



Coastal Salinity and Water Management Practices in the Bengal Delta: A Critical Analysis to Inform Salinisation Risk Management Strategies in Asian Deltas

Sean E. Feist¹ · Mohammad A. Hoque¹  · Kazi M. Ahmed²

Received: 25 August 2022 / Revised: 30 October 2022 / Accepted: 17 November 2022 / Published online: 5 December 2022
© The Author(s) 2022

Abstract

Salinisation within delta environments is a dynamic process governed by the interaction between coastal, fluvial and geomorphological systems. Increasingly, these have been modified through human activity and management practices, which lead to unintended problems associated with waterlogging and salt accumulation in soils and water resources. As a result of these issues, over 100 million people in the Ganges–Brahmaputra and other Asian deltas are negatively affected by a lack of freshwater availability and decreased crop yields. Rising sea levels, climate change, and population increase are all likely to exacerbate these problems. Using an iterative approach of literature review, we analyse the evolution of water management practices and policy and how these have influenced salinity within the delta, with a conceptual framework of understanding developed to guide risk management strategies. We find that management of coastal flooding and salinisation is hampered by socio-economic conditions and the dynamic hydro-morphology of the delta, which has increasingly been altered through diversion and abstraction of upstream flow. Whilst engineering solutions protect large areas from inundation, interruption of natural flood-dynamics also increases the potential impact from storm-surge and fluvio-tidal flooding. To limit salinity, policies based on salinisation science, as well as the implementation of adequately financed, multi-layered, integrated risk management plans at the local, regional, and river basin levels, are required. The promotion of stakeholder engagement should be encouraged to ensure local co-operation and effective implementation of policies. The mitigation of the multiple and cascading hazards associated with salinisation caused by anthropogenic activity, climate change and socio-economic development is crucial for the populations of delta regions across Asia.

Keywords Salinisation · Risk management · Delta coasts · Climate change

1 Introduction

Asian deltas are among the most densely populated regions of the world. They are characterised by low elevations, high rainfall, and a high rate of sediment deposition. Salinisation is a pervasive problem in low-lying coastal regions of the world's deltas (Rahman et al. 2019). The Bengal Delta is no exception. The coastal delta in Bangladesh, home to ca. 30 million people, faces increased exposure to elevated salinity

in water and soil resources, threatening ecosystem services and human welfare (Hoque et al. 2016; Szabo et al. 2016; Vineis et al. 2011; Alam et al. 2018; Rahman and Ahmad 2018). Salinity within the network of tidal river channels, which are characteristic of the region, experienced a step-wise increase during 2006–2007 (Sherin et al. 2020), with future increases and further inland progression of saline water predicted over the coming century (Dasgupta et al. 2015a; Akter et al. 2019). The full extent of soil salinisation in the region is unknown, with a 2009 survey identifying 10,560 km² of net cultivable land as affected, an increase of 26% compared to 1973 (SRDI 2010). Modelling of regional trends in climate data have been used to predict the increased occurrence of saline soils and a rise in salt accumulation of 39% by 2050 (Dasgupta et al. 2015b; Payo et al. 2017). The result for agricultural productivity is predicted to be a decline in yield of 25 to 50% by 2098 (Clarke et al. 2015).

✉ Mohammad A. Hoque
mo.hoque@port.ac.uk

¹ School of the Environment, Geography & Geosciences, University of Portsmouth, Portsmouth, PO1 3QL, UK

² Department of Geology, University of Dhaka, Dhaka, Bangladesh

The impact on the wellbeing of the population may be aggravated by the salinisation of groundwater and surface water resources, with an association between drinking water salinity and prevalent hypertension identified in the region (Khan et al. 2014; Scheelbeek et al. 2017). Ecosystem services (forest products, aquatic resources and natural hazard protection) are also at risk (Dearing and Hossain 2018; Newton et al. 2020), weakening resilience of the coastline to sea-level rise and cyclone-induced storm surge.

Under natural conditions, low-lying regions of the Bengal Delta (Fig. 1) maintain a dynamic equilibrium with sea level through sedimentation driven by the Ganges Brahmaputra (G-B) river system (Auerbach et al. 2015a). However, elevations below 5 m (of which ca. 25,000 km² are within 2 m of current sea level), frequent cyclones and the dynamics of the active delta system place the local population at risk from coastal flooding, which can have both short- and long-term impacts on economic activity and farming (Rahman et al. 2020). For thousands of years, delta dwellers attempted to manage water resources, with overflow irrigation systems established ca. 3000 years ago (Willcocks 1930). Catastrophic floods and subsequent famine from 1954 to 1956 lead to the most significant modern adaptation within the southern tidally active delta, with the reclamation of agricultural land by polder construction during the 1960's–1980's. Although potential consequences of extensive embankment construction, including subsidence, poor drainage and waterlogging, were raised by the Krug Mission under the auspices of the United Nations in 1957 (van Staveren et al. 2017), the immediate need was prioritised and isolation of the embanked areas from the surrounding delta floodplains ensued.

The subsequent evolution and application of water management from the 1960's has occurred against the backdrop of escalating natural events (e.g., sea-level rise, subsidence and cyclone storm surge) and anthropogenic alterations (e.g., construction of the Farakka Barrage) (Islam and Peterson 2009; Becker et al. 2020; Mirza 1998). The resulting interaction with hydro-morphology, coastal processes, the built environment and service sectors have variably impacted salinisation, particularly in the coastal belt (Auerbach et al. 2015a; Mirza 1998; Rahman et al. 2019; Sherin et al. 2020). Improved stakeholder participation occurred through the 1980's–1990's (van Staveren et al. 2017), with an integrated and ambitious delta-wide strategy, The Bangladesh Delta Plan 2100, being developed in the early part of this century (Alam et al. 2018).

The problem of salinisation in the Bengal Delta is complex, but it is expected to be comparable to that of other Asian deltas, requiring a thorough analysis of the delta's hydrology, geology, and ecology, as well as its water management strategies. The extensive history of water management regulations in Bangladesh, as well as its sensitivity to

climate change, provide a great opportunity to develop an understanding. Given that sea level rise is anticipated to continue for the rest of the century and that the salinisation that will arise from it will be the most difficult issue for Asian deltas, the knowledge obtained in the Bengal delta will be helpful for all deltas.

Drawing together a contemporary understanding of the hydrological processes, considering both historical water management practices and salinity in reference to the delta ecosystem, provides the basis for building a new conceptual model. This step is crucial for creating effective adaptation strategies to prevent and mitigate increases in soil and water salinity (Suter 1999; Norton et al. 1992; Auerbach et al. 2015a; Islam et al. 2019). We aim to map the understanding of salinisation, with specific reference to Bangladesh, by looking into the literature to answer specific research questions as outlined in Sect. 3. Critical gaps in knowledge will be identified with a discussion on the current risk facing the delta, the interaction of historical management strategies and whether these can be addressed in an integrated framework to address the hazards in the region from ongoing climate and hydro-morphological processes.

2 The Bengal Delta, Bangladesh—A Brief Overview

The Bengal delta—administered by both India and Bangladesh—is positioned at the juncture of three major river systems, the Ganges, Brahmaputra and Meghna (GBM), which drain over 1,500,000 km² of the Himalayas and its foothill regions (Akter et al. 2016). A combined monthly river discharge of ca. 7000 m³ s⁻¹ (dry season) to 90,000 m³ s⁻¹ (wet season) (Islam 2016) delivers an annual sediment load of ca. 1 billion tonnes yr⁻¹ (Wilson and Goodbred 2015). This morphologically active delta, with an area over 200,000 km² (Uddin and Lundberg 1999), receives an average rainfall of 1200–1900 mm yr⁻¹ of which 80% occurs within the monsoon months of June–September when the GBM system also receives water and sediment from its vast catchment (Caesar and Janes 2018).

The landforms and gently, southerly sloping topography of the delta are principally fashioned by the GBM rivers that flow into the Bay of Bengal, with elevated Pleistocene blocks outcropping in a landscape dominated by Holocene deposits (Morgan and McIntire 1959). The flat delta surface, dominantly composed of silty-clay over bank deposits, is underlain by extensive unconsolidated, semi-confined, fluvial channel sand aquifers, which provide an invaluable groundwater resource for the > 100 million inhabitants of the delta in Bangladesh and West Bengal (Ravenscroft et al. 2005; Hoque et al. 2014).

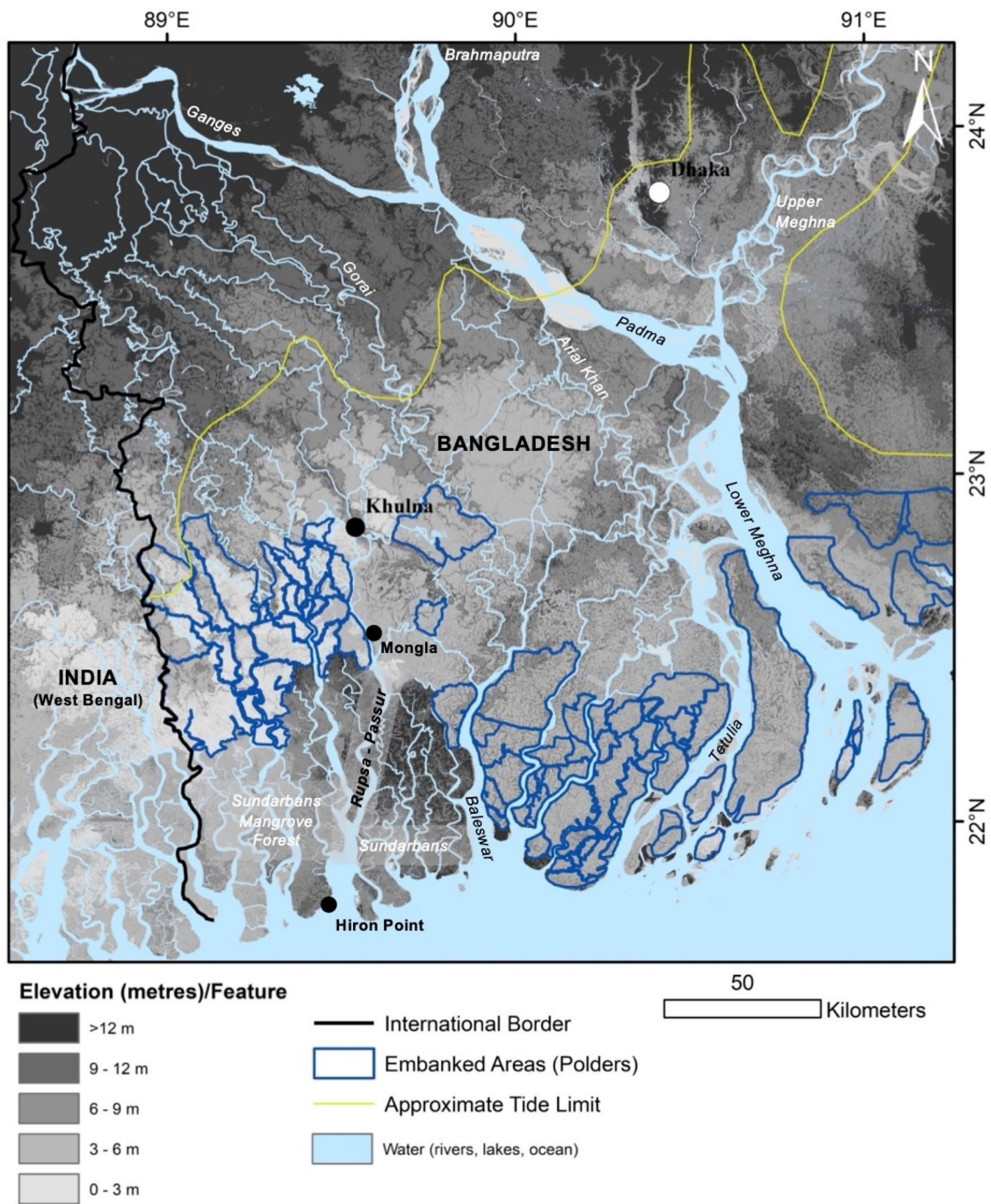


Fig. 1 The Bengal delta. Digital elevation model at 90 m resolution derived from SRTM – Shuttle Radar Topography Mission data (USGS 2018), shows the delta’s low-lying topography, gently sloping to the south. Regions below 3 m are concentrated in the southwest of Bangladesh, into West Bengal (India). The apparent increased eleva-

tion in the region of the Sunderbans results from the height of the vegetation canopy, and does not indicate true land elevation. Polders, highlighted in blue, are concentrated in coastal locations and isolate multiple stream channels

The hydro-morphological evolution of the delta from west to east is well documented and attracts continued attention (e.g., Allison, et al. 2003; Sarkar et al. 2009; Wilson and Goodbred 2015; Dewan et al. 2017). Spatial variation is

also observed across the modern delta with fluviially dominant systems in the east associated with the Lower Meghna and interconnected distributary channels, and a tidally dominant regime in the west where freshwater availability

is predominantly governed by the flow on the Gorai River (Fig. 1) (Wilson and Goodbred 2015). Semi-diurnal tides have ranges of ~2 m at the coast (Hiron Point), amplifying to ~3.5 m (Mongla) before subsiding and reaching in excess of 120 km inland during the dry season (Wilson et al. 2017). Increasingly over the last century, fluvio-tidal interactions have been modified by anthropogenic activity (Dewan et al. 2015; Wilson et al. 2017).

3 Research Approach and Methodology

A hermeneutic approach with a circular framework (Boell and Cecez-Kecmanovic 2014) was used to map the current understanding of salinisation by searching for literature, and examining and interpreting the text. While the systematic literature review is more focused on collecting data and more likely to result in identifying larger, more generalizable knowledge gaps, the hermeneutic approach is more focused on interpreting and analysing the text in order to identify what is known or poorly understood. We used hermeneutics philosophy as we focused more on specific knowledge gaps in our understanding of salinisation risk assessment (Fig. 2). In it, two hermeneutic circles, the search and acquisition circle and the analysis and interpretation circle, were used to develop a deeper understanding of the influence of policies and natural attributes as a factor in salinisation. The first circle involved searching, sorting, selecting, acquiring,

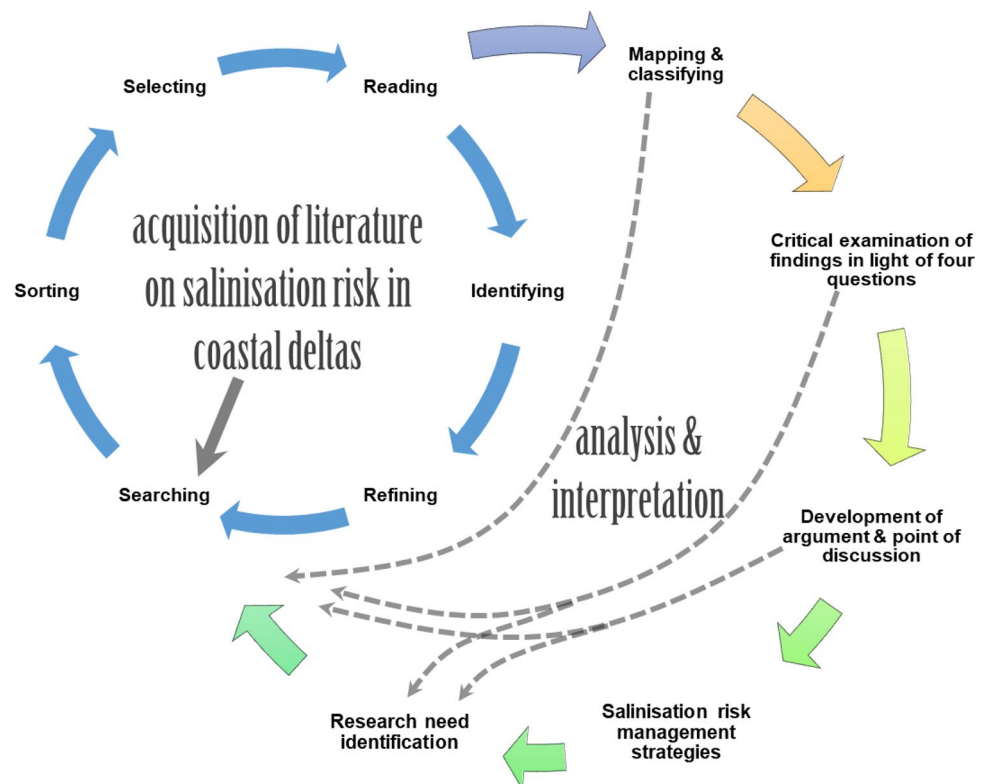
and reading, whereas the second circle involved analytical reading, mapping and categorising knowledge, and critical assessment of existing understanding.

Since our focus is on the risk of salinisation, we chose a few key publications on salinisation across a range of topics (policies, land use, hydro-morphology, health and agricultural impact). We then employed tracking references in those articles to find more relevant material as we read. After the first set of articles is read based on the extended understanding of the topic searching for additional documents was carried out. The title and abstracts of articles were used in order to establish if they are relevant in the context of the search. Furthermore, when an important paper was identified, Google Scholar and Web of Science databases were used to find other papers citing that paper allowing literature to be tracked forward in time.

In the second circle of this hermeneutic approach, an analytical framework is drawn up to meet the aim by focusing on literature that deals with the key issues of salinisation, climate change and coastal hazards, particularly in the context of low-lying coastal delta settings and Bangladesh. To map the current understanding of salinisation in low-lying deltas, we try to look for an answer to the following four questions using knowledge from the literature:

- What historical hydrological interventions in the Bengal delta have affected the coastal region? What have been the implications?

Fig. 2 The hermeneutic circles that were adopted following Boell and Cecez-Kecmanovic (2014). The acquisition circle and the analysis and interpretation circle were all used to complete the critical literature review, to develop management strategies, and to highlight unmet research needs



- What is the extent of salinity? How is this going to change in the future?
- What are the drivers of salinisation? Can we segregate the dominance of factors across the delta?
- Can we create a conceptual framework to understand the impact of salinisation, considering feedback loops?

These questions help to identify key information within the multiple sources available, with the objective questions providing a scaffold for the literature search and to focus knowledge toward the aim of the study (e.g., Webster and Watson 2002; Sackett and Wennberg 1997).

Subsequently, also under the second circle, we aim to integrate our understanding, by applying the Source–Pathway–Receptor (S-P-R) concept, previously utilised in assessing risk within coastal regions e.g., (Grilli et al. 2017). We focus on salinisation and its link to natural and anthropogenic influences and assess whether the current knowledge, placed in the S-P-R framework and accounting for feedback from previously implemented strategies, can be used to provide policy recommendations. An in-depth analysis has been considered to produce a reflective account of the link between salinisation and sea-level rise, and subsequently, the policy perspective on mitigation is discussed along with further research needs.

4 Analysis of Current Knowledge

What historical hydrological interventions in the Bengal delta have affected the coastal region?

The historical development of water resource management within the delta started ca. 1000 BC with the construction of small channel networks for overflow irrigation

and to prevent nutrient deficiency in soils (Willcocks 1930). When the system fell into disrepair and became dysfunctional in the mid-eighteenth century, temporary earth dams and canals were built in coastal areas to prevent saline incursions during the dry season (Dewan et al. 2015). This water management practice was devolved to *Zamindars* (landlords) during British colonial rule (van Staveren et al. 2017). Fast moving political events in the twentieth century, including the independence of India in 1947 and formation of the Peoples Republic of Bangladesh in 1971, have influenced water management policies in the delta. Major water management policies are highlighted in Fig. 3, focussing on those with connection to salinisation in coastal areas. More detailed accounts of policies and their implication can be found in the literature (e.g., Dewan et al. 2015; van Staveren et al. 2017; Rahman et al. 2020).

Localised earth dam water management, aligned to the natural dynamics of the delta, engaged communities in construction and maintenance (van Staveren et al. 2017) and was replaced by a large-scale engineering approach from the 1960's under the control of national government agencies e.g., the East Pakistan Water and Power Development Authority which evolved to the Bangladesh Water Development Board (BWDB) from 1971 (Dewan et al. 2015). Construction of 139 polders was carried out during the 1960's to 1980's, primarily to protect against coastal flooding and to reclaim agricultural land (Alam et al. 2018). This isolated floodplain areas from river channels, reduced sediment deposition and created waterlogging, which over time has reduced agricultural productivity (van Staveren et al. 2017; Wilson et al. 2017).

The slow evolution from a top-down based policy model was, in part, driven by international funding bodies from the late 1970's–1980's and intended to benefit local

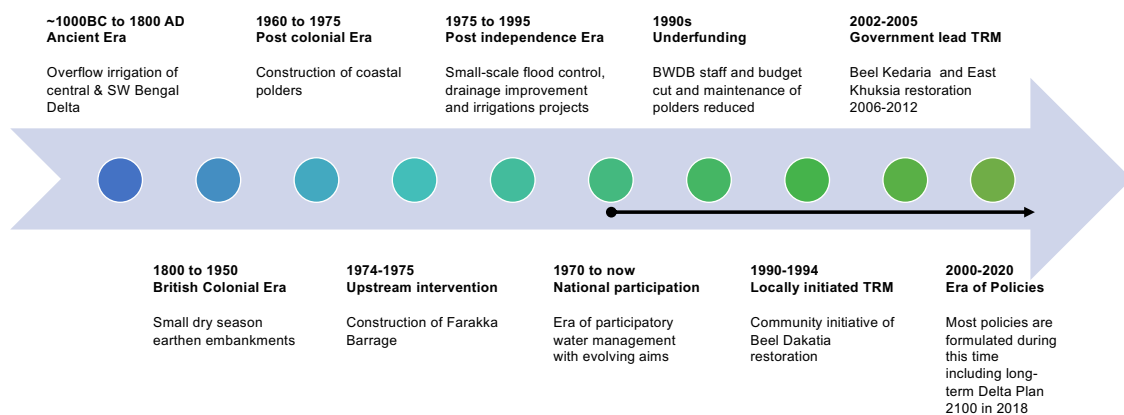


Fig. 3 Evolution of water management strategies and policies within Bangladesh and the Bengal delta. A temporal shift from systems aligned with the natural flood dynamics of the delta to engineering solutions which primarily aim to exclude flood waters can be

observed. More flexible approaches, including tidal river management (TRM) started to evolve in the late twentieth century (compiled from various sources)

communities and combat poverty (Dewan et al. 2015). It was not until the 1990's that the push for more equitable stakeholder engagement gained traction through popular opposition of centralised policy, however, in practice, the lack of power and funding at local level hindered application of localised mitigation (Van Staveren et al. 2017). The reduction of national scale funding for maintenance during the late 1990's as part of decentralisation also led to increased risk of coastal inundation associated with potential infrastructure failure (Dewan et al. 2015). Previous attempts to draw together knowledge in an integrated framework have been undertaken within the Ecosystem Services for Well-Being in Deltas project (Nicholls et al. 2018), with the ambitious national scale Bangladesh Delta Plan 2100 developed to manage rivers, flooding, water resources and associated aspects of the delta environment (Alam et al. 2018).

Bangladesh also faces competition for water resources due to its position as the downstream riparian partner to India (Ganges and Brahmaputra Rivers) and China (Brahmaputra River), with national management strategies potentially reliant on international co-operation for water sharing. This dependence is highlighted by the negotiations surrounding water flow on the Ganges after the construction of the Farakka Barrage by India during 1975, and the subsequent water sharing agreements and Ganges Treaty of 1996 (Baten and Titumir 2016). However, reductions in freshwater flow between pre- and post-Farakka periods are repeatedly highlighted (Mirza 1997; Gain and Giupponi 2014) and have been linked to increases in river salinity in southwest Bangladesh (Mirza 1998), with decreases in discharge proposed as a leading mechanism of salinisation in the region (Akter et al. 2019). The continuing challenges of trans-national water management are likely to impact national policy well into the future (Baten and Titumir 2016).

What is the extent of salinity? How is this going to change in the future?

Salinisation has impacted Bangladesh on a large scale, with the tidally active western portion of the delta showing the most severe increases during the dry season (Dasgupta et al. 2015a; Clarke et al. 2015; Wilson and Goodbred 2015). The spatial distribution of salinity within the delta is highlighted in Fig. 4, which shows the average salinity maxima between 2000 and 2017 at 54 monitoring stations, with elevated values focused in the southwest. Rising salinity is reported in multiple river channels over various timescales including the Rupsa 1965–1992 (Mirza 1998), Passur 1962–2008 (Dasgupta et al. 2015a), and the Shibsa, Kakshiali and Morishan Rivers (Shammi et al. 2017). Predictive models also suggest future upstream penetration of salinity, with the 2 ppt (parts per thousand) isohaline extrapolated over 80 km inland in the central and eastern sectors of the delta by 2050 (Dasgupta et al. 2015a). On a localised scale,

the 10 ppt front is also predicted to intrude 21 km inland along the Passur River as a consequence of the locally anticipated 0.59 m sea-level rise (SLR) (Bhuiyan and Dutta 2012). Recent studies indicate a rapid shift in salinity during the dry season of 2006–2007, however, the driving mechanism behind this change remains unresolved (Sherin et al. 2020).

Salinity already affects 20–30% of net cultivable land in Bangladesh (Baten et al. 2015) with increased river salinity in the southwest mirrored by the spatial distribution of soil salinity in coastal regions (Salehin et al. 2018). Mean electrical conductivity (EC) values > 3 dS/m are recorded in soils of the southwest and coastal regions of the central and eastern portions of the delta (Dasgupta et al. 2015b). Computer modelling predicts increased occurrence of saline soils through the twenty-first century combined with associated decreases in crop yields (Payo et al. 2017; Dasgupta et al. 2015b; Clarke et al. 2015).

High levels of salinity up to ~ 13.5 g/L are also recorded in groundwater (e.g., Ayers et al. 2016; Saha et al. 2018; Sarker et al. 2014; Worland et al. 2015) with a naturally occurring saline front present in coastal areas (Ravenscroft et al. 2013). Whilst elevated salinity may (partially) result from connate pore water emplaced during the deposition of marine/estuarine sediments (Ayers et al. 2016), inundation resulting from storm surges has the potential to increase both soil and shallow groundwater salinity (Islam et al. 2019; Rahman et al. 2018).

In contrast to the well-developed north–south oriented palaeo-channels in the southeast of the delta, limited-scale fluvial channel deposits in the southwest retards regional fresh groundwater recharge and limits flushing of salinity from potential aquifer units (Ravenscroft et al. 2005; Naus et al. 2019).

What are the drivers of salinisation? Can we segregate the dominance of factors across the delta?

The spatio-temporal distribution of salinity within the G-B Delta results from the complex interaction between multiple drivers over varying timescales of hours (e.g., tides and storm events—Dasgupta et al. 2015a; Karim and Mimura 2008), months (e.g., river discharge—Mirza 1998), decades (e.g., channel migration—Coleman 1969), centuries (e.g., subsidence—Brown and Nicholls 2015) and millennia (e.g., marine transgression/regression and delta formation—Allison et al. 2003). The shifting hydro-morphology and natural processes within the delta conflict with the stability desired by its human populace. Anthropogenic modification of hydro-morphology within the coastal belt, through freshwater abstraction/diversion, polder construction and land use, directly impacts salinity (Mirza 1998; Pethick and Orford 2013; Islam et al. 2019).

The key role of discharge and flow modification, combined with subsequent impacts on fluvial geomorphology of

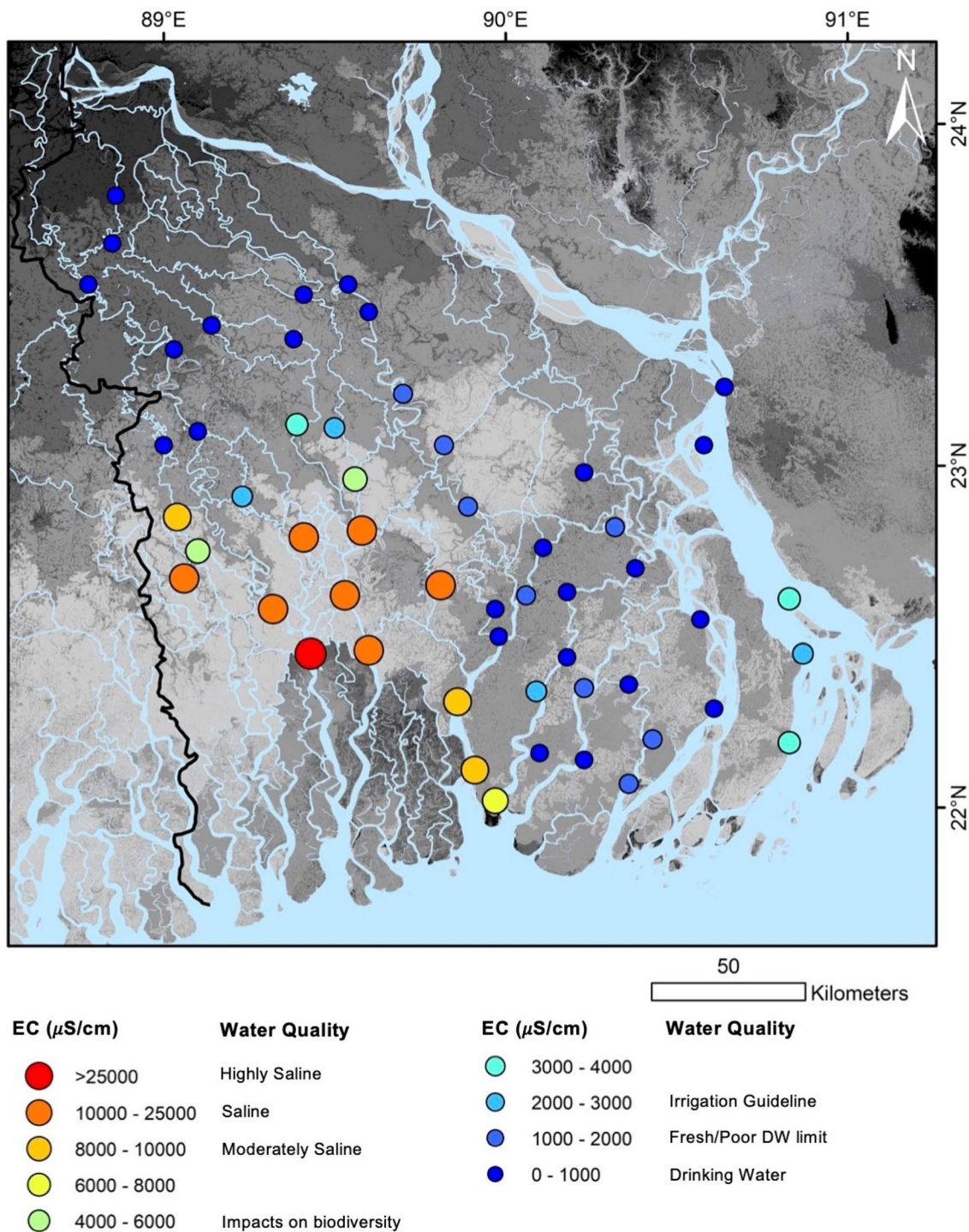


Fig. 4 Salinity maxima in the river system of Bangladesh during the period 2000 to 2017. Elevated salinity is observed in the southwest, in a region where polders dominate the landscape and land elevation is below 6 m (lightest grey colouration) (refer to Fig. 1). The large

volumes of freshwater discharged in the east of the delta are seen to reduce the salinity in this region, despite the tidal propagation (highlighted in Fig. 1) penetrating over 100 km inland

the Gorai River are highlighted in the work by Mirza (1998). Correlation between high flow volumes along the Gorai and decreased salinity in the region has been demonstrated

before. Dredging on this channel, as a management strategy, is accredited with increasing flow by 5–13% during the dry seasons between 2010 and 2013 (MoP 2014), however,

long-term sustainability is unlikely because of the dynamic geomorphology of the river and high costs (Gazi et al. 2020). The concept that salinity is linked to reduced upstream flow is supported by Akter et al (2019), who propose this as the dominant mechanism within the region, with the impact of SLR suggested to be limited to coastal areas, and further localised influence on salinity from cyclone-induced storm surge.

Polder construction has further influenced the balance between tidal flow and river discharge, by altering channel geometry (Du et al. 2018). The isolation of river channels from the floodplains has also restricted active channel length, by up to 60%, with a reduction exceeding 600 km in the southwest delta floodplain (Wilson et al. 2017). Greater estimates of > 1000 km are forecast for the whole delta (Pethick and Orford 2013). This decreased capacity has created higher water levels in coastal areas and pushed saline waters further inland through the remaining open channel network (Pethick and Orford 2013).

Salinisation of soils has been associated with increases in salinity in adjacent rivers (Salehin et al. 2018), irrigation (Clarke et al 2015; Salehin et al. 2018) and saltwater shrimp farming (Be et al. 1999; Ali 2006; Chowdhury et al. 2011). Inundation resulting from the overtopping of flood defence embankments during storm surge events can also be a source of saline water (Auerbach et al. 2015a; Ikeuchi et al. 2017). If un-remediated this flooding can also increase underlying shallow groundwater salinity (Rahman et al. 2018; Islam et al. 2019). Salinity variations in the shallow aquifer (< 60 m depth) are linked to land use and hydro-morphological features, including the location of freshwater ponds, elevation, siting of brackish water shrimp ponds and areas exposed to more regular tidal flooding (Naus et al. 2019; Islam et al. 2019). The high salinity in the southwest of Bangladesh has led to increased development of brackish water aquaculture, which covers an area ca. 150,000 hectares in the region (Ahmed and Diana 2015), and conflicts with the freshwater demands of agriculture. With saline waters actively introduced into the polders which are designed to protect the land and water resources from sea-water flooding. Active breaching of polders at the community level may also be initiated to reduce waterlogging (van Staveren et al. 2017), however, whilst this may achieve the addition of sediments within the affected area, saline water may be trapped within the sediment, or infiltrate into underlying groundwater enhancing salinisation (Auerbach et al. 2015a). Previous predictive models (Dasgupta et al. 2018; Clarke et al. 2015) anticipate that, without suitable adaptation strategies, salinities in the southwest will exceed 20 ppt by the end of the century, essentially limiting dry season agriculture.

Can we create a conceptual framework to understand the impact of salinisation, considering feedback loops?

Salinisation impacts multiple aspects of delta ecology, ecosystem services, agriculture and human health through the introduction of potentially harmful sources of excess sodium (Na) to ecological (Herbert et al. 2015) and human receptors (Scheelbeek et al. 2017) as summarised in the conceptual framework presented in Fig. 5. Increased salinity within coastal wetlands and mangrove forests results in shifts in floral and faunal distribution and is linked to dying back of Sundari and Goran trees in the Sunderban (Newton et al. 2020). These changes threaten to affect ecosystem services including forestry, fishing and honey/wax collection, whilst reducing natural protection against cyclonic storm surges and coastal erosion (Islam and Bhuiyan 2018).

Agricultural productivity is closely linked to soil quality, with nutrient cycling critical for healthy crop growth. Both abiotic and biotic elements of soils are negatively affected by increased salinity through alteration of cation exchange capacity and increased faunal mortality which reduce nutrient availability/cycling (Evangelou and McDonald 1999; Herbert et al. 2015; Butcher et al. 2016). Physical degradation of soils, caused by the adsorption of Na⁺ ions onto clay mineral surfaces and subsequent expansion of clay particles also results in reduced porosity/permeability (Vengosh 2005)—exacerbating problems associated with waterlogging. High levels of soluble and exchangeable Na within soils and pore water can decrease crop yields by reducing water uptake via osmotic stress and toxicity within plant cells (Butcher et al. 2016; Dasgupta et al. 2018; Zörb et al. 2019). Increased salinity in irrigation water not only reduces rice yields (water exceeding > 2000 µS/cm causes in a 10% decline), but it is also associated with lower yields in other locally grown crops such as Melon, Mustard, Sweet Potato and Potato (Haque et al. 2014; Rahman et al. 2011). These negative impacts on agriculture are proposed to reduce income within the affected areas and to be a driver behind internal migration within Bangladesh (Chen and Mueller 2018).

Surface water and aquifer resources are also threatened by increasing salinity (Hoque et al. 2016), with storm surge inundation not only driving the salinisation of shallow groundwater (Islam et al. 2019) but also resulting in the contamination of drinking water ponds (Hoque et al. 2016). Cohort studies have identified an association between increased Na concentration in drinking water and increased rates of hypertensive disorders such as (pre)eclampsia (Khan et al. 2011, 2014), increased infant mortality (Dasgupta et al. 2016) and other cardio-metabolic health issues (Scheelbeek et al 2017). In coastal Bangladesh and other Asian deltas, drinking water sources with high saline content are reported

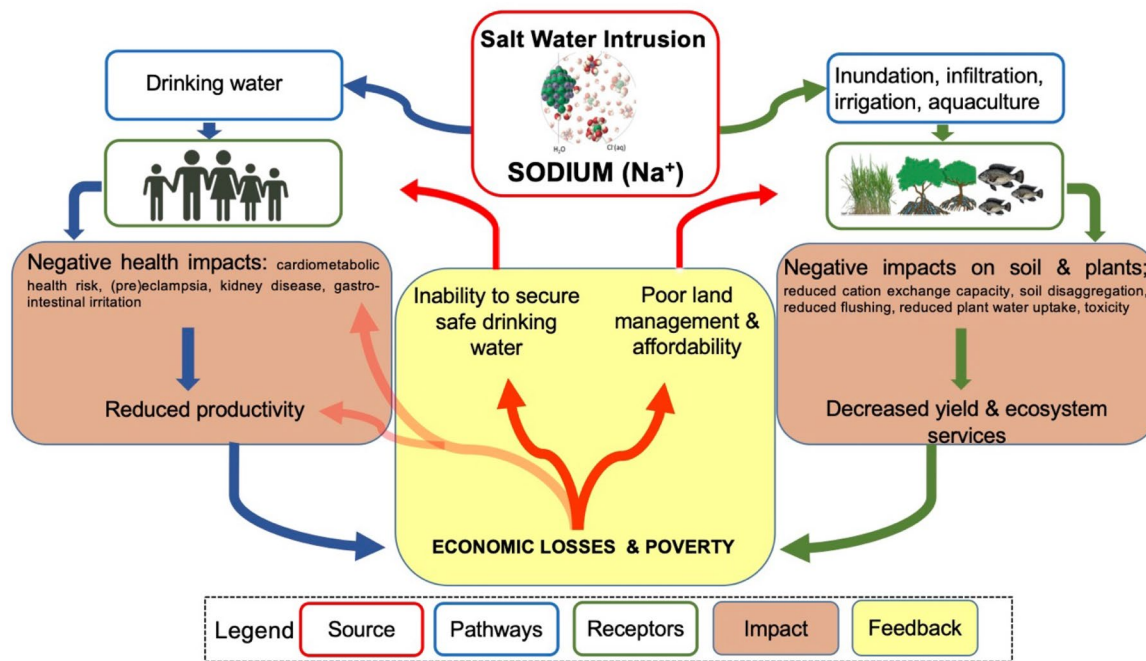


Fig. 5 The process and impact of salinisation. The conceptual understanding of saltwater intrusion on ecosystems and human health based on the Source–Pathway–Receptor (S-P-R) and feedback loop concept. Coastal salinity ubiquitously introduces excess sodium,

impacting human health, crop yield and ecological balance. Initial negative impacts feedback into the system causing a cycle of increased land degradation and poverty

to be contributing to an increased intake of sodium (Hoque and Butler 2015).

5 Discussion

5.1 Interaction of Natural and Anthropogenic Processes and Enhanced Risk

The current consensus is that fluvio-tidal and storm surge flooding are the primary causes of episodic inundation of vast areas in southwest Bangladesh (Adnan et al. 2019). The landfall of tropical cyclones, which occur at an average frequency of 10 per decade (Islam and Peterson. 2009), can produce a surge of seawater linked to a low-pressure induced rise in water level at the centre of the storm. This sudden rise in sea level can be amplified by the timing (e.g., high spring tides) or by the narrow width and shallow depth of tidal creeks/channels (Woodruff et al. 2013; Du et al. 2018). The large-scale polders designed to prevent coastal flooding and protect agricultural land (Adnan et al. 2019) have, in the long term, increased the vulnerability of enclosed areas, with increased risk of breaching or overtopping through differential subsidence, SLR and altered channel geometry (Auerbach et al. 2015a; Du et al. 2018; Becker et al. 2020). Inundation now initiates a cascading hazard (Fig. 6), with

multiple sequential impacts and feedback on the livelihoods of the local population and regional economy (Szabo et al. 2016; Chen and Mueller 2018). This risk is compounded by the potential for coastal erosion and the dynamic geomorphology of the delta (Wilson et al. 2017).

Over time, the construction of polders has resulted in waterlogging problems, increased salinity and decreased nutrients, all limiting potential for crop growth and agricultural productivity (van Staveren et al. 2017; Haque et al. 2014). Subsequent changes in land use, through increased adoption of shrimp farming, have further enhanced exposure of flood protected land to sources of salinity (Ahmed and Diana 2015). Increased potential for exposure to salinisation is predicted through increased cyclone frequency in the post-monsoon season (Sahoo and Bhaskeran. 2016) and through globally accelerating SLR (Dangendorf et al. 2017; IPCC 2021).

The primary controls on the spatial distribution of salinity are temporally variable, with current SLR and subsidence rates increasing average tidal water levels within the delta (Becker et al. 2020; Feist et al. 2021). The intra-regional and local spatial variability remain poorly defined, with recent studies (Sherin et al. 2020) providing limited insight into short term dynamics and driving mechanisms. However, since the mid-twentieth century human activity appears to play an increasing role in salinisation, through modification

(Pescaroli and Alexander 2018). Hazard identification and risk management must, therefore, address the multiple tiers and timescales involved in order to protect society from the physical and economic hardships introduced by salinisation.

5.3 Multi-barrier Risk-Based Mitigation of Hazards—Salinity Safety Planning

The management of salinisation requires action at various spatial and temporal scales; ranging from regional, river basin and at individual polder levels, providing multiple tiers of hazard mitigation potentially capable of addressing the issue of cascading hazards. Approaches based on the concept of risk management through the removal of salinity sources, disruption of pathways of exposure, or removal of receptors should incorporate an assessment of vulnerability to identify areas where mitigation is a priority due to environmental and socio-economic factors (Das et al. 2020).

Landward progression of saline water along river channels is currently limited on the tidal plains by a single level of protection—polder embankments and associated infrastructure—which are vulnerable to overtopping/breaching/failure (Adnan et al. 2019). Limiting the source of salinity at the regional/river basin scale, through maintenance of upstream flow is key to lowering salinity within river

channels (Akter et al. 2019). However, the natural upstream hydro-morphological dynamics and uncertain, location-specific, interactions between discharge and SLR (e.g., on the Gorai River) add further complexity. The conflict between fresh and brackish water demand, driven by increased aquaculture within the polder and providing both a source and pathway of exposure, also requires careful management. Further challenges exist with regard to the impacts of international water-sharing agreements and potential rising demand due to population growth, economic development and climate change (Brichieri-Colombi and Bradnock 2003; Szabo et al. 2016).

At the polder scale, consideration of short-, medium- and long-term strategies to isolate salinity from potential receptors is essential and can be incorporated into a Salinity Safety Plan (SSP) (Fig. 7). Short-term measures require the identification of existing regular and intensifying hazards (e.g., SLR-induced erosion) which are a risk factor for embankment/infrastructure breaching, overtopping or failure. Medium-term options include annual maintenance programmes for embankments, sluice gates, and other critical infrastructure within the polders. With long-term measures focussing on the mitigation of unintended consequences of polder construction, such as relative subsidence and drainage problems.

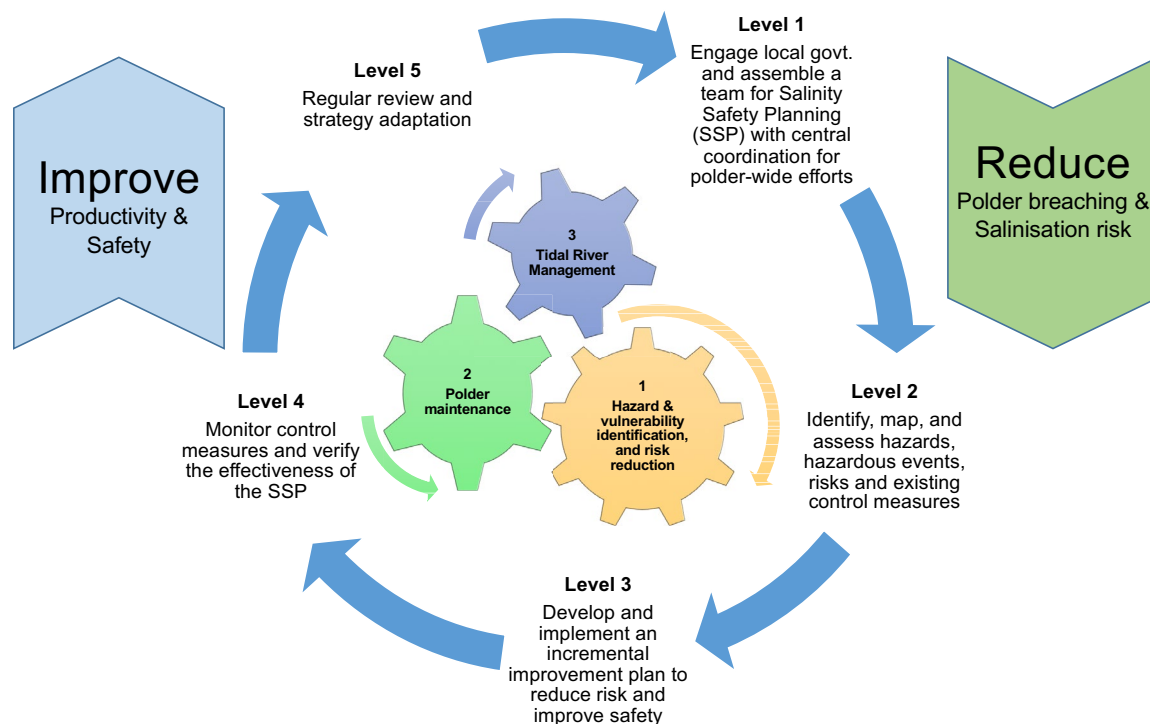


Fig. 7 The Salinity Safety Plan (SSP) with implementation levels in the centre. The systematic processes and steps outlined in the diagram highlight the multiple and iterative stages of planning required with feedback guiding future adaptation of planning strategies and mitiga-

tion measures based on their relative success/effects. Flexibility and adaptation are key to the process in order to avoid entrenchment and single policy dominance

Whilst individual levels of risk management cannot address all of the hazards present, the overlap of multiple mitigation steps should minimise risk and provide timely remediation options to prevent salinisation. This tiered approach is utilised within the drinking water industry and community water supply system where the Water Safety Plan (WSP) is well established (Mahmud et al. 2007; WHO 2012). A similar approach and development of the SSP may be adopted to promote local community engagement (Fig. 7). Viable plans with adequate funding for mitigation and maintenance require development, that supports/enhance measures being adopted by neighbouring polder units, and are approved by the local community working in unison with the local government.

Local measures should harmonise with regional and national policy, the latter prioritising maintenance of freshwater flow, and utilise the natural flood dynamics of the delta. Although WSP considers safety from the catchment to the user level (Mahmud et al. 2007), its scope is often limited, therefore, SSP may require initiation at a regional level with multi-level nesting of working groups. The SSP needs to consider freshwater flow at the river basin scale, sediment dynamics at the tidal basin scale, protection at the polder embankment scale, and for the worst case scenario—embankment failure—protection of critical infrastructure within the polder (e.g., power supply, health, social services).

Historical water management practices in coastal areas prior to polder construction favoured approaches which maintained natural ecological balances (Willcocks 1930; Dewan et al. 2015). Recent attempts to mimic these practices under TRM (tidal river management) show promising results, but not without social and hydrological consequences (Gain et al. 2017). TRM returns the polder to the tidal plain by the removal of embankments, allowing the flood and tidal waters to regularly inundate the previously isolated area. Within 3–5 years' sedimentation restores surface elevation resolving waterlogging (Gain et al. 2017), with estimations of up to 1.4 m of elevation could be added within 5 years (Adnan et al. 2020). However, this prevents agricultural activity during implementation of the TRM, with salinisation remaining a potential problem for soil and groundwater in strongly tidal areas (Auerbach et al. 2015a; Gain et al. 2017). River channels adjacent to polders in coastal areas are frequently at or below 3 m elevation (Fig. 1), equivalent to the regional tidal range (Wilson et al. 2017). These channels are flooded twice a day and hydrodynamic equilibrium is established between saline river water and the underlying aquifer, forming a pathway for groundwater salinisation (Smith and Turner 2001). During extreme high tides, these streams may also flood surrounding farmland resulting in the further accumulation of salts in soils.

TRM is, therefore, not a universal solution, with greater potential for success in specific areas. Auerbach et al. (2015a) highlight the potential for sediment delivery and elevation recovery during periods of exposure to tidal action, clarifying the saline nature of these sediments and complexities of TRM in coastal areas in later correspondence (Hossain et al. 2015; Auerbach et al. 2015b). Whilst modelling studies demonstrate that limiting TRM to the monsoon season, when river water is fresh and loaded with sediments, will have greater freshening impact on groundwater and soil salinity (Islam et al. 2019). The latter approach has greater affinity with water management practiced by the *Zamindar* from the 1700's to 1950's (Dewan et al. 2015; van Staveren et al. 2017; Adnan et al. 2020).

In regions where salinisation has become extreme, increased adoption of shrimp farming has already occurred (Ahmed and Diana 2015), with increased rates of migration away from the affected areas (Szabo et al. 2016; Chen and Mueller 2018). Future action may be necessary to provide compensation for farmers forced to leave their land due to loss of productivity or lack of potable water. Whilst the scale of managed retreat in global coastal communities has so far been limited (Oppenheimer et al. 2019), where required a highly targeted approach could enable the distribution of resources to areas where mitigation can be most effective (Hino et al. 2017; Carey 2020). It is acknowledged that this approach could prove unpopular and problematic in an area of high population density, however, this step could provide the opportunity to enhance natural environmental systems through reforestation, ultimately increasing coastal protection and ecosystem services (Dearing et al., 2018; Newton et al. 2020).

5.4 Research Challenges and Opportunities

This study has attempted to draw together and synthesise the current knowledge available within the published literature in order to formulate a method for risk management for salinisation. However, potential limitations of a single approach to managing salinisation are acknowledged due to the significant spatial and temporal variability in the drivers of salinity and anthropogenic interaction with deltaic processes (e.g., tides, sedimentation, erosion, channel morphology, etc.). Significant challenges also exist due to the incomplete understanding of the rates of change in natural processes and their spatial variability within the delta, and the spatio-temporal scales at which various drivers are operating.

Whilst the S-P-R framework provides a method to outline the problem of salinisation within the delta, a complex network of feedback loops between natural and anthropogenic systems are identified which require further investigation. Identifying regional trends in driving factors, such as river

discharge, subsidence and SLR e.g., (Becker et al. 2020; Sherin et al. 2020; Feist et al. 2021) can help identify the overall risk to the delta. However, these can mask local and intra-regional variability (e.g., Fujihara et al. 2016; Valle-Levinson et al. 2017), knowledge of which is required to target the most vulnerable areas.

Local association between decreased river discharge and increased salinity has already been demonstrated (Mirza 1998). However, despite further study (Akter et al. 2019; Sherin et al. 2020), the association between SLR and salinisation within the delta remains poorly defined. Previous studies have focussed on modelling approaches for investigating inland tidal propagation (e.g., Bhuiyan and Dutta; 2012; Dasgupta et al. 2015a; Akter et al. 2019) with limited use of in situ observation data (e.g., Mirza 1998; Rahman et al. 2000; Sherin et al. 2020).

Multiple studies also identify the potential pathways for salinisation through interaction between surface waters, soil and shallow groundwater (e.g., Islam et al. 2019; Rahman et al. 2018; Naus et al. 2019). However, the relationship between river salinity and soil/groundwater salinisation remains poorly constrained, with associations restricted to coastal areas (Salehin et al. 2018). Insights into river—groundwater interaction are also limited in the region (Peters and Hornberger 2020) with the potential for density driven flow in coastal rivers identified in other tidal channel settings (Smith and Turner 2001).

These knowledge gaps restrict the ability to develop integrated risk management plans and combine with climate change and increasing populations to increase the vulnerability of water and agricultural security within the region (Hoque et al. 2016). Sea-level, water-level and river salinity monitoring data, available for Bangladesh from the BWDB, Bangladesh Inland Water Transport Authority and open source data repositories (e.g., the Permanent Service for Mean Sea level [PSMSL]), provide the opportunity to define these processes within the G-B Delta, with potential for application in other Asian deltas. Targeted research in these areas will provide a baseline understanding for the local SSP framework and for regional policy guidance for climate change adaptation and infrastructure risk management planning.

6 Conclusions

The review of historical—modern day water management processes and policies, and their association with salinisation in Bangladesh allows us to assess the current knowledge surrounding the mechanisms of salinisation and the potential for the application of an integrated risk management process in low-lying deltas.

Historical interventions within Bangladesh have changed from being aligned with the natural deltaic processes to one of protection and isolation. This has led to problems of waterlogging and differential subsidence, with an associated risk of increased vulnerability resulting from embankment overtopping/failure. These issues are now better understood, with limited application of tidal river management being used to mitigate the increased risk.

Salinisation of water and soil resources in the region is extensive, particularly in the southwest of Bangladesh. However, whilst changes in river discharge are singled out as a potential leading driver, there is little consensus on the relative contribution of SLR, cyclones or groundwater flow to the process, with limited quantification of the rates of change affecting these drivers. The characterisation of the spatio-temporal distribution of salinity and its rate of change in surface water and soils is poorly defined from observed data, and is reliant on modelling to provide predictions. An increased level of analysis on monitoring data, available for Bangladesh, would help build on our current understanding and assist in model development.

The construction of a conceptual model, based on the S-P-R framework, aids in linking our understanding of salinisation within the delta and the feedback loops, which adversely impact the local population and lead to increased exposure of soil and water resources to salinity. The adaptation to salinisation by increased brackish water shrimp farming within the polders breaks down the fundamental purpose of these engineered barriers, and does not address the underlying issues that are leading to increased outward migration from the affected regions. Developing the model into a framework of cascading hazards we also identify the complexity and multiple aspects of risk associated with elevated salinity within coastal areas which, based on current changes of tidal water levels in the delta of ca. 3 mm yr⁻¹, and predictions derived from modelling studies which indicate increased salinity will be encountered further inland.

The Salinity Safety Plan (SSP) has also been proposed to aid policy development and provides a robust and systematic method to address the issues identified and to ensure the adoption of flexible mitigation strategies that can be adapted based on the feedback encountered from the initial implementation. These plans require integration with national and regional policy and should be led at the community level to ensure engagement and its relevance to the needs of the local populace.

Crucially, in order to develop policy recommendation, gaps in our knowledge must be addressed through continued analysis of the processes governing salinisation within delta environments, which are currently facing increased risk from the consequences of changing climate and pressures from increased populations.

Acknowledgements This work was funded by The University of Portsmouth.

Author Contributions S. F.: conceptualisation, formal analysis, writing—original draft, review and editing, funding acquisition. M. H.: conceptualisation, supervision, writing—review and editing, funding acquisition, and overall project management. K. M. A.: supervision, writing—review and editing, funding acquisition.

Declarations

Conflict of Interest The authors declare no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Adnan MSG, Haque A, Hall JW (2019) Have coastal embankments reduced flooding in Bangladesh? *Sci Total Environ* 682:405–416. <https://doi.org/10.1016/j.scitotenv.2019.05.048>
- Adnan MSG, Talchabhadel R, Nakagawa H, Hall JW (2020) The potential of Tidal River Management for flood alleviation in South Western Bangladesh. *Sci Total Environ* 731:138747. <https://doi.org/10.1016/j.scitotenv.2020.138747>
- Ahmed N, Diana JS (2015) Threatening “white gold”: Impacts of climate change on shrimp farming in coastal Bangladesh. *Ocean Coast Manag* 114:42–52. <https://doi.org/10.1016/j.ocecoaman.2015.06.008>
- Akter J, Sarker MH, Popescu I, Roelvink D (2016) Evolution of the Bengal delta and its prevailing processes. *J Coastal Res*. <https://doi.org/10.2112/JCOASTRES-D-14-00232.1>
- Akter R, Asik TZ, Sakib M, Akter M, Sakib MN, Al Azad ASMA, Rahman MM (2019) The dominant climate change event for salinity intrusion in the GBM delta. *Climate* 7(5):1–23. <https://doi.org/10.3390/cli7050069>
- Alam S, de Heer J, Choudhury G (2018) Bangladesh Delta Plan 2100: Baseline Studies on Water Resources Management. Dhaka.
- Ali AMS (2006) Rice to shrimp: Land use/land cover changes and soil degradation in Southwestern Bangladesh. *Land Use Policy* 23(4):421–435. <https://doi.org/10.1016/j.landusepol.2005.02.001>
- Allison MA, Khan SR, Goodbred JL, Kuehl SA (2003) Stratigraphic evolution of the late Holocene Ganges-Brahmaputra lower delta plain. *Sed Geol* 155(3–4):317–342. [https://doi.org/10.1016/S0037-0738\(02\)00185-9](https://doi.org/10.1016/S0037-0738(02)00185-9)
- Auerbach LW, Goodbred SL, Mondal DR, Wilson CA, Ahmed KR, Roy K, Ackerly BA (2015a) Flood risk of natural and embanked landscapes on the Ganges-Brahmaputra tidal delta plain. *Nat Clim Chang* 5(2):153–157. <https://doi.org/10.1038/nclimate2472>
- Auerbach LW, Goodbred SL, Mondal DR, Wilson CA, Ahmed KR, Roy K, Ackerly BA (2015b) Reply to ‘Tidal river management in Bangladesh’. *Nat Clim Chang* 5(6):492–493
- Ayers JC, Goodbred S, George G, Fry D, Benneyworth L, Hornberger G, Akter F (2016) Sources of salinity and arsenic in groundwater in southwest Bangladesh. *Geochem Trans* 17(1):1–23. <https://doi.org/10.1186/s12932-016-0036-6>
- Baten MA, Titumir RAM (2016) Environmental challenges of trans-boundary water resources management: the case of Bangladesh. *Sustain Water Res Manag* 2(1):13–27. <https://doi.org/10.1007/s40899-015-0037-0>
- Baten MA, Seal L, Lisa KS (2015) Salinity intrusion in interior coast of Bangladesh: challenges to agriculture in south-central coastal zone. *Am J Clim Chang* 04(03):248–262. <https://doi.org/10.4236/ajcc.2015.43020>
- Be TT, Dung LC, Brennan D (1999) Environmental costs of shrimp culture in the rice-growing regions of the Mekong Delta. *Aquac Econ Manag* 3(1):31–42. <https://doi.org/10.1080/13657309909380231>
- Becker M, Papa F, Karpytchev M, Delebecque C, Krien Y, Khan JU, Shum CK (2020) Water level changes, subsidence, and sea level rise in the Ganges-Brahmaputra-Meghna delta. *Proc Natl Acad Sci USA* 117(4):1867–1876. <https://doi.org/10.1073/pnas.1912921117>
- Bhuiyan MJAN, Dutta D (2012) Assessing impacts of sea level rise on river salinity in the Gorai river network, Bangladesh. *Estuar Coast Shelf Sci* 96:219–227. <https://doi.org/10.1016/j.ecss.2011.11.005>
- Boell SK, Cecez-Kecmanovic D (2014) A hermeneutic approach for conducting literature reviews and literature searches. *Commun Assoc Inf Syst* 34(1):12. <https://doi.org/10.17705/1CAIS.03412>
- Brichieri-Colombi S, Bradnock RW (2003) Geopolitics, water and development in South Asia: cooperative development in the Ganges-Brahmaputra delta. *Geogr J* 169(1):43–64. <https://doi.org/10.1111/1475-4959.t01-1-00002>
- Brown S, Nicholls RJ (2015) Subsidence and human influences in mega deltas: the case of the Ganges-Brahmaputra-Meghna. *Sci Total Environ* 527–528:362–374. <https://doi.org/10.1016/j.scitotenv.2015.04.124>
- Butcher K, Wick AF, Desutter T, Chatterjee A, Harmon J (2016) Soil salinity: a threat to global food security. *Agron J* 108(6):2189–2200. <https://doi.org/10.2134/agronj2016.06.0368>
- Caesar J, Janes T (2018) Regional climate change over South Asia. In *Ecosystem Services for Well-Being in Deltas* (p. 207). Palgrave Macmillan, Cham.
- Carey J (2020) Managed retreat increasingly seen as necessary in response to climate change’s fury. *Proc Natl Acad Sci* 117(24):13182–13185. <https://doi.org/10.1073/pnas.2008198117>
- Chen J, Mueller V (2018) Coastal climate change, soil salinity and human migration in Bangladesh. *Nat Clim Chang* 8(11):981–987. <https://doi.org/10.1038/s41558-018-0313-8>
- Chowdhury MA, Khairun Y, Salequzzaman M, Rahman MM (2011) Effect of combined shrimp and rice farming on water and soil quality in Bangladesh. *Aquacult Int* 19(6):1193–1206. <https://doi.org/10.1007/s10499-011-9433-0>
- Clarke D, Williams S, Jahiruddin M, Parks K, Salehin M (2015) Projections of on-farm salinity in coastal Bangladesh. *Environ Sci: Process Impact* 17(6):1127–1136. <https://doi.org/10.1039/c4em00682h>
- Coleman JM (1969) Brahmaputra River: channel processes and sedimentation. *Sed Geol* 3(2–3):129–239
- Dangendorf S, Marcos M, Wöppelmann G, Conrad CP, Frederikse T, Riva R (2017) Reassessment of 20th century global mean sea level rise. *Proc Natl Acad Sci USA* 114(23):5946–5951. <https://doi.org/10.1073/pnas.1616007114>
- Das S, Ghosh A, Hazra S, Ghosh T, de Campos RS, Samanta S (2020). Linking IPCC AR4 & AR5 frameworks for assessing vulnerability and risk to climate change in the Indian Bengal Delta. *Progress in Disaster Science*, 100110.

- Dasgupta S, Hossain MM, Huq M, Wheeler D (2015b) Climate change and soil salinity: the case of coastal Bangladesh. *Ambio* 44(8):815–826. <https://doi.org/10.1007/s13280-015-0681-5>
- Dasgupta S, Huq M, Wheeler D (2016) Drinking water salinity and infant mortality in coastal Bangladesh. *Water Econ Policy* 2(01):1650003
- Dasgupta S, Hossain MM, Huq M, Wheeler D (2018) Climate change, salinization and high-yield rice production in coastal Bangladesh. *Agric Res Econ Rev* 47(1):66–89. <https://doi.org/10.1017/age.2017.14>
- Dasgupta S, Akhter Kamal F, Huque Khan Z, Choudhury S, Nishat A (2015a) River Salinity and Climate Change: Evidence from Coastal Bangladesh. In *Asia and the World Economy* (pp. 205–242). WORLD SCIENTIFIC. doi:https://doi.org/10.1142/9789814578622_0031
- Dearing JA, Hossain MS (2018) Recent trends in ecosystem services in coastal Bangladesh. In: Nicholls RJ, Hutton CW, Adger WN, Hanson SE, Rahman MM, Salehin M (eds) *Ecosystem Services for Well-Being in Deltas*. Palgrave Macmillan, Cham, pp 93–114
- Dewan C, Mukherji A, Buisson MC (2015) Evolution of water management in coastal Bangladesh: from temporary earthen embankments to depoliticized community-managed polders. *Water Intern* 40(3):401–416. <https://doi.org/10.1080/02508060.2015.1025196>
- Dewan A, Corner R, Saleem A, Rahman MM, Haider MR, Rahman MM, Sarker MH (2017) Assessing channel changes of the Ganges-Padma River system in Bangladesh using Landsat and hydrological data. *Geomorphology* 276:257–279. <https://doi.org/10.1016/j.geomorph.2016.10.017>
- DMB. (2010). National Plan for Disaster Management, 2010–2015. Disaster management Bureau.
- Du J, Shen J, Zhang YJ, Ye F, Liu Z, Wang Z, Wang HV (2018) Tidal response to sea-level rise in different types of estuaries: the importance of length, bathymetry, and geometry. *Geophys Res Lett* 45(1):227–235. <https://doi.org/10.1002/2017GL075963>
- Evangelou VP, McDonald LM Jr (1999) Influence of sodium on soils of humid regions. *Handbook Plant Crop Stress* 2:17–50
- Feist SE, Hoque MA, Islam MA, Ahmed KM, Fowler M (2021) Recent trends in inland water level change in coastal Bangladesh—implications of sea level rise in low-lying deltas. *Global Planet Change* 206:103639. <https://doi.org/10.1016/j.gloplacha.2021.103639>
- Fujihara Y, Hoshikawa K, Fujii H, Kotera A, Nagano T, Yokoyama S (2016) Analysis and attribution of trends in water levels in the Vietnamese Mekong Delta. *Hydrol Process* 30(6):835–845. <https://doi.org/10.1002/hyp.10642>
- Gain A, Giupponi C (2014) Impact of the farakka dam on thresholds of the hydrologic flow regime in the lower Ganges River basin (Bangladesh). *Water* 6(8):2501–2518. <https://doi.org/10.3390/w6082501>
- Gain AK, Benson D, Rahman R, Datta DK, Rouillard JJ (2017) Tidal river management in the south west Ganges-Brahmaputra delta in Bangladesh: Moving towards a transdisciplinary approach? *Environ Sci Policy* 75:111–120. <https://doi.org/10.1016/j.envsci.2017.05.020>
- Gazi MY, Hossain F, Sadeak S, Uddin MM (2020) Spatiotemporal variability of channel and bar morphodynamics in the Gorai-Madhumati River, Bangladesh using remote sensing and GIS techniques. *Front Earth Sci*. <https://doi.org/10.1007/s11707-020-0827-z>
- Grilli A, Spaulding ML, Oakley BA, Damon C (2017) Mapping the coastal risk for the next century, including sea level rise and changes in the coastline: application to Charlestown RI, USA. *Nat Hazards* 88(1):389–414. <https://doi.org/10.1007/s11069-017-2871-x>
- Haque MA, Jahiruddin M, Hoque MA, Rahman MZ, Clarke D (2014) Temporal variability of soil and water salinity and its effect on crop at Kalapara Upazila. *J Environ Sci & Nat Res* 7(2):111–114
- Herbert ER, Boon P, Burgin AJ, Neubauer SC, Franklin RB, Ardón M, Gell P (2015) A global perspective on wetland salinization: ecological consequences of a growing threat to freshwater wetlands. *Ecosphere* 6(10):1–43. <https://doi.org/10.1890/ES14-00534.1>
- Hino M, Field CB, Mach KJ (2017) Managed retreat as a response to natural hazard risk. *Nat Clim Chang* 7(5):364–370. <https://doi.org/10.1038/nclimate3252>
- Hoque M, Butler A (2015) Medical Hydrogeology of Asian Deltas: Status of Groundwater Toxicants and Nutrients, and Implications for Human Health. *Int J Environ Res Public Health* 13(1):1–20. <https://doi.org/10.3390/ijerph13010081>
- Hoque MA, McArthur JM, Sikdar PK (2014) Sources of low-arsenic groundwater in the Bengal Basin: investigating the influence of the last glacial maximum palaeosol using a 115-km traverse across Bangladesh. *Hydrogeol J* 22(7):1535–1547. <https://doi.org/10.1007/s10040-014-1139-8>
- Hoque MA, Scheelbeek PFD, Vineis P, Khan AE, Ahmed KM, Butler AP (2016) Drinking water vulnerability to climate change and alternatives for adaptation in coastal South and South East Asia. *Clim Change* 136(2):247–263. <https://doi.org/10.1007/s10584-016-1617-1>
- Hossain F, Khan ZH, Shum CK (2015) Tidal river management in Bangladesh. *Nat Clim Chang* 5(6):492
- Ikeuchi H, Hirabayashi Y, Yamazaki D, Muis S, Ward PJ, Winsemius HC, Kanae S (2017) Compound simulation of fluvial floods and storm surges in a global coupled river-coast flood model: Model development and its application to 2007 Cyclone Sidr in Bangladesh. *J Adv Model Earth Syst* 9(4):1847–1862. <https://doi.org/10.1002/2017MS000943>
- IPCC, (2021). Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In: Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.). Cambridge University Press. In Press.
- Islam SN (2016) Deltaic floodplains development and wetland ecosystems management in the Ganges–Brahmaputra–Meghna Rivers Delta in Bangladesh. *Sustain Water Res Manag* 2(3):237–256. <https://doi.org/10.1007/s40899-016-0047-6>
- Islam SMD-U, Bhuiyan MAH (2018) Sundarbans mangrove forest of Bangladesh: causes of degradation and sustainable management options. *Environ Sustain* 1(2):113–131. <https://doi.org/10.1007/s42398-018-0018-y>
- Islam T, Peterson RE (2009) Climatology of landfalling tropical cyclones in Bangladesh 1877–2003. *Nat Hazards* 48(1):115–135. <https://doi.org/10.1007/s11069-008-9252-4>
- Islam MA, Hoque MA, Ahmed KM, Butler AP (2019) Impact of climate change and land use on groundwater salinization in southern Bangladesh—implications for other Asian Deltas. *Environ Manage* 64(5):640–649. <https://doi.org/10.1007/s00267-019-01220-4>
- Karim M, Mimura N (2008) Impacts of climate change and sea-level rise on cyclonic storm surge floods in Bangladesh. *Glob Environ Chang* 18(3):490–500. <https://doi.org/10.1016/j.gloenvcha.2008.05.002>
- Khan AE, Xun WW, Ahsan H, Vineis P (2011) Climate change, sea-level rise, & health impacts in. *Environment* 53(5):18–33. <https://doi.org/10.1080/00139157.2011.604008>
- Khan AE, Scheelbeek PFD, Shilpi AB, Chan Q, Mojumder SK, Rahman A, Vineis P (2014) Salinity in drinking water and the risk of (Pre)Eclampsia and gestational hypertension in coastal

- Bangladesh: a case-control study. *PLoS ONE* 9(9):1–8. <https://doi.org/10.1371/journal.pone.0108715>
- Mahmud SG, Shamsuddin SAJ, Feroze Ahmed M, Davison A, Deere D, Howard G (2007) Development and implementation of water safety plans for small water supplies in Bangladesh: benefits and lessons learned. *J Water Health* 5(4):585–597. <https://doi.org/10.2166/wh.2007.045>
- Mirza MMQ (1997) Hydrological changes in the Ganges system in Bangladesh in the post-Farakka period. *Hydrol Sci J* 42(5):613–631. <https://doi.org/10.1080/02626669709492062>
- Mirza MMQ (1998) Diversion of the Ganges Water at Farakka and Its Effects on Salinity in Bangladesh. *Environ Manage* 22(5):711–722. <https://doi.org/10.1007/s002679900141>
- MoP (2014) Mid-term Evaluation of Gorai River Restoration Project, Phase-II: Final Report. Ministry of Planning, Dhaka.
- Morgan JP, McINTIRE WG (1959) Quaternary geology of the Bengal basin, East Pakistan and India. *Geol Soc Am Bull* 70(3):319–342
- Naus FL, Schot P, Ahmed KM, Griffioen J (2019) Influence of landscape features on the large variation of shallow groundwater salinity in southwestern Bangladesh. *J Hydrol X*. <https://doi.org/10.1016/j.hydroa.2019.100043>
- Newton A, Icelly J, Cristina S, Perillo GME, Turner RE, Ashan D, Kuenzer C (2020) Anthropogenic, Direct Pressures on Coastal Wetlands. *Front Ecol Evol* 8(July):1–29. <https://doi.org/10.3389/fevo.2020.00144>
- Nicholls RJ, Hutton CW, Adger WN, Hanson SE, Salehin M (2018) Ecosystem Services for Well-Being in Deltas. In: Nicholls RJ, Hutton CW, Adger WN, Hanson SE, Rahman MM, Salehin M (Eds.). Cham: Springer International Publishing.
- Norton SB, Rodier DJ, Gentile JH, Van Der Schalie WH, Wood WP, Slimak MW (1992) A framework for ecological risk assessment at the EPA. *Environ Toxicol Chem* 11(1663):1672. <https://doi.org/10.1016/j.solener.2019.02.027>
- Oppenheimer M, Glavovic BC, Hinkel J, van de Wal R, Magnan AK, Abd-Elgawad A, Cai R, Cifuentes-Jara M, DeConto RM, Ghosh T, Hay J, Isla F, Marzeion B, Meyssignac B, Sebesvari Z (2019) Sea Level Rise and Implications for Low-Lying Islands, Coasts and Communities. In: Pörtner H-O, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, Mintenbeck K, Alegría A, Nicolai M, Okem A, Petzold J, Rama B, Weyer NM (eds) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Cambridge University Press, Cambridge, UK and New York, USA, pp 321–445. <https://doi.org/10.1017/9781009157964.006>
- Payo A, Lázár AN, Clarke D, Nicholls RJ, Brichenno L, Mashfiq S, Haque A (2017) Modeling daily soil salinity dynamics in response to agricultural and environmental changes in coastal Bangladesh. *Earth's Future* 5(5):495–514. <https://doi.org/10.1002/2016EF000530>
- Pescaroli G, Alexander D (2018) Understanding compound, interconnected, interacting, and cascading risks: a holistic framework. *Risk Anal* 38(11):2245–2257
- Peters CN, Hornberger GM (2020) A Search for freshwater in the saline aquifer of coastal Bangladesh. *Groundwater* 58(4):645–660. <https://doi.org/10.1111/gwat.12937>
- Pethick J, Orford JD (2013) Rapid rise in effective sea-level in south-western Bangladesh: Its causes and contemporary rates. *Global Planet Change* 111:237–245. <https://doi.org/10.1016/j.gloplacha.2013.09.019>
- Rahman MM, Ahmad S (2018) Health, Livelihood and Well-Being in the Coastal Delta of Bangladesh. In: Nicholls RJ, Hutton CW, Adger WN, Hanson SE, Rahman MM, Salehin M (eds) Ecosystem Services for Well-Being in Deltas. Palgrave Macmillan, Cham, pp 131–145
- Rahman MM, Hassan MQ, Islam MS, Shamsad SZKM (2000) Environmental impact assessment on water quality deterioration caused by the decreased Ganges outflow and saline water intrusion in south-western Bangladesh. *Environ Geol* 40(1–2):31–40. <https://doi.org/10.1007/s002540000152>
- Rahman MH, Lund T, Bryceson I (2011) Salinity impacts on agrobiodiversity in three coastal, rural villages of Bangladesh. *Ocean Coast Manag* 54(6):455–468. <https://doi.org/10.1016/j.ocecoaman.2011.03.003>
- Rahman AKMM, Ahmed KM, Butler AP, Hoque MA (2018) Influence of surface geology and micro-scale land use on the shallow subsurface salinity in deltaic coastal areas: a case from southwest Bangladesh. *Environ Earth Sci* 77(12):423. <https://doi.org/10.1007/s12665-018-7594-0>
- Rahman MM, Penny G, Mondal MS, Zaman MH, Kryston A, Salehin M, Müller MF (2019) Salinization in large river deltas: Drivers, impacts and socio-hydrological feedbacks. *Water Security* 6:1–34. <https://doi.org/10.1016/j.wasec.2019.100024>
- Rahman MM, Ghosh T, Salehin M, Ghosh A, Haque A, Hossain MA et al (2020) Ganges-Brahmaputra-Meghna Delta, Bangladesh and India: A Transnational Mega-Delta. In: Nicholls RJ, Adger WN, Hutton CW, Hanson SE (eds) Deltas in the Anthropocene. Palgrave Macmillan, Cham, pp 23–51
- Ravenscroft P, McArthur J (2004) Mechanism of regional enrichment of groundwater by boron: the examples of Bangladesh and Michigan, USA. *Appl Geochem* 19(9):1413–1430. <https://doi.org/10.1016/j.apgeochem.2003.10.014>
- Ravenscroft P, Burgess WG, Ahmed KM, Burren M, Perrin J (2005) Arsenic in groundwater of the Bengal Basin, Bangladesh: Distribution, field relations, and hydrogeological setting. *Hydrogeol J* 13(5–6):727–751. <https://doi.org/10.1007/s10040-003-0314-0>
- Ravenscroft P, McArthur JM, Hoque MA (2013) Stable groundwater quality in deep aquifers of Southern Bangladesh: The case against sustainable abstraction. *Sci Total Environ* 454–455:627–638. <https://doi.org/10.1016/j.scitotenv.2013.02.071>
- Sackett DL, Wennberg JE (1997) Choosing the best research design for each question: It's time to stop squabbling over the "best" methods. British Medical Journal Publishing Group.
- Saha R, Dey NC, Rahman S, Galagedara L, Bhattacharya P (2018) Exploring suitable sites for installing safe drinking water wells in coastal Bangladesh. *Groundw Sustain Dev* 7(March):91–100. <https://doi.org/10.1016/j.gsd.2018.03.002>
- Sahoo B, Bhaskaran PK (2016) Assessment on historical cyclone tracks in the Bay of Bengal, east coast of India. *Int J Climatol* 36(1):95–109. <https://doi.org/10.1002/joc.4331>
- Salehin M, Chowdhury MMA, Clarke D, Mondal S, Nowreen S, Jahiruddin M, Haque A (2018) Mechanisms and drivers of soil salinity in coastal Bangladesh. In Ecosystem Services for Well-Being in Deltas (pp. 333–347). Palgrave Macmillan, Cham
- Sarkar A, Sengupta S, McArthur JM, Ravenscroft P, Bera MK, Bhushan R, Agrawal S (2009) Evolution of Ganges-Brahmaputra western delta plain: Clues from sedimentology and carbon isotopes. *Quatern Sci Rev* 28(25–26):2564–2581. <https://doi.org/10.1016/j.quascirev.2009.05.016>
- Sarker MH, Akter J, Sarker MH, Haque P (2014) Morphological processes and effective river erosion Management: a case study of the Arial Khan River in Bangladesh, (July 2014). Retrieved from <https://www.researchgate.net/publication/263125733>
- Scheelbeek PFD, Chowdhury MAH, Haines A, Alam DS, Hoque MA, Butler AP, Vineis P (2017) Drinking Water Salinity and Raised Blood Pressure: Evidence from a Cohort Study in Coastal Bangladesh. *Environ Health Perspect* 125(5):057007. <https://doi.org/10.1289/EHP659>
- Shammi M, Rahman MM, Islam MA, Bodrud-Doza M, Zahid A, Akter Y, Kurasaki M (2017) Spatio-temporal assessment and trend analysis of surface water salinity in the coastal region of Bangladesh. *Environ Sci Pollut Res* 24(16):14273–14290. <https://doi.org/10.1007/s11356-017-8976-7>

- Sherin VR, Durand F, Papa F, Islam AS, Gopalakrishna VV, Khaki M, Suneel V (2020) Recent salinity intrusion in the Bengal delta: Observations and possible causes. *Continental Shelf Res.* <https://doi.org/10.1016/j.csr.2020.104142>
- Smith AJ, Turner JV (2001) Density-dependent surface water-groundwater interaction and nutrient discharge in the Swan - Canning estuary. *Hydrological Processes* 15(13):2595–2616. <https://doi.org/10.1002/hyp.303>
- SRDI. (2010). Saline Soils of Bangladesh Surveyed and data Compiled by Soil Resource Development Institute. Dhaka. Retrieved from [http://srdi.portal.gov.bd/sites/default/files/files/srdi.portal.gov.bd/publications/bc598e7a_df21_49ee_882e_0302c974015f/Soil salinity report-Nov 2010.pdf](http://srdi.portal.gov.bd/sites/default/files/files/srdi.portal.gov.bd/publications/bc598e7a_df21_49ee_882e_0302c974015f/Soil%20salinity%20report-Nov%202010.pdf)
- Suter GW (1999) Developing conceptual models for complex ecological risk assessments. *Hum Ecol Risk Assess (HERA)* 5(2):375–396. <https://doi.org/10.1080/10807039991289491>
- Syvitski JPM, Kettner AJ, Overeem I, Hutton EWH, Hannon MT, Brakenridge GR, Nicholls RJ (2009) Sinking deltas due to human activities. *Nat Geosci* 2(10):681–686. <https://doi.org/10.1038/ngeo629>
- Szabo S, Brondizio E, Renaud FG, Hetrick S, Nicholls RJ, Matthews Z, Dearing JA (2016) Population dynamics, delta vulnerability and environmental change: comparison of the Mekong, Ganges-Brahmaputra and Amazon delta regions. *Sustain Sci* 11(4):539–554. <https://doi.org/10.1007/s11625-016-0372-6>
- Uddin A, Lundberg N (1999) A paleo-Brahmaputra? Subsurface lithofacies analysis of Miocene deltaic sediments in the Himalayan-Bengal system, Bangladesh. *Sed Geol* 123:239–254. [https://doi.org/10.1016/S0037-0738\(98\)00134-1](https://doi.org/10.1016/S0037-0738(98)00134-1)
- USGS (2018) USGS EROS archive - digital elevation - Shuttle Radar Topography Mission (SRTM) Void Filled. US Geol Surv. <https://doi.org/10.5066/F7F76B1X>
- Valle-Levinson A, Dutton A, Martin JB (2017) Spatial and temporal variability of sea level rise hot spots over the eastern United States. *Geophys Res Lett* 44(15):7876–7882. <https://doi.org/10.1002/2017GL073926>
- van Staveren MF, Warner JF, Khan MSA (2017) Bringing in the tides from closing down to opening up delta polders via Tidal River Management in the southwest delta of Bangladesh. *Water Policy* 19(1):147–164. <https://doi.org/10.2166/wp.2016.029>
- Vengosh A (2005) Salinization and Saline Environments. In: Lollar BS (ed) *Environmental Geochemistry*. Elsevier, pp 333–366
- Vineis P, Chan Q, Khan A (2011) Climate change impacts on water salinity and health. *J Epidemiol Global Health* 1(1):5–10. <https://doi.org/10.1016/j.jegh.2011.09.001>
- Webster J, Watson RT (2002) Analyzing the past to prepare for the future: Writing a literature review. *MIS Quarterly*, xiii–xxiii.
- WHO. (2012). Water safety planning for small community water supplies: step-by-step risk management guidance for drinking-water supplies in small communities. World Health Organization.
- Willcocks W (1930) Lectures on the ancient system of irrigation in Bengal and its application to modern problems. Calcutta University Press, Calcutta
- Wilson CA, Goodbred SL (2015) Construction and maintenance of the ganges-brahmaputra-meghna delta: linking process, morphology, and stratigraphy. *Ann Rev Mar Sci* 7(1):67–88. <https://doi.org/10.1146/annurev-marine-010213-135032>
- Wilson C, Goodbred S, Small C, Gilligan J, Sams S, Mallick B, Hale R (2017) Widespread infilling of tidal channels and navigable waterways in human-modified tidal delta plain of southwest Bangladesh. *Elem Sci Anth* 5:78. <https://doi.org/10.1525/elementa.263>
- Woodruff JD, Irish JL, Camargo SJ (2013) Coastal flooding by tropical cyclones and sea-level rise. *Nature* 504(7478):44–52. <https://doi.org/10.1038/nature12855>
- Worland SC, Hornberger GM, Goodbred SL (2015) Source, transport, and evolution of saline groundwater in a shallow Holocene aquifer on the tidal delta plain of southwest Bangladesh. *Water Resour Res* 51(7):5791–5805. <https://doi.org/10.1002/2014WR016262>
- Zörb C, Geilfus CM, Dietz KJ (2019) Salinity and crop yield. *Plant Biol* 21:31–38. <https://doi.org/10.1111/plb.12884>