

Research on application of ecohydrology to disaster prevention and mitigation in China: a review

Guangli Fan^{a,*}, Jun Xia^{a,b}, Jinxi Song^a, Haotian Sun^a and Dong Liang^a

^a Northwest University, Xi'an, Shaanxi 710127, China

^b Research Institute for Water Security (RIWS), Wuhan, Hubei 430072, China

*Corresponding author. E-mail: fanguangli2000@gmail.com

ABSTRACT

In this paper, the ecohydrology measures including water management and interaction of ecological hydrology were considered to take a holistic view on the impact of climate, ecology, environment, and topography on different types of disasters. In the first step, the contents of the grim disaster situation and the information framework of ecohydrology with disasters were evaluated. Next, the creation of ecohydrology and its work with related disasters were summarized. Three disasters including flood, drought, and geohazard were evaluated and three examples (Dujiangyan Irrigation Project, Karez, and Ecological slope) have been separately discussed for considering the concept of the problem. Depending on the characteristics and potential for an effect in different disasters, there needed to be some challenges and opportunities for ecohydrology facing related disasters in various fields, such as National Space Planning, Sponge City and the 'One Belt And One Road' Initiative. Finally, some valuable conclusions were drawn on the application of ecohydrology to disaster prevention and mitigation. Furthermore, the key systemic settings between water management, hydrology, and ecology were described, which is of the main importance for social disaster reduction, emergency management, and protection of accident prevention.

Key words: disaster, drought, Dujiangyan Irrigation project, ecohydrology, flood, geohazard

HIGHLIGHTS

- Comprehensive analysis of the convergence of water and environment and economy can be efficiently extended to disaster prevention and mitigation activities.
- The creation of ecohydrology in disaster reduction and mitigation activities are closely linked, communicated, and promoted.
- Ecohydrology is an application technology that takes a holistic view of ecology, hydrology, topography soil, and biology.

1. INTRODUCTION

Disaster is a major disruption to the functioning of a community or society involving serious human, material, economic or environmental losses (Lalehzari & Kerachian 2020; Sun & Khayatnezhad 2021; Zhu *et al.* 2021). Disasters are seen in contemporary academia as the consequence of poorly controlled risk (Ren 2021). Previous studies indicated that all disasters should be seen as man-made, their rationale being that human actions can prevent them from developing into a disaster before a hazard strikes. Consequently, all disasters are the result of human failure to implement appropriate disaster management measures (Li *et al.* 2021). Disasters may pose an adverse effect on the well-being of humans, societies, and socio-ecological systems.

The 2019–20 Australian bushfire season, well known as the Black Summer, was a period of exceptionally intense bushfires throughout Australia. In June 2019, the Acting Director of Queensland Fire and Emergency Services warned that the bushfire season, which usually begins in August, could start early. The warning was based on a seasonal outlook related to bushfires in northern Australia, noting unusually dry conditions as well as a lack of soil moisture, coupled with early fires in central Queensland. During the summer, hundreds of fires have broken out, mainly in the southeast of the country. Major fires peaked between December and January. As a result, these events severely disrupted the social function and incurred widespread human, material, economic or environmental losses, which increased the coping capacity of the affected community or society (Withey 2019).

This is an Open Access article distributed under the terms of the Creative Commons Attribution Licence (CC BY 4.0), which permits copying, adaptation and redistribution, provided the original work is properly cited (<http://creativecommons.org/licenses/by/4.0/>).

Lives and property losses have been the most serious in recent years. The frequency and intensity of disasters have been on the rise with changes in the natural condition and human activities. One of the greatest future challenges in China is how to inherit and carry forward the successful experience of the ancient eco-hydrology concept and practice which involves harmony between man and nature. The current practical situation ought to be combined with the new science and technology, creating new ideas and methods for effective disaster prevention and reduction.

On August 30th, 2020, China's National Emergency Management Department issued early warnings on the following three days, East Northwest, North China, Northeast and Southwest Zones, Strong Rainfall Phase, Sichuan, Yunnan, Shandong, Liaoning, Jilin, Rainfall Area, and Early High Overlap. Parts of soil water tend to be saturated, and it should be emphasized to prevent flash floods and waterlogging caused by a rainstorm. Then, in some of these areas, more serious water-related disasters occurred than in 1998.

In recent years, thousands of natural hazards have occurred in China. According to the China statistical yearbook and National Loss from natural disasters notification, from 2011 to 2018, drought disaster areas ranged from 7,711.8 (1,000 Ha) to 16,304.2 (1,000 Ha), as well as areas of geo-hazard from 5,808.8 (1,000 Ha) to 17,524.6 (1,000 Ha) (Figure 1). Although the trends in the disaster area have been reduced to some degrees, a significant gap in data and the type of disaster prevention and mitigation still exists.

2. ECOHYDROLOGY

Ecohydrology is concerned with the effects of hydrological processes on the distribution, structure, ecosystem function, and with the effects of biotic processes on elements of the water cycle (Hannah *et al.* 2004), which is a different concept from hydroecology, which emphasizes the effects of the ecological process on hydrological processes. The ecohydrological principle of water management focuses on the natural flow mechanism and the essential relationship between the conservation of habitats and ecological health events (Figure 2). With a certain degree of variability, ecosystems can remain safe (Tao *et al.* 2021; Xu *et al.* 2021). But water should also be monitored to preserve volatility and uncertainty, including extreme events. From the public point of view, however, volatility should be decreased (in terms of causes and effects, floods and droughts should be minimized). Taking into account the many threats spread across water systems, often resulting from mismanagement of land and water supplies, and the non-water related disasters, the availability of safe and adequate water is a crucial factor in survival and recovery. How to utilize the ecohydrology resources to protect the safety of people's lives and the property deserves attention.

The ultimate goal of this paper is the application of the ecohydrology concept to prevent and mitigate disasters, protect people's life and property protection, and enhance human well-being. In this paper, the grim disaster situation and the information framework of ecohydrology are reviewed. The creation of ecohydrology and its work with related disasters are then

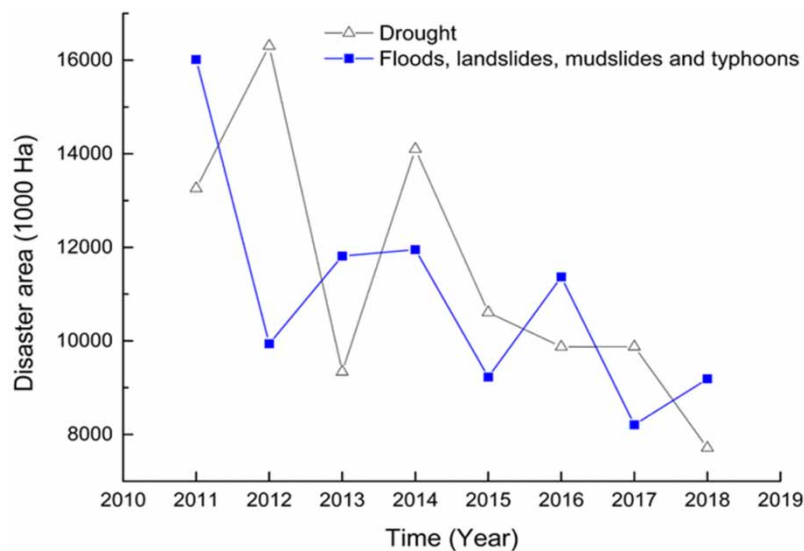


Figure 1 | The disaster area caused by natural hazards in China from 2011 to 2018.

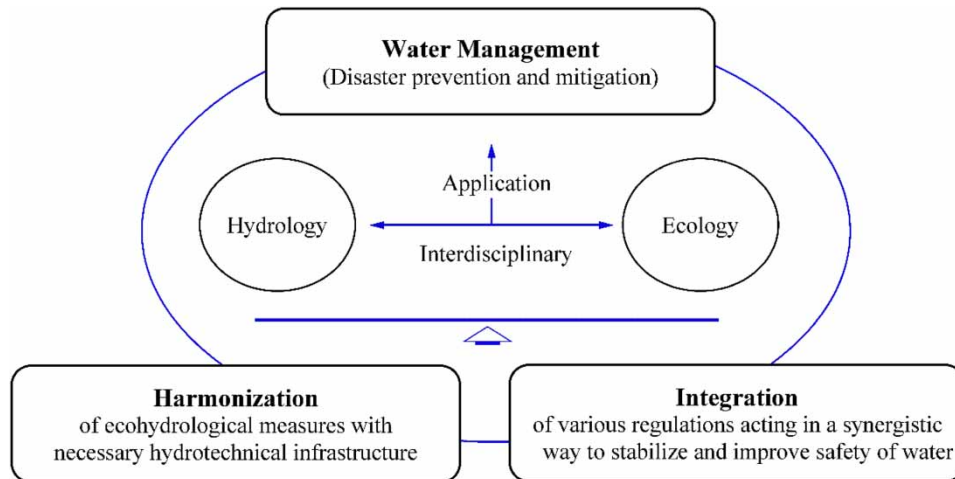


Figure 2 | Main structural setting among water management, hydrology, and ecology.

implemented. Three separate examples of effective ecohydrology disaster relief are illustrated. At the end of the article, there must be some challenges and opportunities for ecohydrological facing related disasters in various fields.

2.1. Ecohydrology and related disaster

Ecohydrology is an interdisciplinary field that studies the interactions between water and ecosystems. Generally, these interactions may occur in water bodies (i.e. rivers and lakes), or on land (i.e. deserts, forests, and other terrestrial ecosystems). Ecohydrological research covers areas that include transpiration and plant water use, biological adaptation to the water environment, the impact of vegetation on river flow and function, and feedbacks from ecological processes and the hydrological cycle.

In the component of international environmental issues, ecohydrology is an established cross-discipline (e.g. freshwater shortage, water quality deterioration, and reduction of biodiversity) (Zalewski 2003). Practices for an environmentally safe, economically feasible and efficient way of making sustainable use of freshwater supplies have been created (Wang *et al.* 2001). Ecohydrology is a modern way to solve the problems of ecological stability, environmental security and water security in the sustainable development of human society. It has therefore been widely concerned and well established in recent years and has been widely used in many fields of study, such as hydrology, ecology, climate, and so on (Xia *et al.* 2003; Guo *et al.* 2021; Hou *et al.* 2021; Wang *et al.* 2021).

The center of ecohydrology is to research the relationship between plants and water in terrestrial-aquatic environments, including the effects on hydrological processes of changes in ecosystems (Rodriguez-Iturbe 2000), the impacts on ecosystems of changes in hydrological processes, the combination of water-ecology-society and basin-wide water management, and ecohydrological processes in atmospheric-hydrological system modeling. The increased focus on ecological and environmental concerns is currently largely encouraging (Xia *et al.* 2018), as well as presenting challenges, the growth opportunities for ecohydrology. Since the 21st century, the research category of ecological hydrology in the world has been divided into four main directions: the theoretical growth of ecohydrology; the reciprocal input of hydrological and ecological systems; the question of scale between water and ecosystems; the management of basin water supplies and the decision-making of sustainable development issues.

In recent years, ecohydrology has not only sponsored research on the aspects of hydrology, biodiversity, climate change and research on the prevention of geological disasters (Li 2012a), but has also had a substantial scientific effect on the achievement of China's strategic goals for social progress and the creation of a system of guarantees of sustainable development at various scales (Gong *et al.* 2010). Ecohydrology is a newly established discipline, and this paper divides its phase of growth into five stages and summarizes the present milestones at each point.

The main topics of ecohydrology at present are vegetation, water volume, water quality, climate change, human activities, remote sensing, ecohydrological models and scales (Fatichi *et al.* 2016; Woznicki *et al.* 2016), and so on. More attention should be paid in the future to the following aspects: the bilateral linkage mechanism of vegetation-water in multi-scales;

the linkage between the land surface and atmospheric boundary layers; eco-hydrochemical processes (Kekelidze *et al.* 2009); the strengthening of observation systems and the ability to obtain glacial surface parameters (Guo *et al.* 2019); the ecohydrological effects of human activity and climate change (Koeplin *et al.* 2013; Duan *et al.* 2017).

2.2. Ecohydrology components

Ecohydrology can be described as a discipline that expresses the hydrological mechanism of ecosystems from a scientific point of view (Figure 2). However, ecohydrology can also be seen as a systematic cross-disciplinary discipline, from the point of view of the application of ecological services to research the process of hydrology and biology and to consolidate general ecological services in the landscape (such as coasts, cities, rural areas).

Through the introduction of the theory, method, and application in the field of ecohydrology to disaster prevention and mitigation in China, this article builds a disciplinary ecohydrology framework based on the core contents of theoretical system-methodology practice. This framework will reasonably address questions such as what ecohydrology is, how to use ecohydrology to minimize the risk of disasters, where to use ecohydrology to preserve life and ensure normal economic and social activities, and so on. On the basis of the literature review, ecohydrology is evolving rapidly in the following ecohydrology research in four aspects: ecohydrological monitoring technologies and experimental methods, research on the mechanism of ecohydrological processes; ecohydrological models; and the application of ecohydrology, which also provides a viewpoint for the future growth of ecohydrology. Further, the basic theories of ecohydrology, including the theory of water-heat coupling, the theory of soil-vegetation-atmosphere, the combination of ecological and hydrological processes and the theory of water-socio-ecological relations, are all still hotspots of ecohydrology science.

Now, the principles of ecohydrology are manifested as three sequential components: (1) Hydrology: the quantification of the hydrological cycle in a basin should be a template for the functional integration of hydrological and biological processes. (2) Ecology: integrated processes at the watershed scale can be guided to improve watershed carrying capacity and ecosystem services. (3) Ecological engineering: regulation of hydrological and ecological processes based on the integrated system approach is a new tool for integrated watershed management. Based on the above testable hypotheses, the principles of eco-hydrology can be regarded as: hydrologic processes usually regulate biota; in return, biota can be molded to regulate hydrological processes; the above regulation can be integrated with hydro-technology infrastructure to fulfill sustainable water resource and ecosystem services.

Knowledge of the ecohydrology principles provides a scientific background for regulating processes and interactions from the molecular scale to landscape scale, enhancing water resources, maintaining and restoring biodiversity, offering ecosystem services to societies, and building resilience including vitality to climatic and anthropogenic impacts (Zalewski *et al.* 2016). Through multi-dimensional management of water (W), biodiversity (B), ecological services (S), resilience to climate change (R), and culture, the resilience of the area and lake ecosystems are enhanced to maintain the sustainability of ecological and human development (Figure 3). Meanwhile, a harmonious WBSR relationship can effectively ensure the well-being of mankind by protecting the safety of people's lives and property, mitigating natural disasters.

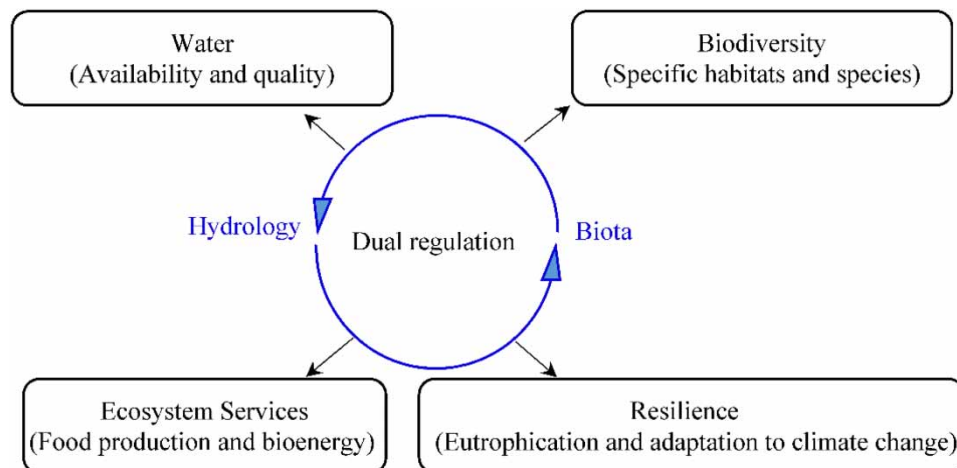


Figure 3 | The relationship between ecological hydrology and related fields.

3. FLOOD

Flooding may occur as an overflowing from water bodies, such as rivers, lakes, or oceans, in which the water vests or breaks levees, resulting in water escaping from its usual boundaries (Plate 2002), or it may happen because of an accumulation of rainwater on saturated ground in a regional flood (Costa & O'Connor 1995; Ren & Khayatnezhad 2021). While the size of lakes or other bodies of water varies seasonally with precipitation and snowmelt, these changes in size are impossible to consider as significant unless they endanger life or flood property (Li & Simonovic 2002). The main effects of flooding include not only loss of life, but also damage to buildings and other structures (i.e. bridges, sewerage systems, roadways, and canals). Floods also frequently destroy power transmission or power generation, causing a chain reaction by the loss of power (Yao *et al.* 2019). Drinking water treatment and water supply capacity may suffer, leading to the loss of drinking water or serious water contamination. Using a new-high-resolution climate model, people would evaluate the effects of global warming caused by greenhouse gases on heavy or prolonged precipitation events that trigger devastating flooding (Christensen & Christensen 2003). However, it may also cause the loss of sewage treatment facilities. The lack of clean water, combined with human sewage in floods, raises the risk of water-borne diseases, which may include typhoid fever, cryptosporidium, cholera, giardia, and other diseases, depending on the location of the flood (Alderman *et al.* 2012).

3.1. Dujiangyan Irrigation Project

In the process of water management, to predict the effect of ecohydrological factors on runoff, not only to study climate, topography, soil, vegetation on hydrological processes and the influence of water flow, but also to deepen understanding of the characteristics of the full hydrological cycle of the basin, to understand the root and root layers of the soil and, under geological conditions and transpiration, the effect of water intake on the formation of the base flow, and so on. These components could be incorporated in an irrigation network for agricultural water management.

Dujiangyan Irrigation Project, 45 km north of Chengdu, is an ancient wonder. The Project's infrastructure is located on the Minjiang River, the longest tributary of the Yangtze, in Sichuan, China (Li & Xu 2006). The area is located in the west of Chengdu flatlands at the junction between the Sichuan basin and the Qinghai-Tibet plateau. Originally the Minjiang flowed down from the Min Mountains, but slowed abruptly after reaching the Chengdu Plains, causing the river channel to fill up with silt, making the surrounding area easily prone to flooding. More than 2000 years ago, Li Bing (250–200 BC), a then local governor, designed this water control and irrigation system using a new method to channel and divide the water (Zhang *et al.* 2013) (Figure 4(a)), and organized thousands of local people to complete the project. As a large hydraulic water project, the system consists of three main parts: the Fish Mouth Water-Dividing (Figure 4(b)), the Flying Sand Fence (Figure 4(c)), and the gate of the Bottle-Neck Channel (Figure 4(d)). Due to the successful construction of the project, the Chengdu agricultural area and the local farmers have no longer suffered from flooding (Cao *et al.* 2010). Known as the 'living water conservancy and museum', the project is characterized by the world's oldest and only retention, diversion method. To date, the system has supported the water conservancy works, coordinating the social and economic benefits, and ecosystem through nature-based solutions (Willmott 1989).

4. DROUGHT

Owing to the rise in water demands and looming climate change, much focus has been put on global drought scenarios in recent years (Huang *et al.* 2021). As a natural hazard, drought is best defined by various climatological and hydrological parameters (Mishra & Singh 2010). A drought is a period with below-average precipitation in a given region, resulting in chronic shortages of water supply, whether atmospheric, surface, or groundwater. Drought can last months or years or may be declared after at least 15 days (Farooq *et al.* 2009), posing threat to the local ecosystem and economy (Bin & Polasky 2004). The effects of water shortage can be divided into three categories: environmental, economic, and social consequences. In the case of environmental impacts: lower surface and underground water levels, flow with lower levels less than the minimum leading to danger for amphibians' life, could increase pollution of surface water, the drying up of wetlands, larger and more fires, loss of biodiversity, worse health of trees and appearance of pests and dendroid diseases. Economic direct losses include the lower output of agriculture, forests, games, and fishing, higher costs of food production, lower hydro plants of energy production levels, indirect losses caused by poor water tourism and transport revenue, water supply problems for the energy sector, technical processes in metallurgy, mining, chemical, paper, wood, food industries, and disruption of municipal water supplies of economies (Prokurat 2015). Meanwhile, social costs include a negative effect on the health of



Figure 4 | Dujiangyan Irrigation Project. (a) Schedule for Dujiangyan Irrigation project; (b) the water-diversion rule of Fish-mouth; (c) Spillway of the Flying Sand Fence; (d) Gate of the Bottle-Neck Channel.

those who are directly exposed to this excessive heat wave phenomenon, possible restrictions on water supplies and increased pollution levels, high food costs, stresses caused by poor harvests (Brouwer & Van 2004).

4.1. Water supplement

The interaction between groundwater and surface water in the sustainable management of water resources in semi-arid regions was considered as a fundamental concept of the ecohydrology by Diiwu (2003). Because, integrated water resources management or conjunctive use of water resources has become critically important for ecological water treatment and water resource beneficiaries (Sheng *et al.* 2013). Karez is a kind of underground water conservancy project created in the long historical development of the laboring people in arid areas (Cressey 1958). By using the principle and method of expression ecohydrology, the ancient irrigation system consisted of a tunnel with a very light upward slope into the rising ground (Mustafa & Qazi 2007), so that water from deep within the earth flowed to the surface (Figure 5). In the mountainous and foothill areas of Middle Asia and Transcaucasia, such structures are universally used. Water from a karez landscape is used for water supply and irrigation (Kahlowan & Hamilton 1994). A karez consists of water-catchment tunnels 1.0–1.4 m high and 0.5–0.6 m wide, with reinforced walls run through an aquifer horizon, as well as vertical ventilation wells of different depths and a water tunnel connected to a flow discharge channel. Karez tunnels can be several kilometers long. The average yield of the water-catchment tunnel is 0.3–0.6 lit/sec.m of the tunnel. Karez was developed in Persia and adopted throughout the Middle East and North Africa (Mustafa & Qazi 2007).

5. GEOHAZARD

A geohazard, including ice jams on rivers, landslides, mud-flows, rock falls, shorelines, and stream erosion, can cause damage or loss of property and life (Solheim *et al.* 2005). China boasting complicated natural geography, geological structure, landform, and climate conditions, geological disasters are widely distributed and frequently occur in mountain regions (Cui *et al.* 2011). The systematic study on both ecological-water-soil coupling dynamic process of mountain disasters and the relationship from mountain disasters to ecology & climate are considered to be the basis for the development of mountain disaster theory and dynamic genetic mechanism model, which related to the construction of mountain disaster risk prevention and

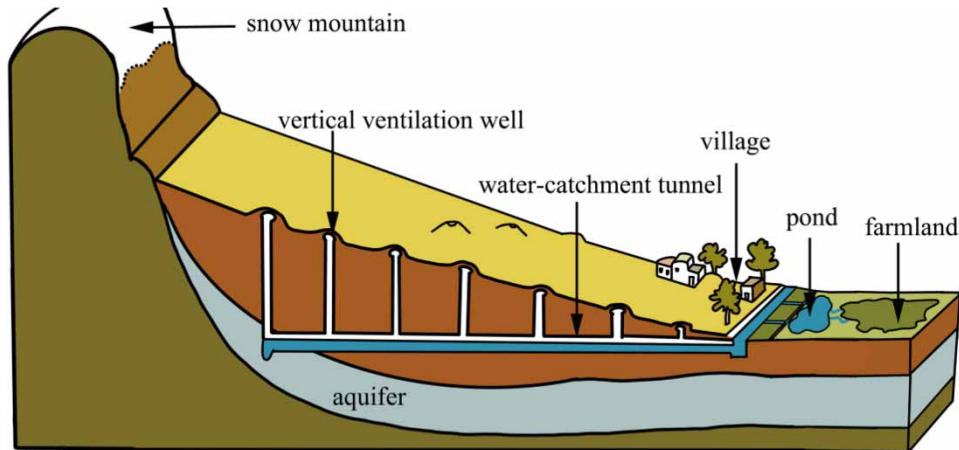


Figure 5 | Schematic diagram of Karez system structure.

control theory and method (Cui 2014). Therefore, it is urgent to improve the research level of regional law of mountain disasters and evaluate the vulnerability of mountain disasters by expounding the driving mechanism and differentiation law of mountain ecohydrological process and developing heterogeneous geotechnical mechanics theory dominated by ecohydrological coupling process.

5.1. Ecological slope protection

The unique environment and energy gradient of the mountain make it a highly developed area of natural disasters such as debris flow, landslide, collapse, avalanche, soil erosion, mountain flood, and so on. Climate change, ecology, hydrological, and other processes in mountain areas are the key factors driving the process of disasters. A large number of studies show that in the past, the stability and catastrophe theory and method of homogeneous rock and soil cannot be applied to the stability analysis of rock and soil under the action of different ecosystems in the mountainous area, and it is urgent to clarify the formation and maintenance mechanism of the equilibrium state of rock and soil under the interaction of complex vegetation from the water cycle to rock and soil process in the mountainous area. Only by understanding the effect of the ecohydrological process and its impact on the mechanical properties and stability of hillside rock and soil, can we identify the changing law of mountain hydrological processes and mountain disaster processes.

Considering the slope drainage and water storage function, ecological slope protection is an effective means of slope protection, which is carried out on the slope reinforcement using growing plants, as well as use of plant and the interaction of geotechnical engineering (root anchorage effect), after the excavation slope formed. Thus, the requirements of stability of slope surface and natural ecological environment conservation can be strengthened, as well as preventing geological disasters could be fulfilled (Xiao 2009). On slopes, botanical methods for flow control usually adopt highly effective spatial configuration patterns of multiple forest types and tree species, which are integrated combinations of trees, shrubs, and herbs, with irregular patch and mosaic shapes (Schiechl & Stern 1996). Geotechnical engineering (i.e. water storage and diversion, slope stabilization, sediment interception, drainage, diversion flow, and siltation) (Xi & Xiao 1995) are constructed to control some processes of geologic disaster (i.e. debris-flow formation and damage in the source area, spread area, and accumulation area) (Figure 6). Such measures are usually utilized to protect important objects in situations of a potentially massive disaster such as collapse landslide and scale debris flow, accompanied by abundant loose materials and enough energetic hydrodynamic condition. Through the incorporation of botanical method and geotechnical engineering, geologic disasters prevention and mitigation system of origination control for runoff and solid materials in hazard chain is set up to limit formation conditions of debris flow and regulate its movement. The designed vegetation reduced hydrodynamic conditions of landslides and debris-flow formation by playing its role in intercepting rainfall, retaining soil, and regulating water flow. Moreover, the function of plant roots, which strengthens soil anti-tensile and soil shear strength after soil consolidation, can decrease the volume of unconsolidated material in landslide formation (Wang *et al.* 2005). Besides, the vegetation method can not only improve soil's moisture parameters and infiltration capacity but also upgrade land productivity through soil amendment (Cui & Lin 2013).



Figure 6 | Application effect of ecological slope protection.

The three above cases indicate that certain principles and methods of ecohydrology have some guidelines for disaster prevention and reduction that are successful and scientific to a certain degree. However, on a larger scale, defects exist, such as floods in Chengdu Plain caused by the Sichuan flood in 2020, rapid melting of snow and ice caused by global warming, hidden trouble for the follow-up water supply of Karez, local failure of ecological slope protection caused by rare extreme weather, thus rare systemic risks still need to be taken seriously.

6. CHALLENGES FOR ECOHYDROLOGY IN CHINA

Although ecohydrology has made rapid progress in the study of wetlands, rivers, lakes, forests, grasslands, farmland, and other habitats, most of them still focus on experimental observation (Zalewski 2013), discovery mechanisms, numerical simulation, and other aspects of a single ecosystem. Many watersheds around the world, especially key watersheds in China (i.e. Yellow River, Yangtze River, Haihe River, Huaihe River, and Liaohe River) face multiple challenges, such as destruction of habitats, floods, drought, soil erosion (including debris) and water pollution, with regular transfers of materials and energy in all parts of the earth system and intensification (Xia 2002). Multiple challenges still exist in a single system of small scale ecohydrological processes: to explore the cause of the above-mentioned problem, to identify key factors of influence, and to formulate counter-measures, such as ecohydrological elements of synchronous observation and integration, more ecological hydrology law or a field scale to the basin or a global transformation mechanism, climate change and a high degree of human effect on ecohydrological processes multiple identification and assignment, watershed-scale two-way coupling factors for ecohydrological processes and the system simulation (Xia *et al.* 2020a, 2020b). In the face of the worsening domestic and global disasters and ecological status, many countries have rolled out some important measures, including National spatial planning, Sponge city construction, and the Belt and Road Initiative. Consequently, for the great system of the ecohydrological environment, more severe tests and requirements are put forward. Based on not breaking the ecological red line, factors such as theories technologies, and methods related to ecohydrology are needed to improve the ecological environment and hydrological conditions. Thus, disaster prevention and mitigation can be effectively achieved. Meanwhile, people's lives and property will be ensured. Lastly, the implementation and realization of national security development will be fulfilled. Therefore, China's ecohydrology must have a strong application orientation in disaster prevention research and application, which should support the significant needs of the state to protect people's life and property at the level of applied research. On the contrary, the urgent needs of the country can also drive the construction and development of ecohydrology, which constantly promotes breakthroughs in theory, technology and method at the application level. Centering on the above major secure development needs of the country, the development of ecohydrology in China has some challenges and prospects as follows.

6.1. National spatial planning

In China, the Ministry of National Resources is engaged in the preparation of national spatial planning systems to provide contexts for sustainable development and environmental quality. With the suggestion of national spatial planning, China's urban-rural planning framework has entered a new period of growth, and the conventional national spatial growth dominated

by the development of production space has also shifted to the current national spatial development, in which ecological, living, and production spaces are integrated (Lu *et al.* 2015). However, how to promote cognition from the conventional national territorial area based on the concept of 'Sansheng spaces' (production, living and ecological space) to the complex national attractive territorial area, which enriches the cultural context, ecohydrological character, and the basis of life, matching the growth goals of various regions to minimize the impact of the disaster and avoid blindly following the same development model (Lin *et al.* 2020). These are all key challenges facing both central and local governments.

Ecosystem provides human activities with space and energy, which are closely linked to the ecosystem by spatial occupation and ecological environment resource acquisition (Baldocchi *et al.* 2001). In space, three layers of the ecosystem, production system and living system are superimposed, resulting in the basic pattern of functional differentiation of terrestrial surfaces (Gkartzios & Scott 2009). It is important to take into account not only the increasing and abundant ecohydrological needs of human production and living space but also the sustainable development potential of natural habitats without being harmed, for scientific awareness, detection, and deployment of disaster prevention (Harris *et al.* 2002). Also, an important factor should be the protection of life and property security for citizens. Ecological space, such as mountain hilly regions in the national pattern of land development as a whole, assumes the position of China's ecological security if the development of such regions cannot be combined with regional modernization, ecological protection, and other productivity, is bound to slow down China's overall modernization, and the overall quality of the country's ecological protection construction has a significant impact. If such a region deviates from the development path of healthy population, resources and the environment, unified economic, social and ecological benefits and protection, negative effects may go well beyond its regional reach and pose a serious threat to the sustainable development of the regional economy and society (Li 2012a). For example, the Three River Headwater Region is an important source of water in China (Zhang *et al.* 2011), which supplies 25 percent of the total volume of water in the Yangtze River, 49 percent of the total volume of water in the Yellow River, and 15 percent of the total volume of water in the Lancang River, playing an important role in China's ecological status and national economic development. Harm to the ecohydrology of the region would have a far-reaching impact on China in both scale and scope. The middle and lower reaches of the river basin alone account for more than 70% of China's total land area. The economic and social impact of the decrease in ecological space and the spread of related disasters is incalculable.

6.2. Sponge city

Waterlogging, floods, droughts are all major disasters related to water in most of China's cities and directly limit their urbanization processes. The construction of Sponge city is an effective approach to addressing urban water issues, especially those related to problems. Both urban problems arose at the stage of rapid urbanization in China and the demands and challenges of the Sponge city's construction related to water problems were examined, as well as the opportunities and challenges for Sponge city's construction in the future. It was found that existing stormwater management concentrated on the development of gray infrastructure based on the concept of rapid discharge, which was expensive and difficult to cope with the rapid growth of the city and its impervious surface while ignoring green infrastructure (i.e. river, lake, and wetland). Moreover, the new construction of Sponge city was still limited to the low impacted development (LID) approach, which concentrated on source management measures without taking into account the essential functions of the surrounding environment (i.e. mountain, river, wetland, forest, farmland, and lake) when implementing the integrated urban water system approach and its supported technologies including municipal engineering, urban hydrology, environmental science, social sciences, and eco-scape is relatively poor and needed to be strengthened (Dietz 2007). Also, the lack of a special Sponge city plan and demonstration area was a major issue. Some viewpoints on Successful Sponge city design have been suggested, such as the argument that the concept of urban planning and construction should be compatible with an essential and systemic view of sustainable urban growth (Li *et al.* 2017). Both basic theoretical research and basic infrastructure development, such as the monitoring system, the drainage facility, and the demonstration field, should therefore be improved, thus reforming and innovating the urban water management system and the education system should also be implemented urgently. The latest study was intended to provide a deeper insight into the current development of the Sponge city in China and to provide some recommendations for potential directions for urban planning and building, as well as how urban ecohydrology discipline can be applied to urban disaster prevention and reduction (Xia *et al.* 2017).

Social management related disaster of sponge cities should follow the concept of adaptation to local conditions and on-site absorption, making full use of topography, land and natural ecohydrological environments, and implement various engineering steps to maintain good urban water circulation and reduce the effect of urban growth on water circulation. The key issues

of urban flood management and drainage are urban rainwater modeling, flood control assessment, determination of the overall annual flow control and optimization LID, etc., at the same time as evaluating the underlying surface conditions and the output flow situation, identification of the main area of waterlogging and road drainage in the region. It is proposed a cumulative annual runoff management target for lower LID interventions in different parts of the program (Liu *et al.* 2016).

6.3. Belt and road initiative

The Belt and Road Initiative refers to the ‘silk road economic belt’ and the ‘21st-century maritime silk road’. The main development initiatives introduced and supported by China’s national leaders constitute an essential part of China’s overall strategy to open up wider to the outside world in the new period (Jin 2016). It is committed to the connectivity of the continents of Asia, Europe, Africa and their neighboring oceans, the establishment and strengthening of connectivity partnerships between countries along the Belt and Road, the establishment of an all-dimensional, multi-tiered, and composite connectivity network, and the implementation of diverse, autonomous, healthy and sustainable development of countries along the Belt and Road (Swaine 2015). The Belt and Road Initiative calls for building four silk roads, which including the green silk road, the health silk road, the intellectual silk road, and the peace silk road. Among them, the Green Silk Road proposed deepening environmental protection, practicing the concept of green development, and strengthen the protection of the ecological environment, which coincides with the efforts of ecohydrology to address global water protection problems and improve the adaptability and resilience of ecosystems in a changing environment (Xia *et al.* 2020a, 2020b). But along the complex geological structure, with a large difference in elevation, an active erosion agent, weak engineering geology and monsoon climate control, earthquake activity is frequent. Due to precipitation of high intensity based on an active fault, droughts, serious geological disasters such as wide distribution, harm from the disaster restricts the construction of infrastructure in the region, social and economic growth, the development of resources and the major possibility of reducing danger. Therefore, related studies show that countries along the Silk Road Economic Belt are situated in one of the regions with the most severe natural disasters and the most significant losses in the world (Gao 2015). For example, apart from geohazard, frequent forest fires occur in eastern Kazakhstan; land degradation is extreme in Turkmenistan, Tajikistan, Uzbekistan, Mongolia, and other countries. The Green Silk Road is aims to promote environmental protection, sustainable civilization construction, green building, disaster prevention, and mitigation, maintaining the lives and property of countries along the way, and enhancing human well-being. Given the above, there is an urgent need for research into natural disasters and major project threats for the Silk Road Economic Belt from the point of view of ecohydrology in terms of policy alignment, facility connectivity, unimpeded trade, financial integration, people-to-people connectivity, and capacity building (Cui *et al.* 2018). The ideas, techniques, and knowledge of ecohydrology are used to address the safety problems posed by natural disasters in major projects. At the same time, the law on temporal and spatial evolution and the hydrological process of ecohydrological characteristics along the ‘One Belt And One Path’ should be studied to preserve the appropriate size of the ecological corridor and the appropriate quantity and quality of the water supplies, to coordinate the relationship between the upstream and downstream countries of cross-border rivers and ensure environmental and water protection along the One Belt and One Road.

7. CONCLUSION

With global warming and the rise in human activities, intensified disasters have been posing threat to the well-being and property of humans. This article offers advice and thought on the theoretical and realistic exploration of disaster prevention and mitigation by ecohydrology. Moreover, this study addresses a range of active cases, including the Dujiangyan Irrigation Project, Karez, and Ecological slope protection, which separately illustrate the application of the ecohydrology principles for disaster prevention and reduction from the perspective of flood protection, drought tolerance, and geological disaster prevention, respectively. Comprehensive analysis of the convergence of water and environment and economy can be efficiently extended to disaster prevention and mitigation activities. The creation of ecohydrology in disaster reduction and mitigation activities are closely linked, communicated, and promoted. Besides effective disaster prevention and mitigation of ecohydrology, which aims to unite nature and man at home and abroad, continues to be instructive in today’s disaster prevention work. Furthermore, ecohydrology is an application technology that takes a holistic view of ecology, hydrology, topography soil, and biology. Its application faces huge challenges and opportunities in the field of national space planning, sponge city development, and the Belt and Road Initiative. The implication of the study can be summarized in developing a framework to manage

the water resources considering the precipitation intensity under drought conditions and social and economic growth. Hydro-ecological measures and uncertainty analysis of the related phenomena should be evaluated in future studies.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

REFERENCES

- Alderman, K., Turner, L. R. & Tong, S. 2012 Floods and human health: a systematic review. *Environment International* **47**, 37–47.
- Baldocchi, D., Falge, E. & Gu, L. 2001 FLUXNET: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. *Bulletin of the American Meteorological Society* **82** (11), 2415–2434.
- Bin, O. & Polasky, S. 2004 Effects of flood hazards on property values: evidence before and after Hurricane Floyd. *Land Economics* **80** (4), 490–500.
- Brouwer, R. & Van, E. R. 2004 Integrated ecological, economic and social impact assessment of alternative flood control policies in the Netherlands. *Ecological Economics* **50** (1–2), 1–21.
- Cao, S., Liu, X. & Er, H. 2010 Dujiangyan Irrigation System—a world cultural heritage corresponding to concepts of modern hydraulic science. *Journal of Hydro-Environment Research* **4** (1), 3–13.
- Christensen, J. H. & Christensen, O. B. 2003 Severe summertime flooding in Europe. *Nature* **6925**, 805–806.
- Costa, J. E. & O'Connor, J. E. 1995 Geomorphically effective floods. *GMS* **89**, 45–56.
- Cressey, G. B. 1958 Qanats, karez, and foggaras. *Geographical Review* **48** (1), 27–44.
- Cui, P. 2014 Progress and prospects in search on mountain hazards in China. *Progress in Geography* **33** (2), 145–152.
- Cui, P. & Lin, Y. M. 2013 Debris-flow treatment: the integration of botanical and geotechnical methods. *Journal of Resources and Ecology* **4** (2), 097–104. doi:10.5814/j.issn.1674-764x.2013.02.001.
- Cui, P., Chen, X. Q. & Zhu, Y. Y. 2011 The Wenchuan earthquake (May 12, 2008), Sichuan province, China, and resulting geohazards. *Natural Hazards* **56** (1), 19–36.
- Cui, P., Hu, K. H. & Chen, H. Y. 2018 Risks along the Silk Road Economic Belt owing to natural hazards and construction of major projects (in Chinese). *Chinese Science Bulletin* **63**, 989–997. doi:10.1360/N972017-00867.
- Dietz, M. E. 2007 Low impact development practices: a review of current research and recommendations for future directions. *Water, Air, and Soil Pollution* **186** (1–4), 351–363.
- Diiwu, J. Y. 2003 Groundwater-surface water interaction as a component of the ecohydrology of semi-arid regions. *Journal of Environmental Syst.* **30** (2), 91–104.
- Duan, L., Man, X., Kurylyk, B. L., Cai, T. & Li, Q. 2017 Distinguishing streamflow trends caused by changes in climate, forest cover, and permafrost in a large watershed in northeastern China. *Hydrological Processes* **31** (10), 1938–1951.
- Farooq, M., Wahid, A., Kobayashi, N., Fujita, D. & Basra, S. M. A. 2009 Plant drought stress: effects, mechanisms and management. In: (Lichtfouse, E., Navarrete, M., Debaeke, P., Véronique, S. & Alberola, C., eds) *Sustainable Agriculture*. Springer, Dordrecht, pp. 153–188.
- Fatichi, S., Pappas, C. & Ivanov, V. Y. 2016 Modeling plant–water interactions: an ecohydrological overview from the cell to the global scale. *Wiley Interdisciplinary Reviews: Water* **3** (3), 327–368.
- Gao, Z. H. 2015 The belt and road development strategy and international disaster reduction cooperation (in Chinese). *Disaster Reduction China* **23** (17), 123–138.
- Gkartzios, M. & Scott, M. 2009 Planning for rural housing in the Republic of Ireland: from national spatial strategies to development plans. *European Planning Studies* **17** (12), 1751–1780.
- Gong, H. L., Zhang, J. & Zhou, D. M. 2010 Hydroinformatic and ecohydrology tools for ecologically sustainable development in northern China. *International Association of Hydrological Sciences Publication* **338**, 129–136.
- Guo, H., Fu, W. & Liu, G. 2019 Glacier satellite. In: *Scientific Satellite and Moon-Based Earth Observation for Global Change*. Springer, Singapore, pp. 397–427.
- Guo, L. N., She, C., Kong, D. B., Yan, S. L., Xu, Y. P., Khayatnezhad, M. & Gholinia, F. 2021 Prediction of the effects of climate change on hydroelectric generation, electricity demand, and emissions of greenhouse gases under climatic scenarios and optimized ANN model. *Energy Reports* **7**, 5431–5445.
- Hannah, D. M., Wood, P. J. & Sadler, J. P. 2004 Ecohydrology and hydroecology: a ‘new paradigm’? *Hydrological Processes* **18**, 3439–3445.
- Harris, N., Hooper, A. & Bishop, K. 2002 Constructing the practice of ‘spatial planning’: a national spatial planning framework for Wales. *Environment and Planning C: Government and Policy* **20** (4), 555–572.
- Hou, R., Li, S., Wu, M., Ren, G., Gao, W., Khayatnezhad, M. & Gholinia, F. 2021 Assessing of impact climate parameters on the gap between hydropower supply and electricity demand by RCPs scenarios and optimized ANN by the improved Pathfinder (IPF) algorithm. *Energy* **237**, 121621.
- Huang, D., Wang, J. & Khayatnezhad, M. 2021 Estimation of actual evapotranspiration using soil moisture balance and remote sensing. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*. <https://doi.org/10.1007/s40996-020-00575-7>.
- Jin, C. T. 2016 ‘One belt and one road’: connecting China and the world. Global Infrastructure Initiative website.

- Kahlowan, M. A. & Hamilton, J. R. 1994 Status and prospects of Karez irrigation. *JAWRA Journal of the American Water Resources Association* **30** (1), 125–134.
- Kekelidze, N., Buachidze, N. & Jakhutashvili, T. 2009 Quantitative estimation of natural and anthropogenic impact on values of some hydrochemical parameters of water quality of the river Kura in area of some large settlements. *International Multidisciplinary Scientific GeoConference: SGEM* **2**, 219.
- Koepflin, N., Schaedler, B. & Viviroli, D. 2013 The importance of glacier and forest change in hydrological climate-impact studies. *Hydrology and Earth System Sciences* **17** (2), 619–635.
- Lalehzari, R. & Kerachian, R. 2020 Developing a framework for daily common pool groundwater allocation to demands in agricultural regions. *Agricultural Water Management* **241**, 106278.
- Li, C. 2012a Ecohydrology and good urban design for urban storm water-logging in Beijing, China. *Ecohydrology & Hydrobiology* **12** (4), 287–300.
- Li, L. & Simonovic, S. P. 2002 System dynamics model for predicting floods from snowmelt in North American prairie watersheds. *Hydrological Processes* **16** (13), 2645–2666.
- Li, K. & Xu, Z. 2006 Overview of Dujiangyan Irrigation Scheme of ancient China with current theory. *Irrigation and Drainage: The Journal of the International Commission on Irrigation and Drainage* **55** (3), 291–298.
- Li, H., Ding, L., Ren, M. & Li, C. 2017 Sponge city construction in China: a survey of the challenges and opportunities. *Water* **9** (9), 594.
- Li, A., Mu, X., Zhao, X., Xu, J., Khayatnezhad, M. & Lalehzari, R. 2021 Developing the non-dimensional framework for water distribution formulation to evaluate sprinkler irrigation. *Irrigation and Drainage*. <https://doi.org/10.1002/ird.2568>.
- Lin, G., Jiang, D. & Fu, J. 2020 Spatial conflict of production–living–ecological space and sustainable-development scenario simulation in Yangtze River Delta agglomerations. *Sustainability* **12** (6), 2175.
- Liu, C. M., Zhang, Y. Y. & Wang, Z. G. 2016 The LID pattern for maintaining virtuous water cycle in urbanized area: a preliminary study of planning and techniques for Sponge City. *Journal of Natural Resources* **31** (5), 719–731.
- Lu, W. H., Liu, J. & Xiang, X. Q. 2015 A comparison of marine spatial planning approaches in China: marine functional zoning and the marine ecological red line. *Marine Policy* **62**, 94–101.
- Mishra, A. K. & Singh, V. P. 2010 A review of drought concepts. *Journal of Hydrology* **391** (1–2), 202–216.
- Mustafa, D. & Qazi, M. U. 2007 Transition from Karez to tubewell irrigation: development, modernization, and social capital in Baluchistan. *Pakistan. World Development* **35** (10), 1796–1813.
- Plate, E. J. 2002 Flood risk and flood management. *Journal of Hydrology* **267** (1–2), 2–11.
- Prokurat, S. 2015 Drought and water shortages in Asia as a threat and economic problem. *Journal of Modern Science* **26** (3), 235–250.
- Ren, J. 2021 Evaluating the storm water management model to improve urban water allocation system in drought conditions. *Water Supply*. <https://doi.org/10.2166/ws.2021.027>.
- Ren, J. & Khayatnezhad, M. 2021 Evaluating the storm water management model to improve urban water allocation system in drought conditions. *Water Supply*. <https://doi.org/10.2166/ws.2021.027>.
- Rodriguez-Iturbe, I. 2000 Ecohydrology: a hydrologic perspective of climate-soil-vegetation dynamics. *Water Resources Research* **36** (1), 3–9.
- Schiechl, H. M. & Stern, R. 1996 *Ground Bioengineering Techniques for Slope Protection and Erosion Control*.
- Sheng, Z., Fox, G. & Abudu, S. 2013 Special section on interconnection of atmospheric water, Surface Water, and Groundwater. *Journal of Hydrologic Engineering* **18**, 1191–1192.
- Solheim, A., Bhasin, R., De, B., Blikra, L. H., Boyle, S., Braathen, A. & Harbitz, C. B. 2005 International Centre for Geohazards (ICG): assessment, prevention and mitigation of geohazards. *Norwegian Journal of Geology/Norsk Geologisk Forening* **85**, 45–62.
- Sun, X. & Khayatnezhad, M. 2021 Fuzzy-probabilistic modeling the flood characteristics using bivariate frequency analysis and α -cut decomposition. *Water Supply*. <https://doi.org/10.2166/ws.2021.186>.
- Swaine, M. D. 2015 Chinese views and commentary on the ‘One Belt, One Road’ initiative. *China Leadership Monitor* **47** (2), 3.
- Tao, Z., Cui, Z., Yu, J. & Khayatnezhad, M. 2021 Finite difference modeling of groundwater flow for constructing artificial recharge structures. *Iranian Journal of Science and Technology, Transactions of Civil Engineering*. <https://doi.org/10.1007/s40996-021-00698-5>
- Wang, G. X., Qian, J. & Chen, G. D. 2001 Current situation and prospect of the ecological hydrology. *Advance in Earth Sciences* **16** (3), 314–323.
- Wang, W. S., Yang, X. H. & Xie, Y. L. 2005 Mechanism of biotechnical protection for highway slope. *Journal of Chang'an University (Natural Science Edition)* **4**, 26–30.
- Wang, C., Shang, Y. & Khayatnezhad, M. 2021 Fuzzy stress-based modeling for probabilistic irrigation planning using copula-NSPSO. *Water Resour Manage* **35**, 4943–4959. <https://doi.org/10.1007/s11269-021-02981-6>.
- Willmott, W. E. 1989 Dujiangyan: irrigation and society in Sichuan, China. *The Australian Journal of Chinese Affairs* **22**, 143–153.
- Withey, A. 2019 *Bushfire Season Starts Early Across Northern Australia due to Ongoing Hot, Dry Conditions*. ABC News (available at: abc.net.au/news/2019-06-27/bushfire-outlook-queensland2019/11251150).
- Woznicki, S., Nejadhashemi, A. P., Abouali, M., Herman, M. R., Esfahanian, E., Hamaamin, Y. A. & Zhang, Z. 2016 Ecohydrological modeling for large-scale environmental impact assessment. *Science of the Total Environment* **543**, 274–286.
- Xi, J. Z. & Xiao, F. Z. 1995 Reinforcement action of slope protection with herbage at shallow layer. *Journal of Northern Jiaotong University* **2**, 48–59.
- Xia, J. 2002 A system approach to real-time hydrologic forecast in watersheds. *Water International* **27** (1), 87–97.

- Xia, J., Feng, H. L. & Tan, G. 2003 Ecohydrology concept, framework and system. *Journal of Irrigation and Drainage* (01), 4–10. doi:10.13522/j.cnki.ggps.2003.01.003.
- Xia, J., Zhang, Y. Y., Xiong, L. H., He, S., Wang, L. F. & Yu, Z. B. 2017 Opportunities and challenges of the sponge city construction related to urban water issues in China. *Science China Earth Sciences* **60** (4), 652–658.
- Xia, J., Zuo, Q. H. & Chun, H. 2018 Disciplinary system and development strategy for eco-hydrology. *Advance in Earth Sciences* **7**, 665–674.
- Xia, J., Zhang, Y. Y., Mu, X. M., Zuo, Q. T., Zhou, Y. J. & Zhao, G. J. 2020a Progress of ecohydrological discipline and its future development in China. *Acta Geographica Sinica* **75** (03), 445–457.
- Xia, J., Zuo, Q. T. & Wang, G. X. 2020b ‘Chapter v, Section 4’, in, Ecohydrology: science press. The National Development Strategy in association with industrial colleges, p. 277–281.
- Xiao, M. D. 2009 Ecological application of ecological slope protection and vegetation community selection for slope protection. *Journal of Anhui Agricultural Sciences* **31**, 72–81.
- Xu, Y. P., Ouyang, P., Xing, S. M., Qi, L. Y., Khayatnezhad, M. & Jafari, H. 2021 Optimal structure design of a PV/FC HRES using amended Water Strider Algorithm. *Energy Reports* **7**, 2057–2067.
- Yao, H., Dong, Z. & Jia, W. 2019 Competitive relationship between flood control and power generation with flood season division: a case study in downstream Jinsha River Cascade Reservoirs. *Water* **11** (11), 2401.
- Zalewski, M. 2003 Guidelines for the integrated management of the watershed: phytotechnology and ecohydrology. *Freshwater Management* **85** (5), 3–16.
- Zalewski, M. 2013 Ecohydrology: process-oriented thinking towards sustainable river basins. *Ecohydrology & Hydrobiology* **13** (2), 97–103.
- Zalewski, M., McClain, M. & Eslamian, S. 2016 *New Challenges and Dimensions of Ecohydrology–Enhancement of Catchments Sustainability Potential*.
- Zhang, S., Hua, D., Meng, X. & Zhang, Y. 2011 Climate change and its driving effect on the runoff in the ‘Three-River headwaters’ region. *Journal of Geographical Sciences* **21** (6), 963.
- Zhang, S., Yi, Y., Liu, Y. & Wang, X. 2013 Hydraulic principles of the 2,268-year-old Dujiangyan Project in China. *Journal of Hydraulic Engineering* **139** (5), 538–546.
- Zhu, P., Saadati, H. & Khayatnezhad, M. 2021 Application of probability decision system and particle swarm optimization for improving soil moisture content. *Water Supply*. <https://doi.org/10.2166/ws.2021.169>

First received 7 September 2021; accepted in revised form 25 November 2021. Available online 10 December 2021