Hydrological Cycles, Models, and Applications to Forecasting

Sharad K. Jain and Vijay P. Singh

Contents

S. K. Jain (✉)
Jal Vigyan Bhawan, National Institute of Hydrology, Roorkee, Uttarakhand, India
e-mail: skj.nihr@gov.in; s_k_jain@yahoo.com

V. P. Singh
Department of Biological and Agricultural Engineering and Zachry Department of Civil Engineering, Texas A and M University, College Station, TX, USA
e-mail: vsingh@tamu.edu

Q. Duan et al. (eds.), *Handbook of Hydrometeorological Ensemble Forecasting*,
https://doi.org/10.1007/978-3-642-39925-1_20

Abstract

This chapter presents an overview of hydrology, water cycle, land surface processes (e.g., precipitation, snow, glaciers and frozen soils, evapotranspiration, surface and subsurface runoff, overland and river flow routing), and hydrologic modeling and its history. The chapter is concluded with an outlook for future.

Keywords

Hydrologic cycle · Watershed · Catchment · Models · Precipitation · Evapotranspiration · Surface water · Ground Water · Climate change · Black-box · Conceptual · Distributed · Calibration · Validation · Uncertainty · Data · Remote sensing · GIS

1 Hydrology: An Overview

All life on Earth is dependent, one way or another, on water. Hydrology can be defined as the science that deals with space-time characteristics of the quantity and quality of the waters of the Earth, encompassing their occurrence, movement, distribution, circulation, storage, development, and management. These characteristics are determined by the relation of water to the Earth. This definition of hydrology is not unique, but may suffice to indicate its scope.

Customarily, hydrology is partitioned into surface-water hydrology and groundwater hydrology. Surface-water hydrology is confined to the relation between water and the surface of the Earth. Groundwater hydrology deals with the relation between water and the lithosphere or the subsurface portion of the Earth. Between these two partitions is subsurface hydrology, often called vadose or unsaturated zone hydrology.

The definition of hydrology encompasses some aspects of a multitude of disciplines involving agriculture, biology, chemistry, geography, geology, glaciology, meteorology, oceanography, and physics. The involvement of hydrology with these sciences comes about due to the close association of water with the atmosphere and the Earth. Many branches of hydrology, therefore, have been distinguished. This association also points out that hydrology is an interdisciplinary science that touches almost all aspects of life. Frequently, hydrology is thought of as an element of agriculture, engineering hydraulics, forestry, geography, or geology. Present sociopolitical culture requires an environmental assessment of all changes in the natural relation of water to the surface of the Earth. Therefore, hydrology should be perceived in terms of the entire reaction of water with the environment.

2 Hydrologic Cycle

The *Hydrologic Cycle,* also known as the water cycle, is a fundamental concept in hydrology and is among a number of cycles 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 the cycle in all the three states, viz., solid, liquid, and gas. It is necessary to study the hydrologic cycle, because water is essential for the survival of life and is an important input in many economic activities. But the needed quantity of water of the desired quality may not be available. A pictorial representation of the hydrologic cycle is given in Fig. 1.

The hydrologic cycle (Oki and Kanae 2006) considers the processes of motion, distribution, and storage of the Earth’s waters. It connects the atmosphere and two storages of the Earth system: the oceans and the landsphere (lithosphere and pedosphere). The water that is evaporated from the Earth and the oceans enters the atmosphere. From the atmosphere, water falls on the Earth and the oceans by precipitation. Oceans also receive streamflow and ground water flow from the landsphere. Water leaves oceans only through evaporation.

In hydrologic cycle, at some point in each phase, usually there is: (a) transport 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 by change from vapor to the liquid or solid state. In the atmosphere, water is present in the vapor form, while it is mostly liquid in the oceans.

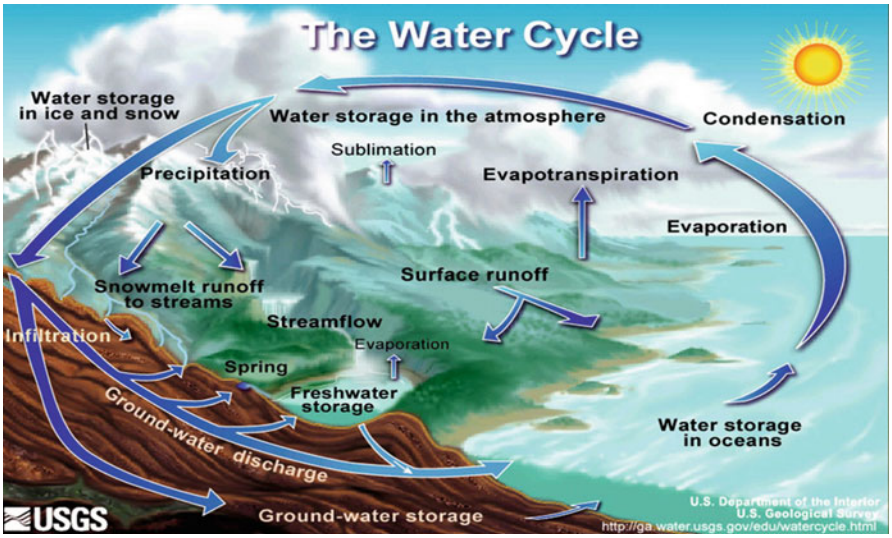

Fig. 1 Pictorial representation of hydrologic cycle (Source: http://water.usgs.gov, accessed on 12/6/2014)

Three major subsystems of the hydrologic cycle are readily identified. The atmosphere functions as the storehouse, carrier, and deliverer of water in the moisture form; the land is the user of water where it is also stored and the oceans are the biggest reservoir and source of water. Water availability at a particular place changes with time because of changes in the supply and consumption.

The landsphere receives water through precipitation. Water leaves land area through evapotranspiration (ET), streamflow, interflow, and ground water flow. ET and precipitation are the processes that take place in the vertical plane, while streamflow, interflow, and ground water flow occur mostly in the horizontal plane.

Shiklomanov (1999) called the exchange of water among the oceans, land, and the atmosphere as "the turnover." Besides, water is a good solvent and hence geochemistry is an integral part of the hydrologic cycle, since water mixes with many chemicals and consequently its quality changes. The hydrologic cycle is, thus, the integrating process for the fluxes of water, energy, and chemical elements (NRC 1991).

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.

3 Components of Hydrologic Cycle

The hydrologic cycle can be divided into the following major components: 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, interflow, and baseflow).

Water evaporates from the oceans and the land surface mainly due to solar energy. Therefore, sun is the prime mover of the hydrologic cycle. The moisture moves in the atmosphere in the form of water vapor which precipitates on land or oceans in the form of rain, snow, hail, sleet, etc. Part of the precipitation falling on land is intercepted by vegetation or buildings. Of the amount reaching the land, a part infiltrates into the soil and the remaining water runs off the land surface to join streams. Most streams finally discharge into the ocean. Some of the infiltrated water percolates deep to join groundwater. Depending upon the topography and geology, some of the percolated water returns to the streams or emerges out as springs.

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 moves water on the Earth surface from high to low elevation; anthropogenic activities also play a role in the movement of water.

We now briefly describe the various components of hydrologic cycle.

3.1 Atmospheric

Precipitation is the most important atmospheric component of the hydrologic cycle.

3.1.1 Precipitation

Precipitation is received on the land surface in the form of rain, snow, hail, frost, and dew. Out of these, rainfall is the predominant component and primarily responsible for streamflow generation or floods in most natural rivers. In many places, rainfall is usually synonymous to precipitation. Rainfall is perhaps the most important and primary input to most hydrological models that are employed for planning, design, and operation of water resource projects. The pattern and magnitude of precipitation depend on the climatic factors, such as temperature, radiation, pressure, humidity, and wind speed. Temporal and spatial variation of these factors makes rainfall a function of both time and space.

Several conditions must be satisfied for the precipitation to occur: the atmosphere should contain moisture and a mechanism should be present to cool it. The cooled moisture should be able to condense. Hence, it must pass through a process of condensation and cloud formation. Since the moist air is lighter than the dry air at a given temperature, it moves upward and gets cooled. For a given amount of moisture, droplets of adequate size will form only in the presence of an optimum number of nuclei. The size of most water droplets in a rainfall event is 0.5–6.0 mm. Larger drops tend to break during fall. Snow is the solid form of precipitation which consists of ice crystals which generally combine to form flakes.

The total amount of precipitation reaching the ground in a stated period is expressed as the depth covering a horizontal projection of the given area in liquid form. In volumetric terms, the total amount of precipitation is the product of the depth and the catchment area. The snowfall is also expressed in terms of equivalent depth of water. The daily amount of precipitation is read to the nearest 0.1 mm.

3.2 Surface Components of Hydrologic Cycle

3.2.1 Interception

Where precipitation does not fall directly on bare soil, it is caught by vegetation or other surface covers and part of it may then be evaporated back to the atmosphere (never reaching the ground). This intercepted amount is known as the interception loss. The remainder of the precipitation eventually reaches the soil but with some delay after temporary storage on the surface cover. The amount of water stored on the wetted surface of the land cover is the interception storage. Interception has the greatest influence during low intensity rainstorms.

The amount of interception depends on the characteristics of precipitation and the form, density, and surface texture of the leaves, stems, or other surfaces, including layering of canopies in the vertical. Dunne and Leopold (1978) note that the total volume of rainfall is the factor used most successfully in the prediction of interception losses. The subtraction of interception loss from gross precipitation makes an insignificant impact during large rainstorms; interception does not affect the development of major floods.

3.2.2 Evaporation

Evaporation is the transfer of water from liquid to vapor state and back to the atmosphere. Evaporation occurs when some water molecules attain sufficient kinetic energy to escape the liquid surface. The rate of evaporation depends on the temperature of the evaporating surface and the ambient air and the difference in vapor pressure between the water surface and the atmosphere; this difference is called the vapor pressure deficit. As evaporation proceeds, the air above the water is gradually saturated and when it is unable to take up any more moisture, evaporation ceases. Since the replacement of saturated air by drier air helps evaporation, wind speed is an important factor in controlling the rate of evaporation. In addition, evaporation from a vegetated surface also depends on soil moisture. Evaporation is one of the most difficult components to quantify in the hydrologic cycle.

3.2.3 Transpiration

Transpiration is the loss of water from the cuticle or the stomatal openings in the leaves of plants. Water is vaporized within the leaf in the intercellular spaces and passes out of stomata by molecular diffusion. The stomata are pores on the undersurface of a leaf which open in sunshine, and when they are open, water vapor can diffuse from wet cells into the atmosphere. This transpired water is replaced by water taken by the roots of the plant from the soil. When computing water loss from a vegetated surface, it is usually impossible to separate transpiration and evaporation from the soil surface, ponds, lakes, and rivers. The term evapotranspiration (ET) represents the two processes together. Thus, ET is the total loss of water by both evaporation and transpiration from a land surface and its vegetation. The amount of ET varies according to the type of vegetation, its ability to transpire, and the availability of water in the soil.

Potential evapotranspiration (PET) is the amount of ET that would take place given an unlimited supply of moisture under the given meteorological conditions. If water is in limited supply at some time during the year, the actual ET may be less than the potential rate. ET is even more difficult to measure than precipitation, partly because this process is not visible.

ET from a reference surface, not short of water, is called the reference ET and is denoted by ET_0 (Allen et al. 1998). The reference surface is a hypothetical grass reference crop with specific characteristics. Reference ET is expressed in the units of depth/time, e.g., mm/day. Crop ET under standard conditions (ET_c) refers to the ET from excellently managed, disease-free, large, well-watered fields that achieve full production under given climatic conditions. To estimate ET_c, ET_0 is multiplied by an empirical crop coefficient which accounts for the difference between the standard surface and the crop. ET can be either measured with a lysimeter, water balance approach, or estimated from climatological data. FAO recommends the use of the Penman-Monteith (PM) method to compute reference ET from a grass surface (Allen et al. 1998).

3.3 Infiltration

From the Earth surface, water seeps into the ground through soil pores. The infiltrated water is useful for plant growth and irrigation demand arises when plants cannot extract water from the soil pores in the root zone. The water that percolates further down meets the groundwater table and becomes part of the groundwater reservoir.

The rate at which the water enters ground is known as infiltration rate. Field capacity denotes the maximum amount of water that can be stored in the soil against gravitational forces. The permanent wilting point is the lower limit of water available in the soil for the use by plant roots. Thus, the field capacity and permanent wilting point represent the moisture availability under two extreme moisture situations.

The forces of soil water retention are known as matric forces because they result from the soil matrix. The matric suction is a function of soil water content. If the suction (expressed in cm of water column) is plotted on a logarithmic scale against the water content, the resulting curve is called a moisture retention or ψ-θ curve, where ψ refers to the suction head and θ is soil moisture content. The soil water retention property signifies the water storing capacity of soils. Whether water transmission actually takes place through soil pores depends on the property known as hydraulic conductivity or permeability.

3.4 Ground Water

The term "ground water" denotes subsurface water that exists at pressures greater than or equal to atmospheric pressure. Pressures of subsurface water in the capillary fringe and above are below atmospheric pressure and typically capillary water is not considered as ground water.

A geologic stratum that has porosity and hydraulic conductivity to store and transmit significant quantities of water is called an aquifer. Materials with sufficient porosity to store water but a very small capacity to transmit it are called aquicludes, e.g., clays and shales. Aquitard refers to a geologic material, whose hydraulic conductivity is too small to permit the development of wells or springs. Aquifers serve two main functions: They store water for varying periods in the underground reservoirs and also act as pathways to pass water. Some aquifers are more efficient as pathways (e.g., cavernous limestones) and some are more effective as storage reservoirs (e.g., sandstones); most aquifers perform both functions.

Water table is that surface in the groundwater body at which the water pressure is atmospheric. Aquifers may be classified as unconfined or confined, depending on the presence or absence of water table. For an unconfined aquifer, the water table serves as the upper surface of the zone of saturation. The water table in an unconfined aquifer is in contact with the atmosphere through pores in the unsaturated soil. Such aquifers are sometimes called water table aquifers. When a well is drilled in an unconfined aquifer, water will nearly remain at the level where it is first encountered. In a confined aquifer water is under pressure greater than the atmospheric. The upper boundary of a confined aquifer is an impermeable formation that "confines" water in the aquifer, separating it from the atmosphere. An imaginary surface passing through all points to which water will rise in wells penetrating a confined aquifer is called the piezometric surface. When water is first encountered during drilling in a confined aquifer, water will rise in the well and stand at a level above the top of the aquifer. Depending on local conditions, water in a well tapping a confined aquifer may rise until it flows at the surface without pumping. Such a well is called an artesian well; confined aquifers are often called artesian aquifers.

The two most important aquifer parameters are transmissivity (T) and storage coefficient (S). Transmissivity can be defined as the rate of flow through a cross-section of unit width over the whole thickness of the aquifer under unit hydraulic gradient. It is the product of the average hydraulic conductivity and the thickness of the aquifer. Its common units are m^2/day or m^2/hr. The storage coefficient and the specific yield are defined as the volume of water released and stored per unit surface area of the aquifer per unit change in the component of head normal to that surface. The storage coefficient refers only to the confined parts of an aquifer and depends on the elasticity of the aquifer material and the fluid. It has an order of magnitude of 10^{-4} to 10^{-6}. The specific yield (S_y) refers to the unconfined parts of an aquifer.

3.5 Overland and Channel Flow

Based on the path taken by water, streamflow may be divided into surface flow, interflow, and base flow. Figure 2 shows components of a typical hydrograph. A number of conceptual models are available to describe runoff generation in catchments.

Overland flow frequently occurs as a saturation excess mechanism. All other things remaining the same, soil tends to saturate first where the antecedent soil moisture deficit is the smallest. This will be in valley bottom areas, where flow converges and slopes gradually decline towards the stream. Saturation rapidly occurs where soils are thin or have low permeability. The areas of saturated soil expand with increased wetting as rains continue and reduce after rainfall stops. This concept is called the dynamic contributing

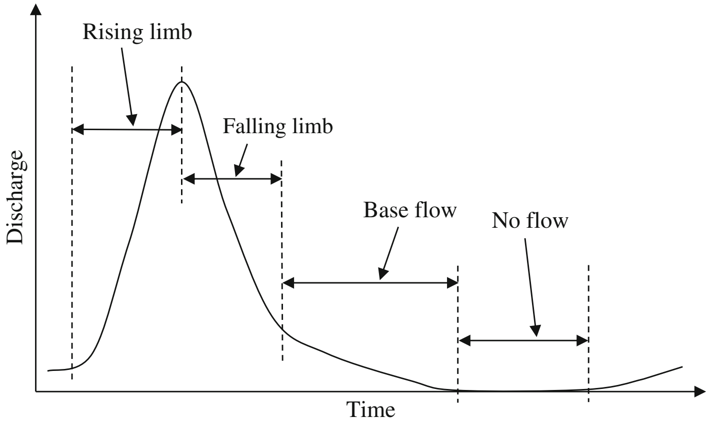

Fig. 2 Components of a streamflow hydrograph

area concept. In addition to contribution from rainfall, surface runoff from such a saturated area may also be due to the return flow of subsurface water (Fig. 3).

A similar concept may be applicable in areas whose responses are controlled by subsurface flows. When saturation starts to build up at the base of soil over a relatively impermeable bedrock, water will start to flow downslope. The connectivity of saturation in the subsurface is, however, important initially. It may be necessary to satisfy some initial bedrock depression storage before there is a consistent flow downslope. The dominant flow pathways may be localized, at least initially, related to variations in

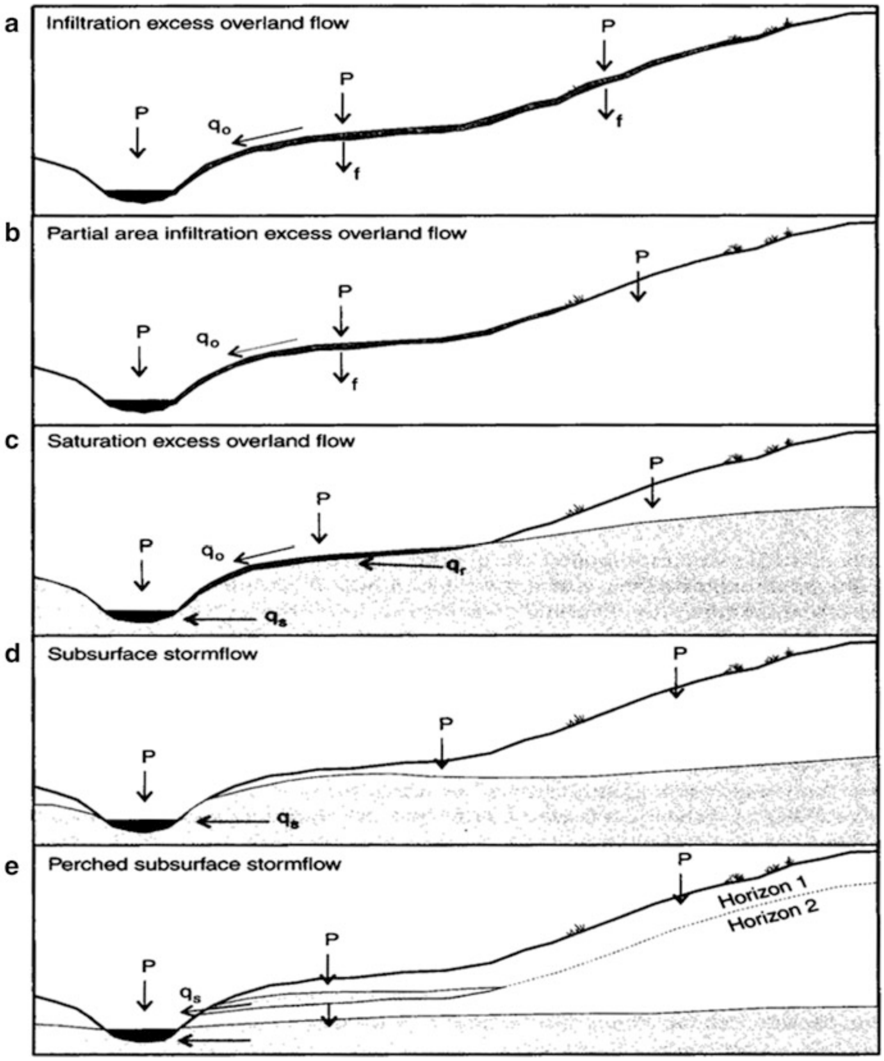

Fig. 3 Various hillslope runoff mechanisms (Source: Beven 2001)

the form of bedrock surface. In the catchments whose soils are deep and have high infiltration capacities, responses may be dominated by subsurface stormflow.

Traditionally, it has been usual to differentiate between different conceptualizations of catchment response based on the dominance of one set of processes over another. An example is the Hortonian model in which runoff is generated by an infiltration excess mechanism all over the hillslope (Fig. 3a). Many forested catchments have deep soils with high infiltration capacities. Response of these catchments during storms is often controlled by subsurface processes and surface runoff is restricted mainly to the channels (Fig. 3d).

Betson (1964) hypothesized that only a part of a catchment is likely to produce runoff in any storm. Since infiltration capacities decrease with increasing soil moisture and the downslope flow of water on hillslopes tends to result in wetter soils at the bottom of hillslopes, the area of surface runoff would tend to start near the channel and expand upslope. This partial area model (Fig. 3b) allowed for a generalization of the Horton conceptualization. It is now realized that the variation in overland flow velocities and the heterogeneities of soil characteristics and infiltration rates are important in controlling partial area responses. If runoff generated on one part of a slope flows onto an area of higher infiltration capacity further downslope, it will infiltrate (the run-on process). When the high intensity rainfall producing overland flow is of short duration, it is also likely that water will infiltrate before it reaches the nearest channel.

3.6 Base Flow

ASCE (1996) defined base flow as the runoff that has reached the stream or river by passing first through the underlying aquifer, rather than by flowing directly on the ground surface. Thus, base flow is that portion of streamflow that is naturally and gradually withdrawn from groundwater storage or other delayed sources. The other names of base flow are groundwater flow, seepage flow, low flow, and fair weather flow.

Base flow contribution to streamflow varies widely, according to the geologic nature of the water-table aquifer. The lateral movement of groundwater is slower than vertical movement because the hydraulic gradient is smaller for lateral movement. The supply from groundwater to the channel will continue as long as the necessary gradient is present. If there is no additional infiltration to aquifer, the hydraulic gradient decreases as water moves to the stream from higher elevations, then lesser water will travel to the stream with time. This process is called base flow recession.

Perennial streams depend on base flow for discharge between runoff producing events. The presence of base flow around the year indicates humid climate and a shallow water table that is hydraulically connected with the stream. Base flow is absent in (semi)arid climates and areas of deep groundwater. Base flow depends on precipitation, the geologic conditions, and the hydrogeologic controls governing groundwater movement. Climate influences recession through recharge and ET.

3.7 Scales for the Study of Hydrologic Cycle

Depending on the purpose of study, the hydrologic cycle is studied over a range of spatial and temporal scales. Regarding space, two scales are readily distinct: the global scale and the catchment 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. The study at the global scale helps understand the global fluxes and global circulation patterns. Results of these studies form important inputs for water resources management at national, regional, and local scales, weather/flow forecasting, and study of impacts of climate change.

While studying the hydrologic cycle on a catchment scale, the spatial coverage can range from a few hectares to thousands of square km. The timescale can be a short duration storm to a study spanning many years. For the water movement in the Earth system, three systems can be recognized: the land (surface) system, the subsurface system, and the aquifer (or geologic) system. In the hydrologic cycle of the land system, the dominant processes are precipitation, evapotranspiration, infiltration, and surface runoff. These subsystems subtract water from precipitation through interception, depression, and detention storage. The exchange of water among these subsystems takes place through the processes of infiltration, exfiltration, percolation, and capillary rise. Fig. 4 shows the schematic of the hydrologic cycle at global scale, in the Earth system, and microscale view of the cycle in the land system.

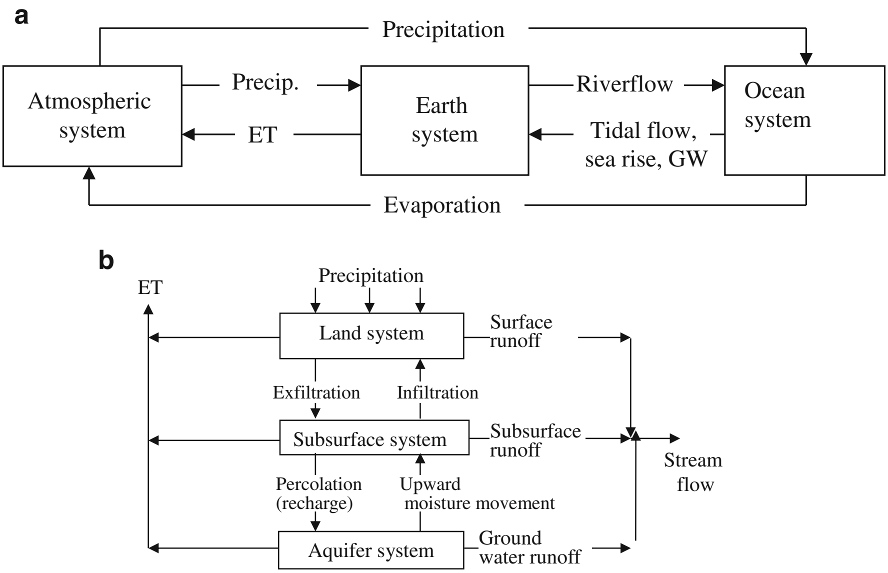

Fig. 4 (**a**) A global schematic of the hydrologic cycle (Source: Singh 1992). (**b**) A schematic of the hydrologic cycle of the Earth system (Source: Singh 1992)

The time required for the movement of water through various components of the hydrologic cycle varies considerably. Streamflow moves with much higher velocity compared to ground water. The time-step size for an analysis depends upon the purpose of study and the availability of data. The time step should be sufficiently small so that variations can be captured in required detail, but it should not be a burden on data collection and computational effort.

3.8 Mathematical Representation of the Hydrologic Cycle

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

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

where I and Q are the inflow and outflow of water to the study area during any given time period, and ΔS is the change in storage of water in the given area during the time period. If I and Q vary continuously with time, then Eq. (1) can be written as

$$d[S(t)]/dt = I(t) - Q\big(\text{Uttarakhand}\big) \tag{2}$$

Integration of this equation yields

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

$$S(t) - S(0) = \int_0^t I(t)dt - \int_0^t Q(t)dt = V_I(t) - V_0(t) \tag{3}$$

where $S(0)$ is the initial storage at time $t = 0$, $S(t)$ is the storage at time t, $V_0(t)$ and $V_{\mathrm{I}}(t)$ are the 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 which can be subdivided and even eliminated from the equation, depending upon the temporal and spatial scales of the study. For a watershed, Eq. (1) may be written as

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

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

The hydrologic equation may be applied to any area, but the complexity of computation greatly depends on the size of the area under study. The smaller is the area, the more complicated is its water balance.

3.9 Influence of Human Activities and Land Use Change on Hydrologic Cycle

A host of factors influence the hydrologic regimes, and it is important to detect changes in the hydrologic cycle by separating natural variability from the variability and trends caused by other reasons. Natural hydrologic regimes at most places have been highly modified by increasing withdrawals and land use changes. These changes can both accelerate (e.g., by urbanization) and dampen (e.g., through afforestation) hydrologic responses. The hydrologic cycle is also modified by human intervention (dams, diversions, interbasin transfers), and application of river or ground water for irrigation and its return flows (Chen et al. 2016). While climate change is influencing the hydrologic cycle, other bio-geochemical cycles, energy generation, water supply and demand for irrigation, drinking, and the quality of water, its signals are difficult to detect and isolate. Already there are noticeable changes in many regions of the world in the key climate parameters, such as temperature and rainfall. However, the climate change signal in derived hydrologic variables, such as river runoff and ground water, is weak or not yet detectable in many parts of the world.

Most watershed changes can be distinguished as point changes or nonpoint 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/travel time, etc. Afforestation, agriculture, mining, and urbanization are nonpoint changes that affect catchment response. A qualitative discussion of the hydrologic consequences due to watershed changes is given next.

Agricultural changes typically imply that a forested or a barren land is put to cultivation. As a result, the vegetal cover changes, the slope may be altered a little bit, and artificial bunds may be placed causing changes in water retention and infiltration. The effect on the hydrologic regime is pronounced and may be multiplicative. Large amounts of water may be withdrawn from the aquifer or canal irrigation may be introduced leading to noticeable changes in the water table behavior. The changes are also observed in evapotranspiration, overland flow, channel flow, and infiltration. Fertilizer, pesticide, and insecticide applications affect the quality of runoff from agriculture areas.

A land area under forest or 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 considerably reduces infiltration and the removal of storm water is accelerated. Urban development usually increases the volume and peak of direct runoff, but the time of travel of water is reduced. Thus, the hydrologic effects of urbanization are: (a) increased water withdrawals from surface and subsurface sources; (b) increased peak flow and diminishing baseflow of streams; (c) reduced infiltration; (d) increased pollution of rivers and aquifers, endangering the ecology; and (e) changes in local microclimate.

3.10 Impact of Climate Change on Hydrologic Cycle

Increased emission of green-house gases is believed to be the cause of gradual increase in Earth's temperature. Global warming is likely to 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 sea water level rise and inundation of islands of low elevations as well as coastal cities. Most climate scientists agree that climate warming will intensify, accelerate, or enhance the global hydrologic cycle. Enhancement could be caused by increasing rates of evaporation, ET, precipitation, and streamflow. There are likely to be associated changes in atmospheric water content, soil moisture, ocean salinity, and glacier ice contents.

Given here are the broad impacts of global warming on the various components of the hydrologic cycle. The mode of precipitation is as important as the magnitude in determining hydrologic impacts, and precipitation variability at multidecadal scales can mask long-term trends. Increases in heavy precipitation events have been observed in some places where total precipitation has decreased. In addition, more precipitation now falls as rain rather than snow in northern regions. These changes are expected in a warmer atmosphere with a greater water-holding capacity. Results of reported studies suggest that over large areas of Asia and North America, on average, actual ET is increasing, even though pan evaporation is decreasing.

Worldwide glaciers have retreated since the mid-nineteenth century at varying rates, and this retreat is expected to accelerate on account of global warming and changes in precipitation amount and form. Although there is evidence of glacier retreat globally, all glaciers are not equally sensitive to climate change and there are pockets of anomalous behavior. Studies suggest that the number of days of snow cover is decreasing and snow melt is occurring earlier. Some studies suggest that these changes may have accelerated in the last several decades.

4 Hydrological Modeling

A hydrological model represents the physical/chemical/biological characteristics of the catchment and simulates the natural hydrological processes. A model aids in making decisions, particularly where data are scarce, understanding is incomplete, or there are large numbers of options to choose from (e.g., optimization of reservoir release rules) or it is not possible to experiment with the prototype system. The value of a model is in its ability, when correctly chosen and adjusted, to extract the maximum amount of information from the available data and answer the question: What if?

4.1 Types of Hydrological Models

Broadly, hydrological models can be divided in two categories: physical (or laboratory) and mathematical (or intellectual). A physical model is a replica of the prototype and is constructed by some physical material, say concrete. These models are not much popular in hydrology. A mathematical model is a quantitative description of the processes or phenomena by using a collection of mathematical equations (often partial differential equations), logical statements, initial and boundary conditions, expressing relationships between input and output.

Commonly, the aim is to model the interactions of inputs (e.g., climate) with the system (e.g., a catchment) to produce an output (e.g., the outflow hydrograph) (Fig. 5). The mathematical functions employed in a model simulate the natural hydrological processes by using the available knowledge, mathematical constraints, data availability, and user requirements. Depending on the accuracy requirement, skills, funds, efforts needed for data collection and modeling, the natural system is represented in greater or smaller details.

The structure and architecture of a hydrologic model are determined by the objective for which the model is built. Hydrologic models can be classified in different ways but not all models fit in a given classification. A general classification of models is shown in Fig. 6. In a different classification, the models can be divided into the deterministic and the stochastic groups. These two groups can each be further divided into conceptual and empirical. Further subdivisions could be spatially lumped/or spatially distributed and linear or nonlinear models.

Singh (1995) classified hydrologic models based on (1) process description, (2) timescale, (3) space scale, (4) techniques of solution, (5) land use, and

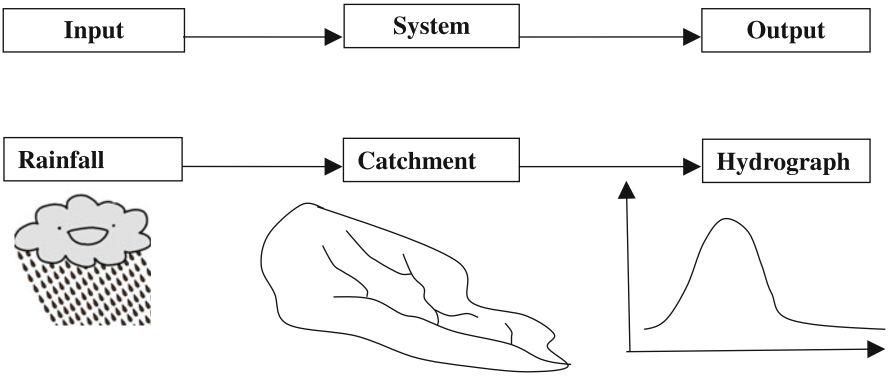

Fig. 5 Representation of input, system, and output for a mathematical model

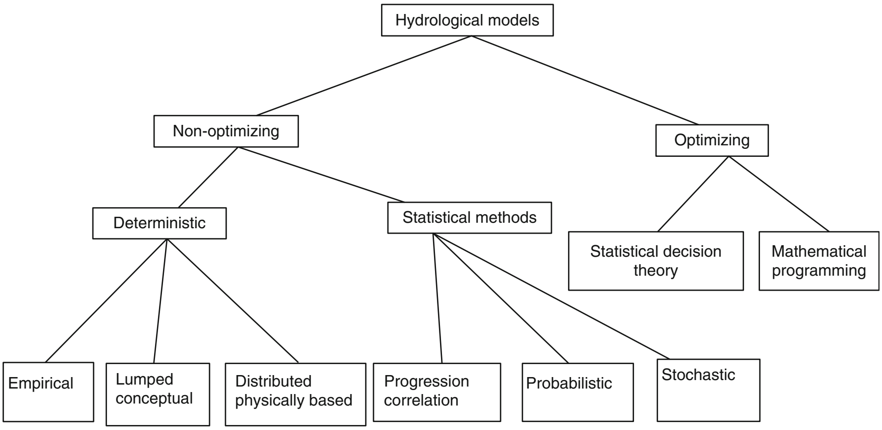

Fig. 6 Classification of hydrologic models

(6) model use. ASCE (1996) reviewed and categorized flood analysis models into (1) event-based precipitation-runoff models, (2) continuous precipitation-runoff models, (3) steady flow routing models, (4) unsteady-flow flood routing models, (5) reservoir regulation models, and (6) flood frequency analysis models.

Two main groups of hydrologic models are: deterministic and stochastic and further discussion follows along these lines.

4.2 Deterministic Models

Deterministic models can be classified according to whether the model describes the catchment as a spatially lumped or distributed system, and whether the description of the hydrological processes is empirical, conceptual, or based on physical laws. In practice, most conceptual models are (semi)lumped and most fully physically based models are distributed, so three main groups of deterministic models are identified in Fig. 6. Over the last many decades, model developments have followed a progression from black box models to grey box models (lumped, conceptual) and to increasingly sophisticated physically based, distributed models (white box). This progression has been supported by four factors: (a) improved understanding of the physics of hydrological processes; (b) increasing quantity, coverage, and quality of hydrological data collected by better sensors and satellite systems; (c) exponential advancements in computational technology; and (d) need for better forecasts and values of more variables in decision making.

Demands to address the increasingly complex problems arising from unwise and unsustainable water resources development, the impacts of landuse land-cover changes, increasing pollution of sources of water, and problems arising due to climate change are some of the reasons for increasingly sophisticated modeling.

4.3 Black Box or Empirical Models

Such models usually utilize relationship between input and output and parameters are calibrated from observed hydrometeorological records. A well-known black box model is the unit hydrograph model. Within the range of calibration data, empirical models may be highly successful because the mathematics of the model is backed with an implicit understanding of the physical system. However, extrapolation beyond the range of calibration is not advisable, since the implicit understanding may no longer be valid. Moreover, many black-box models are linear, while the real-world hydrological systems are nonlinear, which may make such extrapolation of dubious worth. The black box models cannot be employed for some practical problems, e.g., to predict the effects of land-use change on hydrologic response.

Black box models were in widespread use before advances in computer technology enabled the use of more physically correct models. These days black box models often form components of a larger model, e.g., the unit hydrograph is often used for streamflow routing in conceptual rainfall-runoff models.

4.4 Lumped Conceptual Models

These models occupy an intermediate position between fully physically based and black box models. Lumped conceptual models consist of a small number of components, each of which is a simplified representation of an element in the hydrologic system. Typically, each component of the model consists of a nonlinear reservoir in which the relationship between outflow (Q) and storage (S) is given by

$$Q_{\mathrm{i}} = f\ (\mathrm{K}, S^{n}) \tag{5}$$

where K and n are constants, to be calibrated from existing records. The model operation is normally a bookkeeping system which accounts for the movement of moisture in various storages at each time step. Nonlinearities in the behavior of the real system arising mainly in determining excess rainfall, soil moisture movement, and surface/subsurface runoff are taken care of by thresholds of different storages. Calibration of the lumped conceptual models is more a curve-fitting exercise which means that these models may not work well beyond the range of calibration data.

An example of the lumped conceptual models is the tank model developed by Sugawara (1967). It is a simple model which has proved to be effective in a range of studies. The HBV model, described in detail by Bergstrom (1976), was developed at the Swedish Meteorological and Hydrological Institute and comparable to the tank model. It has also been applied to many catchments and it is used operationally for forecasting floods and reservoir inflows at several hydro-power systems in Sweden and Norway.

4.5 Fully Distributed, Physically Based Models

These models are based on understanding of the physics of the processes which control catchment response; physics-based equations are used to describe the catchment processes. In these models, the transfers of mass, momentum, and energy are calculated by solving the governing partial differential equations, for example, the Saint Venant equations for surface flow, the Richards equation for unsaturated zone, and the Boussinesq equation for ground water flow. Usually these equations are solved by using numerical methods. By definition, physically based models are spatially distributed, since the underlying governing equations generally involve one or more space coordinates. These models simulate the spatial variation in hydrological conditions in a catchment and can give value of the variables, e.g., river flow, soil moisture, and actual ET, at any location in a catchment. However, all these features come at a cost. Such models are costly to develop, apply, and have huge computational time and data requirements.

A strong argument to use distributed models in hydrology has been that these models may be more realistic than the simpler models. Physically based distributed models treating a single component of the hydrological cycle have been developed and extensively applied since the late 1970s. For example, most of the groundwater models are of this type. However, physically based distributed catchment models which integrate submodels of the major components of the hydrological cycle came much later, largely because computer and data requirements of such models were quite high compared to the situation about 25 years ago. Further, there were numerical difficulties, such as the stability of numerical schemes, and mass balance errors which were to be overcome in modeling. Gradually, these difficulties were overcome and several physically based distributed models were developed and tested on small basins during the 1980s. Prominent among these is the SHE modeling system (Fig. 7) (Abbott et al. 1986), developed jointly by the Danish Hydraulic Institute, the Institute of Hydrology (UK), and SOGREAH (France). Initially, these models were applied on small well-instrumented basins, and these applications helped debug the models and make them ready for real-life problems. The SHE model was tested on catchments in a variety of environments and at scales ranging from tens of hectares to nearly 1000 km^2 (Jain et al. 1992).

4.6 Advantages and Limitations of Physically Based Distributed Models

The concept behind the physically based distributed models has advantages as well as limitations. While the black box models should not be used for the range of input data which is beyond the range of calibration data, physically based models can, in principle, be applied to any set of data subject to the range over which the underlying physical laws are valid. Black box models must be calibrated for each catchment because their parameters do not have any physical meaning, and therefore, these

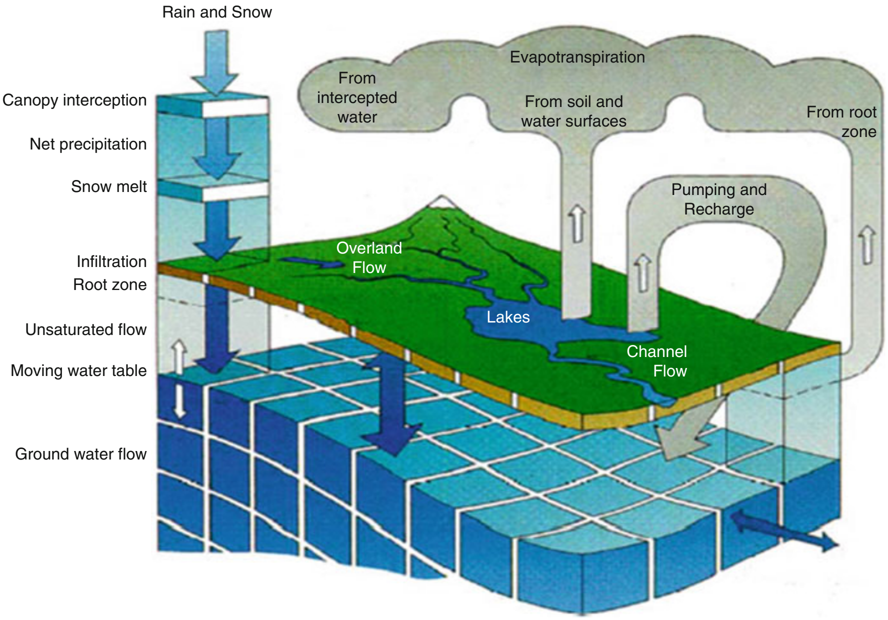

Fig. 7 Schematic diagram of a catchment and a quasi three-dimensional physically based distributed model: the SHE model (Source: http://mikebydhi.com)

cannot be derived from measurements of catchment characteristics. Hydrometeorological records of sufficient length are required for calibration. In contrast, physically based models have parameters with a physical meaning and can in principle be evaluated from direct measurements. This allows such models to be applied to catchments without long data records and to the future state (changing land use) of catchments. In principle, physically based models should not require calibration. In practice, because of model approximations and simplifications, some calibration is required, but this can be carried out on the basis of a short data record.

A given black-box model may not apply to all catchments because the various hydrological processes are not accounted for separately in these models and hence the changes in their relative impacts cannot be easily allowed. Physically based models are applicable to a much wider range of catchments because the physical laws describing the hydrological processes are the same everywhere. Physically based models can use all available information (e.g., topography, soil and vegetation maps, understanding of soil physics and plant physiology, historical information on extreme event characteristics) and may evolve continuously as new insights into hydrological processes are developed.

Limitations

Computer and data requirements to run a physically based distributed catchment model are rather heavy. These include large storage capacity and high processing speed, because calculations are repeated at each time step for a number of (grid) points. Short time steps may be necessary for stability of numerical schemes during periods of rapid changes. Some of these issues are not very critical these days because of steep decline in hardware costs. But the users are now adopting finer spatial scales, which means some of the advantages of faster processing speed are lost.

With distributed modes, there are problems parameterizing subgrid scale processes (Beven 2001). Theoretical understanding of hydrological processes is not always sufficient or mathematically tractable and amenable. Beven (2001) states that the problem of nonlinearity is at the heart of many problems faced in applying distributed models in hydrology.

4.7 Statistical Models

While most of the deterministic models rely on physics-based approach, statistical methods usually involve functional relationships between hydrological properties of various measured data. Statistical methods in hydrology have been developed extensively with support from basic statistical theory developed and applied in other fields.

5 History of Hydrologic Modeling

Hydrological modeling has a long history which can be traced back to the nineteenth century. The rational method was developed by Mulvany in 1850 and is a clear exposition of the concept of time of concentration and its relation to the maximum runoff (Todini 2007). Sherman (1932) introduced the unit hydrograph (UH) concept to relate the direct runoff from a catchment to rainfall excess. UH is the direct surface runoff hydrograph resulting from an excess rainfall of unit duration (e.g., 1 h) falling uniformly over a catchment. A storm rainfall can be divided into several unit durations and their responses combined to yield the storm hydrograph. In fact, much of the nonlinearity of the rainfall runoff process is taken care of while determining the excess rainfall. Another form of UH is used in hydrology. The impulse response of a linear system is represented by the Instantaneous Unit Hydrograph (IUH). An IUH is obtained when the unit duration of the rainfall excess is infinitesimally small. IUH has the advantage that the assumption of uniform rainfall during the unit duration is avoided. At about the same time when UH idea was developed, Horton (1931) developed a theory of infiltration to estimate rainfall excess. In 1945, Horton developed a concept of erosion and streamflow generation dominated by overland flow. This pioneering work presented a set of empirical laws, known as Horton’s laws, which constituted the foundation of quantitative geomorphology.

Using simplified principles of physics, Green and Ampt in 1911 developed a theory of infiltration. Their formula is still popular for computing the infiltration capacity rate. In 1948, Thornthwaite and Penman made important contributions to models of evapotranspiration.

In 1956, the Soil Conservation Service (SCS) of the US Department of Agriculture (now called as the Natural Resources Conservation Service, NRCS) developed a method for computing the amount of storm runoff taking into account the abstractions. These abstractions depend on the land use, soil type, and antecedent soil moisture content which is specified by "Curve Number (CN)." Although originally intended to model daily runoff as affected by land use practices, the SCS-CN method has been very widely used to model infiltration as well as runoff hydrograph for continuous hydrologic simulation either as a standalone model or as a part of detailed hydrologic models, such as the SWAT model (Neitsch et al. 2002).

The subsurface phase of the hydrologic cycle was investigated by Theis (1935) who combined Darcy's law with the continuity equation to derive the relation between the lowering of the piezometric surface and the rate and duration of discharge of a well. Work by Theis laid the foundation of quantitative groundwater hydrology. The study of groundwater and infiltration led to the development of techniques for separation of baseflow and interflow in a hydrograph.

After an interregnum of nearly a quarter century, a major effort in the area of rainfall-runoff modeling employed the theory of linear systems which led to the theory of the instantaneous unit hydrograph by Nash (1957) and then the generalized unit hydrograph theory by Dooge (1959). In 1955, Lighthill and Whitham developed kinematic wave theory for flow routing in long rivers which now has become a main stay in watershed runoff modeling (Singh 1996, 1997). Nash (1957) visualized a catchment as a cascade of N linear reservoirs, each with a residence time of K units.

With the advent of computers, models of different components of the hydrologic cycle were integrated to simulate an entire watershed. A pioneering watershed model was the Stanford Watershed Model-SWM (now HSPF) developed by Crawford and Linsley (1966). SWM was probably the first comprehensive attempt to model the entire hydrologic cycle. At around the same time, a number of other watershed models were developed and applied to diverse problems of hydrologic design. Examples are the models by Dawdy and O'Donnell (1965), HEC-1 by US Army Corps of Engineers in 1968, NWS River Forecast System (Burnash et al. 1973), and the SSARR (Rockwood 1982). During the sixties, a number of conceptual models which represented the various watershed processes through storages or tanks were developed, e.g., the Tank Models developed by Sugawara (1967) and Sugawara et al. (1974). Backed by a large number of applications, many versions of HEC-1 model were brought out. With time, it migrated from mainframe to desktop computers (or PCs). It has been re-christened as HEC-HMS (Hydrologic Modeling System) (http://www.hec.usace.army.mil/software/hec-hms/) and the later versions have the GIS capabilities as well.

6 Integrated Modeling of Hydrologic Cycle

In the 1970s, it was hypothesized that runoff is produced by the basin when the soil moisture content reaches the field capacity. The Xinanjiang model developed by Zhao et al. (1980) was based on this concept. Explicit Soil Moisture Accounting (ESMA) is the name given to the models where a collection of storage elements that represent different processes that are important in controlling the catchment response are employed. Exchange of soil moisture fluxes between these elements is described by mathematical equations. ESMA models differ in the number of storage elements used as well as the functions and parameters describing moisture movement. Todini (1996) developed a new conceptual model which was applied to the Arno River and hence it was called as the ARNO model. Wood et al. (1992) further expanded the concept by including subgrid soil heterogeneity and soil layers in the Variable Infiltration Capacity (VIC) model.

Since the 1980s, there has been a proliferation of watershed hydrology models; the popular ones in the list include the Systeme Hydrologique Europeen (SHE) (Abbott et al. 1986), TOPMODEL (Beven and Kirkby 1979), Soil and Water Assessment Tool (SWAT), and Variable Infiltration Capacity (VIC) model (Liang et al. 1994; Gao et al. 2010). Some of these models have been significantly improved after their first appearance. SHE has been extended to include sediment transport and is applicable at the scale of a river basin (Bathurst et al. 1995) and was later packaged as a commercial suite. TOPMODEL has been extended to contain increased catchment information, more physically based processes, and improved parameter estimation.

Singh (1995) edited a book that summarized 26 popular models. Wurbs (1998) listed a number of generalized water resources simulation models in seven categories and discussed their dissemination. Singh and Frevert (2002a, b, 2006) summarized a large number of additional hydrologic models.

Although the mathematical equations embedded in watershed models are continuous in time and often space, analytical solutions cannot be obtained except in very simple circumstances. Numerical methods (finite difference, finite element, boundary element, boundary fitted coordinate) must be used for practical cases. The most general formulation would involve partial differential equations in three space dimensions and time. If the spatial derivatives are ignored, the model is said to be "lumped"; otherwise it is said to be "distributed" and the solution (output) is a function of space and time. Strictly speaking, if a model is truly distributed, then all aspects of the model must be distributed, including parameters, initial and boundary conditions, and sources and sinks. Practical limitations of data and discrete descriptions of watershed geometry and parameters to conform to the numerical solution grid or mesh do not permit a fully distributed characterization.

Several well-known general watershed models are in current use in many countries; some models are global and some are popular in a region. These models vary significantly in the model construct of each individual component process partly because these models serve somewhat different purposes. A number of catchment models are freely available in public domain. Some popular free hydrologic models include SWAT, VIC, HEC-HMS, MODFLOW, and CROPWAT. HEC-HMS is frequently used for design of drainage systems, quantifying the effect of land use change on flooding, etc. The NWS model is the standard model for flood forecasting in USA. Mike and SHE are the standard models for hydrologic analysis in many European countries. The HBV model is the standard model for flow forecasting in Scandinavian countries. The ARNO, LCS, and TOPIKAPI models are popular in Italy. The tank models are well accepted in Japan. The Xinanjiang model is a commonly used model in China. SWAT and VIC models are popular in diverse studies, including the impact of climate change. CROPWAT is extensively used to compute crop water requirements and MODFLOW is the most popular groundwater flow model.

6.1 Model Calibration

Once one or more models have been chosen for a project, it is necessary to determine their parameters. In general, it is not possible to measure the parameters of models or estimate them a priori. Studies that have attempted these have generally found that even after intensive measurements, satisfactory estimates of parameter values could not be obtained. Prior estimation of feasible ranges of parameters also often results in wide ranges of predictions, which may still not always contain the measured responses.

A good automatic parameter estimation methodology requires four elements: (1) objective function, (2) optimization algorithm, (3) termination criteria, and (4) calibration data. The choice of an objective function influences parameter estimates as well as the quality of model results. Sorooshian and Gupta (1995) discussed several optimization methods, including local search methods (direct search methods and gradient search methods) and global search methods (random search methods, multistart algorithms, and shuffled complex algorithms). The shuffled complex evolution (SCE-UA) global optimization algorithm has been found to be consistent, effective, and efficient in locating the globally optimum hydrologic model parameters (Duan et al. 1992).

The model performance is typically evaluated from the comparison of simulated and observed discharge data by using statistical indices. Commonly used indices are: coefficient of determination, Nash and Sutcliffe efficiency, index of agreement, and root mean square error. In addition, visual comparison of the observed and computed values and scatter plot between them are always helpful.

There are two major reasons for difficulties in calibration. First, the scale of measurement techniques available is generally much less than the scales at which parameter values are required. For example, consider hydraulic conductivity which is a common parameter in watershed models. Techniques for measuring soil hydraulic conductivities generally integrate over areas of less than 1 m^2. However, the size of typical elemental area in a distributed model would be about 100 m^2 or more. Studies suggest that effective values might change with scale. Thus, the small-scale values that are typically measured and the effective values required at the model element scale may be different. Hence, the parameter values for a particular model will need to be calibrated.

Most calibrations involve some form of optimization of the parameter values by comparing the simulated values with observed values of the variables of interest. The parameter values are adjusted after each model run, either manually or by some optimization algorithm, until some “best fit” parameter set is found.

It needs to be highlighted here that the model structure and the observations are not error-free. Thus, the optimum parameter set is model specific and may not remain optimum if the model structure or the calibration data changes. While one optimum parameter set can often be found, there will usually be many other parameter sets that are very nearly as good, perhaps from a different part in the parameter space. The idea of equifinality of parameters (Beven and Freer 2001) suggests that given the limitations of both the model structures and observed data, there may be many representations of a catchment that may be equally valid in terms of their ability to produce acceptable simulations of the available data.

6.2 Selection of Appropriate Model Type

In the presence of a large number of hydrological models, a frequent question is “which model is most appropriate for a particular problem?” This question cannot be answered by giving the name of a particular model. Instead, one may only recommend as to which of the above mentioned model types is most appropriate for the given hydrological problem, available data, and resources.

For some hydrological problems, the best model type is nearly obvious, e.g., probabilistic models for frequency analysis and stochastic models to generate long synthetic streamflow series. Empirical (black box) models are mainly employed for event-based modeling or as components of more complicated models. Lumped, conceptual models are suited to simulate the rainfall-runoff process when adequate data exist to calibrate the model. Typical applications of such models are extension of streamflow records based on long rainfall records, water balance, and real-time flood forecasting.

Theoretically, physically based distributed models can be applied to almost any hydrological problem. However, for many problems, the solutions can be obtained by less sophisticated empirical, lumped conceptual, or statistical models. Of course, there are complex problems, for which it is necessary to use a physically based distributed model. Some examples of their application are:

- Natural and anthropogenic changes in land-use and land cover, such as urbanization, forest clearance for agricultural purposes. The parameters of a physically based, distributed model have a direct physical interpretation. Hence, they can be estimated for the new state of the catchment and the impacts of changes can be examined before they occur.
- Ungauged catchments. Modeling of an ungauged catchment requires a program of fieldwork to provide data and parameters for calibration. Due to the physical

significance of the parameters, a physically based model can be applied to an ungauged basin or to a basin having shorter data record.
- To model the movement of pollutants and sediments, it is necessary to model the water flows which provide the basic frame work. Since water quality and sediment problems have a spatial aspect, distributed models are best suited for such problems.

6.3 Uncertainty in Hydrologic Modeling

Uncertainty is defined as a measure of imperfect knowledge or probable error which can occur during the data collection process, modeling and analysis of engineering systems, and prediction of a random process. In simple terms, uncertainty is the occurrence of events that are beyond human control. Uncertainty may also classified into two categories: (1) inherent or intrinsic, caused by randomness in nature; and (2) epistemic, caused by the lack of knowledge of the system or paucity of data. There are six sources of uncertainty in evaluating the reliability of environmental and water resources systems: (1) Natural uncertainties associated with random temporal and spatial fluctuations inherent in natural processes, e.g., climatic variability, occurrence of hydrologic extremes; (2) model structure uncertainty which reflects the inability of the simulation model to represent precisely the system's true behavior or process; (3) model parameter uncertainties which reflect the variability in determining the parameters to be used in a model or design; (4) data uncertainties arising due to measurement inaccuracy and errors, inadequacy of the data gaging network, and data handling and transcription errors; (5) computational uncertainties arise due to truncation and rounding off errors in doing calculations; and (6) operational uncertainties associated with construction, manufacturing, maintenance, and other human factors that are not accounted for in the modeling or design procedure. Montanari (2007) identified four types of techniques for assessing the uncertainty of the output of a hydrological model: (a) approximate analytical methods, (b) techniques based on the statistical analysis of model errors, (c) approximate numerical methods/sensitivity analyses, and (d) nonprobabilistic methods. To identify the uncertainty assessment method, one should take into account the following main issues: the type of model whose output uncertainty is to be inferred (simulation, forecasting) and the type of information available (observed data, information about model uncertainty).

7 Emerging Technology for Hydrologic Modeling

New data collection techniques, especially remote sensing, satellites, and radar, have received a great deal of attention and developments since the 1980s. Notable advances have been made in recent years which are gradually alleviating the scarcity of data which is one of the major difficulties in watershed modeling. Space-based technology provides data regarding topography, land use, land cover, soil parameters, initial conditions; inventories of water bodies, such as dams, lakes, swamps, flooded areas, rivers; mapping of snow and ice conditions; water quality parameters; etc. (Engman and Gurney 1991). Satellite data are being increasing used for the estimation of precipitation, temperature, evapotranspiration, and other meteorological inputs. Attempts are underway to estimate river flows from satellite data and these have the potential to overcome the handicaps due to missing river flow data in future.

A multitude of satellites, such as the Landsat Thematic Mapper (TM) Multispectral Scanner (MSS), the European Satellites, and the Indian Remote Sensing satellites, produce imageries which in conjunction with terrain data are successfully providing data for mapping and classification of land use, and vegetative cover. Similarly, the airborne Light Detection and Ranging (LIDAR) technology is being employed to provide real-time flood inundation maps. Special purpose satellites have been launched to measure precipitation, soil moisture, snow cover, and map topography at finer resolutions. Global Positioning System (GPS) has revolutionized field investigations. With the vastly improved capability, remote sensing and space technology is being increasingly coupled with watershed models for a variety of applications.

Physical characteristics of a watershed, such as soils, land use, and topography, vary spatially. Advances in digital mapping have provided essential tools to closely represent the three-dimensional nature of natural landscapes. One such tool is the digital terrain (DTM) or digital elevation (DEM) model. GIS systems now have the capability to automatically extract topographic features, such as basin geometry, stream networks, slope, aspect, flow direction, from raster DEMs.

8 Future Outlook

Mathematical models of watershed hydrology are now the most common and the best tools for all aspects of water resources management. The future is expected to witness a greater and growing integration of these models with environmental and ecological management. With growing technologies triggered by the information revolution, remote sensing technology, GIS, and data base systems, the hydrologic models are getting more sophisticated. These are increasingly being integrated with environmental, economic, and social models.

The future of hydrologic models will be shaped by several simultaneous factors. Two aspects that have begun to drive the application of hydrologic models are: (a) possible adverse impacts of climate change on society and water sector and what is a good adaptation strategy and (b) check the degradation of aquatic ecosystems due to faulty planning and indiscriminate exploitation. These issues cannot be handled without hydrologic models and this is gradually resulting in growing application of such models. In addition, increasing societal demand for integrated environmental management by incorporation of biological, chemical, and physical aspects of the hydrological cycle, rapid advances in remote sensing, and geographical information systems (GIS) are setting the directions for changes and improvements in hydrological models. It is anticipated that the hydrology models will be required to be interfaced with economic and social models in future. These models will also become more global, not only in the sense of spatial scale but also in the sense of hydrologic details (Singh and Woolhiser 2002). New initiatives will lead to enhanced role of models in planning and decision making and growing demand for bundling models in a decision support system (DSS) framework. Users would expect clearer statements of reliability and risk associated with model results and decisions.

References

M.B. Abbott, J.C. Bathurst, J.A. Cunge, P.E. O'Connell, J. Rasmussen, An introduction to the European hydrological system – system Hydrologique European “SHE”. History and philosophy of physically based distributed modelling system. J. Hydrol. **87**, 45–59 (1986)

R.G. Allen, L.S. Pereira, D. Raes, M. Smith, Crop Evapotranspiration, Irrigation and Drainage Paper No. 56, Food and Agriculture Organization, Rome (1998)

ASCE, *Handbook of hydrology,* ASCE Manual and Reports on Engrg. Pract. No. 28 (New York, 1996)

J.C. Bathurst, J.M. Wicks, P.E. O’Connell, The SHE/SHESED basin scale water flow and sediment transport modeling system, Chapter 16, in *Computer Models of Watershed Hydrology*, ed. by V.P. Singh (Water Resources Publications, Littleton, 1995), pp. 563–594

S. Bergstrom, Development and application of a conceptual runoff model for Scandinavian countries. SMHI Reports, No. 7, Norrkoping (1976)

R.P. Betson, Water is watershed runoff? J. Geophys. Res. **69**(8), 1541–1552 (1964)

K. Beven, *Rainfall-Runoff Modelling – The Primer* (Wiley, Chichester, 2001)

K. Beven, J. Freer, Equifinality, data assimilation, and uncertainty estimation in mechanistic estimation of complex environmental systems using the GLUE methodology. J. Hydrol. **249**, 11–29 (2001)

K.J. Beven, M.J. Kirkby, A physically-based variable contributing area model of basin hydrology. Hydrol. Sci. Bull. **24**(1), 43–69 (1979)

R.J.C. Burnash, R.L. Ferral, R.A. McGuire, A generalized streamflow simulation system-conceptual modeling for digital computers. Rep., U. S. Dept. Commerce, National Weather Service and State of California, Department of Water Resource (March, 1973)

J. Chen, H. Shi, B. Sivakumar, M.R. Peart, Population, water, food, energy and dams. Renew. Sust. Energ. Rev. **56**, 18–28 (2016)

N.H. Crawford, R.K. Linsley, Digital simulation in hydrology: Stanford Watershed Model IV. Tech. Rep. No. 39 (Stanford University, Palo Alto, 1966)

D.R. Dawdy, T. O’Donnell, Mathematical models of catchment behavior. J. Hydraul. Div. ASCE **91** (HY4), 123–127 (1965)

J.C.I. Dooge, A general theory of the unit hydrograph. J. Geophys. Res. **64**(2), 241–256 (1959)

O. Duan, V.K. Gupta, S. Sorooshian, Effective and efficient global optimization for conceptual rainfall-runoff models. Water Resourc. Res. **28**(4), 1015–1031 (1992)

T. Dunn, L.B. Leopold, *Water in Environmental Planning* (W.H. Freeman, San Francisco, 1978), p. 818

E.T. Engman, R.J. Gurney, *Remote Sensing in Hydrology* (Chapman and Hall, London, 1991)

H. Gao, et al., Water budget record from Variable Infiltration Capacity (VIC) model Algorithm Theoretical Basis Document for Terrestrial Water Cycle Data Records (2010)

Horton, R.E. (1931). The Field, Scope, and Status of the Science of Hydrology. Pp 189–202. in Trans. AGU, Reports and Papers, Hydrology. National Research Council, Washington, DC

S.K. Jain, B. Storm, J.C. Bathurst, J.C. Refsgaard, R.D. Singh, Application of the SHE to catchments in India – Part 2: Field experiments and simulation studies with the SHE on the Kolar subcatchment of the Narmada river. J. Hydrol. **140**, 25–47 (1992)

X. Liang, D.P. Lettenmaier, E.F. Wood, S.J. Burges, A simple hydrologically based model of land surface water and energy fluxes for general circulation models. J. Geophys. Res. **99**(D7), 14415–14428 (1994)

A. Montanari, What do we mean by ‘uncertainty’? The need for a consistent wording about uncertainty assessment in hydrology. Hydrol. Process. **21**, 841–845 (2007)

J.E. Nash, The form of the instantaneous unit hydrograph. Hydrol. Sci. Bull. **3**, 114–121 (1957)

S.L. Neitsch, J.G. Arnold, J.R. Kiniry, R. Srinivasan, J.R. Williams, *Soil and Water Assessment Tool, User Manual, Version 2000* (Grassland, Soil and Water Research Laboratory, Temple, 2002)

NRC, *Scientific Basis of Water Resource Management* (National Research Council, National Academy Press, Washington D.C, 1982)

NRC, Opportunities in the Hydrologic Sciences, in *Committee on ‘Opportunities in the Hydrologic Sciences’ of National Research Council* (National Academy Press, Washington, DC, 1991)

T. Oki, S. Kanae, Global hydrological cycles and world water resources. Science **313**(5790), 1068–1072 (2006)

D.M. Rockwood, Theory and practice of the SSARR model as related to analyzing and forecasting the response of hydrologic systems, in *Applied Modeling in Catchment Hydrology*, ed. by V.P. Singh (Water Resources Publications, Littleton, 1982), pp. 87–106

L.K. Sherman, Stream flow from rainfall by the unit graph method. Engrg. News Record. **108**, 501–505 (1932)

I.A. Shiklomanov, *World Water Resources: Modern Assessment and Outlook for the 21st Century. (Prepared in the Framework of IHP, UNESCO)* (State Hydrology Institute, St. Petersburg, 1999)

V.P. Singh, *Elementary Hydrology* (Prentice Hall, Engelwood Cliffs, 1992)

V.P. Singh, *Computer Models of Watershed Hydrology* (Water Resources Publications, Littleton, 1995)

V.P. Singh, *Kinematic Wave Modeling in Water Resources: Surface-Water Hydrology* (Wiley, New York, 1996), p. 1399

V.P. Singh, *Kinematic Wave Modeling in Water Resources: Environmental Hydrology* (Wiley, New York, 1997), p. 830

V.P. Singh, D.K. Frevert, *Mathematical Models of Small Watershed Hydrology and Applications* (Water Resources Publications, Littleton, 2002a), p. 950

V.P. Singh, D.K. Frevert, *Watershed Models* (CRC Press, Boca Raton, 2002b), p. 653

V.P. Singh, D.K. Frevert, *Mathematical Models of Large Watershed Hydrology* (Water Resources Publications, Littleton, 2002c), p. 891

V.P. Singh, D.A. Woolhiser, Mathematical modeling of watershed hydrology. J. Hydrol. Eng. ASCE **7**(4), 270–292 (2002)

V.P. Singh, D.K. Frevert, *Watershed Models* (CRC Press, Boca Raton, 2006)

S. Sorooshian, V.K. Gupta, Model calibration. Chapter 2, in *Computer Models of Watershed Hydrology*, ed. by V.P. Singh (Water Resources Publications, Littleton, 1995), pp. 23–68

M. Sugawara, The flood forecasting by a series storage type model. *Internatl Symposium Floods and their Computation*, pp. 1–6, Leningrad, U.S.S.R., 1967

M. Sugawara, et al., Tank model and its application to Bird Creek, Wollombi Brook, Bikin River, Kitsu River, Sanga River and Nam Mune. Research Note of the National Res. Center for Disaster Prevention, No. 11, (1974), pp. 1–64

C.V. Theis, The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage: American Geophysical Union Transactions, 16th Annual Meeting, vol. 16, pt. 2 (1935), p. 519–524

E. Todini, The ARNO rainfall-runoff model. J. Hydrol. **175**, 339–382 (1996)

E. Todini, Hydrological catchment modelling: past, present and future. Hydrol. Earth Syst. Sci. **11**, 468–482 (2007). https://doi.org/10.5194/hess-11-468-2007

E.F. Wood et al., A land-surface hydrology parameterization with subgrid variability for general-circulation models. J. Geophys. Res.-Atmos. **97**(D3), 2717–2728 (1992)

R.A. Wurbs, Dissemination of generalized water resources models in the United States. Water Int. **23**, 190–198 (1998)

R.J. Zhao, Y.-L. Zhuang, L.R. Fang, X.R. Liu, Q.S. Zhang, The Xinanjiang model. Proceedings, Oxford Symposium on Hydrological Forecasting, IASH Pub. No. 129 (1980), pp. 351–356