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How resilient are waterways of the Asian Himalayas? Finding adaptive measures for future sustainability

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Abstract

The high-mountain system, a storehouse of major waterways that support important ecosystem services to about 1.5 billion people in the Himalaya, is facing unprecedented challenges due to climate change during the 21st century. Intensified floods, accelerating glacial retreat, rapid permafrost degradation, and prolonged droughts are altering the natural hydrological balances and generating unpredictable spatial and temporal distributions of water availability. Anthropogenic activities are adding further pressure onto Himalayan waterways. The fundamental question of waterway management in this region is therefore how this hydro-meteorological transformation, caused by climate change and anthropogenic perturbations, can be tackled to find avenues for sustainability. This requires a framework that can diagnose threats at a range of spatial and temporal scales and provide recommendations for strong adaptive measures for sustainable future waterways. This focus paper assesses the current literature base to bring together our understanding of how recent climatic changes have threatened waterways in the Asian Himalayas, how society has been responding to rapidly changing waterway conditions, and what adaptive options are available for the region. The study finds that Himalayan waterways are crucial in protecting nature and society. The implementation of integrated waterways management measures, the rapid advancement of waterway infrastructure technologies, and the improved governance of waterways are more critical than ever.

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KEYWORDS

adaptive capacity, Himalayas, resilient waterways, sustainability, thresholds of change

1 | INTRODUCTION

Global waterways, such as rivers and lakes, are some of the most precious and fundamental resources for humanity, not only due to their indispensable role in the hydrological cycle regulating the Earth system's functioning, but also due to their role in sustaining water, energy, and food supplies for the burgeoning global population (Best, 2018; Falkenmark, 2016; Immerzeel et al., 2020). At the same time, these waterways have confronted serious challenges. Approximately half of all freshwater withdrawn for societal use evaporates, and 25% of the rivers on land are affected by overuse, causing considerable natural and societal damages (Rockström et al., 2014). Between 1984 and 2015 alone, 90,000 km^2 of surface water worldwide disappeared (Pekel et al., 2016), which is a strong indication of the severe threat to global water security (Gain et al., 2016). The total terrestrial water storage could decline substantially by the end of the 21st century, resulting in a three-fold increase in the number of people living under exceptional drought (Pokhrel et al., 2021). An estimated 80% of the world's population faces high-level water security or water-related biodiversity risk (Kattel, 2019).

Major waterways in Asia including the Indus, Ganges, Brahmaputra, Yangtze, Yellow, Mekong rivers, and several high mountain lakes (Figure 1) together support more than 1.5 billion people, and are largely dependent on the freshwater that originates from snow and ice reserves in the Himalayas and the Tibetan Plateau (Immerzeel et al., 2020; Li et al., 2021). Regional-scale hydro-climatological controls of water availability and local-scale cultural beliefs and practices that have evolved over centuries have led to unprecedented changes of waterway conditions in the 21st century. Regional climate warming has intensified rapid melting of Himalayan ice, drastically altering inter-annual and seasonal variability in the amount of water available for most Asian waterways, consequently affecting regional water supplies and food security (Cui et al., 2023; Immerzeel et al., 2010). Such effects of regional climate change are expected to be intensified by more distant hydroclimatic phenomena, including oceanic climate change (Zhang et al., 2023). Even if the increase in global average temperature is maintained at 1.5°C compared to preindustrial levels, there will still be significant ramifications for Asian waterways. For instance, global climate models (GCMs) have simulated a 1.5°C versus a 2°C global warming for major waterways of Asia, including the Indus, Ganges, and Brahmaputra river basins, and suggest that a 1.5°C increase in the mean global temperature will result in a temperature increase by 1.4–2.6°C ($\mu = 2.1$) for these river basins, whilst for the 2.0°C scenario, the increase would be 2.0–3.4°C ($\mu = 2.7$), with significantly adverse climate change impacts on regional water resources under the 2°C versus the 1.5°C scenario (Lutz et al., 2018).

Many densely populated river basins in the Himalayas are fully or partially reliant on snow and glacial meltwater for irrigation of intensive multi-cropping systems in the monsoon season (Pritchard, 2019). Snow and glacier melts modulate river flows and, together with groundwater, provide water during the dry season to support crop production (Shamsudduha & Panda, 2019). A coupled cryosphere–hydrology–crop model shows that irrigation water dependence in the Indus river basin in the pre-monsoon season, for instance, could reach as high as 60% of the total irrigation withdrawals, originating from mountain snow and glacier melt contributing further 11% to total crop production in the basin (Biemans et al., 2019). Interactions between permafrost, precipitation and groundwater recharge play a critical role for the maintenance of regional water availability in the Himalayan waterways (He et al., 2023). A study in Mt. Everest's Khumbu region in Nepal suggests that the northern Bay of Bengal is potentially an important moisture source during the monsoon period (June–August) and that westerly trajectories over snow-capped landmasses dominate precipitation events during the post-monsoon, winter, and pre-monsoon seasons (Perry et al., 2020). Despite the projected increase in precipitation in the monsoon season (Mondal et al., 2022; Rao et al., 2020; Talchabhadel et al., 2018), the post-monsoon season is likely to continue to experience the lowest observed precipitation and

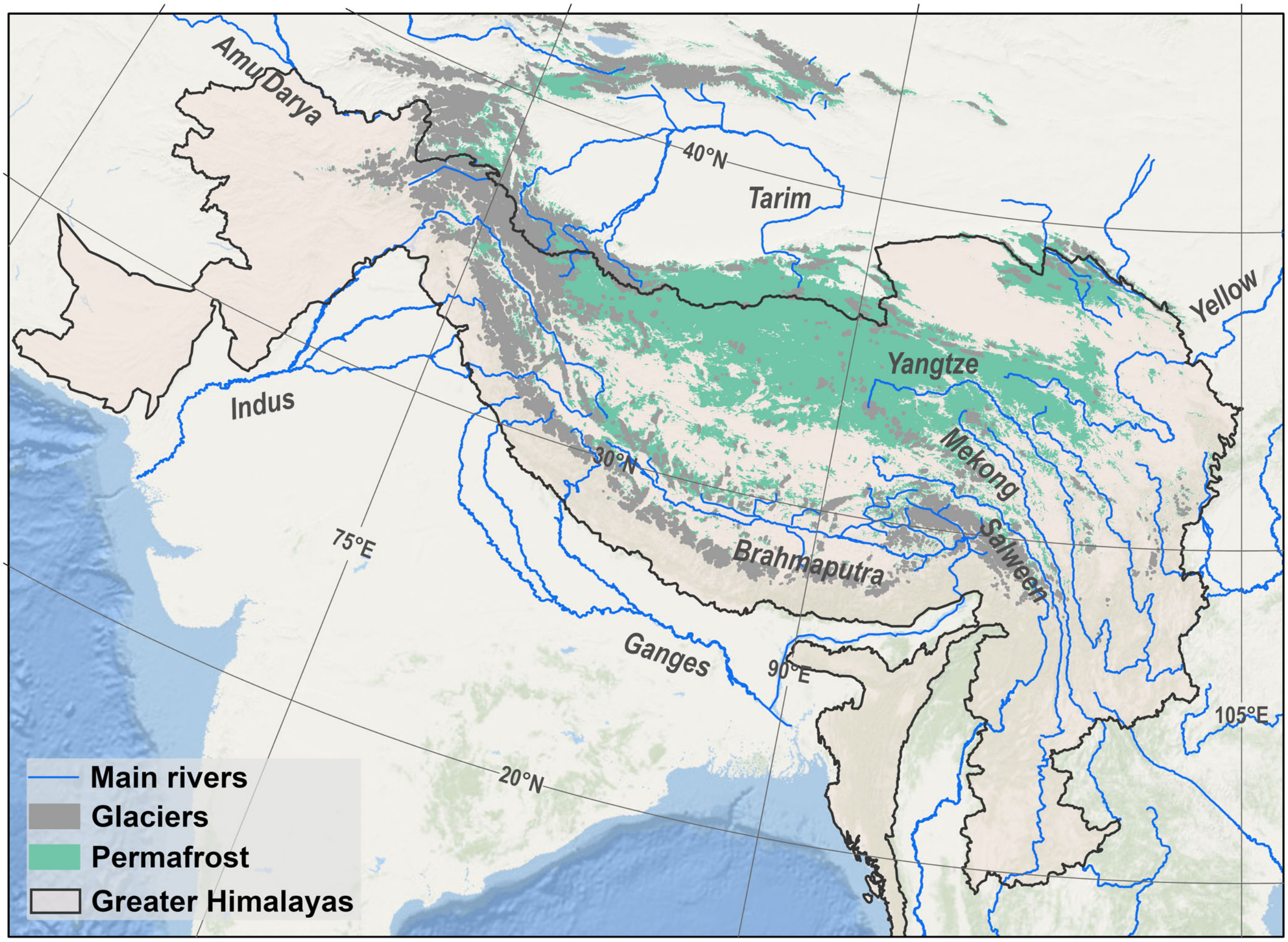

FIGURE 1 Major Himalayan waterways (mainly the rivers shown in the map) as well as the distribution of glaciers and permafrost.

river discharge, determining the future water availability for agriculture, hydropower, ecosystem functioning and its services in downstream river basins (Dahal et al., 2020). Collectively, these findings indicate that the wellbeing of an estimated 1.5 billion people is under direct threat due to temperature rise, glacier and snow melt and the consequent dwindling supplies of freshwater from the high mountain systems of the Himalaya to downstream river basins (Quincey et al., 2018). Water shortages are likely to increase during the dry season.

Today, at a time when the waterways of the Himalayas are at a critical juncture of transformation, how resilient they are, and how they will maintain the foundation of civilization and humanity in the region into the future have emerged as critical questions (Quincey et al., 2018). Resilience is the capacity of waterways to absorb perturbations before a system changes its structure by modifying the variables and processes that control its behavior (Holling, 1973). Waterway resilience is closely linked to how society has evolved through time (Adger, 2000; Agnew and Woodhouse, 2010). As societal development requires sustainable use of water resources, better understanding the linkages between resilience and sustainability is becoming increasingly important. In the UN's sustainable development goals (SDGs), resilience of the environment has been emphasized as the pursuit of well-being of people with no poverty, no hunger and good health (Benson et al., 2019; Tortajada, 2020; Tortajada & van Rensburg, 2019). However, there has been a challenge, particularly for developing nations in south and southeast Asia to achieve SDGs by 2030 unless ecosystems, including freshwater systems, are integrated within a climate adaptation framework to complement and substitute socio-economic development (Fuldauer et al., 2022). The SDGs narrative in resilience is therefore important for the Himalayan waterways, as it links sustainability and societal development in south and southeast Asian regions (Chaigneau et al., 2021). However, challenges remain in making the Himalayan waterways resilient and sustainable.

Human impact on aquatic ecosystems, rapid economic growth, and increase in water-related hazards (e.g., floods and droughts) associated with glacier-snow melt, permafrost degradation, and hydropower development, are all becoming major challenges (Bakker, 2012; Li et al., 2022). These challenges have been exacerbated by hydrological variability and losses in biodiversity and ecosystem services (Arora et al., 2016; Kattel, 2022; Miller et al., 2012). While there are inherent economic, social, and environmental linkages and complexities, adaptive management solutions have shown to resolve water security challenges (Varady et al., 2016). Such solutions should be integrative, learning-centered, and constitute a resilience thinking approach, which would lead to strong and sustainable water–food–energy systems (Allan et al., 2013). Thus, resilience management maintains a diversity of functions and homeostatic feedbacks, keeping the system from potentially crossing thresholds, and building the ability to cope with transformation through learning and adaptation (Allen et al., 2011; Kattel, 2020). The resilience of Himalayan waterways remains largely unknown; the human-water linkages, how the system would adapt under modified climatic conditions, and how it would cope with the condition of transferability at a time of change are aspects that are yet to be explored (Boltz et al., 2019). Here, we present a focus paper by reviewing the resilience of Himalayan waterways, followed by a synthesis on the challenges of waterways management in the region. Subsequently, we introduce a range of waterways resilience frameworks to address the growing challenges of regional water insecurity issues in the Greater Himalayas.

2 | HOW RESILIENT ARE HIMALAYAN WATERWAYS?

2.1 | Historical and cultural perspective

The resilience of waterway systems in many parts of the world, including the Himalayas, is largely shaped by the history and culture of local people, who share a significant stake in water resource management arising from their customary systems of water use (Davis et al., 2020; Jackson & Langton, 2000; Wester et al., 2019). Over millennia, Himalayan glaciers have supported various cultures, languages, religions, and traditional knowledge and belief systems, and are deeply associated with cultural, spiritual, environmental, educational, and ritualistic values of local people (Norgay, 2004). People's wellbeing, including spiritual and mental health, are maintained by diversified cultural values, which are strongly linked to the cryosphere (Talukder et al., 2021). Snow or ice-covered mountains in the Himalayas feeding lakes and rivers are of high spiritual value for local communities. For instance, a large perpendicular slab of ice with horizontal rock layers in Tibet is regarded as a symbol of Buddha's spiritual strength (Su et al., 2019). In the higher Nepalese Himalaya, the Mai Pokhari—or the holy pond—is where local people receive blessings for health, fertility, good harvests, and financial security (Chaudhary et al., 2019).

Despite a global threat to indigenous people and culture, there is a growing evidence base of their adaptive nature when faced with extreme environmental changes. For years, a place may be formed as an indigenous belief system, and also a local knowledge hub, where environmental changes are experienced, understood, resisted or adapted to by the people (Ford et al., 2020; Marshall et al., 2013). For instance, hot water springs, "tato pani," in the Nepali and Sikkim Himalayas are believed to have healing powers as their source is thought to be protected by goddesses (Das et al., 2012). This water is regarded as a holy substance for either religious purposes or bathing, symbolizes a victory over evil (Quincey et al., 2018). Indigenous knowledge through religious and spiritual practices in the Himalayas over time has become significant for the purification of the soul, or the freeing of disease.

Although the Himalayan people have transformed the landscapes through deforestation and irrigation for the service of agriculture and pastoralism, they still have maintained the resilience of waterways without interfering with their sustainability. Indigenous knowledge has been crucial for waterway resilience supporting socio-economic development. For instance, Nepal's capital, Kathmandu, had the Royal canals—"Raj kulo"—which were built for water supply for farming during the Medieval period. Farmers managed irrigation systems as a water conveyance and management system within the Kathmandu valley to resolve the acute shortage of water during dry seasons (Gautam et al., 2018). Similarly, the Dao philosophy in China, has been used for centuries as a synonym for harmony between humans and nature, and, in broader context, as a part of sustainable water resource development (Varis & Kummu, 2019). However, changing hydroclimatic conditions interfere with traditional irrigation and farming practices. The important knowledge of traditional water management practices under changing hydroclimatic conditions in the past (Sima, 2021) receives little attention, resulting in poor integration of traditional knowledge and values in critical policies and management schemes (Gain et al., 2016).

In addition, melting glaciers have constantly undermined the traditional cultural values of water in the region. There is a belief that a divine power sits at the top of the Himalayas, controlling the waterways, and is being angered by human actions (Chaudhary et al., 2019). Glacial decline is therefore not only a natural and scientifically proven process, but also deeply embedded within people's cultural beliefs (Talukder et al., 2021). Recently, there have been debates that cultural science should be acknowledged in shaping the public sphere of waterways (Lund, 2015). The integration of cultural values and narratives moderates internal organizational behavioral dynamics and communications among stakeholders, and shapes, informs, and constructs better organizational cultures for improving waterway resilience (Kirsop-Taylor et al., 2020). Hence, the integration of both physical and human pressures on water resources including ongoing population growth, climate change, and urbanization, is fundamental for an improved understanding of the cultural perspectives of waterway resilience.

2.2 | Natural perspective

Waterways play a central role in ecosystem functioning and determine quantity and quality of ecosystem services. Any shift in patterns of waterways in space and time can define key pathways and boundaries for human-related water resource development and resilience (Boltz et al., 2019). Being an important component for the structure, stability and functioning of the biophysical system, Himalayan water regulates the global climate system together with carbon, nitrogen, and phosphorus recycling. Water flushes pollutants, transports chemicals, and generates ecosystem goods and services for society (Falkenmark, 2016; Kattel, 2022). The underlying concept behind resilience of waterways in the Himalayas is therefore crucial in determining how humankind is supported by a sustained production of ecosystem services under uncertainty and surprises brought upon by climate change and social perturbations in the region over time (Folke, 2003).

Hence, from a natural or reference condition perspective, waterway resilience has strong roots in both natural and social science disciplines (Höllermann & Evers, 2020). Resilient waterways in the Himalayas are thought to absorb perturbations, such as natural climate variability, and remain in the same state to continue being the life-supporting system for regional civilization over millennia (Boltz et al., 2019; Boyd et al., 2015). As resilience comprises the system's ability to be reorganized and renewed, as per the degree of disturbance and change (Holling, 1973), the Himalayan waterways display some of the most complex socio-ecological and hydrological interactions, capable of self-organizing after changes, through learning and adaptation (Dasgupta et al., 2022; Kattel, 2020). Studies have shown natural systems with reduced resilience may still maintain function and generate services to society (Folke et al., 2004; Holling & Allen, 2002). At a time of disturbance such as climate-related events, the naturally resilient system can potentially create opportunities for reorganization, development, and innovation that help adaptation (Holling & Allen, 2002). Thus, under the natural perspective of waterway resilience in the Himalayas, the freshwater ecosystem is thought to withstand short-lived extremes (i.e., flood and drought), as well as adapt to long-term ecological and hydrological shifts (Quincey et al., 2018), as crises offer both lessons and opportunities for resilience locally and regionally (Rodina, 2019).

2.3 | Management interventions perspective

In the 21st century, resilience has received a broader recognition in water management and has become an integral component in achieving the SDGs, proposed by the United Nations (Dewulf et al., 2019). This is largely because both water quantity and water quality problems are becoming increasingly severe worldwide. Water resources are being depleted with increased water pollution in lakes, rivers, and groundwater aquifers (Pandit et al., 2014). The disparity in the volume of water released from the Himalayas between the monsoon and the dry season has led to extremes of high rainfalls, floods, and losses of infrastructure and lives, and also large-scale crop failure and water scarcity due to prolonged droughts (Chinnasamy et al., 2015; Hamal et al., 2020; S. Sharma, Hamal, et al., 2021). Projections of future runoff tend to carry large uncertainty, which undermines system resilience and can have significant implications for water supply to downstream communities (Quincey et al., 2018). When waterways are faced with poor resilience and are subject to a sudden event (e.g., a flood, heavy rainfall, drought, and/or water pollution), a critical threshold may be reached, and they may experience the transition into a less desirable regime with a lower capacity to deliver ecological functions for societal development (Liu et al., 2015). In an increased period of vulnerability, such as during land-use change, redirection of freshwater flows, and changes in freshwater quality due to chemical perturbations, even a small event may be devastating for the long-term sustainability of the waterway system, with society being highly susceptible to more uncertainty, surprise, and crisis (Folke, 2003; Folke et al., 2002; Gunderson et al., 2017). Given the remote location, resilience of the high-altitude Himalayan waterways under severe disturbances is not yet well explored.

Since the past decade water resource management has more often been viewed from an economic perspective; yet, the natural value of water and how it functions, beyond its direct economic value, is usually underestimated (Golubev, 2009). With continuing population growth, urbanization, and water pollution in the Himalayas under climatic warming, the conventional water management approach will need to change (Kattel, 2019; Momblanch et al., 2019). Although some key measures, including the maintenance of diversity and redundancy, connectivity and feedbacks, adaptive systems thinking, learning, broadening participation and promoting polycentric governance, have been proposed (Folke et al., 2016; Kattel, 2020; Pahl-Wostl, 2009; Pahl-Wostl & Knieper, 2014), no firm measures are being developed for building resilience for Himalayan waterways in the face of rapid change. A variety of statistical and mathematical approaches have been developed to detect thresholds, and water resilience (Buelo et al., 2018; Qian et al., 2003). Unfortunately, there is limited guidance about which model is most appropriate for environmental thresholds for a specific situation. An integrated and iterative framework, adopting threshold approaches to understand system dynamics, and providing management guidance to show the utility of threshold models in system resilience, is urgently needed for coupled natural and human associated waterways in the Himalayas (Li et al., 2016).

3 | REGIONAL WATER INSECURITY AND CHALLENGES OF WATERWAY RESILIENCE

3.1 | Increased water insecurity and stress

Global mean temperatures have increased by 1.2°C relative to a preindustrial time (1861–1880) and a global mean temperature increase beyond 1.5°C is suggested to be detrimental to humanity (King et al., 2021). Under the Paris Agreement of 2015, all signatory countries have agreed upon "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C" and garnered a response to assess the impacts of 1.5 and 2.0°C increase above the pre-industrial levels on various sectors, including water (King et al., 2021).

Establishing water indices, identifying the magnitude of water insecurity, and quantifying the status of water security for specific spatial contexts are becoming increasingly important, particularly in data-scarce areas such as the Himalayas. For instance, Liu et al. (Liu et al., 2022) identified the present water security status of the Qinghai-Tibet Plateau under the rapidly changing ecological environment in the 21st century by assessing the supply–demand relationship of water. Although they found the Qinghai-Tibet Plateau region was water secure for the years 2000, 2005, 2010, and 2015 as the corresponding annual total water surplus was 6.71 × 1011 m^3, 8.43 × 1011 m^3, 7.86 × 1011 m^3 and 2.91 × 1011 m^3 for those years, respectively, the area with low-security levels (Level I and Level II) is increasing (Liu et al., 2022). In particular, many rapidly growing cities, such as Kathmandu, Sri Nagar, Islamabad, among others, are increasingly emerging as densely populated centers facing increased water insecurity. Climate warming and human impacts together have caused the drying out of nearby spring water sources of these cities during the dry season (Bharti et al., 2020). Water quality of tributaries and wells in the monsoon season are deteriorating, while excessive groundwater abstractions have led to reduced availability of water for drinking and irrigation purposes (Bharti et al., 2020). Cities' networks of pipelines and storage systems are usually outdated, causing further contamination from industrial pollution and domestic effluents. This water crisis has forced cities to import clean water; for example, the city of Kathmandu diverts 170 million liters of water per day (MLD) from the Melamchi river through a 26-km long tunnel, which is not only costly during construction but also has long-term maintenance issues and costs (Bharti et al., 2020). This highly modified water regime has brought about critical challenges for waterway resilience with abrupt changes in both water quantity and water quality. As a result, many countries in the region are not meeting national surface water quality standards for drinking water (Evans et al., 2012; Wester et al., 2019).

Agricultural modernizations including the use of biotechnology and machinery have intensified to meet the rising food demand in the region (Cai et al., 2012), which has resulted in further intensifying water use and exacerbating water quality (Rockström et al., 2017). The regional water demand has, in recent years, exceeded the available volume, particularly during the dry periods (Munia et al., 2016) causing water stress across national and transboundary river basins in the region (Hansaz, 2017; Varis et al., 2014).

3.2 | Challenges of waterway resilience

Water scarcity brings tremendous challenges to waterway resilience, particularly in achieving sustainable development of water resources, food, and energy security in the region (He et al., 2019; Immerzeel et al., 2020; Yao et al., 2022). The food-energy-water nexus is important in the Himalayan waterways, as they feed two-thirds of the world's population and account for 59% of the planet's water consumption (Rasul, 2014). Today, more than 40% of the world's poor lives in countries including Afghanistan, Bangladesh, Bhutan, India, Maldives, Nepal, and Pakistan, and some 51% of the population is food–energy-water deficient (Rasul, 2016). In the river basins fed by Himalayan glacial-snow melt water, over 281 million people are still undernourished, 362 million people have no access to electricity and at least 600 million depend on biofuel for cooking (Amjath-Babu et al., 2019). In addition, production of rice and wheat—the staple foods—requires huge amounts of water and energy.

In order to meet these interrelated and growing demands, water fluxes have been constantly modified for flood control, water supply, irrigation, hydropower production, recreation, or a combination of these (Ferrazzi & Botter, 2019; Li et al., 2022). By the early 21st century, 45,000 large dams were constructed in over 140 countries around the world, significantly fragmenting fluvial systems and altering their hydrological balance (Grill et al., 2015; Grill et al., 2019; Nilsson et al., 2005). Despite noticeable changes in freshwater conditions caused by flow regulation in many global regions (Chaudhari & Pokhrel, 2022; Pokhrel et al., 2017), their effects are highly uncertain, especially in the remote and data-scarce Himalayan waterways. Regulations are found to have intensified evapotranspiration of reservoirs and reduced temporal runoff variability with very high human footprints on water consumption (Jaramillo & Destouni, 2015). The Himalayan waterways have experienced rapid anthropogenic modifications of natural flow regimes through dams and reservoirs altering sediment loads of many rivers (Benda & Dunne, 1997; Li et al., 2018), disrupting the equilibrium between water flow and patterns of erosion and sedimentation, leading to a general rearrangement of channel and floodplain morphology throughout entire river networks. The altered natural flow and sediment regimes, through the changing of magnitude, timing, and amount of flow, can result in potentially permanent damage to the ecological integrity of terrestrial and river-floodplain ecosystems downstream (Dang et al., 2022; Pokhrel et al., 2018). Often such hydrological alterations can create new thermochemical regimes and habitat conditions, which threaten the survival of native species (Ferrazzi & Botter, 2019). Hence, transboundary water resources already pose complex and often contentious management challenges in the Himalayas (Akamani & Wilson, 2011; Qamar et al., 2019) with increased water insecurity and long-term sustainability issues of waterways (Bakker, 2012; Vinca et al., 2020).

4 | ARE THERE ADAPTIVE MEASURES FOR WATERWAY RESILIENCE IN THE ASIAN HIMALAYAS?

Tackling water insecurity and challenges in the Asian Himalayas needs a range of frameworks to achieve long-term waterway resilience in the region. These frameworks should not be viewed in isolation, as they have overarching applicability, which should be reassessed on a regular basis.

4.1 | Detecting critical thresholds of waterways

Biophysical system thresholds occur during regime shifts, or major changes in ecosystems, which usually have multiple causes that could be either gradual changes in climate or rapid land modification and urbanization, transforming the quality of surface and groundwater systems (Hughes, Carpenter, et al., 2013). Resilient biophysical systems usually maintain critical functionalities by absorbing disturbances and reorganizing while undergoing state changes (Folke, 2003). However, when the ecosystem is consistently or repeatedly exposed to disturbances, there is an underlying risk of ecosystem shift from a more desirable state to an undesirable state. Biophysical system thresholds are the points (Figure 2) where even small environmental changes due to external perturbations can lead to switches from the desirable state into the undesirable state (Horan et al., 2011; Sasaki et al., 2015).

Hence, the thresholds (tipping points) of a biophysical system have been widely illustrated as a ball that moves across two or more valleys or basins of attraction (Figure 2). For a resilient system, the ball stays within the same valley, a stable landscape domain, which often returns to the original state following the perturbation or reduction in human

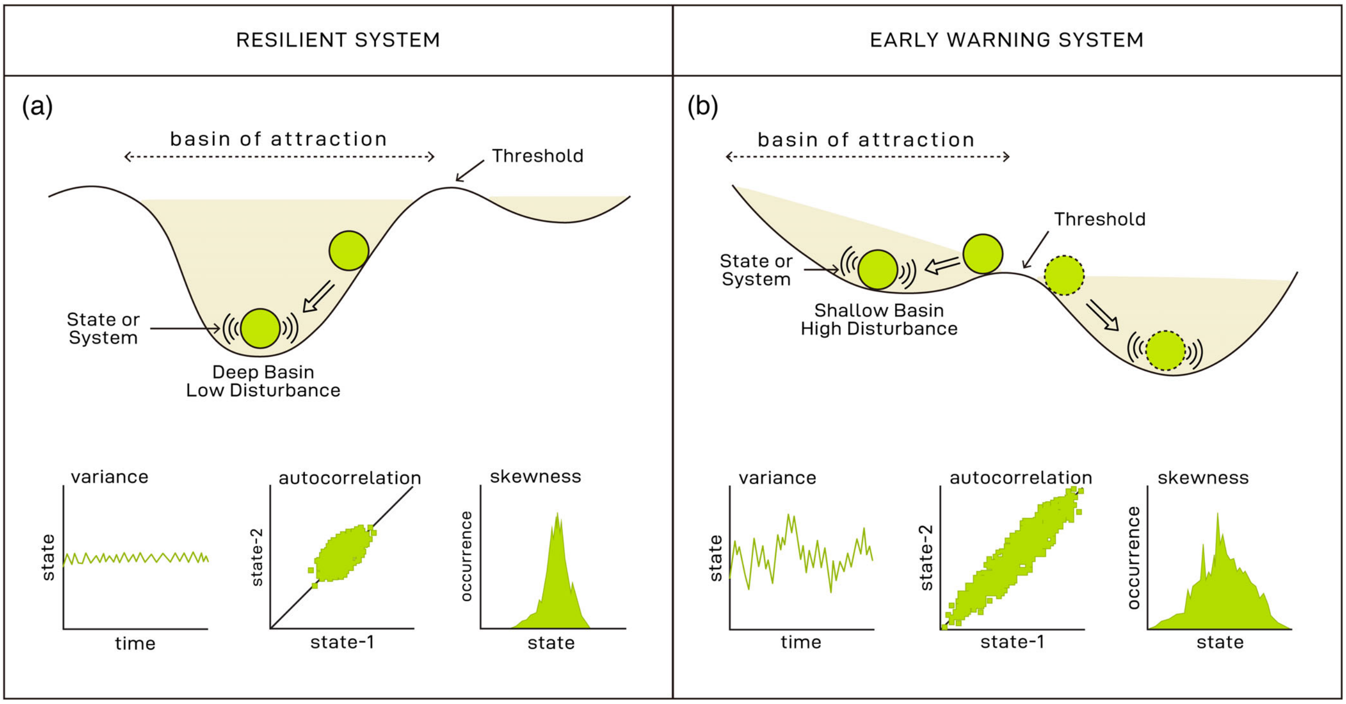

FIGURE 2 A conceptual resilience framework for the detection of early warning system (EWS) and thresholds when exposed to both climatic and human perturbations.

pressures, rather than flipping into a new regime or the state of a different basin of attraction. The peaks separating valleys depict unstable thresholds between the two or more alternative ecosystem states (Folke et al., 2004). Human perturbations influence the shape and depth of the stability domains, and the thresholds leading to regime shifts. The threshold usually characterizes a nonlinear relationship between the driver (e.g., climate change or pollution) and the ecosystem state. A steeper slope arises if there is positive feedback, and often results in an unprecedented shift in the ecosystem, even with a small alteration in drivers. The existence of positive feedback further sharpens the bend of the curve, subsequently producing two alternative stable states of ecosystems (Hilt et al., 2011; Hughes, Linares, et al., 2013).

While quantification of nonlinear relationships between nutrient inputs and biological responses in waterways, by establishing nutrient thresholds or critical levels of N or P, has already been proposed as the best approach to maintain the threshold level in different waterways (Xu et al., 2015), there are advancements being made in further quantifying nonlinear relationships through early warning systems (EWS) of threshold crossing (Zhang et al., 2021). In EWS, ecosystems often flicker before making a critical transition, and are quantified by variance, skewness, and autocorrelation of time series data (Figure 2) with the degree of dispersion and symmetry (Dakos et al., 2012; Eby et al., 2017; Guttal & Jayaprakash, 2008). Hence, it is increasingly crucial that the resilience of Himalayan waterways can be assessed not only by quantifying the critical levels of nutrient load or temperature change, but also by developing the EWS metric systems. In situ observations of the biophysical system including biota, nutrients and the geo-chemistry of water in remotely located areas of the Himalaya are therefore fundamental for better understanding the eco-hydrologic processes, and other geomorphologic, and thermodynamics conditions (Kattel & Wu, 2023). As these systems are rapidly changing and are non-linear in nature with complex interactions of various climatic and anthropogenic factors, real-time monitoring of biophysical parameters would help develop adaptive measures for the Himalayan waterways (Krause et al., 2015; Leng et al., 2022).

Being a highly sensitive biophysical system under rapid climate warming and increasing anthropogenic activities, Himalayan waterways need to be maintained in a desirable state for the continuous generation of ecosystem services to people in the region. One of the latest threats discovered in Himalayan waterways is the severe degradation of water quality caused by harmful cyanobacterial blooms. With increased population, urban centers, and industries, as well as intensified agriculture, some of the Himalayan waterways receive excessive nitrogen (N) and phosphorus (P) loads, causing harmful algal blooms (Badar et al., 2013). Harmful algal blooms are undesirable ecosystem states as they lead to the collapse of drinking water supplies, food webs and the overall degradation of freshwater ecosystems. Developing an effective and quantifiable nutrient reduction tool is an effective solution to fix the impaired water quality and increase resilience in the region (Bhagowati & Ahamad, 2019; Özkundakci et al., 2011; Romshoo & Muslim, 2011). However, the waterways are confounded by various drivers in which the relationships among drivers and biological parameters are nonlinear and difficult to quantify. The interacting processes of how climatic and anthropogenic impacts would lead to vulnerable waterways in the Himalayas is therefore critical.

4.2 | Establishing an aquatic and terrestrial biodiversity, ecosystem function, and ecosystem services response framework

Development of an aquatic and terrestrial biodiversity, ecosystem function and ecosystem services response framework can be one of the significant adaptive measures for waterway resilience in the Himalayas. Need of such framework is becoming increasingly urgent as several national and international organizations indicated the problem of biodiversity and ecosystem services loss. For instance, the Intergovernmental Panel on Climate Change (IPCC) and the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) have identified risks to humanity posed by the loss of biodiversity and ecosystem services worldwide, as well as derailing progress toward meeting the SDGs (Arneth et al., 2020; Kattel, 2022). The Aquatic-Terrestrial Biodiversity-Ecosystem Functioning-Ecosystem Services (ATB-EF-ES) interactions have recently been established in the Himalayas under climatic and human perturbations (Kattel, 2022). Linkages of abiotic attributes, productivity, and biodiversity across terrestrial and aquatic realms are thought to strengthen ecosystem functioning, and to contribute ecosystem services through the exchange of cross-system subsidies, maintenance of ecosystem engineering, and the interaction of surface water-groundwater hydrology (Dahlin et al., 2021). Hence, understanding the relationship between multiple pressures, conditions and services of both inland aquatic and terrestrial ecosystems helps design measures to achieve the target of good ecological status that benefit nature conservation and restoration (Grizzetti et al., 2016). Lack of a clear framework could hamper waterways sustainability. The 'diversity stability' hypothesis suggests that ATB-EF-ES interactions are enhanced when species richness increases, and vice versa; however, the "redundancy" hypothesis suggests that the ATB-EF-ES interactions may become critical in the face of collapse, when species losses would continue to occur with no compensatory mechanism for the loss (Allan et al., 2015). The "idiosyncratic" hypothesis, on the other hand, suggests that biodiversity and ecosystem interactions may become unpredictable at a time when keystone species losses occur (Dudgeon, 2010). Keystone species in the community and ecosystem have disproportionately large impacts and strengths relative to the abundance, and play a significant role in the maintenance and resilience of lake and river ecosystems (Mills et al., 1993; Power et al., 1996).

The ecosystem functioning of the Himalayan waterways is largely mediated by natural variability, predominantly the changes of temperature, precipitation, soil, nutrients, substrate, altitude, pH, light, water transparency, minerals and conductivity (Gillette et al., 2022; Momblanch et al., 2020). For example, *Daphnia* in the Himalayan waterway systems, are a keystone grazer, having the potential strength to transfer energy to fish, and recycle nutrients (regulating ecosystem services) across the trophic level by reducing algae (Kattel, 2022). The consequence posed by the loss of keystone species including *Daphnia* and other biota under climate warming and anthropogenic impacts, such as species invasion, land use change, and tourism is yet to be comprehensively understood. Recently, a study on snow trout (*Schizothorax richardsonii*), a flagship-keystone species in Himalayan waterways with great commercial and recreational values, has been found to be poorly distributed within their habitat range due to the introduction of exotic brown trout (*Salmo trutta*) and other land use intensifications, including river valley modifications and destructive fishing practices (A. Sharma, Dubey, et al., 2021a; A. Sharma, Dubey, et al., 2021b). Establishing the ATB-EF-ES interactions response framework with the role of flagship- keystone species can be an important approach for understanding and managing fish habitats enhancing diversity of Himalayan waterways under climatic and anthropogenic perturbations. While doing this, further identifying, and removing or controlling the reproductive habitats of non-native fish species would be essential to increase waterways resilience in the region. Incorporating fish biodiversity and habitat conservation measures would be significant for improving waterway resilience in the Himalayas.

4.3 | Geo-informatic and predictive waterways modeling

When the availability and consistency of water-related data is an ongoing issue in the Himalayas (Momblanch et al., 2019), improved geo-informatic and other predictive models with high quality observed data are essential for waterways resilience under rapid regional climate warming (González Vilas et al., 2015). Climate warming has intensified positive feedbacks of snow-albedo and cloud-radiation interactions causing glacial and snow melt followed by variation in downstream flows (Takeuchi et al., 2018; Yasunari et al., 2013). For example, the annual mean surface temperature and monsoon variability range for the Tibetan plateau are estimated to be as high as 8.4°C and 1%–23%, by the end of the 21st century, causing severe hydro-climatic changes including glacial lake outburst floods (GLOF) (Gurung et al., 2017). Due to changes in the upstream, the downstream Himalayan waterways have undergone changes in the timing, location, quantity, and quality of water and sediment, leading to contemporary water resources management challenges, including drinking water and irrigation challenges (Ingole et al., 2015; Wahid et al., 2014). Coincident with population growth and regional economic development and land use change, technological, behavioral, and infrastructural advancements all have resulted in an increased water demand. Better predictive models with a robust spatio-temporal assessment of the impacts on water resources are urgently needed to improve water security of the region (Momblanch et al., 2020). Subbasin modeling of temporal and spatial rainfall runoff and meltwater-induced runoff and mapping would be significant for assessing waterways resilience (Figure 3).

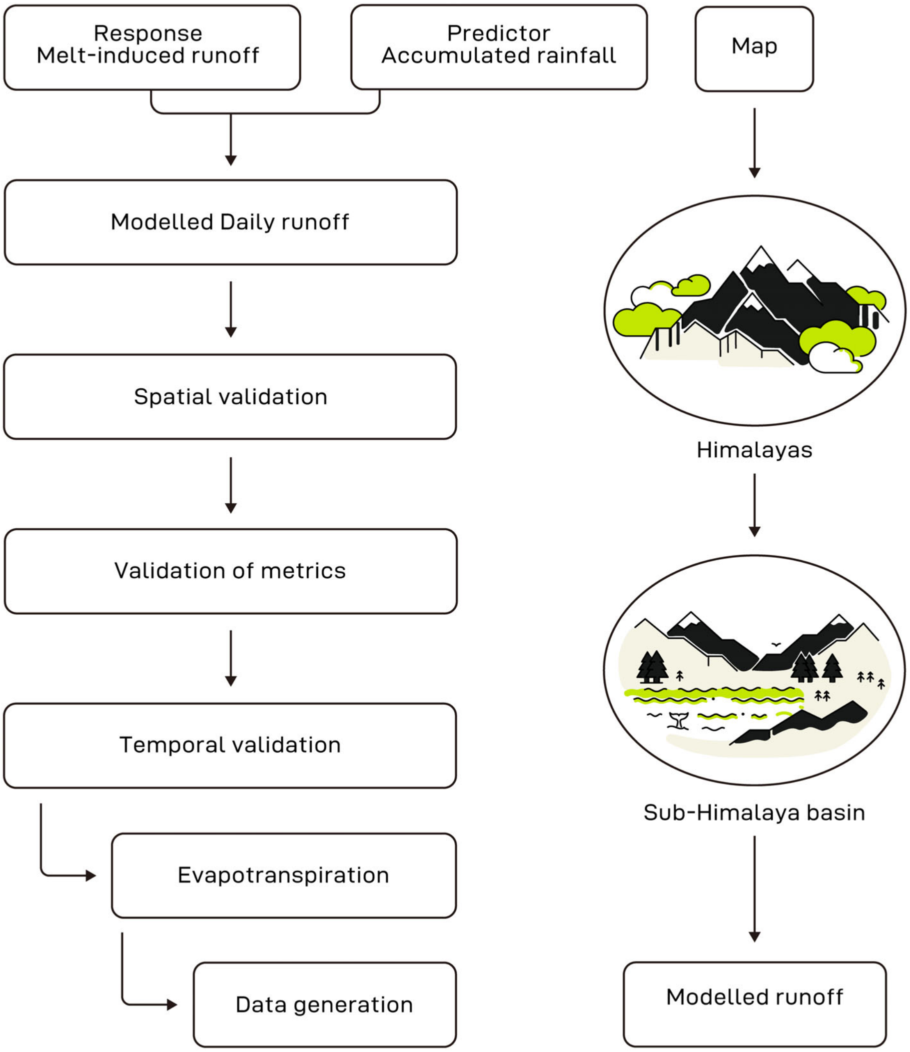

FIGURE 3 A conceptual framework on glacier-snow-meltwater modeled runoff in the sub-Himalayan basin. Modeled daily runoff in the catchment is estimated based on spatially validated climate-induced runoff and rainfall data in the Himalayas.

A satellite-based surface water assessment (Pekel et al., 2016), including spatial and temporal variability in water storage and discharge is significant to overcome data gaps in ungauged river basins and to help improve predictive models. Optical imagery such as LandSAT, SPOT, IRS, and MODIS, alongside RADAR imagery such as RADARSAT, JERS, and ERS at different spatial and temporal resolutions, accurately estimate the extent of change, including mapping land cover and flood inundations during the monsoon (Thakur et al., 2016; Wahid et al., 2014). Conditions of waterways in inaccessible or remote areas are captured by remote sensing within a very short span of time, thus are efficient for exploration, evaluation, and analysis. Satellite-based assessments of geomorphology, topography, geology, structural controls, soil types, and the land use and land cover (Ingole et al., 2015; Romshoo & Muslim, 2011; Thakur et al., 2016) and the Surface Water and Ocean Topography (SWOT) analysis all provide critical datasets which are urgently needed for studying the changing Himalayan waterways (Pekel et al., 2016). While the predictive models on water quality and species-environment relationships have markedly enhanced conservation efforts in the Himalayas (Bhat et al., 2021), artificial intelligence (AI) and machine learning (ML) has become a promising alternative to conventional statistical approaches, as AI is well suited with non-linear datasets and geographic information systems that help enhance the accuracy of predicting future changes in waterways in the Himalayas (Joy & Death, 2004).

4.4 | Development of sustainable waterway technologies

Water supply conditions in Himalayan river basins can be addressed by better management and technology development (Gohar et al., 2015). Mitigating demands and enhancing supplies are useful management approaches which implement water conservation practices by enforcing the law, influencing user-responsible behavior on water fares and pricing (Brent & Ward, 2019). The supply enhancement, on the other hand, can be achieved by utilizing sustainable waterways technologies including smart water technology (Gude, 2017). Unlike the vast number of infrastructure built for economic benefits in the past, sustainably designed infrastructure provide essential water-related services to society (Thacker et al., 2019). Hence, Himalayan waterways should embrace sustainability concepts in infrastructure designs built for the protection of people and nature, such as fish friendly hydropower dams, flood control reservoirs, and irrigation and drinking water supply systems. Consideration of fish passages to mitigate the barrier effect of hydropower dams on migrating fish species in some of the Himalayan waterway systems, including the Mekong river, has been promising over the recent decade, as the scheme protects nature by facilitating successful upstream and downstream migration of fish through the barrier (Baumann & Stevanella, 2012). However, adoption of an adaptive management approach, which includes planning, implementation, and operation, and innovation of fish passage systems is essential, as the provision of such approaches caters migration of large numbers of fish species with high biomass at variable flow regimes (Silva et al., 2018).

Lessons learnt from other river basins are useful for the management of Himalayan waterways. For example, once the mighty Colorado river, which used to supply plentiful water and food resources to more than 40 million people in the seven western US states, is rapidly drying today (Milly & Dunne, 2020). Climate warming and prolonged droughts have led to a failure of the 20th century Colorado river commission accord, which was to fulfill the demand of water, energy and food resource supplies through irrigation and hydropower energy (Barnett & Pierce, 2009; Bennett et al., 2019). It is said that science was long ignored, which has led to the current crises in many urbanizing environments. Urbanization has altered the hydrological cycles, and redirected natural river networks into the stormwater and wastewater transmission facilities (Golden & Hoghooghi, 2018). Urban flooding followed by stormwater and wastewater pollution increases due to limited infrastructure provision. Flood control mechanisms are often poor (Goytia et al., 2016). Provision of nature-based systems is therefore significant as they can typically absorb excessive runoff and have the capacity to attenuate and restore the environment to pre-flood conditions (Breed et al., 2015). Urban flood risk can be better managed if Green Infrastructure (GI) is optimized alongside gray infrastructure (traditional stormwater management approaches), delivering multiple co-benefits to waterways and society (Green et al., 2021). Being in a flood prone region (Thompson et al., 2020), the Himalayas need strong flood defense mechanisms together with the use of green infrastructures to adapt to the changes.

With the advancement of internet technologies, the Himalayan waterways management authorities should consider incorporating smart technologies (Figure 4). For instance, smart irrigation technologies should include feedback and demand-driven algorithms together with weather and soil condition forecasts, ensuring increased water security and crop productivity (Ilyas et al., 2022). Such technologies should be accompanied by appropriate information systems to generate data and to develop water accounting and demand control frameworks that maximize user applicability and

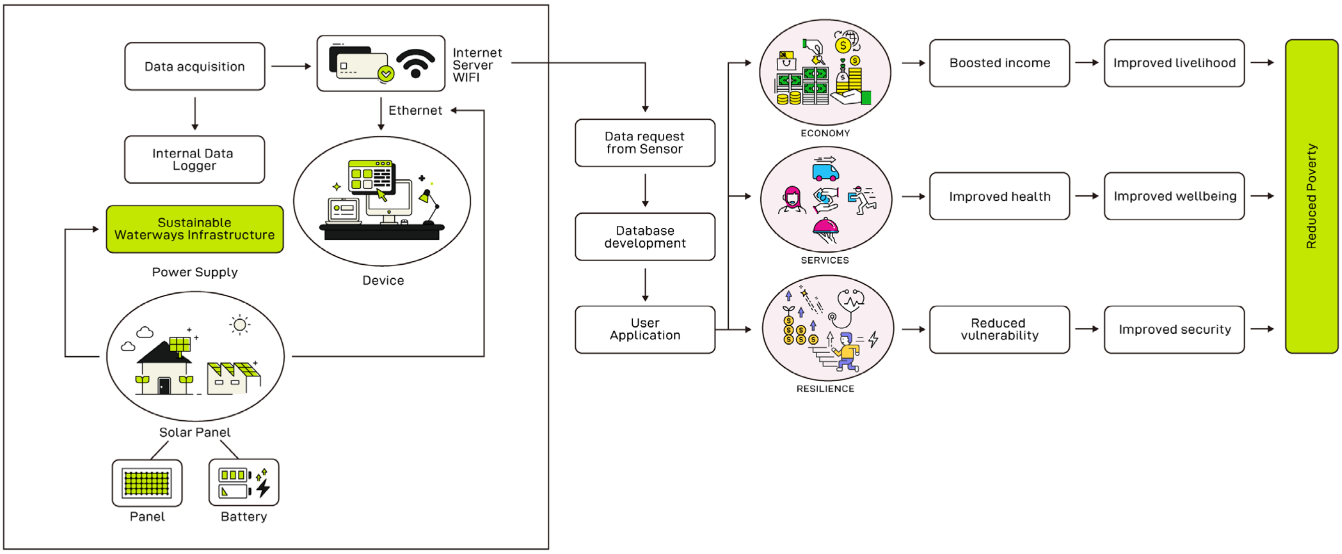

FIGURE 4 Conceptual framework for smart waterway infrastructure in the Himalayas. Internal data logger and data acquisition in the computer are made by setting up the internet server in the field with the help of green energy (solar power) technology. Various environmental data, including flow variability, temperature and precipitation are requested directly from the sensor. The database has greater user applications to improved economy, goods and services, and waterway resilience.

subsequently reduce poverty through improved ecosystem service generation (Figure 4). Many emerging urban centers in the Himalayas are faced with inefficient drinking water supplies. Water quality indices in the Indus river delta, for instance, do not meet the World Health Organization (WHO) guidelines for potable water (Solangi et al., 2019). When improved water quality delivery is increasingly urgent in many Himalayan cities, smart water systems utilizing advanced technologies, together with the provision of adaptive and integrated water management that can detect blockages, leaks, or contaminants can significantly reduce water stress. Such technologies are also software-enabled for water redirecting and real-time meter reading to better understand the use and demand (Oberascher et al., 2022). Additionally, smart technologies in the city provide real-time water quantity and quality monitoring and adaptive control of water storages and flows, which eventually improve resilience by enhancing recovery and preventing disruptions (Marchese et al., 2020). This type of smart water system information is fundamental for better policies and operations for improved sustainability and efficiency of water delivery in the region.

4.5 | Integrating the social, ecological, and hydrological systems

Human-nature system processes and dynamics are complex and uncertain (Horan et al., 2011). The complexity, variation, and uncertainty of the human-nature system are due to inherent properties of interconnected social and natural processes, so that natural resource management strategies are regarded as a pursuit of sustainability of such complex systems (Fischer et al., 2015; Grant et al., 2012; Konar et al., 2016; Nicholls et al., 2016). Theoretical and empirical models are developed for better understanding the complexity of human-natural system dynamics. For example, Holling and others described perpetual cycles of the complex human-natural system with phases of accumulation, destruction, release, and renewal by describing the linkages of empirical knowledge or the theory of "panarchy" (Gunderson et al., 2017; Holling, 1973; Walker et al., 2020). The framework has generated how knowledge should be produced and used to achieve specified desirable (natural resource management) outcomes so that waterway resilience is maximized (Medema et al., 2008).

The Himalayan waterways system is one of the best examples of complex human-natural systems on the planet. Water resource management in the region requires a sophisticated framework and narrative on feedbacks, thresholds, and critical transitions of social, hydrological, and ecological indices simulated with projected climate change. A catchment-wide simulation of socio-economic and biophysical processes using multi-sensor and multi-temporal satellite data, together with field data verification, have substantially increased the knowledge-base and maximized waterways resilience (Badar et al., 2013). However, as yet, no cross-scale interactions and feedbacks between natural and human processes have been addressed comprehensively while developing the frameworks for socio-ecological and socio-hydrological systems, impeding sustainable waterways management in the region. The integration of social-ecological and hydrological systems promotes the coordinated development of waterways and maximizes economic and social welfares in an equitable manner without compromising the sustainability of vital ecosystems (Benson et al., 2019). Optimization of the social-ecological-hydrological system approach (Figure 5) would be potentially significant for Himalayan waterway resilience to help meet the SDGs by 2030, since this approach comprehensively uses information needed to evaluate thresholds and feedbacks under water stress, including under climate change.

4.6 | Developing improved and effective water governance frameworks

Water governance is critical to water security, and to the long-term sustainability of waterways (Bakker & Morinville, 2013). Water crises are often regarded as crises of governance (Pahl-Wostl, Palmer, & Richards, 2013; Pahl-Wostl, Vörösmarty, et al., 2013). Crises arise as a result of various factors, including the issues of water ownership and accessibility and transboundary use of water resources across river and lake basins (Gupta et al., 2013). Water security is a desirable goal for the Himalayas, to ensure sufficient quantity and quality of water for life-supporting processes, as well as socio-economic development in the region. Effective water governance can address the complexity of water security issues in the region through integrated and interdisciplinary approaches. Many waterways around the world have adopted the Integrated River Basin Management (IRBM) approach as a means to achieve water security goals (Julio et al., 2022). Adaptive governance processes within such an approach emphasize collaborative and coordinated actions by recognizing waterways within river basins as complex systems. Resilient waterways in the Himalayas require effective interdisciplinary coordination for understanding the complex interactions between physical, socio-economic, cultural, and historical factors. Local communities should be part of the efforts, and the governance framework that is developed should be simple and practical to water management, including storage, supply and consumption elements (Quincey et al., 2018).

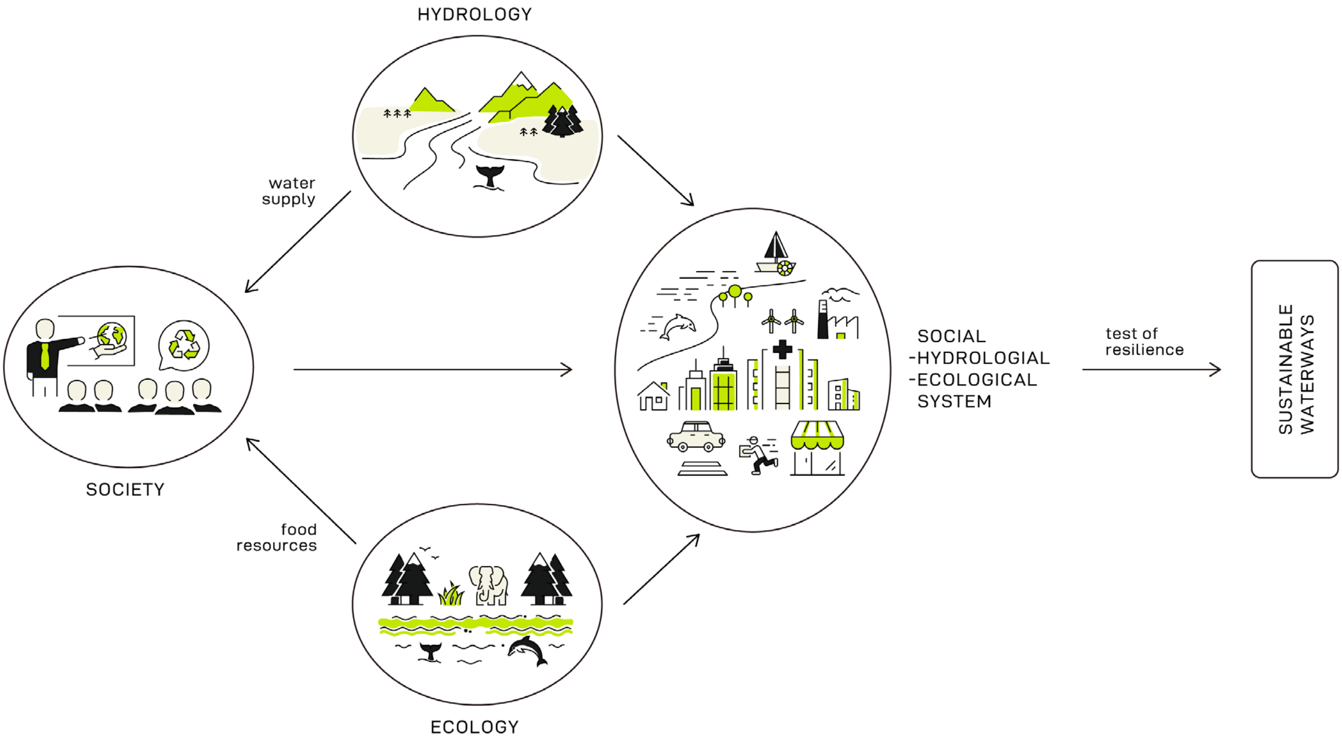

FIGURE 5 Conceptual framework on social-ecological-hydrological system of waterways in the Himalayas. One-sided arrow shows hydrology and ecology generate provision to water and food to society. Test of social-hydrological-ecological system resilience is significant for sustainable waterways in the Himalayas.

Social dimensions are critical in water governance, as they adopt adaptive water management approaches to tackle water insecurity during periods of abrupt change and investigate social-ecological system renewal and reorganization. In most social-ecological and social-hydrological systems, individuals, organizations, agencies, and institutions at multiple organizational levels are all well interconnected. Such systems are also tied with strong leadership, trust, and vision. Over the past few decades, the transboundary water resource use in the Himalayas among different social groups has posed complex and often contentious management challenges. The threats of climate change have further heightened the societal conflicts as downstream outflows have greatly reduced as a direct result of increased water extractions upstream, as well as increased flooding aggravating people's lives due to inundation. Improved governance with equitable shares of resources among transboundary consumers, are significant to maintain healthy rivers and societal harmony and resilience (Grafton et al., 2012).

Hence, an adaptive governance approach is a unifying framework that provides better policies and aims to promote conservation of transboundary water resources (Akamani & Wilson, 2011). Adaptive governance systems are self-organized and have the capacity to be governed successfully. The social networks bring various knowledge systems and experiences for the development of common understandings and policies useful for governance (Groffman et al., 2006; Gunderson & Light, 2006). The adaptive governance approach acts as “resilience-based management” by addressing nonlinear responses of water resources to change and by enhancing system robustness (Srinivasan et al., 2017). Interactive social learning generates knowledge, shared understanding, and trust that usually leads to a collective action for management. Learning can, under different iterative feedback loops (single-to-multiple), transform the underlying values of knowledge and help enhance the adaptive capacity of the system. In turn, the outcomes would be fundamental for drawing new policies and decision-making procedures (Lebel et al., 2010). Formation of so-called ‘bridged individuals-and-institutions’ through learning would be useful for transboundary river basins in the Himalayas as this can reduce the collaboration costs and resolve conflict and enable water related legislations (Folke et al., 2004). Hence, adaptive capacity is considered as a property of resilient and transformative waterways systems across transboundary communities (Gunderson, 2000).

While there is limited scientific knowledge on waterways in the Himalayas hindering water governance in transboundary communities, scientific knowledge aligned with water governance generates better outcomes. Scientists, national governments, and international agencies working for conservation all seek for better governance which can mitigate the climatic and human impacts on the environment (Kenward et al., 2011). For example, the use of indices to understand complex ecosystems in waterways has appealed to policy makers and water resource managers in assisting the development of effective water governance frameworks at the local level (Kattel, 2020; Vidal-Abarca et al., 2016). In the absence of essential policy interventions backed up by scientific knowledge, there is a failure in waterways management, which can have cascading impacts on wealth, jobs, and culture. Under climatic severity, water governance in the Himalayas needs to be advanced through collaboration with local, regional, and international agencies, including the United Nations, to maximize learning and to shape projected water futures in the region (Dellapenna et al., 2013).

5 | CONCLUSIONS

In our study, we found that Himalayan waterways face multiple sustainability challenges during the 21st century. Unprecedented increases in temperature and droughts have enhanced the rates of glacial-snow melt and permafrost thaw causing mass imbalance, and seasonal variability of flows has resulted in significant changes in the socio-ecological integrity in downstream river basins. Population growth and urbanization have intensified the use of water resources for hydropower generation, agriculture, and industries to meet cities' increasing demands of water, food, and energy, consequently altering natural flow regimes further as well as chemical perturbations. As a result, cities, and transboundary communities in the region have become increasingly vulnerable as they are facing extreme water insecurity due to reduction in the water quantity and quality. Hence, we conclude that resilient waterways are a fundamental requirement for the Himalayas to combat challenges posed by climate change and human disturbances on water resources and ecosystem services during the 21st century.

We also find that the application of resilience concepts is essential for sustainable development in Himalayan waterways. We have identified some key take home messages on waterway resilience which will be useful in framing regional water policies. These include: (i) the linkages among biodiversity, ecosystem functioning, and ecosystem services should be considered intact, and essential for protecting keystone species and improved food security in the Himalayan waterways; (ii) early warning systems are crucial to avoid threshold crossing, and undesirable ecological regime shifts in waterways; (iii) application of geoinformatics, remote sensing and artificial intelligence systems are critical for the prediction of future change; and (iv) smart water technologies are increasingly urgent for efficient and equitable water allocation to society and nature. To achieve these goals, an integration of social–ecological-hydrological systems is indispensable, especially toward achieving sustainability together with economic and social welfare. However, our focus paper highlights that the management of the Himalayan waterways needs a comprehensive and integrated knowledge-based platform, which is currently lacking. Relevant information including indigenous, cultural, and scientific knowledge, values and people's experiences, and extended participations, debates and learnings that improves waterways governance, are all urgently needed.

AUTHOR CONTRIBUTIONS

Giri R. Kattel: Conceptualization (lead); data curation (lead); formal analysis (lead); funding acquisition (lead); investigation (lead); methodology (lead); project administration (lead); resources (lead); supervision (lead); validation (equal); visualization (equal); writing – original draft (lead); writing – review and editing (equal). **Amelia Paszkowski:** Conceptualization (supporting); formal analysis (supporting); investigation (supporting); methodology (supporting); resources (supporting); supervision (supporting); validation (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Yadu Pokhrel:** Conceptualization (supporting); formal analysis (supporting); investigation (supporting); methodology (supporting); resources (supporting); supervision (supporting); validation (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Wenyan Wu:** Conceptualization (supporting); formal analysis (supporting); investigation (supporting); methodology (supporting); resources (supporting); supervision (supporting); validation (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Dongfeng Li:** Conceptualization (supporting); formal analysis (supporting); investigation (supporting); methodology (supporting); resources (supporting); supervision (supporting); validation (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting). **Mukund P. Rao:** Conceptualization (supporting); formal analysis (supporting); investigation (supporting); methodology (supporting); resources (supporting); supervision (supporting); validation (supporting); visualization (supporting); writing – original draft (supporting); writing – review and editing (supporting).

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CONFLICT OF INTEREST STATEMENT

The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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