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RESEARCH ARTICLE

Can crop production intensification through irrigation be sustainable? An *ex-ante* impact study of the south-central coastal zone of Bangladesh

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Abstract

In Bangladesh's south-central coastal zone, there is considerable potential to intensify crop production by growing dry winter season '*Boro*' rice, maize, wheat, pulses and oilseeds using irrigation from southward flowing and predominantly freshwater rivers. However, the impacts of surface water withdrawal for sustained irrigation and its safe operating space remain unclear. We used field measurements and simulation modeling to investigate the effects of irrigation water withdrawal for *Boro* rice–the most water-consumptive crop–on river water flow and salinity under different climate change and river flow scenarios. Under the baseline conditions, about 250,000 ha could potentially be irrigated with river water that has salinity levels below 2 dS/m. The impact on river water salinity would be minimal, and only between 0.71 to 1.12% of the cropland would shift from the 0–2 dS/m class to higher salinity levels. Similarly, for the moderate climate change scenario (RCP 4.5) that forecasts a sea level rise of 22 cm in 2050, there would be a minor change in water flow and salinity. Only under the extreme climate change scenario (RCP 8.5), resulting in a sea level rise of 43 cm by 2050 and low flow conditions that are exceeded in 90% of the cases, the 2 dS/m isohaline would move landward by 64 to 105 km in March and April for the Tentulia and Buriswar Rivers. This would expose an additional 36.6% of potentially irrigable cropland to salinity levels of 2 to 4 dS/m. However, *Boro* rice will already be well established by that time and can tolerate greater levels of salinity. We conclude that there is considerable scope to expand irrigated crop production without negatively exposing the cropland and rivers to detrimental salinization levels while preserving the ecosystem services of the rivers.

1. Introduction

Bangladesh, a deltaic country in South Asia, has a land area of 14.5 million ha and a human population of over 170 million. While the population is still growing at about 1% per year,

the data justify the study's conclusions. On reasonable request, the raw data will be provided.

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agricultural land availability decreased from 9.4 million ha in 1976 to 8.5 million ha in 2011, resulting in 0.05 ha of arable land per person [1]. Food security remains a concern, especially in the coastal zone [2]. New avenues are needed for low-cost and sustainable food production and to create opportunities for farmers to generate more income, as poverty and hunger are closely interlinked [3]. The United Nations' sustainable development goal (SDG) 2, "Zero hunger," advocates that increased agricultural productivity must be achieved in a sustainable manner. Expansion of the cropland area entails risks, including further encroachment into forests and other natural habitats [4]. In response, sustainable intensification (SI) has been proposed as a set of principles to increase crop and livestock yields and associated economic returns without negative impacts on soil and water resources or the integrity of non-agricultural ecosystems [5, 6]. The diversion of river water for irrigation in a delta region is risky, as it can alter water flow and thus cause saltwater intrusion, which is likely to get exacerbated by sea level rise caused by global warming [7]. This study explores whether it is possible to intensify crop production with irrigation in the delta region of Bangladesh while staying within the safe operating space and thus preserving the ecosystem services of the rivers [8, 9].

Exempting Bangladesh's coastal zone and mountainous eastern fringes, most land is already cropped with 2–3 crops per year, mainly rainfed rice during the monsoon '*Aman*' season, and irrigated rice and other crops during the dryer winter months ('*Rabi*' season). In the north, groundwater is the primary source of irrigation water. However, in the low-lying coastal zone in the south, which is about 1 to 3 m above sea level, easily accessible groundwater is generally too saline for irrigation [10]. About 0.24 million ha of cropland is left fallow during the dry winter months in southwestern Bangladesh [11–13]. Most of the winter fallow land (0.074 million ha) is in the Barisal division in the south-central hydrological coastal zone, with a cropland area of approximately 0.54 million ha [14]. In that division, about 0.32 million ha are cultivated under low input conditions with little to no irrigation and fertilizer in the winter. Only 0.15 million ha are cropped using higher rates of water and nutrients [14]. Krupnik et al. [14] also mentioned that, using diversified crop (maize and wheat instead of '*Boro'* rice) with proper irrigation management at least 20,800 and 103,000 ha of fallow and rainfed agriculture can be converted into enhanced double cropping, respectively. Hence, there is a considerable potential to intensify crop production by growing *Rabi* season rice (also known as '*Boro*'), maize, wheat, pulses and oilseeds during the winter in this division. However, most of these crops will require irrigation, which can potentially be supplied using surface water when and where it is sufficiently fresh [15–17]. Schulthess et al. [18] reported yields as high as 7 t ha^{-1} for maize and higher than 2 t ha^{-1} for wheat for this area. Bhattacharya et al. [19] concluded that by draining surface water just before monsoon rice maturity, it is possible to practice highly productive and profitable triple-cropping systems in low soil salinity portions of the coastal zone by including maize or sunflower in the winter season, a short duration rice in pre-monsoon (*Kharif*-1) season, and a medium duration rice in the full monsoon (*Kharif*-2) season. The use of surface water for irrigation responds to Bangladesh Government's priorities articulated in a policy that encourages substantial investments to increase cropping intensity on currently winter fallow and rainfed croplands and to expand the use of surface water irrigation during the dry season [20]. Such developments could be a logical place to start defining the environmentally sound 'envelope' for intensification potential in this region.

In the Barisal division, five major rivers and numerous canals cross the landscape. Canals are natural and assist in bringing tidally mediated water inland and drain out excess water during the rainy season, both of which are important ecosystem services [21]. Considering the ecosystem service of freshwater supply, Krupnik et al. [14] reported that nearly 0.06 million ha of land could be irrigated in this division with surface water pumps using river and canal water during the winter. That study limited the area that can be irrigated to a buffer of 0.4 km on both sides of the rivers and major canals due to the limited lift and water conveyance capacity of most surface pumps. In our study region, canals have been partially used for irrigation, transport, and supply of fish species, but many have become silted up, rendering some sluice gates that have been installed to manage fresh and saline water flow inactive [22, 23]. However, with rehabilitation and appropriate water flow infrastructure, rivers and canals could be utilized efficiently by irrigating most of the land [14]. Hence, an ex-ante analysis of the safe operating space is a prerequisite for their restoration, as it would require a significant investment. Conversion to large scale irrigation during the winter months may need a considerable amount of water, which in turn could reduce river flow. This, combined with sea level rise (SLR), may cause an increase in salinity conditions at the downstream end of these tidal rivers.

The dense network of canals and rivers, tidal amplitude and flow dynamics, the extent of landward entry of tides, the volume of freshwater flow from upstream catchments, and salinity fluctuations in the river basins strongly govern the availability of fresh water for dry season cropping in the southern delta [24, 25]. Assessment of water flow and salinity of the regions' rivers and interlinked natural and man-made canal systems are essential starting points to determine the quantity of available freshwater during the *Rabi* season. The water flow and salinity could be estimated by field sampling and measurements, although such measurements and monitoring at every point of interest would neither be feasible nor cost-effective. Instead, well-calibrated simulation models can be applied to understand and quantify the water flow, as well as soil and water salinity under the current and future climate change.

Hence, the objectives of the current study were to (i) improve the river water flow and river water salinity models for their applications in southern coastal Bangladesh and (ii) apply those models under different climate change scenarios to quantify the effects of river water withdrawal on surface water availability and salt intrusion to assess the potential for crop intensification in the coastal region at present and under future climate change conditions. These objectives were achieved by calibrating the models for the rivers and canal systems of the south-central coastal area based on field measurements and secondary data and applying them under various scenarios of climate change and SLR. The overall goal was to determine the safe operating space for expanding irrigated dry-season agriculture using available surface water. We wanted to determine whether critical levels of river flow could be maintained to safeguard the river ecosystem and prevent the intrusion of saline water into the delta under various climate change scenarios. We present it as a case study that links different disciplines and addresses SDG 2 (Zero hunger), SDG 6.4 (sustainable freshwater withdrawals) and SDG 13 (combat climate change and its impacts). Such a study could largely be applied to most deltas globally exposed to SLR and salt intrusion and with a scarcity of quality irrigation water for sustainable crop intensification.

The manuscript is divided into the five sections. Section 1 is introduction. Section 2 describes the climate conditions, river data collection plan (water level, flow and salinity), description of river basins and hydrological situation of the study area, description of the mathematical model framework, calibration and validation of the model, and scenario generation with climate change projection and upstream flow condition. Section 3 elaborates on the calibration and validation of the models that simulate water level, river flow and surface water salinity and quantifies the impact of climate change on salinity intrusion due to potential abstraction of river water for irrigation. The discussion (section 4) puts the study results in a larger context and section 5 summarizes the outputs of the study and mentions topics that require further inquiries.

2. Materials and methods

2.1. Characteristics of the study area

The southern coastal region of Bangladesh consists of three major zones: south-west, south-central and south-east. Polders embark the southern halves of the south-west and south-central zones. Their construction began in the 1960s to reclaim large tracts of land for agriculture. This study focuses on the south-central zone, which covers most of the Barisal division. Water and soil salinity levels in this zone are generally much more conducive to crop production than in the south-west zone [14]. That zone depends mainly on the Gorai River (shown in S1 Fig), which tends to run almost dry during the winter months, which in turn causes the intrusion of saline water.

2.1.1. River network of study area. The south-central zone possesses several tidal rivers and an extensive network of surface water irrigation and navigation routes, with tidal effects extending inland as far as 150 km [26]. The river system exhibits the highest flow rates during the monsoon (June/July to September/October) season, whereas the flow rates are lowest between January and March. The study area covers five major river basins (Baleswar, Bishkhali, Buriswar, Lohalia and Tentulia) within four districts (Barisal, Jhalokhati, Patuakhali and Pirojpur) in the south-central zone (Fig 1). Being the most active hydrological zone in which surface water irrigation has potential [14], these adjacent basins were chosen for our study.

The Baleswar River basin in the upstream gets flow from the Arial Khan River, which is fed by the Padma River (Fig 1). The Bishkhali, Buriswar, Lohalia and Tentulia River basins are mainly linked with the Arial Khan and the Lower Meghna Rivers. The Padma River contributes about 90% to the flow of the Lower Meghna River, the latter also carrying the flow of the Upper Meghna River [25, 27]. There are many small, narrow and shallow canals of varying lengths, with their water draining into various flowing rivers. These rivers and canals and their water depths are strongly influenced by river discharge and tidal phenomenon in the Bay of Bengal (BoB).

2.1.2. Climate. The climate of the study area is tropical with three main seasons: summer or pre-monsoon (*Kharif*-1) from March to May, monsoon or *Aman* (*Kharif*-2) from June to October, and dry winter (*Rabi*) from November to February. The maximum daily temperature in the region can exceed 35˚C in April, while the minimum temperature can be below 10˚C in January. The average annual rainfall in the region is 1950 mm. Peak rainfall (75–80%) occurs from June to September, with maximum monthly rainfall varying from 296 to 693 mm. The annual average potential ET is 1275 mm, which is quite evenly distributed, though generally highest during March-April [28]. Daily rainfall, evaporation and sunshine hours data were collected from the Bangladesh Meteorological Department (http://live4.bmd.gov.bd/).

2.2. Characterization of baseline conditions

Previous simulation studies had focused on the south-west zones using the South-West Regional Water Flow (SWRM) and salinity models [29, 30]. As described below, we collected additional data to parameterize these models for our study area.

2.2.1. Water level, water flow, and water salinity measurements. Water flow conveyance data are needed to calibrate the water flow model and to simulate the water levels. A field campaign was carried out during the dry season of 2014/15 to measure the time series river water level, flow and salinity at selected river stretches in the study region (Fig 2). Rivers and canals cross-sectional data with close intervals (250 m and 500 m) were ascertained by considering the width, depth and bends of the rivers. They were used to assess the water flow conveyance, water flows and water salinity concentrations. In addition, daily water flow time series data

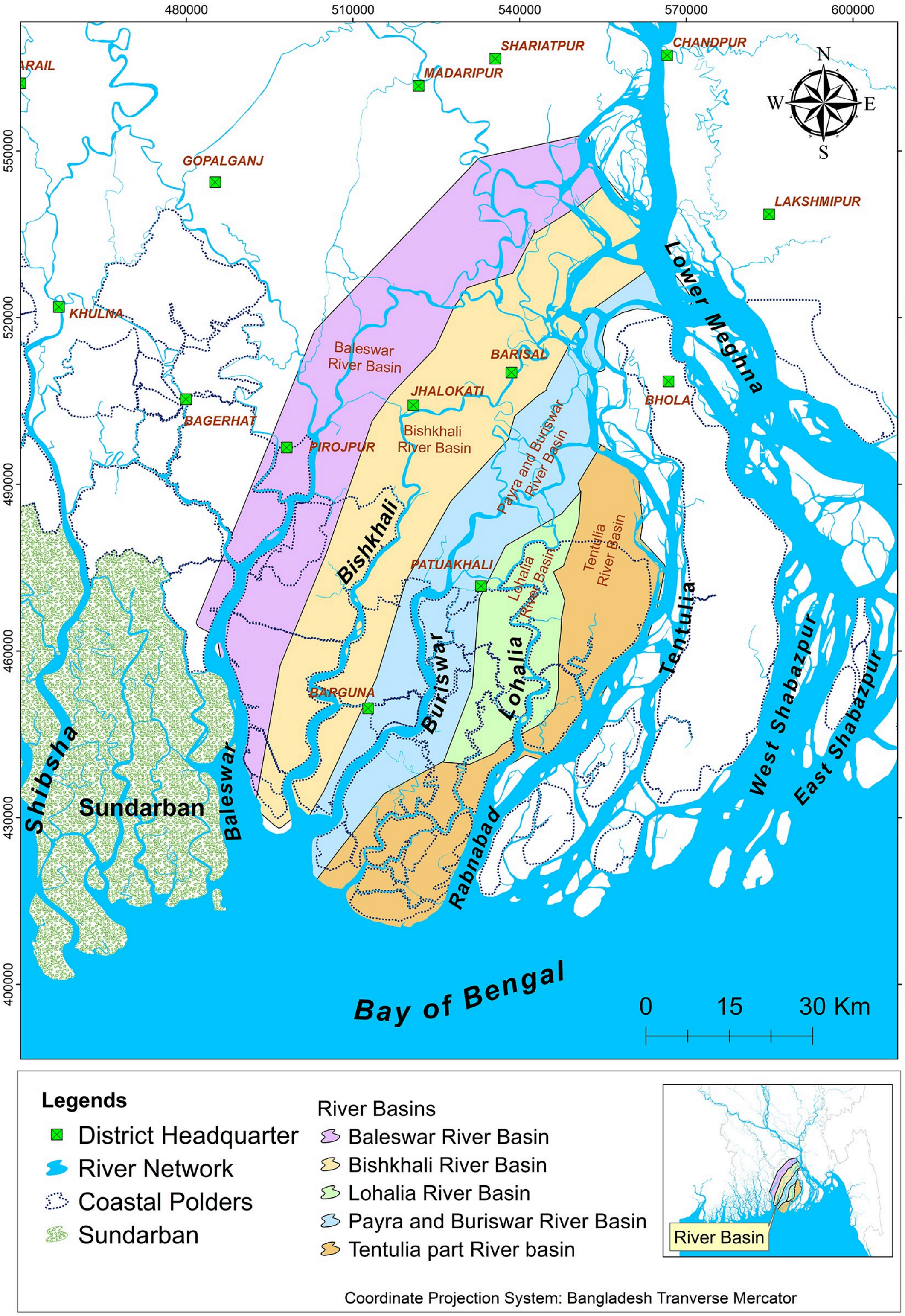

Fig 1. Study area located in the south-central delta region of Bangladesh. It encompasses five major river basins.

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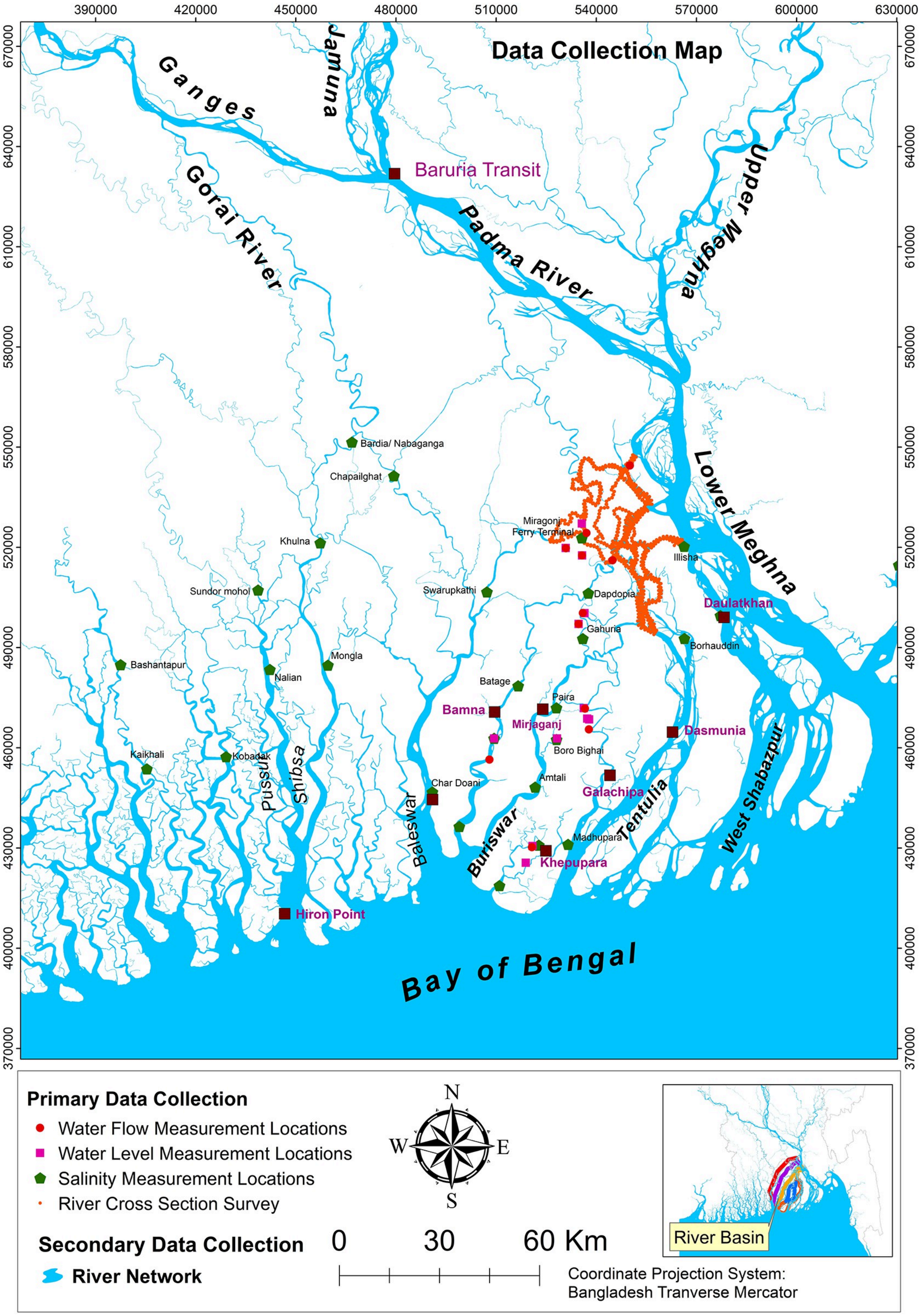

Fig 2. Map of sites where river water flow (discharge), level and salinity were measured during the period from January to April 2015.

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were collected from the Bangladesh Water Development Board (BWDB; http://www.hydrology.bwdb.gov.bd/) and Bangladesh Inland Water Transport Authority (BIWTA).

A cross-sectional survey of the rivers and canals was carried out using a differential global positioning system (GPS), echo sounder, total sounder, and pressure sensor to assess the conveyance and surface water availability. About 775 cross-sections were surveyed in different rivers and internal canals to collect the bathymetry data. The leveled machine was used in the non-navigable while echo sounder was in the navigable rivers/canals. In both cases, the position and alignment of the rivers/canals cross-sections were maintained by satellite-based GPS.

Water level and water flow. Water level was measured at various river locations to examine the tidal characteristics and water level variation, provide input data as the model boundary, and calibrate the water flow model. The tidal water level was measured at hourly intervals for four months in 11 locations of all five river basins using pressure sensors and staff gauges. Water flow was measured for a full tidal cycle (one cycle of 12 hrs and 50 min) in spring and neap tides in February and April for flow characterization and calibration of the water flow model. The flow duration curve provides the probabilistic description of stream flow at various percentages at a given location. HYMOS, an information system for storing, processing and presenting hydrological and environmental data [31], was used to prepare cumulative maximum, average, and minimum 90%, 50% and 10% hydrographs.

Water salinity. Salinity in river and canal water was measured to understand its spatial variation over the year and to calibrate the surface water salinity model. The locations of salinity monitoring stations were selected based on variations in historical salinity, tidal amplitude, and upstream freshwater flow. Salinity was measured using a salinity meter at low and high-water slack (twice a day) on alternate days from February 2015 to May 2016 at 30 locations downstream of the Bishkhali and Khaprabanga Rivers. The salinity model was used to generate salinity time series data and characterize the baseline condition to assess the likely impacts of salinity (exposure of cropland to salinity intrusion) in the future.

2.2.2. Determination of baseline water flow hydrograph. To establish the upstream boundary flow conditions for the simulation model, we analyzed 30 years of daily water flow/discharge time series data prior to 2015 that had been collected by the BWDB at the Baruria station in the Padma River (Easting: 480650; Northing: 629040). This is the only flow/discharge gauging station at this river, which contributes about 90% to the flow of the lower Meghna River. Fig 3 shows the water flow hydrograph, depicting the 10th, 50th and 90th percentile of dependable water flow and the water flow in 2015, the reference year used for this study. The 10th percentile indicates conditions with a high flow, as this threshold is exceeded only 10% of the time. In contrast, in the case of the 90th percentile, representing a low flow, the threshold is exceeded in 90% of the time or in 27 out of the 30 years used in the baseline.

2.2.3. Estimation of baseline field water requirements. Assessment of field water requirement entails the delineation of the command area, selection of crops, and estimation of crop water requirement. The command area of five major river basins was delineated considering land topography, internal road network, river/canal systems, and conveyance capacity of the major rivers and canals (Fig 1, S1 Table). For the Tentulia river basin, only the western part of the river was considered. Cropland was delineated using a supervised classification of RapidEye satellite images with a resolution of 5 m. They had been acquired between January and March 2015. We followed the methodology outlined by Krupnik et al. [14].

To estimate the potential water withdrawal, we assumed that all croplands would be planted with *Boro*, the crop with the highest irrigation water demand [28, 32]. Portable flow meters (6" diameter) were installed at the pump locations for two independent irrigation schemes in Kalapara (21.938 N, 90.175 E) and Patuakhali (22.319 N, 90.327 E) districts. Farmers had dug various canals to transport water by pumps to the paddy fields. They were submerged

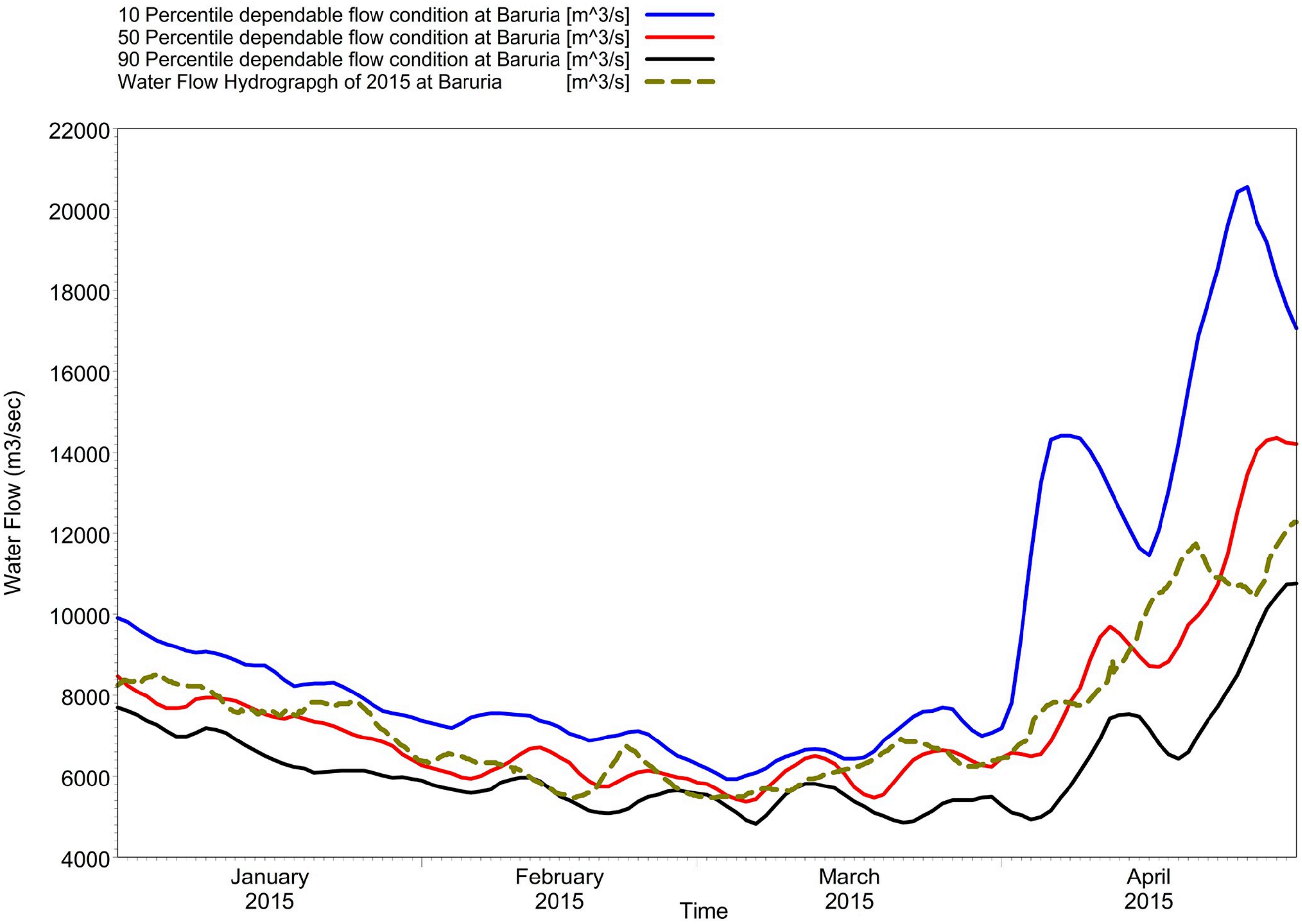

Fig 3. Water flow hydrograph established based on daily water flow rates measured by the Bangladesh Water Development Board at Baruria (Padma River) over the 30 years prior to 2015. Flow rates in 2015 are shown as well. Baruria represents the upstream flow conditions used for the different scenarios analyzed in this study.

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throughout the growing season. The areas of the irrigation scheme were 0.98 ha in Kalapara and 0.14 ha in Patuakhali. At each location, water application for land preparation and post-transplanting and each irrigation during the *Boro* rice growing period was measured. They lasted from January 23 to March 26, 2016 in Kalapara and from January 22 to April 14, 2016 in Patuakhali. Water flow was measured for each of the 13 irrigations in Kalapara and 16 in Patuakhali. It should be noted that the field-level irrigation can be misleading as it could underestimate total irrigation requirements at the irrigation scheme and landscape level [33]. The non-consumptive seepage, percolation and evaporation losses were assumed to be accounted for from the irrigation flow meter measurements. We were, however, unable to measure water losses from canals. Hence, we estimated the losses based on Brouwer et al. [34], who suggested that irrigation water losses from canals vary according to canal length and soil type. The majority of the soils in the study area are loamy. Canals typically are unlined with varying lengths. Hence, as per Brouwer et al. [34], we chose the mean efficiency loss of 77% and increased all measured irrigation flows accordingly to compensate for the loss. Based on the field measurements, Patuakhali had a total irrigation water requirement for *Boro* rice of 13,272 m^3 ha^{-1}, while Kalapara had a 9,930 m^3 ha^{-1}.

2.3. Model description, calibration and application

2.3.1. Model description. Two existing regional water flow and salinity models, the South-West Regional model (SWRM) and the Bay of Bengal (BoB), were linked to simulate the current baseline as well as future scenarios under climate change (Fig 4). Both models are driven by the MIKE simulation algorithm [29, 30]. The SWRM was used to estimate the water level, flow and salinity of the rivers, while the BoB model accounted for the effects of SLR on the downstream boundary conditions (water flow and salinity). Those conditions, together with the downstream flow, control the salinity intrusion. Uddin et al. [35] provided a more

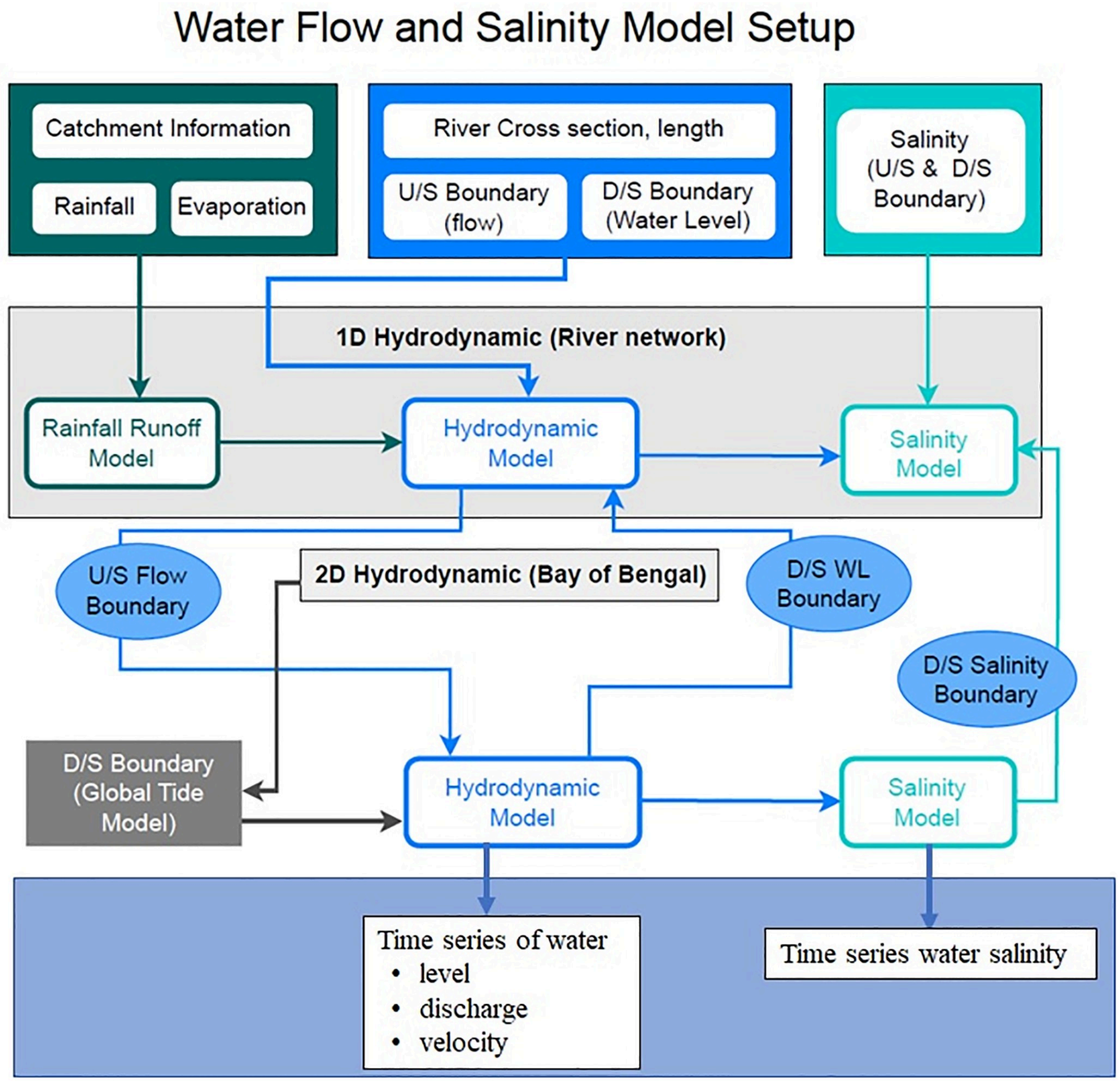

Fig 4. Flow chart of the linked Southwest Regional Water Model (SWRM) and the Bay of Bengal (BoB) models used to simulate water level, discharge, velocity and salinity levels in the river network.

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detailed model description. The SWRM network is superimposed on the BoB model domain (shown in S2 Fig).

Previous model applications concentrated on the South-West, while the current study focused on the south-central region, for which less detailed data were available prior to this study. Simulations covered the baseline conditions in 2015, as well as different climate change scenarios in 2030 and 2050, as outlined in Table 1.

2.3.2 Model calibration. The SWRM and BoB models had been previously calibrated for the southwest region [25, 36–39]. The following three model parameters were fine-tuned for the south-central region: "Manning's roughness number (M), which is 1/n, where 'n' is Manning's roughness co-efficient. It is used in both models. The salinity requires two additional parameters: dispersion coefficient and the mixing coefficient (K_{mix}). For the estuarine area and in the large rivers, with widths varying from 1 to 6 km, the dispersion factor varies from 600 $m^2 s^{-1}$ to 1200 $m^2 s^{-1}$, whereas in the small rivers with a width of 0.5 to 1 km, the dispersion co-efficient varies from 300 to 500 $m^2 s^{-1}$). The mixing coefficient captures the saltwater and fresh water mixing process in the estuary.

We updated the calibration using data from the above-mentioned field measurements, as well as with data obtained from different government agencies: The BIWTA provided the tidal water level data, the BMD the daily weather data, and the BWDB water flow and water level data. The calibration locations for water flow, water level, and water salinity are shown in Fig 5. The robustness of the model was ascertained using the coefficient of determination.

2.3.3 Selection of climate change scenarios and projections of climate parameters. Changes in precipitation and SLR due to climate change can cause considerable changes in river water salinity, affecting freshwater availability in time and space [40]. We considered two climate change scenarios from the IPCC Assessment Report 5—moderate (RCP 4.5) and high (RCP 8.5) emission scenario [41]—to simulate the impact of water withdrawal for irrigation for *Boro* rice on water availability and salinity in the south-central coastal zone. Projections of the mean monthly temperature change (%), mean monthly precipitation change (%), and change in SLR (cm) in 2030 and 2050 were established based on IPCC reports and other

Table 1. Scenarios used to assess the impact of surface water withdrawal and climate change on surface water flow and salinity intrusion. The scenarios are constrained by the upstream (US) and downstream (DS) boundary conditions.

Climate change	Boundary conditions	US dependable flow percentiles			Scenario
		10	50	90	
Baseline without water withdrawal	• Tidal water level at DS boundary • Salinity boundary at DS from recorded tidal water levels	X			S-0-10
			X		S-0-50
				X	S-0-90
Baseline with water withdrawal	• Tidal water level at DS boundary • Salinity boundary at DS from 2D simulation model results	X			S-1-10
			X		S-1-50
				X	S-1-90
Moderate climate change 2050 (RCP 4.5)	• 22 cm SLR at DS tidal water level boundary • Change in precipitation			X	S-2-90
Extreme climate change condition 2030 (RCP 8.5)	• 22 cm SLR at DS tidal water level boundary • DS salinity boundary at 22 cm SLR • Change in precipitation			X	S-3-90
Extreme climate change condition 2050 (RCP 8.5)	• 43 cm SLR at DS tidal water level boundary • DS salinity boundary at 43 cm SLR • Change in precipitation	X			S-4-10
			X		S-4-50
				X	S-4-90

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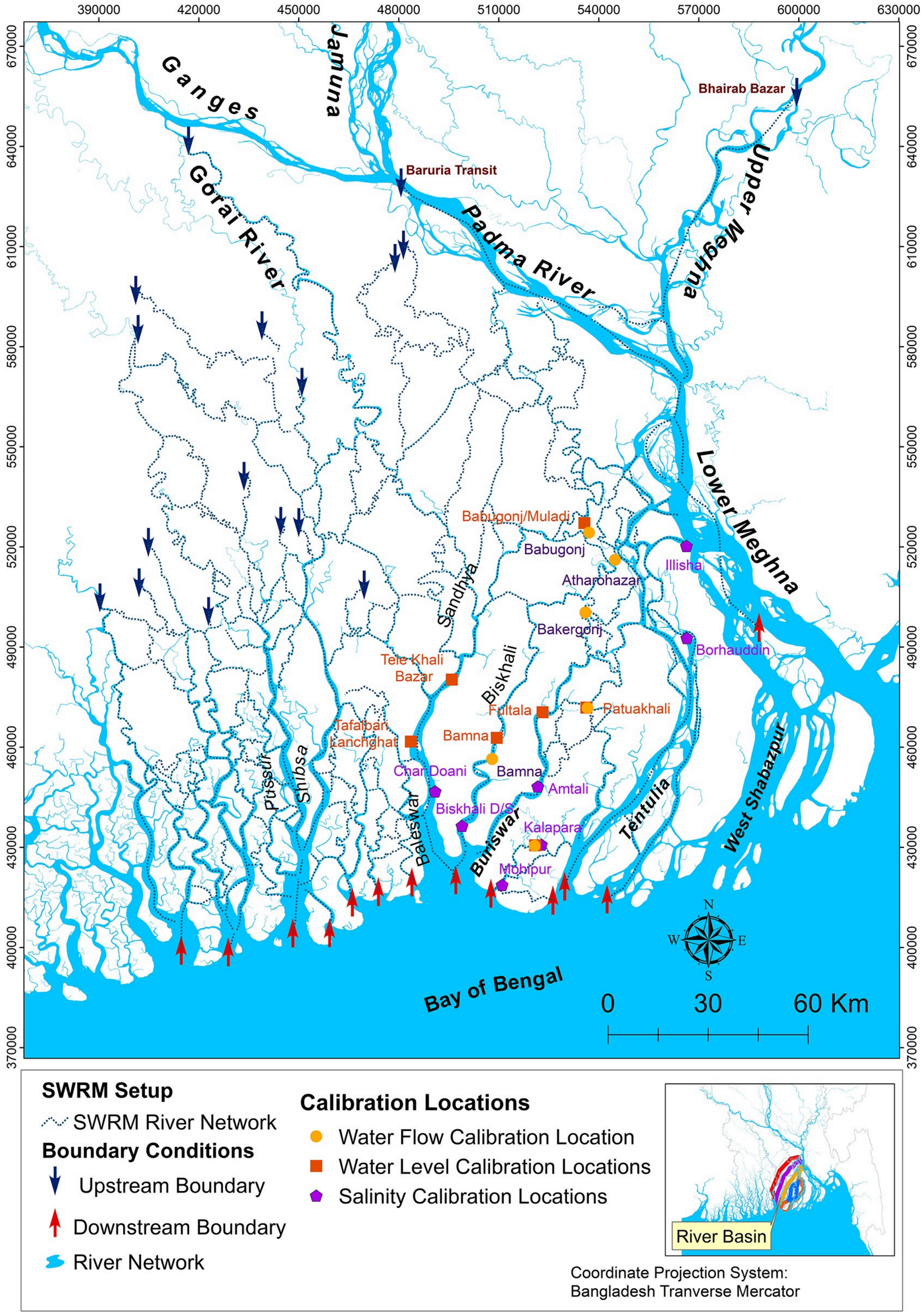

Fig 5. Sites defining the up- and downstream boundary conditions for water flow and salinity used as inputs for the Southwest Regional Water Model (SWRM) and the Bay of Bengal (BoB) model. The calibration locations for salinity, water level and water flow are also shown.

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Table 2. Projections of change in rainfall (%) from January to April in south-west and south-central coastal zones of Bangladesh under moderate (RCP 4.5) and extreme (RCP 8.5) climate change scenarios in 2050. The respective monthly averages calculated over 30 years prior to 2015 were used as a reference.

	Moderate (RCP 4.5)		Extreme (RCP 8.5)	
	South-west	South-central	South-west	South-central
January	0.88	-8.54	-12.39	-14.53
February	4.25	4.71	4.68	3.24
March	6.3	2.63	-5.29	-0.4
April	-7.14	-9.87	-11.85	-10.7

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literature. Projections for rainfall for the three southern coastal zones for 2030 and 2050 were used from secondary sources (http://climatewizard.ciat.cgiar.org/wbclimateanalysistool/), which had been derived based on a statistical downscaling of 15 GCMs. Relative mean SLR along the coast had been established under the World Bank-funded Coastal Embankment Improvement Project Phase 1 (2013–2022) considering subsidence, sedimentation, and absolute SLR under different climate change scenarios [42, 43]. Table 2 illustrates the projections of change in rainfall for January to April for southwest and south-central coastal zones under the extreme and moderate climate change scenarios for 2050.

2.3.4 Estimations of water flow at upstream and salinity along the coast. The changes in water flow in the upstream during the dry season depend on changes in temperature, precipitation and evaporation in the Ganges, Brahmaputra and Meghna basins. Comparing observed flows with monthly projected flows for different scenarios revealed that the peak flow could increase by 4 to 39% in the monsoon, and the low flow in the dry period could drop by 4 to 27%, indicating more pronounced seasonality [44]. These changes in discharge/water flow were incorporated in the upstream boundary of the model for simulations of salinity under different scenarios and hydrological events in 2030 and 2050 (Table 1).

2.3.5 Assessment of likely impacts of water withdrawal for irrigation and of climate change on river water flow and salinity. With the calibrated model, we simulated the impact of the scenarios outlined in Table 1 on water availability and salinity intrusion. Current water availability, i.e., the baseline condition, was assessed based on field measurements as well as simulations of water flow and salinity without considering water withdrawal or SLR or change in precipitation. Next, we simulated the impact of withdrawing water for irrigation, considering no climate change and in a last step, we considered RCP scenarios for 2030 (RCP 8.5) and 2050 (RCP 4.5 and 8.5). The upstream boundary conditions (Table 3) were modulated assuming a 10, 50 and 90 percentile dependable flow (Fig 3). Different SLR levels caused by climate change defined the downstream tidal water level boundary conditions. The following key parameters were generated with the SWRM: Water level, flow and salinity during high (flood) and low (ebb) tide.

Table 3. Change, using 2015 as a reference, of upstream boundary flow during January to April under moderate (RCP 4.5) and extreme (RCP 8.5) climate change scenarios in 2030 and 2050.

Month	Moderate (RCP 4.5)	Extreme (RCP 8.5)	
	2050	2030	2050
Jan	-4%	-7%	-8%
Feb	-5%	-8%	-9%
Mar	-6%	-10%	-13%
Apr	-9%	-5%	-8%

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Scenarios for water withdrawal for *Boro* rice were based on actual field measurements as presented above. These water withdrawal estimates were fed back into the SWRM. Water withdrawal in the five major river basins was simulated at a 1 km interval. The cropland was categorized into three classes based on the degree of exposure to salinity from irrigation water. The high, moderate and marginal potential croplands were those that had water salinity levels of 0–2, 2–4, and >4 dS/m, respectively [14]. The environmental impact of irrigation water withdrawal was then assessed by comparing the simulated water flows, salinity intrusion, and change in the exposure of cropland to increased river water salinity due to SLR.

3. Results

3.1 Observed river water flow, level and salinity

Water availability in south-central Bangladesh during the dry period mainly depends on Padma and Lower Meghna River flows. They feed the five major river basins Baleswar, Buriswar, Bishkhali, Lohalia and Tentulia (Fig 1). According to 42 years of data collected by the BWDB at Baruria, the monthly mean daily discharge of the Padma River varies from 5,800 m^3 s^{-1} in February to 72,000 m^3 s^{-1} in August (Source: Department of Hydrology, BWDB). The river system in the study area, which is located between the Padma River and the BoB, accordingly, also exhibits high seasonality over a year. The highest flow rates were observed during the monsoon season from June to September, while the lowest occurred between January and March.

In the south-central region, water levels are dominated by tide and seasonality. There is a distinct seasonal variation between the dry and monsoon period. Tidal differences for the Baleswar River were close to 2 m, whereas the seasonal differences were 0.84 m during 2014 (Fig 6).

During the dry period, upstream freshwater flow is less compared to monsoon flow and consequently, salt water intrudes towards upstream. The main shift occurs between January and March when the salinity fronts of 2 dS/m and 4 dS/m move upstream with the decrease of freshwater flow from the upstream. The landward/upstream movement of 2 dS/m is highest for Baleswar and Tentulia rivers. It moves 28 km for the former and 18 km for the latter. Buriswar River does not show any change in the salinity front of 2 dS/m, and the Lohalia River does not experience any salinity during the dry season. Fig 7 shows the characteristics of salinity fronts in the river systems for March 2015.

The intersection of cropland with river water salinity showed that approximately a quarter of a million ha of cropland could be safely irrigated, assuming no climate change. The area of cropland that could be irrigated with water that has a salinity level below 2 dS/m dropped from 276,000 ha in January to 234,000 ha in March (Fig 8). This was mainly due to the shift of the 2 and 4 dS/m contour lines in the Baleswar River basin. River water salinity levels exceeded 4 dS/m for close to 100,000 ha in March and April. Most of the affected land was in the estuary region.

3.2 Model calibration and validation

The purpose of the SWRM was to establish estimates of water level, flow and salinity for the entire length of the five major rivers of the south-central region for the scenarios outlined in Table 1. For each calibration site (Fig 5), we compared measured and predicted estimates of river water level, flow and salinity over an extended period, ranging from several days (water levels and flow) to months (salinity). Results revealed all coefficients of determination (R^2) values greater than 0.80 (S2 Table). The simulated water flow data for six locations in south-central Bangladesh generally closely matched the observed ones (Fig 9). Only for Babuganj, the

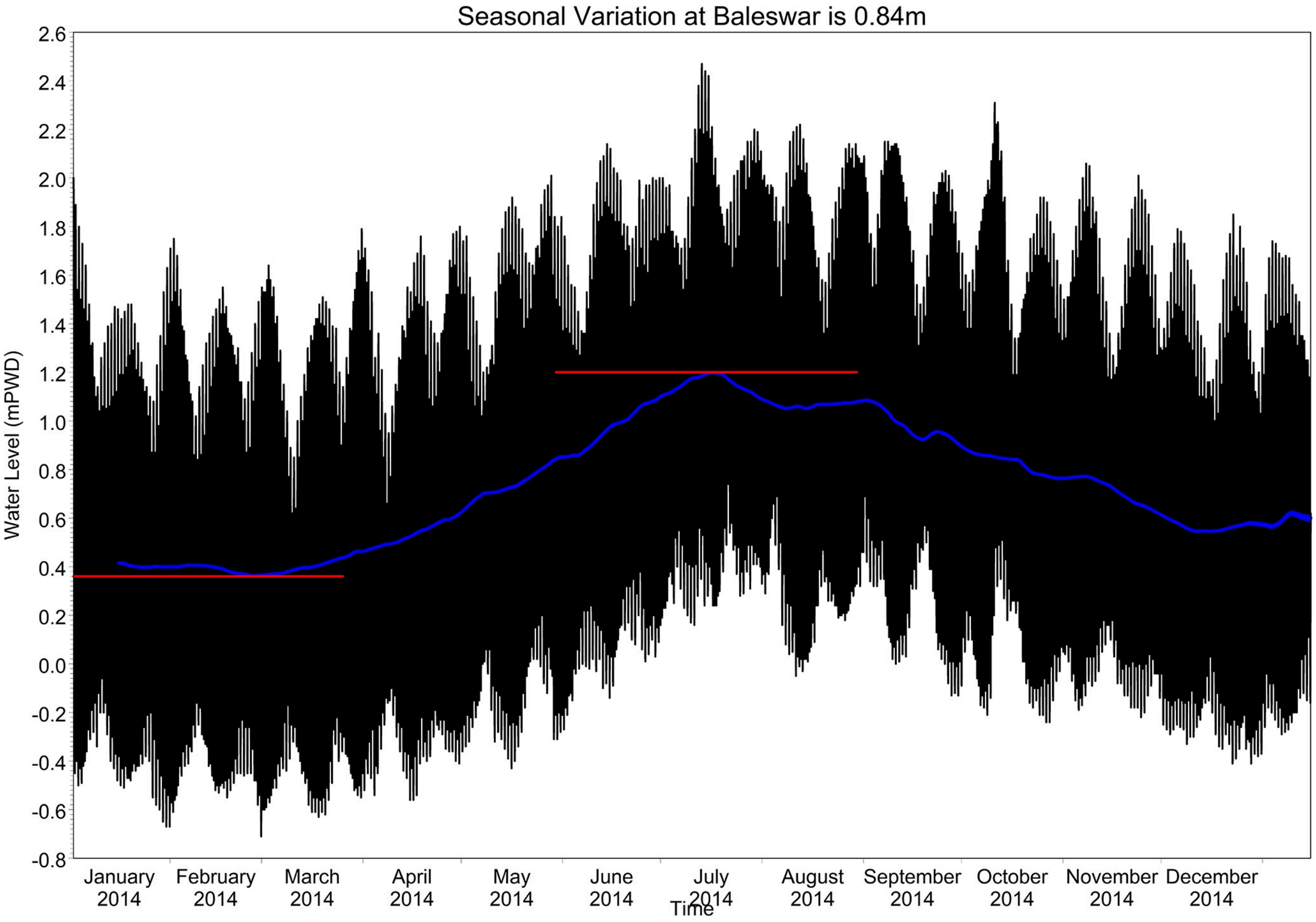

Fig 6. Seasonal and tidal variation at Baleswar River between January and December 2014. Data location: Downstream of Rayenda Khal in Baleswar River (794640.77 m E, 2470338.60 m N); Data Source: Calibrated South-West Region Model (SWRM) maintained by Institute of Water Modelling (IWM) Datum: mPWD, unit maintained by Department of Public Works.

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most northern test site, some predicted data points were outside the range of the observed ones. Simulations of the river water salinity varied across locations, with the best match for Mohipur at the Khaprabanga River. At the other three locations, the simulated salinity estimates were within the range of the observed ones. However, the simulations did not always match the observed short-term fluctuations (Fig 10).

The validation was conducted using the 2012 data as a reference. Calibration parameters were kept at the same level. Fig 11 shows that, the simulated data are in close agreement with the measured data.

3.3 Calculation of the salinity exposure of cropland

To calculate the exposure of cropland to the river salinity, we extracted simulated monthly maximum river salinity data at each node of the model grid points. The data were then imported into ArcGIS and krigged, which resulted in a two-dimensional salinity raster. Next, we created three salinity classes: 0–2, 2–4 and >4 dS/m and overlayed the raster on the cropland and water body data layers to calculate the areas of cropland exposed to the three salinity classes for each of the scenarios listed in Table 1.

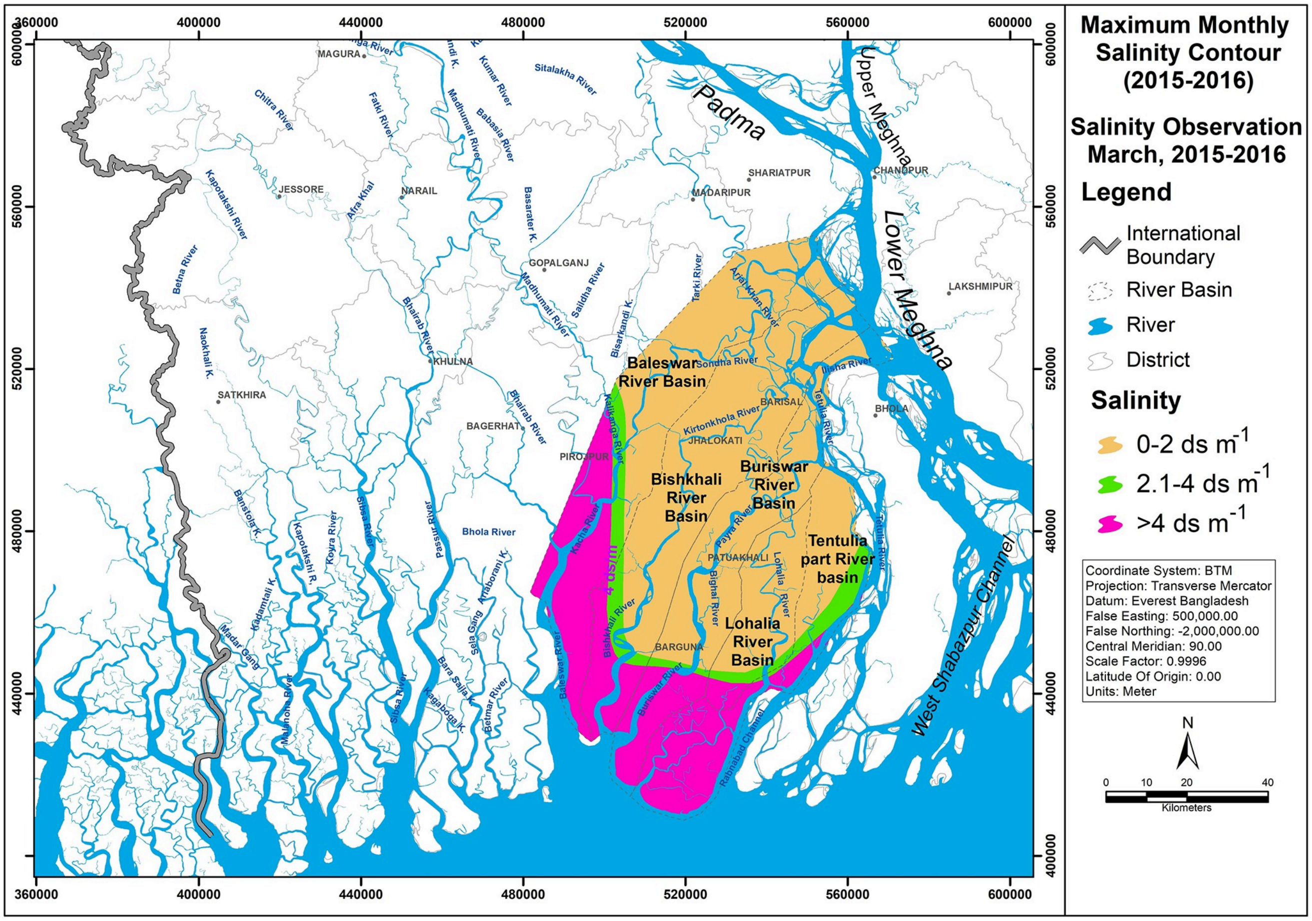

Fig 7. Potential exposure of cropland in South-Central Bangladesh as a function of river water salinity in March of 2015.

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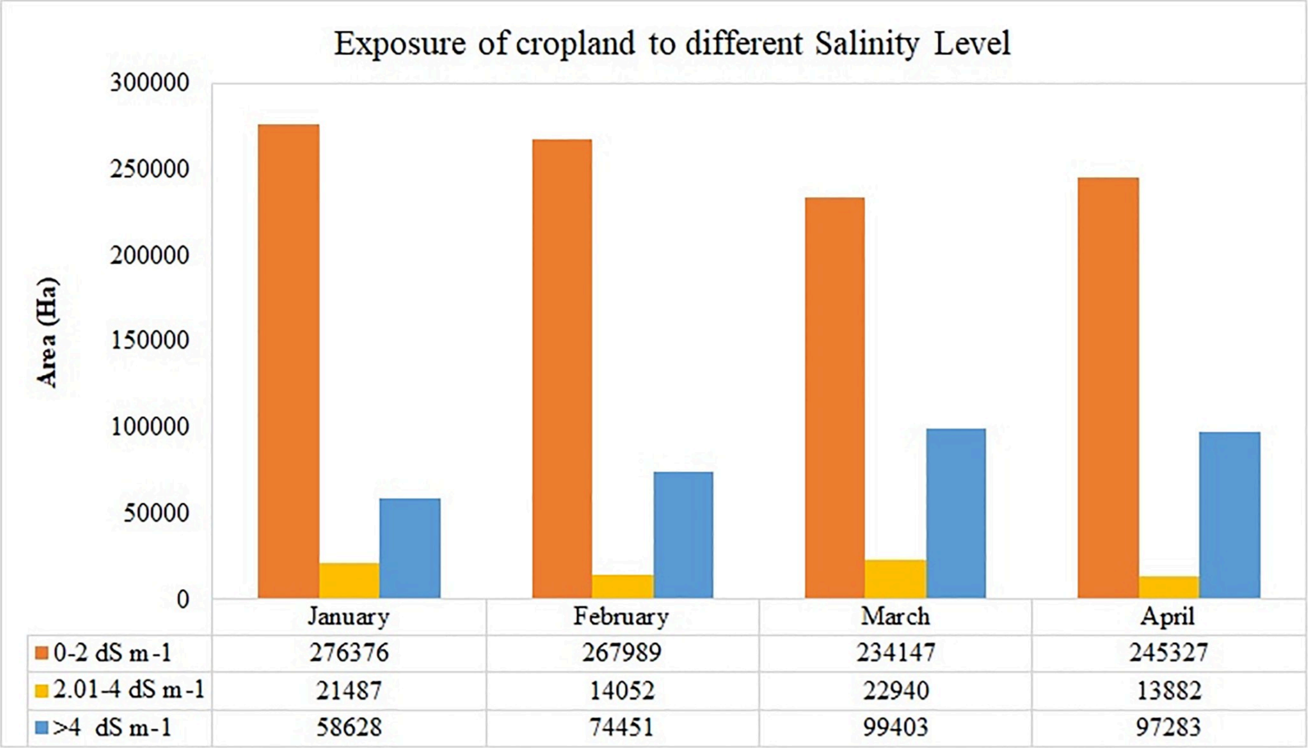
3.4 Impact of climate change on irrigation potential

Under the baseline conditions of 2015, about 250,000 ha could potentially be irrigated with river water that has salinity levels below 2 dS/m. Freshwater flow from upstream rivers and tidal effects from the Bay determine the level and extent of salinity in the area. There is also considerable spatial variation of salinity levels in this southern coastal delta because of different upland freshwater flow, salinity at the coast, and tidal characteristics. We used simulations with the linked SWRM and BoB model to estimate the impact of water withdrawal for irrigation, which decreases upstream flow, and SLR on the dynamics of river water salinity between January and April. The changes in river water salinity, in turn, may reduce the area of cropland that could potentially be irrigated.

At first, simulations were carried out considering only the water withdrawal from the five rivers for irrigation and upstream flow condition of 90% frequency of exceedance, i.e., low flow conditions. The likely impact on flow availability is assessed considering the change of exposure of cropland to three salinity ranges (0–2, 2–4, and >4 dS/m) and thus the shifting of salinity front/isohaline of 2 and 4 dS/m.

The water withdrawal for irrigation caused the 2 dS/m isohaline to move by 0.8 km to 2.2 km from January to April to landward in the Bishkhali River. A similar change was also simulated for the Buriswar River, with the isohaline moving from 1.1 to 1.9 km (S3 Table). In the



	January	February	March	April
🟧 0-2 dS m-1	276376	267989	234147	245327
🟨 2.01-4 dS m-1	21487	14052	22940	13882
🟦 >4 dS m-1	58628	74451	99403	97283

Fig 8. Change in cropland area that could potentially be irrigated in the south-central region of Bangladesh from January to April 2015.

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Tentulia River, shifting of this isohaline was less compared to Bishkhali and Buriswar Rivers since the upstream freshwater is higher in this river and pushes the salinity front downward. In the Baleswar River, the maximum upward movement of this isohaline was about 6 km because the salinity at the Baleswar coast was higher than the Bishkhali, Buriswar or Tentulia Rivers. For higher rates of water flow, i.e., for scenarios with 50% and 10% frequency of exceedance, the shifting of 2 dS/m isohaline was much less, and that of the 4 dS/m isohaline was negligible. Accordingly, abstraction of water from the rivers for irrigation under present conditions has minimal impact on the exposure of cropland to salinity. Between 0.71 and 1.12% of the cropland would shift from the 0–2 dS/m class to higher salinity levels.

Considering the impact of climate change, the simulation results under low flow conditions showed that in 2050 under the moderate climate change scenario RCP 4.5, the effects of water withdrawal on salinity intrusion in the five river basins will also be insignificant. In the Bishkhali, Buriswar, and Baleswar Rivers, the 2 dS/m isohaline moves to landward by 1.02 to 8.5 km. In the Tentulia River, this salinity intrusion under the moderate scenario will only be considerable for a few days in March. As expected, the potential impact becomes even smaller when water flow increases from low flow to 50% or 10% frequency of exceedance, and almost no changes for the 4 dS/m isohaline to landward for any of the five rivers. The slight decrease, by 1.7% to 2.5% (Fig 12), of high potential cropland under the moderate climate change scenario by 2050 was evident.

The response of water withdrawal under the extreme climate scenario (RCP 8.5) in 2030 will also be insignificant since salinity intrusion in the five rivers to landward will likely be within 1.15 to 9 km except for a few days in March (Fig 13). However, the likely impact under the extreme climate scenario in 2050 will be significant. Under the low flow conditions and

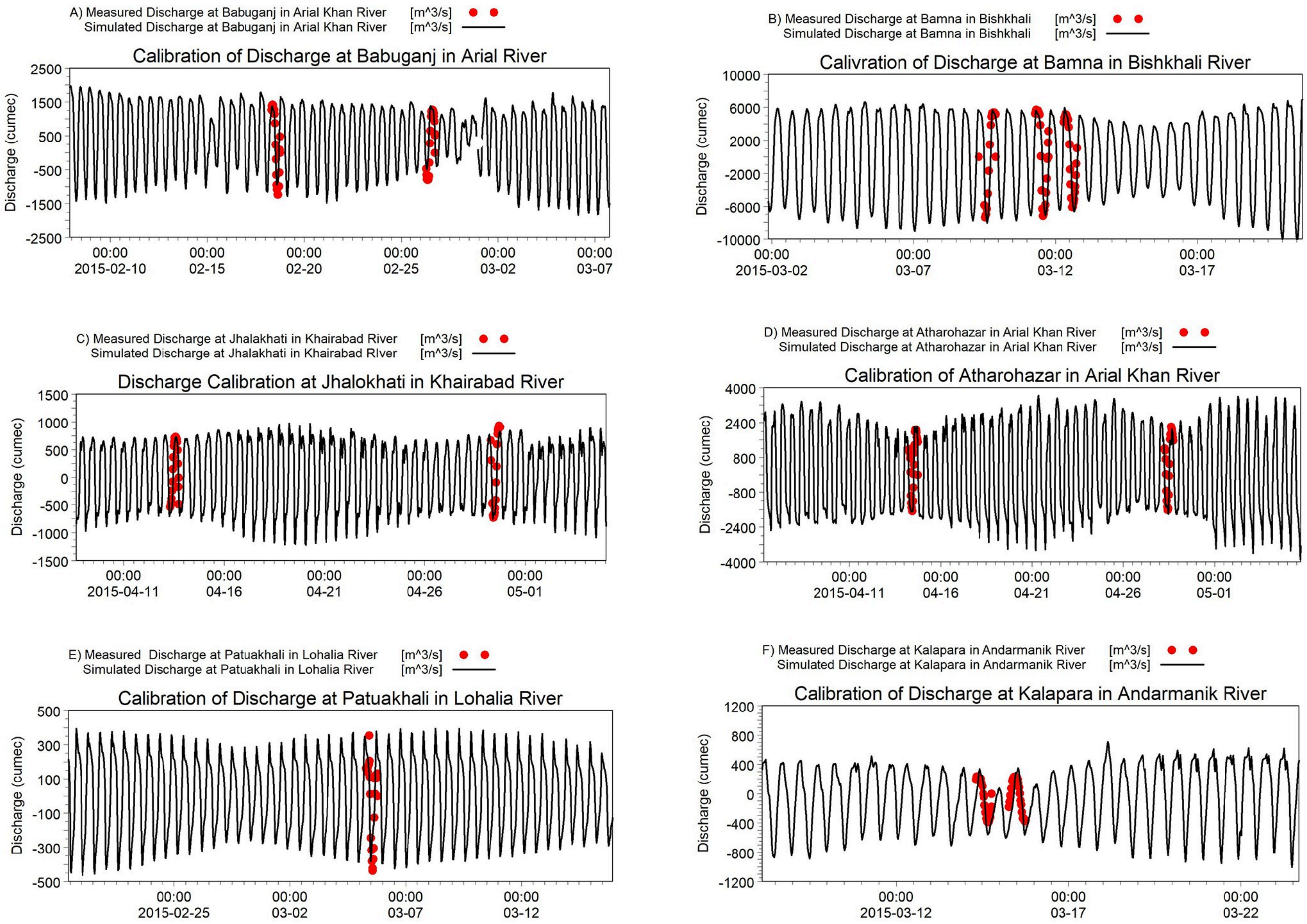

Fig 9. Calibration results for water flow obtained at six locations in 2015. Locations: A) Babuganj at the Arial Khan River, B) Bamna at the Bishkhali River, C) Jhalakhathi at the Khairabad River, D) Atharohazar at the Arial Khan River, E) Patuakhali at the Lohalia River and F) Kalapara at the Andharmanik River.

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extreme climate scenario, the 2 dS/m isohaline moves landward by 64 to 105 km in March and April for the Tentulia and Buriswar Rivers. Fig 13 shows the change of the isohalines of 2 and 4 dS/m and thus exposure of cropland under low flow (90% dependable flow) conditions using the present conditions (with and without water extraction) in response to the extreme climate scenario in 2030 and 2050. The exposure analysis (Fig 12) indicates a substantial reduction of the high-potential cropland area (0–2 dS/m) by 38% in March and April. Out of this, almost 37% of the area is turned into moderate cropland (2.01–4 dS/m) and 1% of the area into the highest salinity class (> 4 dS/m) for extreme climate change scenarios in 2050. This large change is due to the combined effect of SLR and a decrease in the flow of freshwater from the upstream sources. It is evident that SLR has a rather significant impact on the salinity intrusion along the Buriswar, Lohalia and Tentulia rivers. A 22 cm SLR causes an increase in salinity along the Tentulia river and a 47 cm SLR further affects the Lohalia and Buriswar rivers.

3.5 Policy implications

Salinity intrusion is a significant environmental challenge for our study area. The government has implemented various policies and initiatives related to integrated water management to

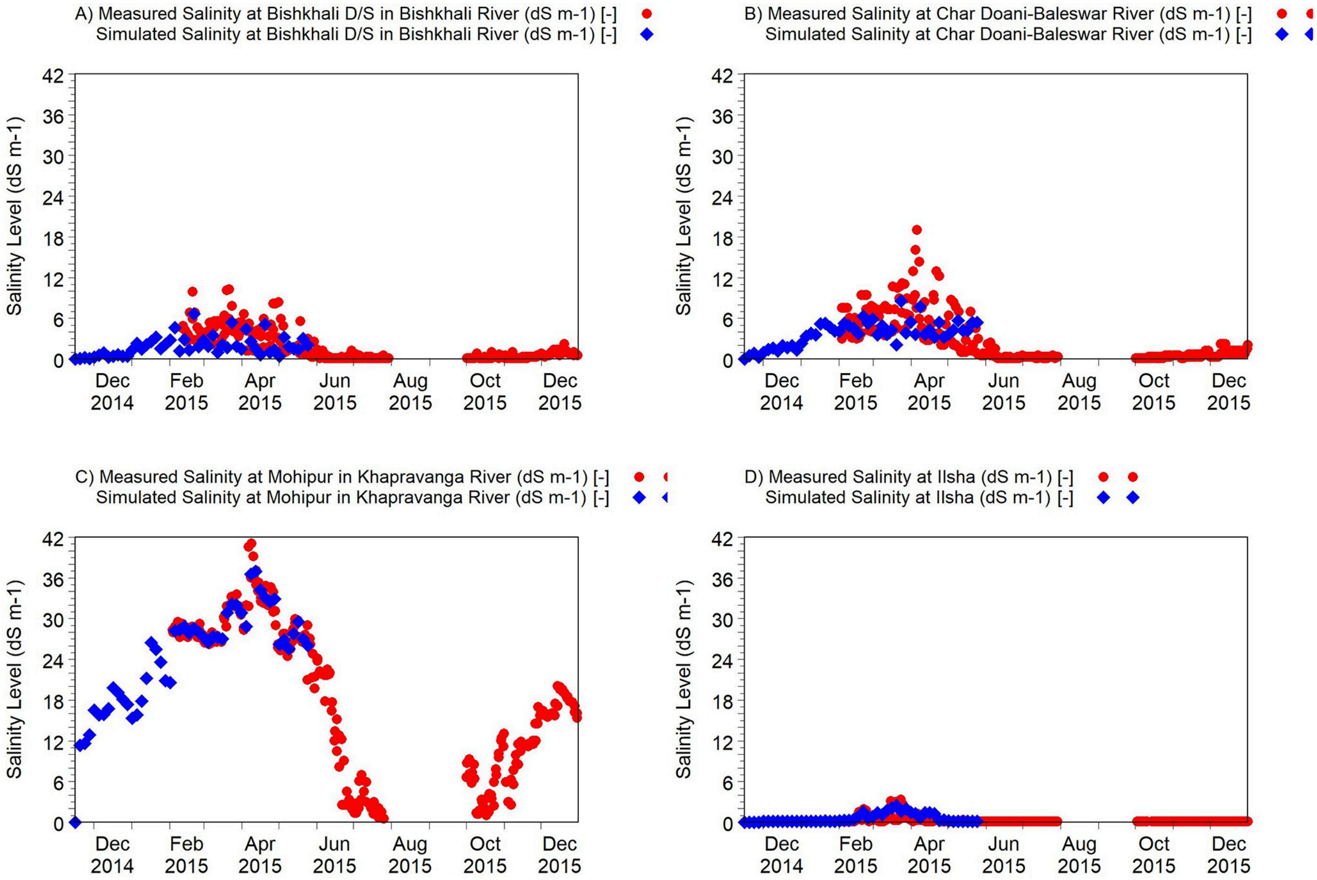

Fig 10. Calibration results for salinity at four locations in the south-central region of Bangladesh. Locations: A) Downstream of Bishkhali River, B) Char Doani at Baleswar River, C) Mohipur at Khaprabanga River and D) Illisha at Illisha River.

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address the salinity intrusion issue. Our results suggest that in 2050 for RCP8.5 SLR, the 0–2 dS/m saline zone will be decreased (Fig 12) and the 2 dS/m isohaline moves upward along the Buriswar river and Tentulia river systems (Fig 13). For that reason, surface water irrigation and household use will be hampered. The Bangladesh government has planned to adopt a project titled “Rationalization of Polders in Baleswar—Tentulia Basin” [45] under the BDP2100 initiative. Besides this, the Bangladesh Government operates community-based water management programs such as BlueGold Program (http://www.bluegoldbd.org/). It introduces the concept of Water Management Groups (WMGs) and Water Management Associations (WMAs) in the coastal polders. These groups or associations promote the dissemination of knowledge and aim to accelerate the adoption of modern crop and water management technologies.

4. Discussion

This study, at the nexus of SDG 2 (Zero Hunger), SDG 6 (Clean Water) and SDG 13 (Climate Action), seeks to determine whether it is possible to abstract surface water for irrigation in the dry winter months to increase agricultural production, while ensuring sustainable management of river water by staying within the safe operating space. The ex-ante analysis considers the baseline water level and salinity conditions of 2015. It assesses the potential impact of

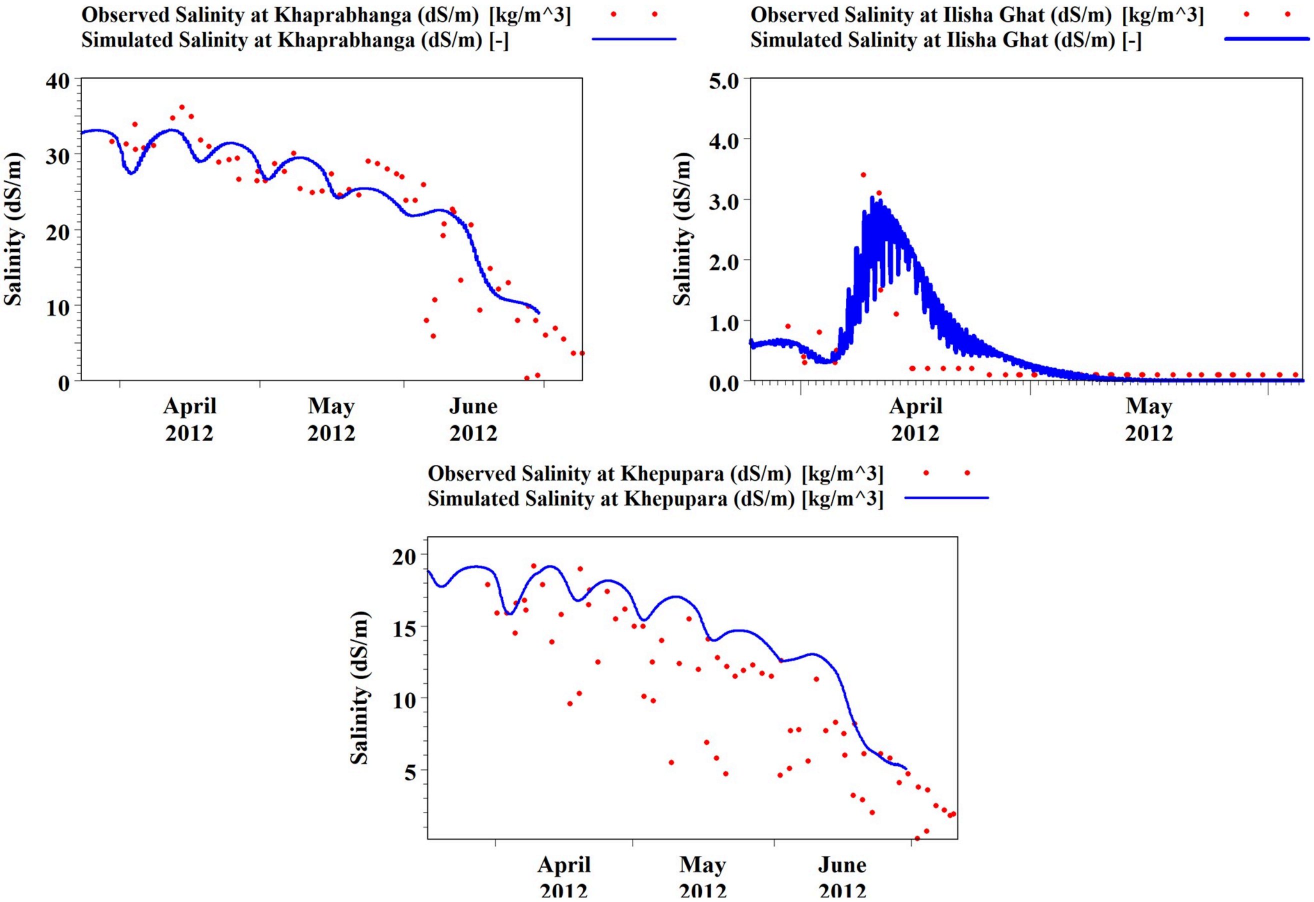

Fig 11. Validation for salinity at selected locations in the south-central region of Bangladesh. Locations: A) Downstream of Bishkhali River, B) Mohipur at Khaprabanga River and C) Illisha at Illisha River.

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climate change in 2030 (RCP 8.5) and 2050 (RCP 4.5 and 8.5) on river water flow and salinity. The output will support planning for adaptation to climate change. We assessed several factors that may negatively impact freshwater availability from the rivers of the southcentral zone of Bangladesh: 1) Withdrawal of river water to meet the increased demand for irrigation, 2) a change of upstream flow, and 3) rise in sea level under plausible climate change scenarios.

Previous analyses have shown that under baseline conditions, there is plenty of fresh water for irrigation in much of the Barisal division throughout the dry season [26, 46, 47]. Freshwater availability is abundant due to the connectivity of these rivers to the lower Meghna River. Water abstraction for irrigation would not impact salinity levels in the rivers (Figs 12 and 13). Simulation results showed mean monthly water flow varying from 5,823 to 7,074 $m^3 s^{-1}$ over the dry season (January to April) in the Bishkhali River. In the Buriswar River, the mean monthly flow ranged from 5,143 to 5,971 $m^3 s^{-1}$. Water flows are also abundant during the dry season in Tentulia, Baleswar and Lohalia Rivers. Tentulia and Baleswar Rivers have significant water flows both in the ebb and flood tides from spring to neap tides; the mean monthly water flows at the downstream river stretches of Tentulia River are within 9,456 to 12,173 $m^3 s^{-1}$.

The salinity levels in the five rivers exhibit distinct seasonal variation with the change of upstream freshwater flow. Freshwater flow from upstream rivers and tidal effects from the BoB together determine the area's salinity level and extent. The daily salinity level in the river

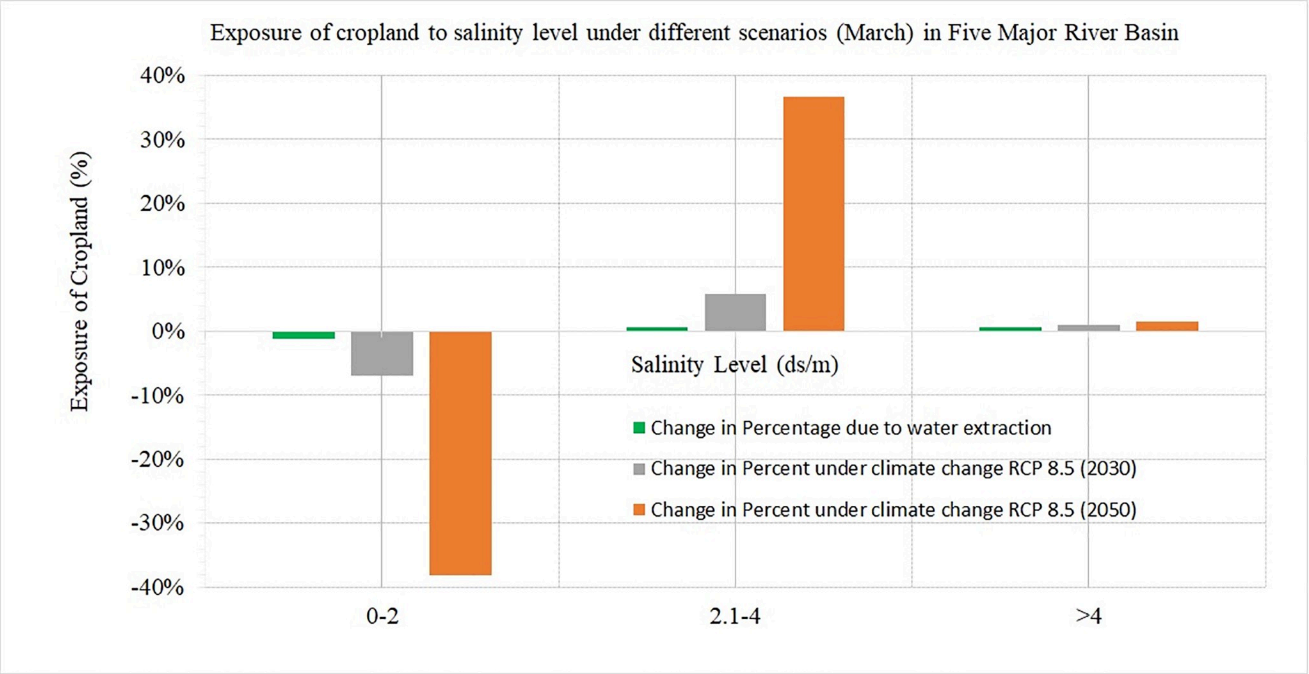

Fig 12. Changes of exposure of cropland to salinity levels in response to water extraction combined with two climate change scenarios (RCP 8.5) in 2030 and 2050.

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changes from spring to neap tides and with the season. The higher water levels along the coast during spring tides result in a higher volume of saline water flow to the upstream of the rivers compared to neap tides. For the Buriswar River, the salinity level remains below 0.2 dS/m over the dry season at the middle and upstream stretches, confirming a reliable source of irrigation water and other domestic and industrial uses. The salinity level at the downstream end of this river varies over the year where salinity starts to build from December, peaks in late March or early April, and drops from late May to December. For the Tentulia River, the salinity level remains below 1.8 dS/m in the upstream stretches, while it is within 3 dS/m in the downstream stretches. However, climate change may cause less favorable conditions for the people living in the Buriswar and Tentulia river basins. The simulations revealed that the salinity levels of these two rivers are likely to increase under RCP 8.5 by 2050. This is due to less flow from the upstream and the SLR by 0.43 m. Therefore, 2 dS/m salinity isohaline shifted upward by more than 100 km. Managing irrigation with water that has salinity levels higher than 2 dS/m requires careful and skillful management practices, especially during the establishment of the crops, when they are most sensitive to high salinity levels. Fortunately, the major shift of the isohaline occurs in March only, whereas maize and wheat can be established right after the harvest of the *Kharif*-2 season *aman* rice crop in December. *Boro* rice can be transplanted as early as late January.

All in all, the exposure analysis showed that the area of high potential cropland, i.e., exposed to low salinity levels in the range of 0 to 2 dS/m, currently is 276,300 ha. This is about 78% of the total cropland of the five river basins. Thus, there is a high potential for the intensification of irrigated agriculture in the southcentral zone. As irrigation and water management experiments by Krupnik et al. [14], Bhattacharya et al. [19], and Schulthess et al. [18] and modeling scenarios by Timsina et al. [17] have shown, relatively high yield levels can potentially be

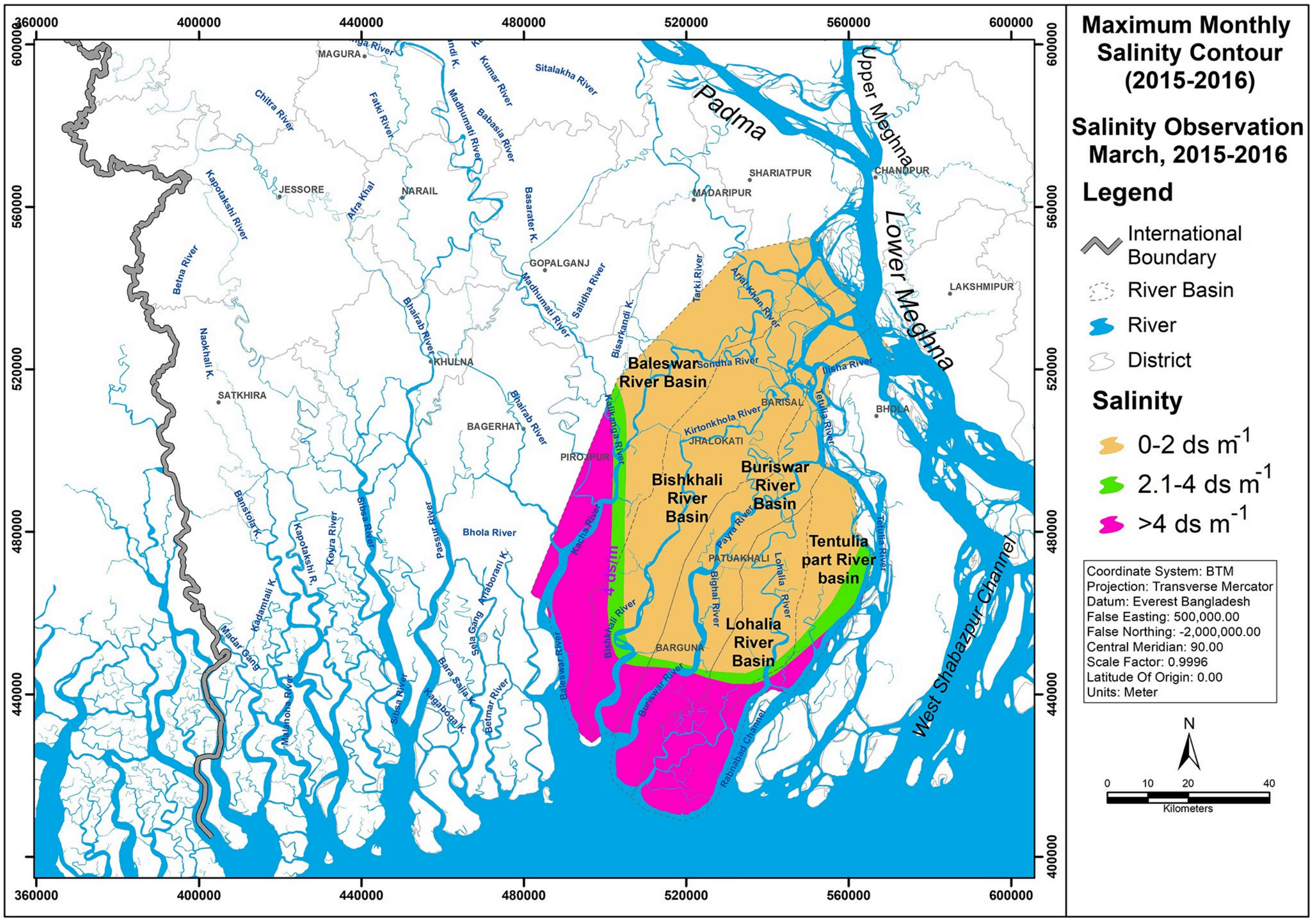

Fig 13. Potential exposure of cropland to river water salinity level during March under 2015 conditions without (S-0-90) and with water extraction (S-1-90) and 2 climate change scenarios (RCP 8.5) in 2030 and 2050. S-4-90 indicates conditions in 2050 assuming RCP 8.5 and 90 percentile dependable water flow and irrigation, S-3-90 is the same as S-4-90 for 2030. For details, see Table 1.

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achieved for *Boro* rice, wheat, maize, sunflower, soybean and mungbean in southern Bangladesh.

Our study did not consider potential changes in upstream boundary flow due to the construction of dams along the Ganges and Brahmaputra rivers and the redirection of water into other basins. Nor did it consider salt intrusion into landward due to cyclones, storm surges, and land subsidence [9]. The salinization of large parts of the south-western zone can be taken as an example to illustrate the consequences of a reduction in upstream boundary flow. The operation of the Farakka Dam in Murshidabad district in the Indian state of West Bengal from 1975 and the diversion of fresh water from the Ganges River towards India during dry season have already decreased the amount of freshwater entering the Ganges delta. The diversion of water reduces the supply of water from rivers and ultimately threatens crop and fish diversity [48]. Tuong et al. [49] also reported that salinity intrusion during the dry season is more sensitive to transboundary flows than SLR. Hence, ensuring transboundary flows during the dry season is highly important for sustainable agriculture and aquaculture in the southern coastal regions.

Managing water in the delta region is a complex task, as it needs to balance different users' interests. These resources are largely shaped by tidal dynamics and transboundary and upstream flows and are affected by natural, socio-economic, and institutional changes. Transboundary river basin management is more complex than for rivers flowing through one country due to the challenges in the design and implementation of joint monitoring programs [50]. Since rivers in Southern Bangladesh originate from the Himalayas and flow through India, a transboundary river basin management involving all countries is paramount.

Water management in the coastal delta is generally planned and performed through participatory approaches involving water management organizations, local government institutions and farmers [51]. The internal canals and peripheral rivers and regulators and sluice gates form the integral parts of the water management system, and involve effective drainage and irrigation with the appropriate operation of the control structure and pumps [52]. However, in practice, there is inadequate involvement of local governments and communities in water management and a lack of maintenance of flap and vertical lift gates and regulators, many of them becoming non-functional [53]. Past studies have revealed that lack of appropriate water management at the field level is one of the crucial factors limiting the intensification of agriculture and the increase of water productivity. Tuong et al. [49] emphasized that participatory water management including water governance and equity is essential for sustainable water management in the polders of southern coastal Bangladesh. For sustainable coastal water management that would require strengthening and formalizing the role of local governments in local water management and ensuring their access to permanent maintenance funds, severe hydrological and socio-economic challenges facing the coastal zone would need to be addressed [53]. Improved governance and equity and access to water management would be important as these can play a vital role in the intensification of *Rabi* crops and further development of aquaculture-agriculture systems [54].

Improved water resource management in coastal regions would need frameworks that recognize the importance of rivers and aquatic resources in providing various ecosystem services. Meynell et al. [55] developed a framework of ecological importance as a tool for river basin planning and water resource management, obtaining baseline information for impact assessment of infrastructure, and protecting ecologically important areas for rivers of mainland southeast Asia. The framework maps out the relative contributions of river reaches to a wide range of ecosystem services and allows prioritization of river ecosystem services to be assessed and mapped according to importance in different river reaches and basins within a region. Likewise, Tickner et al. [56] developed a conceptual framework for a coherent approach to river management research, policy and planning to encourage informed, equitable and sustainable river management. They applied it to the Great Ruaha River basin in Tanzania. The framework integrates concepts from ecosystem science, water resource management, social science and political economy, thereby linking concerns about the river ecosystem with the concerns of decision makers and allowing broader analysis that supports an understanding of how and why different groups within society benefit from the services a river provides. Such frameworks are currently lacking in Bangladesh. Similar frameworks are needed to identify and prioritize the critical ecosystems services provided by the networks of rivers and canals and applying them to policy and to plan for sustainable management of river basins in southern coastal Bangladesh.

5. Conclusions

The overall goal of this study was to determine the safe operating space for the expansion of irrigated dry season agriculture using available surface water. We wanted to determine whether critical river flow levels could be maintained to safeguard the river ecosystem and prevent the intrusion of saline water into the delta under various climate change scenarios. Our results showed that the abstraction of river water, even for *Boro* rice, the crop with the highest water demand, would not change the salinity dynamics in the rivers under baseline conditions (2015) nor the moderate climate change scenario (RCP 4.5) in 2050 or the extreme scenario (RCP 8.5) in 2030. Only under the low flow conditions (90% frequency of exceedance) for RCP 8.5 in 2050 the 2 dS/m isohaline would shift landwards by more than 100 km for the Buriswar and Tentulia River basins. An additional 36% of the cropland in the south-central zone would be exposed to river water salinity ranging between 2 and 4 dS/m. For most crops, this may entail some yield depressions. However, water abstraction per se under the baseline scenarios would increase the 2–4 dS/m area by 0.5% only. Thus, the change would be almost entirely due to climate change, independent of water abstraction. Other factors, which we did not simulate, such as a reduced upstream boundary flow caused by the construction of dams and redirection of water into other basins, may cause further salinization in the estuarian zone. This would pose a great threat to the sustainability of crop production, endanger the entire ecosystems and reduce the ecosystem services provided by rivers and canals in the south-central region of Bangladesh.

There is a need for additional research to study the impact of salt water intrusion on groundwater quality and bio-diversity of aquatic flora and fauna. In addition, the government needs to prepare and engineer interventions for the preservation of the freshwater zone, and last but not least, analyse the transboundary flow regime for managing salt water intrusion under sea level rise.

Supporting information

S1 Table. Command area of the five major river basins located in the south-central coastal zone of Bangladesh.
(XLSX)

S2 Table. Summary of calibration results for river water flow, water level and water salinity.
(XLSX)

S3 Table. Monthly shifting of isohalines during the different periods at different dependable flow conditions.
(XLSX)

S1 Fig. Map of south west region. It is divided into three regions according to salinity level and availability of fresh water.
(TIF)

S2 Fig. Superposition of South West Regional Model (SWRM) domain onto Bay of Bengal (BoB) model domain.
(TIF)

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