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Reconfiguration of ecohydrology as a sustainability tool for Himalayan waterways

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Abstract

Twenty first century faces unprecedented challenges for the management of global waterways. The Himalayan waterways in Asia are exposed to unpredictable climatic warming together with anthropogenic perturbations caused by population growth, land use change and socio-economic development. Given the increased public concerns on the Himalayan Mountain development programmes including the hydropower and tourism, there has been a growing need of the use of interdisciplinary scientific approaches to address water resources challenges that the Himalayan region has faced during the 21st century. Ecohydrology is an emerging scientific tool that explores key hydrological processes regulating structure and function of ecosystems, as well as assessing the impact of biological processes on water cycle variables under rapidly changing environment. The International Geosphere-Biosphere Programme and the International Hydrological Programme hosted by the United Nations Educational, Scientific and Cultural Organization have adopted ecohydrology as a sustainable development tool by linking water resources and poverty eradication and ecosystem restoration, irrigation, energy and sanitation. However, ecohydrology tool needs to be reconfigured for sustainable development of rapidly changing Himalayan waterways. Here we propose the advancement of ecohydrology by developing various integrated frameworks of ecology, hydrology, hydraulics and sociology for resilient waterways in the Asian Himalayas.

KEYWORDS
ecohydraulics, ecohydrology, Himalayan waterways, integrated water resource management, nature-based solutions, sustainability

1 | INTRODUCTION

Twenty first century has witnessed unprecedented challenges for managing global waterways (Kattel, 2019; Rockström & Gordon, 2001). Rapid and unpredictable climatic warming together with anthropogenic perturbations caused by population growth, land use change and urbanization have posed many waterways at a brink of collapse, and unforeseen human suffering from water scarcity has been experienced worldwide (Vörösmarty et al., 2010). Ecohydrology has emerged as an interdisciplinary scientific tool to address challenges of waterways management through exploration of hydrological processes on structures and functions of ecosystems, as well as impacts of biological processes on water cycle variables under rapidly changing environments worldwide (Jenerette et al., 2012; Rockström & Gordon, 2001; Xia et al., 2021; Zalewski, 2010; Zalewski et al., 2016). Today, ecohydrology is adopted as a sustainability tool

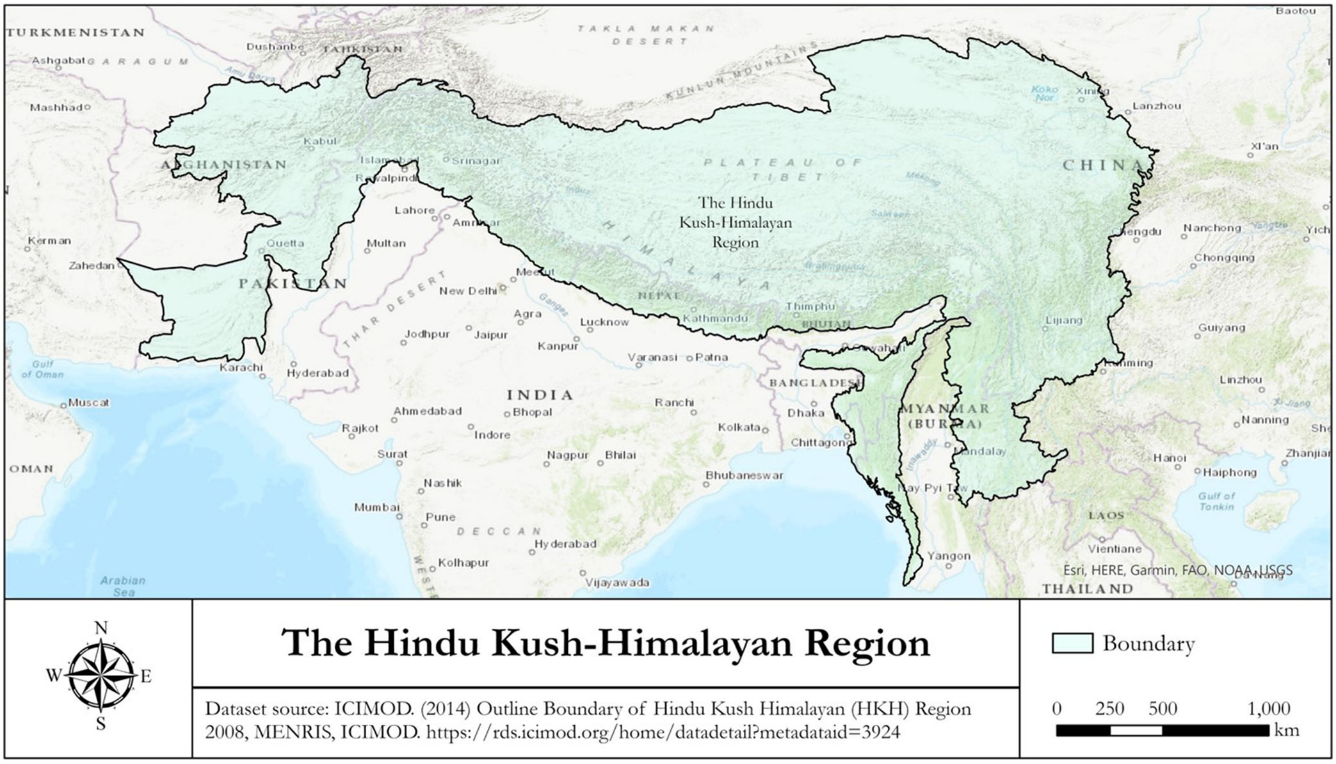

FIGURE 1 The Hindu Kush Himalayan region showing various waterways.

for waterways management by the International Geosphere-Biosphere Programme (IGBP/BAHC) and the International Hydrological Programme hosted by the United Nations Educational, Scientific and Cultural Organization (UNESCO/IHP) (Xia et al., 2021). Ecohydrology addresses issues related to sustainable development by improving water resources, which inherently link to poverty eradication and ecosystem restoration irrigation, energy and sanitation (Zalewski, 2010).

The role of ecohydrology in sustainability of global waterways has been studied since the concept was introduced in 1992 by UNESCO. For instance, the UNESCO/IHP-V launched the project 'Hydrology and water resources development in a vulnerable environment' to ascertain sustainable use of landscape resources, and ecohydrological processes. With the advancement of the concept and the use of the ecohydrological tool, our understanding of interactions and dynamics of river systems, floodplains and wetlands as well as the hydrological cycle in different ecosystems, environmental flow, sediments, nutrients and pollutants in various scales, climatic and geographical regions has been greatly improved, and such understanding has significantly helped evaluate waterways conditions and vulnerability worldwide (Janaue, 2000).

The Himalayas, often referred as the Hindu Kush Himalayan (HKH) region (Figure 1), are the source of vast number of waterways (ICIMOD, 2020, 2021) in Asia supporting important ecosystem goods and services to the millions of people downstream (Immerzeel et al., 2010; Li et al., 2021). Being one of the most important regions of the planet earth for water resources, environments, hydropower and tourism development, the global community would like to see the ecologically and socially prosperous HKH region in Asia (Nepal, 2002; Smadja et al., 2015). Water originating from the HKH are a significant source of food, energy and ecosystem services to up to more than one billion people downstream (Mukherji et al., 2015). However, climate change and socio-economic and demographic changes all have put unprecedented pressures on these water resources, leading to uncertain supplies, increased demands and higher risks of extreme events such as floods and droughts (Mukherji et al., 2015). Particularly, during the 21st century, the Himalayas have gone through considerable transformations in meteorological, cryospheric, hydrological and ecological processes. Rapid climate warming in the HKH region has reduced glacier volumes and snow cover followed by the changes in the pattern of flow regimes (Nie et al., 2021). The rate of flow and volume of glacial-fed rivers and lakes are constantly threatened by climate change (Nie et al., 2021; Sigdel et al., 2020). Variable patterns of summer monsoons and the melting of the large reserve of ice and snow together has caused adverse effects on the amount of water availability in the downstream basins in dry seasons causing severe water shortages and agriculture productivity in the HKH region (Li et al., 2022; Rühland et al., 2006; Shrestha & Aryal, 2010). Further, changes in runoff have increased fluvial sediment fluxes in the high mountain region with severe implications for hydropower generation and development, as well as water quality, and regional energy, food and environmental security (Li et al., 2021). Lately, there has been a shift in farming practices in the Himalayas. Crops have been replaced by horticulture to higher economic returns that, in turn, have resulted in massive increases in the use of fertilizers and pesticides. These compounds have also added heavy metals into the high mountain aquatic system (Bhat et al., 2022).

Ecohydrology is thought to play a fundamental role to tackle challenges of the Himalayan waterways, but are yet to be investigated in the context of rapidly changing river flows, ecological and sedimentary processes and biodiversity and ecosystem functioning (Sinha et al., 2019). Being a potential source of ecosystem goods and services for the millions of people, the maintenance of flows of the Himalayan waterways is crucial for flood attenuation, water purification and fisheries production (Karki et al., 2020; Kattel et al., 2016). Ecohydrology has been successfully applied for hydrologic information in the waterways across sparsely gauged landscapes by exploring spatial patterns in hydrologic variability, and the identification and prioritization of conservation areas (Olden et al., 2012). Ecohydrology has been used for scale-dependent spatial patterns in vegetation distribution and catchment water balance as well as the effects of spatial scale on runoff and erosion influenced by vegetation to address waterways issues in arid and semi-arid regions (Thompson et al., 2011; Wilcox et al., 2003). However, exchange of nutrients including carbon and nitrogen, and intact physical properties of water such as pH, conductivity and other geomorphologic hydrologic, and thermodynamics conditions for functioning of aquatic ecosystems in the HKH region through ecohydrologic lens are not yet well explored to date (Timchenko, 2016). Lately, flow regimes have been consistently modified to meet increasing demands of water for various purposes in Asia. For instance, construction of hydroelectric dams in the HKH region has considerable implications for migratory fish (Marquardt et al., 2016; Yang & Lu, 2014) and macroinvertebrate community structure (Tachamo Shah et al., 2020). However, the widespread hydrological alterations in the Himalayas are often ignored or sidelined while planning the waterways development. As the demand for energy and water is continuously growing for agriculture food production, hydropower and industrial use in the HKH region, the application of ecohydrology is becoming more essential for the future mankind than any time in the past (Olden et al., 2014).

It has been widely anticipated that the ecohydrology tool, as currently being defined and used, should further need to be reconfigured for waterways management in the HKH region. Growing use of ecological engineering or ecotechnology such as hydro-dams and irrigation canals in the Himalayan waterways suggest urgent needs of the advancement of ecohydrological tools and their applications to achieve waterway sustainability during the 21st century (Grumbine & Pandit, 2013; Momblanch et al., 2020). For instance, nature-based solutions including the filtering of pollutants by the mountain lakes and reservoirs under climate warming and anthropogenic disturbances have been proven to be successful to promote water quality including the ecological resilience of waterways (Bridgewater, 2018). Further, an integration of ecology, hydrology and hydraulics has been found to solve the issues related to surface roughness of riverbeds, followed by improved hydraulics and flow with considerable reduction in the ecological impacts on river catchments (Jørgensen, 2016; Jørgensen et al., 2019). The loss of surface roughness of riverbeds due to hydrological and hydraulic alterations has been found to lower the algal growth affecting the base of the food web and modifying the patterns of trophic transfer of food resources in the river system (Cardoso-Leite et al., 2015). Reconfiguration of the ecohydrological tool brings knowledge base on waterways management and improves sustainability and resilience of water resources that are exposed to climate warming and anthropogenic disturbances in the HKH region during the 21st century. Here we synthesize the current state of the Himalayan waterways and define ecohydrology in the context of sustainability and waterways management in the region and propose the advancement of ecohydrological tool by developing various integrated and sustainability frameworks of ecology, hydrology, hydraulics and sociology for resilient waterways in the Asian Himalayas.

2 | CHANGING HIMALAYAN WATERWAYS

The Himalayan waterways are rapidly changing due to both climatic warming and anthropogenic disturbances. For example, the mean annual rate of climatic warming in the Himalayas is projected to be as high as -12°C by the end of the century if no coordinated efforts being made to curb global greenhouse gas emissions (Borunda, 2019). This change has led to glacier and snow melting (Lau et al., 2010) and consequently intensifying the runoff and sediment fluxes in summer and water shortages in winter (Li et al., 2021; Slemmons et al., 2013). A total of 54,252 glaciers extended to an area of 60,054 km^2 in the Himalayas today are becoming increasingly sensitive to melting, particularly those lying below 5,700 m above mean sea level (Bajracharya et al., 2015). The large river, Indus, Ganges and Brahmaputra, basins have 79%, 60% and 77% of their total glacier area, is expected to fall below the critical level of elevation (Bajracharya et al., 2015). Glaciers of the Ganges, Indus and Brahmaputra are already losing about 24 Gt of ice every year with foreseeable decline of waterways in downstream basins (Slemmons et al., 2013). Such changes have influenced surface energy budget and freshwater resources, as well as the sustained climate warming have altered timing, magnitude, and frequency of discharge, sediment transport and speciation of nutrients and ecosystems across the Himalayas (Huss et al., 2017; Li et al., 2021; Milner et al., 2017; Williams et al., 2016).

Many studies in the HKH region suggest that climatic extremes enhance hydrological extremes followed by increased discharge in future, but in the meantime, low flow conditions may also occur less frequently leading to increased future uncertainties (Li et al., 2021; Mukherji et al., 2015; Nie et al., 2021; Smadja et al., 2015; Wijngaard et al., 2017). Most hydrogeochemical characteristics in the HKH already have been profoundly modified by climatic change along with other anthropogenic activities. For instance, in Nepal's west, many small-scale river basins are potentially influenced by a sharp topographic variation, climatic and land-use/cover changes with transport of toxic chemicals causing severe decline in water quality and quantity (Pant et al., 2021). Hydrogeochemical characteristics are strongly linked to a decline in the surface water quality resulting from many environmental factors including the increase in temperature, precipitation fluctuations, deforestation, urbanization, land-use changes and exploitative mineral resource extraction (Bhat et al., 2021). The changes in surface water quality are directly affecting the people's lives in the region.

Climate warming has particularly intensified the seasonality of water discharge and supplies in many parts of the Himalayas. Modelling projects the contrasting seasonality in the hydrological regimes in many Himalayan river basins including the Jhelum, Kabul and upper Indus as well as the Karnali river basin in the Nepal's west under different climate warming scenarios (Dahal et al., 2020; Hasson et al., 2019). Studies suggest that lesser discharge during the post-monsoon dry seasons has critically altered the need of water for downstream agriculture, hydropower and ecosystem functioning (Dahal et al., 2020). For example, today, only 11.5% of the total runoff is contributed by the Upper Ganges river basin to its hydrological regime due to the extreme seasonality factor on the alteration of the flow regime of the Himalayan river system (Lutz et al., 2014). Societies dependent on meltwater for drinking water supplies, irrigation, mining, hydropower, agriculture and recreational use, hence, are critically affected by such extreme seasonality in the water availability in the HKH region (Biemans et al., 2019; Huss et al., 2017).

Over the past few decades, one of the crucial waterways in the HKH region, such as the Indus River, has been severely impacted. For example, the tributaries of the Upper Indus basin are particularly highly seasonal and heavily reliant on runoff from the snow and glacial melt during the spring and summer (Orr et al., 2022). As the upper Indus basin supports exceptional economic, social, cultural and political benefits to the hundreds of millions of people across the four riparian countries including Afghanistan, Pakistan, India and China, the extreme seasonality and the low flows have already become a highly critical for the regional sustainability of water, ecosystem, agriculture, hydro-power generation, domestic use, industry, tourism, fishing and religious practices (Orr et al., 2022). As a result, both urban and rural populations in the basin today are increasingly threatened by the endemic poverty and vulnerability of the social-ecological change (Orr et al., 2022). This is because there is no effective water demand management practiced for agriculture and other sectors including the hydropower and household drinking and sanitation in the region (Grumbine & Pandit, 2013; Orr et al., 2012). Mainly the poor irrigation and river management practices and the lack of policy reforms have consistently threatened the water and food security in the region (Grumbine & Pandit, 2013; Mukherji et al., 2015; Orr et al., 2012, 2020; Xu et al., 2014). The irrigation system, which is entirely dependent on snowmelt and glacial melt runoff, both in the upper and lower river basins of the Himalayas, has already become critical to collapse (Biemans et al., 2019; Li et al., 2021; Mukherji et al., 2015; Xu et al., 2009). For instance, the mismanagement of water in the lower Indus basin has already reached an average water footprint as high as 182 km^3 $year^{-1}$ in which, 75% is composed by the blue water (irrigation water from surface water and groundwater sources) alone (Muzammil et al., 2020). In those areas, sugarcane, cotton and rice are highly water-intensive crops consuming 57% of the annual water use constantly demand improved waterways management (Muzammil et al., 2020).

3 | DEFINITION AND PERSPECTIVES OF ECOHYDROLOGY

Ecohydrology is a fast-moving discipline. This is commonly defined as an interdisciplinary research endeavour that involves scientific fields as diverse as hydrology, fluid mechanics, ecology, biogeochemistry, plant physiology, statistical mechanics and social science (Yin et al., 2019). However, the trajectory of ecohydrology definition goes back for decades. The concept has advanced initially from the 'non-engineering' hydrology in the 1960s mainly associated with forest and land use to the 'environmental hydrology' in the 1970/1980s associated with the range of disciplines including environmental physics (evaporation), hydrogeology, fluvial geomorphology, physical geography, soil science–soil physics and forestry (Bonell, 2002; Jun & Chen, 2001; Rodriguez-Iturbe, 2000). Today, the ecohydrology is largely defined as coupling landscape processes involving water, nutrient transfer, sediment transfer with in-stream hydrobiology and the critical role of riparian zones, as well as surface water–groundwater interactions in the hyporheic zone (Bonell, 2002; Hiwasaki & Arico, 2007; Yin et al., 2019; Zalewski, 2015). Ecohydrology encompasses diverse ideas at the interface between hydrology and ecosystem science with functional interrelationships between hydrology and biota at the catchment scale provisioned to achieving sustainable management of water (Hannah et al., 2004). Hence, ecohydrology views water management holistically considering that the science alone does not determine management (Nuttle, 2002; Owusu, 2016; Pataki et al., 2011). In the following sections, we have synthesized the overarching perspectives of ecohydrology as a form of waterway management and sustainability tool in the Himalayas.

3.1 | Ecohydrology: A perspective for waterway management

Ecohydrology is regarded as an interactive scientific discipline between the hydrological cycle and ecosystems. As ecohydrology mutually interacts and integrates ecology and hydrology, the concept is found to play a greater role in waterways management and development particularly in the vulnerable environments such as the areas of water shortages and ecosystem degradation caused by climatic and anthropogenic drivers at both spatial and temporal scales (Porporato & Rodriguez-Iturbe, 2002). Although ecohydrology holds the components of hydrological and ecological science, this uses a comprehensive approach for waterways management by integrating science with society further (Zalewski, 2010, 2013). Hence, ecohydrology combines scientific and societal knowledge base and work as an overarching paradigm for broader waterways management (Hiwasaki & Arico, 2007; Nuttle, 2002). Today, the application of ecohydrology is indispensable at increased rates of climate warming and population growth and degradation of biological integrity of ecosystems in the areas like the Asian Himalayas, which are facing challenges of water resources and ecosystem management (Kattel, 2022; Xu et al., 2009). Overexploitation of water resources in a region can alter ecosystem processes to the point at which the ecosystem's ability to provide desired resources to the people can be seriously diminished (Kattel, 2019; Mukherji et al., 2015). The integration of ecology and hydrology enhances ecosystem goods and services in Himalayan waterways by maximizing the opportunities for sustainable development through waterways regulation (Zalewski, 2002; Zomer et al., 2014; Zomer & Sharma, 2009). Hence, the ecohydrology addresses complexities of the sustainability of waterways under various climatic warming and anthropogenic disturbances (Tague & Aubrey, 2010; Wang et al., 2012; Zalewski, 2013, 2015; Zalewski et al., 2016).

3.2 | Ecohydrology: A perspective of waterway sustainability tool

Ecohydrology has become a valuable tool to address sustainability issues of global waterways (Zalewski, 2010). Ecohydrology resolves the broader scientific issues of water resource management by considering hydrological processes, distribution, structure, and function of ecosystems (Nuttle, 2002; Zalewski, 2015) and also the issues related to ecological and societal aspects of waterways management (Zalewski, 2002). Being such an interdisciplinary component of biological and hydrological processes, ecohydrology is able to create a scientific basis for a socially acceptable, cost-effective and systemic approach for sustainable water resource development (Owusu, 2016; Zalewski, 2015). In some sustainable water resource development programmes, ecohydrology has been linked further with integrated water resources management for implementing environmentally friendly economic activities to meet desirable water flow and a steady supply of watershed services for societal needs, and the integrity of aquatic vegetation and animal species (Msuya & Lalika, 2018). For instance, physical, chemical and biological properties of many rivers worldwide have been profoundly impacted by construction of hydropower and irrigation dams with severe implications for migratory fish populations (Dugan et al., 2010). The critical loss of economically important fish species has motivated a series of management actions including stocking, fishery control and fish passage construction to restore and/or conserve migratory fish populations in many river basins including in the Himalayas (Baumann & Stevanella, 2012). Ecohydrology is an alternative approach of management of aquatic resources due to its holistic perspective in treating ecosystems (Guswa et al., 2020). In ecohydrology, successful maintenance of aquatic resources depends on actions that restore natural ecological and evolutionary processes that are dependent on regional hydrological dynamics. In ecohydrology, restoration of spatiotemporal and hydro-sedimentological dynamics are well incorporated (Schiemer et al., 2007). Landscape and biota are viewed as an integrated system. Based on a profound knowledge of the dynamics that underlie natural rhythms, ecohydrology aims to increase the capacity of systems in reabsorbing environmental impacts, by using properties of the ecosystem itself as management tools (e.g., rehabilitation of natural hydrological pulses, heterogeneity of habitats and riparian vegetation (Agostinho et al., 2008). With strong human actions, such approach is proven to be a sustainable human development by preserving functions and services provided by aquatic ecosystems (Singh & Singh, 2020).

Having unprecedented increase in the institutional challenges for implementing the sustainable waterways management worldwide, ecohydrology tool has an ability to coordinate and integrate various institutional actors including resource managers and decision makers (Stringer et al., 2018). Study suggests that due to the coordinated efforts of stakeholders, ecohydrology has got to overcome consistent failures of the management of waterways exposed to anthropogenic modifications of the water cycle, resulting from catchment disturbance, urbanization, agriculture, overexploitation of water and pollution (Zomer & Sharma, 2009). For instance, standalone engineering-based solutions are often resulted in as being unsustainable due to the financial and energy constraints, as well as causing damages in habitats and ecological processes consequently intensifying the water pollution (Zalewski, 2015). However, sustainability of waterways has been found enhanced when the ecohydrological tool is added with various disciplines and actors. The addition of ecohydrology is able to identify major hydrological and ecological problems and assist in decision-making process through the use of various efficient waterways management approaches including the cost–benefit analysis, and development of effective water policy measures (Zalewski, 2002). When hydrology is shaping biogeochemical processes in rivers and lakes, the condition enhances the ecosystem resilience through energy cycling and nutrient budgeting, meanwhile the ecohydrology promotes comprehensive understanding of ecological processes through environmental management and empowers biosphere conservation through integrative approach of sustainability science (Zalewski, 2013; Zalewski et al., 2016).

Experience also suggests that the waterways related to large river restoration programmes require the development of integrative scientific approaches between ecology, hydrology and river engineering, reflecting the role of a strong and intact ecohydrological tool in sustainability of waterways (Saha & Setegn, 2015). Achieving long-term sustainability goal of such projects is not easy, which needs a comprehensive synthesis of reference condition of waterways including the understanding of the dynamic equilibrium of fluvial processes, habitat composition and characteristic patterns of biodiversity and biogeochemical processes. During this time, ecohydrology addresses many unanswered questions associated with waterways sustainability including the fluvial dynamics, habitat composition and ecology, and has an ability to evaluate restoration outcomes and to predict effects at a range of temporal and spatial scales (Schiemer et al., 2007). In addition, ecohydrology identifies the short-term changes of biological structures and dynamics under extreme climatic and anthropogenic conditions of hydrological processes and provides better solutions for waterways management for longer time scale. To tackle challenges posed by climatic- and human-related impacts in the HKH region, and to propose long-term solutions, ecohydrology should be placed as a central to waterways sustainability and should carry out reduction in nutrients by putting an appropriate safeguard in the watershed including the use of integrated engineering technology and water governance to enhance biological diversity and ecosystem services (Tundisi & Tundisi, 2016; Zalewski, 2002). Hence, the ecohydrology-based future adaptation measures to ecological and hydrological changes are becoming fundamental solutions to meet the sustainability goals of the Himalayan waterways. However, in the face of rapid climatic warming and human disturbances in the region, reconfigurating of ecohydrology is becoming essential to overcome waterways management challenges in the HKH region during the 21st century.

4 | RECONFIGURATING ECOHYDROLOGY FOR SUSTAINABILITY OF THE HIMALAYAN WATERWAYS UNDER CLIMATE WARMING

Reconfigurating ecohydrology for sustainable waterway management in the Asian Himalayas is becoming a fundamental need during the 21st century. When the HKH region is exposed to unprecedented climate warming together with anthropogenic disturbances, the complexity of waterways management has significantly increased (Bandyopadhyay, 1995; Saravanan, 2008). An exchange of knowledge, experience and views between scientists, representatives of industry and business, public government officials and community leaders has become increasingly essential to tackle the problem (Jacobs et al., 2016). The joint efforts enhance awareness among people on the most important areas of science of waterways including the changes of water quality, and quantity, ecosystem and food web structure and dynamics, and markedly assist waterways management and socio-economic development in the region (Liu et al., 2015). Today, sustainability of waterways in the HKH region is the key for stable socio-economic development. However, without reconfiguring ecohydrological tools at a larger regional scale, water-related challenges faced by the society in the HKH region under rapid climate warming is difficult to address in future (Zalewski, 2013). Below we have outlined some of the key ecohydrological tools to be applicable for sustainable waterways management in the HKH region.

4.1 | Use ecohydrology as nature-based solutions of the Himalayan waterways

Nature-based solutions (NbS) are an emerging concept of sustainability of natural or modified ecosystems, which address societal challenges posed by climate change, food and water security crises. Ecohydrology explores NbS through interactions between the structure and function of ecosystems and the dynamics of flow and quality of freshwater. Advancement of science and mathematical modelling has improved NbS for water resource development and created new opportunities to address interesting and important ecohydrological questions such as how vegetation canopies and their communities interact with precipitation to affect the quantity and quality of water fluxes in waterways and how do changes to the landscape affect the quantity, distribution and quality of river flow and lake residence time (Borgogno et al., 2009; Guswa et al., 2020). NbS not only explore ecosystem structure and functions but also enhance economic competitiveness through the use of nonrenewable energy resources and offer a credible transition path for a sustainable economy (Maes & Jacobs, 2017). Particularly, cities have modified ecosystems, which demand high-quality environmental and ecosystem services for better life and human health (Kattel et al., 2013). Processes such as water circulation, matter and energy flow within the urban system are becoming fundamental where NbS plays an important role (Wagner & Zalewski, 2009).

The use of ecohydrology as NbS is going to be important for waterways management in the Himalayan cities to adapt and to better mitigate climate change effects. NbS are the part of water-related ecosystem services which perform an 'infrastructure-like' function at underlying ecohydrologic mechanisms of climate–soil–vegetation dynamics (Rodriguez-Iturbe, 2000). The use of ecohydrology as NbS was proposed primarily by the Convention on Biological Diversity of the UNESCO's Ecohydrology and Biosphere Reserves and the IHP-MAB for sustainable development of water resources (Bridgewater, 2018). Various NbS technologies have been used to promote sustainability of water resources. For instance, shrimp farms constructed with sequence of ponds and adjoining buffer zones and halophyte plantations have become an important ecohydrologic tool to have maximized food security in cities in Bangladesh (Sohel & Ullah, 2012).

Similarly, ecohydrology approach is used as NbS for greater scientific understanding of the integrated hydrology–biota relationships in the Ganga river in India, where several action plans are implemented to manage ecosystems including the creation of riparian buffer strips as a cost-efficient tool for river management. The new engineering technologies as a part of NbS are increasingly efficient for environmental management by reducing the cost of investment and establishing riparian buffer zone to improve river water quality through filtering and retaining sediments and pollutants coming from the upland catchment area (Singh & Singh, 2020). The Himalayan forests, aquifers, lakes and wetlands act as water and carbon storage basin, and they are not only protecting downstream environment from flooding but also mitigating climate change by storing carbon (Huang et al., 2021; Kattel, 2022). Many Himalayan rivers and wetlands act as NbS, which purify water by filtering industrial and household pollutants (Figure 2) while rivers are significant for irrigation and provide important conveyance for navigation, and wetlands and rivers support functioning of the ecosystem and generate significant ecosystem services in HKH region (Zomer et al., 2014; Zomer & Sharma, 2009).

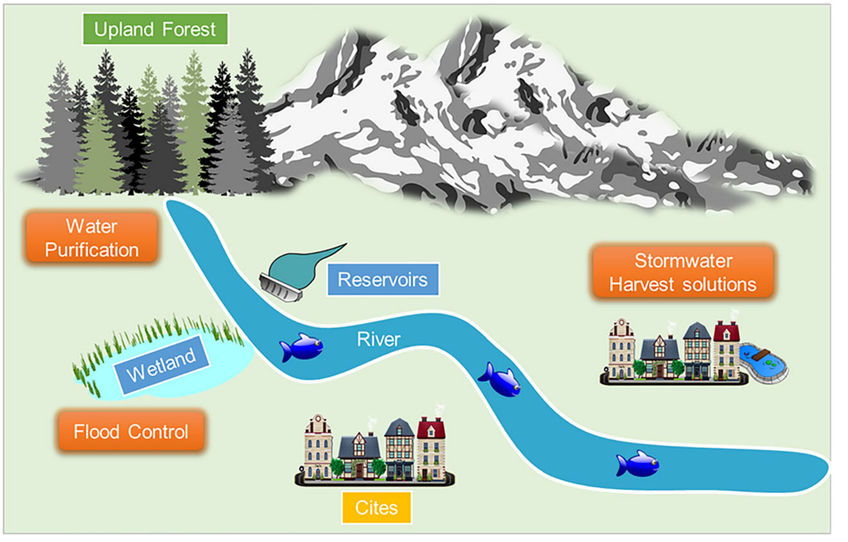

FIGURE 2 A framework on the use of ecohydrology as nature-based solutions (NbS). The meltwater from the Himalayas forms glacial-fed rivers and lakes. Forests in the river catchments mobilize carbon and groundwater, while reservoirs and wetlands purify water by removing pollutants emitted by factories, as well as control floods. Rivers when connected with wetlands support important feeding and reproductive habitats of migratory fish.

4.2 | Develop a simple ecohydrologic framework for solving the complex waterways management issues

A half of the Earth's land surface is already facing the water scarcity (Rockström & Gordon, 2001). Himalayas are no exception due to the variability in climates. Variable distributions of water and nutrients in the Himalayan waterways are sensitive to climate and cryosphere change. Frameworks on the linkages among hydrological, biogeochemical and ecological processes are becoming fundamentally significant to accomplish complex waterways management issues. Integrated and interdisciplinary approaches have been widely proposed to problem solving and hypothesis testing through modelling and place-based science. Ecohydrological approach is useful to develop new methodologies and ways of thinking about these complex environmental systems and help improve forecasts of environmental change including weather and flood (Newman et al., 2006). The knowledge around the 'complexity of sciences' behind ecology, hydrology and other environmental-related disciplines can appeal a mechanistic understanding of the system dynamics (Jenerette et al., 2012; Kunz et al., 2013). Such mechanistic understanding enhances water-related ecosystem services including climate moderation, water supply and quality, and flood mitigation (Zomer & Sharma, 2009).

In ecohydrology, energy, water, carbon and nutrient cycles are closely coupled, and this interconnectivity forms the basic supporting services to ecosystems (Sun et al., 2017). However, the knowledge on the complexity of system dynamics of the Himalayan waterways is still limited. Hence, the conventional simple conceptual framework of ecohydrology with multiple linkages can be useful for addressing more complex ecological and hydrological problems in the HKH region (Jenerette et al., 2012). For example, the variability in precipitation is the major driver of hydrology and ecology of many Himalayan river basins during the 21st century (Qazi, 2020). Precipitation determines the flow of ecosystem services in the downstream river basin through regular monitoring and maintenance of ecosystems and species diversity, as well as water quality (Qazi, 2020). Hence, developing a simple ecohydrologic framework can be easily utilized for addressing the complex issues of the Himalayan waterways (Figure 3). Such simple frameworks can make further understanding of the 'system complexity' or the combined effects of various drivers and help forecast

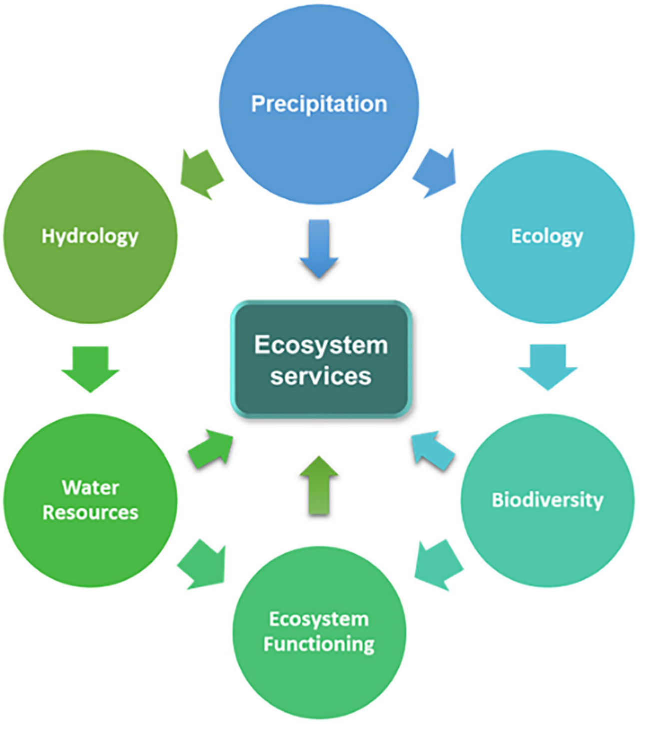

FIGURE 3 A simple ecohydrological framework reflecting a complex ecosystem dynamic in the Himalayas. Climatic drivers, such as precipitation that strongly mediates both hydrology and ecology, the interactions between water resources and biodiversity make ecosystem functioning thereby generate ecosystem services to the people residing downstream river basins.

waterways change through modelling (Newman et al., 2006; Rodriguez-Iturbe et al., 2009).

In the HKH region, study suggests that the complex hydrological and biogeochemical interactions vary at the condition of intermittent rainfall pulses to influence water recycling and ecosystem functioning, thereby ecosystem services (Wang et al., 2015). Hence, a simple framework on rainfall and chemical patterns through monitoring can help in understanding the complexity of the regional hydro-ecosystem. The modelling further integrates climate, land use and biotic responses to address the range of water management options and help for decision making and adaptation process more smoothly (Brewer et al., 2018). However, the development of a simple framework may not always address the coupled ecological, hydrological, geomorphological and biogeochemical processes as such multiple disciplines usually demand novel adaptation strategies (Krause et al., 2015).

4.3 | Integrate ecohydrology and ecohydraulics for waterways modelling

Interactions that occur between water and ecosystems such as flow–ecology relationships are significant for ecosystem functioning (Nestler et al., 2016). However, the role of ecohydraulics in such interactions is not well utilized in the management perspective of waterways. Ecohydraulics deals with hydraulic properties and processes of waterways and ecosystems (e.g., fish migration through natural and artificial passages) (Kemp et al., 2013). For instance, in natural rivers, spatial variation in bedform elevation, planform curvature and confluences with tributaries cause non-uniform flows with increased ‘hydraulic complexity’ that affect sediment transport, with feedback to impact on velocity (e.g., morphodynamics), as well as on biological habitats such as slow- or fast-moving water regimes for fish migrations (Gualtieri et al., 2017; Pasternack et al., 2008). Hence, integrating ecohydrology and ecohydraulics would be important for the management of waterways in the Himalayas, where the existence of active river morphodynamics plays a significant role in fish migration and conservation (Bockelmann et al., 2004).

Integration of ecohydrology and ecohydraulics has benefits to improve waterways both in the use of water resources and ecosystem dynamics (Benjankar et al., 2019). Integration improves the predictive ability of how organisms will respond to environmental gradients including the different degree of hydraulic-associated flow regimes (Yao, 2021). For example, in an intermittently operating lentic system where the ‘lotic in-channel’ and ‘lentic off-channel’ refugia during drought in spring flow can have an increased hydrodynamic complexity, with longitudinal integrity of lotic conditions and replenished low-lying wetlands (Mallen-Cooper & Zampatti, 2018). In such lotic–lentic system, an integration of ecohydrology and ecohydraulics has been found to work perfectly when a robust decision-making (MORDM) tool is used as the state-of-the-art multi-objective optimization algorithm (MOEA) to advance the knowledge of conjunctive water use and avoid jeopardizing the downstream ecosystem and agricultural development (Li & Kinzelbach, 2020). With integrated use of ecohydrology and ecohydraulics, the MORDM has resolved complex conjunctive water use issue and overcome the groundwater extraction issue in the watershed (Li & Kinzelbach, 2020).

The ecohydrologic and ecohydraulic models being developed and used in other parts of the world are becoming increasingly useful for the Himalayan waterways to address complex interactions between ecosystem processes and the storage and flux of water across the scales (Tian et al., 2019; Yao, 2021). The HKH region, which still requires many unanswered questions to be resolved on the roles of ecohydrology and ecohydraulics, the integration of the two can answer the research questions of ‘what if’, and ‘where how’ and consequently assist waterways management. For example, direct observations related to hydrology, water quality and ecology as well as ecohydraulics in the HKH can be made by designing plots, hillslopes, streams and watersheds, as the integration of different ecohydrologic and ecohydraulic components can act as a complementary to field-based and data-driven science with combination of theory and empirical relationships among various physical and biological parameters (Rice et al., 2010) (Figure 4). Study suggests that the output of integrated models has been the new scientific domain in which data are well encoded and questions are successfully tested for the development of future adaptation strategies (Tague & Frew, 2020).

4.4 | Incorporate ecohydrology in waterways resilience and governance framework

The IGBP provides scientific basis for sustainable development policies for waterways management, where land use change and ecohydrology are highlighted (Bass et al., 1998). Better water governance has an ability to recognize the issue and improve adaptation strategies of river and lake ecosystems. Because of the scale and complexity of the interactions between nonlinear ecohydrological and socio-economic processes, developing an effective governance framework is difficult particularly for the HKH region where accessibility of data is usually limited. However, adopting ecological and hydrological theories together with use of the holistic management approach of water resources is crucial. Holistic ecohydrological practices increase sustainability of ecosystems and human well-being through managing water, biodiversity, ecosystem services and resilience (Kemp et al., 2013). Three major hydrological, ecological and engineering principles at the same time play a significant role in quantification of flow, ecological processes, and in understanding evolution and ecosystem properties (Singh & Singh, 2020).

In an increasingly competing world, if water is valued as an economic commodity, governance related to efficient use and conservation of water and its security should be enhanced (Agnew & Woodhouse, 2010). Study shows that better water governance has improved through efficient water pricing, which determines allocation priorities and the valuation of ecological services and increases adaptation and resilience of waterways (Edwards, 2003). Valuation of water in different water sectors in the HKH region is therefore

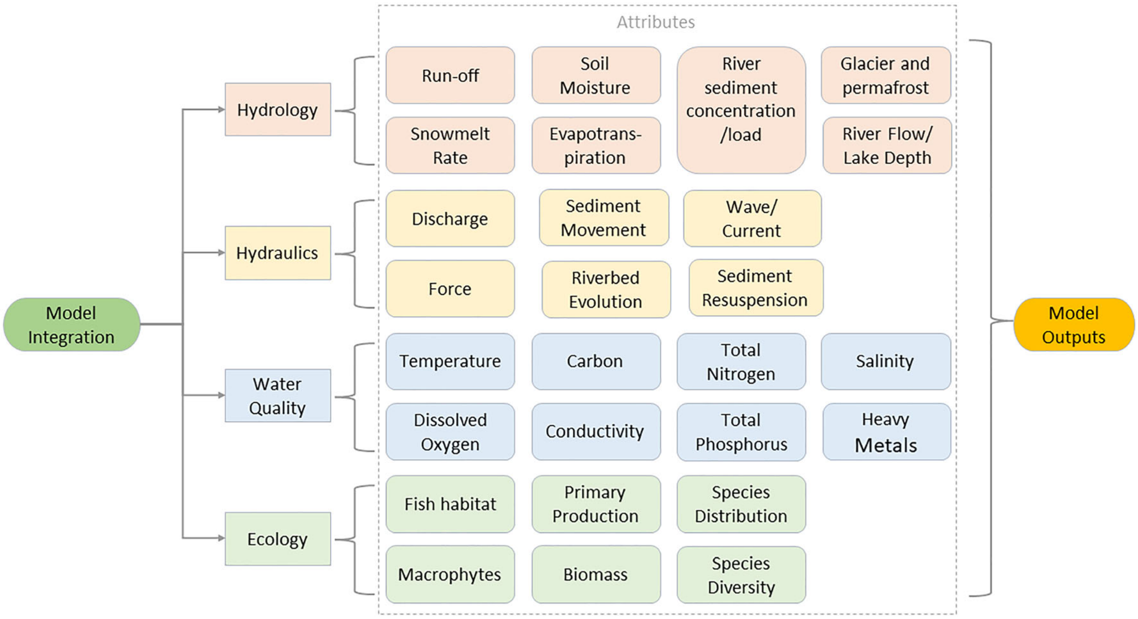

FIGURE 4 A framework for an integration of various attributes of hydrology (e.g., runoff), hydraulics (e.g., discharge force), water quality (e.g., dissolved oxygen) and ecology (e.g., species diversity) and modelling can result in the model output as a new scientific domain to address the waterways management issues in the Himalayas.

significant so that it would promote stewardship of water resources among local stakeholders. However, waterway in the HKH region primarily needs improved water allocation rights and water rights trading system, which can then resolve water shortages issues. Water rights and trades are found to improve the economy and support water reforms, water investments and water use efficiency (Kattel, 2019, 2021; Rosegrant & Binswanger, 1994). Despite the significance of water rights in the Himalayas, trades in water services would require extensive research and innovation (Crow & Singh, 2009). Market-based incentives such as damages for exceeding pollution standards; water markets based on reallocation of water resources between irrigation and municipal uses; payments for watershed services; partnerships and financing in the re-examination and retrofitting/refurbishment of existing water management infrastructures, including dams, due to their inadequacy in reflecting the high social value of freshwater services; and appropriate restoration programmes all are found significant water governance as market-based water management systems are often considered as efficient, tend to externalize and thereby ignore both environmental and social costs (de Economia & Mateen, 1995; Hiwasaki & Arico, 2007). Water right systems usually meet stakeholders' needs and expectations and raise their willingness to pay for water services (Hiwasaki & Arico, 2007). The governance based on institutional principles is therefore important for decision making in which the distribution is usually made equal for both society and nature (Bakker & Morinville, 2013; Kattel, 2019). Incorporation of combined biophysical, ecohydrological and social dimensions of waterways promote governance to meet better water supply and demand and consequently benefit sustainable water resources development in the Himalayas (Pataki et al., 2011).

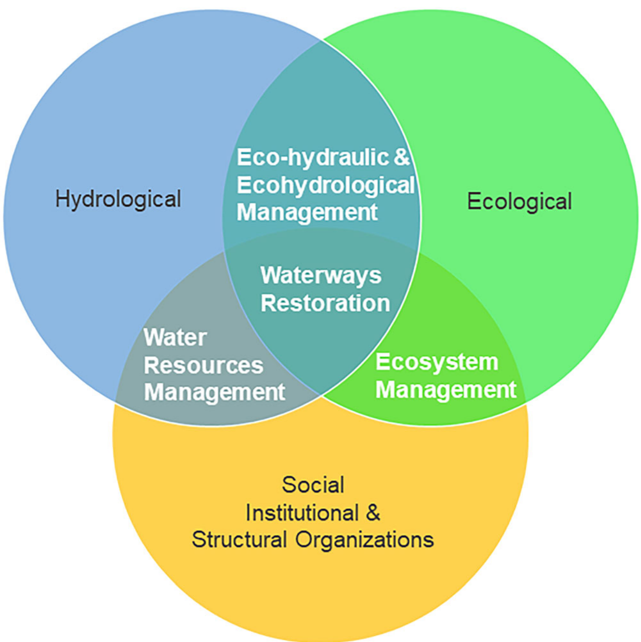

FIGURE 5 An overarching framework for ecological, hydrological and social systems to maximize waterways restoration in the Himalayas. Each ecological, hydrological and social components play a significant role in water governance and sustainable water resources development and waterways resilience in the region.

Identifying the relationship between the water and the surrounding environments with social and cultural dimensions and bringing them into the governance framework is thought to be a prerequisite and is becoming increasingly essential in waterways governance

(Hiwasaki & Arico, 2007; Jackson & Langton, 2000). Lately, socio-ecological and socio-hydrological approaches are being used to address the problems of complex water resource management (Vollmer et al., 2018). Resilience of waterways reduces at a time of the occurrence of unpredictable shifts caused by various drivers including climate change and anthropogenically induced pollution in the social-ecological system (Bass et al., 1998). Incorporating the components of ecological, hydrological and social system into the governance are essential for sustainable water resources development and waterways resilience (Figure 5). Because of the increased waterways sensitivity to the environmental change in the HKH region, the shift to a new system may occur at any time as a sudden and unpredictable fashion; during that period, the use of ecohydrological tool can play a key role for effective waterways governance and enhance resilience.

5 | CONCLUSIONS

In our study here, we have made three important conclusions. First, the Himalayan waterways play an important role in generating the significant ecosystem goods and services to more than one billion people residing downstream Asia. However, with rapid transformation of hydrological and ecological processes under climatic warming and anthropogenic disturbances, water resources including water quantity, water quality and overall aquatic ecosystems and biodiversity in the region are threatened. In such condition, ecohydrology is emerging as an integral tool to tackle waterways management as the integration of ecology and hydrology can address various water-related issues including the understanding of hydrological processes and distribution, structure and function of ecosystems under different flow regimes followed by the dynamics of ecosystem goods and services. However, the use of the conventional ecohydrology tool does not address contemporary management challenges of the Himalayan waterways. Hence, second, we recommend reconfiguration of the ecohydrology tool in the HKH region. The newly configured ecohydrology tools are innovatively designed (e.g., NbS) and adopted with modern technologies. The reconfigured ecohydrology tool is also integrated with ecohydraulics, and other social dimensions, useful for equitable water allocation and protection of threatened aquatic species. Finally, provision of an improved institutional water governance is essential for effective application of ecohydrology for resilient and sustainable waterways in the Himalayas.

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CONFLICT OF INTEREST

The authors have no conflict of interest for declaring.

DATA AVAILABILITY STATEMENT

The data are available upon request from the corresponding author (G. R. K.).

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