Research

Adaptation pathways to cope with salinization in south-west coastal region of Bangladesh

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ABSTRACT. Salinization in coastal regions of Bangladesh challenges sustainable development of different sectors like agriculture, forestry, fisheries, livestock, and health. Particularly its southwest region largely faces increased salinity risks because of its geographical location and environmental settings. This study analyzes the causes of salinity increase, their cascading impacts on different coastal systems, and their livelihood implications, and assesses potential coping measures through innovative adaptation pathways for the most affected coastal systems. These pathways integrate bottom-up and top-down perceptions in adaptation planning through a driver-pressure-state-impact-response framework, multicriteria analysis, and adaptation turning point approaches. We surveyed 200 households and interviewed 20 key informants. We observed that household-level respondents' perceptions are more closely related to socioeconomic aspects than to the biophysical environmental aspects and focus on issue-based action. However, the key informants focus more on the biophysical changes and the large-scale measures. The developed framework shows that salinity increase is an interconnected process of climatic-social-ecological-economic systems in the coastal environment. It also shows that responses already taken, i.e., polders and shrimp farming, to cope with salinization have later become pressures, i.e., riverbed siltation, waterlogging, and intensive salinization, on the systems. In total, we identified six interconnected causes of salinity increase and 24 potential measures to address them. Also we distinguished three coastal systems, i.e., crop-agriculture, drinking water sources, and the Sundarbans mangrove, most affected by salinity increase. Finally we proposed 16 adaptation pathways for these coastal systems based on the multicriteria analysis and adaptation turning points of the potential measures.

Key Words: *adaptation pathway; coastal systems; salinization*

INTRODUCTION

Climate change impacts such as sea level rise, more frequent natural hazards, and sea water intrusion are considered as the major causes for salinity increase in the world's deltaic regions (Nicholls and Cazenave 2010). For instance, several studies found that the Mekong Delta (Renaud et al. 2015), the Nile Delta (El Barmelgy and Rasheed 2016), and the Ganges tidal floodplain (Rahman and Rahman 2015) face increasing salinity problems. As part of Ganges Delta, Bangladesh is experiencing similar problems, particularly in its southwest region (Khanom 2016). This exposed coastal region lies about 1.5 meters above mean sea-level and this makes it vulnerable to sea-level rise, inundation, and salt-water intrusion (Chowdhury 2009).

Recent research has shown that salt intrusion is rapidly increasing in the region. From 2000 to 2009, salt-water intrusion increased up to 15 km north of the coast because of sea-level rise, and currently in the dry season, salt-water intrudes up to 160 km inland on account of reduced upstream river flows (SRDI 2010). This salt intrusion has large impacts on both ecological and socioeconomic systems that provide essential social, economic, and ecosystem services. Hence, its highly diverse ecosystems, like the world's largest single tract of mangroves (the Sundarbans), wetlands (vast network of rivers of the Ganges-Brahmaputra tidal plains), and inlands (mostly crop-agriculture) have already started to be severely affected by this salinization (Rabbani et al. 2013, Rasel et al. 2013, Sarker et al. 2016). In addition, this salinization leads to extreme drinking water scarcity for about 6.2 million people (Abedin et al. 2014).

The general causes and impacts of increasing salinity at large regional scale are broadly recognized (e.g., Khan et al. 2011, Mahmuduzzaman et al. 2014). However, understanding local socioeconomic and biophysical conditions is often too incomplete to identify the intermingling causes of the salinity increase and its cascading impacts on different coastal systems for integrated and sustainable adaptation planning (Nandy et al. 2013). For instance, extensive shrimp farming on the southwest coast of Bangladesh has created a direct conflict with crop agriculture. Shrimp farming has not only damaged agriculture but also agro-forestry, fisheries, livestock, and physical infrastructures (Nowreen et al. 2014). Most coastal development interventions have largely focused on structural protection measures like dams, embankments, polders through top-down approaches and have largely ignored the complex and dynamic social, ecological, and economic systems in the region (Ayers et al. 2014). Therefore, adaptation approaches are unlikely to be effective if not all parts of the environment, i.e., biophysical and socioeconomic, are taken into account while identifying potential measures (Füssel 2007). In addition to the infrastructural developments both upstream (the Farakka barrage) and downstream (polders and embankments), climate change and sea-level rise exacerbate the salinity increase. Climate change increased the frequency and severity of hydro-climatic extremes, such as cyclones, tidal surges, and floods (Penning-Rowsell et al. 2013).

Although salt intrusion clearly has increased over the last decade, future salt intrusion rates are highly uncertain because of

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unknowns in future climate change (Dessai and van der Sluijs 2008) and upstream developments. As a result, policy makers often struggle with where, when, and which different measures need to be implemented. To deal with such uncertain futures, adaptation pathways based on adaptation turning points have been developed (Wise et al. 2014). Such adaptation pathways support decision making under uncertain future conditions (Haasnoot et al. 2014). Adaptation pathways have been mainly used in developed countries to identify potential flood defence measures in the Netherlands (Haasnoot et al. 2013) and robust options for coastal natural resource management in Australia (Bosomworth et al. 2015). However, the approach is relatively new in developing countries, such as Bangladesh.
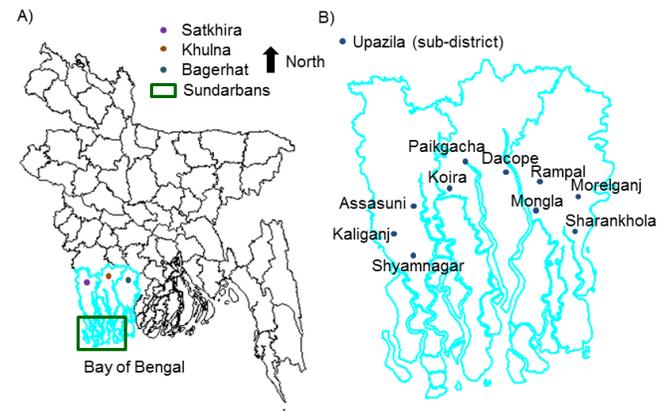
A saline environment has always been part of Bangladesh's southwest and local people have been living with salt for the last three decades. However, the recent excessive salinization and its unfavorable impacts have forced people to already take small scale adaptation measures, like cultivating salt tolerant crops, raising the plinth of the houses and tube-wells, afforestation, and rain-water harvesting. However, large scale initiatives have not yet been considered. Hence, to obtain greater benefits, i.e., food security, biodiversity conservation, environmental protection, and sustainable livelihood, large scale adaptation planning is now needed. In this context, the Bangladesh Climate Change Strategy and Action Plan (BCCSAP 2009) was created. Implementing this action plan fundamentally requires better identification of the causes of salinity increase and characterization of its impacts because local adaptation is highly context dependent. Therefore, individual communities and ecosystems may require different adaptation plans based on varying causes and impacts of salinization (Huq et al. 2015).

In the context of BCCSAP 2009 and the problems policy makers have with implementing timely adaptation measures under changing climatic and socioeconomic conditions, our aim was to develop adaptation pathways to cope with salinization in Bangladesh's southwest coastal region. To develop the adaptation pathways, we studied the interconnected causes of salinity increase, the social and natural systems affected by salinity increase, and how they are affected. We also identified potential adaptation measures along with their contribution and adaptation turning points to address the identified causes and most affected coastal systems.

METHODS
We focus on three districts (Fig. 1A) of Bangladesh's southwest coast, i.e., Khulna, Bagerhat, and Satkhira, in that people of these three districts are severely affected by salinity increase. In our previous studies, we looked into the biophysical changes in the coastal environments and the Sundarbans mangrove, and we found significant changes over the forest (Hossain, Ludwig, and Leemans, *unpublished manuscript*) and hydro-climatic variables due to climate change, climate-change induced problems, and reduced upstream river flow (Hossain, Ludwig, and Leemans, *unpublished manuscript*). Hence, we selected these three districts to study the causes and impacts of, and adaptation pathways to cope with, salinization through household surveys, key informant interviews, the driver-pressure-state-impact-response (DPSIR) framework, multicriteria analysis, and the adaptation pathway approach based on an adaptation turning point (Table 1).

Fig. 1. Study area.

Table 1. Approaches used in this study along with their specific purpose.

Approaches used	Description	Purpose
Household level survey	Local people's opinion on a structured questionnaire	To get bottom-up perceptions
Key informant interview	Observation of the knowledgeable persons on a structured questionnaire	To get top-down perceptions
DPSIR framework	Integration of the information on driver-pressure-state-impact-response	To make social-ecological-economic connections
Multicriteria analysis	Analysis of a measure under different criteria, i.e., effectiveness, side effects, cost, feasibility, and uncertainty	To identify the suitable adaptation measures
Adaptation turning point (ATP)	A situation (for this study, salinity) where a measure's threshold is reached	To develop an adaptation pathway
Adaptation pathway	A set of measures that can be implemented gradually depending on the ATP	To develop large scale adaptation plan

As part of our bottom-up approach, 200 households through simple random sampling from 10 selected *upazilas* (subunits of a district) based on nearness to the coast (Fig. 1B) of three above-mentioned districts were surveyed during December 2015 and January 2016 with a structured questionnaire. This questionnaire was designed to gather information on respondents' socioeconomic status along with their views on salinization, affected livelihoods and coastal systems, ways of being affected, and finally to obtain their opinion on potential (i.e., short-, medium-, long-term) measures that consider their own perceived risks along with adaptation turning points (salinity in parts per thousand [ppt]) and expected contributions to the particular system.

The household survey resulted in too little information on mid- and long-term adaptation measures and potential adaptation turning points. To fill this gap, 20 key informants from different government and nongovernment organizations, universities, and research institutes (Fig. 2) were interviewed from July to August 2017 to get top-down perceptions on the same issues. Key informants were selected from the water, agriculture, forestry, fisheries, environment, and planning sectors by systematic sampling based on their research and work experience. The DPSIR framework (Smeets and Weterings 1999) was used to integrate the information of local people's perceptions and key informants' opinion to determine connections among the climatic, social, ecological, and economic systems (Pinto et al. 2013).

Fig. 2. Categories of key informants from different organizations and institutes.

The assessment of potential adaptation measures identified by two different levels of respondents was done using a multicriteria analysis (L. H. Phi 2011, *unpublished report*). Measures were with regard to five different criteria: effectiveness, side effects, cost, feasibility, and uncertainty, which can be scored from being very negative (---) to being very positive (+++). The criteria and their ranges were described to the respondents (Table 2) in the local language to score the measures. Each positive score was assumed to be valued by +1 and each negative score by -1 to rank them for identifying suitable measures.

Then the identified potential measures recommended by the household level respondents to address their own perceived causes of salinity increase were listed in combination with the results of the multicriteria analysis (Appendix 1). In addition, the potential set of measures recommended by the key informants to address the observed causes of salinity increase were recorded (Appendix 2). Based on the score of the multicriteria analysis, the best measures to address the main causes of salinity increase were selected. Because of a lack of responses from the household level respondents on long-term measures along with their tipping points and contributions for the most affected coastal systems, only key informants' observations were considered (Appendix 3). Because expected contributions of the identified adaptive measures interrelate, the main pressure on the particular system in combination with the major contribution of the identified measures to address that pressure were considered for developing adaptation pathways.

Table 2. Description with score card for the selected criteria of multicriteria analysis.

Criteria	Description	Range	
		+++	---
Effectiveness			
	Ability of a system to cope with the consequences	Highly effective	Not effective
Side effects			
	Secondary effects, both positive and negative, that are not directly related to the primary purpose	Positive effect	Negative effect
Cost			
	Comprising construction/ implementation cost, maintenance cost, and transaction costs	No cost	High cost
Feasibility			
	Looks at the barriers that can potentially hamper the adaptation process. For example, limited technical capacity, economic strength, socio-cultural acceptance, and potential conflicts with current legal settings	Highly feasible	Not feasible
Uncertainty			
	Performance of a measure under a wide range of changes in climatic and socioeconomic conditions	No uncertainty	Highly uncertain

Initially, the potential measures to address the dominant causes of salinity increase considering the top-down and bottom-up perceptions had been identified. Finally, the adaptation pathway maps for the most affected coastal systems were developed considering dominant cause of salinity increase in that particular system and results of the multicriteria analysis along with the tipping points for each of the potential measures suggested by the key informants. The Pathways Generator program was used to visualize the pathways maps (https://publicwiki.deltares.nl/display/AP/Pathways+Generator). An example is given in Appendix 4 to facilitate interpretation of the developed pathway maps. It is a very new approach for Bangladesh, but will likely help to develop an adaptation plan for sustainability under climate change (Werners et al. 2013).

RESULTS

Demographic and socioeconomic status of the household level respondents

Most of the respondents of the survey were male, on average 35 years old, and illiterate (Table 3). We found nine different professions among the respondents. Agriculture was the dominant profession, followed by shrimp farming, and people dependent on other services derived from Sundarbans.
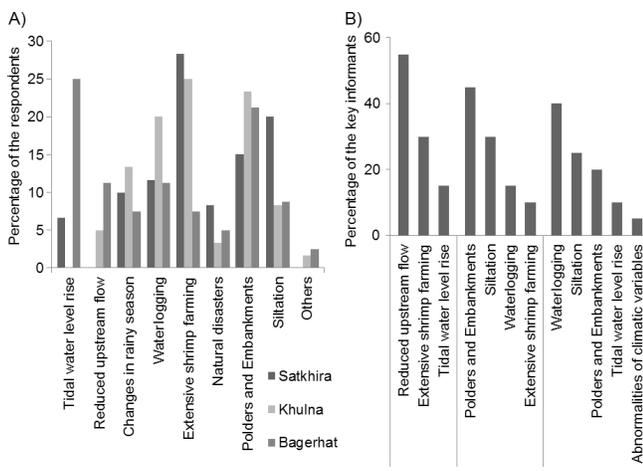
Dominant cause of salinity increase

Household respondents identified nine causes for the observed salinization (Figure 3A). In Satkhira, people perceived extensive shrimp farming as its main cause followed by siltation and polders.

Also in Khulna, people identified extensive shrimp farming as the main cause followed by polders and waterlogging. However, in Bagerhat most respondents perceived that tidal water-level rise is the main cause behind salinity increase, followed by polders, waterlogging, and reduced upstream flow. Key informants, however, explained salinization by a combination of different processes (Figure 3B). They identified reduced upstream flow as the dominant cause in combination with polders and waterlogging, and closely followed by extensive shrimp farming and siltation.

Table 3. Demographic and socioeconomic status of the household level respondents.

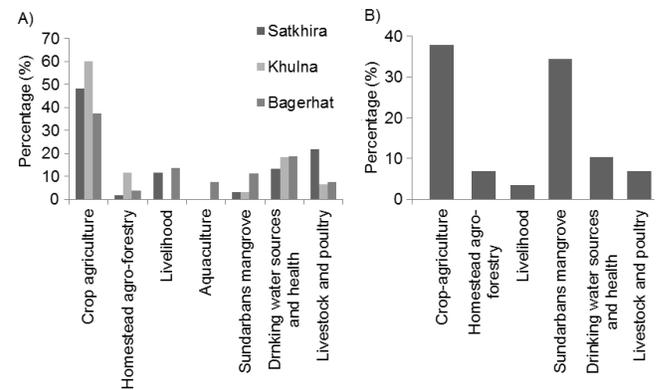| Category	Characteristic	Percentage (%)		
		Khulna	Bagerhat	Satkhira
Gender	Male	62	70	83
	Female	38	30	17
Age	21–30	22	7.5	15
	31–40	32	39	45
	41–50	30	26	18
	51–60	13	16	10
	61–70	3	11	7
	71–80	0	0	5
Education	Illiterate	38	48	55
	Primary	33	31	20
	Secondary	23	18	15
	Higher Secondary	2	4	2
	Graduate	2	0	7
	Postgraduate	2	0	2
Profession	Agri-crop farmer	22	19	38
	Shrimp farmer	14	14	13
	Fish farmer	0	13	0
	Businessman	5	11	0
	Daily laborer	10	13	13
	Sundarbans dependent	17	15	18
	Homestead agro-forestry	13	11	12
	Crab farmer	10	3	0
	Livestock and poultry farmer	9	3	5

Fig. 3. Perceived causes of salinity increase by different categories of respondents.

Coastal systems affected by salinity increase

Household respondents identified seven coastal systems that are affected by salinity increase (Fig. 4A). Almost half of the people in Satkhira, Khulna, and Bagerhat and most key informants (Fig. 4B) thought that crops were affected most. Experts identified similar vulnerabilities but eliminated aquaculture. Also most articulated was crop-agriculture. However, experts also indicated Sundarbans mangrove as the second most affected coastal system while the household respondents highlighted drinking water sources and health.
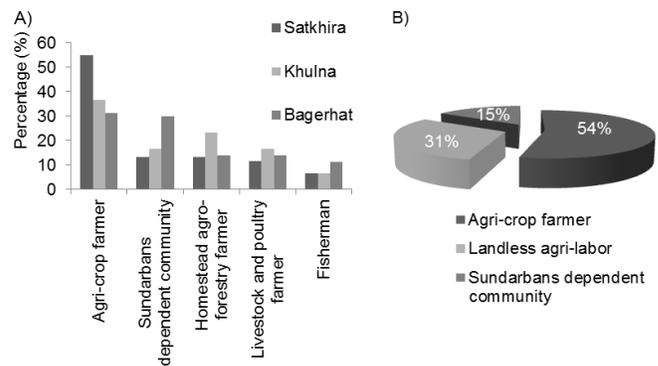
Fig. 4. Coastal systems most affected by salinity increase in southwest region.

Coastal communities affected by salinity increase

Household respondents identified five different communities that are affected by salinity increase (Fig. 5A). Crop farmers were the most severely affected coastal communities followed by Sundarbans dependent communities. On the other hand, experts identified only three communities that were affected by salinization (Fig. 5B). More than half of the experts indicated the Sundarbans dependent people as the most affected communities followed by landless agri-laborers and crop farmers.

Fig. 5. Coastal communities most affected by salinity increase.

Ways of being affected

Both respondents identified similar effects on different coastal systems (Table 4). Crop agriculture was affected by degrading of soil quality. This results in less production and profit, land use changes, mostly shifts from crop agriculture to shrimp farming,

Table 4. Observed effects of salinity increase by different categories of respondents.

Systems affected	Ways of being affected	
	Household level respondents (local people)	Key informants (Experts/resource persons)
Crop-agriculture	Reduced soil fertility	Degradation of soil quality
	Less production and profit	Less production
	Land use change (mostly crop-agriculture to shrimp)	Uncertainty
	Loss of agri-lands	Change in agriculture pattern
		Food insecurity
Homestead agro-forestry	No or less production	No or less production
		Reduction in homestead tree coverage
Livelihood	Livelihood loss/change	Livelihood change
		Unemployment
		Migration
Aquaculture	Threatened local fresh water fish species	
Sundarbans mangrove	Lack of healthy trees	Vegetation change
	Thin forest/reduced forest cover	Reduced tree growth
	Less forest resources (both timber and nontimber)	Invasion of top dying
	Reduction in number of wild animals	Reduced stock density
	Reduced amount of fish	Reduced biodiversity
		Habitat degradation
		Decreasing trend of fish resources
Drinking water sources and health	Drinking water crisis	Salinization of open and ground water sources
	Skin diseases	High blood pressure during pregnancy
	Diarrhoea and digestion problems	Eclampsia
	New born babies with different types of difficulties	
	Pregnancy problems	
Livestock and poultry	Increased cost of rearing livestock and poultry	Fodder crisis
	Fodder crisis	

which causes loss of agri-lands and uncertainties ensuing from changes in agriculture pattern and food insecurity. The extent of homestead tree coverage was reduced gradually for lower productivity and in some cases no production at all. Local fish species were also threatened. The livestock and poultry sector were suffering from the fodder crisis, which contributes to increasing rearing cost. Sundarbans mangrove habitats degraded and this resulted in reduced forest growth and biodiversity, changes in vegetation, invasion of the undesirable top-dying disease and production of less forest resources, i.e., lack of heathy trees, reduction in number of wild animals, and decreasing fish species. Changes in or loss of livelihoods triggered unemployment and outmigration. Salinization of surface and ground water sources created a drinking water crisis. This generated different diseases and health problems like skin diseases, diarrhoea, digestion problems, and increase infant's diseases, i.e., anaemia and jaundice, and pregnancy complications, i.e., high blood pressure and eclampsia.

DPSIR framework for salinity increase
The developed DPSIR framework (Fig. 6) showed salinization drivers were not only related to biophysical changes in coastal environments but also with socioeconomic circumstances. Most of the identified pressures were man made and not environmental. The ecological, social, and economic state of different coastal systems, mostly crop agriculture, wetlands, and Sundarbans mangrove, were threatened by salinity increase. Threatened states of the these systems were creating conflicts among ecosystem, human health, and socioeconomic functions that eventually lead toward small- and large-scale measures, action plans, and policy

responses. However, the responses were inadequate to address the identified pressures of salinity increase. Rather one of the responses, i.e., polders, has become the pressure for salinity increase initiating sedimentation on the river bed and waterlogging.
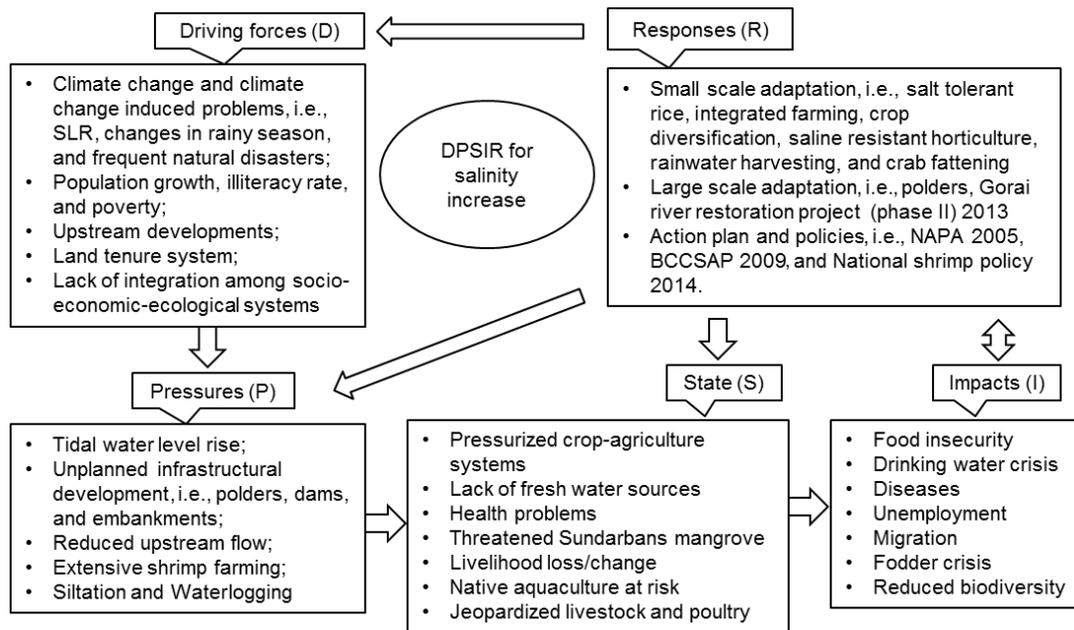
Potential measures to address the identified salinization drivers and pressures, along with their contribution and multicriteria analysis
Local people identified five short-term and two midterm measures to address salinization drivers and pressures. These measures should contribute to halting salinization of new lands, to maintaining the natural flow of the tidal rivers, to connecting the rivers with their flood plains, and to extending fresh water sources (Table 5). However, they did not identify any long-term measure. A multicriteria analysis of these measures (Appendix 1) shows that the local government's initiative to stop planned ingression of salt water is the most effective short-term measure and land zoning is identified as the most suitable midterm measure. On the other hand, key informants identified in total 18 potential measures to cope with salinization (Table 5). Among the identified measures, planned shrimp farming is the most suitable short-term measure followed by tidal river management as the midterm measure and long-term coastal land use zoning (Appendix 2).

Adaptation pathways to cope with salinization for the most affected coastal systems
Key informants identified 31 possible forms of different adaptation turning points from 7 to 20 ppt for the most affected coastal systems (Appendix 3). Among these, 16 measures had

Fig. 6. Interaction between society and coastal systems. (Here, SLR denotes sea-level rise; DPSIR: driver-pressure-state-impact-response; NAPA: National Adaptation Programme of Action; and BCCSAP: Bangladesh Climate Change Strategy and Action Plan).

been filtered through a multicriteria analysis as the suitable measures. These are visualized in the adaptation pathway map (Fig. 7). For crop-agriculture, most suitable measures included crop diversification, adaptive agriculture, alternate cropping, and arable field management. A combined approach of crop diversification, arable field management, and alternate cropping was expected to sustain salinity levels until 12 ppt. Saline resistant horticulture was expected to sustain salinity levels until 15 ppt. However, for long-term adaptation planning, i.e., salinity levels up to 20 ppt, land zoning was the most suitable measure to promote agriculture, to improve farmers' socioeconomic conditions, and to resolve the conflicts between crop and shrimp farming. For drinking water sources, the adaptation pathway map showed six measures at different turning points. Among them rainwater harvesting, pond sand filter, pond excavation, and managed acquirer recharge were identified as the most suitable measures to be implemented in salinity ranges from 7 to 20 ppt. For Sundarbans, public awareness combined with strengthening the Bangladesh Forest Department, ban catching fish during dry season, and canal (re)-excavation were the potential measures to deal with salinity levels from 7 to 12 ppt. Periodic or scheduled (re)-excavation to mainly restore the Gorai River was the next adaptive measure for salinity levels up to 15 ppt. However, if salinity levels cross 15 ppt, tidal river management and a Ganges Barrage were the suitable measures. These adaptation measures were expected to assist in sediment management and ensure ecological flow for the downstream rivers during the lean period with salinity levels beyond 17ppt.

DISCUSSION

We identified six major interconnected climatic-social-ecological-economic issues responsible for salinity increases in the southwest of Bangladesh. However, perceptions and observations of two different levels of the respondents on different processes of salinity increase varied. Household-level respondents' perceptions were closely related to local land use changes such as shrimp farming and polders. Polders contributed to reducing floodplain storage that caused river bed sedimentation, serious waterlogging, and thus salinization (WARPO 2001). This process was enhanced by expanded trends of shrimp farming (Swapan and Gavin 2011). Conversely, key informants focused more on the large-scale biophysical changes such as reduced fresh water inflow in combination with sea-level rise. Currently, tidal-water level is rising at 10 to 12 cm per decade (Bhuiyan and Dutta 2012) and fresh water influx is reducing significantly during the dry season (Mirza 1998).

Although both levels of our respondents agree on the most affected coastal system, i.e., crop-agriculture, their second choice was different. Local people, who have been living with salt for years, were more concerned about health risks related to drinking water sources while key informants were more concerned about ecological importance of the Sundarbans mangrove. Considering the significance of the Sundarbans mangrove ecosystem, major livelihoods depending on crop agriculture, and basic need for drinking water, we developed separate adaptation pathways for these three coastal systems.

Salinity is likely to increase in the future but by how much is uncertain. Hence, our adaptation pathways clearly show which measures can be implemented to cope with different levels of salinity. Some of the current measures are suitable, if salt intensification remains limited. For example, rainwater harvesting is a traditional measure to supply drinking water. However, uncertainties associated with this practice are the

Table 5. Potential set of measures and their contribution to address the observed causes of salinity increase.
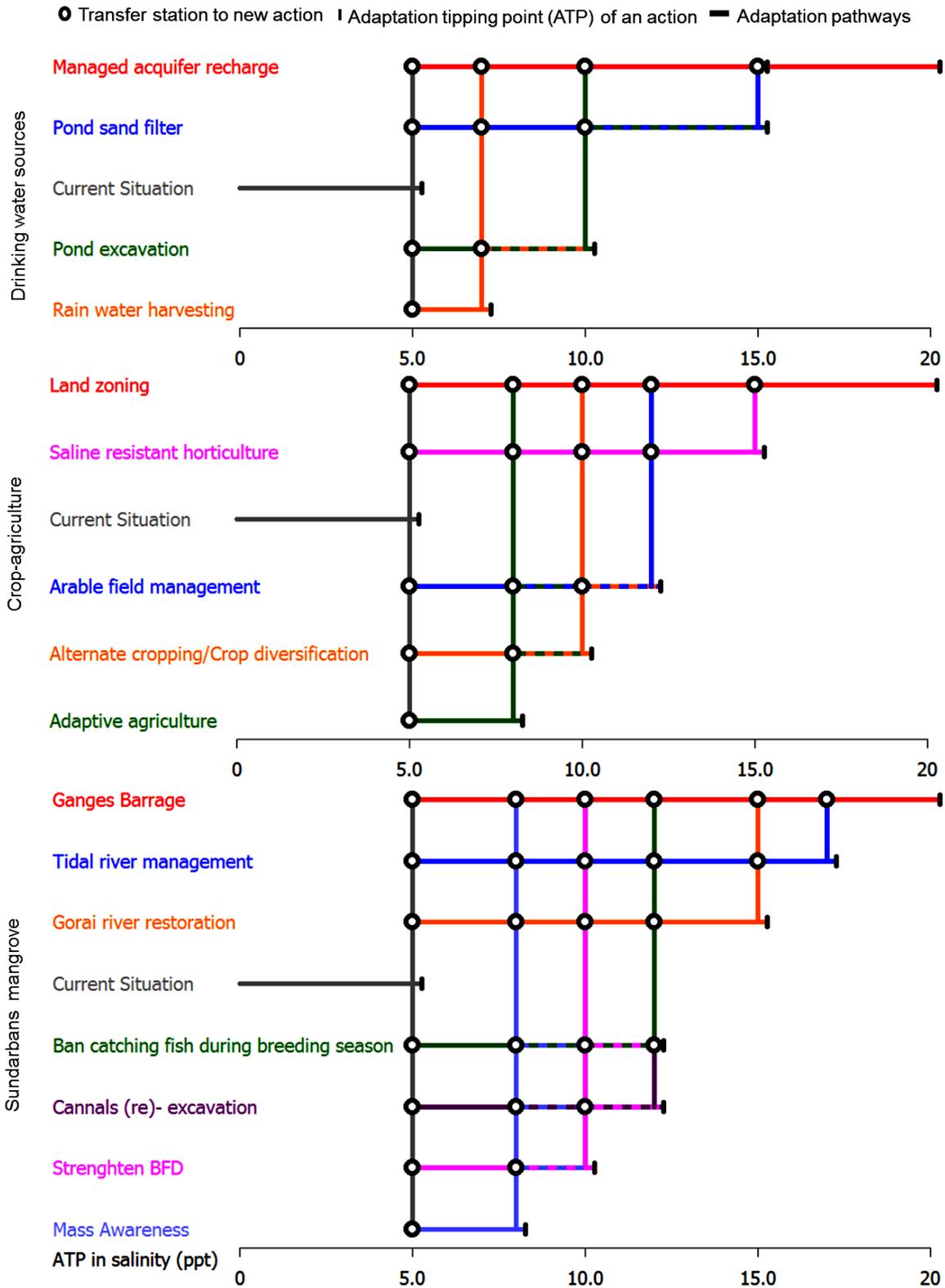
Main causes	Potential measures along with the score from multicriteria analysis in (..)						Expected Contributions
	Short term		Midterm		Long term		
	Household respondents	Key informants	Household respondents	Key informants	Household respondents	Key informants	
Extensive shrimp farming	Local government's initiative to change the leasing system of khash lands (12)	Planned shrimp farming practice (14)	Land zoning (11)	Designing land management practice (5)		Coastal land use zoning (11)	Discontinue salinization of new lands
							Offset salinization in agri-lands
Unplanned Infrastructural development and waterlogging	Operational sluice gates of the existing polders (7)	Functional management of the existing polders (6)	Outlaw building of unnecessary dams on the rivers (11)	Planned infrastructural development in water resource management (5)		Integrated management of different systems (3)	Ensure the natural flow of the tidal rivers;
							Improve the drainage systems
Siltation	(Re)-Excavation of silted rivers (6)	Periodic/scheduled (re)-excavation as a regular exercise (5)		Tidal river management (TRM) along with sediment management practice (14)		Continuous monitoring on river flow and sedimentation rate (5)	Make sure of the connection of the rivers with the flood plain
							Liberate the natural process of land formation through sedimentation
Tidal water level rise	River bank protection (pilling) (5)	Strengthen and heighten existing embankments (3)		Planned infrastructural development (5)		Delta plan / Integrated long-term plan for the coast (8)	Reduce tidal inundation and resist land loss
							Integrate all the interacting systems of coastal region for planned adaptation
Reduced upstream flow	Government initiative to change the leasing system and use of Khash lands (10)	To be active in transboundary negotiation process on water sharing (3)		Administrative unit wide assessment on demand of water for different category (5)		Water budget and allocation plan (6)	Extend storage of rainwater harvesting
		Develop upstream water management plan/strategy for dry season (3)		Enforcement of Water Act 2013 on priority basis (5)		Ganges barrage for sustainable river flow (7)	Create transparency on water demand and supply
							Increase fresh water influx during dry season
							Ensure sustainable environmental flow

changed rainfall pattern, storage facilities, and future salt concentrations. Other suitable measures, i.e., pond excavation and pond sand filter, are related to surface water sources. However, these sources are exposed to rises in tidal water levels, floods, cyclones, and tidal surges. Therefore, these measures are probably unsustainable in the long run. Hence, mechanisms to recharge ground water resources need to be adopted to ensure long-term safe drinking water supply. According to the multicriteria analysis, managed aquifer recharge likely is the most suitable measure to ensure availability and quality of drinking water sources. In addition, such recharge also serves to control salt-water intrusion, prevent land subsidence, and sustain other coastal systems' functioning. However, aquifer conditions must be suitable and water sources need to be ensured. This measure is successfully implemented for coastal urban areas in Australia (Dillon et al. 2009).

Artificial water logging conditions for shrimp farming are also accelerating the salinization of fresh water resources through seepage and natural bleaching. Most of the khash lands, i.e., government owned fallow land, leased to shrimp farmers are located in the inland part of the coastal zone, which is topographically and hydrologically unsuitable for shrimp

Fig. 7. Adaptation pathway map for the most affected coastal systems.

farming. Shrimp farmers transport salt water through narrow channels from the rivers and the development of earthen embankments on the rivers. Leasing the khash lands for shrimp farming is thus increasing transport of saline water from the rivers to more area inland. Therefore, as a short-term measure, local people suggested limiting the leasing of the khash lands to the shrimp farmers. Also better planned and regulated shrimp farming can be a suitable measure to reduce the conflict with crop-agriculture. In the long term, changed leasing systems and better planning may not be able to resist extensive shrimp farming. Therefore, improved regulations that follow natural salinity gradients, and coastal land use zone planning are needed. Improved coastal zone management should clearly outline the space for the conflicting sectors such as fresh water resources, shrimp, agriculture, and forestry.

Land zoning was also identified as the most suitable long-term measure by experts to strengthen crop-agriculture. Other potential measures such as crop diversification, adaptive agriculture, alternate cropping, and arable field management are currently implemented locally to adapt to moderate salt water intrusion. However, these adaptive agriculture measures will not be sufficient if the main pressure on the whole agriculture system, i.e., shrimp farming, is not addressed (Swapan and Gavin 2011), and at high levels of future salt intrusion, crop systems will continue to disappear. Hence, coastal land zoning that considers the natural salinity gradients and local land suitability in terms of hydro-climatic variables and socioeconomic conditions for different land uses is likely the most suitable adaptation measure to promote both crop-agriculture and shrimp farming.

Local people suggested to use khash lands for storing fresh water during the monsoon to deal with reduced upstream flow, instead of using the increasingly saline water for shrimp farming. This is probably a suitable measure for fresh water sources and agriculture during the dry season. However, the continuously increasing land demand by the increasing population challenges the implementation of this measure Therefore, key informants want to actively negotiate the transboundary process of water sharing as a more suitable immediate measure. However, previous records do show little progress in these negotiations (Morton 2011). Therefore, water sharing is probably a poor option because of a highly uncertain outcome. Other options, like upstream water management strategies for the dry season, administrative unit wide assessments on water demand, water budgets, and water allocation plans, can be developed but are currently too immature for implementation. Main uncertainties involve population growth and land demand, flash floods during monsoons and upstream agricultural water demand during the dry seasons. The Ganges barrage is the most suitable long-term measure to increase fresh water flow into the southwest, and therefore, increase freshwater resources availability and reduce salinization in the Sundarbans. Reduced upstream flow is the major cause for salinity increase in the Sundarbans mangrove (Bhuiyan and Dutta 2012) and a Ganges barrage could probably solve this. However, such barrage is very costly and also has several negative impacts. For instance, it will submerge a large area. This will make people's livelihoods vulnerable if proper replacements are not arranged.

Moreover, the adaptation pathways also suggest a range of measures to ensure long-term adaptation of the Sundarbans

mangrove forest to future climate change. To improve the sustainable use and management of the forest, improved awareness raising and training of forest department staff is needed. However, to save the forest ensuring increased freshwater flow into the system is necessary to reduce salinity increase. Periodic (re)-excavation to restore the Gorai River can potentially increase the freshwater inflow. However, continuous (re)-excavation may not be an economically viable measure in the long-term sustainability. Therefore, large scale tidal river management is proposed to ensure the connection of the rivers to the flood plain and to restore the natural process of land formation through sedimentation. This aims to reduce river bed siltation, waterlogging, and the effects of tidal water-level rise on the Sundarbans mangrove. This measure is highly likely to not only protect the Sundarbans against salinization but also stimulate crop-agriculture and fresh water sources. Such management is actually periodically cutting and closing polders, developed by local people to reduce drainage congestion induced by the polders (Hossain et al. 2015). It has been successfully implemented locally in the Hari River basin in the southern part of Jessore district for land reclamation (Paul et al. 2013). Shampa and Paramnik (2012) also suggested this socially acceptable and low cost ecotechnique to mitigate waterlogging problems in the Kobadak River basin area of Satkhira district. Also the multicriteria analysis shows that the measure is highly effective and feasible because it has low cost and negative side effects. The only challenge of this measure is the large-scale implementation and identification of the proper flood plains (locally called *beels*) for the tidal water inflow. Although it is a people-oriented approach, a good coordination among local stakeholders, government, and nongovernment entities is needed to overcome the challenges of large-scale implementation and long-term sustainability.

The methodology adopted in this study to develop adaptation pathways is a combination of different approaches with each approach having its own purpose. During our literature review, we identified that previous adaptive measures in the southwest coast of Bangladesh pressured the system backwards. One of the main reasons for this is probably the top-down decision-making approach (Fraser et al. 2006). Therefore, to fill this knowledge gap we surveyed local people to study their perception complemented with key informant interviews. This part of our study integrates both top-down and bottom-up observations. Although we did not receive adequate feedback from the household-level respondents on the long-term measures and potential adaptation turning points, they provided valuable information on the local socioeconomic processes of salinity increase and suggestions to address those. This information was incorporated in the DPSIR framework and also considered in the identification of potential measures to address the observed causes of salinity increase in addition to the key informants' perceptions. Besides, local people's perception on causes of salinity increase and suggestions to address those causes were taken into account during developing adaptation pathways. For instance, unplanned and extensive shrimp farming identified as the key cause of inland salinization and main pressure for the crop-agriculture system by the local people, can be tackled through land use zoning.

The identified interconnected climatic-social-ecological-economic causes of salinization are similar for all coastal systems. However,

to address each of the causes, different measures are needed. For instance, an upstream barrage can be a potential option to address reduced freshwater influx while land zoning can control extensive shrimp farming, and tidal river management can reduce waterlogging and river bed siltation. All these measures contribute to adaptation. Hence at large scales, a combination of different measures helps to enhance resilience to salinization, however, at local scales different measures are more suitable for the different coastal systems. For example, Sundarbans mangrove is surrounded by the wetlands that are connected to the Bay of Bengal, coastal inlands, and upstream river networks. Therefore, reduced fresh water influx and tidal water-level rise are the major concerns for salinization in the Sundarbans. Conversely shrimp farming, waterlogging, and river bed siltation currently are the major concerns for crop-agriculture systems. Therefore, we developed three different adaptation pathways for the three most affected coastal systems. However, it is important to acknowledge that all systems are connected and intervention in one system will have impacts on the other systems as well.

Qualitative, i.e., multicriteria analysis, and quantitative, i.e., adaptation turning points, assessment to identify the potential adaptation measures and develop the adaptation pathway consequently, were based on the perceptions and observations of the key informants and local people. Hence, the adaptation turning points, suggested for each of the measures, may not be precise because we did not test the measures. However, it indicated a salinity range when shifting or adding another measure is necessary. The adaptation turning points can be improved through multiple climate model projections and calculation uncertainties ranges to develop more robust adaptation pathways (Tanaka et al. 2015). However, when using models, the number of measures that can be tested, are often limited. The developed adaptation pathways in our study included a large set of measures, which can be implemented at different salinity levels. This study, therefore, is a valuable first step in merging the top down and bottom up perceptions, in developing the DPSIR framework for salinity increase and adaptation pathways to cope with salinization.

CONCLUSIONS
The southwest coastal region of Bangladesh consists of complex, interacting, dynamic ecological and social systems. Hence, adaptation planning to cope with salinization is a complex endeavor for this region. The identified salinization pressures and impacts result from a series of systemic interactions in coastal environments at small- and large-scale processes. At larger scales, sea-level rise and reduced upstream flows are causing increased salinity while at local scales land use change, polders, and siltation are contributing. Increased salinity is affecting different social-ecological-economic systems. It reduces crop production, affects drinking water resources, and biodiversity of the Sundarbans mangrove. The diverse causes of salt intrusion in combination with different systems it affects ask for a wide range of adaptation measures. This study also reveals that if the societal value of the coastal environment that supports life and livelihood of many coastal communities is ignored during adaptation planning, salinization likely gives rise to severe ecological, economic, and social problems and conflicts. To show how different measures can be used to adapt to different severities of salinity, three different adaptation pathways were developed giving a clear

perspective for policy makers on how to plan for adaptation. Our adaptation pathways consider both the societal values and top-down perceptions, which suggest land zoning, managed aquifer recharge, and tidal river management to sustain at high salinity concentrations for crop-agriculture, fresh water sources, and the Sundarbans mangrove. Because different potential adaptive measures of the developed adaptation pathways for different coastal systems interrelate, the combined action is needed to ensure greater long-term benefits for the studied region.

Responses to this article can be read online at:
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Appendix 1. Multicriteria analysis of the potential measures recommended by the household level respondents to address the perceived causes of salinity increase

Sl. No.	Potential measures	Criteria[*]					Score
		Effectiveness	Side effects	Cost	Feasibility	Uncertainty	
1	Limit shrimp farming practice	+++	+++	+++	+	+	11
2	Local government's initiative to prevent on purpose ingression of salt water	+++	+++	+++	++	+	12
3	Outlaw building unnecessary dams on the rivers	++	+++	+++	++	+	11
4	Operational sluice gates of the existing polders	++	+++	-	++	+	7
5	(Re)-Excavation of the silted rivers	+++	+++	--	+++	-	6
6	Riverbank protection	+++	+++	---	+++	-	5
7	Government initiative to change the leasing system and the use of Khash lands	++	+++	+++	+	+	10

[*]*For description with score card for the selected criteria please see Table 1*

Appendix 2. Multicriteria analysis of potential set of measures recommended by the key informants to address the observed causes of salinity increase

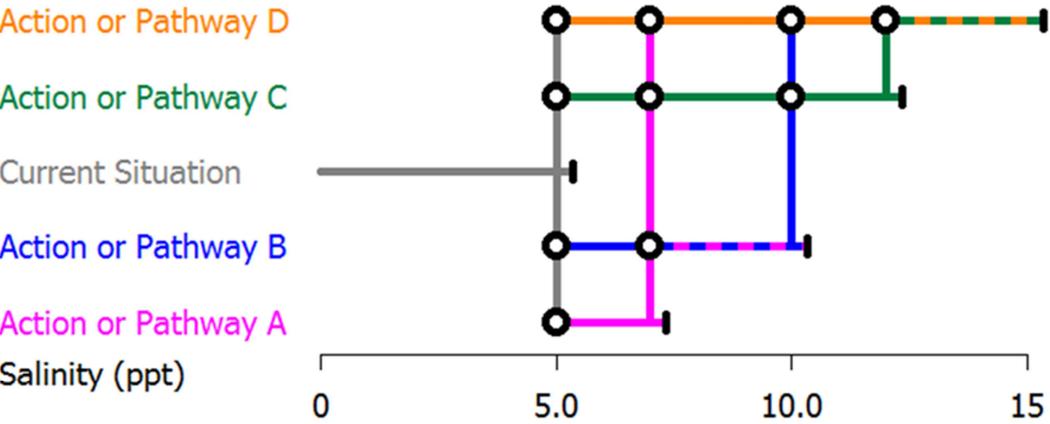| Sl. No.		Potential measures	Criteria[*]					Score
			Effectiveness	Side effects	Cost	Feasibility	Uncertainty	
1.		Planned shrimp farming practice	+++	+++	+++	++	+++	14
2.		Functional management of the existing polders	+++	+++	-	++	-	6
4.		Periodic/scheduled (re)-excavation	+++	+++	--	++	-	5
5.	Short term	Strengthen and heighten the existing embankments	++	++	-	+	-	
6.		Reduce dependency on ground water extraction for upstream irrigation	+	+++	-	+	--	2
7.		To be active in transboundary negotiation process on water sharing	+	+++	+	+	---	3
8.		Designing land management practice	++	+++	-	++	-	5
9		Planned infrastructural development in water resource management	+++	+++	---	+++	-	5
10.		TRM along with sediment management practice	+++	+++	+++	++	+++	14
11.	Mid-term	Administrative unit wise assessment on demand of water for different category enforcement of Water Act 2013 on priority basis;	++	+++	-	++	-	5
12.		Develop upstream water management strategy for dry season	+	+++	-	+	-	3
13.		Enforcement of Water Act 2013 on priority basis	++	+++	--	+	+	5
14.		Land use zoning	+++	+++	+	+++	+	11
15.		Integrated management of different systems	++	++	--	++	-	3
16.	Long term	Continuous monitoring on river flow and sedimentation rate	+++	+++	---	+++	-	5
17.		Delta plan/Integrated long term plan for the coast	+++	+++	--	+++	+	8
18.		Water budget and allocation plan	++	+++	--	++	+	6
19.		Ganges barrage	+++	+++	---	+++	+	7

[*]*For description with score card for the selected criteria please see Table 1*

Appendix 3. Potential set of measures and their contribution recommended by the key informants for the most affected coastal systems

Mostly affected coastal systems	Potential measures along with the score from multi-criteria analysis in *(..)* and Adaptation turning point (ATP)			Expected Contribution
	ATP (7-12ppt)	ATP (15-17ppt)	ATP (≥20ppt)	
Crop Agriculture	i. Crop diversification from subsistence crop to commercial crop/cash crop *(5)* ii. Adaptive agriculture (Floating bed agriculture; Macha agriculture, Integrated farming/composite agriculture) *(3)* iii. Alternate cropping through vibrant technology *(5)* iv. Arable field management *(6)*	i. Genetically modified salt tolerant crop *(2)* ii. Saline resistant horticulture *(6)*	i. Alternative Income Generation (AIG) activities and micro finance *(2)* ii. Land zoning *(7)*	• Promote agriculture; • Uplift socio-economic status of the farmers; • Reduce the direct conflict of crop agriculture with shrimp agriculture;
Drinking water sources	i. Rain water harvesting *(7)* ii. Pond excavation *(7)*	i. Pond sand filter *(5)* ii. Desalinization plant *(2)*	i. Permanent storage for monsoon water *(2)* ii. Managed Aquifer Recharge (MAR) *(6)* iii. Pond Technology *(2)*	• Reduce the scarcity of drinking water; • Contribute in health issues;
Sundarbans Mangrove	i. Mass awareness *(8)* ii. Ban catching fish during the breeding season *(8)* iii. Strengthen BFD *(8)* iv. Canals (re)-excavation *(6)* v. Gorai river restoration *(5)* vi. Develop water diplomacy (Re-negotiation for Ganges water sharing and Teesta agreement) *(4)*	i. Captive breeding of vulnerable/threatened species *(3)* ii. Livelihood diversification *(3)* iii. Tidal River Management *(14)*	i. Regional and Global Co-operation *(3)* ii. Ganges Barrage *(7)* iii. Water reservoirs in the upstream (at Modhumati / Gorai) *(1)*	• Ensure lean period upstream water sharing; • Reduce extraction of the forest resources; • Reduce local people's dependency • Lessen the external disturbance (human interference) on the natural systems; • Promote in-situ conservation; • Control Snaring and rampant Poaching; • Support the fishery resources in Sundarbans; • Quantify the resource extraction scenario; • Ensure Thousands of ecosystem services; • Identification of the research gaps and more research; • Ensure eco-flow of water; • Reduce much intervention and participatory management ;

Appendix 4. An example to facilitate interpretation of an adaptation pathway map to cope with salinization

The adaptation pathway map

How to interpret the map

Action or Pathway A can sustain up to salinity level 7ppt while the Action or Pathway B in combination with A will sustain till 10ppt of salinity. If salinity level crosses 10ppt, Action or pathway C is the most suitable measure until the salinity level goes beyond 12 ppt. Finally the Action or pathway D combined with Action C are expected to sustain up to 15 ppt of salinity.