J. Geogr. Sci. 2021, 31(8): 1085-1101
DOI: https://doi.org/10.1007/s11442-021-1886-0

A review of the ecohydrology discipline:
Progress, challenges, and future directions in China

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Abstract: In recent decades, the ecohydrology discipline was developed to provide theoretical and technical foundations for the protection and restoration of complex ecological systems (e.g., mountains, rivers, forests, farmlands, and lakes), and to further ecological civilization construction and green development in China. In this study, the progress and challenges of the ecohydrology discipline are elaborated, and the future development directions are proposed according to international scientific frontiers and national ecological civilization construction demands. Overall, the main discipline directions are to develop new ecohydrological monitoring methods, to comprehensively understand ecohydrological mechanisms and their basic theories, to promote integration of multi-scale and multi-variable models by considering both terrestrial and aquatic ecosystems, and to encourage multidisciplinary integration, particularly with the social sciences. Furthermore, the future research interests in China include: combining multi-source information, constructing comprehensive monitoring systems, studying spatiotemporal patterns of key ecohydrological variables and their variation characteristics, developing integrated models of ecological, hydrological, and economic processes, estimating their uncertainty; and conducting interdisciplinary studies that include the natural and social sciences. The application prospects in China are further explored for a variety of ecosystems, including forests, grasslands, rivers, lakes, wetlands, farmlands, and cities. This study will provide a reference to support the development of the ecohydrology discipline in China, and will provide a solid theoretical and technical foundation for the implementation of national ecological civilization construction.

Keywords: ecohydrology discipline; theory and method; comprehensive observation; mathematical modelling; scale issue

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Received: 2021-05-11 **Accepted:** 2021-06-21

Foundation: The Strategic Priority Research Program of the Chinese Academy of Sciences, No.XDA23040301; The Developmental Strategies of the Discipline of the Academic Divisions of the Chinese Academy of Sciences, No.2017DXA; National Natural Science Foundation of China, No.42071041

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Ecohydrology is an interdisciplinary approach that explores impacts of hydrological processes on structures and functions of ecosystems, as well as impacts of biological processes on water cycle variables under changing environments (Nuttle, 2002). Although interdisciplinary research has a long history between ecology and hydrology, such as forest hydrology and wetland hydrology, ecohydrology was formally proposed at the International Conference on Water and Environment in 1992. However, core contents in this discipline must be further improved regarding connotations, extensions, research objects, theories, and methods. Ecohydrology has developed rapidly owing to the implementation of the Biospheric Aspects of Hydrological Cycle in the International Geosphere Biosphere Programme (IGBP/BAHC) and the International Hydrological Programme hosted by United Nations Educational, Scientific and Cultural Organization (UNESCO/IHP), and has become a hotspot in the hydrology community. This paper summarizes the research progress and existing problems of the ecohydrology discipline locally and globally, and proposes the future development directions, interests, and application prospects in China. This paper will act as a reference for the future development of the ecohydrology discipline, as well as a solid theoretical basis and technical support for the implementation of major national strategies, such as the ecological protection and restoration of mountains, rivers, forests, fields, lakes, and grasses, the construction of ecological civilization, and green development in China.

1 Research progress of ecohydrology discipline

In 1961, the International Hydrological Decade (1965–1974) of the International Association of Hydrological Sciences (IAHS) proposed that hydrological process research should consider the impact of other processes such as ecology. Thus interdisciplinary research of ecological and hydrological processes was initiated. As individually, the ecology and hydrology disciplines were unable to comprehensively explain ecohydrological processes and their interaction mechanisms, a new combined discipline was developed, called ecohydrology. Many scholars have explored the interactions between ecosystems and hydrological processes from various perspectives, such as ecological hydraulics (Nuttle, 2002), soil hydrology (Eagleson, 1978), and river ecology (Ward and Stanford, 1983).

"Ecohydrology" was first used professionally by Ingram (1987), and widely used in ecological and hydrological process studies of wetland in the 1990s (Pedroli *et al*., 1990; Bragg *et al*., 1991; Hensel *et al*., 1991). The ecohydrology discipline was formally established at the United Nations Conference on Water and Environment in 1992. The first monograph regarding ecohydrology, *Mires*: *Process*, *Exploitation and Conservation*, was published in 1993 (Heathwaite and Göttlich, 1993). Since then, the ecohydrology discipline has continuously improved, but mainly focused on wetland ecosystems in transitional zones. For example, Gieske *et al*. (1995) investigated the interaction between vegetation patterns, wetland ecosystems, and hydrological processes. Wassen *et al*. (1996) provided a relatively complete definition of ecohydrology, focusing on the functional value of hydrological factors for river protection and restoration. In the same year, the fifth stage of UNESCO/IHP (1996–2001) was launched, and ecohydrology became one of its research topics, causing ecohydrology to rapidly develop. Zalewski (1997) published the monograph *Ecohydrology*, which stated that ecohydrology is a spatiotemporal comprehensive science concerning hydrological processes and biological dynamics. Zalewski also proposed that the ecohydrological research should be further extended to regulating hydrological processes at basin scales and comprehensive investigations of long-term hydrological processes at large scales. Poff *et al*. (1997) proposed the theory of the natural flow paradigm, which comprehensively described the natural runoff hydrograph using flow regime metrics related to river ecology (such as flow magnitude, amplitude, frequency, duration, time, and rate of change), thereby promoting the development of river ecohydrology. Baird *et al*. (1999) used plants and water as research objects, summarized the research development of vegetation ecohydrology, and clarified the response relationship between plants and water under different conditions, such as dry lands, wetlands, temperate zones, tropics, rivers, and lakes, promoting the comprehensive development of vegetation ecohydrology. Ecohydrological studies have gradually extended from wetland ecosystem studies in the transitional zone to comprehensive studies of multiple systems and freshwater resources, including vegetations, rivers, lakes, and forests (Acreman, 2001; Eagleson, 2002). Since 2008, two consecutive five-year programs of UNESCO/IHP have used ecohydrology as a specific theme. Wood *et al*. (2008) compiled the monography *Hydroecology and Ecohydrology*: *Past*, *Present and Future*, which comprehensively summarized the research progress and methods in the fields of ecology and hydrology. Goldsmith (2013) investigated ecohydrological processes and their effects on the soil-plant-atmosphere continuum (SPAC) of different ecosystems. Simultaneously, because of the strong impacts of rapid economic and social development, watershed ecohydrology (Poff and Zimmerman, 2010) and urban ecohydrology (Pataki *et al*., 2011) were developed with the consideration of human activities. In addition, several academic journals have been launched, including *Ecohydrology*, and *Ecohydrology* & *Hydrobiology*. To date, the framework of integrated terrestrial and aquatic ecohydrology has been established, which covers a variety of ecosystems, including forests, grasslands, wetlands, agriculture, rivers, lakes, and cities. Thus, ecohydrological research has gradually shifted from small-scale experimental observations and analyses to multi-scale comprehensive model explorations (van der Tol *et al*., 2008), and the discipline theory and methods have experienced significant progress.

The ecohydrological research in China began in the 1980s and mainly concerned water transportation and energy balances in agricultural SPAC system. Accordingly, Chinese scholars developed a series of theoretical concepts and computational models based on the SPAC theory. In particular, Shao *et al*. (1986) proposed a calculation formula for flow resistance in the SPAC system. Kang *et al*. (1993) explored hydraulic resistance in the SPAC system and developed models for estimating leaf stomatal resistance and farmland transpiration and evaporation. Liu (1997) explored a method for controlling water consumption in the SPAC system, and proposed the concept of "water transformations among air, surface, ground, soil, and plant" for an agricultural SPAC system. To date, China has made several notable achievements, including vegetation changes and their effects on runoff, sediment, soil moisture variation and dissipation, and hydrological cycles (Wang *et al*., 2015; Zhou *et al*., 2015; Feng *et al*., 2016). Further, in ecohydrology related studies of aquatic systems, remarkable contributions have been made to the impact mechanisms of flow regimes, associated water quality processes on aquatic communities, and ecohydrological process simulations based on the theories of river continuum, flood pulse, and natural flow paradigm (Zhang *et al*., 2012; Chen *et al*., 2013; Xu *et al*., 2013; Zhu *et al*., 2018). These contributions have been practically applied to control cyanobacterial blooms in the Taihu Lake, simulate fish habitats under flow regime variations, and ecologically regulate the Three Gorges Dam.

2 Problems and challenges in the ecohydrology discipline

The ecohydrology discipline has achieved rapid developments in wetland, river, lake, forest, grassland, farmland, and other ecosystem researches. However, existing studies have mainly focused on experimental observation, mechanism exploration, and numerical simulations for individual ecosystems. Owing to frequent exchanges of material and energy among different layers of the earth system, as well as intensifications of climate change and human disturbance, several water issues (e.g., ecosystem degradation, flood, drought, soil erosion, and water pollution) exist in various basins, especially the Yangtze River, Yellow River, Haihe River, Huaihe River, and Liaohe River basins. In addition, for small scale ecohydrological processes in a single system, many problems and challenges still exist regarding causes of the aforementioned water issues, identifying their critical influencing factors, and proposing countermeasures. These problems and challenges include the simultaneous observations, the fusion of multiple ecohydrological variables, the conversion of ecohydrological mechanisms from point or field scales to watershed or global scales, the detection and attribution of multiple impacts on ecohydrological processes, such as climate change and high intensities of human activities, and two-way coupling of ecological and hydrological processes at the watershed scale. In addition, with the acceleration of global socio-economic development and urbanization, ecohydrological research must focus not only on physical processes but also impacts of human activities, such as socioeconomic and human developments, especially regarding urban ecohydrology.

Therefore, in addition to the theoretical developments in fields related to earth science and technological innovations, including observation technologies, information transmission, and computing capabilities, it is necessary to strengthen the investigations concerning the linkages and interaction mechanisms among ecosystems or ecohydrological processes. Furthermore, additional efforts should also be made to include integrated observations of multiple variables (e.g., water, soil, air, and ecology), consider interactions among multiple ecohydrological processes, evaluate impact mechanisms of global changes and human activities, achieve comprehensive simulations and system integrations, and further multidisciplinary research. Overall, the basic framework, theoretical system, and technical methods of ecohydrology must be improved.

3 Development directions in China

The Chinese government has always attached importance to ecological protection and ecological civilization construction. In particular, the government has repeatedly emphasized the importance of ecology, stating that "lucid waters and lush mountains are invaluable assets" and "the mountains, rivers, forests, lands, and lakes are a life community". According to the current progress and challenges of ecohydrology, as well as major national demands (i.e., ecohydrological construction and green development), the main development directions are summarized in this section.

3.1 Developing new ecohydrological monitoring methods and improving comprehensive observation network

Field observations are conducted to study certain ecohydrological processes (Yu *et al*., 2014). Ecohydrological variables include meteorological variables (e.g., rainfall, air temperature, wind speed, radiation, and evapotranspiration), hydrological variables (e.g., water level, water discharge, and flow velocity), environmental variables for different ecosystems (e.g., water, carbon, nitrogen, and phosphorus), and ecological variables (e.g., vegetation and its net primary productivity, plankton, benthos, and fish). Observation techniques and methods for various variables at different scales vary significantly, but the current attention mainly focuses on carbon flux, soil water transport, evapotranspiration, and soil water-related parameters observation at a point or a field scale. Remote sensing provides an effective method for achieving scale expansion from a point to an entire area (Montaldo *et al.*, 2013). As a good tracer of water movement in different forms among soil, vegetation, atmosphere, and ocean, isotopes have become an important research tool in various disciplines, including meteorology, hydrology, and ecology. Therefore, in the future, we should focus on developing comprehensive monitoring technologies, including continuous flux and isotope measurements, field monitoring, remote sensing, and radar at multiple scales.

In addition to further research concerning the interaction mechanisms between ecological and hydrological variables, it is necessary to establish and improve a comprehensive ecohydrological observation network nationwide. Several long-term ecological monitoring programs exist globally, such as the Global Flux Network, the US National Ecological Observatory Network and Long-Term Ecological Research, and the European Flux Program. To date, China has mainly focused on monitoring network construction for individual variables, such as meteorology, hydrology, water quality, and ecology. The existing networks are ground meteorological observation networks and high-altitude meteorological observation networks that are operated by the China Meteorological Administration, the National Hydrological Station Network of the Ministry of Water Resources, the surface water quality monitoring network in the Ministry of Ecology and Environment, the Chinese Ecosystem Research Network, and the China Terrestrial Ecosystem Flux Observation Research Network. These observation networks have greatly promoted the development of ecology, hydrology, and other disciplines in China, but most are limited to single departments or disciplines, such as meteorology, water conservancy, ecology, and environment. Thus, long-term monitoring networks at a large scale and integration of data sharing must be improved. Meanwhile, ecohydrological observations in China should comprehensively consider regional divisions of physical geography, ecology, hydrology, and water resources, and should be expanded to include more indicators in the hydrology, ecology, climate, and soil fields. Moreover, the existing monitoring network systems should be optimized and improved at multiple spatiotemporal scales, and the relevant data sources of ecohydrology among different disciplines and departments should be shared. Together, these changes could provide a solid basis for the development of a comprehensive ecohydrology discipline in China.

3.2 Strengthening mechanism investigations and improving basic theories of the ecohydrology discipline

Investigations of the interaction mechanisms of various variables in terrestrial and aquatic ecohydrological processes, coupling mechanisms between hydrological and ecological processes, and their responses to global changes, are not only the core themes in the comprehensive theory of ecohydrology, but also the foundations to support understanding water cycle evolution. Currently, studies on terrestrial ecohydrological processes have mainly focused on the response mechanisms among ecohydrological variables in farmlands and forests, most of which use the SPAC and Budyko water-heat balance theories to analyze the exchange mechanisms of energy and water between soil, vegetation, and atmospheric interfaces (Yang *et al*., 2016). However, there are more studies worthy of exploration regarding ecohydrological conversion mechanisms from field scales to watershed or global scales. Rivers and lakes are important parts of natural ecosystems and are the main pathways of material circulations, energy conversions, and information exchanges between terrestrial and aquatic ecosystems. Currently, most of the existing studies on ecohydrological processes exist at the stages of field experimental observation and semi-quantitative research (Zolezzi *et al*., 2009). Thus, it is important that future aquatic ecohydrological mechanism research comprehensively reveals the continuity characteristics and heterogeneities of ecohydrological processes via field monitoring, laboratory experiments, and numerical simulation approaches.

In addition to improving the ecohydrological mechanism and basic theoretical paradigm, it is necessary to further the exploration of coupling mechanisms and theoretical paradigms of terrestrial and aquatic ecohydrological processes, and clarify migration and transformation rules and evolution characteristics of biogenic (e.g., carbon and nitrogen), biological, environmental, and climatic factors at the soil, vegetation, atmosphere, and water interfaces. Meanwhile, the dynamic response mechanism of key ecohydrological variables to climate change and human activities should be further explored as it has become a research topic. In addition, it is important to develop a multi-scale and multi-variable theoretical system to comprehensively research terrestrial-aquatic ecohydrological processes in a changing environment.

3.3 Comprehensive simulation and integration of terrestrial-aquatic ecosystems at multiple scales

In the Outline of 13th Five-Year Plan for Economic and Social Development in China (2016–2020), it is clearly stated that “the protection of the ecological environment should be strengthened with the improvement of environmental quality as the core, and with the solution of outstanding problems in the field of ecological environment as the focus”. Currently, the main research areas of terrestrial ecohydrological processes include water transport along the vertical gradient, physiological and ecological vegetation processes, and impact of ecosystems on hydrological processes and underlying surfaces. Conversely, the main research areas for aquatic ecosystems include relationships between biological habitats, ecosystem composition, and runoff processes. As vegetation, soil, and water are the key carriers of various life activities in both terrestrial and aquatic ecosystems, they are also the main reaction sites for biological, physical, and chemical processes. The contradiction between traditional socioeconomic development and ecological environment improvements grows increasingly worse, causing significant spatial variations in vegetation and biological communities, and remarkable ecosystem changes. This contradiction further aggravates the risk of ecological environment deterioration and restricts the construction of a national ecological civilization. Therefore, developing comprehensive research on terrestrial-aquatic ecohydrological processes is of great scientific significance and practical value (Xia *et al*., 2015). In addition to cross-disciplinary development, ecohydrological process studies incorporate ecological principles, ecological models, and spatiotemporal scales, leading them to the direction of comprehensive terrestrial-aquatic ecosystem research. To meet societal needs and achieve regional sustainable development, it is necessary to integrate multi-source observations (e.g., remote sensing and stations), build a comprehensive ecohydrological process model for multiple-scales (e.g., station, patch, and watershed), and assess and regulate stability of ecohydrological systems. Meanwhile, it is important for China to rationally allocate water resources and ensure functional integrity and species diversity of terrestrial and aquatic ecosystems.

3.4 Integrating ecohydrology and social sciences, and promoting comprehensive global ecohydrological research

Multiple aspects of socioeconomic development, including agricultural production, urban expansion, construction and regulation of water conservancy projects, have negatively affected ecohydrological processes, leading to imbalanced development of ecosystems. Comprehensive ecohydrological research is one way to solve many water issues, including resource shortages, environmental pollution, and ecosystem degradation, and is also one of the core topics of major global research programs. In 2004, the Earth System Science Partnership proposed the "Global Water System Plan", which focuses on the role of human activities in global water system processes (i.e., physical processes, water quality and ecological processes, and human economic processes). In 2013, IAHS launched a scientific plan covering the next ten years (2013–2022), i.e., Panta Rhei-Everything Flows, with the theme of "Change in hydrology and society", in which ecohydrology for the sustainable world is one of the six core themes. In 2017, an International Ecohydrology Conference was proposed to promote ecohydrological research oriented toward a circular economy, and to advocate for solutions that integrate the concept of a circular economy and follow natural ecological processes. Therefore, integrated research on ecohydrology and social science, and investigations regarding the impacts of human activities have important scientific significance and practical value for analyzing evolution characteristics of ecohydrological variables and formulating plans to restore and reconstruct ecohydrological systems.

Because of global change and economic integration, ecohydrological studies at the site or basin scale must be expanded to comprehensive studies at the global scale. The rapid development of global earth observation technology, data sharing mechanisms, and computer technology have provided strong basic supports for studying multiple ecohydrological processes in the world. For example, a large number of ecohydrological element products exist at the global scale, including global precipitation products (e.g., NCEP/NCAR, CRU TS, and CPC), global runoff databases (e.g., GRDC), global land cover data (e.g., GlobCover), global land use data (e.g., UMD and GLCC), and global evapotranspiration and soil datasets (e.g., GLDAS). Therefore, exploring the coupling mechanisms of energy, and hydrological, ecological processes in the terrestrial and aquatic systems, and economic and human processes at the global scale in order to realize a comprehensive simulation of global ecohydrological variables, and assess impacts of climate change and intensive human activities has become an ecohydrology research hotspot.

4 Research interests in China

4.1 Combining multi-source ecohydrological information and constructing a comprehensive observation network

Multi-source information monitoring and comprehensive network construction are the cornerstones of multi-scale comprehensive ecohydrological research. Owing to the existing problems of current monitoring technologies and scale limitations, the comprehensive monitoring methods of ecohydrological variables and functions must be further developed, and the technology of large-scale lysimeters, eddy covariance, stable isotopes, and quantitative remote sensing must also be further improved regarding evaporation, soil moisture movement, carbon-water flux, plant transpiration, and soil evaporation processes. In the future, comprehensive monitoring of multi-source information combined with multiple monitoring technologies must be implemented, and comprehensive continuous measurement technologies for flux observation and isotopes should be improved. The integration of field observations at the site scale, remote sensing measurements, and other multi-scale observations should also be further developed. Moreover, real-time information collection, transmission, and remote monitoring technologies should be developed for automatic monitoring of ecohydrological variables. Furthermore, national technical standards and specifications should be formulated for long-term monitoring and systematic observation networks. Finally, a comprehensive monitoring network of ecohydrological variables for terrestrial-aquatic systems should be designed by integrating existing observation network systems, such as meteorology, hydrology, water quality, and ecosystems (Figure 1). Meanwhile, it is necessary to comprehensively consider regional divisions of physical geography, ecology, hydrology, and water resources in order to further improve monitoring network system, which would provide a solid foundation for future ecohydrological studies in China.

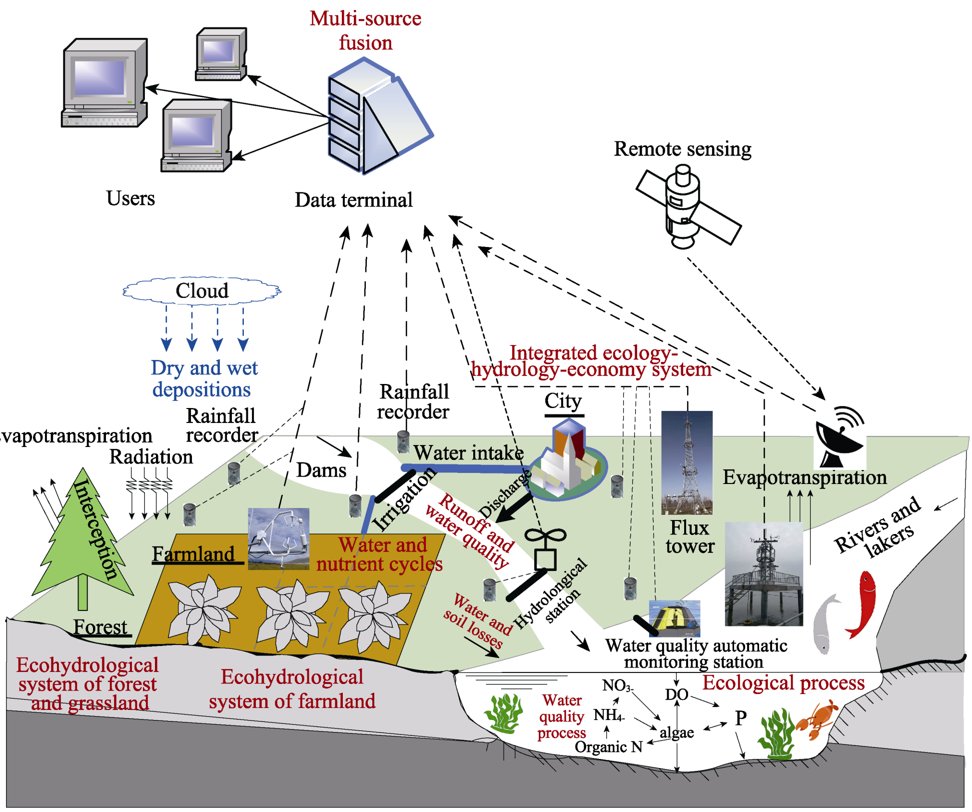

Figure 1 Integrated ecohydrological system and its observation network at the watershed scale

4.2 Spatiotemporal distribution of critical ecohydrological variables and their evolution characteristics

The spatiotemporal distributions of critical ecohydrological variables and their evolution characteristics are of increasing interest regarding ecohydrological mechanisms, and also can reveal the evolution mechanisms of ecohydrological processes and develop their basic theories. The specific ecohydrological characteristics of the spatiotemporal evolution of hydrological variables are presented as follows. Natural runoff variability is considered to be the driving force for landscape changes in the riparian zone, and spatiotemporal changes in the flow regimes and their interaction with groundwater can cause structural and functional changes in river ecosystems. Furthermore, variation analyses of flow regime metrics have become important for studying landscape patterns of aquatic ecohydrological systems (Vigiak *et al.*, 2018). Moreover, evapotranspiration is a critical ecohydrological process, as its variation could disorder the ecohydrological regional pattern. Water quality is an essential indicator of the water environment, as its characteristics reflect water responses to the ecohydrological system. In addition, the ecohydrological characteristics of the spatiotemporal changes in ecological factors are presented as follows. Vegetation type and its structural shift directly affect the hydrological cycle (such as interception, runoff, and evapotranspiration), affecting the healthy operation of integrated ecological, hydrological, and socioeconomic systems at watershed or regional scales (Blanco- Gutierrez *et al.*, 2013). As a paramount ecological indicator, the net primary productivity of vegetation precisely affects the spatiotemporal patterns of evapotranspiration and water use efficiency, and can be applied to regulate the impact and energy storage of ecological processes. Plankton is an important component of aquatic ecosystems, and its spatiotemporal distribution characteristics reflect ecosystem health. The habitat, species types, and distributions of fish or large invertebrates are also applied to evaluate river ecological health conditions, which can reveal potential problems and their causes in river ecosystems. By investigating the spatiotemporal patterns of these ecohydrological variables, a comprehensive analysis of ecohydrological evolution characteristics and driving mechanisms can be developed, acting as a foundation for the implementation of numerous ecohydrological studies.

4.3 Integrating ecohydrological modelling of multi-variables at multi-scale and its uncertainty analysis

A terrestrial ecohydrological model was developed based on a traditional rainfall-runoff relationship model, and coupled with other models, including the vegetation growth model and soil biogeochemical process model. It is advantageous for quantifying interactions between vegetation, nutrient, and hydrological processes, as well as the dynamic mechanism between hydrological and ecological processes. The existing models include the Rutter, Massman, and Philip models, which simulate canopy interception and forest soil water infiltration. The SVAT model is used to simulate ecohydrological processes for diverse ecological types. Watershed hydrological models (e.g., DHSVM, VIC, SWAT, and HEQM) consider dynamic vegetation processes, and MXW and IRM models examine the relationship between groundwater and vegetation communities. Hence, more attention should be paid to exploring the mechanisms of vegetation dynamics and water-nutrient cycles, and considering the effects of climate change and human activities in order to strengthen the physical mechanisms of terrestrial ecohydrological models. A river ecohydrological model was developed based on hydrological, hydraulic, and water quality models, and comprehensively considered the growth status of aquatic organisms and quantified the response mechanisms among various water quality variables, flow regimes, and aquatic biological communities. The spatial dimensions of this model range from one to three, which is similar to those of MIKE, EFDC, and HSPF. In China, some conceptual models for river ecohydrology that integrate river ecohydrological processes and take advantage of existing models have been proposed, such as a conceptual model based on the relationship between flow regime and fish demand, a holistic conceptual model for the structure and function of river ecosystems, and a conceptual model based on the relationships between flow and ecological responses (Dong *et al*., 2010; Wang *et al*., 2013; Xu *et al*., 2013). In the future, aquatic ecohydrological models should be developed to construct a comprehensive mathematical model that describes river hydrology-water quality processes and ecosystem changes affected by human activities using high-precision terrain data, nutrient observations, aquatic growth cycles, and human activities (e.g., dam regulation, water intake, and sewage).

In addition, integrated ecohydrological process models that consider multiple variables in a multi-scale terrestrial-aquatic ecosystem have emerged owing to the maturity of single ecohydrological process models, as an important research direction for ecohydrological model development. For instance, RHESSys was developed by coupling the distributed hydrological (TOPMODEL) and the forest carbon cycle models (Forest-BGC) at the watershed scale, and realized the two-way coupling of ecological and hydrological processes (Mackay and Band, 1997). Chinese scholars also developed the vegetation interface processes model (VIP) and the China AgroSys, which simultaneously simulated crucial ecohydrological processes, such as crop yield, evapotranspiration, runoff yield, and routing at the watershed or regional scale (Mo and Liu, 2001; Yu *et al*., 2007). In addition, Xia *et al*. (2017, 2018) explored the link and feedback mechanisms among hydrology, ecology, and human activities by considering the hydrological cycle, and developed integrated water system simulation platforms, such as the Yangtze River Simulator and Urban Water system model 5.0.

The scale mismatch of time and space in different ecohydrological processes has always been a challenge for comprehensive simulations and integrations of ecohydrological processes. Currently, it is still technically difficult to extend laws and conclusions from a small-scale to a watershed scale, which restricts ecohydrological simulations (Figure 2) (Gao and Yu, 2018). Theoretically, simulations at a smaller scale will be closer to the actual conditions. However, owing to the spatial heterogeneity at a small scale, it is difficult to generalize the obtained laws to a larger scale. Hydrological models generally simulate hydrological processes at sub-basins or grids on a daily or even hourly scale. For ecological models, the basic data observations are usually at the site or field scale, while the simulations of vegetation biochemical processes are at an hourly scale. To overcome this discrepancy, scholars usually adopted multi-scale nested methods. However, if a small-scale process simulation requires outputs from a large-scale process simulation, the outputs are usually regarded as constants, which affect the spatial resolution of final simulation results. It is also important for future ecohydrological models to achieve the dynamic calculation of exchange variables and scale conversion among modules using downscaling or upscaling approaches.

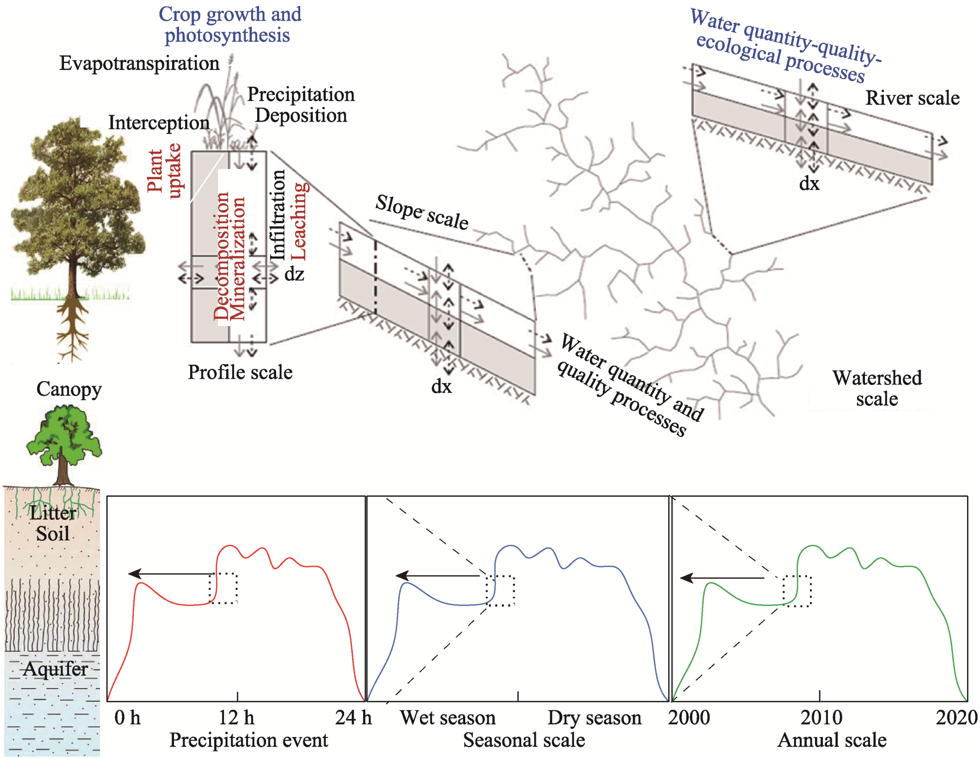

Figure 2 Watershed ecohydrological processes at multiple spatiotemporal scales (revised from Gao and Yu, 2018)

Furthermore, the uncertainty sources of individual processes and their cumulative impacts in the complex model are also critical issues in the ecohydrological model research (Zhang and Shao, 2018). Model uncertainty sources can be roughly divided into uncertainties associated with model inputs, model structure, parameters, and observations used for model calibration (Renard *et al*., 2010). Previous uncertainty studies are limited to uncertainty estimations of a single source and its impact on certain parameters and simulation results. However, estimating uncertainty sources in a complex system model is still in its initial stages. Zhang and Shao (2018) adopted the bootstrap sampling and a multi-objective optimization algorithm to estimate uncertainties and their impact in a complex system model (HEQM), and also proposed a balanced calibration method for multiple processes and multiple variables to handle the uncertainty propagation (Zhang *et al*., 2016) (Figure 3). However, additional studies are required to improve and develop theories and methods for estimating model uncertainty and establishing a scientific and reliable uncertainty evaluation platform.

4.4 Multidisciplinary research on ecohydrology discipline

The interaction mechanism and coupling of terrestrial vegetation ecological processes, river ecosystems, social systems, and hydrological processes are used as the core contents of the IGBP, UNESCO/IHP, Ten-Year Scientific Plan (2013–2022) of IAHS (i.e., Panta Rhei), and Future Earth plan. According to these major global scientific projects, further integration between the natural sciences (e.g., environmental sciences, atmospheric sciences, and others) and social sciences (e.g., socioeconomy and human activity) is a key development direction for ecohydrology. For example, climate change affects both the hydrological and material

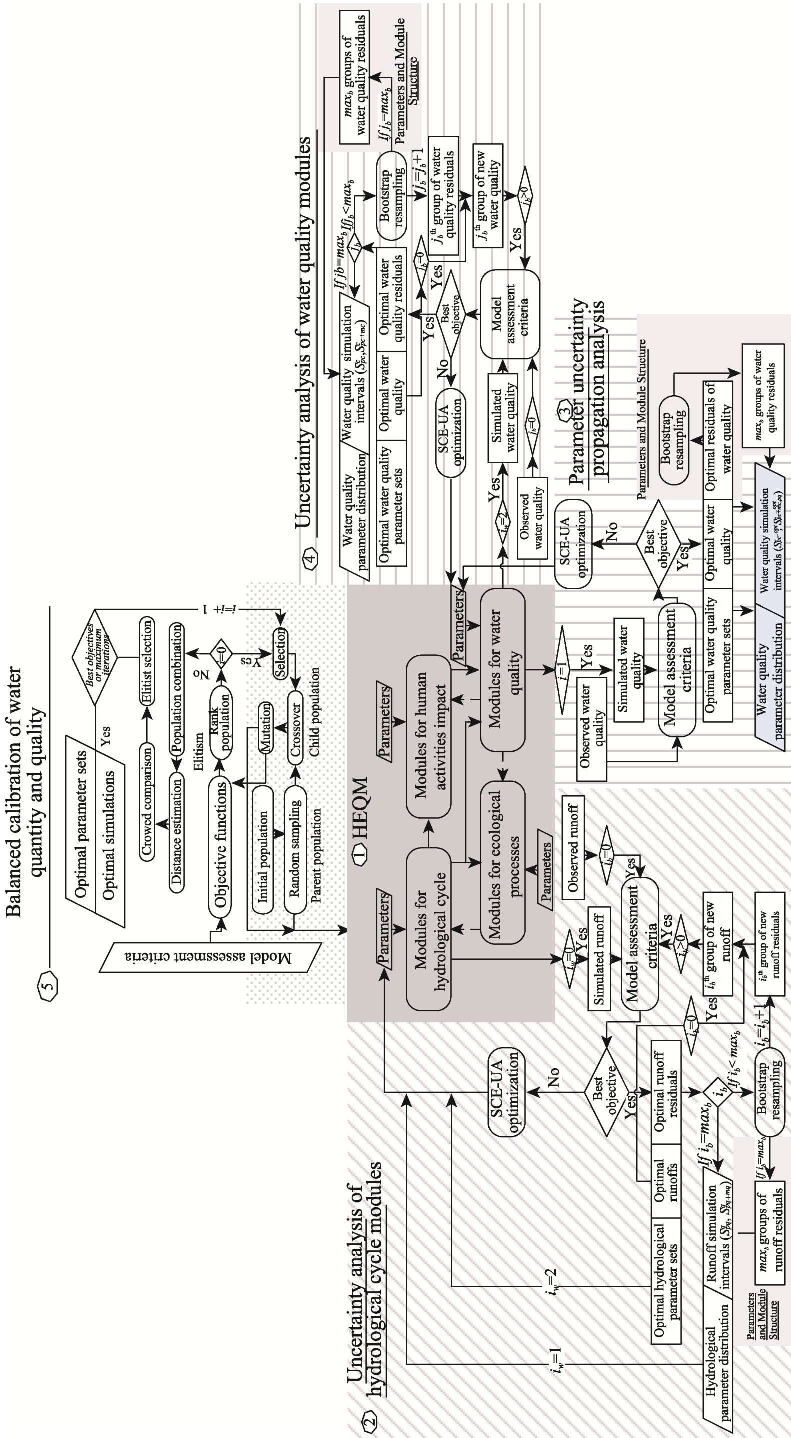

Figure 3 Framework of uncertainty estimations and balance calibrations of multiple processes in an integrated water system model (Zhang *et al.*, 2016; Zhang and Shao, 2018)

cycles of surface ecosystems, vegetation physiology, and ecology (Ouyang *et al.*, 2016). Therefore, investigating the mechanism and feedback of climate change on related ecohydrological processes is also a pertinent issue that must be addressed in the future.

In addition, with rapid economic development, human activities (e.g., construction and regulation of water conservancy projects, massive application of pesticides and fertilizers, excessive discharge of pollutants, vegetation destruction, deforestation, and urbanization) have increasingly affected ecohydrological systems of river basins (Zhai *et al.*, 2014). The solutions to these problems require the integration of multiple ecohydrology-related disciplines. The key scientific issues are as follows: the impact mechanism of water conservancy projects on river ecohydrological systems and rare species protection, nutrient cycle and pollution characteristics in the SPAC system, environmental effects of point and non-point pollution sources and their impacts on ecosystems, impacts of underlying surface changes caused by human activities on ecohydrological changes, urban ecohydrological evolution mechanism, and regulation characteristics of urban sponge measures. The Chinese government has proposed major strategies related to ecohydrology, such as the Beautiful China, the Yangtze River Protection, the ecological protection and high-quality development of the Yellow River Basin, the sponge cities, and the ecological construction of the coastal zone. Several major national science and technology projects have also been designed to meet both national and environmental needs, such as the national key research and development programs: "Typical Fragile Ecological Restoration and Protection" and "High-efficient Development and Utilization of Water Resources", and the strategic priority research program (Class A) of the Chinese Academy of Sciences, "Ecological Civilization Construction Technology Project of Beautiful China". The National Natural Science Foundation of China has also attached importance to developing the ecohydrology discipline, especially in arid and semi-arid areas where water use conflicts are prominent and the ecological environment is poor. Further, several major scientific foundations have been established, including the major research plan "Integrated Research on Ecohydrological Process of the Heihe River Basin," and an innovative research group project "Ecohydrology in Arid Areas" (Cheng *et al.*, 2014). Ecohydrological studies in the Heihe River Basin have not only developed an advanced monitoring system at the basin scale and an integrated ecohydrological process model, but also provided decision-making supports for sustainable development (Wang *et al.*, 2001). Aiming at basin ecological environment protection, a major program of the National Natural Science Foundation of China "Reciprocal impact mechanism and countermeasures on the water cycle change in the Yangtze River Economic Belt and the green development of typical city groups in the middle and lower reaches" has also been proposed. In addition, the 13th Five-Year Plan proposed the development of integrated "ecology-hydrology-economy" research. These major national needs and disciplinary frontiers will further promote multi-disciplinary ecohydrological research in China, including the integration of natural and societal disciplines, and comprehensive investigations of the influence and feedback of economic development and human activities on ecohydrological processes. As a key component of ecological civilization construction in China, the water regulation capacity of the terrestrial ecosystem and its valuation are important for the sustainable management of ecosystems and natural capital (Zhang *et al.*, 2021). They are also research hotspots in the disciplines of ecology, hydrology, ecological economics, and environmental economics.

5 Application prospects in China

Studies in the ecohydrology discipline have consisted of the in-depth research on basic theories, technical methods, and application practices in various branches, such as forest, grassland, river and lake, wetland, agricultural, and urban ecology. These studies have made great progress and provided broad application prospects for ecohydrology. In particular, in the context of ecological civilization construction in China, ecohydrology will be widely used in the restoration and protection of natural communities, including mountains, rivers, forests, farmlands, lakes, grasses, and cities.

In the field of forest and grassland ecology, vegetation ecological restoration, returning farmland to forest and grassland, and soil erosion prevention and control are important applications and technical approaches of the 13th Five-Year Plan and the ecological civilization construction of China (Wang *et al.*, 2001). Regarding vegetation ecological restoration, further studies should be conducted concerning the physiological and ecological water consumption rules of vegetation for different regions, vegetation types, and water supply conditions, the relationships between vegetation and the hydrological cycle, and the ecological water demand for the physiological and ecological rules of vegetation, all of which will increase the effective water utilization rate of vegetation. In terms of returning farmland to forest and grassland, the change characteristics of vegetation composition and spatial distribution patterns, and hydrological response assessments should be examined to provide technical supports and a decision-making basis. In terms of soil erosion prevention and control, it is necessary to explore the impact mechanism of different soil and water conservation measures on ecohydrological processes, realize the expansion of spatiotemporal coupling simulations of erosion in small-scale watersheds to large- or medium-scale watersheds, and provide a theoretical basis and technical support for the prevention and control of soil and water losses in China.

In the fields of river, lake, reservoir, and wetland ecology, ecological water conservancy project, river and lake ecological restoration, and wetland restoration and reconstruction aimed at maintaining river health will have extensive and in-depth applications in the protection and management of ecohydrological systems (Zhang *et al.*, 2014; Zhang *et al.*, 2015). In terms of the design and construction of ecological water conservancy projects, it is necessary to explore the influence of water conservancy projects on the habitats of key protected species, hydraulics, flow regimes, and species communities in order to promote the transformation of water conservancy project regulations from traditional flood control to ecological control. Regarding river and lake ecological restoration, it is necessary to investigate the current ecosystem situation and formulate restoration goals and measures accordingly. It is also important to explore the response mechanism of aquatic organisms to river habitat changes and improve the evaluation system for ecological restoration. Meanwhile, for wetland ecological restoration and reconstruction, it is necessary to estimate the wetland ecological water demand and the comprehensive control of the “ecology-hydrology-economy” system in large river basins, and improve the theoretical and key technologies of water connection between wetland ecological protection and restoration.

In the field of agricultural ecology, further studies must be conducted considering the monitoring and estimation methods of crop water demand at different scales and the response and adaptation mechanisms of crop water demand to changing environments (Kang *et al*., 2016). Meanwhile, attention should be paid to improving the utilization rate of agricultural water resources both theoretically and technically in order to reduce ineffective field evaporation, and promote agricultural water-saving. In the field of urban ecohydrology, the ecohydrological effects of urbanization and sponge city construction should be investigated (Liu *et al*., 2016), including evapotranspiration in forests and grasslands, mitigation mechanisms of green infrastructure on urban hot islands, rain islands and runoff effects, water environment improvements, and ecological function restoration in urban rivers and lakes by canal system repair and treatment of black and odorous water bodies.

This study reviewed the research progress of the ecohydrology discipline and its development status and challenges. The main future directions were also proposed according to the research hotspots and national demands of ecohydrology in China, including the development of multiple ecohydrological process models at large scales, the promotion of integrating multiple disciplines using comprehensive ecohydrological variable monitoring, and the exploration of multi-process interaction mechanisms. In addition, the future research interests were further clarified, including building an integrated monitoring network and combining multi-source information, clarifying the spatiotemporal patterns of key ecohydrological variables and their evolution characteristics, developing integrated multi-variable ecohydrological models at multiple scales in a terrestrial-aquatic ecosystem, and implementing multidisciplinary research, such as “ecology-hydrology-economy” research. This study provides theoretical and basic supports for the implementation of ecological civilization construction and the protection of mountains, rivers, forests, farmlands, and lakes in China.

Acknowledgement

This paper is one of the achievements of the developmental strategies of the discipline of the academic divisions of the Chinese Academy of Sciences. Thanks to the team members, including Cai Qinghua, Chang Jianbo, Chen Qiuwen, Cui Baoshan, Liu Min, Lu Hongwei, Mo Xingguo, Qin Boqiang, Qin Huapeng, Qiu Guoyu, Shen Yanjun, Song Jinxi, Wang Genxu , Wang Yanhui, Wei Xiaohua, Xu Xianli, Yu Pengtao, Zhang Mingfang, Zhang Xiang, Zhang Guangxin, Zhao Changsen, Zhou Guoyi, Zhu Guangwei (Alphabetically listed according to the surname) and reviewers for their valuable suggestions.

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