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Hydrologic modeling: progress and future directions

Vijay P. Singh*

Abstract

Briefly tracing the history of hydrologic modeling, this paper discusses the progress that has been achieved in hydrologic modeling since the advent of computer and what the future may have in store for hydrologic modeling. Hydrologic progress can be described through the developments in data collection and processing, concepts and theories, integration with allied sciences, computational and analysis tools, and models and model results. It is argued that with the aid of new information gathering and computational tools, hydrology will witness greater integration with both technical and non-technical areas and increasing applications of information technology tools. Furthermore, hydrology will play an increasingly important role in meeting grand challenges of the twenty-first century, such as food security, water security, energy security, health security, ecosystem security, and sustainable development.

Keywords: Hydrologic models, Data processing, Computational tools, Hydrologic advances, Future outlook

Introduction

Hydrology has a long history dating back to several millennia (Biswas 1970). However, the birth of hydrologic modeling can be traced to the 1850s when Mulvany (1850) developed a method for computing the time of concentration and hence the rational method for computing peak discharge which is still used for urban drainage design, Darcy (1856) who conducted experiments on flow-through sands and developed what is now referred to as Darcy's law which laid the foundation of quantitative groundwater hydrology, and Fick's first law which states that under steady-state conditions the diffusive flux is proportional to the concentration gradient (spatial) which laid the foundation of water quality hydrology. About half a century earlier, Dalton (1802) formulated the law of evaporation which states that the rate of evaporation is directly proportional to the difference between saturation vapor pressure at the water surface and the actual vapor pressure in the air. This law constituted the foundation for developing the physics of evaporation. For a period of over a century until the 1960s, many groundbreaking advances in modeling different components of the hydrologic cycle were made. Some of these advances were based on the laws of mathematical physics and some had their basis in laboratory and/or field experiments. The current state of hydrologic science and engineering owes a great deal to the pre-1960 advances. The handbook of applied hydrology edited by Chow (1964) provided an up-to-date account of hydrologic advances until the 1960s, whereas the handbook of hydrology edited by Maidment (1993) and the encyclopedia of hydrology and water resources edited by Hershey and Fairbridge (1998) dealt with advances that occurred during the intervening period. Singh and Woolhiser (2002) provided a historical account of developments that occurred in modeling different components of the hydrologic cycle.

The decade of the 1960s witnessed the birth of computer revolution and hydrologic modeling took a giant leap forward. The computer provided the power for doing computations that was not available before. As a result, a new branch of hydrology, called digital or numerical hydrology, was born. Another branch that came into being was statistical or stochastic hydrology that often required analyses of large volumes of data. Then, several major advances ensued. First, simulation of the entire hydrologic cycle became a reality, as

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*Correspondence: vsingh@tamu.edu
Department of Biological and Agricultural Engineering & Zachry Department of Civil Engineering, Texas A&M University, 321 Scoates Hall, 2117 TAMU, College Station, TX 77843-2117, USA

illustrated by the development of the Stanford Watershed Model (Crawford and Linsley 1966) which was followed in the decades to come by umpteen watershed models that were developed all over the world (Singh 1995; Singh and Frevert 2002a, b, 2006). Second, optimization or operations research techniques were developed, which formed the basis for reservoir management and operation as well as river basin simulation. Some of these techniques were also used for calibrating hydrologic models (Beven 2001; Duan et al. 2003). Third, two- and three-dimensional modeling was made possible because of advances in numerical mathematics. Consequently, two- and three-dimensional models of groundwater as well as of infiltration and soil water flow were developed (Bear 1979; Pinder and Celia 2006; Remson et al. 1971). Fourth, simultaneous simulation of water flow and sediment and pollutant transport was undertaken; likewise, simultaneous simulation of different phases of flow, such as liquid and gaseous, was done (Bear and Verruijt 1987; Charbeneau 2000). Fifth, modeling at large spatial scales, such as a large river basin like the Mississippi, and that at small temporal scales, such as seconds or minutes, was undertaken (Molley and Wesse 2009; Sorooshian et al. 2008). Sixth, integration of hydrology with allied sciences became possible. For example, it was possible to couple hydrology with climatology for precipitation modeling and forecasting (Sorooshian et al. 2008), with geomorphology for river basin geometric representation (Baker et al. 1988; Bates and Lane 2002; Beven and Kirkby 1993), with hydraulics for describing flow characteristics (Singh 1996), with soil physics for quantifying soil texture and structure (Bohne 2005; Guymon 1994; Miyazaki 2006; Smith et al. 2002; Singh 1997), and with geology for aquifer characterization (Delleur 1999; Fetter 1980; Singh 2017a, b, c). The coupling of hydrology with ecosystems gave rise to ecohydrology (Eagleson 2002; Gordon et al. 2006; Rodriguez-Iturbe and Porporato 2004). Climate change and global warming became part of hydrologic analysis (Arnell 1997). A more detailed account of developments in different components of the hydrologic cycle is given in Singh (2013, 2014, 2015, 2017a).

In the decades that followed, computing prowess increased exponentially and hydrology began maturing and expanding in both depth (vertically) and breadth (horizontally). Tools from fluid mechanics, statistics, information theory, and mathematics were employed and became part of hydrology (Bras and Rodriguez-Iturbe 1985; Clarke 1998; Gelhar 1993; Mays and Tung 1992; Singh et al. 2007; Tung and Yen 2005). Further, computer also made possible the development of user-friendly software, and tools for date acquisition, storage, retrieval, processing, and dissemination (Croley 1980; Hoggan 1989). Remote sensing tools, such as radar and satellites, came into being that made possible to acquire spatial data for large areas (Engman and Gurney 1991; Hogg et al. 2017; Lakshmi 2017; Lakshmi et al. 2015). Likewise, geographical information systems (GIS) were developed for processing huge quantities of raster and vector data (Maidment 2002). The past two decades witnessed the development of artificial neural networks, fuzzy logic, genetic programming, and wavelet models (Kumar et al. 2006; Ross 2010; Sen 2010; Tayfur 2012). New theories borrowed from other areas were introduced in hydrology. Examples of these theories are entropy theory (Singh 2013, 2014, 2015, 2016, 2017b), copula theory (Singh and Zhang 2018), chaos theory (Sivakumar 2017), network theory (Sivakumar et al. 2017), and catastrophe theory (Poston and Stewart 1978; Zeeman 1978). These theories will find increasing place in hydrologic modeling in the years ahead.

Another area that mushroomed subsequent to the precomputer era is instrumentation. New instruments which were more accurate and sophisticated were developed for measuring all kinds of hydrologic variables, such as velocity, soil moisture, water and air quality parameters, fluxes in porous media, energy fluxes, and so on. Further, instrumentation for data transmission from place of measurement to place of storage, processing, storage, retrieval, and dissemination became highly robust and accessible (Liang et al. 2013; Sivakumar and Berndtsson 2010).

The objective of this paper, therefore, is to provide a snapshot of major advances that have occurred for over a century and a half, discuss where hydrology is headed as a science and engineering, and conclude with a personal reflection on future outlook.

History of hydrologic developments

There have been a large number of developments in hydrology since the 1850s, so it will be difficult to do justice to describe all of them. Therefore, only a snapshot of some of the major developments from a personal perspective will be provided. For convenience of easy reference, these developments will be organized topic-wise rather than chronologically.

Watershed geomorphology

In 1945 Horton, derived a set of empirical laws that are now called Horton laws which laid the foundation of quantitative geomorphology. These laws were the law of channel numbers, law of channel lengths, and law of stream slopes. He developed a scheme for channel and basin ordering, called Horton ordering. Horton (1932) also defined drainage density and length of overland flow. He investigated landform development and streamflow generation dominated by overland flow. Strahler

(1952) modified Horton's method for ordering channel networks which is now referred to as Horton–Strahler ordering scheme. Schumm (1956) developed the law of stream areas. Because discharge is highly correlated with drainage area, as shown by Hack (1957) for mean annual discharge and Leopold and Miller (1956), and Gray and Wigham (1970), a law of discharge can be formulated as shown by Singh (1992). Strahler (1957) formulated the law of drainage basin similarity, but Gray (1961) showed that not all basins possessed geometric similarity. Gray (1961) established the relation between drainage area and length which was also investigated by Smart and Surkan (1967). Shreve (1966) developed a statistical law of channel numbers. Using the theory of minimum energy dissipation rate, Yang (1971) developed the law of average stream fall. Much of the progress made in subsequent years draws heavily from these foundational contributions. Fitzpatrick (2017) has reported on watershed geomorphologic characteristics. Smith (1974) derived hydraulic geometry of steady state channels from conservation principles and sediment transport laws. Using entropy theory and theory of minimum energy dissipation rate, Singh et al. (2003a, b) derived a hierarchy of downstream hydraulic geometry and Singh and Zhang (2008a, b) upstream hydraulic geometry. Applications of channel network are included in Beven and Kirkby (1993) and flood geomorphology is presented in Baker et al. (1988). Rodriguez-Iturbe and Rinaldo (2001) have described river basins using fractal geometry. The watershed geomorphology has played a fundamental role in developing runoff prediction models for ungauged basins (Bloschl et al. 2013; Wagner et al. 2004).

Hydraulic geometry

Hydraulic geometry is of two types, at-a-station and downstream, and encompasses relations of channel width, depth, velocity, roughness, and slope each with discharge (Wolman 1955). Leopold and Maddock (1953) derived these hydraulic geometry relations which are of power form. Because of their great practical value in design of stable channels, river flow control works, river improvement works, and irrigation schemes, there is a large body of literature describing the derivation of these relations using different types of theories, including regime theory (Blench 1952), tractive force theory (Lane 1955), minimum entropy production theory (Leopold and Langbein 1962), stability theory (Stebbings 1963), minimum variance theory (Langbein 1964), minimum channel mobility theory (Dou 1964), minimum energy degradation theory (Brebner and Wilson 1967), threshold geometry theory (Li 1974), hydrodynamic theory (1974), minimum stream power theory (Chang 1980), maximum sediment discharge and Froude number theory (Ramette 1980), maximum sediment discharge theory (White et al. 1982), maximum friction theory (Davies and Sutherland 1983), minimum unit stream power theory (Yang and Song 1986), thermodynamic theory (Yalin and da Silva 1997, 1999), minimum energy dissipation theory (Rodriguez-Iturbe et al. 1992), principle of least action (Huang and Nanson 2000), and entropy theory (Deng and Zhang 1964; Singh et al. 2003a, b; Singh and Zhang 2008a, b). Each theory leads to unique hydraulic geometry relations, meaning different values of exponents. Singh (2003) has discussed characteristics of these relations with regard to their basis, tendency to equilibrium state, limitations of the equilibrium assumption, validity of power relations, stability of exponents in power relations, effect of channel patterns, effect of stream size, dependence of exponents on climatic and environmental factors and land use, extension to drainage basins, and impact of boundary conditions.

Surface runoff

In 1850, Mulvany developed a method, called rational method, for computing peak discharge due to a rainfall event with uniform intensity and duration equal to or greater than the time of concentration. The method was meant for small urban watersheds which are in use for urban drainage design to date. St. Venant de (1871) derived equations for modeling surface flow and these equations are now called St. Venant equations. Two decades later, Manning (1895) developed an equation for computing flow velocity in open channels. Imbeau (1892) developed a relation between storm runoff peak and rainfall intensity. Sherman (1932) developed the unit hydrograph concept which laid the foundation of linear systems hydrology. Horton (1939) derived a semi-empirical formula for overland flow. Barnes (1940) developed a technique for hydrograph separation. Applying hydraulic principles, Keulegan (1944) showed the adequacy of simplified momentum equation for modeling overland flow. Izzard (1944) conducted experiments on overland flow on paved surfaces. Clark (1945) developed a unit hydrograph method for deriving the rainfall–runoff hydrograph. These contributions laid the foundation for conceptual as well as physically based rainfall–runoff modeling. However, for application of these methods the amount of surface runoff was assumed to be known and, therefore, rainfall excess was known.

In 1956, the Soil Conservation Service (SCS) [now called National Resources Conservation Service (NRCS)] of the U.S. Department of Agriculture (USDA) developed a method, now called SCS-Curve Number (CN) method, based on a large amount of data, for computing the amount of runoff generated by a rainfall event, taking into account abstractions, antecedent soil moisture condition, hydrologic condition of land use and land cover, and soil type through curve number. This method is still quite popular for determining the amount of runoff or rainfall excess from small and medium agricultural watersheds, and has been extended to urban and forested watersheds. Nielsen et al. (1959) investigated the source-area contribution to runoff.

In 1956, the U.S. Army Corps of Engineers published the summary report of the snow investigations as a book entitled "Snow Hydrology" that laid the foundation for much of the work that has since ensued. The book described virtually all aspects of the snow environment. Martinec (1960) developed a degree-day method for determining snowmelt. Anderson (1968) developed and tested snowpack energy balance equations. Colbeck (1972) developed a theory of water percolation in snow and Colbeck (1975) developed a theory of water movement through a layered snowpack. Gray and Prowse (1993) provided an excellent discussion of different aspects of snow and floating ice. Singh et al. (1997a, b) developed the kinematic wave theory of vertical movement of snowmelt water through snowpack and of saturated basal flow in a snowpack. Kuchment (2017) proved an excellent review of snowmelt runoff generation and modeling. Singh et al. (2011) prepared an encyclopedia of snow, ice and glaciers.

Nash (1957) developed a theory of instantaneous unit hydrograph (IUH) that led to what is now called the Nash model. Nash (1959) also developed the theory of moments for determining his model parameters. Dooge (1959) developed the generalized unit hydrograph theory that included the Nash IUH theory as a special case. These IUH theories led to the development of systems hydrology detailed by Singh (1988, 1989) in which systems techniques can be applied to flow routing, base flow, water quality routing, erosion and sediment transport. Combining laws of geomorphology with the IUH theory Rodriguez-Iturbe and Valdes (1979) developed the geomorphologic unit hydrograph that has since received a great deal of attention and is now frequently used in practice.

Physically based surface runoff modeling was based on the St. Venant equations and simplifications thereof whose solutions required the use of numerical algorithms and became popular in the 1960s and the ensuing decades. Depending on the simplification, these equations give rise to five types of waves: dynamic waves, steady dynamic waves, gravity waves, diffusive waves, and kinematic waves, and hence five types of models. Using different techniques, Lighthill and Whitham (1955), Iwagaki (1955), Woolhiser and Liggett (1967), Ponce and Simons (1977), Menendez and Norscini (1982), and Ferrick (1985) analyzed the characteristics of these waves. They showed that diffusive and kinematic wave approximations would suffice for most cases. Singh (2017a, b, c) presented the kinematic wave theory of surface runoff. Woolhiser and Liggett (1967) derived the kinematic wave number which served as a criterion for the kinematic wave approximation. This work gave the real impetus to the popularity of kinematic wave approximation. Morris and Woolhiser (1980) revised the kinematic wave number with the use of Froude number. Singh (1994) derived the error differential equation for judging the accuracy of kinematic and diffusive approximations. Moramarco et al. (2008a, b) made a comprehensive analysis of the accuracy of kinematic wave and diffusion wave approximations. Kibler and Woolhiser (1972) developed the kinematic cascade. Smith and Woolhiser (1971) explicitly incorporated infiltration in overland flow modeling. Berod et al. (1999) developed a geomorphologic kinematic wave model. These investigations established that the kinematic wave approximation would be sufficiently accurate for surface runoff modeling and has since been a standard technique. Singh (1996) prepared two treatises on kinematic wave modeling in surface water hydrology and environmental hydrology that comprehensively summarize the kinematic wave literature.

Reservoir and channel flow routing

Analogous to surface runoff modeling, both hydrologic systems and physically based techniques have been applied to route flows through reservoirs and channels. Puls (1928) presented a method for reservoir flow routing. MeCarthy and others (U.S. Army Corps of Engineers 1936) developed the Muskingum method for routing of flow in channels. Kalinin and Miljukov (1957) developed a unit hydrograph model for channel flow routing. Cunge (1969) developed a method for estimating the Muskingum method parameters from hydraulic and channel geometry characteristics. Since then, the Muskingum method has been a popular method and its several variants have been developed. Koussis (2009) provided an assessment and a review of the hydraulics of storage flood routing 70 years after the introduction of the Muskingum method.

Stoker (1953) and Isaacson et al. (1954, 1956) used the complete St. Venant equations for flood routing in the Ohio River. Abbott (1976) and Grupert (1976) summarized the flood routing models. Fread (1984) developed a one-dimensional dynamic wave model in a single or branched waterway. Linear forms of the St. Venant equations were employed since the work of Dooge (1967), and Dooge and Harley (1967). Kundzewicz (1986) discussed physically based flow routing methods. Abbott (1979) presented numerical methods for solving free surface flow equations.

Hayami (1951) employed diffusion wave approximation for flood routing. Lighthill and Whitham (1955) showed that diffusion waves were described by a convection–diffusion equation. Cunge (1969) showed the connection between Muskingum method and convection–diffusion equation. Huang (1978) used a finite difference solution of kinematic wave equation for routing flows in channels. Singh (1996) has given a full account of different routing methods. Perumal and Price (2017) have reviewed reservoir and channel routing.

Interception and depression storage

Interception loss in humid forested watersheds may account for as much as 25% of annual precipitation. Helvey and Patrick (1965) found that this loss might be of the order of 15 cm for such watersheds. Horton (1919) developed a series of empirical equations for computing storm interception for a variety of vegetative covers. Linsley et al. (1949) developed an exponential type model for computing interception by vegetation. Merriam (1960) modified the Horton model. Bultot et al. (1972) derived empirical relationships for computing interception loss. Deguchi et al. (2006) computed the influence of seasonal changes in canopy structure on infiltration loss. Gash (1979) developed an analytical model for infiltration loss by forests. Gerrits et al. (2010) discussed the spatial and temporal variability of canopy and forest floor interception in a beech forest.

Horton (1939) and Holtan (1945) empirically evaluated depression storage. Turner (1967) derived curves for depression storage intensity as a function of time for different antecedent conditions. Using a digital surface model, Ullah and Dickinson (1979a, b) investigated geometric properties of depressions for hydrologic modeling. Soil Conservation Service (1956) included interception and depression storage losses as a fraction of maximum soil moisture retention capacity in the SCS-CN model (Mishra and Singh 2010c). Linsley et al. (1949) presented an exponential model for computing surface depression storage for a given effective rainfall. Borselli and Torri (2010) discussed the relationship between surface storage and soil roughness and slope on impervious areas and suggested an empirical model.

Evaporation

Evaporation and evapotranspiration are amongst the most important components of the hydrologic cycle and their significance increases with the increase in timescale. Richardson (1931) and Cummings (1935) investigated evaporation from lakes. Thornthwaite (1948) developed an empirical model for computing monthly evaporation which is still used. Combining energy balance and mass transfer, Penman (1948) developed what is now referred to as the combination method for computing evaporation from saturated water bodies as well as vegetated surfaces. The Penman method laid the foundation for subsequent developments in the evaporation field. Budyko (1955, 1974) prepared an atlas of heat balance of Earth. Monteith (1965, 1973, 1981) modified the Penman method which is now called the Penman–Monteith method. Morton (1965, 1969) developed a method, called complementary method, for computing regional evaporation. Priestley and Taylor (1972) developed an equation for computing evaporation. Doorenbos and Pruitt (1977) developed methods for computing evapotranspiration and hence crop water requirements. Jensen and Allen (2016) have comprehensively summarized methods for computing evaporation, evapotranspiration, and irrigation water requirements. Hobbins and Huntington (2017) have provided an up-to-date account of evapotranspiration and evaporative demand.

Infiltration and soil water flow

Infiltration is fundamental for computing surface runoff modeling, groundwater recharge, and agricultural irrigation. In 1911, using physical principles Green and Ampt developed a formula for computing infiltration capacity rate which is one of the most commonly used infiltration formulae today. Richards (1931) derived what is now called Richards equation for modeling flow-through unsaturated soils (Richards 1931, 1965). This equation laid the foundation for vadose zone hydrology. Kostiakov (1932) derived an empirical equation for computing infiltration capacity rate. Horton (1933, 1939) developed a theory of infiltration which was based on a hydrologic systems concept. Horton (1940) tested his infiltration theory on experimental plots. Philip (1957) developed a theory of infiltration that led to Philip infiltration equation. Mein and Larson (1973) developed a model for computing infiltration under steady rain. Fok (1987) summarized developments in infiltration and its application. Singh and Yu (1990) developed a generalized framework for infiltration and derived several popular infiltration models as special cases. Smith et al. (2002) prepared a treatise on infiltration theory for hydrologic applications. Corradini et al. (2017) have reviewed the state of art of infiltration modeling.

Subsurface flow

Subsurface flow is also referred to interflow and is sometimes divided into quick interflow and delayed interflow (Chow 1964) and generates subsurface runoff. Lowdermilk (1934), Hursh and Brater (1944), Hursh (1936) observed subsurface flow as part runoff hydrograph in humid regions. Hoover and Hursh (1943), and Hursh (1944) showed that subsurface storm flow constituted a significant portion of streamflow in humid areas. Remson et al. (1960) and Hewlett (1961a, b) developed concepts of source area and partial area that contributed to streamflow generation and showed that downslope unsaturated flow could contribute to streamside saturation and hence generate streamflow.

Macropores and preferential flow paths can significantly contribute to subsurface flow under certain conditions. Germann (1985, 2014) reviewed preferential flow and has given a full account based on the kinematic wave theory. Macropores are pipe structures in soil matrix and result from physical processes, such as erosion due to desiccation cracking and biological activity such as animal burrows and decaying plant root channels. Tanaka et al. (1988) found that more than 90% of runoff originated from below the ground mainly through pipe flow. Leaney et al. (1993) noted that winter stormflow reached the channel primarily through macropores. Newman et al. (1998) inferred that most of the lateral subsurface flow occurred in B horizon through macropores. Thus, subsurface flow-through macropores and other preferential flow paths can be a major contributor to streamflow generation.

Groundwater

In 1852, Darcy conducted experiments on flow-through sands and developed what is now referred to as Darcy's law which laid the foundation of quantitative groundwater hydrology. Theis (1935) derived the relation between drawdown in piezometric head and pump discharge from a well. Muskat (1937) published a treatise on flow of homogeneous fluids in porous media. Hubbert (1940) described the theory of groundwater motion. Meinzer (1942) edited a book on hydrology. Jacob (1943, 1944) established the relationship between infiltration and groundwater. Dynamic changes in streamside groundwater flow were reported by Roessel (1950). Hantush and Jacob (1955) derived equations for unsteady radial flow in leaky aquifers. Hantush (1960, 1964) revised the theory of leaky aquifers. Freeze (1975) presented a stochastic conceptual analysis of one-dimensional groundwater flow in nonuniform homogeneous media. The field of groundwater has since expanded dramatically. A large number of books have been published that detail hydrogeological, scientific, numerical, and engineering aspects of groundwater. Freeze and Cherry (1979) discussed groundwater and contamination from a hydrogeology perspective (Fair and Hatch 1933), Bear (1979) hydraulics of groundwater, Todd (1980) hydrology of groundwater, Domenico and Schwartz (1990) physical and chemical hydrogeology of groundwater, Gelhar (1993) stochastic aspects, and Delleur (1999) groundwater engineering. Pham and Tsai (2017) have reviewed groundwater modeling.

Erosion and sediment yield

Cook (1936) identified major factors that impact erosion by water. Considering the effect of slope steepness and slope length, Zingg (1940) developed an empirical equation for calculating field soil loss. Smith (1941) developed an equation considering additional factors, such as cropping system and support practices. Browning et al. (1947) included soil erodibility and management factor in the Smith equation. Smith and Whitt (1948) developed an equation as product of average annual soil loss for claypan soils for a specific rotation, slope length, slope steepness, and row direction; slope steepness; slope length; soil erodibility; and support practice. Musgrave (1947) developed an equation considering factors reflecting the effect of rainfall and surface runoff as impacted by slope steepness and length, and vegetative cover. Using 10,000 plot years of basic runoff and soil loss data, Wischmeier and Smith (1957, 1965, 1978) developed the Universal Soil Loss Equation (USLE) that has undergone several revisions and its new incarnation is Revised USLE (Renard et al. 1997). A comprehensive account of soil erosion prediction and prediction is treated in Soil Conservation Society of America (1977).

Soil erosion by water was also investigated using hydraulic equations. Foster and Meyer (1972) derived an equation for sediment transport under steady-state condition for rill and inter-rill detachment and/or deposition. Hjelmfelt et al. (1975) considered the kinematic wave formulation of erosion on a plane. Singh and Regl (1983a, b) developed the kinematic wave theory for erosion due to rainfall. Considering surface flow and rain-drop impact, Hairsine and Rose (1992a, b) derived a model for soil erosion which was based on the equation developed by Rose et al. (1983a, b). Both USLE and physically based equations of soil erosion have been included in a wide range of watershed hydrology or erosion models which have recently been reviewed by Pandey et al. (2016). Flanagan and Huang (2017) have provided a review of soil erosion.

Sediment transport

There is vast literature on sediment transport in reservoirs, rivers and channels that has culminated into a new field of sedimentation engineering. A number of formulae have been developed for bed load and suspended load. The earliest bed load formula was developed by DuBoys (1879) assuming uniform grains moving as series of layers. Shields (1936) developed a criterion for incipient motion of sediment particles. Assuming graded sediment, Meyer-Peter and Muller (1948) developed a formula for bed load sediment transport. With extensive analysis based on fluid mechanics and probability theory, Einstein (1942, 1950) developed a bed load function for sediment transport in open channels. Brown (1950) modified the Einstein formula. Parker et al. (1982) developed a bed load equation for coarse-bed material and gravel-bed rivers.

Einstein (1950) computed suspended sediment discharge considering vertical variations in velocity and sediment concentration. Colby (1964) determined bed-material discharge as a function of mean flow velocity, depth, mean sediment size, water temperature and concentration of fine sediment. Using physical laws, Bagnold (1966) developed an approach for transport of sediment. Engelund and Hansen (1967) derived a sediment transport equation using the concept of stream power. Yang (1972) developed a bed-material load equation based on the rate of energy dissipation of flow. Ackers and White (1973) developed an equation to sediment transport in open channel flow as a function of mobility factor. The state of art of sedimentation engineering was provided by Vanoni (1975). Simons and Senturk (1977) discussed sediment transport technology. An up-to-date account of sedimentation engineering, including processes, measurements, modeling, and practice, was presented by Garcia (2008). Papanicolaou and Abban (2017) have provided an up-to-date account of channel erosion and sediment transport, whereas Sarkar (2017) has discussed sedimentation in floodplains, lakes and reservoirs.

Pollutant transport

Water quality has always been a major concern but in hydrology it started receiving attention since the 1970s with the establishment of Environmental Protection Agency (EPA). Tremendous work has since been done in the hydrology of surface water, vadose zone, and groundwater quality. Both physical and biochemical aspects of water quality have been emphasized. Water quality has been investigated using both systems approach as well as science-based approach. In 1925 Streeter and Phelps derived a model for dissolved oxygen in surface waters. Taylor (1953, 1954) developed a theory of dispersion of matter in flow in pipes. Elder (1959) determined dispersion in turbulent open channels. Fisher (1967, 1968) described mixing in inland and coastal streams. Yotsukura and Sayre (1976) developed a model for transverse mixing in natural channels. Yotsukura (1977) derived equations for solute transport in turbulent natural flow. Thomann (1972) provided a treatise on systems approach to water quality management. Rinaldi et al. (1979) prepared a treatise on river water quality modeling and control. Tchobanoglous and Schroeder (1985) comprehensively discussed water quality characteristics, modeling and modification. Thomann and Mueller (1987) presented principles of surface water quality modeling and control. Ji (2008) treated the hydrodynamic modeling of water quality of rivers, lakes, and estuaries.

De Josselin de Jong (1958) developed a random walk model for describing longitudinal and transverse dispersion in granular materials. (Scheidegger 1961) described the general theory of dispersion in porous media. Bear and Verruijt (1987) presented the theory and applications of transport in porous media. Palmer (1992) and Fetter (1999) discussed principles of contaminant hydrogeology (Fick 1855). Charbeneau (2000) discussed the hydraulics of groundwater and pollutant transport. Gelhar (1993) presented stochastic method in subsurface hydrology.

Agricultural chemicals, fertilizers, weedicides, and pesticides are applied to agricultural fields for increasing crop productivity. Many chemical compounds generated by industries are sometimes dumped on the soil surface. Sometimes there is a chemical spill on the surface. Whatever the source or cause, some of the pollutants enter the soil, contaminant it, and percolate down to contaminate the ground water. Earliest attempts to model solute transport in the unsaturated zone were made by soil scientists. Nielsen and Biggar (1961) discussed a wide range of problems related to miscible displacement and pollutant transport. Knisel (1980) reported a field-scale model for chemicals, runoff, erosion from agricultural management systems, called CREAMS. Leonard et al. (1987) presented a model, called GLEAMS: groundwater loading effects of agricultural systems. Carlsel et al. (1985) developed a pesticide root zone model (PRZM). Shaffer and Larson (1987) reported a soil–crop simulation model for nitrogen, tillage, and crop-residue management, called NTRM. Smith (1990) described an integrated simulation model for transport of nonpoint source pollutant at field scale, called OPUS. In the 1980s, the U.S. Department of Agriculture-Agricultural Research Service reviewed the state of water quality modeling and started to develop a model that would address a wide range of agricultural management practices. The resulting model was Root-Zone Water Quality Model (RZWQM) (RZWQM Team 1992) which is a physical, chemical, and biological process model and has since undergone a number of revisions. This model is more advanced than any of the other models developed before. Zamani and Bombardelli (2014) presented analytical solutions for transport of non-reactive species in unsaturated soil. Zamani and Ginn (2017) reviewed the state of art of pollutant transport in vadose zone as well as numerical models, including SUTRA (Voss and Provost 2002), VS2DT (Healy 1990), HYDRUS (Radcliffe and Simunek 2010), among others.

Reservoir operation

For reservoir design, operation, and management, water surplus, deficit, range, and storage are computed. Two different tracks, deterministic and stochastic, were pursued for reservoir operation and management. The deterministic track entailed various optimization techniques. Indeed these techniques gave birth to the field of water resource systems engineering. One of the earliest studies in this field was by Mass et al. (1962) under the Harvard water Program. Hall and Dracup (1970) authored a popular book on water resources systems engineering. With the advent of computers and their growing computational power, this field took a giant leap in the 1970s and 1980s. As a result, numerous popular books and other publications enriched the literature. A sample of books includes those by Haimes (1977), Loucks et al. (1981), and Meta Systems, Inc. (1975). Lund et al. (2017) have provided reservoir operation design. The optimization techniques employed for analysis and synthesis of water resources systems allowed to integrate seemingly disparate areas, such as economics, politics, decision-making, environmental science, and ecology with hydrology, hydraulics, and water resources engineering. Thus, it was possible to undertake planning of water resources at the river basin scale.

The stochastic track assumed that water surplus, deficit, range, and storage needed for reservoir design, operation and management varies randomly. Therefore, the probability theory was applied to analyze them and compute their probabilities. Three methods have been used for design of reservoirs: empirical, experimental or data generation, and analytical. The best example of an empirical method is the mass curve or Rippl diagram applied in England in 1883. The data generation method is also referred to as Monte Carlo method, synthetic hydrology, or operational hydrology method. Range analysis is an example of the analytical method. Yevjevich (1972) discussed range analysis. Hurst (1951) investigated long-term storage capacities of reservoirs which led to what is now known as Hurst coefficient. Thomas and Fiering (1962) presented a mathematical synthesis of streamflow sequences for analysis of river basins. Matalas (1967) reported a mathematical assessment of synthetic hydrology. Mandelbrot and Wallis (1969) performed computer experiments with fractional Gaussian noises. Valencia and Schaake (1972) presented disaggregation processes in hydrology.

The probability theory of reservoir storage or storage theory was developed in the 1950s, although Saverenskiy (1940) computed probabilities of high and low flows through a probability routing method. Moran (1954) initiated the storage theory considering serially independent reservoir inflows with a fixed probability distribution. Moran's theory is based on Markov process. Gould (1961) incorporated failures within a year. Lloyd (1963) developed a probabilistic storage theory considering serially dependent flows. Kottegoda (1980) discussed stochastic methods for water resources systems, including reservoirs.

Flood frequency analysis

Hazen (1930) presented a treatise on frequency analysis of both maximum and minimum flood flows. Foster (1934) derived duration curves. Kendall (1938) derived a measure of rank correlation. Weibull (1939) presented a formula for plotting probability against its quantile. Gumbel (1941) derived a distribution, now called Gumbel distribution, for frequency analysis of annual maximum flows. This distribution is the extreme value type one distribution (Boughton 1980). Langbein (1949) analyzed flood frequencies using partial duration series. Chow (1951) presented a general formula for frequency analysis based on frequency factor. Jenkinson (1955) derived a general extreme value distribution for frequency analysis of meteorological data. Gringorten (1963) presented a formula for plotting positions.

Hershfield (1962) prepared rainfall frequency atlas of the United States for durations from 30 min to 24 h and return periods from 1 to 100 years, published as U.S. Weather Bureau Technical Report 40, Washington, D.C. NERC (1975) presented a treatise of flood studies. Houghton (1978) presented the Wakeby distribution for modeling flood flows. Todorovic (1978) developed a methodology for frequency analysis using random number of random variables. Landwehr et al. (1979, 1980) developed the probability weighted moments for distribution parameter estimation. Cunnane (1978, 1989) provided a review of frequency distributions and presented a less biased plotting position formula. Hosking (1990) developed the L-moments method for estimating frequency distribution parameters. Dalrymple (1960) developed a flood index method for regional flood frequency analysis. Kite (1988) presented different methods of flood frequencies and risk analysis. Rao and Hamed (2000) provided a comprehensive discussion of flood frequency distributions. Stedinger (2017) has presented an up-to-date account of flood frequency distributions and Ouarda (2017) of regional flood frequency modeling. Vogel and Castellarin (2017) have discussed risk, reliability, and return periods for hydrologic design.

Drought analysis

Recent years have witnessed much interest in drought modeling, partly because of the uncertainty about water availability and supply triggered by climate change. Many areas in the world are experiencing drought or a drought-like situation or downright scarcity. Drought has been defined in different ways. The World Meteorological Organization (WMO 1986) defined drought as a sustained, extended deficiency in precipitation. The

Food and Agriculture Organization (FAO 1983) of the United Nations defined drought hazard as 'the percentage of years when crops fail from lack of moisture. Gumbel (1963) defined drought as the smallest annual value of daily streamflow, whereas Palmer (1965) described drought as a significant deviation from the normal hydrologic conditions of an area. Linsley et al. (1959) defined drought as a sustained period of time without significant rainfall. Clearly, the drought definition varies with the variable used to define it. Mishra and Singh (2010a) provided a comprehensive discussion of drought concepts.

Drought modeling encompasses characterization, space–time analysis, forecasting, and climate change impact. The variables associated with drought are precipitation for hydrometeorological drought, streamflow or lake level for hydrologic drought, groundwater level for groundwater drought, and soil moisture for agricultural drought. The main drought characteristics are intensity, duration, severity, and spatial extent. Several indices have been defined, based on combinations of precipitation, temperature, soil moisture, and evapotranspiration, to characterize, assess, and forecast droughts. Commonly used indices are: Palmer severity drought index (PDSI) (Palmer 1965), Crop Moisture Index (CMI) (McKee et al. 1993), Soil Moisture Drought Index (SMDI) (Hollinger et al. 1993), and Vegetation Index (VI) (Liu and Kogan, 1996). Also, climatic indices, such as El Nino Southern Oscillation (ENSO), Southern Oscillation Index (SOI), Sea Surface Temperature (SST), North Atlantic Oscillation (NAO), Pacific Decadal Oscillation (PDO), Inter-decadal Pacific Oscillation (IPO), and Atlantic Multi-decadal Oscillation (AMO), are used for long-lead drought forecasting. Mishra and Singh (2010b) provided a review of drought models that include regression models, time series models, probability models, artificial neural network models, and hybrid models; and spatio-temporal drought analysis; drought modeling under climate change scenarios. Mishra et al. (2015) edited a special issue of Journal of Hydrology on drought processes, modeling, and mitigation. Hao et al. (2018) reviewed seasonal drought prediction, advances, challenges, and future prospects.

Watershed models

It is seen that for a period of over a century until the 1960s prior to the computer era, many groundbreaking advances in modeling different components of the hydrologic cycle were made. Some of these advances were based on the laws of mathematical physics and some had their basis in laboratory and/or field experiments. The current state of hydrologic science and engineering owes a great deal to the pre-1960 advances. With the advent of computer, the digital revolution started in the decade of the 1960s and by the 1970s computers became accessible to universities, government agencies and industry. The resulting computing capability made possible the simulation of the entire hydrologic cycle and the birth of numerical hydrology. In 1966, Crawford and Linsley reported the first watershed model, called Stanford Watershed Model (SWM) that became HSPF (Hydrologic Simulation Package-Fortran) in its latter incarnation and BASINS (Better Assessment Science Integrating Point and Nonpoint Sources) in its current life. In subsequent years, a number of models were developed in the U.S. Examples of popular ones are HEC-1 (Hydrologic Engineering Center 1968) which in current form is HEC-HMS (Hydrologic Modeling Simulation), SWMM (Storm Water Management Model) (Metcalf and Eddy et al. 1971), NWS-RFS (National Weather Service-River Forecast System) (Burnash et al. 1973), SSARR (Streamflow Synthesis and Reservoir Regulation) System (Rockwood 1982), and USGS Rainfall–Runoff Model (Dawdy et al. 1970) which later became PRMS (Precipitation Runoff Modeling System) (Leavesley et al. 1983). A large number of other hydrology simulation models were developed in Australia, Canada, England, Sweden, and other countries. Many of these models are described in Singh (1995), and Singh and Frevert (2002a, b, 2006). Singh and Woolhiser (2002) appraised the state of art of mathematical modeling of watershed hydrology. Borah (2011) reviewed and compared hydrologic procedures of storm-event watershed models. Donigian et al. (2017) have provided a comprehensive discussion of continuous watershed models, and Gupta and Sorooshian (2017) have discussed the calibration and evaluation of watershed models.

Data observation and tools

Empirical observations form the basis of much of what we know about hydrologic systems as well as for their operation and management. For hydrologic modeling, the types of data needed are hydrometeorologic, physiographic, geomorphologic, pedologic, geologic, hydrometric, land/land cover, and agricultural. Local, state, and federal agencies have been collecting data that are relevant for their operational and management purposes, but the data so collected have also been and continue to be used for research and generating new knowledge. The technology for data collection has undergone a revolutionary change over the past three decades in four ways. First, data collection tools are much more accurate, such as velocity measurements by acoustic Doppler velocimetry (ADV). Second, it is now possible to collect data that was not possible before, such as direct measurement of discharge. Third, it is possible to collect spatial data rather than point data, such as spatial representation of rainfall field by radar. Fourth, it is now possible to collect data in remote inaccessible areas using satellite technology.

Remote sensing tools, particularly satellites and radar, are becoming more popular these days (Engman and Gurney 1991). Since the launch of Landsat-1 [also known as the Earth Resources Technology Satellite (ERTS)], developed by NASA (National Aeronautics and Space Administration) and operated by USGS (United States Geological Survey), in 1972, six other satellites have been launched and land surface data have since been collected (Shen et al. 2013). The next generation of satellites, called Landsat Data Continuity Mission (LDMC), was launched in 2013. Most NASA satellite land measurements can be found in the NASA Land Measurement Portal (http://landportal.gsfc.nasa.gov) which includes data products in four categories: surface radiation budget, vegetation parameters, land cover/land use changes, and land hydrosphere. More specifically, one can obtain for hydrologic modeling synoptic data of meteorological inputs; soil and land use parameters; inventories of water bodies, lakes, reservoirs, rivers, etc.; snow cover and ice fields; and water quality parameters. Other agencies in Japan, China, and India have also launched spaceborne sensors/missions for studying the terrestrial water cycle components. Examples include Advanced Microwave Scanning Radiometer (AMSR) and Soil Moisture and Ocean Salinity (SMOS) for estimating soil moisture; Tropical Rainfall Measuring Mission (TRMM) for precipitation; Moderate Resolution Imaging Spectroradiometer (MODIS) for vegetation; JASON-1 and JASON-2 and TOPEX-POSEIFON for surface water level; and Gravity Recovery and Climate Experiment (GRACE) for groundwater and evaporation. Lakshmi et al. (2015) presented a treatise on remote sensing of the terrestrial water cycle. Lakshmi (2017) edited a book on remote sensing of hydrological extremes.

Weather radar is being employed for spatial mapping of rainfall field and daily weather forecasting. Both ground-based and spaceborne radars are used. With the use of bias correction techniques, radar rainfall data are usually scaled to match data being observed at rainfall gauging stations. Even though radar rainfall data in many cases are available on web, their use with quality control/assurance and bias correction is recommended. Pathak et al. (2017) edited a special issue of Journal of Hydrologic Engineering on radar rainfall and operational hydrology that contains papers dealing with radar rainfall data estimation, improvement, and validation; application of radar rainfall data; and use of radar rainfall for flood forecasting.

Geographical information systems

Geographical information systems (GIS) are a technology for stacking, analyzing, and retrieving large amounts of data (Singh and Fiorentino 1996). The term geographical information here means the x-, y- and z-coordinates of land surfaces defined in a coordinate system. Because GIS is a data processing tool, tools that provide or record information, such as digital elevation model (DEM), topographic surveys, land use and land cover maps, can be dealt within the GIS environment (Maidment 2002). These days, global positioning systems (GPS) and GIS can be combined to provide more complete information. The use of GIS permits integration of spatial, non-spatial, and ancillary data into hydrologic models and thus significantly strengthens hydrologic modeling capability (Mujumdar and Nagesh Kumar, 2012). Griffin et al. (2017) have comprehensively discussed GIS and their applications.

Tools and methods for analysis

The past half a century has witnessed an unprecedented development of new tools and techniques for analysis of hydrologic data. Many of these tools were developed outside of hydrology but they were appropriately tailored for hydrologic applications. Some of these tools include artificial neural networks (Tayfur and Singh 2017), fuzzy logic (Bogardi 2017), genetic algorithms (Kawamura and Merabtene 2017), relevance vector machines (Tripathi and Govindaraju 2017), wavelets (Labat 2017), outlier analysis (Panu and Ng 2017), time series analyses (Sveinsson and Salas 2017), nonstationarity detection and analysis (2017), geostatistical methods (Dwivedi et al. 2017), generalized frequency distributions (Singh and Zhang 2017), data assimilation methods (Todini and Biondi 2017), calibration and validation methods (Todini and Biondi 2017), Bayesian methods (Kuczera et al. 2017), optimization methods (Dozier et al. 2017), nonparametric methods (Lall and Rajagopalan 2017), uncertainty assessment and decision-making (Todini 2017), risk and reliability analysis (Tung and Mays 2017), scaling and fractals (Veneziano and Lepore 2017), chaos theory (Sivakumar 2017), copula theory (Genest and Chebana 2017), entropy theory (Singh 2013, 2014, 2015, 2016, 2017a, c), data mechanistic modeling (Young 2017), decomposition methods (Serrano 2017), and network theory (Sivakumar et al. 2017). These techniques have greatly contributed to not only the increased understanding of hydrologic systems but also hydrologic practice.

Emerging areas

Many new areas have merged during the past couple of decades and others will emerge in the decades ahead. Hydrology of global warming and climate change is an area that has been receiving a lot of attention in public fora, primarily because of increased frequency of hydrometeorologic extremes and significant variability in the space–time distribution of precipitation (McCuen 2017). Ecosystem hydrology is another area that has recently emerged. Hydrologic impacts of hydraulic fracturing are in much public debate these days. Transport of biochemical and microorganisms is receiving plenty of traction. Hydrology of hurricanes and typhoons is a newly emerging area. Atmospheric rivers are receiving much attention. Hydrology of long-distance water transfer is receiving global attention these days. Hydrology has a value to society and a new area, called social hydrology, has lately emerged and is getting traction in scientific discourses.

Integration of concepts and processes

Because of computing prowess and sophisticated instrumentation available these days, integration in and across hydrology is occurring rapidly. Hydrology and climatology are being integrated and hydroclimatology is emerging with renewed emphasis. Ecology and hydrology have combined to give birth to ecohydrology. Likewise, coastal science and hydrology are being integrated leading to coastal hydrology. The field of hydrology is broadening and the areas, such as social science, culture and religion, politics, economics, and health sciences are being interfaced with hydrologic sciences. Greater integration of concepts from intelligent systems, software engineering, information engineering, and humanities is envisioned in the years ahead.

Future outlook

With advances in data capturing and analysis capabilities and information technologies, it seems that the future of hydrology will be even brighter. It can be expected that new tools will be at the disposal of hydrology. For example, drones will become commonplace for acquiring spatial data. Hydrologic models will become so user-friendly that little hydrologic knowledge will be needed to operate them, just like one does not need to be an automobile engineer to drive a car or an electrical engineer to operate an electrical system. Each model, however, simple or complicated, will be associated with a statement of uncertainty. New frontiers of hydrology will unfold with the use of cell phones and newly emerging information technologies. Hydrologic forecasting capability will multiply. There will be greater interaction between the user and the model and the modeler. This has already started happening through what is now regarded as social hydrology. Hydrology will play an increasing role in meeting grand challenges of this century, such as water security, food security, energy security, environmental security, health security, food–water–energy nexus, and sustainable development. These grand challenges will also compel educators to revisit the delivery of hydrologic education and tailor it to produce leaders of tomorrow who will be well equipped to address the societal needs of tomorrow. Likewise, research funding agencies will have to rethink and reprioritize their direction of funding in concert with these grand challenges and pressing societal needs.

Social or rural hydrology, extraterrestrial water, water and food and energy security are newly emerging areas. For management of hydrologic systems, political, economic, legal, social, cultural, and management aspects will need to be integrated. It is vital that both hydrologic science and engineering applications are equally emphasized. Hydrologic science must not be allowed to be overtaken by data cranking methods borrowed from outside. At the same time, data analysis tools must be seamlessly integrated with hydrologic science.

Conclusions

The following conclusions are drawn from this study:

1. Hydrologic modeling has come a long way from its modest beginning in the 1850s. Advances in modeling have occurred at an increasing pace, primarily driven by easy access to almost limitless computing capability, sophisticated instrumentation, and remote sensing and GIS capabilities.
2. Integration of hydrology with allied areas is occurring increasingly and will so continue.
3. The role of hydrology is coming into sharper focus, because of global warming and climate change on one hand and water, food and energy security on the other hand.
4. Information technology is being assimilated in hydrology without much resistance.
5. Hydrology is receptive in adopting techniques being developed in mathematics, statistics, and sciences.

Authors' contributions

VPS conceptualized the framework and crafted the manuscript. The author read and approved the final manuscript.

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