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Role of hydrology in natural resources conservation and management

Vijay P. Singh* **and Qiong Su**

Department of Biological and Agricultural Engineering, Texas A&M University College Station, Texas 77843-2117, USA.

*Corresponding author:
E-mail: Vijay.Singh@ag.tamu.edu (Vijay P. Singh)*

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ABSTRACT

The main mission of natural resources conservation and management (NRCM) is to restore and protect the productivity of land through technical conservation practices, education, and outreach activities. Pursuit of this mission improves soil health, water quality, air quality, wildlife, wetlands, and local economy; and should promote partnership among farming community, and provincial and central government agencies. In other words, NRCM helps keep the entire ecosystem healthy by keeping farms, ranches, forest lands, rivers, lakes, wetlands, wildlife habitats, and the environment healthy. This is accomplished through planning and execution at the watershed scale or watershed management. Fundamental to watershed management is hydrology and hydrologic modeling. This paper attempts to sketch the role of hydrology in NRCM through watershed management.

1. INTRODUCTION

Population and economic growth, increasing industrialization, and infrastructure development pose significant challenges to natural resources conservation and management (NRCM). The degradation of natural resources has become a primary environmental concern worldwide, particularly in developing countries, which are undergoing rapid urban growth (Shivakoti *et al.,* 2016; Surya *et al.,* 2020). Furthermore, climate change results in compound risks to natural resources due to changes in precipitation patterns and the increase in air temperature, which may accelerate the trend of natural resources degradation. The main mission of NRCM is to restore and protect the productivity of land through technical conservation practices, education, and outreach activities. As shown in Fig. 1, natural resources

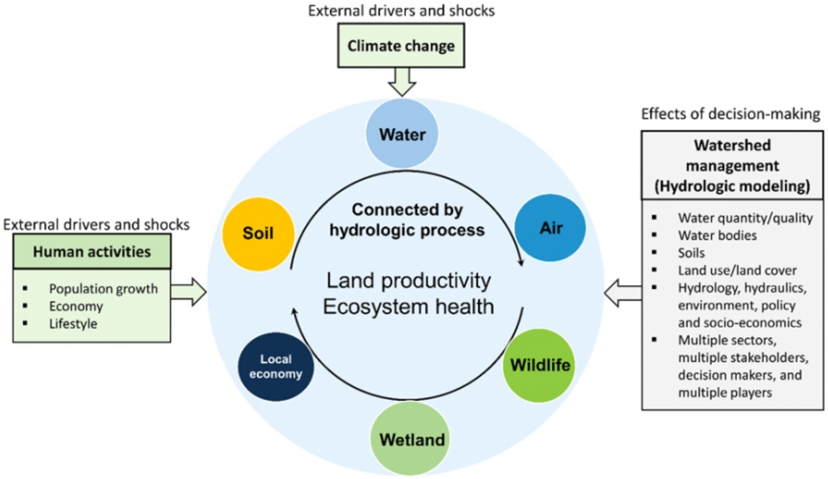

Fig. 1. Schematic representation of the interactions among different components, the external drivers and shocks, and decision−making which affect NRCM at the watershed level

affected by human activities are complex social-ecological systems consisting of different components and subsystems, *e.g.,* soil, water, air, wildlife, wetlands, and local economy. Pursuit of the mission of NRCM improves soil health, water quality, air quality, wildlife, wetlands, and local economy, and promotes partnership among farming community and provincial and central government agencies. Therefore, NRCM helps keep the entire ecosystem healthy by maintaining the healthy conditions of farms, ranches, forest lands, rivers, lakes, wetlands, wildlife habitats, and the environment.

NRCM can be accomplished through planning and execution at the watershed scale or watershed management. Watershed management requires simultaneous consideration of (1) natural resources consisting of water quantity and quality, water bodies, soils, land and its use and cover; (2) science and technology comprising hydrology, hydraulics, agricultural and forest science, environmental science, data science, and artificial intelligence systems; (3) management science, including organization and management structure, policy, and socioeconomics; (4) users, including multiple sectors and multiple stakeholders; and (5) decision makers and multiple players. Fundamental to the science and technology of watershed management is hydrology and hydrologic modeling, in which hydrologic processes are key factors connecting the major components in the complex social-ecological systems, as shown in Fig. 1. This paper attempts to sketch the role of hydrology in NRCM through watershed management.

2. ECOLOGICAL CONTINUUM

To clarify the scope of this paper, it is important to define natural resources. From the conversation and management point of view, there has been a gradual change in the concept of natural resources in the past several decades. In the 1970s, NRCM was considered as the management of environment, of which the three components, *i.e.,* soil (texture, structure), water (quantity and quality), and air (quality), were usually treated independently. In reality, soil, water, and air interact with each other, and any perturbations in one component could induce changes in the other two components. Therefore, the environment should be managed and protected as an integrated system (Singh, 1995a, 1995b). In this case, the environment is treated as a continuum of soil, water, and air (Harmancioglu *et al.,* 1998). As such, the concept of the environmental continuum can be defined as environmental components of soil, water, and air, and continuum (interconnected soil, water, and air), which are important to sustain life on Earth. The concept of Brahmand, so deeply rooted in Indian culture, is analogous to the concept of environmental continuum.

Besides the concept of the environmental continuum, natural resources can be considered as an ecological continuum, including both living and nonliving resources. In this regard, natural resources are defined as all the ecological components, including soil, water, air, and living beings, which are functionally interconnected with each other by the ecological continuum. These components link with each other to form the ecosystem, of which fundamental is water and hence hydrology. Therefore, the conversation and management of natural resources should be planned and executed at the watershed scale.

3. ROLE OF HYDROLOGY

Definition of Hydrology

The anatomy of hydrology, sketched in Fig. 2, is composed of (1) quantity and quality of water; (2) phases of water, including liquid (water), vapor, solid (snow or ice), and the fourth phase of water or structured water, which is defined as the exclusion zone that forms next to submersed materials (Pollack, 2013); (3) place of occurrence, including land surface and below land surface in unsaturated and saturated zones; (4) domain, involving space, time, and frequency of the occurrence of water; (5) scales, including micro-scale, macroscale, mesoscale, and mega scale. Hydrologic processes span a wide range of scales, from microscale (*e.g.,* unsaturated flow in soil profile) to mega-scale (*e.g.,* drought) (Bloschl and Sivapalan, 1995); and (6) hydrologic processes, encompassing the occurrence, distribution, movement, and storage of water.

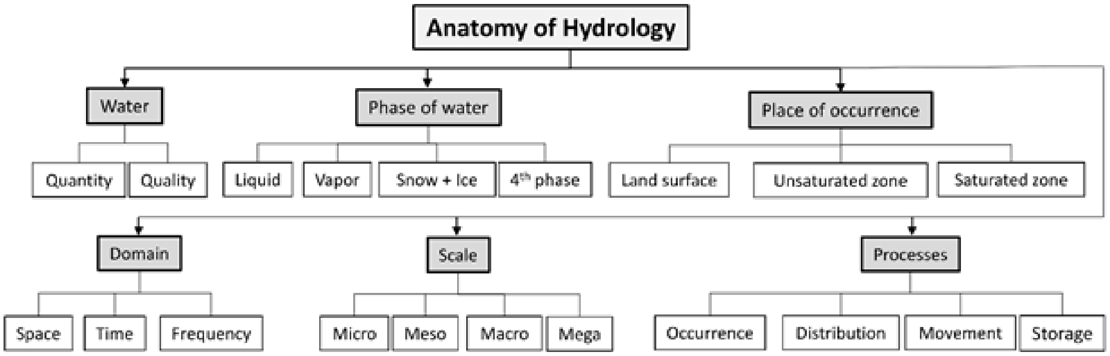

Fig. 2. The anatomy of hydrology

Hydrologic cycle is the movement and interchange of water amongst atmosphere, land surface, pedosphere, lithosphere, and hydrosphere. Each component in the hydrologic cycle can be connected at a large scale through precipitation, evapotranspiration, and streamflow. Therefore, hydrology can be defined as the science that deals with the space, time, and frequency of the occurrence, distribution, storage, and movement of the quantity and quality of water on the land surface and below the surface. This definition encompasses the entire hydrologic cycle. One can even venture to state that hydrology is the study of the hydrological cycle, although this definition is broad and packs specifics. The hydrologic processes are detailed in Fig. 3.

Application of Hydrology

The application of hydrology includes both design and non–design aspects. Hydrology is employed in design of (1) water supply schemes; (2) drainage systems; (3) soil conservation structures; (4) highway pavements, culverts, and bridges; and (5) rehabilitation of aging dams. Hydrology is also applied to (1) pollution abatement; (2) ecological sustainability; (3) assessment of climate change impacts; (4) erosion control measures; (5) soil conservation measures; (6) watershed management; (7) water supply forecasting; (8) wetland restoration; (9) stream restoration; (10) water table management; (11) habitat modeling; (12) hydropower development; (13) flood protection projects, flood warning systems, reservoir release planning, and flood plain management; (14) irrigation water management; and (15) consumptive use and water allocation. It is vital that both the design and non-design applications are equally emphasized.

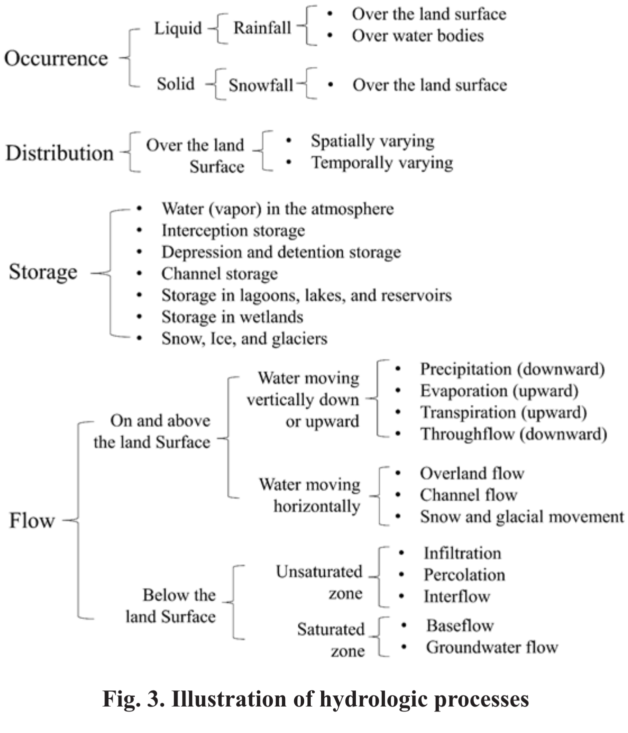

Fig. 3. Illustration of hydrologic processes

4. CLIMATE CHANGE AND ITS IMPACTS

Ecosystems and natural resources are sensitive to climate change. Since the pre-industrial period (1980-1990), both the global mean land surface air temperature and mean surface temperature (land and ocean) have risen considerably (IPCC, 2019). For example, the mean land surface air temperature from 2006 to 2015 increased by 1.53°C as compared to the pre–industrial period level. Global warming has resulted in increased frequency, intensity, and duration of weather and climatic extremes (*e.g.,* high temperature, extreme precipitation, wind, heat-related events, and flooding), decreased water availability, increased soil erosion, coastal degradation, permafrost degradation, and increased wildfire occurrence (Hurlbert *et al.,* 2019). These changes pose increased risk to water security, soil security, energy security, food security, as well as human health and ecosystem integrity.

Water resources are essential for the survival of ecosystems and are required in most human activities, *e.g.,* municipal, industrial, energy, and agricultural uses. Fig. 4 shows schematically how climate change and human activities affect hydrologic changes (water quantity and quality, timing, and extreme events), and their impact and risk for human beings and ecosystems. Freshwater systems and climate change and are interconnected in different ways. For example, climate change has been observed to decrease glacier extent and snow water storage, resulting in reduced streamflow in glacier- or snowmelt-fed river basins. Wetlands in dry regions are sensitive to climate change due to decreased runoff. Climate change affects crop water demand in both rainfed and irrigated croplands because of higher temperatures, stronger radiation, and changed precipitation patterns (Haddeland *et al.,* 2014; Konapala *et al.,* 2020). Land use and land cover change may moderate or amplify the effect of climate change on water resources. Climate change-induced higher water temperatures, reduced river flow, and increased precipitation intensity exacerbate water pollution, which may affect ecosystem serveries, biodiversity, and human health.

The impacts of climate change on hydrologic systems and water resources management can be summarized from different aspects: (1) Freshwater availability: Renewable surface water and groundwater sources are projected to decrease in most dry subtropical regions and increase at high latitudes. (2) Freshwater storage: Higher air temperatures reduce snow and ice water storage and increase evaporation from lakes, reservoirs, wetlands, glaciers, and shallow aquifers, resulting in decreased natural water storage. (3) Rainfall variability: Less rainfall is projected in most dry subtropical regions and Mediterranean climates. A substantial increase in the occurrence of heavy rainfall events is expected, even in regions with decreased total precipitation amounts. In major agricultural production areas, *e.g.,* south, east, and southeast asia and in northern

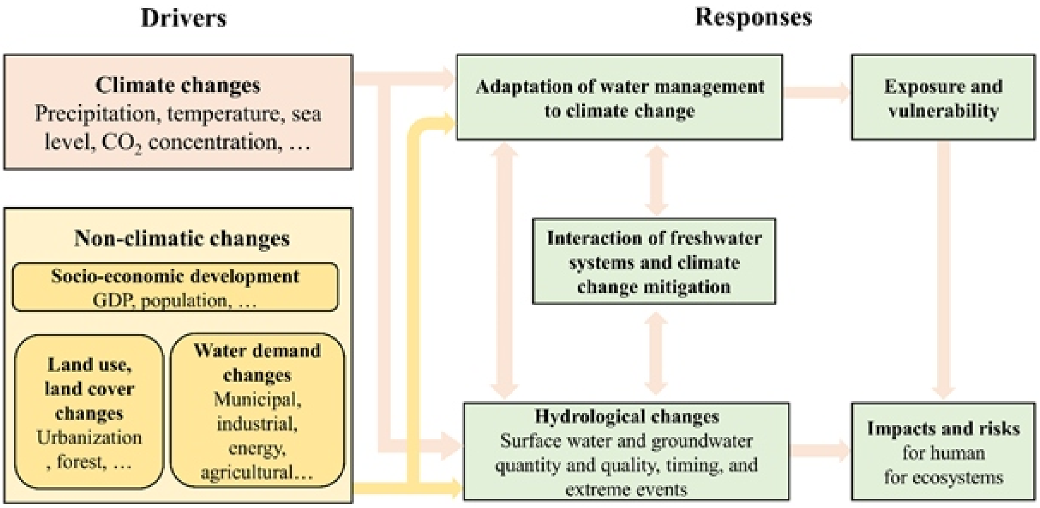

Fig. 4. Framework and linkages considering impacts of climatic and socio−economic changes

europe, heavy rainfall is very likely to occur (IPCC, 2021). The intensity of heavy precipitation is projected to increase as well, by about 7% per 1°C of warming at the global scale. This intensification will mainly occur over the heavily cultivated regions like south and southeast asia and east asia in the mid-to long term. (4) runoff variability: annual mean runoff is projected to decrease in most dry tropical regions and to increase in the wet tropics and at high latitudes. These patterns are primarily driven by the projected changes in precipitation, temperature, and evaporation, and in some regions, such as south asia, large parts of south America, and China, considerable uncertainty exists. (5) flow variability: climate change has reduced the maximum spring snow depth and snowmelt discharge in regions with snowfall. (6) extreme hydrologic events: global flood risks are projected to increase, particularly in parts of northeast, south, and southeast asia, south America, and tropical Africa. The frequency of agricultural droughts due to decreased soil moisture, meteorological droughts due to decreased rainfall, and short hydrological droughts due to reduced surface water and groundwater are likely to increase. In addition, the extension of heat-stressed areas is expected under global warming. For example, heat-stressed areas in south asia will increase by up to 21% in 2050 compared to the baseline (1950-2000) (IPCC, 2019). The increase in weather extremes likely leads to expanded warm, arid regions in many populated regions, and the impacts of climate change are more significant in arid regions than in humid regions. The most considerable impact is anticipated to occur in Africa (Lickley and Solomon, 2018). The effects of climate change impacts on hydrological changes and freshwater-related impacts of climate change on human beings and ecosystems from different studies are summarized in Table 1.

One important question in hydrology is whether the hydrological cycle is being intensified or not by climate change. The observed more frequent floods and droughts events, more availability in rainfall, shorter snowfall season, earlier spring snowmelt, and accelerated glacial melting tend to indicate an ongoing intensification of the hydrological cycle. This may affect water availability and increase the frequency and intensity of floods, droughts, and heavy rainfall in tropical regions (Huntington, 2006).

5. HYDROLOGIC MODELING

Hydrologic Considerations and Data

Integrated management of natural resources at the watershed scale requires two basic tools, *i.e.,* hydrologic models and data. Recognizing the concept of ecological continuum and the interactions of different processes within watersheds, hydrologic modeling should consider the following aspects: (1) occurrence, movement, distribution, and storage of water quantity and quality; (2) spatial, temporal, and frequency domains (or characteristics); (3) quality of water from physical, chemical, and biological perspectives; (4) spatial scales varying from watershed to large scale, *i.e.,* regional (basin), continental, and global; and (5) dynamic interactions among atmosphere, pedosphere, lithosphere and hydrosphere and theirs controlling influences on hydrology.

With respect to data, different components in the ecological continuum should be integrated to produce a complete dataset, including hydro-meteorologic, topographic, geomorphologic, pedologic, land use, geologic, hydrologic, and hydraulic data. Specifically, hydro-meteorologic data contain temperature, solar radiation, rainfall, relative humidity, vapor pressure, wind speed, sunshine hours, and pan evaporation. Geomorphologic data include elevation contours, slopes and slope lengths, drainage area, river networks, and watershed area. Pedologic data include soil types, conditions, particle size, texture and structure, porosity, soil moisture content, saturated hydraulic conductivity, suction or capillary pressure, water holding capacity, steady-state

Table: 1
Effects of different greenhouse gas (GHG) emission scenarios on hydrological changes and freshwater−related impacts of climate change on human beings and ecosystems. Adapted from (Jiménez Cisneros *et al.,* 2014)

Type of hydrological change or impact	Description of indicator	Reference
Decrease of renewable water resources, global scale	Percent of global population affected by a decrease of more than 20% in water resources as compared to the 1990s (mean of 5 General Circulation Models (GCMs) and 11 global hydrological models).	Schewe *et al.* (2014)
Decrease of renewable groundwater resources, global scale	Percent of global population affected by a decrease of more than 10% in groundwater resources by the 2080s as compared to the 1980s (mean and range of 5 GCMs, population scenario SSP2)	Portmann *et al.* (2013)
Exposure to floods, global scale	Percent of global population annually exposed, in the 2080s, to a flood corresponding to the 100 year flood discharge for the 1980s (mean and range of 5-11 GCMs, population constant at 2005 values)	Hirabayashi *et al.* (2013)
Change in irrigation water demand, global scale	Change of required irrigation water withdrawals by the 2080s (on area irrigated around 2000) as compared to the 1980s (range of 3 GCMs)	Hanasaki *et al.* (2013)
River flow regime shifts from perennial to intermittent and *vice-versa*, global scale	Percent of global land area (except Greenland and Antarctica) affected by regime shifts between the 1970s and the 2050s (range of 2 GCMs)	Doll and Mueller Schmied (2012)
New or aggravated water scarcity	Percent of global population living in river basins with new or aggravated water scarcity around 2100 as compared to 2000 (less than 1000 m^3yr^{-1} of per capita blue water resources) (median of 19 GCMs, population constant at 2000 values)	Gerten *et al.* (2013)
Exposure to water scarcity	Population in water-stressed watersheds (less than 1000 m^3yr^{-1} of per capita blue water resources) exposed to an increase in stress (1 GCM)	Arnell *et al.* (2013)
Change of groundwater recharge in the whole of Australia	Probability that groundwater recharge decreases to less than 50% of the 1990s value by 2050 (16 GCMs)	Crosbie *et al.* (2013)
River flow regime shift for rivers in Uganda	Shift from bimodal to unimodal (1 GCM)	Kingston and Taylor (2010)
Agricultural (soil moisture) droughts in France	Mean duration, affected area, and magnitude of short and long drought events throughout the 21st century (1 GCM)	Vidal *et al.* (2012)
Salinization of artificial coastal freshwater lake I Jsselmeer in the Netherlands (a drinking water source) due to seawater intrusion	(1) Daily probability of exceedance of maximum allowable concentration (MAC) of chloride (150 mg L^{-1}); and (2) Maximum duration of MAC exceedance (2050, 1 GCM)	Bonte and Zwolsman (2010)
Decrease of hydropower production at lake Nasser, Egypt	Reduction of mean annual hydropower production by the 2080s compared to hydropower production 1950-99 (11 GCMs)	Beyene *et al.* (2010)
Flood damages in Europe (EU27)	(1) Expected annual damages, in 2006; and (2) expected annual population exposed (the 2080s, 2 GCMs)	Feyen *et al.* (2012)

infiltration, and antecedent moisture content. Geologic data include lithologic data, depth, area, and properties of aquifers. Hydrologic data include streamflow discharge, interflow, baseflow, flow depth, water table, stream-aquifer interaction, drawdown. Hydraulic data include river cross-sections, roughness, river morphology, and flow stage.

Recently, improvements in information and communication technologies significantly facilitated data acquisition, *e.g.,* remote sensing, satellite, and radar technology. These observation tools are being increasingly used in hydrologic models for real-time weather forecasting, flood and drought monitoring, and short-term or seasonal snowmelt runoff forecasting. Various models and tools have been developed to advance hydrologic modeling. Digital terrain and elevation models (DTM or DEM) provide the spatial structure of essential topographic variables for hydrologic modeling. Chemical tracers can be used to obtain flow information of surface and groundwater systems. In addition, the geographical information system (GIS) and database management system (DBMS) can be used for data processing and management, which are suitable for the development of distributed hydrologic models. A more detailed introduction of hydrologic data management can be found in Harmancioglu *et al.,* 1998 and Singh and Frevert, 2006.

Variability in Watershed Characteristics

In hydrologic modeling, the determination and integration of appropriate temporal and spatial scales are important. The temporal and spatial scales should be detailed enough to capture the dominant processes and watershed characteristics variability. At the same time, computational time should be considered to avoid unnecessarily refined resolution (Booij, 2003). Temporal scaling entails time intervals of observations and temporal variability of processes, which determines the temporal resolution of the model and the duration of simulation period. Spatial scaling involves spatial variability in hydrologic processes, spatial heterogeneity in watershed characteristics, as well as the physical spatial size of hydrologic response units (HRUs) and representative elementary area, which determines the computational grid size (spatial resolution). The time step and the spatial resolution affect parameterization, calibration, accuracy, and computational time of the model.

Selection of appropriate temporal and spatial scales depends on the dominant processes and watershed characteristics variability, the research objective, and input data availability. For example, to analyze the impact of climate change on flooding at the watershed level, the dominant processes include precipitation, infiltration, overland flow, saturation excess overland flow, and subsurface stormflow, which affect the hydrograph, runoff dynamics, and formation of shocks. Therefore, the primary variables selected are precipitation, soil type, elevation, and land use. Booij (2003) suggested the spatial scales of daily precipitation, soil, elevation, and land use as 19.9 km, 5.3 km, 0.1 km, 3.3 km, respectively. Based on the relative weight of these variables on flood events, a 9.5 km resolution was suggested to capture the flood model response under climate change. Baffaut *et al.* (2015) analyzed 25 commonly used hydrologic and water quality models and suggested the temporal and spatial scales for modeling hydrologic processes (*e.g.,* infiltration, evapotranspiration, runoff, groundwater discharge, channel flow, river flow, etc.), biological process (*e.g.,* plant growth, carbon cycle, bacterial growth, nutrients, and pesticides, etc.), erosion and sedimentation process (*e.g.,* sediment transport, lake deposition), and physical and chemical process (*e.g.,* leaching, oxygen depletion, groundwater chemistry), varying spatially from point (<1 m^2) to watershed level (>50 km^2) and temporally from seconds (*e.g.,* infiltration) to centuries (*e.g.,* groundwater recharge).

Model Calibration and Validation

Calibration and validation of hydrologic models are required before using them in real-world applications. Optimization methods have been used for model calibration, and four elements are usually involved for automatic parameter calibration: (1) objective function, (2) optimization algorithm, (3) termination criterion, and (4) data required for calibration (Singh and Frevert, 2002c, 2006). Several optimization methods have been discussed by Sorooshian and Gupta (1995), including random search method, direct search method, multistart algorithms, gradient search methods, and shuffled complex algorithms. Artificial neural networks (ANNs) can also be utilized for modeling or model calibration.

Slip–sample approaches are the most commonly used method for the validation of hydrologic models. Also, Monte Carlo simulation, handling data errors, representation of model uncertainty are utilized for model validation. For model performance evaluation, both statistical and graphical methods have been widely used. Typical statistical evaluation metrics include Nash-Sutcliffe efficiency (Nash and Sutcliff, 1970), coefficient of determination, root mean square error, normalized root mean square error, mean absolute error, relative error, standard error of estimate, Kolmogorov-Smirnov test, 95% confidence interval for uncertainty analysis, standard deviation, and percent bias. Graphical methods include cumulative frequency distribution, time series plots, contour maps, and scatter plots. The calibration and validation methods of 25 hydrologic and water quality models are summarized by Moriasi *et al.* (2012) and Saraswat *et al.* (2015).

Hydrologic Models

With the advent of computer, hydrologic modeling began in the 1960s. The most famous early hydrologic model was the Stanford Watershed Model (SWM), developed at Standford in 1966 (Crawford and Linsley, 1966). SWM was used to predict streamflow given observed meteorological variables in the early 1960s. It was the first attempt to simulate the entire hydrologic cycle and the refinements subsequently (1962-1966) was more physically based to reduce the number of parameters calibration (Singh and Woolhiser, 2002). For example, kinematic wave routing was integrated. Fig. 5 shows the model structure of SWM, which is the same as the 1966 origin, only with a few of refinements in the later versions. In the 1970s and the early 1980s, with the recognition of pollution sources and the need to water quality control, SWM was expanded and refined to create Hydrologic Simulation Package-Fortran (HSPF). The first version of HSPF was released in 1980, and it combined the agricultural runoff management (ARM) and the nonpoint source (NPS) pollutant loading models, allowing for the simulation of land and soil contaminant runoff processes. Since the 1980s, HSPF has been continuously upgraded, *e.g.,* sediment-nutrient interactions in 1993, atmospheric deposition and forest nitrogen module in 1997, wetland and shallow water tables and irrigation modeling capabilities in 2001, surface water and groundwater interaction in 2002. Both point and NPS pollutants can be simulated by HSPF, and therefore it has wide application in the total maximum daily load (TMDL) assessment. In 1994, HSPF was incorporated into the US Environmental Protection Agency (EPA) better assessment science integrating point and nonpoint sources (BASINS) system as the core watershed model. BASINS brings together several models

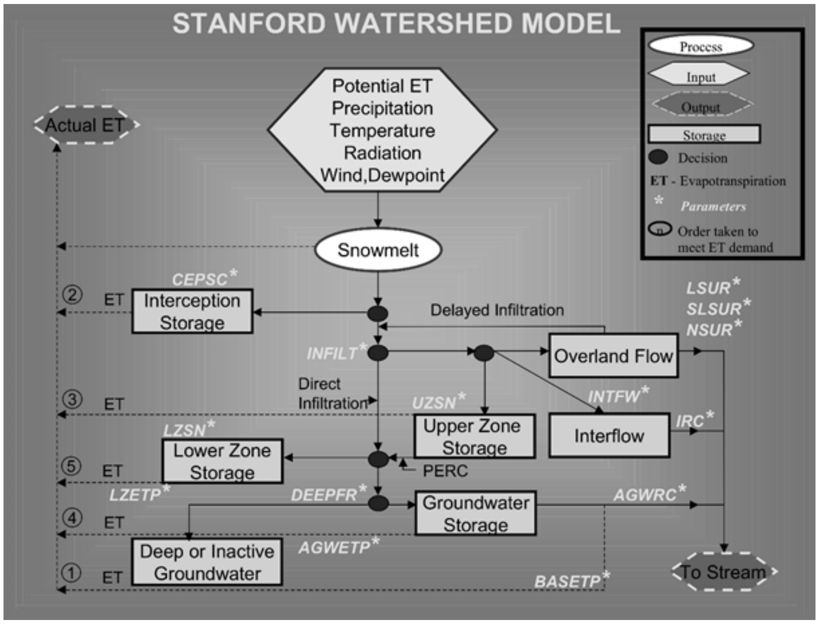

Fig. 5. Flowchart of a mechanistic model: Stanford watershed model. Adapted from Donigian and Imhoff (2006)

using a GIS interface, which can be used for environmental management and decision-making at various spatial scales ranging from small to large watersheds (US EPA, 2019).

Since the 1960s, many hydrologic models have been developed in the US, with a growing emphasis on mechanistic modeling (Singh and Woolhiser, 2002). Examples include the hydrologic modeling system (HEC-HMS), which is an enhancement of the original HEC (Hydrologic Engineering Center, 1968), EPA's storm water management model (SWMM) (Metcalf and Eddy *et al.,* 1971), USGS rainfall-runoff model (Dawdy *et al.,* 1970) which in the current form of precipitation runoff modeling system (PRMS), The water quality analysis simulation program (WASP) (Di Toro *et al.,* 1983), the environmental policy integrated climate (EPIC) model and the agricultural policy/environmental extender (APEX) model (Wang *et al.,* 2012), and the soil and water assessment tool (SWAT) (Arnold *et al.,* 2012). Also, a number of hydrologic models were developed worldwide, *e.g.,* Australia, Denmark, Sweden, the United Kingdom, etc., and these models are described in Singh (1995), and Singh and Frevert (2002a, 2002b, 200c, 2006).

The evolution of the SWM and other hydrologic models has been closely related to the environmental policy and legislation (Donigian and Imhoff, 2006), and to the advances in computer and database technology, as shown in Fig. 6. The evolution was also an example of the collaboration of universities, government agencies, and private organizations to design advanced tools to meet the public need for a better environment. More details of the evolution of hydrologic models have been discussed in Singh and Frevert (2002a, b,c, 2006) and Gupta and Sorooshian (2017).

Emerging Tools

New tools and techniques are emerging for hydrologic data analysis. Some of these tools include intelligent systems, *e.g.,* ANN (Tayfur and Singh, 2017), fuzzy logic (Kambalimath and Deka, 2020), and genetic algorithm (Barnhart *et al.,* 2017), machine learning techniques such as relevance vector machine (RVM) (Liu *et al.,* 2017), wavelet analysis (Lee and Kim, 2019), etc. Most of these techniques and theories were developed outside of hydrology and then introduced for hydrologic applications. Examples of these theories include chaos theory (Sivakumar, 2017), entropy theory (Singh, 2013, 2014, 2015, 2016, 2017), copula theory (Zhang and Singh, 2019), catastrophe theory (Mogaji and San Lim, 2017), and network theory (Sivakumar *et al.,* 2017). These tools and theories have greatly improved the understanding of hydrological systems and will play an increasingly important role in hydrologic modeling in the future.

Challenges

Hydrology plays a vital role in NRCM through watershed management. New challenges are emerging due to the increasing demand for hydrologic models. With the increased frequency of hydrometeorologic extremes, more data at finer spatial and temporal resolutions, regional-scale models, uncertainty analysis, and long-term forecasting ability are required to provide more accurate forecasts. Biochemical and microorganism transportation has gained much attention recently, especially under the COVID-19 pandemic, and integration with bio-geochemical models is needed. Natural resources systems are complex social-ecological systems with different components and subsystems, which are driven

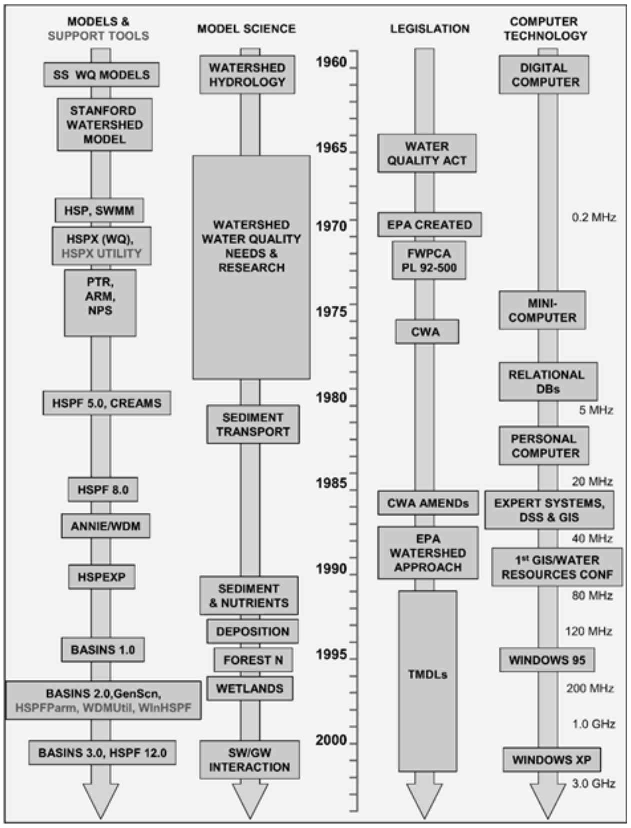

Fig. 6. Evolution in mechanistic hydrologic modeling: Stanford watershed model. Adapted from Donigian and Imhoff (2006)

by both climatic and non-climatic factors. Integrated with climate models, ecosystem models as well as decision-making models (social, political, economic, environmental, etc.) are necessary to address complex social-ecological system issues.

Management of natural resources requires partnerships among farming communities, provincial and central government agencies, and private organizations. Design of user-friendly models with more choices and credibility will improve communication between different communities and agencies.

Future Outlook

With the increasing societal demand for hydrologic models, hydrologic sciences are interacting with social, cultural, political, economic, and health sciences. It can be expected that increasing emphasis on linking models to environmental and ecosystem models, incorporation of information technology, computer-based design, artificial intelligence, and space technology, and improved model reliability and competitiveness are envisioned in the future. Furthermore, the role of hydrology in meeting the challenges of water security, food security, energy security, environmental security, ecosystem security, and sustainable use of natural resources will become increasingly important. These challenges will also call for a reexamination or reflection of the water-energy-soil security system, partnerships among academia, government sector, non-government organization (NGOs), and private sector, and hydrologic educational system.

For the management and conservation of natural resources, interdisciplinary research with consideration of social, economic, political, legal, cultural, management aspects is required. It is vital to develop diverse and multi-institutional partnerships to promote communication among the farming community and provincial and central government agencies (Isely *et al.,* 2014; Selfa and Endter-Wada, 2008; Surya *et al.,* 2020). To enhance water use efficiency, pricing and valuing water may be necessary. Also, the planning and management of water, energy, and agriculture should be integrated to ensure a robust regional-capacity building. When properly planned and managed, urbanization can improve quality of life with minimum impact on natural resources. However, rapid and uncontrolled urbanization can lead to inequality, pollution, and overexploitation of natural resources. Future can be bright or dark, which is all in our hands.

6. CONCLUSIONS

The major conclusions of this paper can be summarized as:

- The conversation and management of natural resources should be planned and executed at the watershed scale.
- Hydrology or hydrologic modeling is fundamental to watershed management.
- Interdisciplinary integration must occur increasingly in hydrology.
- The role of hydrology is increasing in water, food, and energy securities or water-soil-food-energy-environment nexus under changing climate.
- Re-examination and re-evaluation of our social values and value systems are needed.

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