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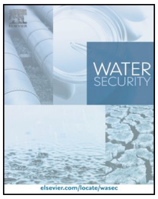

Salinization in large river deltas: Drivers, impacts and socio-hydrological feedbacks

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ABSTRACT

Salinization of freshwater and soils is a global phenomenon that adversely affects 500 million people, particularly in low-lying river deltas. Impacts of salinity on food and water security and agricultural livelihoods are well documented and reviewed herein, along with additional effects on human health that have received less attention and warrant further study. Populations forced to consume saline waters display increased occurrence of diseases such as hypertension in Bangladesh, particularly among the rural poor in coastal areas. This review synthesizes knowledge on socio-hydrological drivers of salinization in large river deltas globally. Multiple drivers arise at different scales and include agricultural practices, upstream water diversion, and relative sea level rise and can be amplified through feedback from inappropriate adaptation strategies. Understanding deltas as truly coupled socio-hydrologic systems is critical to anticipate these feedbacks.

1. Introduction

Salinization, the accumulation of soluble salts in soils and freshwater, is a global phenomenon unfolding at an unprecedented scale. The process of salinization emerges from natural (e.g., tidal inundation) and anthropogenic (e.g., excessive groundwater abstraction) causes [1–4] and can irreversibly contaminate rivers, aquifers and soils [4–10], with direct implications for the food and water security of millions of people [11–14]. The ubiquitous nature of salinization is becoming increasingly clear [14,15], with a substantial volume of literature discussing the phenomenon in coastal aquifers [9] and inland waters in arid and semi-arid regions [8,16–18]. The emerging threat and disastrous consequences of salinization are also increasingly recognized in diverse ecosystems such as estuaries [19], inland waters [8], freshwater wetlands [3] small islands [20], deltas [21–23] and low-lying coastal regions [9,14,24,25]. In particular, the issue is emerging as a major social-ecological concern in global river deltas, which are home to over 500 million people with more than seven times the global mean population density [23,26,27].

As unique, naturally dynamic coastal social-ecological systems [26,28], deltas provide important ecosystem services worth trillions of dollars [23], including rich biological diversity, fertile alluvial soils, and aquatic habitat for fisheries [11,29]. Many deltas are also challenged by rapid population and economic growth [30,31], environmental degradation [32], and climate change [22,33,34]. The threat of climate change is particularly concerning for deltas [35,36], most of which were formed in the early Holocene when sea level rise resulting from de-glaciation decelerated enough for delta initiation to take place [37]. With relative sea level rise (actual sea level plus subsidence) and diversion of fluvial sediment now increasing rapidly in the emerging Anthropocene, many deltas are literally sinking [26,32,38]. Many of the climate-related threats to deltas, including storm surges, flooding, and coastal erosion, have been abundantly studied [23,26,32], while the study of delta salinization is emerging within specific deltas and ecosystems. We review the dimensions of river delta salinization in terms of causes, consequences, and feedbacks, building on place-based research to synthesize examples from a cross-section of river deltas and demonstrate various ways in which salinization emerges.

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Section 2 reviews recent literature on the impact of salinization on food and water security, with a particular focus on the Ganges-Brahmaputra-Meghna (GBM) delta where the immense threat of climate and environmental change is magnified by a large population and high population density, economic development and regional politics [11,12,39–47]. We also discuss emerging research and public health concerns regarding the direct impacts of salinization on human health [48,49], both through the consumption of saline water (a leading cause of hypertension) and changing environmental microbiology (which affects the prevalence of water-borne pathogens).

Section 3 reviews the socio-hydrologic drivers of salinization identified in global deltas. While the physical mechanisms that give rise to salinization are well established, the interactions (across spatial and temporal scales) and relative influence of drivers (both natural and anthropogenic) are often poorly understood. In the GBM, for instance, transitioning from paddy to shrimp farming (a local land-use change) [41] compounds the combined effect of decreased freshwater inflow (a regional water-use change) and sea level rise (a global change) to increase seepage of brackish water (long-term salinization). Land subsidence also decreases resilience to storm surge (short-term salinization). Under these conditions, identifying the critical factor(s) that drive the phenomenon requires substantial (and location-specific) modeling and observation efforts. We select eight global deltas (Fig. 1) capturing cross-sections of climate, population density, regional politics, and vulnerability, and we use these examples to synthesize knowledge pertaining to drivers of delta salinization.

In Section 4 we discuss deltas as coupled human-natural systems, focusing on salinity adaptation strategies and subsequent socio-hydrologic feedbacks, especially those with undesirable consequences. The unforeseen consequences of such feedbacks, which are pervasive in socio-hydrologic systems [28,50,51], can increase overall system vulnerability (e.g., [3]) and understanding them is critical in generating effective mitigation and adaptation policies.

2. Impacts

When salinity intrusion primarily occurs in sparsely populated areas, salinization can alter native habitats resulting in considerable ecosystem changes, including migration or death of vegetation. In the Orinoco delta, mangrove forests have migrated up to 100 km inland [53], and in the Mississippi delta, some areas have experienced up to 85% tree mortality [54]. These impacts have undeniable societal implications in terms of lost ecosystem services (e.g., fisheries, decreased resilience to storm surges) [23,29,47]. However, in densely populated and cultivated deltas, these effects are often dwarfed by the sweeping consequences of salinization on food security, livelihoods, and health (Fig. 2). The effects on food security and livelihood (including well-being) are wide-ranging and include declining material resources and income, mental health concerns including emotional stress and identity crisis due to deprivation of a “sense of place”, and loss of livelihood viability and migration [4,12,44].

2.1. Food security and livelihood

A. Agricultural productivity

Salinization reduces agricultural productivity when salts accumulate in the root zone, interfering with plant growth when concentrations exceed the tolerance limits of the crop [11,55]. Salt in the root zone decreases the germination rate, shoot length and root length of certain plants and ultimately lowers crop yield. Salinity conditions in soils have more recently been reported to influence crop yields through their effect on soil microorganisms, with a marked negative effect on respiration [56]. Decreased respiration affects bacterial decomposition activities and their ability to cycle nutrients, which in turn reduces crop yield. While declining crop yields associated with salinization are common in low lying deltas [57,58], the issue is particularly urgent in Bangladesh, a middle-income country of 157 million people lying almost exclusively in the GBM delta and vulnerable to the effects of climate change. Rice production decreased by 15–31% in a salinity-affected coastal area of south-west Bangladesh over a period of about 15 years [59], a trend which is expected to persist as salinization progresses. A World Bank study suggests that increased salinity alone from a 0.3 m sea level rise will cause a net reduction of 0.5 million metric tons of rice production [60]. Salinization has forced many small-scale farmers to cease rice cultivation and transition to brackish water shrimp farming or to lease or sell their land to larger farmers, in some cases resulting in local conflict and violence [61]. The seasonal nature of salinity in Bangladesh (due to monsoon-related seasonal freshwater

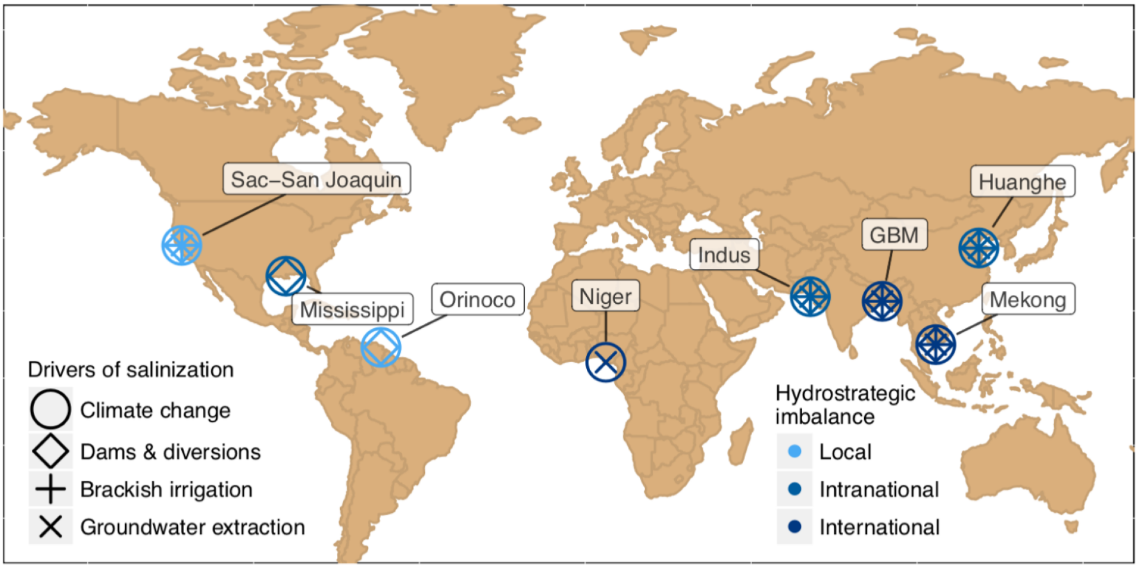

Fig. 1. Major drivers of salinization in eight global deltas, selected to capture cross-sections of climate, population density, regional politics, and vulnerability. This map represents the most important drivers and pathways of salinization (schematized in Fig. 3) described in literature, but not necessarily the only ones. Hydrostrategic imbalance refers to the lack of political influence within the delta relative to the major water users and diversions upstream in the watershed that cause salinization via regional drivers (Section 3.2). For instance, although the Indus River is transnational, the majority of the watershed diversions are in upstream states within Pakistan and as it pertains to delta salinization, the hydro-strategic imbalance occurs between states in Pakistan [52].

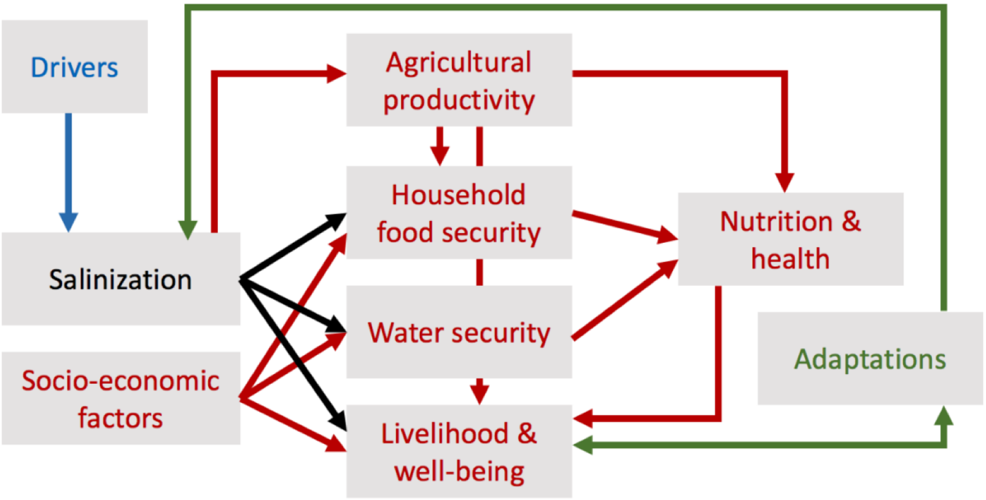

Fig. 2. Illustrative example of possible social consequences of salinization (adapted from Szabo et al. [12]). Social characteristics and processes of the system (red) described within Section 2. Drivers (blue), salinization (black), and adaptations (green) elaborated in Sections 3 & 4.

inflows) also affects traditional planting practices. Winter crops in the coastal area, which depend on (now brackish) ground water for irrigation in critical maturity stages, are particularly affected [62]. Although important, it is worth noting that reduced crop yields are not the only effect of salinization on food availability. In the Indus delta, salinization has resulted in considerable loss of arable land, livestock, and freshwater fish, all of which are important components of the local diet, and resulted in the migration of tens of thousands of people [44,63].

B. Food insecurity

When studying the great Bengal Famine, Sen [64] famously showed that food insecurity rarely arises from absolute food shortage alone and that food accessibility plays a key role. He identified four economic pathways to procure food, including own cultivation, purchase, aid and labor (work for food), all of which, with the exception of aid, are affected by salinization. Across Bangladesh in 2011, nearly 50% of low-income, ever-married women skipped at least one meal due to lack of food [65], and the problem is often worse in rural areas with high salinization. Nearly 60 million people are smallholder subsistence farmers, whose food security is threatened by the aforementioned processes [66]. Although household wealth and education are the most important predictors of food security, salinization does play a role in food insecurity, especially among poorest and least educated households [12]. Relative to other households, these households generally obtain a higher portion of income from crop production, spend a higher portion of their income on food, and are most likely to face the greatest consequences of salinization, both in terms of lost income and food security. Over 60% of households in areas with saline soils faced a food crisis between 2009 and 2013 due to decreasing rice production [59]. The effects of salinization and decreasing crop yield trickle down to affect various sectors of the rural economy in coastal Bangladesh, including fishermen, wage laborers, and others relying on ecosystem services for food [40,67,68]. These effects on rural livelihoods coincide with substantial migration to urban slums, particularly to Dhaka and Chittagong, with detrimental effects on health and food security. Households who previously relied on own cultivation now must purchase food with precarious income and cope with global food price fluctuations [69]. While the causal nature of the relation between salinization and rural-urban migration in Bangladesh is still disputed [67], the evidence basis is growing [68]. Migration caused by salinization has also been reported in other parts of the world. For instance, in Pakistan, people are leaving the lower Indus delta because soil salinization interferes with crop growth and productive agriculture [23].

2.2. *Water security and health*

Increased salinity in drinking water is an emerging concern for water quality in several global deltas (e.g., Mekong, Niger, GBM, Orinoco, Rhine and Sacramento - San Joaquin river deltas), along with potential long-term health consequences of consuming saline water [70–77].

The World Health Organization recommends consuming less than 2 g of sodium (5 g of salt) per day [78] and, although it has no official salinity guideline for drinking water, suggests drinking water contain less than 1000 mg/L of total dissolved solids (TDS), a proxy for salinity [7,79]. Chloride is the more prevalent ion in many coastal aquifers, [80] but the WHO has not proposed any health guideline for chloride in drinking water [81]. High sodium consumption increases blood pressure and risk of hypertension, which are associated with a number of health risks including cardiovascular disease, heart attacks, and stroke [49,74–76,78]. Elevated salt intake has also been associated with skin diseases, acute respiratory infection, diarrheal disease, kidney disease, gastric cancer, transmission of mosquito-borne disease [75,76,82], and increased protein excretion, a potentially useful marker for progressive kidney disease [83]. Research into the manifestation of these health concerns within delta populations affected by salinization is nascent and emerging. Hypertension affects almost one in three women in Bangladesh, nearly twice as much as men, and many people have never been tested or are unable to reverse the condition [83]. In coastal Bangladesh, salt intake through drinking water compounds an already high baseline consumption of salt that arises for geographical and socio-cultural reasons (e.g., taste adaptation and food conservation). In these regions, data show higher rates of hypertension and pre-eclampsia among pregnant women hospitalized during dry season (higher salinity) compared with wet season (lower salinity) [48]. A follow-up population-based study using measured salinity in drinking water (ranging from 300 to 900 mg/L) found statistically significant correlations between pre-eclampsia prevalence and salt concentrations in drinking water (population of approximately 143,000 people) [49]. Another study of young adults (age 19–25, N = 253) found significantly higher systolic and diastolic blood pressure in those consuming drinking water with higher salinity (greater than 600 mg/L) than lower salinity (less than 600 mg/L) [84]. Further research is needed to replicate these findings and study the consequences of salinization on health on broader segments of the population [76].

Salinization results in additional health-related consequences, such as households in Bangladesh avoiding salinity in the shallow aquifer by switching domestic supply to deeper, arsenic-contaminated groundwater [85]. Salinity also plays an important role in determining the composition of microbial communities in aquatic environments [86], including coastal lagoons [87]. For instance, *vibrio cholera* (associated with cholera disease) thrives in brackish waters in the GBM delta, while *vibrio parahemolyticus* (seafood-associated acute gastroenteritis) thrives in marine waters. This association indicates the possibility of changes in the distribution of pathogenic species across freshwater systems as they are affected by salinization. This in turn may lead to corresponding changes in the pattern of waterborne diseases, necessitating better monitoring and appropriate adaptation measures [88].

In the GBM delta, improved data collection and data synthesis is important to determine the full public health effects of salinization. Currently, the Bangladesh Water Development Board records weekly salinity measurements at high and low tides within distributaries. The Soil Resource Development Institute (SRDI) has generated spatial datasets of salinity by conducting national soil salinity surveys, with the latest being in 2009 [89]. Despite the fact that these data sets highlight the natural variability in water quality, national water assessments to evaluate household drinking water quality do not consider spatial variability of contaminants (e.g., salinity, arsenic) nor temporal differences in salinity [90].

3. Drivers of salinization across scales

River deltas are naturally exposed to a range of salinity drivers that fluctuate in response to environmental processes, including freshwater inflow from the upstream watershed, tidal oscillations, historic marine transgression, dissolution of evaporative layers, excessive evaporation of surface water or shallow groundwater, storm surges, and groundwater fluxes [7,91,92]. Salinization of river deltas occurs by disrupting the processes that sustain these natural balances, resulting in increased salinity within the delta channel network, soils, and aquifers. For instance, reduced freshwater inflow and rising seas can force salt wedges further upstream into the delta channel network [38], while groundwater abstraction and lateral seepage can bring saline water into aquifers [93,94]. Salinization of delta soils can occur with increased tidal inundation due to land subsidence and climate change, as well as seepage through embankments, capillary rise, or reduced precipitation [36,95]. These mechanisms of salinization are often interconnected because salinization in one domain (channel network, soils, or aquifer) of the delta can lead to salinization within another one via natural (e.g., hydraulics) or anthropogenic (e.g., irrigation) means.

Using examples from the deltas shown in Fig. 1, we illustrate how multiple drivers at local (within the delta), regional (within the upstream watershed), and global scales interact and contribute to salinization (Fig. 3). The relative importance of each driver in inducing salinization varies widely across deltas and is determined by the local social and environmental context.

3.1. Local drivers

Local water and land-use decisions within the delta often play an important role in salinization. Groundwater abstraction in many deltas allows saline water to intrude into the aquifer, and land subsidence resulting from the excessive extraction compounds the problem. In many deltas, including the Niger, Mekong, and GBM, groundwater is the primary source of domestic drinking water [97–99] and salinization is greatest in the shallow aquifer where water is extracted for domestic use [7]. In the Huanghe delta, annual groundwater abstraction reached 100 million m^3 by 2001, both for irrigation and aquaculture [100]. Some deltas have sought to circumvent this problem by irrigating with upstream freshwater sources, such as in the Mississippi delta [96], where salinization of agriculture has largely been avoided. In the Mekong delta, numerous canals and dikes were built to provide freshwater irrigation to farmers, but the canal network has allowed greater salinity intrusion during storm surges when saltwater propagates through the network [58]. Improper maintenance of sea defense infrastructure can lead to significant overtopping of seawater and increase salinity locally [11]. Land use within the delta can also play a role in salinization. Brackish irrigation can lead to accumulation in soil of salts left behind and concentrate as water evapotranspires, or in groundwater after salts are leached from surface soils [101]. Saline aquaculture (e.g., brackish water shrimp cultivation) in the Huanghe [100], Mekong [58], and GBM [11] have also intensified salinization of soils and aquifers.

3.2. Regional drivers

Salinization is subject to an upstream-downstream dynamic because inflow of freshwater into the delta depends on upstream water and land management. Reduced inflow to deltas and their distributaries is ubiquitous across the world (Fig. 1), in many cases driven by upstream dams (e.g., GBM, Mekong, Rhine and Meuse) [11,6,102], diversions (e.g. Mississippi) [103], and consumptive agricultural water use. In river basins with extensive irrigation, the reductions of inflow can be severe. Average annual inflow to the Indus delta has been reduced by 60% or more [52], and by 71% in the Huanghe delta [100]. Diversions within deltas can also be problematic, such as in the Orinoco delta in Venezuela where a distributary was dammed to divert water for hydroelectricity production [53,104]. In the GBM delta, water is diverted at Farakka barrage, directly upstream of the Bangladeshi border, for navigability and drinking water in Kolkata (India), located adjacent to a distributary of the delta [105]. Dams and diversions also trap sediment, altering the natural deposition, accretion, and avulsion of deltas. In the Mississippi and other deltas, loss of sediment influx has resulted in subsidence of wetlands resulting in greater flooding during storm surges and saline intrusion into groundwater [38].

With regards to upstream-downstream dynamics, the Sacramento-San Joaquin delta in California is an interesting case. The Sacramento River north of the delta provides the majority of inflow into the delta, where water is then pumped from the delta for agricultural irrigation and water supply to urban centers south of the delta [106]. In this sense, the delta is situated both downstream and “upstream” of water users in California. Numerous reservoirs within this watershed divert considerable water for consumptive use, but reservoir releases are managed to ensure sufficient inflow to the delta, which to date has sufficiently inhibited salinity intrusion into the delta [106].

Lastly, the role played by hydro-politics in the salinization of deltas should also be noted. In many cases, the influence of agriculture in upstream regions overpowers the concern for salinization in the delta, especially in basins where agriculture plays a major role in the economy such as the Indus and Huanghe deltas [100,107,108]. This hydro-strategic imbalance often has greater consequences in international basins, such as the Mekong and GBM, where transboundary water negotiations are conducted at the state level, with little influence of those who live in the delta and will be most affected by salinization [109–111].

3.3. Global drivers

Local and regional changes are compounded by the effects of climate change, including sea level rise and an increase in both the frequency and magnitude of storm surges [112]. Relative sea level rise results from the combined effect of eustatic sea level rise and land subsidence, driven by natural settling of land and reduced sediment accretion within the delta due to declining upstream flow [38,113]. In some cases, subsidence can lead to relative sea level rise (up to 10 mm per year in the GBM) [114], many times greater than historical eustatic sea level rise (approximately 2 mm per year) [38,115], although the rate of eustatic sea level rise will likely grow and the increase will depend on specifics of the climate scenario that emerges [115].

In the GBM for example, salinity intrusion in the delta channel network, as measured by the 15 ppt isohaline, could penetrate

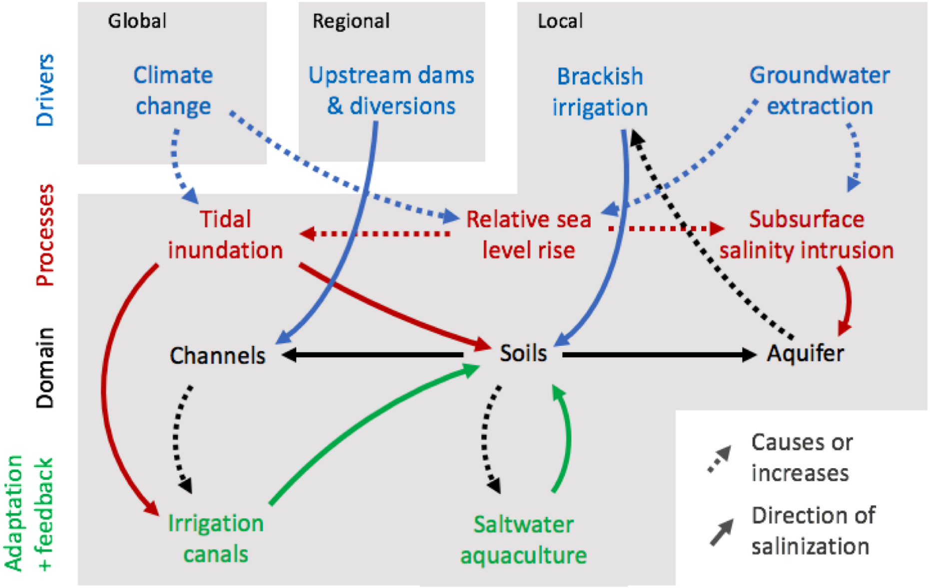

Fig. 3. Drivers of salinization, including multiple interconnected pathways by which salinization can occur.

11–28 km further inland by the end of the century under a scenario of 4.1 °C temperature increase and a sea level rise of 54 cm [116]. Accompanying effects will include even higher soil salinity in the coastal region due to changes in rainfall and temperature-induced evapotranspiration [45]. On top of this, inundation by cyclonic storm surges not only causes problems in the year the cyclone arrives, but substantially affects groundwater on a longer term [9].

Changing precipitation patterns will also likely affect the water balance of deltas, especially in regions that are subject to increasing drought [117]. Reduced precipitation in the upstream watershed will result in reduced inflow to the delta, and less precipitation within the delta itself will slow the leaching of salt from soil in wet season.

4. Adaptation and socio-hydrological feedbacks

Humans are often particularly creative when it comes to adapting to emerging salinization and, in many deltas, adaptation to salinity is a central coastal development goal. In the GBM delta, over 85 types of adaptation have been identified [118] ranging from soft socioeconomic policies, such as allocating financial resources and incentivizing land-use practices, to hard engineering measures, such as rainwater harvesting, salt tolerant crop varieties, solar desalination, community managed ponds, and managed aquifer recharge. Implicit in the drivers discussed in Section 3 is the notion that salinization can be exacerbated by adaptations designed to mitigate the consequences of salinity, creating an undesirable feedback of salinization. These feedbacks suggest that deltas are fully coupled human-water systems, where decisions have complex, far-reaching, and often unintended consequences.

Unforeseen feedbacks often emerge from uncertainty and/or inadequate consideration of the long-term consequences of adaptation actions. For instance, approaches aimed at reducing apparent flood risks (and related salinization) often make use of costly engineering solutions that inhibit natural depositional processes responsible for delta formation [113], leading to a long-term increase in flood hazards [119]. Furthermore, flood protection infrastructure also increases the tendency of communities to build in flood-prone areas, the so-called levee effect [51], with the consequence of increasing both their exposure and vulnerability to increasing flood hazard [119].

Another example of undesirable adaptation feedback relates to coastal land use transitions from freshwater irrigated agriculture (e.g., paddy) to saltwater shrimp aquaculture. The process, which has been heralded as an economically successful strategy to adapt to salinization in deltas [121,122], comes at the cost of several long-term consequences. First, the progressive replacement of freshwater irrigation by standing saltwater for shrimp cultivation exacerbates soil salinity [41,123]. Second, shrimp farming has been associated to issues related to land tenure, economic equity, and conflict for entitlement to natural resources, as revenues are concentrated towards a small number of land owners and smallholder farmers are driven off their land [120,124]. Third, shrimp farm operations are also subject to environmental variability. Sea level rise and tidal surge lead to frequent inundation of coastal land that can change the availability and quality of brackish water environments, leading to losses of shrimp stock [125]. These three effects tend to compound, leading to irreversible losses in the long term. In the Mekong delta the government provided subsidies for shrimp farming as a way for farmers to adapt to salinization, yet many farmers shifted back to rice paddy farms, despite increasingly saline conditions, after many shrimp farms encountered persistent problems with disease and pollution [126].

A third example of adaptation arises as farmers resort to groundwater as an easily accessible source of freshwater to substitute increasingly brackish surface waters. This transition mitigates immediate monetary losses for individual farmers, but accelerates salinization (e.g., through subsidence and saline intrusions into aquifers), which ultimately increases long-term communal exposure to salinity [52]. These characteristics – individual (private) benefits at the expense of communal (public) costs – are the hallmark of common-pool resources. Ostrom [127] famously showed that tragedies of the commons over such resources can be avoided through effective institutional mechanisms that typically emerge from centuries of successful collective action. Furthermore, effective regulation requires proper socio-hydrologic understanding of the linkage between human decisions and environmental feedback, particularly in the context of shared groundwater [128]. Nevertheless, it is important to keep in mind that a prevailing form of adaptation is often acceptance. For example, many people in the GBM delta increasingly consider salinity processes to be normal natural phenomena and adjust their livelihoods by enduring its consequences. However, soil and water salinity will soon reach levels where coping is not a viable choice [129] and sustainable adaptation options are urgently needed.

5. Conclusion

Salinization is an emerging existential threat in many deltas, affecting not only the livelihood and food security of large populations, but also having direct human health impacts through drinking water contamination. However, deltas are complex and coupled socio-hydrologic systems, with the impacts of salinization disproportionately affecting the poor. Secondary outcomes such as salinization-induced migration from rural areas to cities are also increasingly being recognized.

The synthesis presented in this review provides a foundation for future socio-hydrologic research regarding salinization in deltas. Salinization occurs as the result of overlapping drivers of change at multiple scales (Figs. 1 and 3), and the consequences are mediated by the combination of socioeconomic status (Fig. 2) and adaptation options. Understanding the complexity of the system is necessary to avoid undesirable feedbacks, where short-term successful adaptation actions actually worsen the phenomenon in the long-term. This requires (i) urgent and targeted transdisciplinary research that tackles the emergence of salinization in key deltas, embracing the full complexity and strongly coupled nature of the socio-hydrologic system and (ii) a concerted effort to synthesize context-specific knowledge into transferable and generalizable insights.

This review is a first step in that direction, and we highlight that the prevalence and impacts of salinization can be amplified by ongoing climate change, population pressure, economic development and transboundary water policies. For many river deltas, straightforward solutions to maintain water security and public health remain elusive, given the complexity and highly coupled nature of this environmental challenge. The scale and significance of key drivers of salinization are widespread, but they operate at different spatial scales. Agricultural impacts and water consumption act locally. The availability and delivery of freshwater acts regionally, and is often a transboundary issue. In contrast, global changes in sea levels, temperature and precipitation patterns strongly influence large scale hydrologic and environmental balances. These effects are uncertain and challenging to predict, but they disrupt key socio-hydrologic equilibria around which modern societies have been built.

In summary, the interactions between environmental change and human action result in complex feedbacks and, as such, effective adaptation, mitigation, and supportive policy design will be an ongoing challenge. Future solutions will depend on innovations that maintain freshwater availability and security, given the likelihood that climate-induced salinization will become a geographically widespread challenge. Salinization is an invisible, rapidly unfolding phenomenon that requires urgent action. Despite the complexity, synthesis of knowledge about the drivers must be more robust, necessitating transdisciplinary research in order to provide policymakers and stakeholders with adequate knowledge for informed decision-making.

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