Impact of climate change and land use on groundwater salinization in southern Bangladesh- implications for other Asian deltas.

*M. A. Islam[1], M. A. Hoque[2], K. M. Ahmed[3], and A. P. Butler[4]

[1]Department of Oceanography, University of Dhaka, Bangladesh
Email: atik.ocn@du.ac.bd

[2]School of Environment, Geography & Geosciences Sciences, University of Portsmouth, UK
Email: mo.hoque@port.ac.uk

[3]Department of Geology, University of Dhaka, Bangladesh
Email: kmahmed@du.ac.bd

[4]Department of Civil and Environmental Engineering, Imperial College London, UK
Email: a.butler@imperial.ac.uk

Abstract:

Pervasive salinity in soil and water is affecting agricultural yield and the health of millions of delta dwellers in Asia. This is also being exacerbated by climate change through increases in sea-level and tropical storm surges. One consequence of this has been a widespread introduction of salt water shrimp farming. Here, we show, using field data and modeling, how changes in climate and land use are likely to result in increased salinization of shallow groundwater in SE Asian mega-deltas. We also explore possible adaptation options. We find that possible future increase of episodic inundation events, combined with salt water shrimp farming, will cause rapid salinization of groundwater in the region making it less suitable for drinking water and irrigation. However, modified land use and water management practices can mitigate the impacts on groundwater, as well as the overlying soil, from future salinization. The study therefore provides guidance for adaptation planning to reduce future salinization in Asian deltas.

Keyword: Salinization; delta; land use; climate change; groundwater; shrimp farm

1. Introduction

Deltaic coastal plains all over the world are highly vulnerable to impacts from climate change, such as: sea level rise, tidal flooding, storm surges. They are also subject to land subsidence, coastal erosion and land loss, groundwater salinization, and environmentally damaging land use practices (Ericson, et al., 2006, IPCC., 2007). There are eleven mega-deltas along the Asian coastline (Milliman and Meade, 1983) which share similar geo-physical characteristics and are home to millions of people (Woodroffe, et al., 2006). These are particularly vulnerable to salinization, and future climate change is expected to exacerbate this (Hoque, et al., 2016). Various Southeast Asian deltas show that salinity, particularly in surface water, has increased and intruded inland over the last few decades (Mondal, et al., 2013, Noh, et al., 2013). High levels of soil salinity affect 20-30% of net cultivable land, resulting in declines in agricultural productivity (Baten, et al., 2015, Dasgupta, et al., 2015). Whilst, elevated salinity levels (i.e. > 1000 mg/L) in drinking water (Rahman, 2014, Worland, et al., 2015) have been shown to be associated with prevalent hypertension (Scheelbeek, et al., 2017) - a risk factor for pre-eclampsia in pregnant women (Khan, et al., 2011, Khan, et al., 2014) and cardio-metabolic diseases in general, as well as increased rate of infant mortality (Dasgupta, et al., 2015). In addition, high groundwater salinity combined with raised water tables in coastal areas is causing increased maintenance costs for roads (Dasgupta, et al., 2014). Furthermore, as salinity in coastal surface waters increases, this is putting many freshwater ecosystems under threat (Herbert, et al., 2015).

The risk of groundwater salinization is likely to increase further due to rising sea levels, more frequent and/or intense tropical cyclones and land use modification (e.g., Hoque, et al., 2016, Rahman, et al., 2018). According to Singh (2002), the rate of sea level rise is much higher along the Bay of Bengal (4 to 7.8 mm/year) than the global average of 1.8±0.3 mm/year. Karim and Mimura (2008) show that this will significantly widen the extent of future storm surge flooding for similar magnitude cyclones. Understanding the impact of future changes in climate and land use on the coastal hydrological system is important when prioritizing adaptation and long-term planning. In this paper, we are taking the southern coastal zones of Bangladesh as a study area (**Figure 1**) in order to address the above issues using field-based data and modeling.

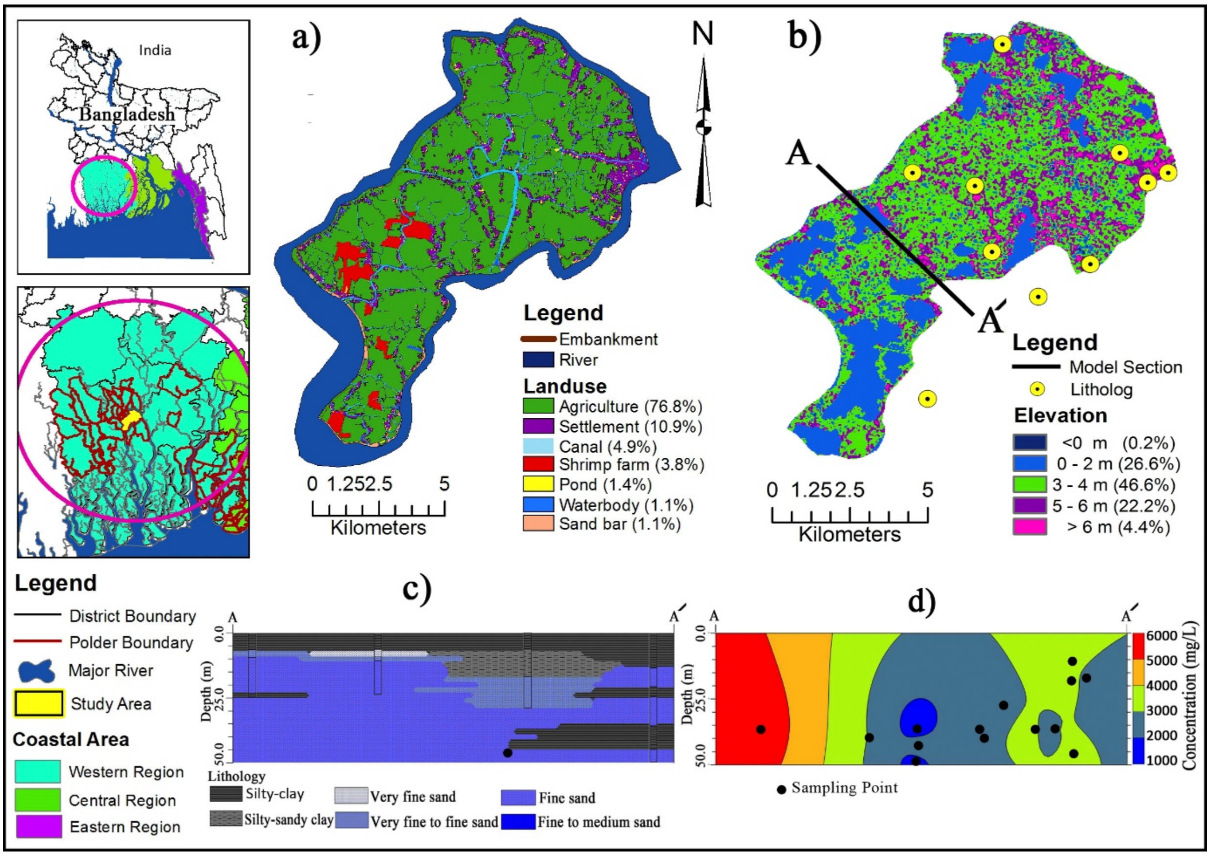

Figure 1: Map of southern coastal zones of Bangladesh. Three broad coastal regions and their associated polders are shown. The study area is marked in yellow. a) Land-use map and b) elevation map of the study area, showing respectively land-use types and elevation ranges and their relative percentages. c) Lithology and d) distribution of groundwater salinity along cross section A-A′.

The coastal region of Bangladesh is part of the Ganges-Brahmaputra Delta (GBD), the world's largest delta (Ericson, et al., 2006, IPCC., 2007), and most vulnerable to salinization among the Asian deltas (Hoque, et al., 2016). Like all Asian deltas, the GBD is regularly impacted by tropical cyclone induced storm surges and coastal flooding. Since the 1970s, these natural hazards, coupled with reductions in upstream river flows, have been causing widespread increases in soil and water salinity in southwest Bangladesh (Salehin, et al., 2018). The actual location and geometry of the saltwater freshwater interface in coastal Bangladesh is unknown but likely to be highly variable because of the complex geological structure, varied submarine groundwater discharge rate (e.g., Werner et al 2013), and the impacts from storm inundation events and monsoonal flushing. The numerical modelling indicates the saline wedge to be extensive at shallower depths in the central coastal region because of infiltration from repetitive storm surge induced inundation (Yu, 2010), and less from lateral seawater intrusion, which is more dominant at deeper depths. The landward extend of this deeper interface is restricted by the substantial submarine groundwater discharge (Faneca et al 2015), but could be affected by rising sea level (Yu, 2010). With soil salinities becoming too great for rice production, local farmers turned to farming salt-water shrimps in, an increasing number of, saline ponds. These ponds are often extensive (*ca.* 0.3 to 1 km^2) and normally maintain a persistent water column of around 1 m deep throughout the year. The practice dramatically expanded during the 1990s and currently the total area of shrimp farming in southern Bangladesh is around 2,000 km^2 (Islam, et al., 2018).

The south-western and south-central coastal islands of Bangladesh are low elevation regions that were enclosed by high (ca. 4 m) embankments to create a network of polders in the 1960s. These act as a protection from regular spring high tides and consequently help increase food security (Auerbach, et al., 2015, Rahman and Salehin, 2013). Sluice gates and culverts, located at various places along the embankments, control water flow into and out of the polder areas. Polder-31, with an area of 80 km^2, has been chosen as the specific study area (**Figure 1**) in the southwest coastal region of Bangladesh. We analyzed satellite images for land use, lithological data for hydrogeological characterization, and carried out field work to validate these analyses. In addition, a reconnaissance field survey of groundwater salinity within the polder was also conducted. We simulated the groundwater flow and salt mass transport along a 2D vertical section across the polder, in order to investigate the effect of different land use types and hydrological attributes (**Figure 2**) on the temporal behavior of groundwater salinity. This provides a basis for assessing the long-term impacts of soil, water and groundwater salinity under various potential adaptation scenarios.

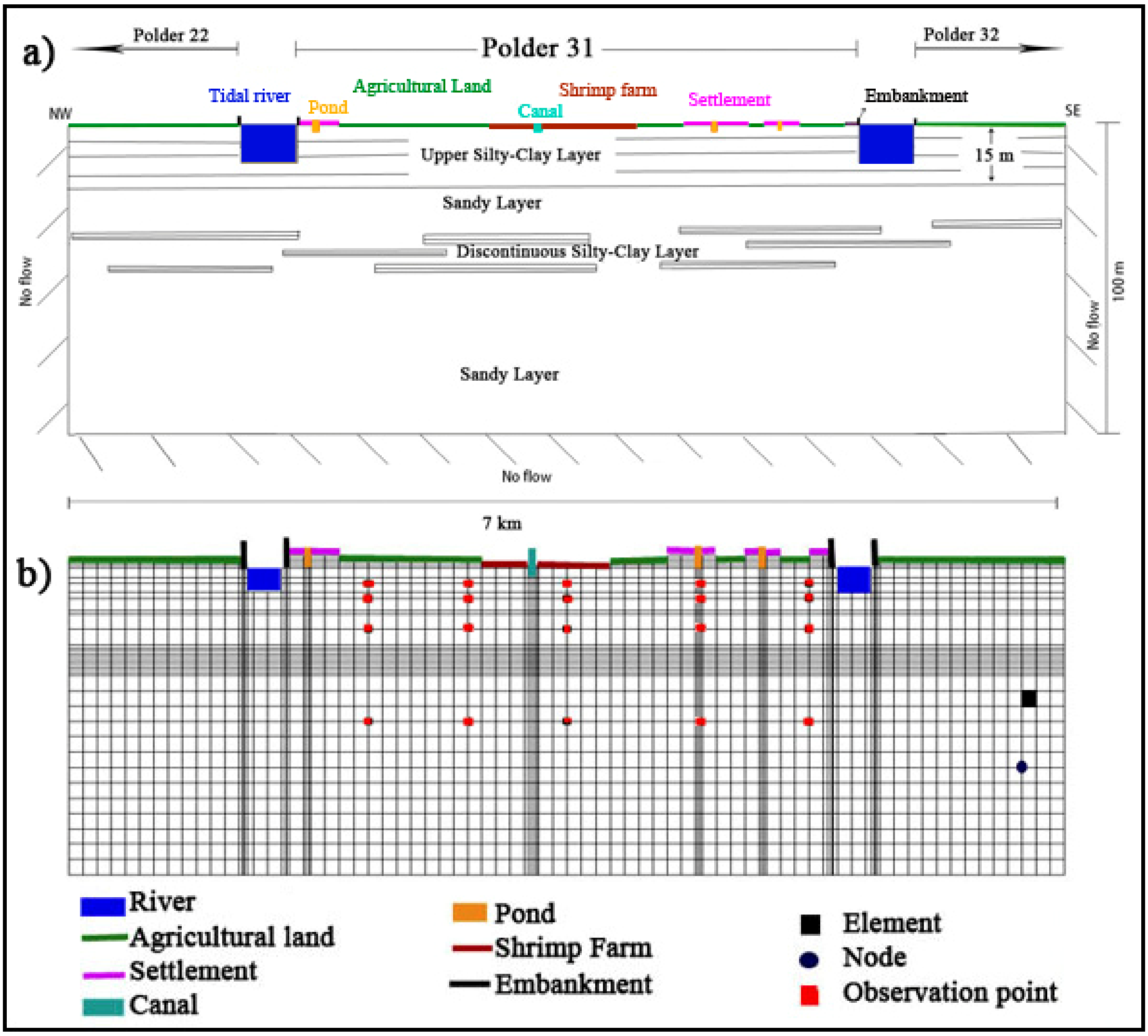

Figure 2: Groundwater model development. a) Conceptual model of the study area showing different land-use features, lithology and polder boundaries. b) SUTRA grid mesh showing different land-use types and observation points as they are simulated in the modelling.

2. Methods

2.1. Land-use

A land use map of the study area was produced using satellite images, dated 12 January 2015, on Google Earth. Various land use classes were identified and geo-referenced and then merged together in ArcGIS for further analysis and field validation. An elevation map was prepared using SRTM 30 m DEM data (EROS, 2002).

2.2. Hydrogeology and salinity

Lithological data for 7 boreholes from Polder-31 were collected and 2 boreholes (Worland, et al., 2015) drilled in Polder-32 were also included as these were in the neighboring region of the studied polder. During the field survey the Electrical Conductivity (EC), as a proxy for salinity, of various water sources were measured in the study area. The EC was measured from 14 tube-wells (Supplementary Information, hereafter SI, **Table S1**) to derive groundwater salinity at various locations and depths. At each location a GPS position was recorded using a Garmin handheld GPS, referenced to WGS 84 datum. Depth of the tube well screens were noted by interviewing the well owner. The EC data were converted to total dissolved solids (TDS) using a standard empirical relationship (i.e., multiplying the EC (µS/cm) by 0.5 to yield a TDS value in mg/L (Freeze and Cherry, 1979)). Linear kriging interpolation was used to generate the vertical salinity profile (Figure 1d).

2.3. Model development

The USGS open access computer code SUTRA 2.2 (which simulates variable density groundwater flow and transport under saturated-unsaturated conditions (Voss and Provost, 2010) has been used to model a set of scenarios related to land use and climate change. The graphical user interface ModelMuse 3.6.3 was used to facilitate input and output generation (Winston, 2014) and Model Viewer 1.6 and GW Chart 1.29.0 were used to visualize the results

(Hsieh and Winston, 2002, Winston, 2000). Assumptions we made in the model development are no unsaturated-flow, static boundary conditions, constant land use, and no pumping. The dimensions of a vertical slice conceptual model were set as 7 km (width) by 100 m (depth). Although the length of the study area is 5 km along the cross-section (**Figure 1b**), the model was extended to 1 km outwards on each side to reduce the effect of the boundary conditions. Similarly, although the main area of interest is the top 50 meters, the model was extended to twice this depth in order to reduce any impact from the impermeable lower boundary. As the upper part of the study area is covered by a thick silty-clay layer, a 15 m silty-clay layer was implemented in the model. Beneath was an 85 m thick layer of fine-sand, within which was a laterally discontinuous zone of silty-clay between the depths of 25 and 35 m (**Figure 2**). We took this simplified geometry because lithological record from the area shows that geological structure is less variable in the area (Figures 1c and S1 in SI). This supports our assumption that the sediments have a 'layer-cake' stratigraphy and therefore it was reasonable to represent this using a 2D model structure. In addition, a recent study from the delta demonstrated that these laterally discontinuous silt-clay layers have an inter-leaved pattern, giving rise of similar influence of 'layer-cake' stratigraphy on groundwater flow systems (Hoque et al 2017).

The various land use types were incorporated into the top 1 m grid layer of the model according to their position on the cross-section, and their elevation was based on the SRTM derived elevation data. The sizes of the rivers vary in the NW and SE boundary of the model and therefore, the depth of the rivers was set at 8 m (NW) and 10 m (SE) below sea level, respectively. Recharge on the land surface is generally controlled by net rainfall and was generally implemented in the model as a time-dependent flux boundary. Those areas, however, where there is standing water (e.g., Shrimp farm, drinking water pond, river) were represented using time-dependent pressure heads and associated concentrations. No flow boundaries were applied at the bottom and sides of the model. For the specified pressure boundary the following equation was used.

$$p(z) = p_0 - [\rho_b + \partial\rho/\partial C . C(z)]gz \quad \text{---} \quad \textbf{(1)}$$

where,

$p(z)$ = Hydrostatic fluid pressure [N/m^2],

p_0 = Atmospheric pressure [N/m^2]

ρ_b= Density of fresh water [kg/m^3],

$\frac{\partial\rho}{\partial C}$= Coefficient of fluid density change with concentration,

$C(z)$= Concentration of fluid [kg/m^3],

g= Gravitational acceleration [m/s^2] and

z= elevation in reference to sea level [m], i.e., $z = 0$ is sea level

The entire model domain (7 km x 100 m) was divided into 3,268 elements and 3,444 nodes using a fishnet mesh (Winston, 2015)(**Figure 2b**). The size of each general rectangular element of the mesh has been kept to 100 m (horizontal) x 5 m (vertical). Elements situated above sea level have a size of 100 m x 1 m. Moreover, elements representing different features have been modified based on their size (**Table S2**). Each of the features has the same elevation.

The initial groundwater concentration in the model was set at C_0=2,500 mg/L, as groundwater concentrations over most of the study area range from 2,000 mg/L to 3,000 mg/L (**Figure 1d**). Time dependent river salinity was set using average seasonal values calculated from BWDB (Bangladesh Water Development Board) data at the Chalna monitoring station (**Table S3).**) Starting from hydrostatic conditions, a steady state model was used to derive an initial pressure field for the transient model, which was then run for 200 years, using 1 month time steps, to assess long-term impacts.

2.4. Parameterisation, validation and sensitivity analysis.

In order to make the model implementation as simple as possible, parameter values were derived from available data for the study area, supplemented by literature values (**Table S4**). Some of the parameters, like recharge, water level, and water salinity are different for different land use types and vary with time (these are tabulated in **Table S5**). Rainfall data for the area, provided by the Bangladesh Meteorological Department (BMD), were obtained by averaging monthly rainfalls for 3 sites in the vicinity of Polder-31 over the period 2000-2014. River water level and salt concentration data were set from monthly average data for 2014 provided by the BWDB. Pond water levels and concentrations have been collected from data given in Rahman et al. (2018). The model was not calibrated, as our objective was to use it in an explanatory manner following the approach encouraged by Voss (2011a, b), however, an extensive sensitivity analysis was undertaken in order to provide robust conclusions. Model performance was assessed through a comparison of simulated hydraulic heads with those monitored by the BWDB for Polder-31 (**Figure S1**).

The sensitivity of the base case model to different aquifer and fluid properties, i.e. porosity, intrinsic permeability, dispersivity, and different side boundary conditions, was undertaken by comparing head and salinity values at different locations in the model (**Table S6**). Among the various parameters, groundwater head is slightly sensitive to changes in the side boundary conditions, while salinity is most sensitive to the reduction of intrinsic permeability. The model output, both in terms of head and salinity, was largely insensitive to the other parameters.

3. Results

3.1. Land use and land form.

The 2015 satellite data indicate that most (77%) of the land area for Polder-31 is agriculture, whilst around 11% is habitable settlements/villages (**Figure 1a**). Each village has several purpose-built ponds, which cover around 1% of the total land and are normally used for drinking and other household purposes. Shrimp farming, around 4% of the total area, is limited to the south-western part of the polder, where ground elevation is relatively lower. In other polders, however, shrimp farming is more extensive (Johnson, et al., 2016) and is often the dominant land use class. The variation in elevation over the area is shown in **Figure 1b**. The land surface is generally below 6 m with only around 4% of the area having an elevation above this. About a quarter (27%) of the land area has an elevation of less than 2 m, while (47%) lies between 3 and 4 m and the remaining 22% is between 5 and 6 m. Areas having an elevation < 2 m are typically flooded during the monsoon and generally used for agriculture during the dry season (Oct-Apr). Ponds and shrimp farms also are generally located in these low-lying areas (**Table S7**). The areas with elevations between 3 and 4 m are mainly used for agriculture. Those with elevations > 4 m are typically artificial constructions, such as the polder embankment, communal settlements and local roads.

3.2. Hydrogeology and salinity.

The main near-surface aquifer is semi-confined. Lithological data show a thick upper silty-clay layer, 5 to 15 m thick, and the presence of some discontinuous silty-clay layers (with thicknesses of about 5 to 10 meters) at a depth between 25 and 35 m. In between these, there is a sandy layer containing very fine to medium sands. A lithological cross-section (**Figure 1c, and Figure S2 in SI**) indicates the laterally discontinuous nature of the silt-clay layers implying, at the local scale, a separation of this shallow aquifer from the relatively deeper aquifer. The hydrogeological framework was corroborated with local drillers who confirm the presence of numerous silt-clay layers embedded in the sandy aquifer materials. The drillers also report that the silt-clay layers (between 30 and 35 m) are discontinuous, and are intercalated with finer sands forming a regional hydrogeological feature. The salinity of the groundwater typically ranges between 1,000 to 6,000 mg/L (Figure 1d). Wells near to rivers/embankments have a relatively high concentration (ca. 5,000 mg/L). Regionally, shallow groundwater is primarily brackish (ca. 3,000 mg/L) with isolated pockets of fresher (<1,500 mg/L) water, (Rahman, et al., 2012), which can be used for irrigation.

3.3. Salinity and present land use condition.

To explore the long-term relationship between salinity and land use, a set of modeling scenarios were developed that consider different land use types found along the cross-section A-A′ (**Figure 1b**). Concentrations of salt (i.e., TDS) in groundwater after 10, 50, 100 and 200 years are plotted (**Figure 3**). These show that, different land use patterns affect groundwater salinity differently. Concentrations decrease slightly below agricultural land and habitable settlements because of rain water recharge. As pond water has a relatively lower salinity compared to groundwater, it also contributes to a decrease in salinity but the influence is limited to a small area. The TDS of groundwater below and surrounding the shrimp farm shows a gradual increase.

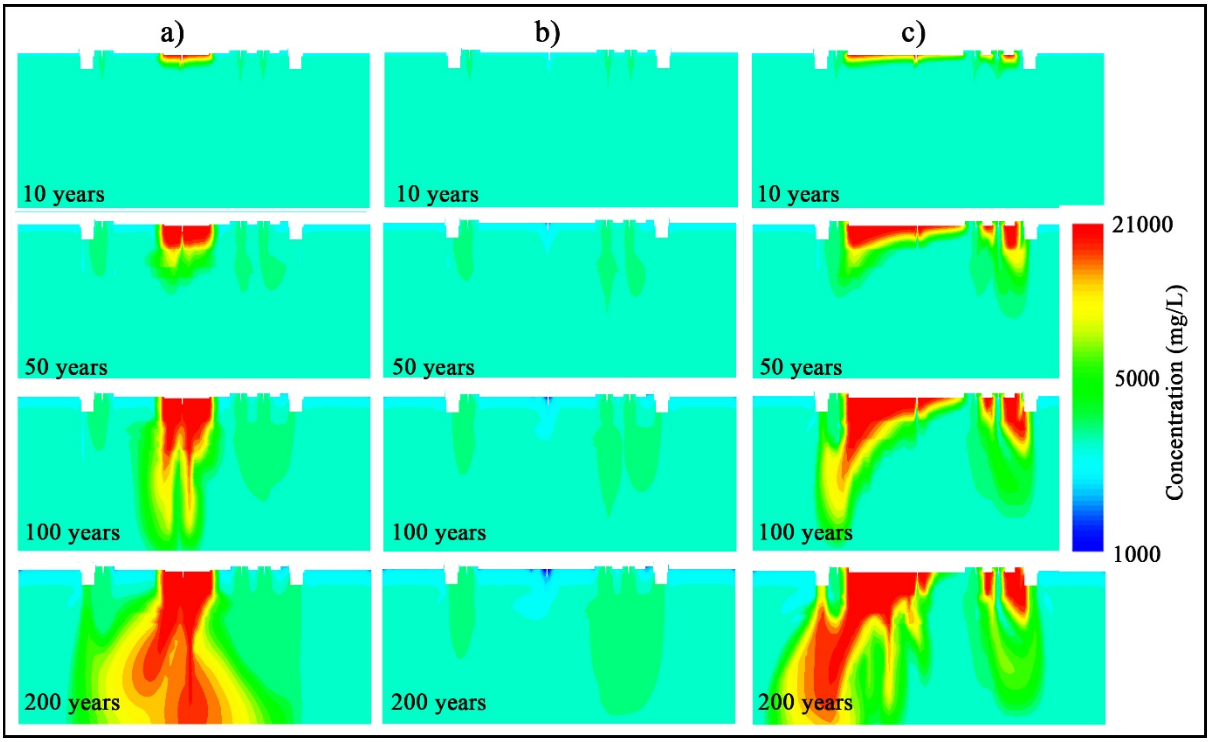

Figure 3: Effects of land-use on groundwater salinity for a) current land use, b) current land use, but without shrimp farms, c) all non-habitable land assumed to comprise shrimp farms. Distribution of TDS in groundwater after 10 years, 50 years, 100 years and 200 years.

3.4. Modification of land use and salinity.

Shrimp farming in recent years has become less profitable due to disease outbreaks in salt water shrimps (Kabir, et al., 2015). As a result, traditional shrimp farming is decreasing in some coastal areas (Iqbal, et al., 2015), however, there are some indications of a reverse taking place in Polder-31 (see SI, **Figure S3**). In order to assess the range of potential impact on groundwater salinity from shrimp farming, scenarios were developed ranging from the case where there was no shrimp farming to that where all agricultural land has been converted to shrimp farms. In the case where there is no shrimp farming, it is seen that groundwater salt content is decreasing in most of the places (**Figure 3b**) apart from where there are drinking water ponds, which are assumed, based on field observations (Rahman, et al., 2018, Scheelbeek, et al., 2017) to have variable TDS concentration ranging between 825 and 7,575 mg/L (**Table S5**). In addition, there is a slight increase in concentration below and surrounding the canals/rivers. In the extreme case, where all agricultural land has been converted to shrimp farming, it can be seen that this results in a progressive salinization of the underlying aquifers over time (**Figure 3c**). The results indicate that prolonged salt water shrimp farming could lead to a deterioration of groundwater quality by salinity over a time period of multiple decades.

3.5. Salinity and frequency of cyclones.

The study area is also affected by tropical cyclones on a regular basis; typically once every 3-4 years (MoEF., 2009). However, although currently inconclusive, some studies have suggested that the frequency and intensity of tropical cyclones could increase in the future due to climate change (IPCC, 2014, Islam and Peter, 2009). On average, an intense cyclone (categories 4 and 5) landfalls once every 10 years (Hoque, et al., 2016). We use the base case model, but without any shrimp farms, to investigate the effect of tropical cyclone storm surge frequency on groundwater salinity by considering recurrent intervals of storm surge inundation of the Polder every 10 and 5 years and, as an extreme case, every year. We assume that, over the relevant land area, the polder is flooded by saline river water (concentration = 28,000 mg/L) to a depth of 1 meter for a period of one year. This is to represent the effect of regular saline water flooding from a breached (and unrepaired) embankment (Mallick, et al., 2011). To account for the effect of dilution from the seasonal monsoon, the model treats the salinity of the infiltrating water as 80% sea water in the first year and decreasing at a rate 20% over the next three years and by 10% in the fifth, according to the recurrence interval. The simulations show groundwater salinity progressively increasing from the surface and extending downwards over time (**Figure 4**). As it is assumed that a storm surge will flood the entire polder, more frequent inundation has a major impact on groundwater salinity.

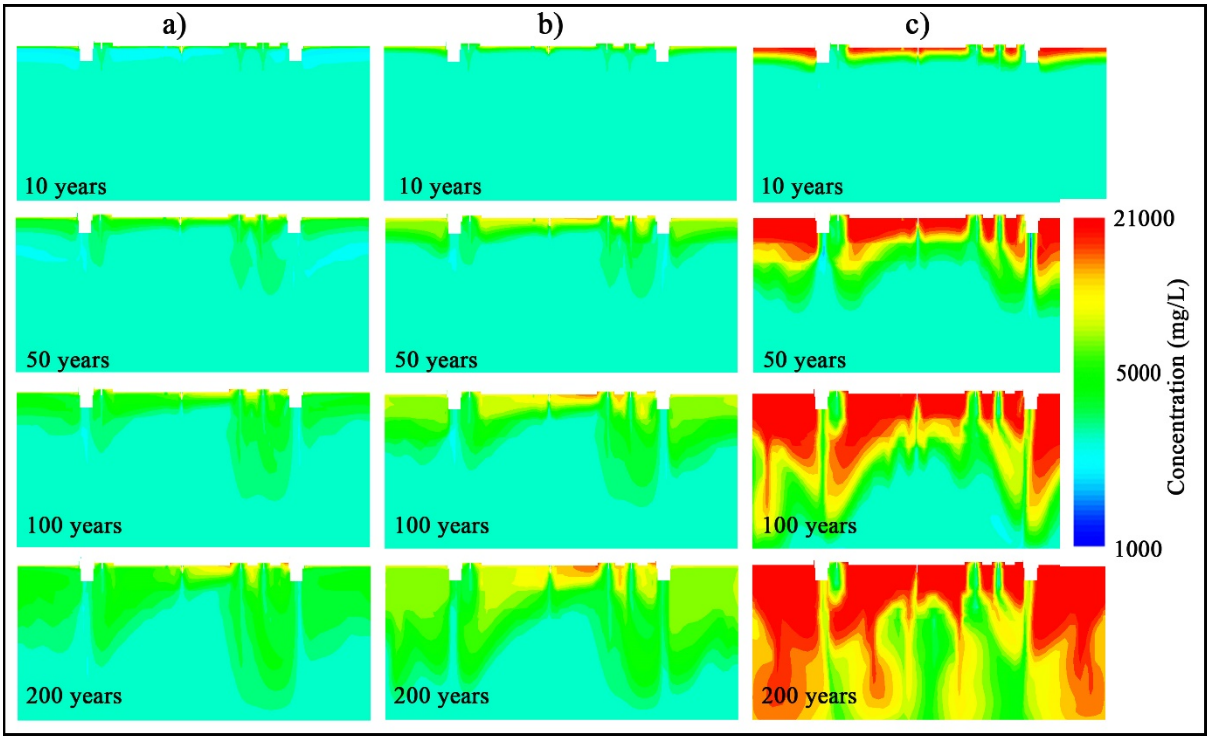

Figure 4: Effects of frequency of cyclone induced storm surges on groundwater for a) every 10 years b) every 5 years, c) every year for current land use without shrimp farming. TDS concentration in groundwater after 10 years, 50 years, 100 years and 200 years.

3.6 Adaptation options for salinity management.

In view of the substantial impacts that both shrimp farming and storm surge inundation could have on groundwater and surface water salinity, and consequently on potential drinking water sources, the model was used to explore possible adaptation options (**Figure 5**). We considered three scenarios: i) current land use, without shrimp farms, inundated by fresh river water during the rainy season and protected during dry season through sluice gate controls; ii) replacing saline water shrimp farms with fresh water shrimp farms; and iii) saline shrimp farms located solely adjacent to the river, and therefore outside of the polder embankment, while the inner part of polder receives seasonal fresh river water inundation each rainy season. It is seen that, if shrimp farms are removed and the polder area is seasonally flooded with fresher river water aquifers freshen up significantly. Replacing salt water shrimp farms with fresh water farms also improves the groundwater quality. In the third option, where salt water shrimp farms are located on the peripheral regions of the polder there is only limited salinization in these areas, whilst there is a general improvement in groundwater quality in the main area of the polder. It is important to note, however, that the modeling did not consider the effects of groundwater abstractions, which might facilitate transport of salt from peripheral zones to the central areas of the polder. On the other hand, this is not considered to be a major concern due to the limited use of groundwater pumping in Polder-31 (cf. Scheelbeek et al., 2017).

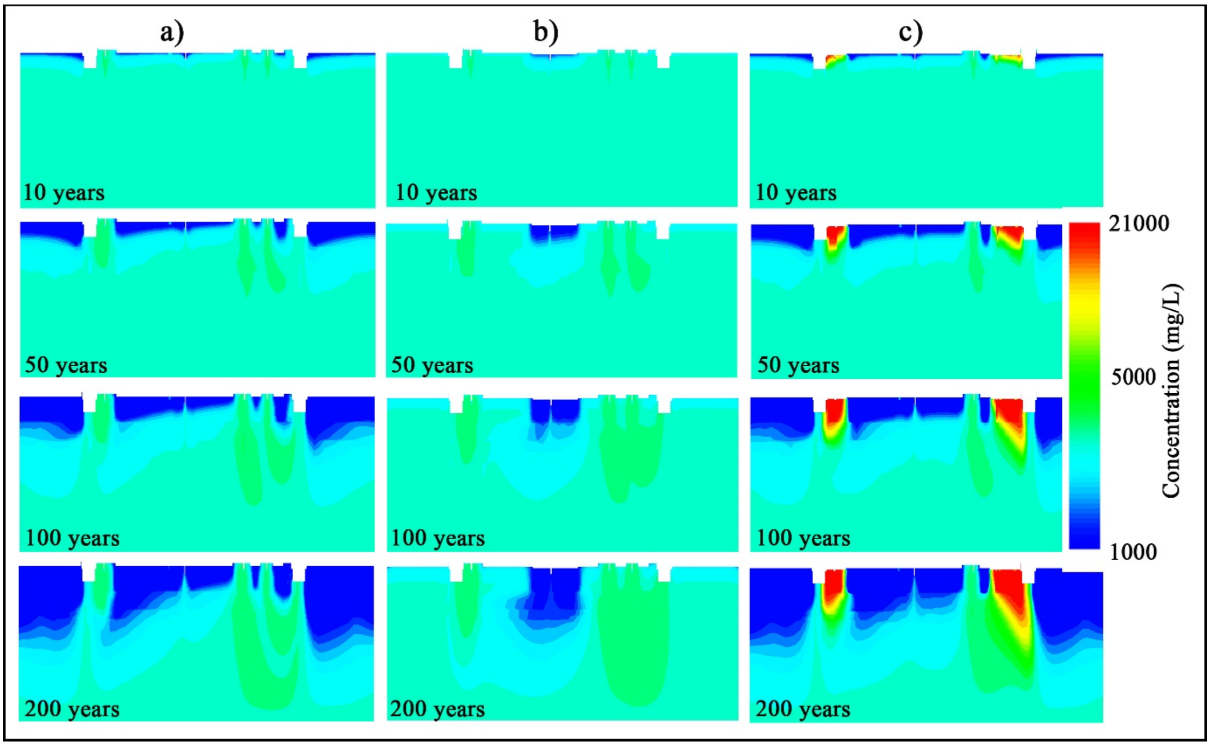

Figure 5: Simulation of various adaptation options. a) Inundated by freshwater during each rainy season and protected during dry season. b) Replacing saline water shrimp farming with fresh water shrimp farming, c) Shrimp farm only by the sides of the river while inner part of polder receives a seasonal freshwater inundation every rainy season.

4. Discussion

4.1 Influence of land use and surface lithology on groundwater salinity

The entire area of Polder-31 is covered by a thick silty-clay layer, with a thickness of 5 to 15 meters, below which is a very fine to fine sandy layer. An EM (Electromagnetic) survey in the adjacent Polder-32 (Worland, et al., 2015) also shows the presence of an upper clay/silty-clay layer of similar varying thickness. This topmost layer acts as an aquitard, making the underlying shallow aquifer semi-confined, which is how it has been mapped in a previous regional scale study (DPHE/DFID/JICA, 2006). Although it has been postulated that the aquitard may protect the underlying aquifer from surface pollution (Yu, 2010), our results indicate otherwise. This is also in agreement with small scale field observations (c. 0.05 km^2) made in Polders-31 and -32, which show salinity levels in the upper few meters of the silty-clay unit that appear to be consistent with the types land use described above (Rahman et al., 2018). One reason for this association could be the relatively permeable nature of the silty-clay unit. Among the various parameters, intrinsic permeability is found to be the most sensitive for salinity; therefore, a lower permeability may slow the process but not stop it. The vertical hydraulic conductivity of which Rahman et al. (2018) found to be c. 0.03 m/day. This value is consistent with the intrinsic permeability values used in the current model simulations (see **Table S4**).

In light of these results, we suggest that surface land use features, and their associated water salinities, can play an important role in the salinization of groundwater in coastal polders. Different land uses, such as agriculture, human settlement and drinking water ponds are sources of fresh water recharge in such aquifers, which contribute to the freshening of the aquifer over time. In contrast, salt water shrimp ponds, and any drainage canals affected by these (i.e. via sluice gates), have relatively high salinities, whose higher relative density results in convective plumes of downward migrating saline water (Xie, et al., 2011) causing increased salinization of the underlying aquifer (**Figure 3**). Our results indicate that the effect of shrimp farms on groundwater could be several times higher than any other kind of land use. This assessment indicates that shrimp farming, if used extensively, could lead to enhanced salinization of groundwater and a deterioration of near surface aquifers as a water resource.

4.2 Influence of climate change on groundwater salinity

Our results indicate that climate change impacts, such as sea-level rise, changes in precipitation patterns, and more frequent and/or intense storm surges could lead to a deterioration in groundwater quality. The study area is frequently affected by tropical cyclones (Ali, 1996, Hoque, et al., 2016, Islam and Peterson, 2008), some of which can over-top and/or breach polder embankments leading to inundation with saline water (Hoque, et al., 2016, IMD, 2009, Mallick, et al., 2011). This inundated saline water can then infiltrate into the subsurface causing groundwater salinization, which will continue until the embankment breaches are fixed and the saline surface water is drained out of the polder. It is anticipated that with climate change there might be higher frequencies of storm surge events capable of breaching or over-topping polder embankments and this is likely to lead to additional salinization of the underlying aquifer (Islam and Peter, 2009). In addition, sea level rise can modify the dynamics of tropical cyclones in this region and further increase the risk of flooding and bank erosion (Karim and Mimura, 2008).

It has been projected that Bangladesh rainfall will increase by 12% in the monsoon and decrease by 3% in winter by 2100 (Agrawala, et al., 2003). However, our results appear to show that these changes in rainfall would have minimal effect on groundwater salinity (**Figure**

S4), as recharge is around 10-15% of the total rainfall (Shamsudduha, et al., 2011), and therefore only represents a minor change.

4.3 Salinity management options

Our results imply that both land use and climate change can have an impact on groundwater salinization. In some cases groundwater salinity has been found to decrease for a given land-use (e.g., rice cultivation using rainy season flood irrigation, **Figure 5a**) or increase for other (e.g., installing shrimp farm, **Figure 3c**). Land use planning and hydrological management scheduling may significantly help in combatting soil and groundwater salinization in these regions. Embankments have a great influence on the groundwater salinity, as these were made to protect the enclosed areas from regular tidal flooding and tropical cyclone storm surges. Sea water inundations of any sort are a potential source of saline water recharge and thus responsible for increasing groundwater salinity. In our simulations, we have considered how controls on the flow of water in and out of a polder via sluice gates placed within the polder's embankments can be used as a salinity management tool. We see that, if the embankments prevent tidal water to enter into the polder, salinization of groundwater decreases remarkably. Furthermore, if saline river water intrusion into the polder is prevented during the dry season but the ingress of fresher river water (i.e. when salinity is <300 mg/l), via sluice gates installed within the embankment, is allowed during the rainy season (Auerbach, et al., 2015, Willcocks, 1930) then over time the aquifer will become fresher (**Figure 5**). In addition, this open tidal hydrological regime during the rainy season will also allow the polder to gain fertile sediments and help it to promote elevation equilibrium between the inside and outside of the polder, as suggested by Auerbach et al. (2015). According to Kibria, et al. (2015) agricultural land in these coastal polders, utilising rainy season flood irrigation for rice, has increased from 22% to 31% post Aila (2009). We suggest that this practice of the ingress of fresher river-water for rice cultivation during the rainy season will be good for both the natural environment and the local resource economy.

5. Conclusion

The study was done in Bangladesh in order to explore the effects of land use and climate change on groundwater salinization. In this study, we consider that the understandings are applicable to other Asian deltas too. The results will facilitate to identify knowledge gaps and design appropriate study for management decisions. The study shows that land use management that has resulted in ponding of saline water at the surface is mainly responsible for the salinization of underlying groundwater. In contrast, we have shown that there are adaptation measures that policy makers can adopt to reduce groundwater salinization (such as relocating shrimp farms, encouraging land use for agricultural purposes, and particularly allowing the polder area to be part of tidal plain during the rainy season). We also find that the embankments are an essential landscape management solution in the face of climate change and sea level rise to protect the polder area from the ingress of saline water, and by allowing the polder area in rainy season to be part of tidal plain when river water is fresher.

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