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Socio-hydrology: A key approach for adaptation to water scarcity and achieving human well-being in large riverine islands

Pankaj Kumar [a,*], Ram Avtar [b], Rajarshi Dasgupta [a], Brian Alan Johnson [a], Abhijit Mukherjee [c], Md. Nasif Ahsan [d], Duc Cong Hiep Nguyen [e], Hong Quan Nguyen [f,g], Rajib Shaw [h], Binaya Kumar Mishra [i]

[a] *Natural Resources and Ecosystem Services, Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan*
[b] *Faculty of Environmental Earth Science, Hokkaido University, Japan*
[c] *School of Environmental Science and Engineering, Indian Institute of Technology, Kharagpur, West Bengal 721302, India*
[d] *Economics Discipline, Khulna University-9208, Bangladesh*
[e] *Southern Institute for Water Resources Planning, Ho Chi Minh City, Viet Nam*
[f] *Center of Water Management and Climate Change (WACC), Institute for Environment and Resources, Vietnam National University - Ho Chi Minh city (VNU - HCM), Viet Nam*
[g] *Institute for Circular Economy Development, Vietnam National University- Ho Chi Minh city (VNU-HCM), Viet Nam*
[h] *Graduate School of Media and Governance, Keio University, Japan*
[i] *School of Engineering, Pokhara University, Nepal*

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ABSTRACT

Rapid global changes (population growth, urbanization and frequent extreme weather conditions) have cumulatively affected local water bodies and resulted in unfavorable hydrological, ecological, and environmental changes in the major river systems. Particularly, communities in isolated riverine islands are heavily affected due to their poor adaptive capacities, which is well documented in the contemporary literature. The focal point for the vulnerability of these people lies in the water resources (drinking water availability, agricultural water quality, salt-water intrusion, flooding etc.) and the future interaction between human and water systems. This paper advocates the importance of socio-hydrological research in the context of enhancing social adaptive capacity as well as for developing a resilient water environment in three very large riverine islands in Asia: Fraserganj (India), Dakshin Bedkashi (Bangladesh) (both from the Ganges-Brahaputra-Meghna Delta) and Con Dao Island (Mekong River, Vietnam). It also explores how the nexus of human–water relations could be applied to improve adaptive measures to manage local water needs while mitigating undesirable changes to the hydrological cycle. Socio-hydrological models as an integrated tool can be used to quantify the feedbacks between water resources and society at multiple scales, with the aim of expediting stakeholder participation for sustainable water resource management. The proposed idea in this study will be helpful to sketch projections of alternatives that explicitly account for plausible and co-evolving trajectories of the socio-hydrological system, which will yield both insights into cause–effect relationships and help stakeholders to identify safe functioning space.

1. Introduction

Rapid global changes in land-use/land management and increasing water demand have transformed the hydrology of many different landscapes around the world, which has significantly impacted societal development via our co-evolution with water [5]. Considering the finite volume of freshwater resources, its sustainable management is a global challenge [22]. Currently around one-third of world's population (about 2.4 billion people) is living in water-stressed countries, which will increase to two-third by the year 2025 [48]. On the other hand, rapid population increase, economic growth, and urbanization are putting further stress on fresh water supplies [23]. Out of the limited existing freshwater reserve, about 50% of the world population depends on groundwater to meet their potable water demand (UNESCO, 2015). It is reported that about 1/4th of the world population has to travel (a round trip of 30 min or more) from their premises to fetch potable water UNICEF [46].

Impacts of rapid global changes include more frequent extreme weather conditions, increased hydro-meteorological hazards, interruption in food production and water supply, human morbidity and mortality, and disruption of the ways that people live and interact with their environment (IPCC, 2014, [27]). The total cost due to hydrological disasters in 2016 is estimated as 59 billion USD, which represents 74% of the annual average of the period (2006–2015) [40]. Among the damage caused by hydrological disasters, flooding is estimated about 98.8% in 2016 [20]. Another most

* Corresponding author.
E-mail address: kumar@iges.or.jp. (P. Kumar).

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common hydro-meteorological hazard in these regions are tropical cyclones, storm surges, soil salinity intrusion, and flash floods; where cyclones appear to be the most devastating ones which causes maximum damage (both tangible and non-tangible) [4].

Despite having a significant share (>35%) of the world's freshwater resources and many of the world's largest river systems (e.g. the Ganges, Brahmaputra, and Mekong), water availability per capita in Asia is behind rest of the world (WWAP, 2015 [52]). Asian countries are facing water stress for a variety of reasons, including frequent extreme weather conditions (e.g. drought), poor governance, socio-cultural practices [16]. Over the last three decades, hydro-meteorological hazards and their induced health impacts were responsible for approximately 3.2 million deaths in India, Bangladesh, and Vietnam alone ([25]; Tamaddun et al., 2019 [44]; [10]).

In response to these rapid changes, rivers are exhibiting significant changes in annual runoff as well as quality deterioration, and this water shortage/scarcity causes a change in socio-cultural practices at local level [1,30]. Such events have extreme effects on the communities in isolated riverine islands because of their poor adaptive capacities (limited resources/infrastructure as well as institutional setup) [42]. Globally, these riverine islands, cater a huge population (more than 6.2 million considering only island with more than 25,000 peoples) (Saikia, 2009 [38]; Sarker et al., 2020; [39]; Statistics Canada, 2016 [43]; US Census Bureau Quick facts, 2019 [47]). Despite having plenty of water in these regions, sharp reduction in the usability of the available water became a serious problem since the past few decades [22]. In many such cases, the focal point for the vulnerability of these people lies in the shrinking water resources (i.e. drinking water availability, agricultural water quality, salt-water intrusion, flooding etc.) and the future interaction between human and water systems is a critical concern for sustainability.

In addition, the link between mental health and water scarcity is gaining strong attention [55]. Examining and understanding the link between mental health and water scarcity is very important from the human well-being perspective. While other dimensions, particularly the physical health component of water insecurity, are generally well-established and thoroughly investigated, coastal salinization also corresponds to a plethora of mental health issues that are often ignored in the policy planning process [53]. Despite its high importance, issues of water resource management and its relation with human well-being is understudied.

Considering the above-mentioned gaps, this opinion paper has following objectives:

1) To highlight issues related to water resources and its effect on human wellbeing in three largest riverine islands in Asia, namely Fraserganj, South 24 Pargana (Ganges River, India), Dakshin Bedkashi (Padma River, Bangladesh) and Con Dao Island (Mekong River, Vietnam).
2) To provide different possible solutions for water resource management from the lens of socio-hydrological approach. Here, this study will sketch different scales of human interaction with the water cycle, along with the coupling effect present between social and hydrological systems. In addition, as an adjoined system, it will explore decisions that influence water as well as its users, i.e. local communities. It also explains how socio-hydrological models can be used to quantify the feedbacks between water resources and society at multiple scales with aim to expedite stakeholder participation for its sustainable management.

More precisely, this work advocates pathway analysis for co-designing different adaptive countermeasures based on the socio-hydrological approach. It will explain how socio-hydrological models can be applied in the field to manage both biophysical sciences of the water scarcity and different societal responses to manage its key factors. Finally, best practices for co-designing the effective management/adaptation strategies for water resource as well as harmonizing it with human well-being will be shown to all the people/organization concern for water resources management.

2. Study area and key issues related to water resource management

The study area is composed of three riverine islands, namely Fraserganj, South 24 Parganas and Dakshin Bedkashi from Ganges-Brahmaputra-Meghna (GBM) Delta and Con Dao Island (Mekong River, Vietnam), as shown in Fig. 1. These islands cater a total population of (41,430 + 19,400 + 7000) 67830 people (Census of India, Bangladesh and Vietnam, 2015). Traditionally, the main occupation for the communities living in these islands was agriculture, but over the last few decades the trend of agriculture is decreasing because of a lack of sufficient water for irrigation as well as salt intrusion in the soil and water (groundwater/surface water).

2.1. Fraserganj, south 24 Parganas, GBM delta, India

Das and Mukherjee (2019) mentioned that cumulative effects of major factors like extreme weather conditions, over-exploitation and natural/anthropogenic contamination results in changes in hydrodynamic processes and hence enhance groundwater-sourced drinking water vulnerability in the Sundarbans delta-front aquifers. Frequent cyclone and stormwater surges induce salinity ingression into the freshwater ecosystems upstream through estuaries, creeks and inlets leading to change in physico-chemical properties of the aqueous medium as well as the ambient media. This increased salinity of water which can cause growth of harmful algal bloom (Chattonella marina) in the inland water bodies like household ponds- further reducing the amount of water available for their house chores [28]. Redfern et al. [37] indicate that each unit (ds/mL) rise of salinity causes roughly 12% reduction in rice yield, the very backbone of socio-economic sustainability in the region. Mitra et al. [29] observed deterioration of water quality for past three decades in Sundarban area because of various factors like climate change, anthropogenic activities etc. Dubey et al. [9], found that because of increasing trend of groundwater salinization and loss of agricultural productivity, many local farmers are switching their occupation to aquaculture by ponding the brackish water in their farms. Although this can increase income in the short term, soil and farmland become unsuitable for long periods in these aquaculture areas. Bhadra et al. [3] have estimated water budget for potable water to help decision makers to execute better policies to achieve sustainable development goal of providing water for all in this region. They found that because of population growth, the water demand will be increased to more than double by year 2051 compare to that of current situation. On the other hand, water availability will not increase hence there will be huge water deficit, hence creating another source of water, like desalinizing shallow groundwater, rainwater harvesting, and/or artificial recharge, are the way forward. Although groundwater salinization is confined to very small geographical areas, it causes cascading effects on agricultural output, health risk, mental unrest, outward migration and hence overall human well-being [7]. Various psycho-social stresses are also reported due to freshwater scarcity, including the increasing incidence of mental disorders, social unrest etc.

2.2. Dakshin Bedkashi, Padma River, Bangladesh

Over the last decade, global climate change has had a significant impact in all spheres of human life, especially for poor, low income and vulnerable groups [19,35]. The impact of this change varies at different stages of communities because of its irregular temporal and spatial distribution [21,35]. Climate change may create stresses through two ways – direct and indirect [21] affecting environmental, economic and social indicators which are computationally difficult to forecast especially in data scarce region like Bangladesh [19]. Exacerbated vulnerability for increased frequency, intensification and complexity of natural disasters like floods, droughts, cyclones are the direct consequences of climate change [35]. Primarily agricultural economies are experienced hardships of immediate effects, particularly veritable for marginalized and poor farmers and landless laborers, shaping by surface and ground water shortage, salinity intrusion, soil and water deterioration, deficit in production and crop failure and incremental mortality rate of livestock and wildlife [21] and leading to food insecurity and migration [35].

In addition, these frequent extreme weather conditions also make different groups of women more vulnerable [21]. Women face disparity in distribution and accessibility to food and nutrition, education, less

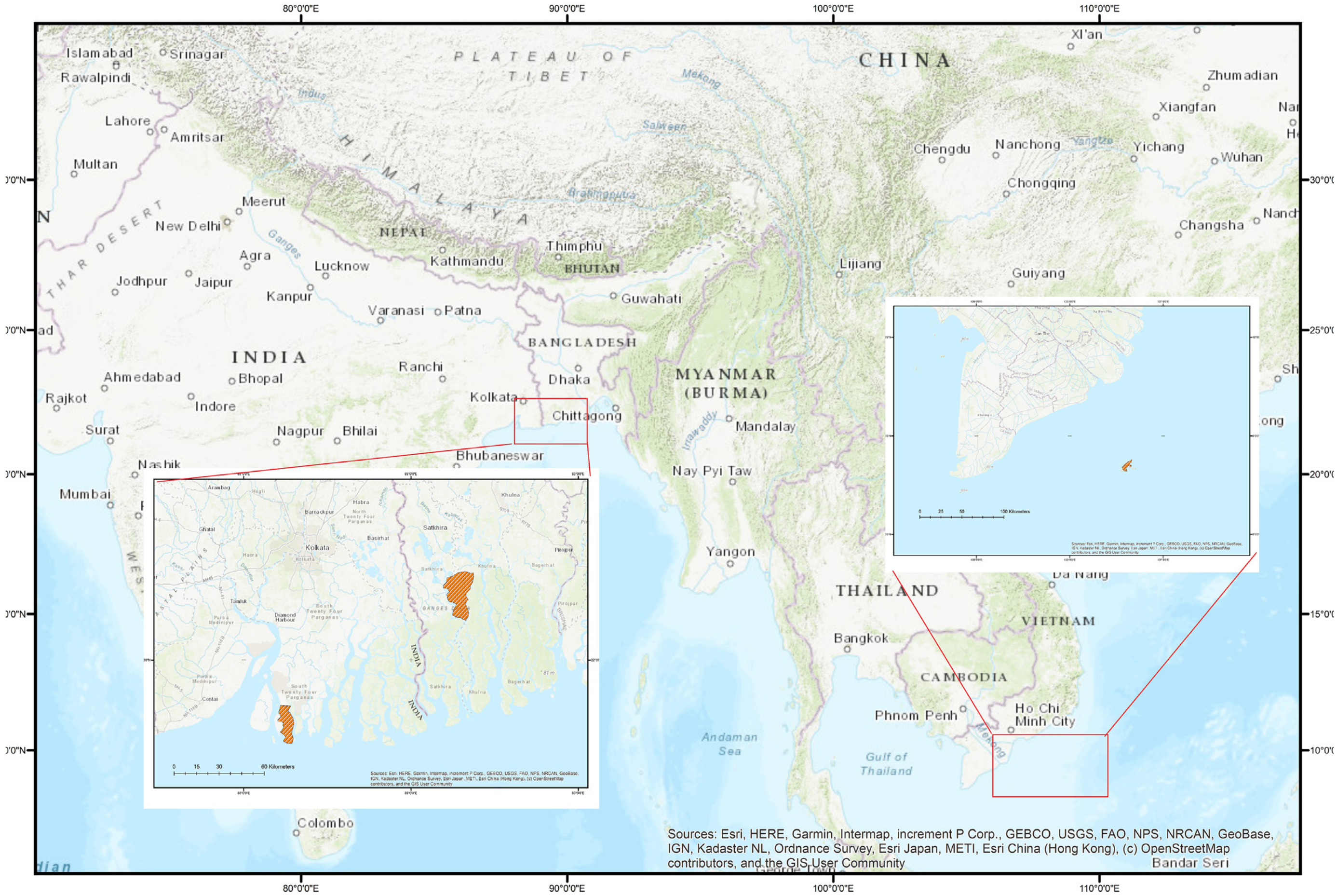

Fig. 1. Study area map.

participation and freedom in decision-making and exercising power due to traditional cultural practice. Because of hyper-masculine behavioral presence in socio-cultural dogmas, different groups of women face sexual violation, abuse and persistent inequality in time of disaster stress [21]. Rahman et al. [35] mentioned that drinking water salinity creates difficulty for pregnant women and increase risk for stroke and cardio-vascular diseases. As women perform households' chores with saline water, salinity increases risk of skin diseases, becomes rough and darker. Due to dry and dark skin, they have to pay higher amount of dowry [19]. Relatively affluent families, having reservoirs, collect sweet water from rainwater, ponds and rivers and use during the times of higher salinity. As a result, women in poor family are more vulnerable to climate change. Accessibility to resource also influence women's capacity to access of water and respond to water scarcity in agriculture [35].

Intersection among gender and other categories of individual lives, institutional, social and cultural ideologies differentially affect resilient behavior to reduce climate stress, which results differentiated vulnerability at different segments [19]. Furthermore, climate change creates damages healthcare infrastructure, reduces accessibility to health care, increase morbidity and mortality rate in vulnerable groups [35], psychological and emotional stress (such as depression and suicide, changing family planning) and community disharmony [21].

Although a significant number of researches have been done for understanding economic and environmental impacts of global change, a few numbers of studies considering social dynamics is exposed [35]. The dissimilarities in gender-based roles and responsibilities as well as their power relation, unequal distribution of intra-household assets [19], socio-cultural and ethical norms and practices, higher reliance on natural resources at different communities, highly densely populated area, lower health facility, mobility and migration, all the dynamisms are matter in order to assuage climatic effect. Unfortunately, these dynamisms affect women more than men especially in case of Bangladesh [35]. Besides, the study of climate-health relationship is poorly designed in lower deltaic area [35].

Deficiency of availability of related and quality data, poorer access of concrete and peer review, limited availability of proper funding and inefficient management, complex and heterogeneous methodology limiting comparison [35], structural and behavioral mismatch among social and ecological institution [19], virtually absence of database of track or trends by sectors or regions [21] are responsible for having few number of studies related to social dynamics.

To investigate indirect or social impact of climate vulnerability, reductionist research approach has a limitation of capturing the risk of the most vulnerable communities [54]. Researchers fail to attribute risk associated with climate stress and variability since the features of climatic system is complex and interconnected with other economic and social phenomena. Zeitoun et al. [54] advocated that comprehensive qualitative risk modeling including ethical questions can be a suitable approach to attribute risk to vulnerability shaping by social dynamisms.

While shallow wells are highly contaminated with saltwater intrusion, Arsenic, Iron, Fluoride; wells from the deep aquifers i.e. >200 m deep are not used for irrigation because of high cost of wells. However, for household supply, municipality and towns such as Khulna, Barisal and Noakhali are entirely depends on wells below 150 m deep because of unavailability of any alternate [11,34,36].

Hossain et al., (2016) [15] used historical approach to explain recent change in ecosystem services and human wellbeing in the Bangladesh Coastal zone. Here they have explained that due to rapid global changes (population increase, climate change induced frequent extreme weather conditions and land use land cover change) food related ecosystem services along with GDP increased since 1980s. In contrast, non-food ecosystem services such as water availability, water quality, and land stability have deteriorated.

2.3. Con Dao Island, Mekong River, Vietnam

In Con Dao Islands, the major source of water supply for domestic use, tourism, and industry comes from aquifer with 25 drilled wells and the total average exploitation volume of 3400 m^3/day. According to the observed data in the dry season, the groundwater level in the Central Town of Con Dao Islands has been dropped to about 1.19 m in the period of 2006–2012 (DWRPIS, 2015 [8]).

In recent years, water shortages for domestic use and tourism are increasing due to the population growth and tourism development. As anticipated, water demand by 2030 will increase over three times for domestic use and over two times for tourism in a comparison to the period of 2015–2020 (MPI, 2011 [26]). On the other hand, water availability is reducing under the impacts of climate change and sea level rise, leading to increasingly pressure on water supply and thus increasing risks of saline intrusion due to over-exploitation of groundwater resources.

The interaction between people and water has been remarkably concerned in Vietnam, as agricultural production is one of important economic sectors in the country, accounting for 14.68% of the total GDP (2018 statistical yearbook of Vietnam). One group of studies are focussed on quantification of water budget (demand and availability) in different river basins of Vietnam such as Ba River (Vu et al., 2012 [50]), Lam River (Dang et al., 2015), Vu Gia-Thu Bon River (Hoang and Ma, 2016), Sesan River [45]. The second group studies focused on monitoring water quality and deducing hydrological processes governing its evolution like for groundwater salinization for different aquifer system in Vietnam (Vu and Bui, 2006 [49]; Nguyen et al., 2008 [31]; [6,14,24]). Third group of studies integrated water resource management in the studied area by using the hydrological models such as HEC-HMS and MODFLOW [24], water balance models such as WEAP and SWAT (Vu et al., 2012; Dang et al., 2015; Hoang and Ma, 2016; [45,49]). These studies not only evaluated water use in the current condition, but also predicted the changes of water supply and demand in the future scenarios, covering the impacts of population growth, socio-economic development, and climate change. In final group of studies, decision support frameworks for water resources plans and projects were evaluated in Vietnam, where the most prominent representative is the Motivation and Ability (MOTA) framework. Developed by Ho et al. [13], MOTA has been widely used to assess the flood control plans for Ho Chi Minh City ([13]; Nguyen et al., 2019 [32]), ecosystem services in prawn-rice rotational crops in Kien Giang Province [12], and livelihood transformations in Ben Tre Province.

2.4. In a nutshell

Based on the above findings from studies conducted all three sites, the common theme is that groundwater salinization is one of the key reasons for water scarcity in coastal areas. It has several cascading effects like water pollution, economic loss, outward migration, mental and psychological effects and finally deterioration in human well-being, as shown in Fig. 2.

2.5. Key findings from our pilot study at GBM delta

To understand this complex issue with better clarity, we have conducted a pilot study in the GBM delta. For this, we carried out fourteen focus group discussions (FGDs) during 13-20th February 2020. The results of these FGDs helped us to design a detailed questionnaire survey to be used in next phase. Participants for the FGDs were chosen based on different age, sex, income, etc. Through the pilot study, it became clear that while clinically diagnosable mental illnesses may be triggered by stressful events such as a large-scale hydro-metrological disaster, gradual salinization of ground water aquifer-the only source of usable fresh water- can be considered a persistent emotional stressor for vulnerable island communities. Unfortunately, the psychological stress is not just limited to bad taste or usability of ground water, rather the consequence is often far-fetched. From our pilot studies in the GBM delta, it was evident there are multiple avenue through salinization is pressing irreversible damage to mental health, leading to severe anxiety, restlessness, domestic violence and homicides. The Fig. 3 provide a conceptual insight on the different avenues through which salinity impacts mental health. The two primary routes are crop failure and lack of sufficient drinking water in the lean seasons. Crop failure has led to drastic changes in occupation, promoting migration of young adults and social vulnerability and economic hardships for the family members. Loss of primary occupation led to financial hardship, which was further escalated due to the lack of provision of drinking water and subsequently, buying potable water- to add to the economic misery. There were also reported social conflicts over limited irrigation sources such as rare sweet water ponds etc. Though still rare, some cases of culpable homicide were also reported. In nutshell, salinity continues to become an emotional stressor badly affecting the socio-psychological wellbeing.

3. Socio-hydrological approach: A way forward for sustainable water resource management

3.1. Why socio-hydrological approach

While much progress has been made in making quantitative assessments of different hydro-meteorological risks, there remains a lack of fundamental understanding of the interplay between physical and social

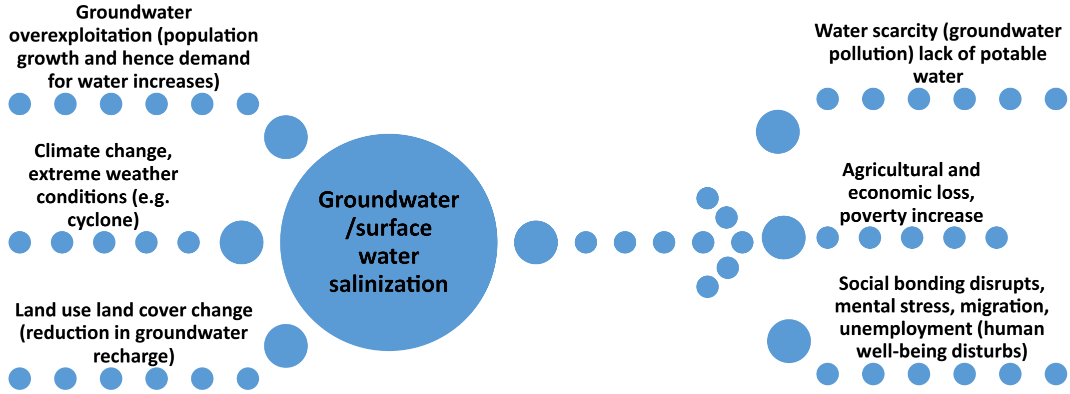

Fig. 2. Snapshot of cause-effect analysis of water related issues in riverine islands.

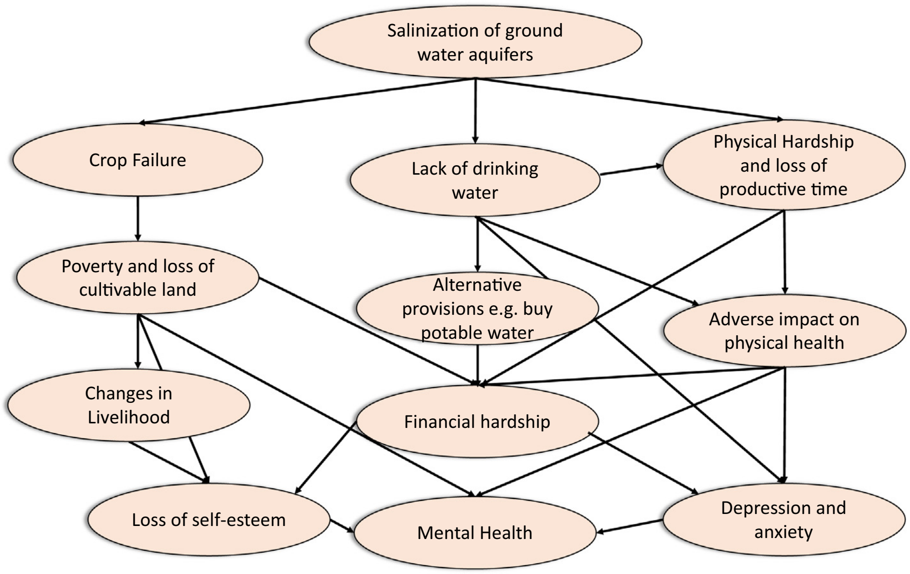

Fig. 3. Conceptual diagram showing key findings from the FGDs.

processes. As a result, the current analytical frameworks somehow failed to capture (or explain) the dynamics emerging from this interplay [2]. Conventional models may help identify desirable future status of water environment, but they cannot guarantee their attainment because of adaptive responses by humans and management decisions which might have unintended consequences [17,33,41]. Therefore, an integrated perspective in analyzing water related risk through socio-hydrological pathways is deemed essential for better understanding the action research and policy implication for sustainable water management [2,51].

To understand this interwoven issue of water and societal interaction, there is a swift change in the direction of transdisciplinary research approaches, which study water resources from humanities, social science, psychological and natural science perspectives that seek to address the hydrological and social challenges related to the complex human-water interactions [5,51]. This study proposes the concept of socio-hydrological approach to solve this complex issue of water resource management (Fig. 4).

The socio-hydrological approach has two main components: (i) a socio-hydrological loop, and (ii) other normalizing factors which have significant impacts on the loop. For the socio-hydrological loop, the first attribute is water demand and availability, which indicates understanding the water budget is key for water resource management. To design robust management policies, it is imperative to understand both the current and future water budget through plausible scenario analysis. The second attribute is socio-cultural responses, which includes indigenous knowledge, perception towards the rapidly changing hydraulic regime, culture, willingness to modify to the traditional ways of farming to minimize the effects of uncertain extreme weather conditions, awareness about global changes,

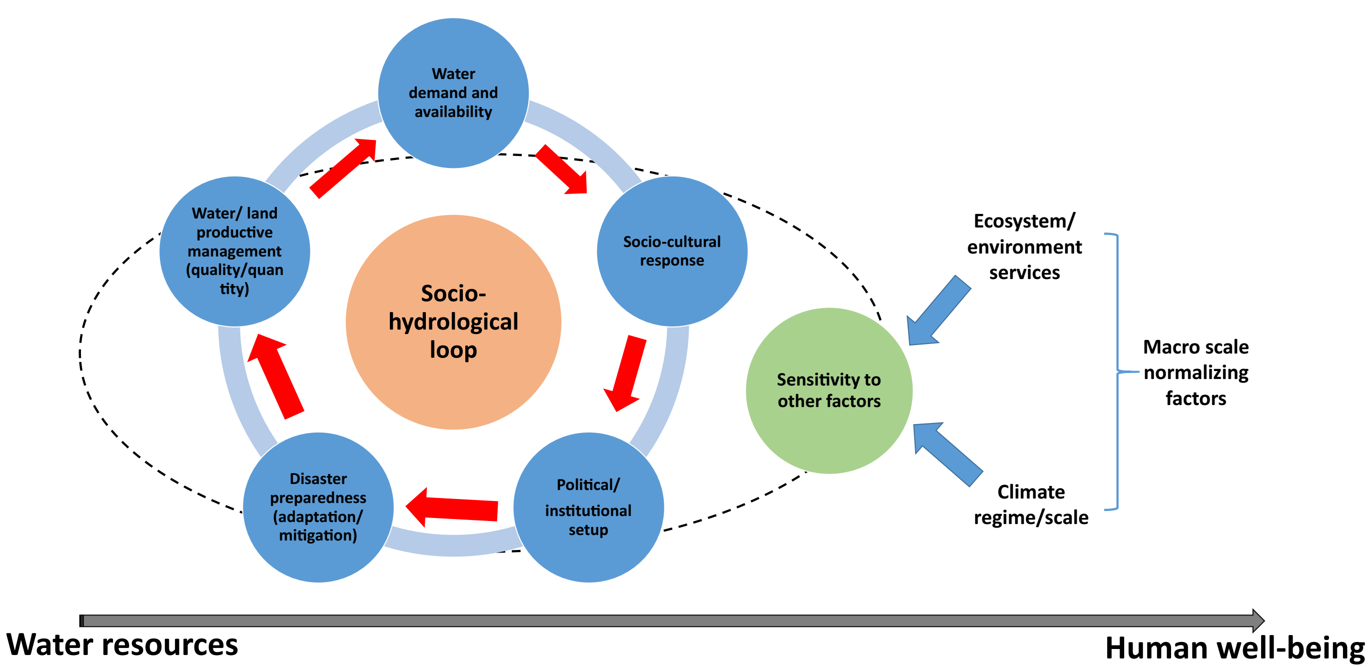

Fig. 4. Conceptual diagram of socio-hydrological approach to bridge the gap between water resources and human well-being.

agricultural practices, water consumption patterns and monitoring efforts to be made to reach the targets can be considered. The third attribute is focusing on political/institutional set-up, which is mainly talking about need for bidirectional, i.e. top-down as well as bottom-up approaches, to achieve a robust management system. For this purpose, a retrofitting model is needed where all the relevant stakeholders ranging from farmers associations to local governing bodies (for irrigation, agriculture, water, fisheries, economic etc.) can provide their inputs at any stage of the model development. The fourth attribute is disaster preparedness, especially for water related hazards, as these regions are hot spots for frequent cyclones, typhoons etc. Here, this concept will mainly focus on how to make our systems more resilient against these extreme hydro-meteorological conditions. The fifth and final attribute of this loop is water/land productive management. Here, this model will mainly focus on how to preserve the precious natural resources i.e. both water and land from saline intrusion in both short and long time along with maintaining its productivity.

The other component of this socio-hydrological conceptual diagram is the macroscale-normalizing factors, which has two attributes, namely ecosystem/environmental services and climate scale/regime. Each of the five attributes from the socio-hydrological loop are sensitive to both normalizing factors. Focusing and maintaining a healthy ecosystem with its all its services is key for designing a management for water resources. Climate regime or scale is one of the key driver or pressure having both direct and indirect impact on hydrological cycle. Hence, it is one of the crucial element to be considered to make management plan more robust.

The whole idea behind considering this socio-hydrological concept is to achieve all six dimensions of water security. These six dimensions are domestic water security, economic water security, urban water security, environmental water security, resilience to water related disaster risk, and transboundary water security. For all dimensions, both safe and desirable water quality as well as sufficient water quality to achieved.

4. Key steps for achieving socio-hydrological concept

To realize this ideal socio-hydrological concept in the field, the project planning should have four steps (Fig. 5). As the term suggests, this concept gives equal weightage to science (hydrology, meteorology etc.) and social part (citizen's participation). Citizen's perspective is very important from information to implement in this project management cycle. The first step includes information gathering or in other words, project scoping. Here, it is necessary to identify the key stakeholders, identify and compile the key risks, and designate “champions” who have credible experience for handling such issues in the field to lead the project implementation. Second step is analysis and decision-making, here we use different numerical tools and scenario analysis will be used to quantify the current and future risks. Addition of citizen's perspective will help to co-design the robust solutions for adaption or mitigation measures. Based on this quantitative analysis, different solutions options will be visualized. However, as explained before, all different models to be used in this case will be retrofitting in nature, so inputs from relevant stakeholders can be given throughout the project cycle. In the third stage, based on the rigorous discussion and communications, the most suitable solutions both for adaptation and mitigation, will be implemented. Finally, in the fourth stage, progress for all these integrated approach will be evaluated and based on feedbacks and suggestions, modification can be done as deemed necessary. For third and fourth stage, inclusion of citizen's perspectives help in co-delivery of the project outcome. This co-design and co-delivery concept will help to make this retrofitting models and approach, more robust and sustainable.

4.1. Relevance

Most of the environmental modeling research focusses on scenario based snapshots of the future world, while policy based interventions hardly get implemented because of the understanding gap between the scientific community and decision makers. Therefore, the proposed concept intends to work on socio-hydrological interactions, which involves public investments with long-ranging impacts on hydrological cycle management. This will use attributes of existing water environment and social dynamics (cultural, political, ethical etc.) for improving adaptation communication in sustainable water resource management. Here, for the modeling purpose biophysical parameters will be given importance, however greater emphasis will be placed on the role of politics and culture in shaping them. Since this work will be based on the concept of “with the people rather than for

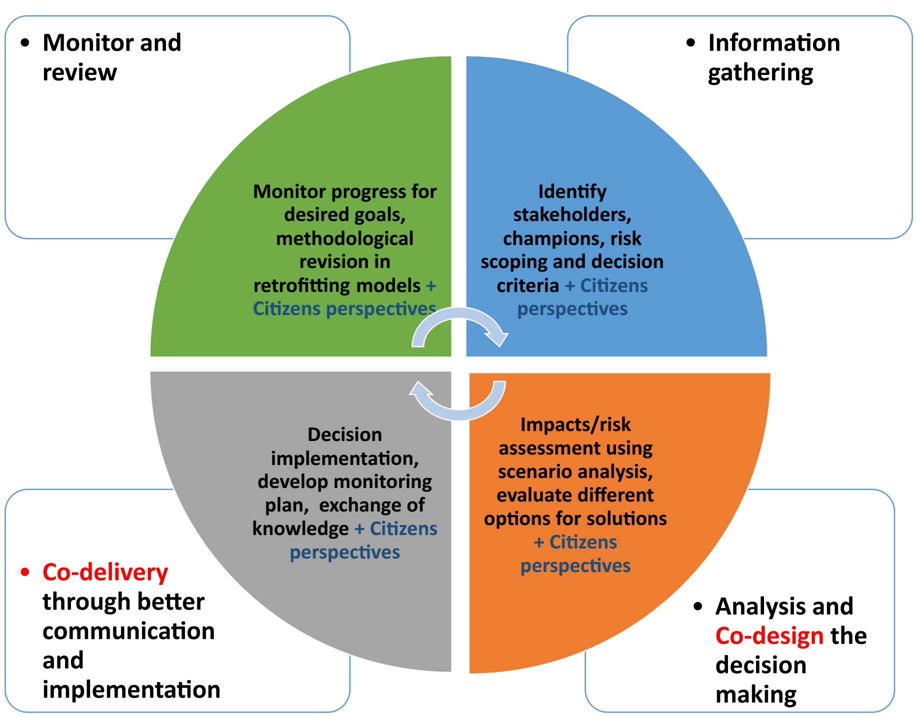

Fig. 5. Key steps for project management (Modified from Jones et al., 2014 [18]).

the people", all the stakeholders will have ownership on the co-designed knowledge base and insights gained in this research.

The expected result will be helpful to sketch projection of alternatives that explicitly account for plausible and co-evolving trajectories of socio-hydrological system, which will yield both insights into cause–effect relationships and help stakeholders to identify safe functioning space. It will try to evaluate key components like the societal measures taken as mitigation means for sustainable water resource management against the rapid global changes, and the societal characterization and monitoring efforts made for choosing management targets and checking the effects of measures taken to reach the targets.

For societal component different variables like institutional set-up, indigenous knowledge, culture, practices and monitoring efforts to be made to reach the regional/ national targets in addition to the sustainable development goals (SDGs). Within the regional pretext, this work will target particularly for the goal 13 (climate action), 6 (clean water and sanitation), 3 (good health and well being), and 15 (life on land). Finally, it will promote adaptation communication in best possible way to advocate local people to use their local resources for managing water resources for both short and long time scale.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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