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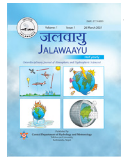

Review Article

Changing Ecological and Hydrological Conditions in the Himalayan Mountains and Measures of Future Adaptation

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Abstract: The Himalayan mountains are one of the important geographical settings of the planet Earth for the source of global freshwaters. The freshwaters from the Himalayas are life supporting systems of the millions of people residing in downstream Asia. However, the high-altitude mountains of the Himalayas have gone through considerable transformations in hydrology and ecology over the recent past. In the 21st century, the hydrological flow regimes of glacial-fed rivers are threatened by both climate change and human disturbances. Rapidly changing temperature and the frequency, duration and timing of monsoonal precipitation have altered glacier melt, river flow, flood, and downstream volume of water. As a result, the ecosystems and biodiversity as well as irrigation-dependent agriculture in the region is profoundly impacted. The fundamental challenge today is therefore to address the issue of water resources through understanding of hydrological and ecological changes of lake and river systems in the region. Ecohydrology is a sustainability concept, which addresses water

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resource management through understanding of water cycle, including hydrological processes of rivers and lakes and the structure, and function of ecosystems. Putting ecohydrology at the center of the water resource management program, this mini review discusses rapid ecological and hydrological changes of freshwater systems in the Himalayan mountains and suggested some of the key future adaptation strategies of water resources to rapidly changing regional environment.

1. Introduction

The Himalayan mountains are one of the most important areas for the source of global freshwaters which support ecosystem goods and services to the millions of people in Asia. However, during the 21st century, the Himalayas have gone through considerable transformations in meteorological, hydrological, and ecological processes. Rapid climate warming in the region has reduced glacier volumes and snow cover followed by water storage capacity of the mountains (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). Climate change in the many high altitudinal environments of the Himalayas have led to major implications for seasonal variation in precipitation, rapid rate of glacier melting and increased frequency of snow avalanches (Ragettli et al. 2016). Climate warming has caused upward shift of the Himalayan tree-lines threatening the entire regional ecosystem and biodiversity (Sigdel et al. 2020). The variations in the frequency of summer monsoon rainfalls and the melting of the large reserve of snow together has caused adverse effects on the rate and the amount of water that flows into the downstream river basins causing severe water shortages, prolonged droughts or flooding, as well as disruptions in irrigation followed by significant reduction in the agriculture productivity (Rühland et al. 2006; Shrestha and Aryal 2010). The fundamental challenge of the region today is therefore how to tackle the issues of water resource management by understanding the both ecological and hydrological processes.

The natural flows maintain ecological and sedimentary processes which include healthy habitats and valuable biodiversity and ecosystems in the Himalayan river and lake systems (Sinha et al. 2019). Rivers and their associated lakes and wetlands are a potential source of ecosystem goods and services for the millions of mountain people in the Himalayas who have been living there for millennia. The flows also play a significant role in flood attenuation, water purification and fisheries production (Karki et al. 2020; Kattel et al. 2016). Hence, the hydrological regime is crucial for ecosystem functioning and maintenance of water quality of both rivers and lakes. Exchange of nutrients including carbon and nitrogen, active hydrodynamic condition, and intact physical properties of water such as pH, conductivity, and other geomorphology such as bottom sediments in rivers and lakes maintain hydrological conditions and the functioning of aquatic ecosystems. These conditions are also important for maintenance of thermal regimes followed by photosynthesis under the influence of light, currents, turbulent mixing, waves and fluctuation of water levels in lakes and rivers (Timchenko 2016).

However, the flow regimes of mountain rivers as well as lake depths have been consistently modified to meet the increasing demands of water for various purposes.

For instance, the construction of hydroelectric dams in most rivers in Asia has made considerable implications for ecology of rivers by disrupting fish migration and upstream sediment trapping (Dugan 2010; Yang and Lu 2014). Reduction in flow due to water diversion projects in some river basins have affected macroinvertebrate community assemblages in rivers (Tachamo Shah et al. 2020). The disturbances over time and space can alter habitat stability affecting species diversity and ecosystem functioning (Kattel et al. 2016). However, the widespread hydrological alterations in the Himalayan mountains and associated hydrological impacts are often ignored or sidelined. With growing population in the region, the demand for energy and water together with irrigated agriculture and food production, and industrial water use has significantly increased. The importance of flow regimes in the health of river and lake ecosystems and biodiversity in the region continues to play a major role for the future mankind (Olden et al. 2014). Today, the development of water resources tools that assist healthier ecology and hydrology in the region is a fundamental necessity.

Ecological engineering or ecotechnology, focuses on nature-based solutions of various environmental problems, which include changing ecological and hydrological conditions and threats in ecosystem goods and services under rapid climatic warming and anthropogenic disturbances. For instance, the loss of surface roughness of the riverbeds due to hydrological and hydraulic alterations can lead to lower algal growth (Cardoso-Leite et al. 2015) consequently affecting the base of the food web. An integration of ecology, hydrology, hydraulics, a discipline of ecotechnology, can be used as an important tool for solving the issue of surface roughness by reducing the impacts on catchments and help address adaptation measures of changing water resources (Jørgensen et al. 2019). Hence, the understanding of the interactions between human and nature would be indispensable component for advancing the knowledge of adaptation measures of water resources in the region. Having such knowledge would help achieve sustainability goals of water resources and ecosystems in the region when they are exposed to a range of environmental changes including climate change and human disturbances (Kattel 2019). In this mini-paper, I discuss ecohydrology is a conceptual framework for sustainability, or a nature-based tool for solving the environmental problems, and the ecohydrology itself acts as key adaptation measures of changing water resources including ecology and hydrology in the Himalayan mountains.

2. Materials and Methods

This mini paper is based on the review of literature published mostly on 'ecohydrology' theme and is relevant to the mountainous regions of the Himalaya.

3. Results

3.1. Ecohydrology: a tool of sustainability concept

Lately, ecohydrology has emerged as an important tool or a framework that addresses sustainability concept. Ecohydrology integrates ecology and hydrology (Fig. 1) and addresses the broader issues of water resource management including the science behind the hydrological processes and distribution, structure, and function of ecosystems, and the effects of biotic processes on elements under different flow regimes (Nuttle 2002). The concept is the sub-discipline of ecological engineering that include several ecological disciplines and contributes to build an important bridge between ecology and the environmental management. Being an inter-disciplinary component of hydrology and ecology, ecohydrology has been advanced as a fundamental process for understanding, rather than simply the establishment of functional linkages between ecology and hydrology. For example, the United Nations Educational, Scientific and Cultural Organization-UNESCO's International Hydrological Program (IHP) and the Man and Biosphere (MAB) Program have employed ecohydrology as an integrated understanding of biological and hydrological processes at a catchment scale in order to create a scientific basis for a socially acceptable, cost-effective and systemic approach to the sustainable management of freshwater resources (Owusu 2016; Zalewski 2015). When hydrology is shaping biogeochemical processes in riverine and lacustrine catchments, the condition enhances ecosystem resilience through energy cycling and nutrient budgeting. Meantime the ecohydrology promotes understanding of ecological processes through environmental management, which consequently empowers biosphere through integrative approach of sustainability science (Zalewski 2013; Zalewski et al. 2016). Hence, in the face of rapid climatic warming and declining water resources in the world's river basins (Kattel 2019), the use of ecohydrology concept has become crucial for water resource development in river basins of entire mountainous regions of the Himalaya.

Ecohydrology has already overcome various problems associated with conventional water management practices, which were not sustainable. In the past, there were consistent failures of the management of water resources exposed to anthropogenic modifications of the water cycle, resulting from catchment disturbance, urbanization, agriculture, overexploitation of water and pollution (Zomer and Sharma 2009). The engineering-based solutions when applied as standalone were unsustainable due to the financial and energy constraints, as well as such actions would also seriously damage riverine and lacustrine habitats and ecological processes and intensify secondary water pollution such as eutrophication (Zalewski 2015). However, incorporation of ecohydrology concept in water resource management has revolutionized sustainability of water resources by identifying major hydrological and ecological problems and proposing the insights into the new nature-based solutions as decision-making tools such as the use of cost-benefit approach, financial investment, and development of effective policy strategies (Zalewski 2002). The application of ecohydrology can assess degradation of short-term biological structures and dynamics under extreme climatic and anthropogenic conditions of hydrological processes and provide better solutions for water resource management for longer time scale. For instance, reduction in incoming nutrients and sediments by putting an appropriate safeguard in the watershed based on integrated engineering technology and water governance together would maintain biological productivity, improve siltation, water quality as well as meet the societal water demand on time (Zalewski 2002). Hence, the ecohydrology-based future adaptation measures to ecological and hydrological changes would become fundamental solution for sustainable water resources in the Himalayan mountain regions where climate change is becoming a critical challenge.

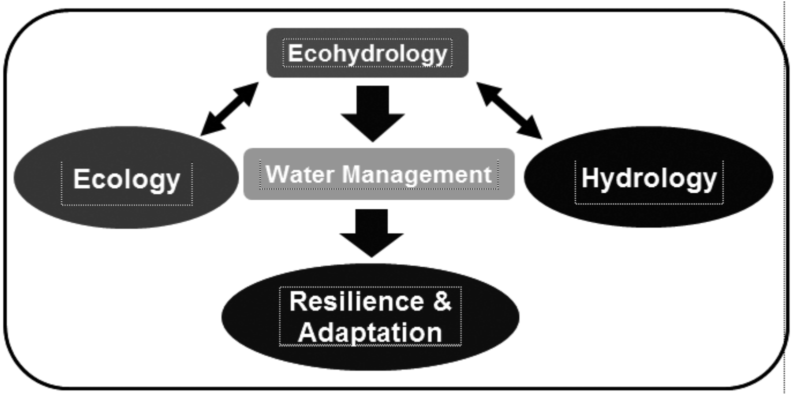

Figure 1. Integration of ecology and hydrology. Ecohydrology enhances sustainability and resilience and adaptation of rivers and lakes to rapidly changing environment in the Himalayan region.

3.2. Ecohydrology as measures of future adaptation to regional environmental change in the Himalayan mountains

Developing the measures of future adaptation to ecological and hydrological changes in the Himalayan mountains is not an easy task. Even today, the exchange of knowledge, experience and views between scientists, representatives of industry and business, and public government officials, that integrates our awareness of the most important fields of science in water resources and socio-economic conditions, is limited (Liu et al. 2015). Under the rapidly changing environment in the Himalayan mountains, sustainability of water resources is the key for stable socioeconomic development in the future. Forward-looking future adaptation measures can resolve the large-scale, water related problems faced by the society in the region (Zalewski 2013). By putting the concept of ecohydrology at the centre of the debate, below, I have described some of the key adaptation measures of freshwater resources that are exposed to a range of ecological and hydrological changes in the Himalayan mountains.

3.2.1. Linking ecohydrology with nature-based solutions (NBS)

Adaptation to unpredictable changes of ecology and hydrology in the mountain regions of the Himalayas can be enhanced through adopting the principle of linkages between ecohydrology and nature-based solutions. For example, in the Ecosystem Approach used by the Convention on Biological Diversity of the UNESCO's Ecohydrology and Biosphere Reserves, the IHP-MAB has successfully provided the practical solutions for global management of water resources and ecosystem (Bridgewater 2018). Some of the cities around the globe have suffered from waterlogging issues. The use of ecohydrology and nature-based solutions such as the advanced urban design for stormwater harvests by making natural pools as green infrastructure within the waterlogged cities has become significant for resolving the problems such as the urban storm waterlogging (USWL) in many countries (Li 2012). Similarly, the ecohydrology-based shrimp farming system which includes the introduction of a sequential ponds, creation of buffer zones with halophytes, and constructed wetlands together has enhanced carrying capacity of the farm and the local ecosystem in coastal regions (Sohel and Ullah 2012). Taking example of similar adaptation measures can be useful to increase overall resilience against climate change and anthropogenic pressures on ecology and hydrology in the Himalayan mountains.

3.2.2. Development of simple frameworks addressing complex scientific issues

Ecohydrology is a reconciliation of multiple concepts and technical approaches that generate knowledge on future adaptation. This knowledge is around the 'complexity of sciences' behind ecology, hydrology and other related environmental disciplines that appeal a mechanistic understanding of all. The approaches based on the multiple linkages can provide a useful framework by showing simple relationships at relatively fine scales and allows interactions among networks. The network of number, diversity, and connectivity of units can greatly influence how these systems behave across space and time. Hence, the use of simple framework can help synthesize complex ecological and hydrological issues (Jenerette et al. 2012). For example, hydrologically controlled river basins are important in maintaining the ecosystems and species diversity, water quality and societal development as the flow regimes regulate the amount of available resources and the severity of disturbances (Jenerette et al. 2012). The combined effects involving these mechanisms are expected to give rise to complex but interesting, perhaps unexpected, dynamics and patterns of science (Rodriguez-Iturbe et al. 2009). Environmental outcomes of such complex scientific issues require the development of a simple, but high-level decision-making framework. Eco-engineering decision scaling (EEDS) tool is one of them, which examines the trade-offs between stakeholder-defined engineering or resource-based outcomes and ecological outcomes (Webb et al. 2020). However, science behind the rapidly changing and nonlinear behaviour of ecosystems represents a challenge for the development of a simple framework which can address the coupled ecological, hydrological, geomorphological and biogeochemical processes that usually demand novel adaptation strategies (Krause et al. 2015).

3.3.3. Advancing the integrated ecohydrology and ecohydrulic models

Riverine and lacustrine systems constrain hydrological and biophysical processes. There are a range of interactions that occur between water and ecosystems such as flow–ecology relationships. Ecohydraulics focuses primarily on the influence of hydraulic properties and processes (e.g., fish migration through natural and artificial passages). Integrating ecohydrology and ecohydraulics modeling is useful to improve the predictive ability of how organisms will respond to environmental gradients including different degree of flow regimes. For example, model integration of ecohydrology and ecohydraulics in an intermittently lentic system where lotic in-channel and lentic off-channel refugia during drought in spring flow can show an increased hydrodynamic complexity, promote longitudinal integrity of lotic conditions and replenish low-flowing wetlands (Mallen-Cooper and Zampatti 2018). The most striking feature has been observed in increased hydrological and biogeochemical linkages when intermittent rainfall pulses which drive biogeochemical reactions. The shorter scale (hours to days) rainfall propagates to a longer time scale (months to years) benefits for water recycling and ecosystem functioning at dry conditions (Wang et al. 2015). Such modelling likely to integrate climate, land use, and biotic responses to address the range of water management options and help decision making and adaptation process (Brewer et al. 2018).

Many-objective robust decision-making (MORDM) tools have successfully integrated the state-of-the-art multi-objective optimization algorithm (MOEA) with robustness-based decision analysis to advance the knowledge of conjunctive water use (Li and Kinzelbach 2020). The MORDM is largely benefitting the rivers facing unsustainable water management with increasing vulnerability of downstream ecosystem and agricultural development (Li and Kinzelbach 2020). In this framework, the areas of overexploitation of water resources, which cannot fulfill the minimum ecological outflow target is optimized by modelling to improve baseline hydraulic flows so that there is a balanced hydrology (flow regime) and water demand for the irrigated agriculture in the basin (Li and Kinzelbach 2020). In mountainous regions, ecohydrology models are even very useful to address complex interactions between ecosystem processes and the storage and flux of water across the scales (Tian et al. 2019). The models can resolve research questions of "what if". Direct observations related to hydrology and ecology can be made in plots, hillslopes, streams, and watersheds as the models which act as complementary to field-based and data-driven science with combination of theory and empirical relationships. Today, integrated models have become the new scientific domain in which data are encoded and the questions are successfully tested for the development of future adaptation strategies (Tague and Frew 2020).

3.2.4. Improving water governance for resilient aquatic systems

Better water governance has an ability to recognize the issue and improve adaptation strategies of river and lake ecosystems. Sticking with ecological theory and adopting the holistic management of the water resources is crucial in the mountains. Individual smaller-scale actions have stronger outcomes in water security of the river or lake basins. Water should be valued as an economic commodity so that the governance of efficient use and conservation of water strongly promotes water security in the mountain river basin (Agnew and Woodhouse 2010). One of the significant actions of water governance is water pricing which determines allocation priorities and the valuation of ecological services and increases adaptation and resilience. While utilizing ecohydrological practices in water resource management in the Himalayan mountains, valuation of water of riverine and lacustrine systems is significant so that it would promote stewardship of water resources among local stakeholders. The governance based on institutional principle is also important for decision making in which the distribution is usually made equally for both society and nature (Kattel 2019). The decision of water distribution based on eco-hydrological modeling and supported by engineering solution of irrigation and cropping pattern in the watershed would usually meet the hydrological needs of the local water users throughout the year (Kihwele et al. 2018).

4. Conclusions

The Himalayan mountain regions are an important source of global freshwaters, which support basic needs of ecosystem goods and services to the millions of people in Asia. However, the entire region today has gone through considerable transformations in hydrological, and ecological processes. Increased anthropogenic disturbances and climate warming together have led to implications for snow melt, hydrological flow regimes and ecosystem functioning of lake and river systems together with alteration of ecosystem and goods and services. Tackling the water resource management issue through understanding the hydrology and ecology of the region has become a fundamental challenge for the future adaptation. The natural flows which maintain ecological and sedimentary processes as well as nutrient cycling of lakes and rivers through flood attenuation, water exchange, purification and fisheries production have been profoundly altered. Construction of dams for hydroelectricity, irrigation and navigation in rivers has modified the flow regime. Climate warming has further intensified the conditions followed by the loss of biodiversity and ecosystem goods and services. Ecohydrology concept has emerged as an important sustainability tool for water resource management under the rapidly changing environment in the Himalayan region. Ecohydrology acts as functional linkages between ecology and hydrology create a scientific basis for a socially acceptable sustainably managed freshwater system. Ecohydrology addresses hydrological processes and distribution, structure, and function of ecosystems, and the effects of biotic processes on elements under different flow regimes. Hence, at rapid climatic warming and anthropogenic disturbances, the use of ecohydrology concept overcomes the challenge of the regional water resource development through adopting various measures for future adaptation. For instance, linking ecohydrology and nature-based solutions can make a difference in the sustainability of water resources system and biodiversity conservation. Ecohydrology deals the issue of 'complexity of sciences' in a simple, but as a strong decision-making tool, which has ability to examine the trade-offs between stakeholder-defined engineering and ecological outcomes. More importantly, when ecohydrology concept is institutionalized with better water governance principles, the efforts in adaptation measures to future environmental changes in the Himalayan region are maximized.

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