Other Forms of the Water Balance Equation

The water balance equation (1) may be simplified or made more complex depending upon several factors. These are the available data, the purpose of computations, the type and size of water body (river basin or artificially separated administrative district, lake or reservoir, etc.), and its hydrographic and hydrologic features. The duration of water balance time interval and the phase of the hydrological regime (flood, low flow) for which the water balance is computed are also important considerations.

In large river basins, Q_{GI} and Q_{GO} are small compared with other terms and can be ignored. In other words, sub-surface water exchange with neighbouring basins is assumed to be zero. There is no surface water inflow into a river basin with a distinct watershed divide (assuming no artificial diversions from other basins), and therefore Q_{SI} is not included in the water balance equation of a river basin. Thus, for a river basin equation (1) is usually simplified as:

$$P - E - Q_{SO} - \Delta S - \eta = 0 \quad (2)$$

Depending on the specific problem, the terms of equation (1) may be further subdivided. For example, in the compilation of water balances for short time intervals, the change in the total water storage (ΔS) in a small river basin may be subdivided into several parts. These could typically be changes of moisture storage in the soil (ΔM), in aquifers (ΔG), in lakes and reservoirs (ΔL), in river channels (ΔS_C), in glaciers (ΔS_G), and in snow cover (ΔS_S). Thus, ΔS can be expressed as:

$$\Delta S = \Delta M + \Delta G + \Delta L + \Delta S_C + \Delta S_G + \Delta S_S \quad (3)$$

Special features of the water balance equation for different time intervals

The Water balance may be computed for any time interval, but distinction may be made between mean water balances and balances for specific periods (such as a year, season, month or number of days), sometimes called current or operational water balances. Water balance computations for mean values and specific periods each have distinctive characteristics. Mean water balances are usually computed for an annual cycle (calendar year or hydrological year), although they may be computed for any season or month.

The computation of the mean annual water balance is the most simple problem, since it is possible to disregard changes in water storages in the basin (ΔS), which are difficult to measure and compute. Over a long period, positive and negative water storage variations for individual years tend to balance, and their net value at the end of a long period may be assumed to be zero.

The reverse situation occurs when computing the water balance for short time intervals. The shorter the time interval, the more precise are the requirements for measurement or computation of the water balance components and the more subdivided should be the values of S and other elements. This results in a complex water balance equation which is difficult to close with acceptable errors. The term ΔS must also be considered in the computation of mean water balance for seasons or months.

Special Features of the Water Balance Equation for Water Bodies of Different Dimensions

The water balance may be computed for water bodies of any size, but the complexity of computation depends greatly on the extent of the area under study.

A river basin is the only natural area for which large-scale water balance computations can be simplified. The accuracy of computations generally increases with an increase in the river basins area. This is explained by the fact that the smaller is the basin area, the more complicated is its water balance. This is because it is difficult to estimate secondary components of the balance such as ground water exchange with adjacent basins; water storage in lakes, reservoirs, swamps, and glaciers, the dynamics of the water balance of forests, and irrigated and drained land. The effect of these factors gradually decreases with an increase in the river basin area and may finally be negligible.

The complexity of the computation of the water balance of lakes, reservoirs, swamps, ground water basins and mountain-glacier basins tend to increase with increases in area. This is due to a related increase in the technical difficulty of accurately measuring and computing the numerous important water balance components of large water bodies, such as lateral inflow and variations in water storage in large lakes and reservoirs, precipitation on their water surface, etc.

CLOSING OF THE WATER BALANCE EQUATION

To close the water balance equation, it is essential to measure or compute all the balance elements using independent methods wherever possible. Measurements and computations of water balance elements always involve errors due to shortcomings in the techniques used. The water balance equation therefore usually does not balance, even if all the components are measured or computed by independent methods. The discrepancy of water balance (η) is given as a residual term of the water balance equation. This term includes the errors in the determination of the components considered, and the value of components not taken into account by the particular form of the equation being used. A low value of η may indicate only that its component parts tend to balance out.

If it is impossible to obtain the value of a balance component by direct measurement or computation, the component may be evaluated as a residual term in the water balance equation. In this case, the term includes the balance discrepancy, and therefore contains an unknown error which may even be larger than the value of the component. Similar considerations apply when measured values of one component are used to estimate the values of another component through an empirical or semi-empirical formula. The value so estimated will include errors due to the imperfections of the formula and in the measured component, and the overall error is again unknown.

GLOBAL WATER BALANCE

According to estimates (Seckler et al., 1998), the annual average depth of precipitation on the land surface is about $108*10^3$ km^3. Out of this, about $61*10^3$ km^3 is returned to the atmosphere as evapotranspiration and the runoff from land to oceans is $47*10^3$ km^3. As far as the water balance of oceans is concerned, the depth of precipitation over them is about $410*10^3$ km^3, 47 $*10^3$ km^3 of water is received as runoff from the land, and $457*10^3$ km^3 is lost as evaporation. If we consider the water balance of atmosphere, $457*10^3$ km^3 water is received as evaporation from oceans and $61*10^3$ km^3 from land. The precipitation over oceans is $410*10^3$ km^3 and it is $108*10^3$ km^3 over land. Table 2 gives quantitative values of water present in various forms on the earth.

Table 2 Water reserves in various phases of the hydrologic cycle

	Distribution area (10^3 km^2)	Volume (10^3 km^3)	Layer (m)	Percentage of global reserves	
				Of total water	Of fresh-water
World ocean	361,300	1,338,000	3,700	96.5	-
Groundwater	134,800	23,400	174	1.7	-
Freshwater		10,530	78	0.76	30.1
Soil moisture		16.5	0.2	0.001	0.05

Glaciers and permanent snow cover	16,227	24,064	1,463	1.74	68.7
Antarctic	13,980	21,600	1,546	1.56	61.7
Greenland	1,802	2,340	1,298	0.17	6.68
Arctic islands	226	83.5	369	0.006	0.24
Mountainous regions	224	40.6	181	0.003	0.12
Ground ice/permafrost	21,000	300	14	0.022	0.86
Water reserves in lakes	2,058.7	176.4	85.7	0.013	-
Fresh	1,236.4	91	73.6	0.007	0.26
Saline	822.3	85.4	103.8	0.006	-
Swamp water	2,682.6	1.47	4.28	0.0008	0.03
River flows	148,800	2.12	0.014	0.0002	0.006
Biological water	510,000	1.12	0.002	0.0001	0.003
Atmospheric water	510,000	12.9	0.025	0.001	0.04
Total water reserves	510,000	1,385,984	2.718	100	-
Total freshwater reserves	148,800	35,029	235	2.53	100

Source: Unesco (1978).

The storages and fluxes of hydrologic cycle have been shown in Fig. 7.

INFLUENCE OF HUMAN ACTIVITIES AND LAND USE CHANGES ON HYDROLOGIC CYCLE

Watersheds are subjected to many types of changes, major or minor, for various reasons. Some of these are natural changes and some are due to human activities. Watershed changes affect virtually all elements of the hydrologic cycle. The quality of water is significantly deteriorating at many places due to industrial and agricultural activities. There has been a growing need to quantify the impact of major human-induced changes on the hydrologic cycle in order to anticipate and minimize the potential environmental detriment and to satisfy water resources requirements of the society. Even if the water of adequate quantity were present at a place, its use may be limited because of poor quality. The classical and the modern viewpoints of role of the humans in the hydrologic cycle are shown in Fig. 8.

Most watershed changes can be distinguished as point changes and non-point changes. Structural changes, such as dam construction, channel improvement, and detention storage are examples of point changes and affect watershed response in terms of evaporation, seepage, residence time, etc. Forestry, agriculture, mining, and urbanization are non-point land use changes that affect catchment response. A qualitative discussion of the hydrologic consequences due to watershed changes is in order.

(a) Effects of Agricultural Changes

These changes imply that a land area that was earlier forested or a barren land, is now being cultivated. As a result, the vegetal cover changes; the land slope may be altered a little bit, soil crusting and infiltration characteristics change, and artificial bunds may be placed. The effect of these changes on the hydrologic regime is pronounced and may be multiplicative. The water may be withdrawn from the ground water zone or canal irrigation may be introduced leading to noticeable changes in the water table behavior. The impacts are also noticed in evapotranspiration, overland flow, channel flow, and infiltration. Fertilizers, pesticides, and insecticides that are applied to crops affect the quality of runoff from agriculture areas.

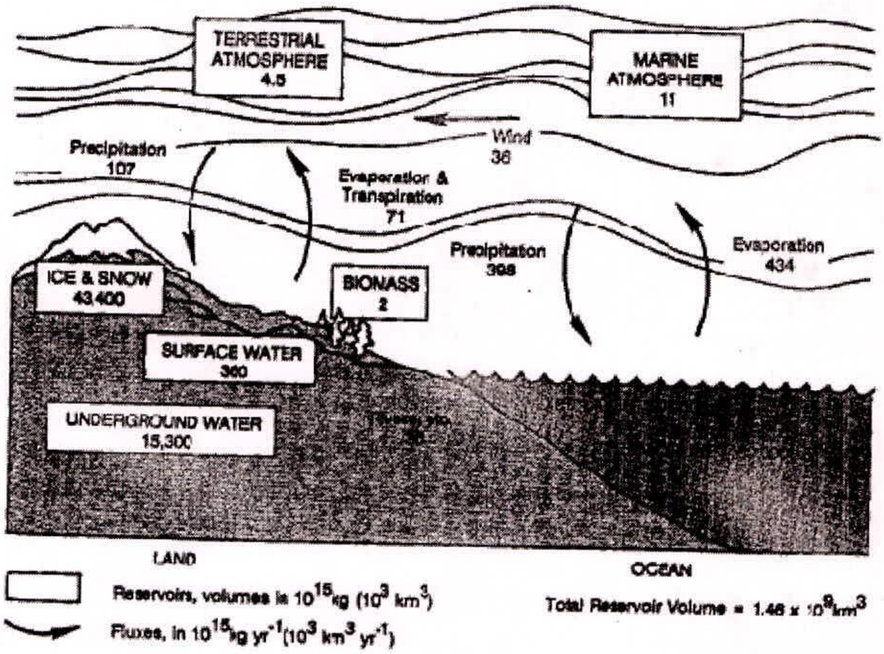

Fig. 7 Volumes and fluxes of the global hydrologic cycle [source: NRC 1986].

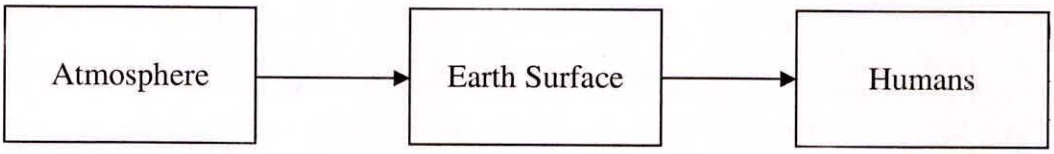

Fig. 8a Classical viewpoint of role of humans in hydrologic cycle.

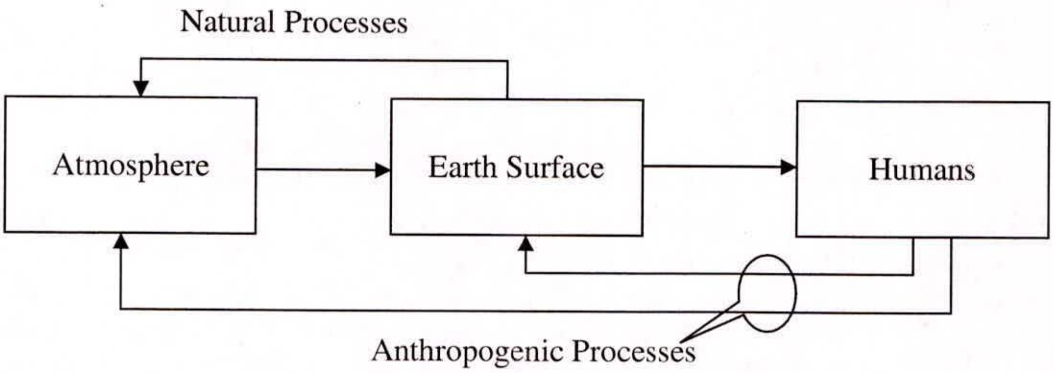

Fig. 8b Modern viewpoint of role of humans in hydrologic cycle (source: NRC, 1982).

(b) Effects of Urbanization

A land area that was being used for purposes, such as forestry, agriculture, might be transformed into an urban area where houses, roads, parks, parking lots, sewers, etc. are constructed. A large increase in the paved (impervious) surface takes place which considerably reduces infiltration and the removal of storm water is accelerated. Urban development usually increases the volume and peak of direct runoff for a given rainfall event. The time of travel of water is reduced, resulting in a lower lag time and a lower time of concentration. However, it is possible to control these effects by providing detention storage or changing the landscape and sizing the storm drains. In brief, the hydrologic effects of urbanization are:

(i) increased water withdrawals from surface and subsurface water bodies, sometimes demands exceed the available natural resources,
(ii) increased peak flow and diminishing baseflow of streams,
(iii) reduced infiltration,
(iv) increased pollution of rivers and aquifers, endangering the ecology,
(v) increased withdrawals from ground water, and
(vi) changes in local micro-climate.

(c) Effects of Forest Activities

These activities may be directed towards planting trees as well as cutting them. The immediate effect of forest activities is changes in vegetal cover. When a forested area is deforested and forest litter removed, the interception of precipitation is virtually eliminated. Litter removal changes infiltration capacity of soil and has a pronounced effect on raindrop impact and the resulting soil erosion. With the loss of vegetation, evapotranspiration is generally decreased. These changes amount to increased production of direct runoff, reduced surface roughness, and decreased recharge to ground water. The hydrograph of direct runoff rises more quickly because of the reduced time to peak. However, when additional trees are planted in an area, the effect is reverse though the impact takes place gradually as the trees grow.

(d) Effects of Structural Changes

Typical structural changes include a dam, a weir, channel improvement works, etc. A dam-reservoir is constructed for many purposes. Regardless of its intended function, it does affect the hydrology of the stream on which it is built. In general, the peak of outflow from a reservoir is less and the flow may be more even than the pre-project condition. The volume of flow downstream may be considerably less in the after-project scenario if the reservoir water is diverted elsewhere.

In contrast with reservoirs, channel improvements have an opposite effect. For example, decreasing channel roughness increases flow velocity and hence peak discharge for the same channel size. The removal of vegetation, lining of the channel, and proper maintenance can greatly reduce roughness. The other alterations, such as straightening the channel, maintenance of bands, or increasing slope, significantly affect travel time and flow velocity. Depending upon the bed material, infiltration through the bed and banks also modifies flow characteristics.

IMPACT OF CLIMATE CHANGES ON THE HYDROLOGIC CYCLE

An analysis of measured data series as well as paleoclimatological records suggests that the climate of the earth may be undergoing a significant change. The climatic change may have important impacts on the hydrologic cycle (the converse is also true). The change may be taking place due to natural and human causes. The major changes that could affect climate are changes in vegetation (changes in evapotranspiration, soil moisture, albedo, and radiation balance), increased use of water for day-to-day needs, burning of fossil fuels, and industrial activities. Large-scale water transfers from one basin to another may also cause climate change in the long run. The change manifests itself in changed patterns of spatial and temporal variability in the components of the hydrologic cycle.

The increased emission of green-house gases is believed to be the cause of gradual increase in earth's temperature. The increase in the temperature of the atmosphere would lead to higher evapotranspiration, changes in precipitation pattern, timing, and distribution, melting of polar ice caps and recession of glaciers. Higher melting of polar ice and glaciers will cause rise of sea water level and inundation of islands of low elevations as well as cities adjacent to seas. Another possibility is that an increase in temperature may mean more precipitation, some of which will be in the form of snow at the poles, leading to an additional accumulation of ice. The coupled atmosphere-ocean general circulation models are widely used to study the response of climate to various changes. Notwithstanding a large number of studies, it is not known with sufficient degree of certainty and accuracy as to what is going to happen and where?

SUMMARY AND CONCLUSIONS

Water is central to the environment and is considered to be the driver of nature. All studies dealing with water are concerned with some part or the other of the hydrologic cycle. The occurrence and availability of water is closely linked with human development. As a result of many human activities, the features/characteristics of many components of the hydrologic cycle are undergoing changes which are likely to result in long-term changes in the climate. It is necessary to predict the magnitude and extent of these changes so that the required ameliorative measures can be initiated well in time.

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