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Groundwater Salinity Modelling in the South West Region of Bangladesh Considering Climate Change

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The coastal area of Bangladesh suffers a lot due to different degrees of salinity in all over the area. Salinity intrusion in this area is mainly derived through climate change as well as anthropogenic factors that make this region more vulnerable. Hence, salinity intrusion has adverse effects on water, soils, agriculture, fisheries, ecosystem, and livelihoods of this region. To ensure the availability of food as well as drinking water, this paper highlights the mechanism of salinity intrusion in groundwater as well extent of salinity front towards inland due to climate change. For assessing the existing situation of salinity in groundwater and to see the impact of climate change, a solute transport model has been developed using FEFLOW modelling software. The model has been calibrated against groundwater level and groundwater salinity. The model results show a quick response of groundwater level in shallow aquifer due to tidal fluctuation in nearby river. In general, the groundwater in shallow aquifer is more saline than that of deeper aquifer. In major cases, the groundwater salinity in shallow aquifer exceeds the allowable drinking limit (1000 ppm). The groundwater salinity was assessed for the base year 2013 and for the year 2050, considering the climate change impact. The simulation results indicated that the groundwater salinity in coastal area would increase in the future. It has been found that the area under high saline zone (salinity > 2000 ppm) would increase by 14% in 2050, due to climate change impact. It is also noticed that in general, the groundwater salinity in north-west part of the study area is less saline but in the remaining parts it is high saline. The study suggests for extensive promotion of alternative technologies such as pond sand filter (PSF), rainwater harvesting (RWH) for the areas having high salinity in groundwater and conducting research about the potentiality of the technologies such as managed aquifer recharge (MAR) or reverse osmosis (RO).

(***Key words:*** *Climate change, Coastal region, FEFLOW, Mathematical modelling, Potable water)*

In the coastal area of Bangladesh, there exists saline and non-saline aquifers with various thickness and degrees of concentration (MPO, 1987; Islam and Haque, 2009). About 53% of the coastal region is affected by different degrees of salinity (Habiba *et al*., 2014). In south west region of Bangladesh, 68% of the area has the soil salinity of 4-8 dS m^{-1}, 13% area has 8-16 dS m^{-1} of soil salinity and 6% area has > 16 dS m^{-1} soil salinity (Karim *et al*., 1990). In many places of the coastal area, groundwater salinity ranges from 1.5-2.0 dS m^{-1} during the dry season (Mondal, 1977; Mondal, 2001).

The area falls under the Ganges tidal flood plain, standing less than 1 m above the sea level. The area being in the Ganges influence area, it is very much affected by the withdrawal of the Ganges water in the lean season. Decrease of upstream freshwater flow is also one of the main reasons for salinity intrusion in the region. Due to reduction of fresh water flow from upstream after 1970 and consequent deterioration of the Gorai off-take through massive sedimentation; dry season flow has been drastically reduced in the Gorai River. The effect of this has been a two-fold increase of Gorai River salinity in the Khulna region (EGIS, 2000). The practice of shrimp farming in the area is also increasing soil salinity (IWM, 2010).

There are about 40 million people living in this area. The local people suffer a lot from different diseases for drinking saline water. For collecting potable water, they have to spend their time and money. The agricultural yield is also hampered a lot due to salinity problem. Due to impact of climate change, this problem will be more acute. With the consequence of climate change, it gradually extends towards inland water and soil. This scenario of gradual salinity intrusion into the

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coastal areas of Bangladesh is very threatening to the primary production system, coastal biodiversity and human health. The main objective of this study was to investigate the movement of saline front toward inland due to climate change effect and also to detect the potable source of water.

Intrusion of salinity occurs in coastal freshwater aquifers when higher densities saline water enters into freshwater aquifers due to difference of density. Salinity intrusion is a physically ‘density-dependent problem’ where two different equations need to be coupled: (i) groundwater flow equation and (ii) solute (salt) transport equation (Li *et al*., 2009; Xu *et al*., 2017). Numerical modelling can serve as a tool to simulate the current levels of salinity in groundwater and surface water as well as salinity intrusion in groundwater under different future climatic scenarios. There are many numerical models in the literature that can simulate and predict salinity intrusion (Rajabi *et al*., 2015; Xu *et al*., 2018): such as FEFLOW (Diersh, 2014), SEAWAT (Guo and Langevin, 2002; Langevin *et al*., 2000), and SUTRA (Voss *et al*., 2002). In this study FEFLOW modelling tools has been used to investigate the issue considering its wide range of application.

MATERIALS AND METHODS

Approach and methodology

The study area (Fig. 1) lies approximately between 89°05′57.6″ E to 89°35′20.0″E longitudes and 22°29′55.0″ N to 23°01′53.5″ N latitudes. The area covers Dumuria upazila and part of Phultala, Khan Jahan Ali, Batiaghata, Dacope and Paikgacha Upazilla of Khulna district; part of Abhaynagar, Manirampur and Keshabpur upazillas of Jessore district; and part of Tala upazila of Satkhira district. The study area covers about 1534 km^2 area. The average highest rainfall occurs in the month of July (372 mm) while the average lowest (6 mm) occurs in December. About 88% of annual rainfall occurs during May to September. The relative humidity of the study area varies from 43% to 86%. Along the west it is bounded by the Kobadak River. Rupsha River flows on the eastern side. These rivers are all tidal and undergo semidiurnal tidal fluctuation. Three different aquifer systems can be found in the study area: i) Upper/composite aquifer, which exists within 50 m below ground level, consisting mostly of heterogeneous assemblage of sand, silt and clay, ii) Lower shallow aquifer systems, which are unconfined to semi-confined, and exists between 50 m - 150 m below ground level, consisting of medium to coarse sand with occasional fine sand and silt, iii) Deep aquifers containing fresh water at 220 to 350 m depth (DANIDA/DPHE, 2001). A sample hydrostratigraphic section, prepared through north-south direction of the study area is shown in Fig. 2.

The area experiences salinity of different level in groundwater. In Bangladesh, the recommended range of salinity as chloride for drinking water is 150 to 600 ppm (ECR, 1997). However, a higher value upto 1000 ppm for problematic areas including coastal belt is considered (DPHE, 2006). For traditional rice production in Bangladesh generally salinity is 2000 ppm (BARC, 2013). In this study, the water has been considered as low saline water (salinity < 1000 ppm), moderate saline water (1000 ppm < salinity < 2000 ppm) and high saline water (salinity > 2000 ppm).

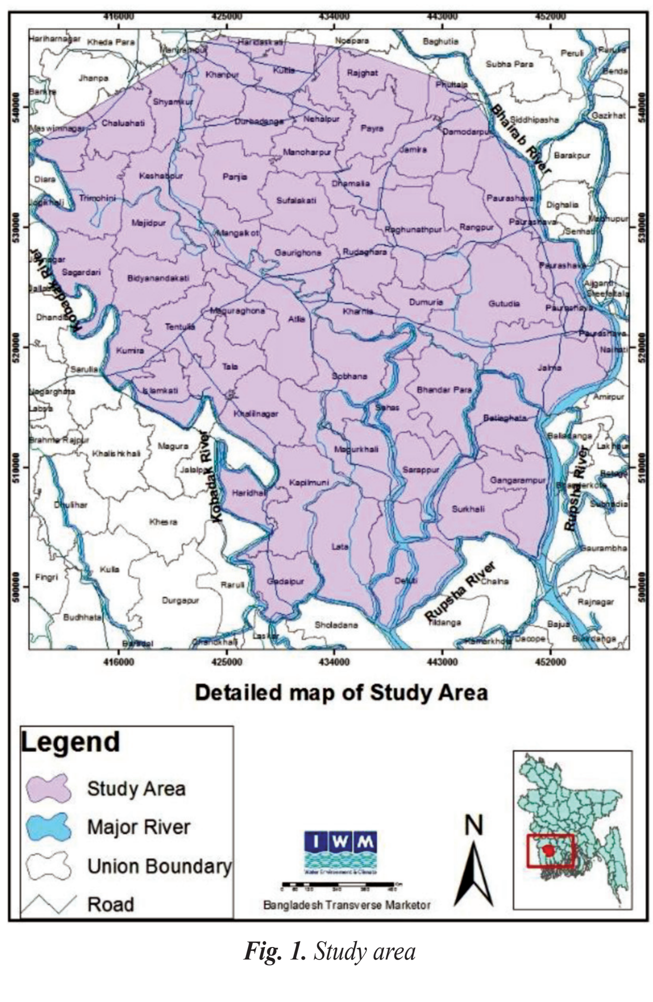

Fig. 1. *Study area*

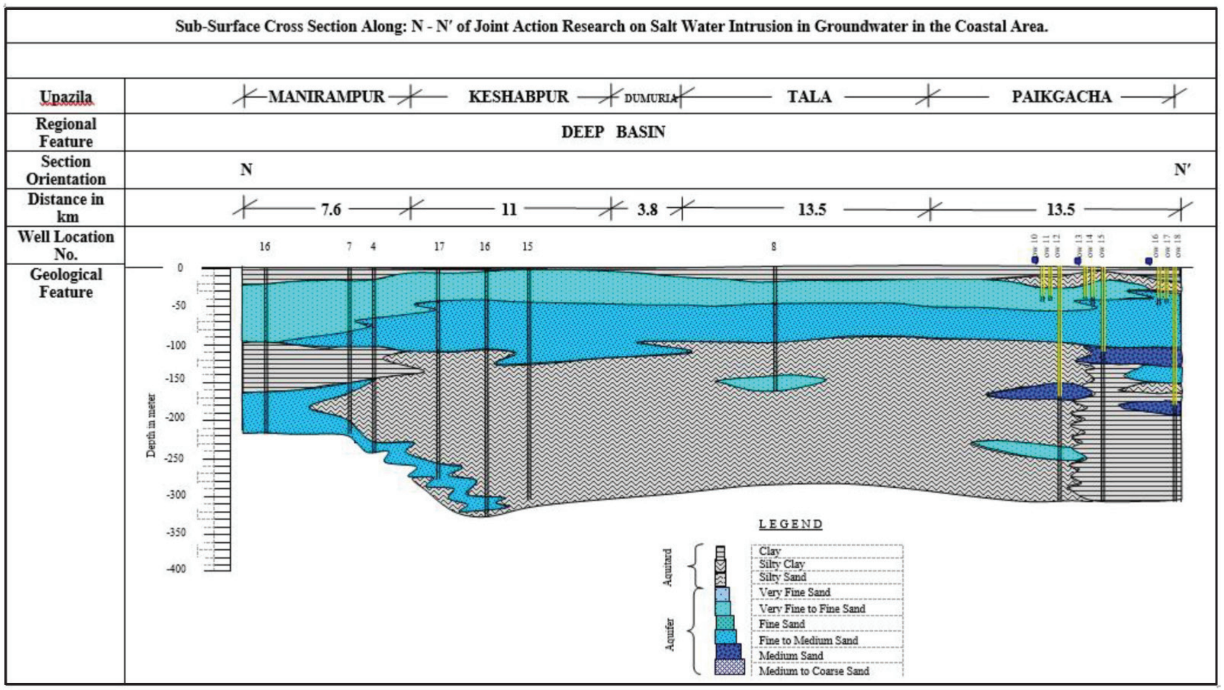

Fig. 2. *Hydrostratigraphic section along North-South of the study area*

Most of the required data and information were collected from different relevant sources. To fill up the data gaps, some data e.g. bore-logs, groundwater salinity, surface water salinity and groundwater level etc. were collected from primary sources. A total of 52 observation wells were installed to measure water level and salinity. In addition to this, geo-electrical logging was performed at 45 bore holes to assess salinity along the drilling depth. Collected geo-electrical logging data and graphs were used in conjunction with the lab test of salinity to ascertain the intensity and extent of salinity along the aquifer depth. This collected information's were used to assess the baseline salinity condition and to develop the salinity model.

In order to understand the river-aquifer water level interaction, auto recorders were also installed at Batiahgata upazila in the Kazibacha River and in the nearby aquifers during the entire monitoring period from March 2012 to July 2013. The 1st auto recorder was installed in the river, the 2nd and 3rd recorders were installed in the shallow aquifer while the 4th one was installed in the deep aquifer. All the collected data both from secondary as well as primary sources, were processed and used for model setup after checking its consistency.

Model setup

In this study, the dynamics of ground water salinity process and impact of external drivers such as climate change was evaluated using mathematical modelling approach. Three modelling software *i.e.* MIKE SHE, MIKE-11 and FEFLOW were used in this study. MIKE-11 model was used for flow assessment in the river, MIKE SHE model was used for groundwater resource assessment. MIKE-11 was coupled with MIKE SHE to consider the groundwater-surface water interaction. FEFLOW (Finite Element subsurface FLOW system) is a popular professional software around the world which is used for modelling fluid flow and transport dissolved constituents and/or heat transport processes in the subsurface. FEFLOW 6.1 version was applied to simulate the salinity in the present study. Surface water level and flow derived from MIKE-11 model was incorporated into the FEFLOW. The calibration and validation were done with updated dataset.

In order to build a 3-D model of the aquifer system, a 2-dimensional finite-element mesh was generated using the advancing front mesh generation algorithm in FEFLOW. The 2D finite element mesh was refined along the rivers (Fig. 3), within the model area. The

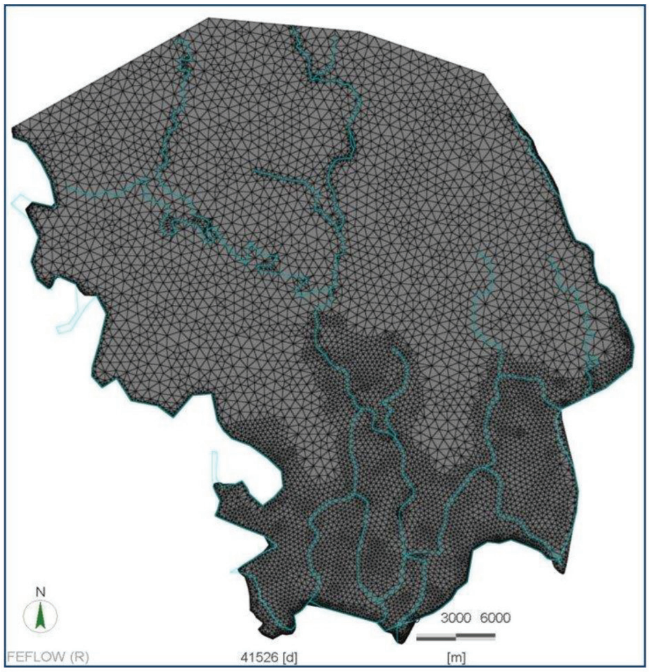

Fig. 3. *2D finite - element mesh generated by the FEFLOW model*

generated 2-D finite-element mesh was extended in the vertical direction (vertical discretization), corresponding to the hydro-geological units *i.e.* topsoil, upper shallow aquifer, lower shallow aquifer, aquitard and deep aquifer. The 2D finite element mesh consists of 9689 nodes and 17261 elements. The length of the triangles varies from 100 m to 250 m, and 250 m to 500 m in zones of mesh refinement and non-refinement, respectively.

The groundwater flow equations used in the FEFLOW model require inputs of hydraulic parameters for the model domain Table 1. For density-dependent flow, mass transport parameters that were used to build the model are listed in Table 2.

The groundwater salinity model needs to be run for both steady and transient states for flow and mass transport. The steady state calibration was carried out for 36,500 days. A steady state distribution of hydraulic heads and salinity concentration were achieved and used as initial conditions for the transient calibration. Potential heads of the observation wells were used to generate initial conditions. The actual historic evolution of the current groundwater salinity distribution is unknown; however, considering the long-term simulation of the model, it was assumed that a fresh aquifer system was there initially, and then it was modelled accordingly. For matching the initial condition with the present situation, A constant boundary concentration (5100 ppm) for the river water were used. A concentration of 250 ppm was imposed on north-eastern side where no river exists. This boundary condition describes a reference hydraulic head, in this case river water level, which has an imperfect hydraulic contact with groundwater body caused by a colmation layer. A transfer rate (leakage) was assigned to describe the hydraulic properties of the colmation layer. In addition, hydraulic head of first kind, Dirichlet type (DHI-WASY, 2004) was applied in the model where the well exists.

Salinity intrusion from the river was then introduced

Table 1. *Hydraulic parameters of the hydrological units*

Geological layer	Horizontal hydraulic conductivity (m day^{-1})			Vertical hydraulic conductivity (m day^{-1})			Specific yield	Storage co-efficient
	Max	Min	Avg	Max	Min	Avg		
Top soil	2.98	0.02	1.5	0.298	0.002	0.15	0.02	
Upper shallow aquifer	14.84	4.06	9.45	1.48	0.41	0.95	0.1	
Lower shallow aquifer	29.78	12.04	20.91	2.98	1.2	2.1	0.1 (unconfined)	10^-6 (confined)
Aquitard	9.31	0.02	4.67	0.93	0.002	0.47	0.02	0.0001
Deeper aquifer	34.93	8.58	21.76	3.5	8.58	2.2		10^-6

Table 2. *Summary of mass transport parameters*

Parameter	Value
Reference concentration	0 mg L^{-1}
Maximum concentration	18000 mg L^{-1}
Density ratio	0.02
Molecular diffusion coefficient	10-9 m^2 s^{-1}
Longitudinal dispersivity	500 m
Transverse dispersivity	50 m

in the groundwater salinity model (FEFLOW) by linking the 1-dimensional hydrodynamic model (MIKE-11). The exchange of flow between the saturated zone component and the river component was mainly dependent on head difference between river and aquifer as well as the properties of riverbed material; such as leakage coefficient. For river-aquifer exchange, leakage coefficients along with the hydraulic conductivity of the saturated zone were considered.

RESULTS AND DISCUSSION

Model calibration

In order to get the reliability of the model, it was calibrated against both groundwater level and groundwater salinity. Model results were compared at certain key locations with observed data. From calibration plot of ground water level (Fig. 4), a good agreement between the observed and simulated groundwater level can be seen for the simulation period where the value of root mean square error (RMSE) is 1.2. The model was also calibrated against the groundwater salinity.

Fig. 5 shows comparison of spatial distribution of groundwater salinity between the observed and the simulated results for the base case (year 2013).

A good agreement of spatial distribution of salinity was seen between the observed and modelled results (Fig. 5). The low salinity zone lies along the western part of the study area and the high salinity zone lies along the eastern side. Salinity distribution for deep aquifer could not be calibrated due to limited number of observed values. Hence this calibrated model was applied with different options for the case of shallow aquifer only. Upper shallow aquifer extends between 35 m and 120 m from the ground surface.

Further, it was noticed from the observed data that the river salinity varies with tidal variation. It was also noticed that the river salinity and shallow aquifer salinity were interlinked. However, no direct influence of the river salinity was noticed on the deep aquifer salinity (Fig. 6).

Future groundwater salinity projection

To predict the future conditions (climate change scenario), parameters that are impacted by climate change have only been changed in the calibrated models IPCC Special Report on Emission Scenarios (SRES) recommended several scenarios that explore alternative development pathways, covering a wide range of demographic, economic and technological driving forces and resulting greenhouse gas (GHG) emission. In this study, the scenario A1B was simulated for 2050 condition as it reflects the moderate condition. Using this prediction for the year 2050, 0.52-m sea level rise was projected. The MIKE-11 model was run to simulate future river flow and salinity conditions, which were then incorporated into the FEFLOW model for future simulation. Propagation of salinity in the aquifer hence was assumed only through the river network (MIKE 11), which was influenced eventually by the tide from the Bay of Bengal (and associated sea level rise). Since river water salinity increases during dry period, groundwater salinity was also assessed for the dry period.

The changes in the spatial distribution of ground water salinity were compared for the base period (2013) and the climate change scenario (year 2050). Areas falling under different salinity groups were determined. The areas falling under low salinity zone were found to decrease and areas falling under high salinity were found to increase under the future climatic conditions (Table 3 and Fig. 7). This finding also similar to the

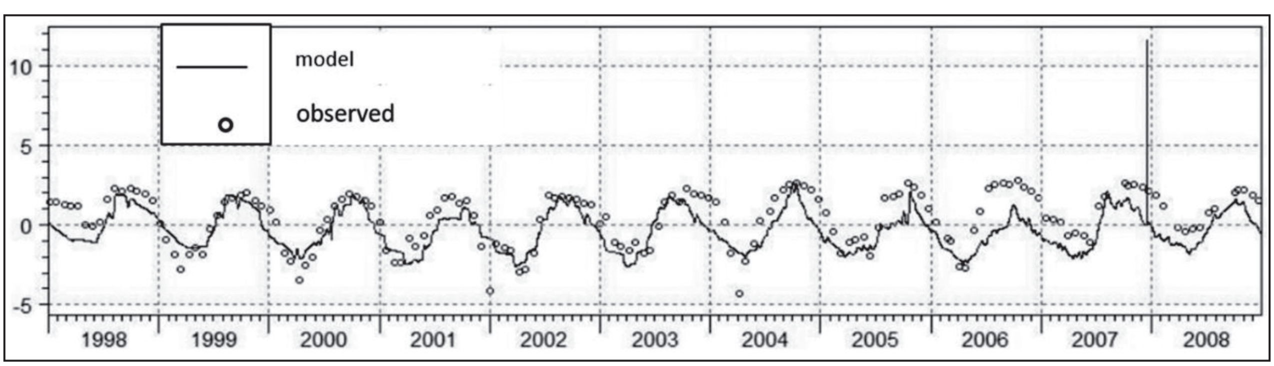

Fig. 4. *Comparison of simulated and observed groundwater level at Keshabpur*

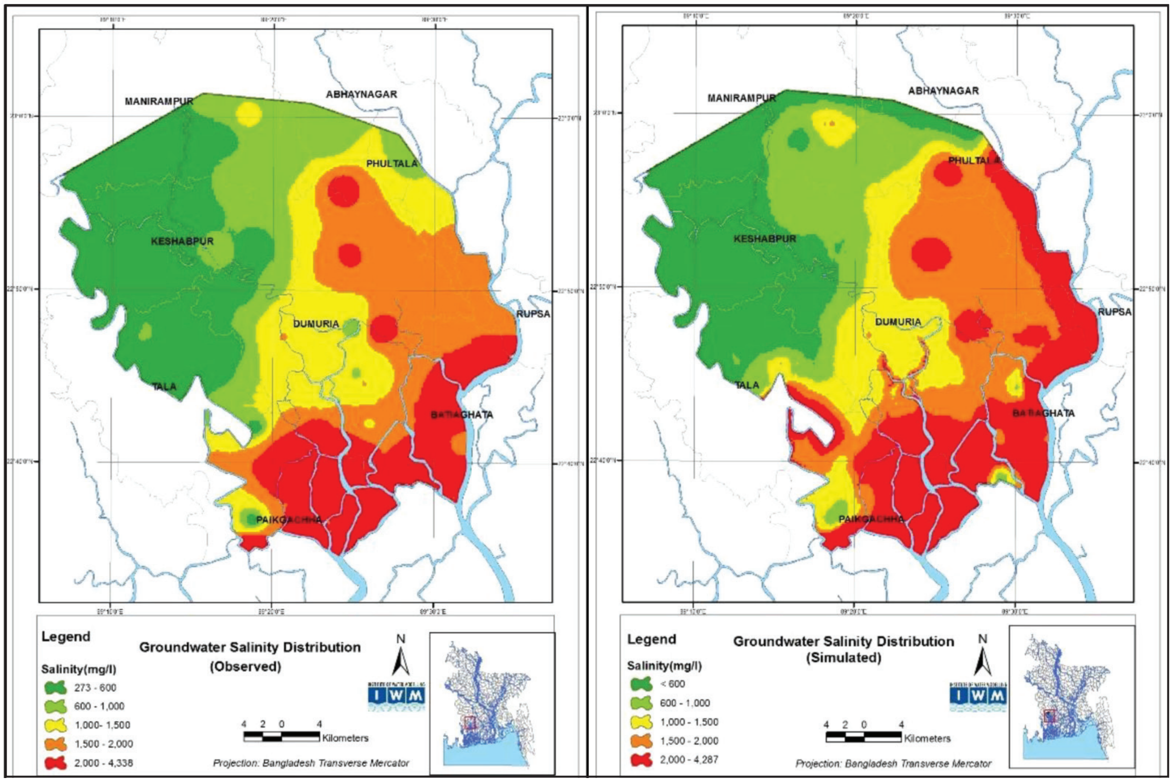

Fig. 5. *Groundwater salinity distribution comparison (Observed vs. Modelled)*

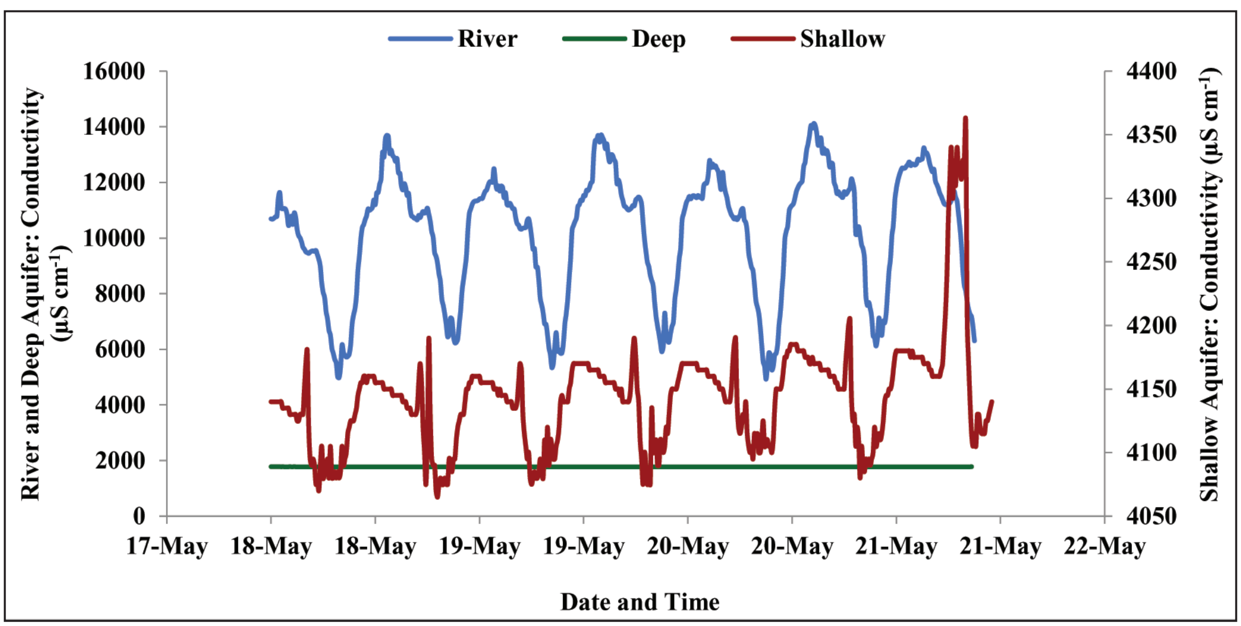

Fig. 6. *Observed electrical conductivity of river, deep and shallow aquifers in 2012*

Table 3. *Comparison of groundwater salinity in the base year (2013) and the climate change scenario (year 2050)*

Salinity (ppm)	Area km^2		Change (%) between 2013 and 2050
	2013	2050	
<600	382	303	-20.67
600-1000	227	285	25.50
Fresh zone (< 1000)	609	588	-3.44
1000-1500	233	240	3.13
1500-2000	323	285	-11.72
>2000	369	421	13.98
Saline zone (> 1000)	925	946	2.27

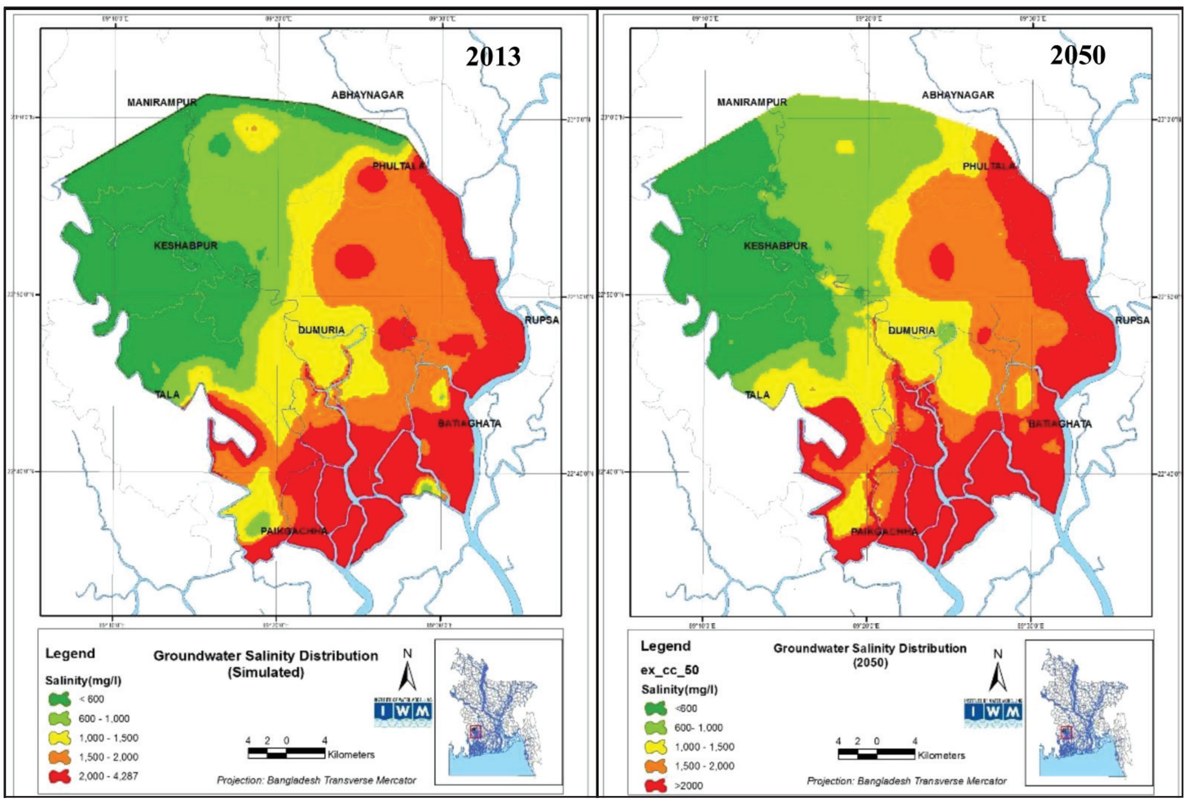

Fig. 7. *Simulated groundwater salinity in the shallow aquifer*

findings of the study conducted by World Bank in 2010 (WB, 2010).

Salinity distribution along the aquifer depth was also evaluated. Vertical salinity along Kobadak-Hari River (Fig. 8) was considered. It was seen that the aquifer salinity generally increases. The groundwater salinity range < 1000 ppm disappear in 2050. Similar trend was noticed for the other river also.

It was observed the in shallow aquifer, groundwater level changes with tidal fluctuation in the nearby river. The changes in groundwater levels and salinity were found to be more distinct in case of shallow aquifer than in the deep aquifer. Within the study area, groundwater salinity varies from 250 ppm to 3500 ppm in present condition and 250 ppm to 5500 ppm for future condition in 2050. South-eastern part of the study area was found

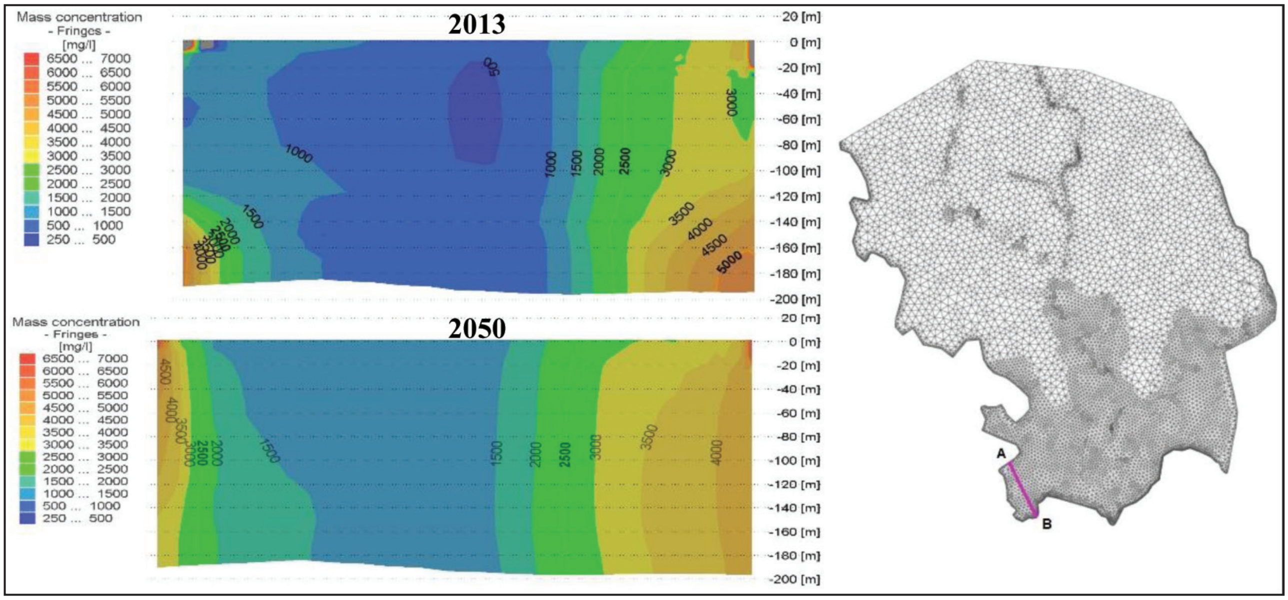

Fig. 8. Simulated groundwater salinity in the shallow aquifer

to be more saline than that of north-western part of the study area. Groundwater in shallow aquifer was found to be more saline than the deep aquifer (with exception of Paikgacha area) and exceeds allowable limit for drinking purposes. Currently, the low saline zone lies along the western part of the study area and the high saline zone lies along the southern and eastern sides. Under climate change condition, it was found that the area of low-saline zone will decrease and area under high saline zone will be increased by 14% in 2050.

The study recommends for restricted utilization of groundwater in the areas having salinity (1000 ppm to 2000 ppm) and for protection of fresh water zone. For high saline zone, extensive promotion of alternative technologies such as pond sand filter, rainwater harvesting or reverse osmosis (RO) can be implemented to meetup the water for drinking and domestic purposes. The study also recommends for increasing freshwater flow from upstream by negotiation with the neighbor country.

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