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Socio-hydrological frameworks for adaptive governance: addressing climate uncertainty in South Asia

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In an era of growing climate change impacts, there is an increasing need to grasp the complex connection between human society and hydrological systems. Socio-hydrology, an interdisciplinary area between hydrology, sociology, and economics, provides essential insights to uncover how people's conduct impacts water and climate systems and resources. In this context, this paper looks at modern socio-hydrology advances and what they suggest for creating resistance or insensitivity to climate evolution. By synthesizing numerous theoretical backgrounds, empirical works, and case analyses within the concept of socio-hydrology, this paper tries to show that the socio-hydrological approach can provide insights for decision-making and policy intervention for building resilience at different levels. In the complex landscape of South Asia, where water resources are intricately linked across borders, socio-hydrology emerges as a crucial framework for fostering collaboration and resilience. By recognizing the socio-economic and political dynamics that influence water management, transboundary water issues can be approached holistically. Socio-hydrological principles explain how human behavior, cultural norms, and governance structures intersect with hydrological processes. This understanding enables the development of inclusive policies, equitable agreements, and cooperative strategies for sustainable water use and conflict resolution. In particular, the analysis supports the prospect of integrating socio-hydrological factors by recognizing the social components of water management, including human perception, cognition, behavior, and institutions. This paper examines modern socio-hydrology advances and what they suggest for creating resistance or insensitivity to climate evolution. It also explores potential theoretical frameworks and models like integrated assessment models (IAMs), system dynamic models, agent-based models (ABMs), and scenario planning models in socio-hydrology for planning and risk assessment to help facilitate adaptive governance. We find that socio-hydrology could provide an essential framework for enhancing climate resilience and sustainable water governance in South Asia. Adaptive governance approaches, collaboration amongst key stakeholders, and inclusive strategies are necessary to navigate tricky transboundary water disputes, socio-economic disparities, and the vulnerability of marginalized communities, all problems emblematic of the region. Further research in this field is necessary to harness socio-hydrology's potential in addressing the interconnected challenges climate change poses.

KEYWORDS

socio-hydrology, adaptive governance, climate change, water management, climate resilience, transboundary water management, South Asia

1 Introduction

Hydrology will be significantly impacted by climate change's rising and compounding effects. Climate change will affect water security, scarcity, and hydrological systems such as the water cycle and ecosystem. Human-induced climate change has intensified the global hydrological cycle, leading to substantial changes in precipitation patterns, snow and ice melting, evapotranspiration, and river flows (Caretta et al., 2022). Climate change is unequal, unpredictable, and unprecedentedly affecting the earth. For instance, the intensity of heavy precipitation has increased in many regions since the 1950s, resulting in more frequent and severe floods. However, there is also a trend of longer dry spells in the same period, contributing to droughts that negatively impact agriculture, water supply, and ecosystem health (Caretta et al., 2022). As water systems are intricately linked to human societies through cultural, economic, and institutional factors, understanding these dynamics requires a comprehensive approach.

The state of the climate and the need for adaptability necessitates a different approach to traditional hydrology. The human impact on climate change and its not-so-subtle interplay with hydrological systems need to be looked at more carefully through a nuanced approach. Considering the dynamic nature and interactivity it faces with various other fields, looking at individual aspects of a complex adaptive system like hydrology will not serve as well. It is becoming more and more necessary to understand the intricate relationships between human society and hydrology. In their seminal paper, Sivapalan, Savenije, and Bloschl describe socio-hydrology as a "new interdisciplinary but quantitative science of people and water, with the ambition to make predictions of water-cycle dynamics, and thus underpin sustainable water management" (Sivapalan et al., 2012). The field aims to bridge hydrological aspects, like physical aspects of the water cycle, with the social sciences that look into human behavior, governance, and policy. This allows us to understand how human actions affect hydrological processes and vice versa. The feedback loop and two-way feedback between humans and water systems is a core idea within socio-hydrology (Pande and Sivapalan, 2017; Sivapalan et al., 2012). By examining this interaction over time and across different scales, socio-hydrology provides a valuable understanding of the resilience and adaptability of coupled human-water systems (Montanari et al., 2013). Socio-hydrology employs diverse methods, from quantitative modeling to qualitative social science techniques, to gain a holistic understanding of water-related issues' complexities and find solutions. This perspective is crucial for ensuring sustainable water management strategies that are equitable, adaptable, and resilient, given climate change's disproportionate impact on vulnerable communities (Caretta et al., 2022). With this context, this paper examines modern socio-hydrology advances and their implications for creating resistance or insensitivity to climate evolution. The term refers to enhancing adaptive capacity and resilience building in response to climate change (Watts, 2024). Drawing from numerous theoretical perspectives, empirical works, and case analyses within the field of socio-hydrology, we argue that this approach can provide valuable insights for decision-making and policy intervention for building resilience at different levels. Understanding the interactions between societal dynamics and hydrological systems is paramount to addressing the significant challenges posed by climate change. This paper underscores the necessity of confronting climate uncertainties and outlines specific research objectives that direct this exploration. First, the paper aims to investigate how human behaviors intricately affect water systems. Second, it seeks to assess the implications of advancing socio-hydrological practices for fostering resilience to the impacts of climate change. Finally, the paper evaluates the effectiveness of methodologies, including Integrated Assessment Models (IAMs) and Agent-Based Models (ABMs). By articulating these goals, we establish a clear framework that highlights the manuscript's contributions to improving climate resilience in South Asia.

South Asia's transboundary issues, inherent socio-economic disparities (Birendra et al., 2021; Adeyeye et al., 2020; Klare, 2020), political dynamics (Pahl-Wostl et al., 2020; Sikka et al., 2021), and the existence of marginalized and vulnerable communities makes the region especially hard to mediate, especially in the context of water. This makes it harder for pure sciences, non-interdisciplinary models or frameworks to portray the South Asian scenario accurately. Therefore, in a landscape as complex as South Asia, where water resources are intricately linked across borders, socio-hydrology emerges as a crucial framework for fostering collaboration and resilience. By recognizing the socio-economic and political dynamics that influence water management, transboundary water issues can be approached holistically. Socio-hydrological principles help us understand how human behavior, cultural norms, and governance structures intersect with hydrological processes, enabling the development of inclusive policies, fair agreements, and cooperative strategies for sustainable water use and conflict resolution. Considering the increasing uncertainty of climate conditions, the paper also explores potential theoretical frameworks and models in socio-hydrology for planning and risk assessment to help facilitate adaptive governance.

The concept of socio-hydrology and its application is nascent in South Asia (Kumar et al., 2020). Therefore, this review article primarily employs secondary literature to synthesize existing knowledge and insights on socio-hydrology in the South Asian region. The article identifies key themes, challenges, and adaptive strategies related to water resource management and community resilience by analyzing prior studies, reports, and policy documents. This method allows for a comprehensive understanding of the socio-hydrological interactions and their implications for local populations. Utilizing secondary literature not only situates the current research within a broader scholarly context but also facilitates the identification of gaps in knowledge and areas for future exploration, ultimately informing sustainable practices and policy recommendations for water management.

This study addresses a critical gap in the literature regarding applying socio-hydrological principles to South Asia's unique water management challenges. While foundational research has established key theoretical concepts in socio-hydrology, limited studies have focused on their practical application within the region's complex, cross-border water dynamics. This manuscript expands on existing work by integrating case studies and offering practical policy recommendations, emphasizing the

importance of methodologies such as Integrated Assessment Models (IAMs) and Agent-Based Models (ABMs). The chosen models—Integrated Assessment Models (IAMs), Agent-Based Models (ABMs), System Dynamics Models, and Scenario Planning Methods—were specifically selected due to their ability to capture the complex interactions between human behavior and hydrological processes. Each model offers unique strengths: IAMs integrate environmental, social, and economic factors for comprehensive scenario analysis; ABMs simulate individual agent interactions, providing insights into micro-level dynamics; System Dynamics Models effectively represent dynamic feedback; and Scenario Planning Methods facilitate the exploration of potential future scenarios under uncertainty. This diverse modeling framework ensures a holistic understanding of socio-hydrological systems and informs adaptive governance strategies.

This paper is divided into five sections. Following the introduction, Section 2 examines socio-hydrology as a co-evolution of human settlements and water systems. It highlights their dynamic interplay and the necessity of integrating social factors into hydrological science to address climate-related challenges and inform resilient, equitable water management strategies across diverse contexts. Section 3 focuses on the socio-hydrology framework that enhances cooperation and climate resilience in South Asia by integrating human and water systems, promoting inclusive governance and adaptive strategies that address complex water-related challenges and marginalized community needs. Section 4 provides the socio-hydrological framework. It looks at it from an interdisciplinary approach to understanding and managing the interactions between social systems and water processes, emphasizing adaptive governance strategies that address climate uncertainties through stakeholder collaboration, scenario modeling, and continuous learning in South Asia. Section 5 concludes the paper by emphasizing the fact that the concept of socio-hydrology provides an essential framework for enhancing climate resilience and sustainable water governance in South Asia. It is done by fostering adaptive, inclusive, and collaborative strategies that address the complex interdependencies between human activities and water systems in the face of climate change uncertainties.

2 Understanding socio-hydrology and its implications for South Asia

Socio-hydrology aims to understand the co-adaptation of human settlements and water (Sivapalan et al., 2012). When looking at the progression of hydrological systems, the distribution of human populations and anthropogenic constructs significantly influenced their development (Sivapalan et al., 2012, 2014). It immediately became apparent that a novel approach to hydrological science was necessary—one that incorporates the social aspects of the multifaceted issues that water creates. Therefore, socio-hydrology is looked at as a positivist scientific field driven by practical applications that involve analyzing real-world systems across gradients of climate change, socioeconomic status, ecological degradation, and human management (Sivapalan et al., 2014; Pande and Sivapalan, 2017). In Socio-hydrology, humans and water systems evolve in a co-evolutionary pattern, influencing and affecting each other. This idea stems from the understanding that water systems and human behavior influence each other through feedback loops, with water systems getting shaped by natural factors and also human decisions, and vice versa, leading to a co-evolutionary process (Di Baldassarre et al., 2019; Pande and Sivapalan, 2017; Sivapalan et al., 2012; Konar et al., 2018). It maintains a quantitative foundation while integrating broader social narratives into modeling these issues (Thaler, 2021; Madani and Shafiee-Jood, 2020; Sivapalan et al., 2012). Including quantitative tools like models and simulations allows for a more rigorous understanding of the socio-hydrological systems (Wagener et al., 2010). However, socio-hydrological models also incorporate social processes such as governance, cultural values, and societal norms to accurately capture the complexity of human-water interactions (Sivapalan and Blöschl, 2015). The first few models in this new field focused on a quantitative-hydrological research approach, with rudimentary and simplistic perspectives on social factors (Di Baldassarre et al., 2013a, 2013b, Chen et al., 2016; Fuchs et al., 2017; Haeffner et al., 2018; Pouladi et al., 2019; Kaiser et al., 2020, as cited in Thaler, 2021). However, this space has since seen much improvement after social scientists' input on the subject (Wesselink et al., 2017; Melsen et al., 2018; Xu et al., 2018; Ridolfi et al., 2020, as cited in Thaler, 2021).

Traditional water-management strategies have relied on scenario-based models that have assumed societal or environmental conditions. Socio-hydrology takes a step away from that line of thought, moving from static models to more dynamic conditions where social and hydrological factors co-evolve unpredictably, more indicative of climate change and political climate (Sivapalan et al., 2012; Elshafei et al., 2014). Another fundamental element of socio-hydrological systems is the recognition that interactions between society and water systems often exhibit non-linear behaviors, meaning small changes in one aspect of the system can lead to disproportionate effects in another. This non-linearity challenges prediction and control, as tipping points and thresholds can emerge unexpectedly (Sivapalan et al., 2012).

Socio-hydrology also stands out for integrating multiple disciplines, including hydrology, economics, sociology, and political science (Sivapalan et al., 2012; Pande and Sivapalan, 2017; Troy et al., 2015; Yu et al., 2022; Döring et al., 2024). This interdisciplinary approach is necessary for tackling real-world challenges like climate change, water scarcity, and sustainable development (Di Baldassarre et al., 2019). A defining feature of socio-hydrology is also that it treats human involvement as endogenous, or internal, to the system (Pande and Sivapalan, 2017; Liu et al., 2015). Rather than treating human activities as external factors, socio-hydrology recognizes that human actions, behaviors, and decisions are intrinsic to the system's dynamics. Socio-hydrology articulates the relationship between water and society through the lens of systems theory. It posits that human society and water constitute two distinct "systems" engaged in constant interaction, culminating in a "supra system" within the socio-hydrological domain. This supra system is characterized by the emergence of novel properties not inherent to either of the constituent systems (Schulz and Gros, 2024).

In their seminal paper, Sivapalan et al. (2012) saw three ways to advance the field of socio-hydrology. First, historical socio-hydrology uses the past to study and drive insights using a socio-hydrological lens. Second, comparative socio-hydrology contrasts and compares various human-water relationships, learning from the similarities and differences of different systems. Third, process socio-hydrology tries to understand current water systems to help foresee where future pathways could lead (Madani and Shafiee-Jood, 2020). As noted by several academics, there has also been significant debate around the legitimacy of socio-hydrology as a "new" science with similarities to Integrated Water Resources Management (IWRM), Coupled Human-Water Systems Studies (CHANS), socio-ecological systems (SES), hydro-sociology, eco-hydrology, and other fields, however, the larger scientific and academic community have largely accepted socio-hydrology as a novel approach to hydrology and the field is receiving significant support from researchers (Madani and Shafiee-Jood, 2020; Pande and Sivapalan, 2017; Ross and Chang, 2020; Schulz and Gros, 2024; Di Baldassarre et al., 2015).

2.1 Socio-hydrology advances and climate resilience

As humanity confronts the multifaceted challenges posed by climate change, the field of socio-hydrology has emerged as a critical lens through which we can enhance our understanding of the complex interactions between human societies and water systems, ultimately informing resilience-building efforts (Garimella and Prakash, 2023). Socio-hydrology, a relatively new scientific discipline, focuses on the dynamic and often bidirectional feedback between water and human systems (Sivapalan et al., 2014). By incorporating insights from various social science disciplines, socio-hydrology has expanded its scope to examine the intricate relationships between water, economics, culture, and governance, providing a holistic perspective on water sustainability (Konar et al., 2018).

One of the key contributions of socio-hydrology has been its ability to uncover the underlying structural features and cross-scale interactions that give rise to water-related challenges in the Anthropocene (Sivapalan et al., 2014). For instance, socio-hydrological studies have shed light on how human interventions, such as water infrastructure development or agricultural practices, can have unintended consequences on water availability and quality, often exacerbating vulnerabilities to climate-induced extremes (Nüsser, 2017). Furthermore, socio-hydrology has emphasized the importance of accounting for social heterogeneity, power dynamics, and cognitive biases in understanding how individuals and communities respond to and adapt to changing hydrological regimes (Di Baldassarre et al., 2019).

By integrating these socio-hydrological insights into decision-making and policy interventions, researchers and policymakers can work toward building more climate-resilient communities. For example, a socio-hydrological case study in South Asia has demonstrated how sustainable agricultural socio-ecological transformations, driven by community-led initiatives and supported by policy frameworks, can enhance resilience to climate-related shocks and stresses (Garimella and Prakash, 2023). The advancements in socio-hydrology have the potential to significantly contribute to our understanding of the complex relationships between water, society, and climate change, ultimately informing more effective and equitable strategies for building climate resilience.

3 Socio-hydrology in the South Asian context

3.1 Examining socio-hydrological principles for collaboration amongst South Asian countries

Socio-hydrology's emphasis on understanding the dynamic interactions between human and water systems can provide valuable insights for enhancing regional cooperation and building climate resilience in South Asia, a region highly vulnerable to the impacts of climate change. The South Asian region, home to the Himalayan Mountain range, is characterized by complex water-related challenges, including glacial melt, changing monsoon patterns, and competing demands for water resources across national borders (Leng et al., 2022). Socio-hydrological approaches can help elucidate how these biophysical processes intersect with social, economic, and political factors, informing collaborative efforts to address transboundary water management and climate adaptation.

The case of Nagaon district, Assam, directly exemplifies socio-hydrology by investigating the evolving relationship between local communities and their water environment. The shift in water source from surface water to groundwater reflects a socio-hydrological change driven by development and impacting water usage patterns and human interaction with water resources (Bhuyan and Deka, 2024). Traditional practices like dyke (aali) construction in paddy fields showcase the long-term adaptation of human activities to hydrological conditions, a core element of socio-hydrological studies (Bhuyan and Deka, 2024). The water scarcity challenges in Nashik, Maharashtra, highlight the vulnerability of human societies to hydrological constraints, a key concern in socio-hydrology. The need for participatory watershed development underscores a socio-hydrological approach that recognizes the importance of integrating social factors and local knowledge into water management strategies for sustainability (Srivastava and Chinnasamy, 2024).

Traditional water harvesting systems like tanks are prime examples of historical socio-hydrological systems, where communities developed and managed water resources through intricate social and ecological understanding (Jain et al., 2024). The decline of these systems due to changes in governance and policy demonstrates how societal shifts can disrupt long-standing human-water equilibria, a significant aspect studied in socio-hydrology (Jain et al., 2024). The emphasis on Participatory Rural Appraisal (PRA) and Water User's Associations (WUAs) in their rehabilitation reflects a socio-hydrological understanding of the need for community involvement in sustainable water resource

management and governance (Jain et al., 2024; Srivastava and Chinnasamy, 2024).

By incorporating diverse perspectives and power dynamics, socio-hydrology can shed light on the needs and priorities of marginalized communities, such as women and indigenous groups, whose voices are often overlooked in traditional water governance frameworks (Prakash et al., 2024). Integrating these insights can lead to more inclusive and equitable water management strategies that enhance the resilience of vulnerable populations to climate change impacts. Furthermore, socio-hydrological principles can guide the development of innovative, community-based interventions that leverage local knowledge and social capital to build adaptive capacity and foster a sense of shared responsibility for water resources (Penny and Goddard, 2018). Such approaches can help bridge the gap between top-down policy initiatives and bottom-up, contextually relevant solutions, ultimately strengthening regional cooperation, and climate resilience in South Asia (Bugler, 2023).

The advancements in socio-hydrology offer a critical pathway for enhancing climate resilience in the South Asian region by promoting a nuanced understanding of the coupled human-water system and informing inclusive, collaborative, and adaptive water management strategies. The growing socio-hydrological research has provided valuable insights for informing decision-making and policy interventions to foster climate resilience. One notable case study comes from an island community in the tropics, where researchers employed a socio-hydrological approach to enhance the resilience of the local water supply system in the face of climate-induced challenges (Nguyen et al., 2021). By examining the complex interactions between the island's social and hydrological systems, the researchers identified key leverage points for intervention, such as community-based water conservation initiatives and integrating traditional ecological knowledge into water management practices.

Similarly, in drought-prone Pacific Island Countries, socio-hydrological insights have informed the development of holistic strategies that combine traditional water usage behaviors with modern technologies and policy frameworks (MacDonald et al., 2020). These approaches have demonstrated the importance of accounting for social and cultural factors in building climate resilience, recognizing that purely technocratic solutions often fall short of addressing the unique challenges faced by remote and marginalized communities. Overall, these case studies illustrate the value of socio-hydrological approaches in moving beyond narrow, technocratic solutions and instead fostering more inclusive, collaborative, and context-specific strategies for enhancing water security and climate resilience (Sivapalan et al., 2014).

3.2 Socio-hydrology's contribution to broader resilience-building efforts

The advancements in socio-hydrology have important implications for building climate resilience beyond the water sector, offering a framework for understanding and addressing the complex, interconnected challenges of climate change. By emphasizing the dynamic feedback between human and natural systems, socio-hydrology underscores the need for holistic, systems-based approaches to climate adaptation and resilience-building (Di Baldassarre et al., 2019). This perspective aligns with growing calls for a shift away from technocratic, siloed solutions toward more integrated, multi-stakeholder approaches that account for the social, economic, and political dimensions of climate change impacts (Kehler and Birchall, 2021).

Moreover, the socio-hydrological emphasis on understanding and incorporating diverse perspectives, power dynamics, and local knowledge can inform the development of more equitable and inclusive resilience-building strategies (Bozorg-Haddad et al., 2021). This is crucial for ensuring that the needs and priorities of marginalized communities are not overlooked in the face of climate-related shocks and stresses. As the global community works to address the pressing challenges of the Anthropocene, the insights and approaches of socio-hydrology will continue to play a vital role in fostering climate resilience, catalyzing collaborative action, and promoting sustainable, equitable outcomes.

In sum, socio-hydrology advancements provide a promising pathway for enhancing climate resilience, particularly in the South Asian region and beyond. Socio-hydrological research can inform more inclusive, collaborative, and context-specific strategies for addressing water security and climate adaptation challenges by elucidating the complex, dynamic interplay between human and water systems. Through applying socio-hydrological principles, decision-makers and policymakers can better understand the social, economic, and political factors that shape water-related vulnerabilities and resilience. This knowledge can then be leveraged to develop innovative, community-based interventions that leverage local knowledge and social capital, ultimately strengthening regional cooperation and climate resilience.

3.3 Integrating socio-hydrological factors

Water-related issues facing South Asian countries necessitate an interconnected perspective that offers a fundamental shift from the conventional water governance paradigms dominated by centralized experts (Nguyen et al., 2021). Especially pertinent to this challenge are the emerging approaches, such as socio-hydrology, which offer a bent to solving such problems by incorporating aspects of both human and water systems (Di Baldassarre et al., 2019; Sivapalan et al., 2014). Fischer et al. (2021), who contribute to this emerging field, point out that people's relationships with water can't be separated from the political economies, culture and politics of the people, and thus, water is a social resource as much as environmental. This approach appears most pertinent in the South Asian region; as much as water is naturally endowed, it is also embedded in historical, social, political, and institutional aspects (Nüsser, 2017).

The first is the understanding of the political economy and policy processes around waters in the region, which explains how governance, social norms and economic factors affect the politics of water, its access and use. Understanding these aspects can assist in crafting policies that incorporate multiple voices and promote equity, such as those of the excluded groups (Saklani et al., 2020; Pata et al., 2022). This is then set into the wider framework,

building on the understanding that informs cooperation between stakeholders and potential agreements. Socio-hydrology explores these factors in cooperation agreements (Wei et al., 2021).

Water in South Asia is a complex interplay of socioeconomic and political dynamics shaped by geographical, cultural, and historical contexts (Pandey et al., 2020). The region, home to over a billion people, faces significant water challenges, including scarcity, pollution, and transboundary disputes, influenced by various factors (Shrestha et al., 2021). Kumar et al. (2020) highlight the socio-hydrology approach to manage water scarcity and enhance human wellbeing in South Asian riverine islands like Fraserganj (India) and Dakshin Bedkashi (Bangladesh) in the Ganga-Brahmaputra-Meghna delta and Con Dao Island in Mekong River, Vietnam. Rapid global changes impact local water systems, emphasizing the need for socio-hydrological research to improve adaptive capacities and resilience. Using the socio-hydrological framework, the study recommends a structured management cycle by integrating scientific and citizen perspectives: scoping, analysis with stakeholder input, solution implementation, and evaluation. This method involves stakeholders in sustainable water management, addressing local cultural and political contexts. It aids in achieving sustainable development goals related to climate action, water, health, and ecosystem preservation.

3.4 Socio-economic dynamics

The socio-economic dynamics are examined from four lenses- population pressure, dependency on agriculture, economic disparities, and unplanned urbanization. South's high population density and rapid growth increase the demand for water in domestic, agricultural, and industrial sectors, straining existing resources (Birendra et al., 2021). With a significant portion of the economy reliant on rain-fed agriculture, climate variability leads to erratic monsoon patterns, causing droughts and floods that threaten livelihoods and food security. Economic disparities further complicate water management as wealthier regions benefit from better infrastructure (Shi et al., 2021), leaving poorer areas and marginalized communities, including women and rural populations (Adeyeye et al., 2020), facing severe water scarcity and increased social tensions (Klare, 2020). Additionally, rapid urbanization in major cities like Mumbai, Dhaka, and Kolkata exacerbates water demand, but inadequate urban infrastructure and planning result in insufficient supply and pollution from untreated waste (Kookana et al., 2020). Overall, these interlinked factors create significant challenges for sustainable water management in the region.

First, south Asia has one of the highest population densities in the world. Rapid population growth increases the demand for water for domestic, agricultural, and industrial use, putting significant pressure on existing water resources (Rahman et al., 2020). The growing middle class demands better services, exacerbating competition for clean water supplies (Sathre et al., 2022). Second, a large portion of South Asia's economy relies on agriculture, which is predominantly rain-fed and vulnerable to climate variability (Behera et al., 2024; Shrestha et al., 2021). Farmers depend heavily on seasonal monsoons, and erratic rainfall patterns due to climate change led to droughts or floods, severely impacting livelihoods and food security. Traditional irrigation and water storage methods often result in inefficient water usage (Habib-ur-Rahman et al., 2022).

Third, the economic inequality within and between countries complicates water management. Wealthier regions often have better water supply and sanitation infrastructure, leaving poorer areas to struggle with inadequate access (Kumar et al., 2021). Marginalized communities, including women and rural populations, often bear the brunt of water scarcity, leading to social tensions and exacerbating disparities (David and Hughes, 2024). Fourth, the rapid urban growth in cities such as Mumbai, Dhaka, and Kolkata intensifies the demand for water in urban centers (Zhang et al., 2020). However, rapidly expanding urban infrastructure often needs to catch up, resulting in inadequate water supply and increased pollution from untreated waste. The need for coordinated urban planning and water management policies further complicates the issue.

3.5 Political dynamics

South faces significant political dynamics in water management, primarily characterized by transboundary water conflicts among countries like India, Pakistan, Bangladesh, and Nepal, which share major rivers (Parven and Hasan, 2018; Ranjan, 2020). Historical treaties like the Indus Water Treaty often lead to disputes, especially during droughts or shifting river flows due to climate change (Abas et al., 2019; Ali and Bhargava, 2021). Fragmented policies, bureaucratic inefficiencies, and corruption hinder effective water management. A lack of political will to prioritize sustainable practices further complicates the issue. Engaging communities and including marginalized groups in decision-making are crucial for equitable policies (Molle and Closas, 2020). Additionally, climate change necessitates adaptive strategies and political commitment to resilience, highlighting the need for integrated approaches and regional cooperation to ensure regional water security (Mishra et al., 2021).

Four factors influence the political dynamics. First are the transboundary water conflicts. Numerous transboundary river systems characterize South Asia. Countries like India, Pakistan, Bangladesh, and Nepal share major rivers such as the Indus and the Ganges (Ranjan, 2020). Historical treaties, such as the Indus Water Treaty, provide frameworks for cooperation but often lead to disputes over water allocation, especially during periods of drought or changes in river flow due to climate change (Williams, 2024). The second issue pertains to policy and governance. Effective water management requires strong governance and legal frameworks (Raut et al., 2022). However, fragmented approaches and a lack of cohesive policies hinder sustainable water management. Bureaucratic inefficiencies, corruption, and inadequate enforcement of existing laws result in mismanagement and abuse of water resources (Pahl-Wostl et al., 2020).

The third factor focuses on political will and stakeholder engagement. Water management often lacks the political will to prioritize sustainable practices over short-term gains (Sikka et al., 2021). Engaging communities and stakeholders in decision-making is crucial for developing equitable water policies. Including

marginalized groups, particularly women, ensures that diverse perspectives are considered, leading to more effective management strategies. Finally, climate change poses a significant threat to water resources in South Asia, necessitating adaptive strategies (Rasul and Neupane, 2021). Political commitment to climate resilience is essential, as policies must integrate water management with disaster risk reduction, environmental sustainability, and energy policy (Cosgrove and Loucks, 2015; Hore et al., 2020).

The socio-economic and political dynamics influencing water management in South Asia are interconnected and multifaceted (Mollinga, 2020). Effective solutions require integrated approaches that consider the region's unique challenges, emphasizing collaborative governance, equitable access, and sustainable practices to ensure water security for future generations (Pande et al., 2020). Addressing these issues through regional cooperation, innovative technologies, and community engagement will be vital to overcoming the profound water challenges faced by South Asia.

4 Socio-hydrological frameworks for adaptive governance

Socio-hydrology is an interdisciplinary approach that examines the interactions between social systems and hydrological processes (Gain et al., 2021). It aims to understand how societal decisions affect water resource management and how water availability influences social structures and behaviors. In the context of climate change and increasing uncertainties associated with water availability, socio-hydrological frameworks are crucial for developing adaptive governance strategies (Almazan Casali, 2022). This paper discusses the theoretical frameworks and models in socio-hydrology for scenario arrangement and risk evaluation, emphasizes the role of adaptive governance in responding to climate uncertainties, and provides recommendations for integrating socio-hydrological approaches into governance strategies in South Asia.

4.1 Theoretical frameworks and models in socio-hydrology

Socio-hydrological models serve as tools for understanding the complex feedback loops between human actions and hydrological outcomes. These models can simulate scenarios involving water distribution, consumption, and policy changes, aiding in risk evaluation and decision-making processes. In this section, we discuss four models (see Figure 1).

Traditional scenario-based models often rely on static assumptions about societal and environmental conditions, typically using predefined scenarios to predict outcomes under certain, relatively fixed conditions. These models generally focus on projecting future water availability or demands based on historical data, with limited integration of human behavioral factors or socio-political dynamics. In contrast, socio-hydrological models go beyond these traditional approaches by explicitly incorporating the feedback loops between human activities and water systems. These models simulate more dynamic scenarios where human actions, such as policy changes, infrastructure development, and socio-economic behaviors, influence hydrological outcomes and vice versa. This iterative process allows for a more comprehensive understanding of how water systems evolve in response to natural and human-driven changes, making them particularly valuable in adaptive governance frameworks that account for uncertainty and the changing nature of both environmental and societal conditions.

Firstly, the Integrated Assessment Models (IAMs) combine environmental, economic, and social factors to assess the impacts of different policy options on water resources (Bell et al., 2014). These models facilitate scenario analysis by integrating hydrological data with socio-economic variables, allowing for a comprehensive understanding of potential outcomes (Rising, 2020). Second, the system dynamics models capture the dynamic interactions between water systems and human behaviors (Mirchi et al., 2012). Using simulations, decision-makers can visualize the impact of regulation changes, consumption patterns, and climate conditions on water resources and social systems (Elsawah et al., 2017; Mashaly and Fernald, 2020). The third is the Agent-Based Models (ABMs) that simulate the behavior of individual actors within a system, considering their interactions, decision-making processes, and adaptive strategies (Magliocca, 2020). This approach is particularly effective in understanding the micro-level implications of governance decisions on water management and resource distribution (Khorshidi et al., 2024). Finally, the scenario planning methods involve developing plausible future scenarios based on current trends and uncertainties (Fu et al., 2022). By systematically evaluating how different scenarios can unfold, stakeholders can identify potential risks and devise strategies to mitigate adverse outcomes. Effective scenario planning fosters stakeholder dialogue and enhances collective understanding, which is critical in adaptive governance (Shirmohammadi et al., 2020). Figure 1 illustrates different approaches to water resource management, showing how various models help tackle complex challenges. Scenario Planning Methods focus on trends and uncertainties to guide strategy, while Integrated Assessment Models (IAMs) bring together hydrological and socio-economic data for a broader perspective. System Dynamics Models examine how regulations, consumption patterns, and climate shifts impact water systems over time. Meanwhile, Agent-Based Models (ABMs) dive into individual behaviors and decision-making within the system. Together, these models provide a well-rounded approach to managing water resources in an adaptive and informed way.

4.2 The role of adaptive governance in addressing climate uncertainty

Adaptive governance refers to a flexible, responsive approach to managing natural resources that acknowledges environmental systems' inherent uncertainties and complexities (Van Assche et al., 2022). Adaptive governance becomes essential for effective water management in the face of climate change, which brings unpredictable shifts in hydrological patterns (Partelow et al., 2020). Adaptive governance emphasizes the need for flexible policies that can be adjusted based on emerging information and changing environmental conditions. This flexibility allows for

FIGURE 1
Socio-hydrological models for water resources management. Source: Authors.

timely responses to extreme weather events, droughts, and floods, enhancing resilience (Cosens et al., 2021).

Engaging stakeholders, including local communities, policymakers, and scientists, is pivotal in adaptive governance. This inclusivity fosters collaborative problem-solving and leverages diverse knowledge systems, enabling context-specific solutions to water management challenges. Adaptive governance incorporates mechanisms for continuous learning through monitoring hydrological changes and evaluating the effectiveness of governance strategies (Cosens and Chaffin, 2016). This iterative process ensures that governance frameworks remain relevant and effective over time. Traditional ecological knowledge is invaluable in understanding local hydrological systems. Integrating this knowledge with scientific data enhances adaptive governance by providing context-rich perspectives on water management, cultural practices, and historical experiences with climate variability (Mehltretter et al., 2024).

Community-based water management projects in India are a prominent example of adaptive governance that effectively addresses climate uncertainty. These initiatives often engage local communities in decision-making processes, enabling them to identify water resource challenges and collaboratively develop solutions tailored to their contexts. For instance, the "Participatory Irrigation Management" program in Maharashtra empowers farmers by involving them in the planning and maintaining irrigation systems. This approach improves water management efficiency and builds local resilience to climate variability by fostering a sense of ownership and collective responsibility (Roy and Singh, 2024).

Stakeholder engagement is vital for the success of adaptive governance in socio-hydrological contexts, yet it faces several challenges. Common obstacles include power imbalances among stakeholders, differing interests, and a lack of trust, which can hinder collaboration (Ali and Haapasalo, 2023). Strategies such as fostering transparent communication, creating inclusive dialogue platforms, and implementing capacity-building initiatives are essential to address these issues. Empowering marginalized voices and promoting stakeholder participation can enhance

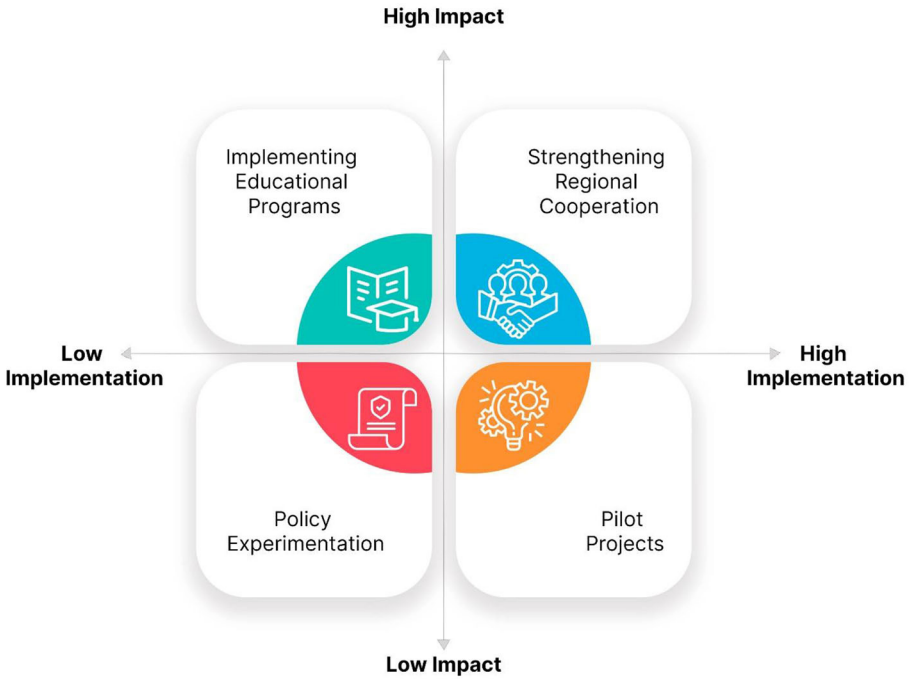

FIGURE 2
Strategies for socio-hydrological governance in South Asia. Source: Authors.

trust and cooperation (Ahmad and Islam, 2024). By proactively addressing these challenges, governance frameworks can improve their effectiveness, ensuring that diverse perspectives are integrated into decision-making processes, leading to more resilient and equitable water management outcomes.

4.3 Incorporating socio-hydrological approaches into adaptive governance strategies in South Asia

Several recommendations can be proposed to utilize socio-hydrological frameworks for adaptive governance in South Asia effectively. First, interdisciplinary collaboratives should be established to unite hydrologists, social scientists, policymakers, and local community representatives. These collaborative efforts will promote shared understanding and foster integrated approaches to water management (Rangecroft et al., 2021). The second is to enhance data and technology access to hydrological data and technological tools that facilitate scenario modeling and risk evaluation. This infrastructure should include local monitoring systems that provide real-time information on water availability and usage patterns (Bakhtiari et al., 2024).

The third factor is to implement educational programs that enhance the capacity of policymakers and community leaders in socio-hydrology and adaptive governance principles. Training workshops can empower stakeholders to engage meaningfully in collaborative decision-making processes (Thaler, 2021). In doing so, implementing pilot projects could become handy in applying socio-hydrological frameworks to real-world governance challenges. These projects will serve as case studies for evaluating the effectiveness of adaptive governance strategies and will help identify best practices for broader implementation (Almazan Casali, 2022). Further, focus on policy experimentation by adopting an experimental approach to policy formulation, allowing for the trial and error of governance strategies. Such flexibility can stimulate innovation, enabling policymakers to learn from successful and unsuccessful interventions. Finally, the call is to strengthen regional cooperation among South Asian countries by sharing knowledge, technology, and resources (Bhujabal and Sethi, 2020). Collaborative frameworks can address transboundary water management issues and improve collective resilience to climate uncertainties. A succinct visual representation is available in Figure 2. To strengthen regional cooperation among South Asian nations in addressing transboundary water issues and bolster collective resilience, fostering knowledge sharing, technology transfer, and resource collaboration is imperative. This can be achieved through a flexible policy formulation approach emphasizing experimentation and learning from interventions. Additionally, implementing educational programmes to strengthen the capacity of policymakers and community leaders in socio-hydrology and adaptive governance principles is crucial. Pilot projects should also be executed to apply socio-hydrological frameworks to real-world governance challenges and to identify best practices.

Implementing these models in real-world governance systems can be challenging due to data limitations, variable stakeholder engagement, and diverse socio-political contexts. Each model may perform differently; for instance, ABMs excel in capturing local dynamics, while IAMs may struggle with context-specific nuances, leading to varying effectiveness across regions. Table 1 provides a brief overview of the strengths and weaknesses of socio-hydrological models discussed here.

TABLE 1 Strengths and weaknesses of socio-hydrological models.

Model	Strengths	Weaknesses
Integrated assessment models (IAMs)	- Provides a holistic view by integrating environmental, social, and economic factors (Bell et al., 2014; Rising, 2020). - Facilitates scenario analysis for informed policymaking (Rising, 2020).	- IAMs rely heavily on arbitrary inputs, particularly functional forms and parameter values (Pindyck, 2013). - IAMs tend to underestimate the risks and potential damages associated with climate change significantly (Stern, 2013; Pindyck, 2017).
System dynamics models	- Captures dynamic interactions between water systems and human behavior (Mirchi et al., 2012). - Enables long-term impact analysis of regulatory and environmental changes (Elsawah et al., 2017).	- Ambiguous in representing complexities of systems (Elsawah et al., 2017). - Limited applicability where spatial dynamics are crucial (Elsawah et al., 2017).
Agent-based models (ABMs)	- Simulates individual behaviors and adaptive strategies, making it effective for micro-level analysis (Magliocca, 2020). - Helps assess bottom-up governance approaches (Khorshidi et al., 2024).	- Requires detailed behavioral data, which can be difficult to obtain (Magliocca, 2020). - Oversimplification and/or prescription of agent behaviors (Magliocca, 2020).
Scenario planning methods	- Helps stakeholders anticipate risks and uncertainties in water management (Fu et al., 2022). - Encourages collaborative decision-making and governance adaptability (Shirmohammadi et al., 2020).	- Scenarios are based on assumptions, which may not fully reflect reality (Fu et al., 2022). - Inaccuracies or limitations of predictive models deeply impact scenarios (Fu et al., 2022).

Source: Authors.

Several specific recommendations can be implemented to enhance adaptive governance in socio-hydrology. First, establish interdisciplinary collaboratives by creating working groups that unite hydrologists, social scientists, policymakers, and community representatives. This will be achieved through regular workshops and meetings to foster collaboration and facilitate cross-disciplinary knowledge sharing. Second, data access can be enhanced by developing a centralized database of hydrological and socio-economic data relevant to the region. Partnering with local universities, government agencies, and NGOs is essential to compile and maintain this valuable data resource.

Third, educational programs should be implemented by designing training workshops for policymakers and community leaders focused on socio-hydrology and adaptive governance principles. Collaborating with educational institutions will be crucial to facilitate these training sessions and ensure ongoing support. Fourth, pilot projects should be launched to apply socio-hydrological frameworks in specific communities or water systems. The lessons learned from these initiatives can be utilized to inform broader policy recommendations and enhance adaptive governance strategies.

Fifth, encourage policy experimentation by fostering a culture of experimentation in policy formulation that allows for trial-and-error learning. Establishing frameworks to evaluate the outcomes of different governance strategies will facilitate sharing best practices across regions. Lastly, regional cooperation can be strengthened by developing frameworks for collaboration among South Asian countries that focus on transboundary water issues. Organizing regional forums will facilitate dialogue, knowledge sharing, and joint initiatives among participating countries, enhancing collective efforts in managing water resources effectively.

5 Conclusion: building climate resilience and sustainable water governance in South Asia

As climate change impacts grow, understanding the link between people and water in an integrated manner becomes of utmost importance (Mishra et al., 2021). This paper has outlined the socio-hydrology concept and emphasized its significance in integrating people and water systems for better management and governance in South Asia's climate change context. Important outcomes have pointed out the necessity of appreciating the complex relationships between society and hydrology (Ross and Chang, 2020). When climate change is restructuring water security, the socio-hydrology framework seems to be a good starting point for understanding these relationships better (Madani and Shafiee-Jood, 2020), and it is possible to propose governance systems that can adapt to the changing realities.

One of the foremost insights from the study is the confirmation of the co-evolutionary nature of human and hydrological systems. Exploring socio-hydrological dynamics reveals that water availability and human activities influence one another through feedback loops, often leading to unpredictable consequences. This understanding is vital given the region's unique challenges, such as transboundary water disputes, socio-economic disparities, and the vulnerability of marginalized communities. The assessment of these factors highlights the necessity for adaptive governance approaches that are flexible, participatory, and inclusive. Engaging stakeholders, including local communities and underrepresented groups, is essential for crafting policies acknowledging diverse perspectives and fostering equitable access to water resources. By integrating local knowledge and experiences into decision-making, adaptive governance can better align with the realities faced by those most affected by climate variability.

Moreover, analyzing theoretical frameworks and models within socio-hydrology has demonstrated their potential for facilitating scenario planning and risk evaluation. Models such as Integrated Assessment Models and Agent-Based Models can provide valuable insights into how policy changes and human behaviors affect water systems. This predictive capacity is crucial for developing informed strategies that enhance resilience in the face of climatic extremes, such as floods and droughts. The shift from static to dynamic models deeply resonates with the need to adapt to uncertainties and non-linearities associated with climate impacts. While the socio-hydrological framework offers substantial promise, further research and action are necessary to harness its full potential

for climate resilience in South Asia. The complexities of water management require ongoing study into the social, economic, and political dynamics at play. Research should focus on long-term monitoring of socio-hydrological interactions, evaluating implementation strategies, and case studies documenting successful inclusive water governance initiatives. Developing and sharing localized models can also enhance understanding of community needs and vulnerabilities, ultimately guiding policy interventions.

Action is also required at multiple levels, from regional cooperation among South Asian countries to more localized, community-driven initiatives. Regional frameworks for water management should prioritize collaboration, knowledge-sharing, and technology transfer between nations. By addressing transboundary challenges collectively, countries can foster a more resilient region capable of adapting to climate unpredictability. This study underscores the critical need for interdisciplinary collaboration in water governance, emphasizing that effective management must integrate socio-economic, political, and environmental factors. By advancing the socio-hydrological framework, the findings can guide policymakers in formulating inclusive strategies that enhance climate resilience for vulnerable communities in South Asia. Ultimately, these insights can inform regional cooperation on transboundary water issues, promoting sustainable resource management amidst climate uncertainties.

In sum, socio-hydrology advancement represents a transformative opportunity to reframe water governance and management in South Asia. By leveraging hydrology and social sciences insights, decision-makers can develop adaptive strategies that address the interconnected challenges posed by climate change. The path forward necessitates a commitment to continuous learning, stakeholder engagement, and innovation. This collaborative effort extends beyond traditional governance paradigms to embrace integrated solutions that empower communities and build resilience for future generations in an increasingly uncertain climate.

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Glossary of Key terms used in this paper

1. **Socio-Hydrology:** An interdisciplinary field studying the feedbacks and interactions between human and water systems, examining how societal actions impact hydrological processes and vice versa over time and across scales.
2. **Adaptive Governance:** A flexible, responsive approach to managing natural resources, incorporating stakeholder participation and iterative learning to address uncertainties and complexities in environmental systems.
3. **Transboundary Water Management:** The process of collaboratively managing water resources that cross political or geographical boundaries to ensure equitable and sustainable usage.
4. **Climate Resilience:** The ability of communities or systems to anticipate, prepare for, and respond to hazardous climate-related events, minimizing impact and recovering effectively.
5. **Integrated Assessment Models (IAMs):** Simulation tools combining environmental, economic, and social dimensions to evaluate the impacts of different policy scenarios on resource management.
6. **Agent-Based Models (ABMs):** Simulation models that represent individual actors within a system, exploring their interactions and adaptive behaviors to understand complex dynamics.