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Strategy Formulation and Adaptation Pathways Generation for Sustainable Development of Western Floodplain of Ganges

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Abstract

The coastal zone of Bangladesh is very heterogeneous in nature and has marvelous potential to create opportunities of national importance and contribute to GDP. Among the potentials—intensification of agriculture, aqua-culture and marine fishery, ship building industry, eco-tourism, deep sea port etc. are most significant. Unfortunately, the coastal zone of the country is disaster prone area. Poor communication, lack of education and health care facilities, prolonged absence of safe drinking water and inadequate cyclone shelters contribute and multiply the dimension of vulnerability. Furthermore, increasing population pressure increases the competition for limited resources. As a consequence, in order to unlock these potentials, existing and new interventions are required to serve in an integrated and inclusive way; calling for a distinct and integrated coastal development strategy. This study aims to investigate the issues of the western floodplain of the Ganges and propose some identical strategies and subsequent adaptation pathways to delineate the development roadmaps to decision makers and researches. Analyses have been conducted through GIS and RS technology, Dynamic Pathway Generator, Excel analysis and field investigation.

Keywords

Strategy, Adaptation Pathway, Assessment Framework, Water Logging, Salinization, Disaster

1. Introduction

The western floodplain of the Ganges is a challenging region within the coastal zone [1]. The area covers around 8000 km^2, and includes the districts of Khulna, Gopalganj, Jessore, Sathkira, Narail and Bagerhat. The region forms an interface between land and water [2]. It is constantly under influence of tides originating in the Bay of Bengal in the South and freshwater inflow through rivers from the North, namely Madhumati, Nabaganga, Kobadak, Sibsha, Rupsa, Bhairab, Atai and Koyra River. The balance in these two systems formed the basis for the present qualities of the area, but also for the challenges ahead. The rivers also connect the region directly with the Bay of Bengal and the Sundarbans. This provided opportunities for the development of ship yards, ports and shrimp farming, but also challenges to the protection of land [1].

In the early 1960's, before embankment construction, the area was under influence of the natural tidal system [3]. This brought benefits as well as costs. Benefits included the nourishment of the area with sediment and regular flushing of natural canals and rivers through tidal movement. A mixed economy existed, consisting of both rice, fish and shrimp culture [4].

In the mid-1960's, the first fully embanked polder developed, through EPWAPDA. Agriculture became the mainstay of the rural economy, with up to 2 rice crops now being possible as well as providing protection against cyclonic floods and tidal inundations. The process of regular natural sedimentation and cycle or movement of brackish and fresh water inside the polders, resulting from the tidal movement, came to an end.

A total number of 145 polders have been constructed throughout the whole coastal zone of the country [5]. Uniqueness in this region is the Sundarbans (UNESCO World Heritage Site), the largest single block of tidal halophytic mangrove forest in the world. The Sundarbans covers approximately 10,000 km^2 area of which 60% in Bangladesh [6]. It provides a unique and complex ecosystem with rich wildlife habitat and the largest reserve for the Royal Bengal tiger.

The policies, studies and plans which have been executed in this region, as well as throughout the country, have tended to be done piece meal with single line agency involvement, not taking a holistic approach to water as a cross-sectoral issue [7]. The institutional aspects of water management tend to be side-tracked or weakly covered. Also demand side or careful assessment of socio-economic impacts is not taken into account [8]. So it has unlocked the space to develop a strategic framework along with development pathway for this region.

2. Methodology and Materials Assemblage

2.1. Literature Review

The coastal zone of Bangladesh is densely populated [9]; with an increasing trend toward conflicts due to scarcity and unequal use of natural resources. To compensate the unequal uses and safeguard of the resources the Government of Bangladesh (GoB) is always sensitive about this region. So a number of plans, policies and strategies have already been prepared. The first national water centric master plan was prepared in 1964 [10] namely, IECO[1] Master Plan, suggesting 58 large flood control, drainage and irrigation (FCDI) projects [11]. The

[1]International Engineering Company (IECO) by American Consultants.

main objective of the plan was only to protect lands from flood and coastal storm surges and produce agricultural crops. The impact on other sectors like fisheries, environment was not assessed [12].

Flood Action Plan (1989-95) is massive and in many respect very thorough in terms of technical and social aspects [13]. The main benefit of the study was that, through the studies a series of planning guidelines had been formulated under different themes such as EIA, SIA[2], project assessment and people's participation.

In National Water Management Plan 2004, the study area has been identified as south-west region indicated as one area that needs urgent attention. Major issues specific to the region are: preservation of the Sundarbans, restoration of dry season freshwater inflows to the region, maintenance of the coastal embankment system, alleviation of coastal drainage congestion, improved cyclone protection, remedial actions for existing FCDI schemes [14]. In NWMP, the programs proposed under the disaster management are in compliance to the study area as: cyclone shelters and killas, flood proofing in the char lands, and for national, regional and key feeder roads, and railways, and supplementary irrigation and rural water supplies [15].

The ICZMP project has been executed during 2002 to 2005. An important output of the ICZMP project is the Coastal Zone Policy [16]. The CZPo was prepared before the Bangladesh Climate Change Strategy and Action Plan [17] was adopted. Still this policy had the farsightedness to propose that an institutional framework be set up to monitor and detect climate change specially sea level rise.

The output 'Coastal Development Strategy' links the Coastal Zone Policy with development programs and interventions. The objectives are to select strategic priorities and actions in implementation of the Coastal Zone Policy with emphasis on the creation of the institutional environment that will enable Government of Bangladesh to embark on a continuous and structured process of prioritization, development and implementation of concerted interventions for the development of the coastal zone [18].

Integrated Planning for Sustainable Water Management (IPSWM) Program was implemented in the area of western floodplain of the Ganges. The main objectives of the program are: 1) to ensure People's Participation at all stages of the water resources; 2) to establish sustainable water management in the selected sub projects; 3) to transfer the management responsibilities from BWDB to the people of the community [19].

2.2. Study Area

The study area lies 300 km southwest of Dhaka, on the coastal plain at the apex of the Bay of Bengal (**Figure 1** and **Figure 2**). The area lies between 22˚00'N and 23˚00'N and 88˚30'E and 90˚30'E. According to Bangladesh Bureau of Statistics (BBS), the population in the study area is around 10.2 million. The area includes

[2]EIA: Environmental Impact Assessment, SIA: Social Impact Assessment.

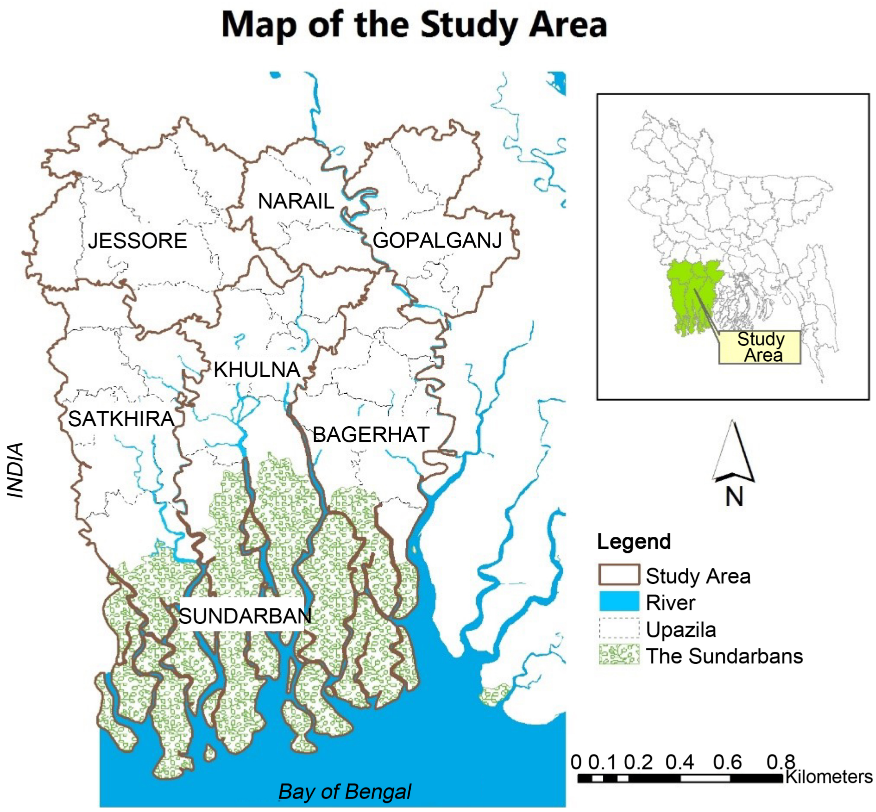

Figure 1. Map illustrating the study area.

Figure 2. Google Earth map of the study area.

the world's largest continuous mangrove forest, the Sundarbans, estuarine marshlands and numerous rivers, canals and their tributaries [6]. The terrain is relatively flat; fertile plain dominated by alluvial soils [20] and the elevation ranges from sea level to 5 m above mean sea level [21].

The presence of the world's largest continuous mangrove forest provides food and nursery for the offshore fishery, protection of the coasts from storm surges and cyclones, domestic and commercial products, recreation and tourist services, and habitat for shrimp and other cultivable species [22]. The western floodplain of the Ganges contains 43 polders (**Figure 3**), often belonging to the first

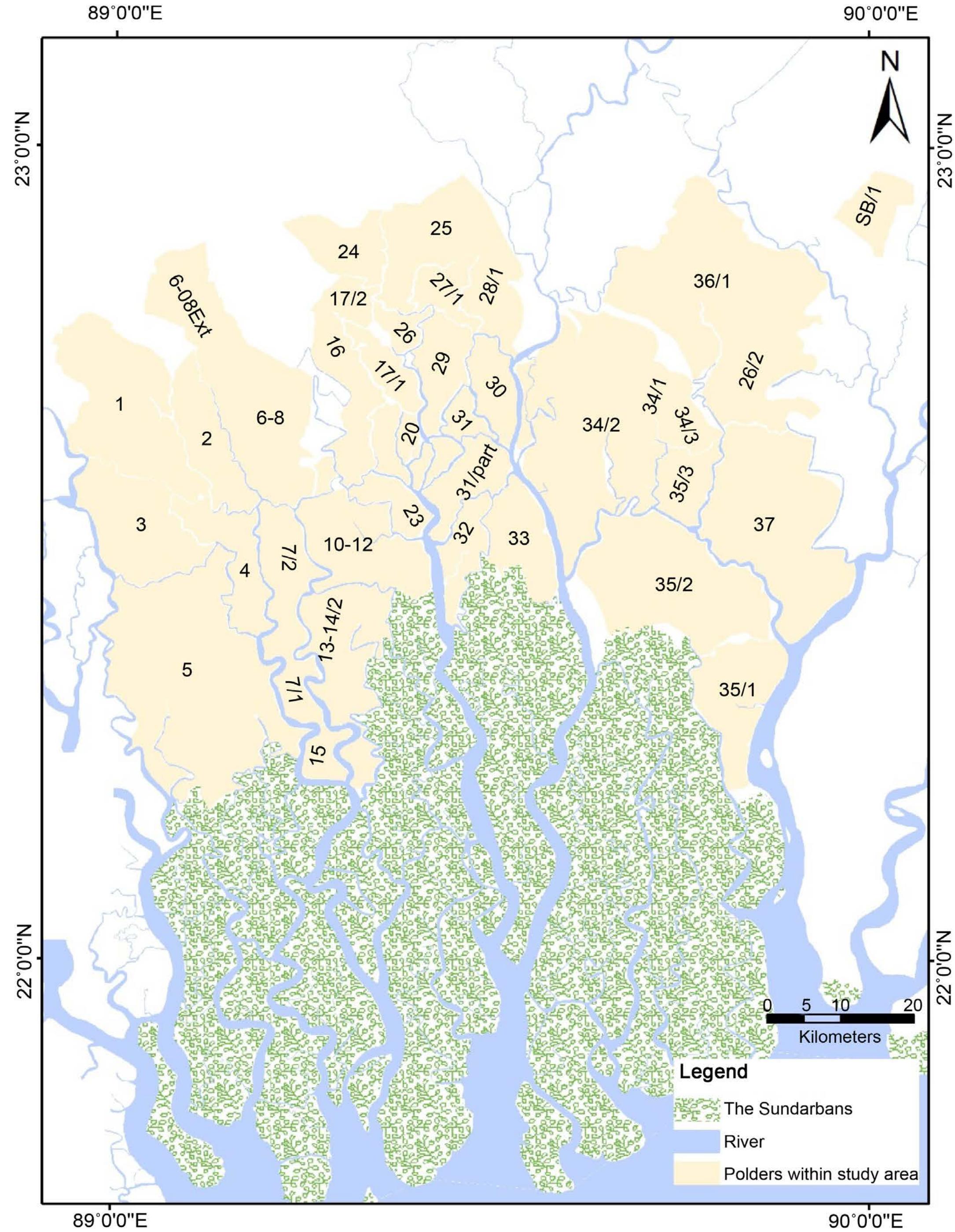

Figure 3. Illustration of polders located within the study area.

generation of polders. The region has different ports, of which Khulna naval base and Mongla seaports are the most important.

A gradient can be found along the region, from North to South [23]. This gradient is the result of changing basic conditions, differentiation in salinity intrusion, siltation and the related problem of waterlogging.

2.3. Steps Followed in the Study

The study has been conducted in several analytical steps, shown in **Figure 4**. At first, the baseline situation studied through field visit, public consultation meetings (PCM) with local stakeholders and literature review. The national documents and international journals and articles have been examined to get better understating about the present water resources condition of the study area. Then the issues were identified and analyzed and tried to discover indigenous solution concepts from the local stakeholders through the PCMs. While identifying the solutions, the vulnerabilities and future uncertainties were kept in mind. After those steps the selected issues and solutions had been scrutinized, analyzed and determined key issues for present situation and for 2050. The key issues then led to actions and measures for future development. The local stakeholders also suggested several solutions which were the building blocks of the strategy development process.

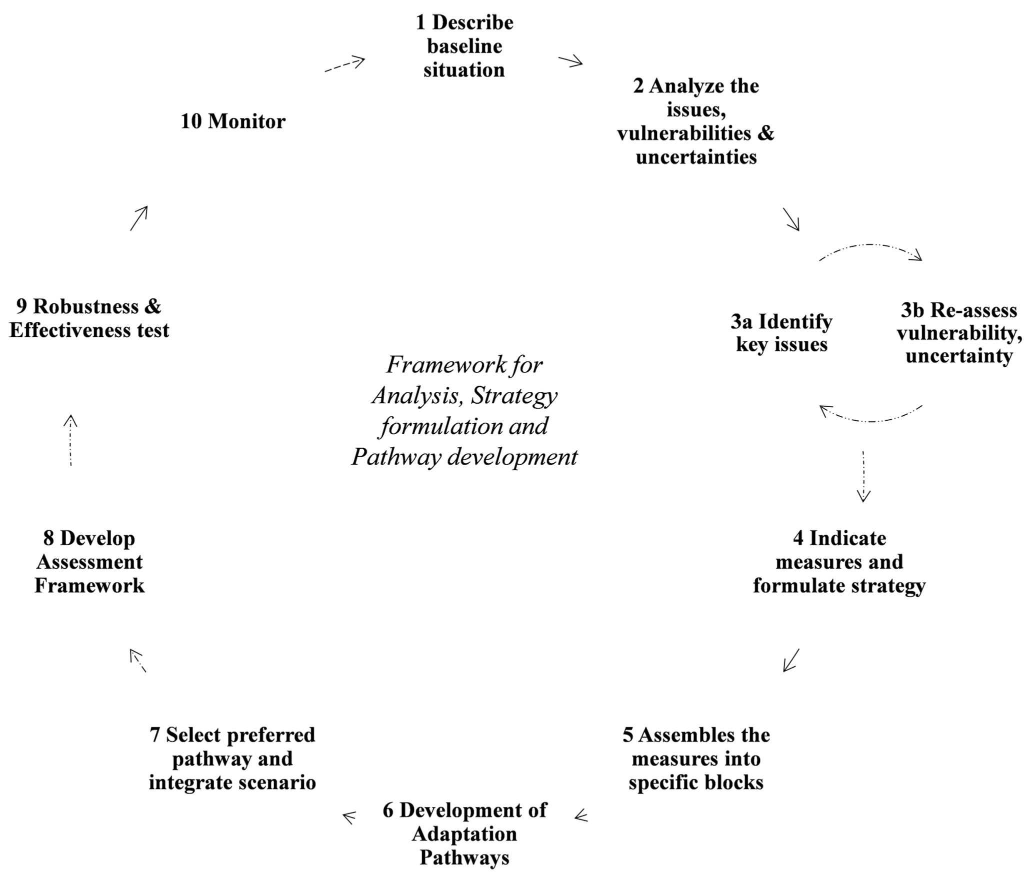

Figure 4. Building blocks or steps followed in the study.

The key measures then assembled into three specific blocks (*i.e.*, Water Logging, Salinity Intrusion and Natural Disasters) to indicate strategies and adaptation pathways. From these different possible pathways the best track has been nominated and integrated with the future scenarios. Then Assessment Frameworks were developed and the selected measures were assessed by the framework. The assessment frameworks support to test effectiveness, robustness and economic impacts of the measures. The results from assessment framework urge to monitor the whole process. This monitoring result could direct to repeat the whole process of the cycle of the study.

2.4. Using GIS Software and Adaptive Pathway Generator

The GIS software has been used in this study to analyze data and prepare map. The data have been collected from National Water Resources Database (NWRD), Bangladesh Agricultural Research Council (BARC) and the knowledge portal of Bangladesh Delta Plan 2100 for analysis.

Another tool has been used namely, Pathway Generator which is developed by Deltares and Carthago Consultancy, The Netherlands. Dynamic Adaptive Pathways support decision making under deep uncertainty using Adaptation Tipping Points in policy analysis [24]. Many investment and policy decisions in water management have significant and often long-term consequences. Moreover, long-term objectives often require near-term decisions. Making sound near-term decisions is critical, yet we live in an increasingly unpredictable dynamic world governed by competing and changing beliefs and preferences. When decision makers and analysts face a deeply uncertain future [25] (e.g. due to climate change), they need more than traditional prediction or scenario-based decision methods to help them to evaluate alternatives and make decisions.

The Dynamic Adaptive Policy Pathways (DAPP) approach aims to support the development of an adaptive plan that is able to deal with conditions of deep uncertainties [26]. The approach is developed by Deltares and TU Delft and has inspired the Adaptive Delta Management concept of the Dutch Delta Program. An adaptive plan specifies actions to be taken immediately to be prepared for the near futures and actions to be taken now to keep options open to adapt if needed in the future.

2.5. Issues and Possible Solutions Identified through Public Consultations/Workshops

The public consultations and workshops were focused on the issues or problems identification. To accumulate in-depth community information, more than 15 focus group discussions (FGD) were carried out. The guidelines followed during the FGD sessions were as like: 1) the participant size was kept reasonable, *i.e.*, minimum 15 to maximum 40 local people; 2) homogeneity maintained in profession and gender among participants (*i.e.*, if the session was conducted with male farmers, then all of them were chosen with similar characteristics and similar age groups); 3) one protocol writer, one moderator, and one organizer were present during the sessions; 4) the sessions were recorded using audio devices to prepare transcriptions; and 5) the collected information and diagrams (*i.e.*, mobility maps) were reproduced by the interviewers and shared with the participants. Mobility maps were shown to depict the natural channels, access to resources and document information for baseline situation of the study area. The key stakeholders, officials and local farmers identify the issues and suggest the solutions. Later, the experts consult with themselves and invent the proper solution and strategy. Table 1 summarizes the issues and solutions as suggested by the local stakeholders.

3. Key Issues

The western floodplain of the Ganges is susceptible to storm surge inundation, riverbank erosion, freshwater flow scarcity, drinking water scarcity, salinity intrusion and other natural disasters [27]. Among these problems, the key issues have been identified for present condition and for the future (2050) which may be accelerated over time due to exogenous factors or uncertainties like climate change, environmental degradation, etc.

The major problems for the western floodplain of the Ganges are waterlogging and salinization. Waterlogging is mainly due to siltation of the peripheral rivers, which is likely to worsen in future with the combined effect of precipitation increase, sea level rise and subsidence [28]. Salinity intrusion is also becoming more and more problematic and challenging-reduced fresh water flow from the north (upstream) due to siltation, reduced Gangs dry season flows, sea level rise and land subsidence are the main causes [29]. Both phenomena, waterlogging and salinization cause major constraints for the agricultural sector and the ecosystem of the Sundarbans. This interdependency and co-relation between the interventions and livelihood and economy have been depicted in Figure 5. For this study, the selected key issues have been assembled into three sections *i.e.*, waterlogging, salinity intrusion and natural disasters, which have been discussed below.

3.1. Water Logging

Water logging is a problem over large parts of the coast, especially in the western floodplain of the Ganges (Satkhira, Jessore and Khulna). But the other three districts of the study Bagerhat, Gopalganj and Narail do not face that much water logging. The region is characterized by numerous morphologically active tidal rivers, which are the main drainage networks for coastal polders and low-lying beels [30]. Thus, the natural drainage pattern of the area is predominant by the influence of the incoming tide from the sea. The distribution of waterlogged areas of eight selected upazilas under three districts is shown in Table 2.

Before polderization, major parts of incoming silt deposited naturally on the low-lying depression areas (beels). On the other hand, continued fresh water flows from the Ganges helped to flush the incoming sediment and thus, the proper drainage pattern of these tidal creeks maintained naturally. After polde-

Table 1. Identified issues and suggested solutions from local stakeholders in the study area.

Issues identified	Solutions suggested by local stakeholders
Water logging in agricultural lands due to drainage problems	- Rethink the polders; basically changing the current main (agriculture) function in selected polders to allow inflow of sediment and mixed farming-aquaculture - Ganges barrage to increase flow and reduce salinity and siltation (before building barrage first use Tidal River Management to reduce sediment and lift polders) - Sediment Management
Tidal floods (during spring tide) may cause severe loss on unprotected coastal lands as well as sometimes breach earthen embankments, leading to potentially more harm	- Strengthening and heightening of the embankments - Repairing the sluice gate and structures in the area
Water logging in urban areas, due to drainage problems	- Clear and widen canals - Excavate ponds and create parks subsequently
Siltation causes blockage of rivers and canals, for fisheries causes further water logging	Dredging periodically (re-excavation) of rivers and canals
Increase salinization due to reducing upstream fresh water flow, affects biodiversity and agriculture	Change to salt tolerant crops (and introduce new technologies)
Constructing of poorly designed bridges, roads and culverts without considering drainage requirements	Redesign roads and bridges alignments and enhance drainage capacity of culverts, canals and sluices
Overtopping of embankments	Redesigning the embankments according to the prediction of climate change
Embankment erosion	- Maintenance and management of the embankments, especially ensuring enough funds for O & M - Construct river bank protection to save valuable land and prevent siltation as well
Loss of water shed area due to siltation, encroachment and illegal occupation	Empowerment local government to prevent illegal occupation
Unauthorized pipe inlet for fisheries and shrimp culture	Restriction and enforcement, including strong communication between stakeholders and decision makers for joint decision-making
Drinking water scarcity due to salinization and arsenic, including excess lifting of groundwater (350 - 400 ft) (arsenic increasing in shallow aquifers)	- Rainwater harvesting, with on-farm reservoirs - Aquifer Storage and Recovery (ASR) - Reduce dependence on groundwater, switch from boro to aman

Continued

Health issues due to salinity, both human and livestock, and arsenic (also creating social problems)	Desalination and arsenic removal techniques
Scarcity of grazing lands for livestock	Supply concentrated livestock feed
Various infectious livestock diseases (including zoonotic)	Introducing new technology livestock production
Inadequate infrastructure (accessibility/market accessibility)	- Developing market infrastructure and communication technologies and local marketing information access
Absence of skilled labor, marketing, selling points, (cold) storage facilities and processing industries	- Regional development (corridors) - Development of marketing strategy/policy
Insufficient research in possible variety in crops or livestock	- Establishment of specific research center - Facilitate training
Change in land use pattern: (illegal) shrimp culture, other crop production and unplanned urbanization	- Improve land use zoning inside polders and adapt in-polder infrastructure to regulate planned aquaculture-rice combinations, also not detrimental to existing rice cultivation - Construction of polders within polders for shrimp cultures
Pollution by industrial effluent, waste generating from urban areas & agricultural activities	- Planned urbanization and industrialization, including solid waste management and wastewater treatment plants (WTP) and safeguard wetlands - Eco-friendly agriculture (bio-fertilizer/bio-pesticides)
Deforestation, forest degradation and over-exploitation from the Sundarbans Sea level rise and temperature rise affects Sundarbans	- Pollution monitoring and improvement of enforcement and clean technology development - Afforestation and plantation in the Sundarbans - Awareness campaign to reduce over-exploitation in Sundarbans
Lack of quality fingerlings	- Development of environment friendly and certified prawn hatcheries - Recover/increase vegetation coverage by promoting agro-forestry techniques and highly productive multi-purpose forestry
Illegal hunting and poaching	Alternative income generating activities, with strong local involvement and innovation
Lack of law enforcement	Law enforcement, with strong local involvement and awareness raising
Lack of management	- Research, Capacity building and alignment - Establishment or strengthening of Water Management Federations, Associations and Groups

Table 2. Major water logged areas in southern region.

Districts	Total area of affected Upazila (ha)	Water logged area (ha) at Present Condition		
		No of Upazila	Area (ha)	% of total affected Upazila
Jessore	94,911	3	15,700	16.5
Khulna	51,245	2	19,023	37.1
Satkhira	96,298	3	33,470	34.8

Source: [31].

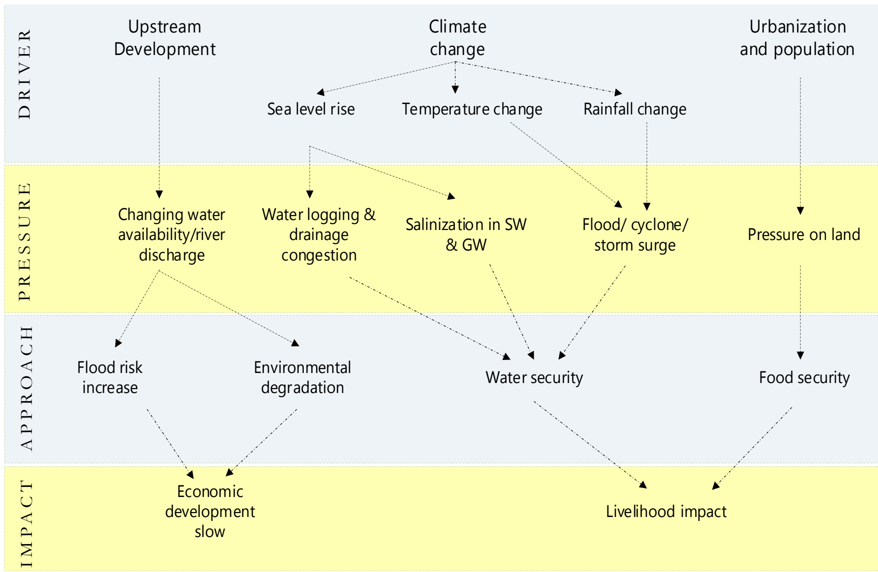

Figure 5. Natural and socio-economic interfaces within the study area.

rization and significant reduction of fresh water flows from the Ganges, this natural process seemed hampered significantly. In addition, the reduction of dry season flow in the downstream of the Ganges and its distributaries due to withdrawal of upstream water by commissioning of Farakka Barrage contributed to sedimentation aggregating in the riverbeds and tidal creeks. This reduction of fresh water had increased the salinity concentration, which proportionately increased sediment concentration and simultaneously silt deposition in the peripheral rivers during ebb tide [32].

More intense rainfall events, lower upstream river flows in the dry season, reducing tidal prism; furthermore, climate change, sea level rise and subsidence will aggravate waterlogging experiencing now. The areas that are not experiencing water-logging now (e.g. non-polder areas in Jhalokati, Patuakhali and Barisal districts) may experience that in the foreseeable future. Several causes directly related to human activity (e.g. floodplain encroachment, polderization, drainage infrastructure blocking, etc.) are also liable for worsen the situation. Apart from agricultural impacts, this will also reduce navigation possibilities, fresh surface water supply and capture fisheries production.

3.2. Salinity Intrusion

The river water salinity in the study area depends on the volume of freshwater discharges from the upstream river systems, the salinity of the Bay of Bengal near the coast, and the circulation pattern induced by the ocean currents and the tidal circulation to the river systems. Thus, average salinity concentrations of the rivers in the study area are higher in the dry season than in the monsoon because of lack of freshwater flow from upstream. Salinity level generally increases almost linearly from October to late May with the gradual reduction in the freshwater flow (**Figure 6**). Observation of salinity shows an increase of salinity from 0.7 ppt to 16.8ppt in the Rupsa River from 1962 to 2015.

Salinity intrusion reducing the freshwater area results in decrease of agricultural production [33], especially the Khulna district and the extreme south of the Satkhira district, and locally in the Bagerhat district. Increase of salinity is damaging the freshwater fish habitat and has adverse impact on the Sundarbans ecosystems.

3.3. Natural Disasters

The natural disasters include the floods, freshwater unavailability due to salinity intrusion and water pollution and environmental degradation, especially the Sundarbans, due to settlement and contamination from households and agriculture. These are discussed in the following sections.

3.3.1. Floods

Almost every year cyclone-induced storm surges inundation and tidal floods impact the western floodplain of the Ganges in pre-or post-monsoon period [34]. Only the sea facing portion is better protected because of the extensive Mangrove forest “Sundarbans”, naturally reducing wave heights. Tidal floods, in the time of spring tide, may cause severe loss on unprotected coastal agricultural lands as well as sometimes breach earthen embankments, leading to potentially

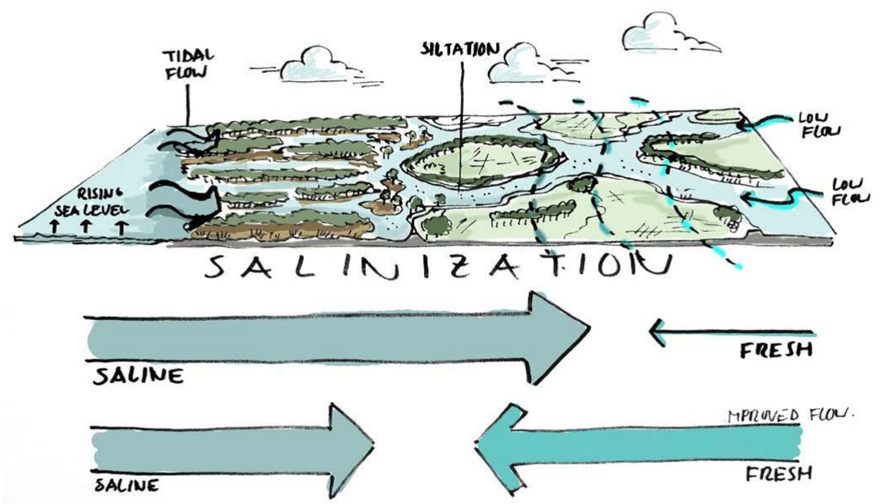

Figure 6. Low fresh water flow and siltation cause salinity intrusion affecting agriculture and the Sundarbans.

more damage.

Figure 7 shows potential modelled flood hazards, providing indicative maximum water depths after overtopping in extreme events (100 year return period). A rapid analysis, based on the modelled information from IWM[3], shows that a substantial part of current total coastal flood risk (combination of hazard and vulnerability) can be found outside the current polder areas, making these areas much risky for extreme flood events.

3.3.2. Freshwater Availability

Currently, the study area is mainly used for two-cycle rice production of rain-fed crops in the monsoon, and boro rice in the dry season by irrigation. This practice is under pressure of increasing salt intrusion in the river water, also because of diminishing freshwater flow from the Gorai river (main source of freshwater for the western floodplain of the Ganges) [35], and groundwater salinity.

In the study area, shrimp culture is progressing, sometimes in combination with rice production in the monsoon period. Also prawn and fish farming is increasingly being practiced in order to adapt the new situation. Freshwater supply for domestic needs is severely constrained due to the elevated salinity level in the shallower aquifer and arsenic contamination in the deeper aquifer. In terms of groundwater, projected sea level rise will cause a higher pressure difference between sea level and groundwater level. This difference may create an upward flow resulting in saline seepage near the inland coast.

The availability of arsenic free groundwater in the coastal zone is probably mostly indirectly influenced by climate change and found in the study area [36]. Arsenic is often found in iron sulphides and oxides, and when the redox conditions change, arsenic can mobilize and can contaminate groundwater further. Climate change may influence the pumping regime due to higher evaporation rates and higher water demands, as well as due to an intensification of droughts. Increased pumping rates during the dry season and heavier rains during the rainy season will influence the fluctuation of the groundwater. This fluctuation induces redox changes, which can increase the mobilization of arsenic. Besides, a change in the regional groundwater flow patterns caused by changes in rainfall

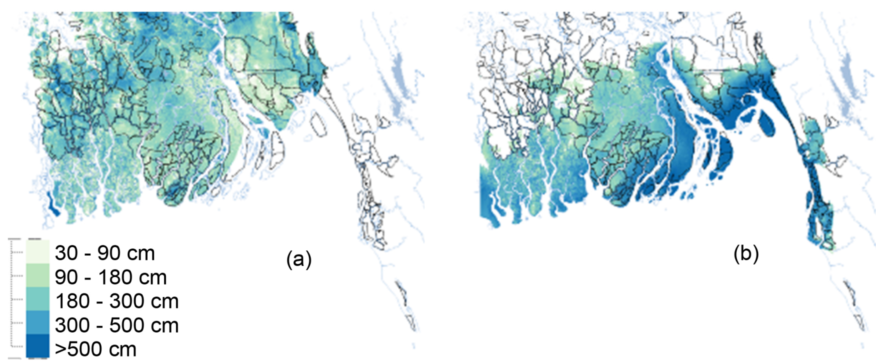

Figure 7. Indication of maximum water depth for 100 years return period for (a) riverine floods and (b) storm surges.

[3]Institute of Water Modelling (IWM), Bangladesh (www.iwmbd.org).

distribution in time and space may also increase the mobilization of arsenic.

Developments of water demands for different sectors are most influenced by land-use changes under influence of population growth and diversifying developing economy. Recent autonomous adaptations to decreased availability for irrigation water towards aquaculture land use may locally further decrease freshwater demands for agricultural consumption in the future.

3.3.3. Environmental Degradation

Environmental degradation is common in the coastal zone, particularly for the "Sundarbans" the largest mangrove nature reserve in the world. Specifically pressures include illegal encroachment, pollution due to boat transport, and increased surface water salinity [37]. Rising salinity levels will severely affect the biodiversity in the longer term [38].

Increased water demand, pollution and on-going urbanization/population increase produce increasing pressures on the already sensitive wetland ecosystems and floodplain-river system. Sources of contamination will be dominated by the domestic and agriculture sectors. Also pollution from industrial and urban sources will increase.

4. Strategy Formulation

The outcomes of the Public Consultation Meetings and Focal Group Discussions have been used as the building blocks for formulating strategies, sub-strategies, possible measures and adaptation pathways. The strategies, sub-strategies and measures are as follows:

Strategy 1: Restoration of severely water logged and drainage congested areas in the western floodplain of the Ganges.

To well define the strategy, it has been downscaled in three sub-strategies to achieve possible measures.

Sub-strategy 1.1: *Restoration of the peripheral rivers to increase conveyance capacity.*

Possible Measures:

- Strategic dredging of the Gorai-Modhumati-Pussur river systems including the Gorai off take and restoration and maintenance of Bhairab, Nabaganga, Hisna, Arial Khan, Mathabhange, Kobadak River, etc.
- Dredging, restoration and maintenance of the peripheral rivers of the polders to increase the conveyance capacity as the bed levels of these rivers have risen up due to siltation process over the years reducing their conveyance capacity significantly.
- Restoration of beels and drainage channels.
- Re-excavation of channels and ponds and dredging of water bodies and peripheral rivers to increase water retention volume and tidal prism.

Sub-strategy 1.2: *Constructing water control structure to reduce drainage congestion.*

Possible Measures:

- Construction of Ganges barrage and its ancillary works to augment the river flow in the western floodplain of the Ganges, hence contributing to the reduction of water logging and drainage congestion.
- Maintenance and retention of water control structures as location specific which will be helpful to reduce drainage congestion.
- Optimized and differentiated use of polders by strengthening the boundary for protecting against tidal inundation, storm surge and coastal inundation.

Sub strategy 1.3: *Ensuring adaptive water management in the floodplain areas.*

Possible Measures:

- Integrated Management of Drainage Congestion by active participation of the responsible agencies and local people.
- Tidal River Management (TRM) for 10 years in broad scale.
- Pumping out the water from the waterlogged areas such as the polders of the Western Ganges tidal floodplain (e.g. Khulna, Satkhira region).
- De-polderization in some selected areas, as it may enhance drainage capacity in its neighborhood or enhances protection/restoration of environmentally sensitive areas (e.g. Sundarbans). As population density is generally high, this measure may be very costly (in social terms) in order to resettle the current population.
- Shifting Mongla Port to a more sustainable location to better safeguard the mangrove forest Sundarbans.

The strategies, sub-strategies and measures are illustrated in Figure 8.

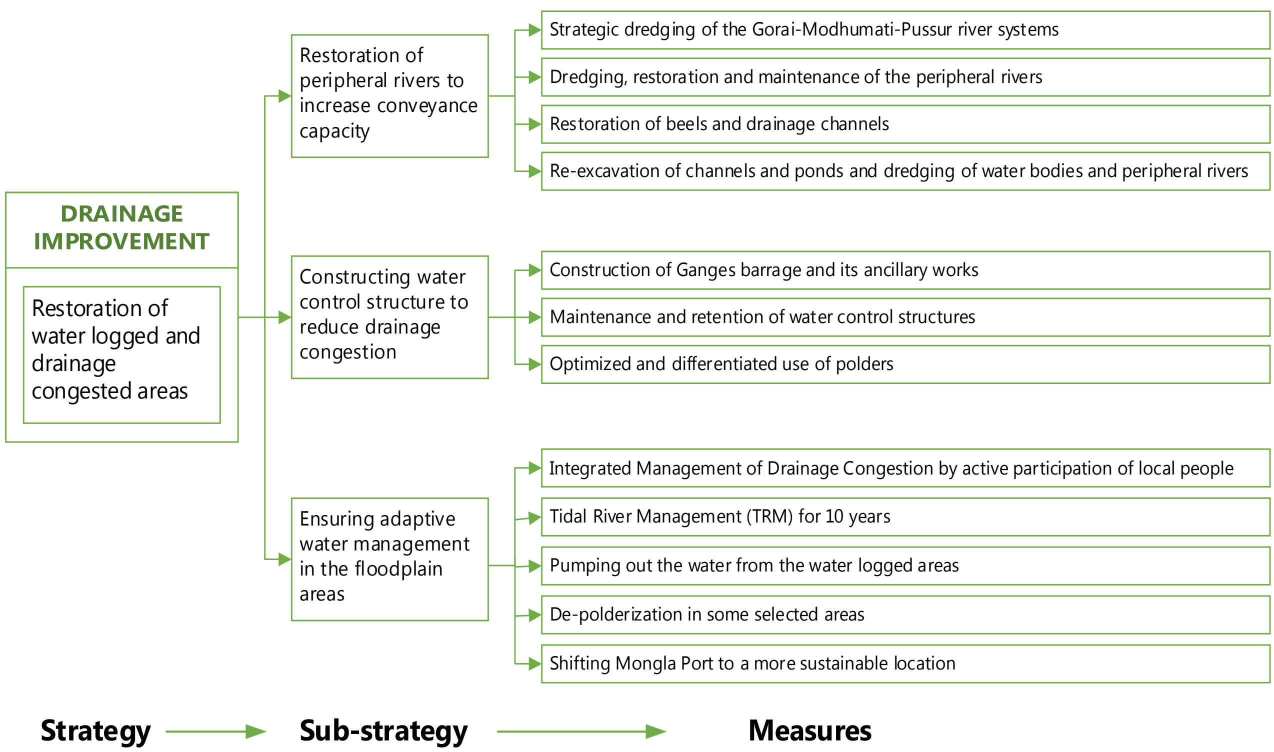

Figure 8. Schematization of the 1st strategy, sub-strategies and measures.

Strategy 2: Enhancing fresh water flow to combat salinization in the study area.

Two sub-strategies have been recommended to define the strategy in well-defined and inclusive manner.

Sub-strategy 2.1: *Ensuring fresh water flow for irrigation*

Possible Measures:

- Construction of the Ganges barrage to restore freshwater flow through the Gorai, would be advantageous in the study area and reducing salinization in the Sundarbans.
- Revitalization and maintenance of regional (some transboundary) rivers is needed to push back the salt water and subsequently ensure a sustainable situation.
- Improvement of the connectivity between wetlands and floodplains and restore the natural capacities of beels and natural water bodies as much as possible to ensure freshwater in the coastal zone for sustaining natural ecosystems (e.g. wetlands, beels, fisheries and the Sundarbans).
- Increase surface water storage in polders and reduce the dependency on groundwater for irrigation water supply.
- Salt resistant crop farming or introducing adaptive agriculture (*i.e.*, precision irrigation like sprinkler irrigation, etc.) practice.

Sub-strategy 2.2: *Ensuring fresh water flow for sustainable water use*

Possible Measures:

- Building mega-structure in western floodplain of the Ganges (salinity barrier/storm surge barrier, etc.).
- Deep well development and groundwater artificial recharge in arsenic and salt contaminated areas to ensure the fresh water supply in the southern floodplain of Ganges area.
- Promotion of water treatment facilities including de-salinization plant to ensure fresh water supply.
- Rehabilitate the sea facing polders and interior water infrastructures in an integrated and adaptive mechanism considering the future climate change.
- Adaptation to shrimp to crab farming.
- Regional connectivity with India, Mayanmar and China for maintaining the normal flow in the surrounding rivers and connecting channels.
- Arsenic filtering on local scale for supplying drinking water supply in the community of the study area.
- Development of coastal green belts as measure against storm surge in the coastal zone, especially the Sundarbans.

The strategies, sub-strategies and measures are illustrated in Figure 9.

Strategy 3: Combating coastal inundation, river bank erosion and natural disasters through integrated management considering future climate change.

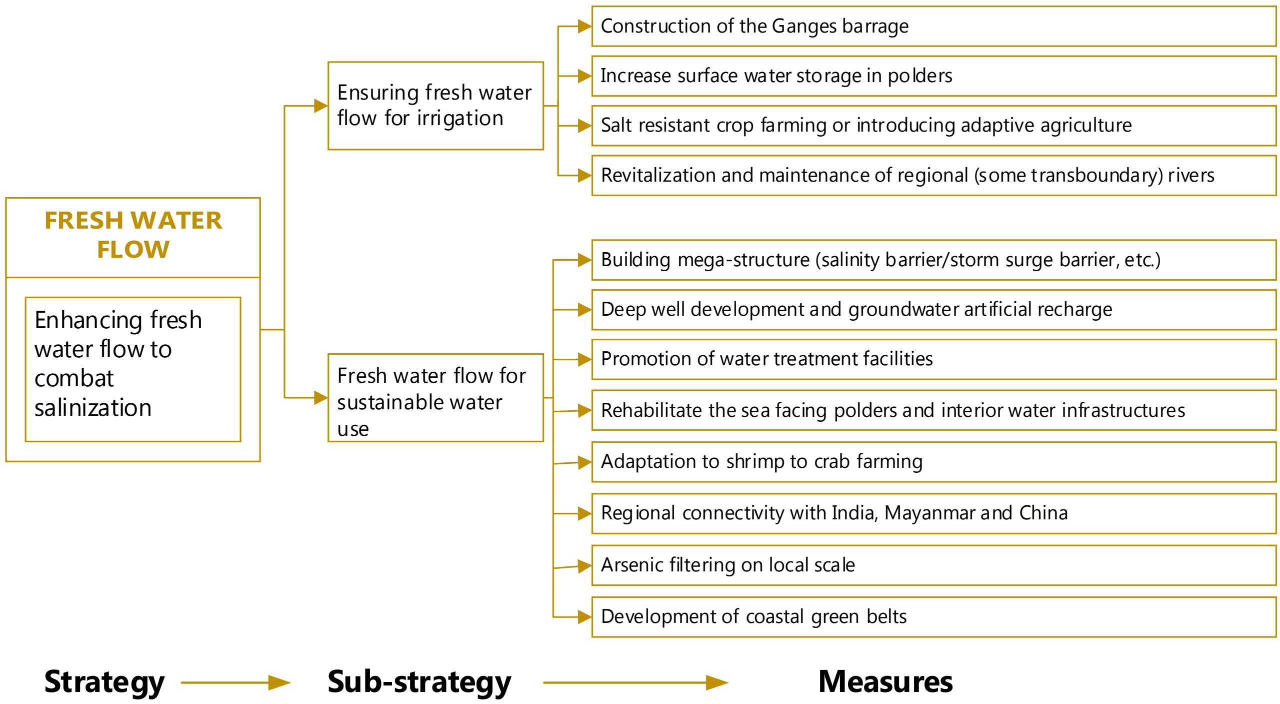

Figure 9. Schematization of the 2nd strategy, sub-strategies and measures.

Two sub-strategies have been recommended for the strategy.

Sub-strategy 3.1: *Rationalization of the existing water control structures considering climate change*

Possible Measures:

- Redesigning of the Sea Facing polders considering the impacts of climate change, sea level rise and frequent other natural disasters. However, sea walls may be constructed in the medium and long term if the coastal inundation increases.
- Construction of storm surge barrier/estuary closure (partly), using international (*i.e.*, Dutch delta development, etc.) experience to safeguard against natural hazard, susceptible to worsen due to climate change.
- Constructing sea dykes where feasible to safeguard economic strongholds and economic zones to be grown the coastal zone.
- Erosion control in the study area.
- Develop multi-purpose flood embankment on right bank of Ganges River from Mathabhanga off-take at Jalangi to Muladi considering climate change.

Sub-strategy 3.2: *Preparedness and awareness building to combat natural disasters*

Possible Measures:

- Flood proofing and preparedness enhancing among the local stakeholders in the coastal regions.
- Foreshore afforestation and protecting the Sundarbans.
- Sediment management of the basins.
- Flood free and cyclone protected sea port and economic zones.

- Development of flood hazard and risk map.
- Construct and maintain multi-purpose cyclone and flood shelters.

The strategies, sub-strategies and measures are illustrated in Figure 10.

For more coastal urban areas or areas of national economic significance (e.g. sea-ports and infrastructure) now or in the foreseeable future, higher levels of protection are preferred (e.g. 1:100-1:250 year including climate change). This should be defined and maintained based on a comprehensive optimized cost-benefit analysis. The future investment programs are to be implemented when it needs, more specifically, when a project reaches to its tipping point [39], afterwards, require further investment and more time-specific suitable programs following best possible pathways.

5. Adaptation Pathways

An adaptation pathway depicts several possible allocations of project combinations to accomplish the goals within the anticipated timeline. It helps to sequence projects so that investments are neither "too much, too soon", nor "too little, too late", but instead deliver "enough, in time". In project sequencing or future investments, as uncertainty is important, adaptation pathways assist in analyzing, programming and developing optimal combinations of interventions to achieve desired goals.

In adaptation pathway different types of interventions/actions are mentioned with respect to some indicators and external scenarios [40]. The colors refer the actions A (red), B (orange), C (green), and D (blue) and the circles denotes the tipping points when a certain intervention or action might not be fitted to achieve the desired goal, for that reason, need to consider other alternatives. The

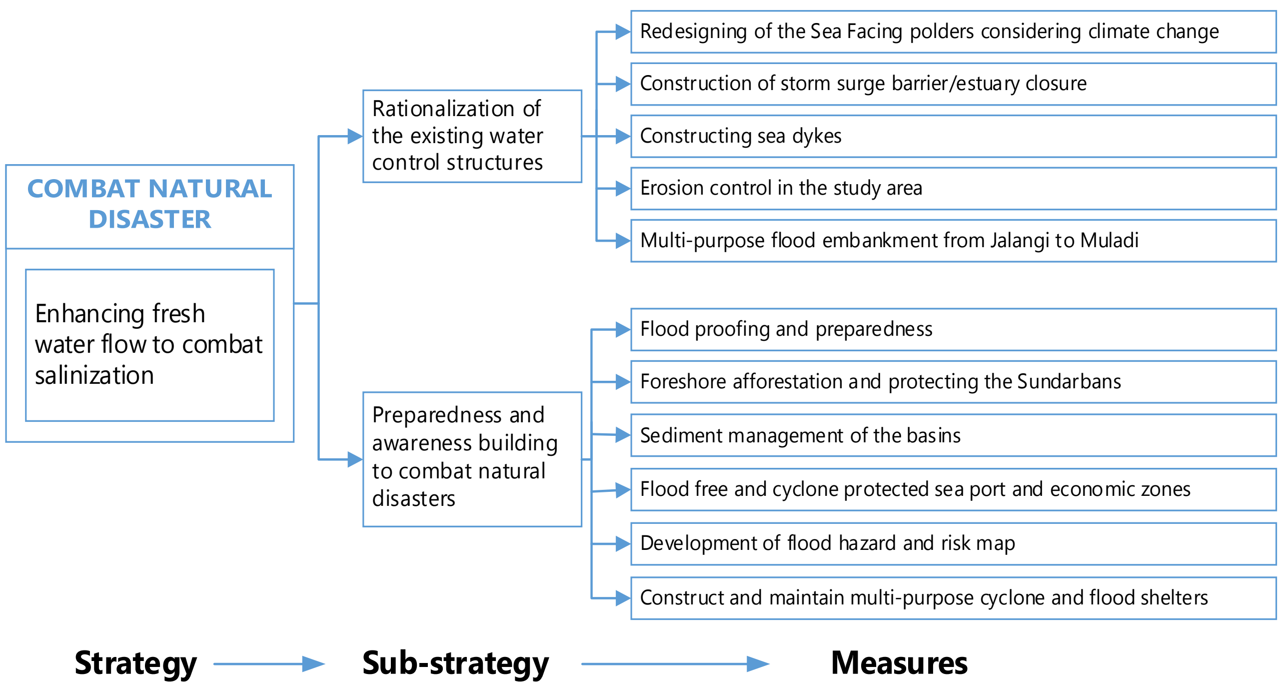

Figure 10. Schematization of the 3rd strategy, sub-strategies and measures.

adaptation pathways shown in Figure 11 shows four different pathways for different scenarios. The red colored pathway (action A) is applicable for next 100 years irrespective of any scenario. Similarly, blue colored pathway (action D) is also implementable for achieving desired goals. On the other hand, if action B (orange colored pathway) is taken, it might reach to its tipping point within the next 5 to 8 years and need to follow another pathway coinciding with action A, C or D. In the same way, if action C is taken into account for implementation of the interventions after a certain period it may reach to its tipping point and need to be revised as it required to be conglomerated with the actions A, B or D.

Logically, in the study area, degree of uncertainty is very high and the time-frame of analysis is vast (up to 2100) and climate change is one of most important uncertainties [41], besides socio-economic changes and upstream developments are playing a significant role. Besides, adaptation pathway development is a continuous decision-making process that requires input and involvement of all stakeholders to reduce the risk of over and under investment. It works best if it is organized in an inclusive manner.

In this study, the issues of waterlogging, salinization and disaster risk management are well-suited to demonstrate the use of adaptation pathways; therefore, three adaptation pathways have been formulated. It should be noted here that, the effectiveness of measures of solving the problem is based on expert judgment and decisions of experts and authors; although, ideally prioritization should be based on model calculations.

5.1. Waterlogging—Diminish Drainage Congestion

The study area experiences persistent waterlogging issues stated earlier, rainwater and catchment flow cannot adequately be drained [42]. To get a sustainable

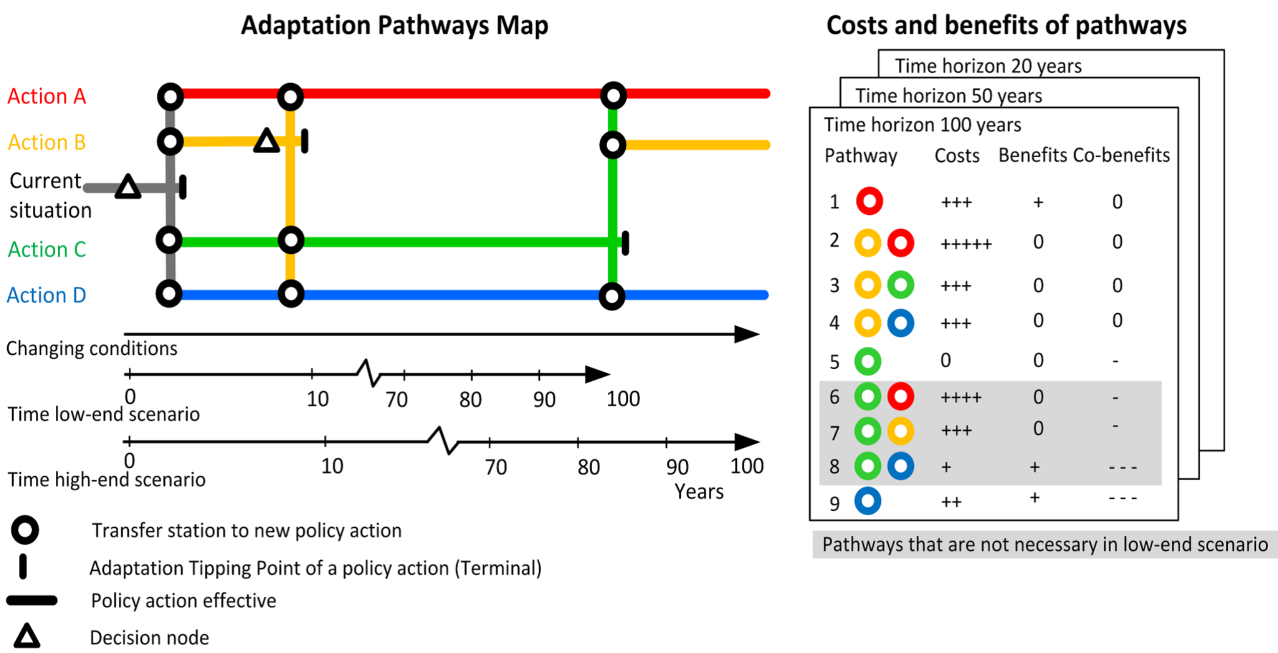

Figure 11. Schematization of a typical adaptation pathway. Source: [43].

solution of the issue, a set of measures have been proposed in the previous section of the article, subsequently an adaptation pathway is generated, illustrated in Figure 12:

The figure represents a number of pathways to achieve desired goals. The following measures could be adopted to diminish water logging in the study area.

1) Ganges barrage and its ancillary works; to effectively improve drainage capacity of peripheral rivers in the dry season. It is estimated that this intervention may be effective for 30 - 40 years under the most favorable future scenario and this measure may reach to its tipping point in the year of 2060, in that time, another measures might be needed to revitalize its service. Construction of Ganges barrage may have enormous socio-economic impact on the study area, it may have impact on agriculture, livelihood and economic condition in the favorable scenario. It is estimated that the construction of Ganges barrage and its ancillary works may improve the drainage capacity in the study area.

2) Restoration of beels or provide channels and regional rivers; several regional rivers have died the last decades in this region. This measure comprises a huge intervention in the water system of the Ganges tidal floodplain, for more than 20 - 30 years in the most favorable future conditions and if executed in parallel with Ganges barrage it may improve the drainage capacity up to 85% in the area and would be effective up 60 years.

3) Strategic dredging of Gorai-Madhumati-Passur (iterative); the main freshwater source of the area, this will improve drainage conditions of the peripheral rivers for a short time (2 - 3 year), unless it is executed periodically. The tipping point of this measure might be reached in 2030. Maintenance dredging is a no-regret measure and supports every other proposed measure. It is however not sustainable for the long-term and not effective to solve the (expected) waterlogging in different futures on its own.

4) TRM for 10 years; this involves cutting embankments (or de-polderization) at strategic locations in order to bring polders for a certain period (±10 years)

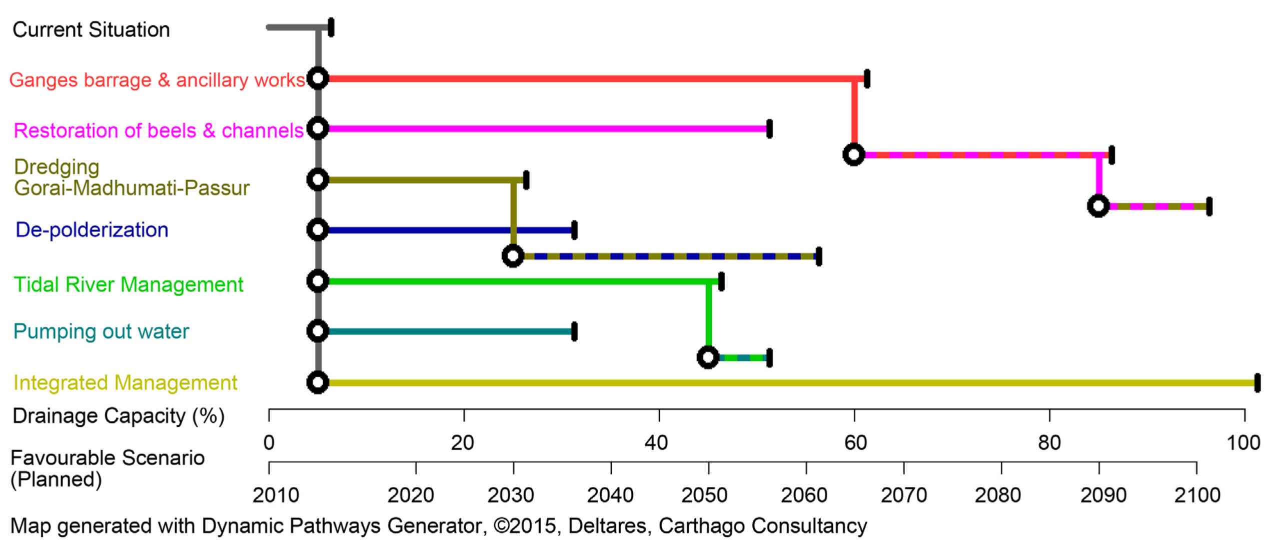

Figure 12. Adaptation pathway on waterlogging.

under normal tidal influence. Sediment will be supplied to the lowest locations, and tides will scour the peripheral rivers, improving the drainage capacity of the water system. This measure can have large socio-economic consequences for the current population, and they have to be compensated [44]. It is estimated that TRM at strategic locations in the coastal zone may improve drainage capacity for 20 years in the most favorable future and 15 years in the least favorable; thus the tipping point might being reached on 2050. TRM can be applied in a cyclic way.

5) Pump and drainage improvement; waterlogging within drainage controlled areas (e.g. polders) can be diminished by small and large mechanical pumping. This measure is including improvement and reparation of the current drainage infrastructure (e.g. khals, sluices). These measures will improve the situation for several years (10 - 20 years in favorable conditions, depending on pumping capacity, 7 - 15 years in the least favorable future conditions).

When considered, however, as part of an integral strategy for the coastal zone, it may be of interest considering national stakes. This measure is also considered effective for the longer-term.

5.2. Salinization

The issue of increasing dry season salinization of the surface water in the Ganges tidal floodplain west is an important component of the freshwater problems in the coastal zone [45]. Improving the fresh surface water situation in the coastal zone will improve the situation for many sectors in need for freshwater. This water is fundamental for boro rice irrigation (dry season), industrial demands, domestic use (drinking water supply) and last but not least for maintaining biodiversity in the Sundarbans. Some of the measures proposed here are similar to the measures to diminish drainage congestion. One of the main questions here is to what extent Bangladesh (is in need of or) wants to sustain rice agriculture as main land use and income activity for the rural population in this coastal zone. Several measures are focused on restoring freshwater conditions fully (if possible), others are focused on adapting to (new) geophysical conditions. The pathways containing those measures are shown in **Figure 13**.

The following measures are to be taken to reduce salinization in the surface water in the western floodplain of the Ganges.

1) Ganges barrage; to effectively improve drainage capacity and freshwater flow of peripheral rivers in the dry season. It is estimated that this intervention will still be effective to reduce salinity in the study area under the most favorable future scenario. In 2055, this measure might reach to its tipping point and may require re-design or another measure to reach the desired goal.

2) Revitalize regional rivers or provide channels; several regional rivers have died the last decades in this region. A study should be commenced to investigate potential revitalization projects of the regional rivers or providing supply channels (water and/or sediment) from the Ganges tidal floodplain east. This measure comprises a huge intervention in the water system of the Ganges tidal floodplain, but may be effective to reduce salinity level.

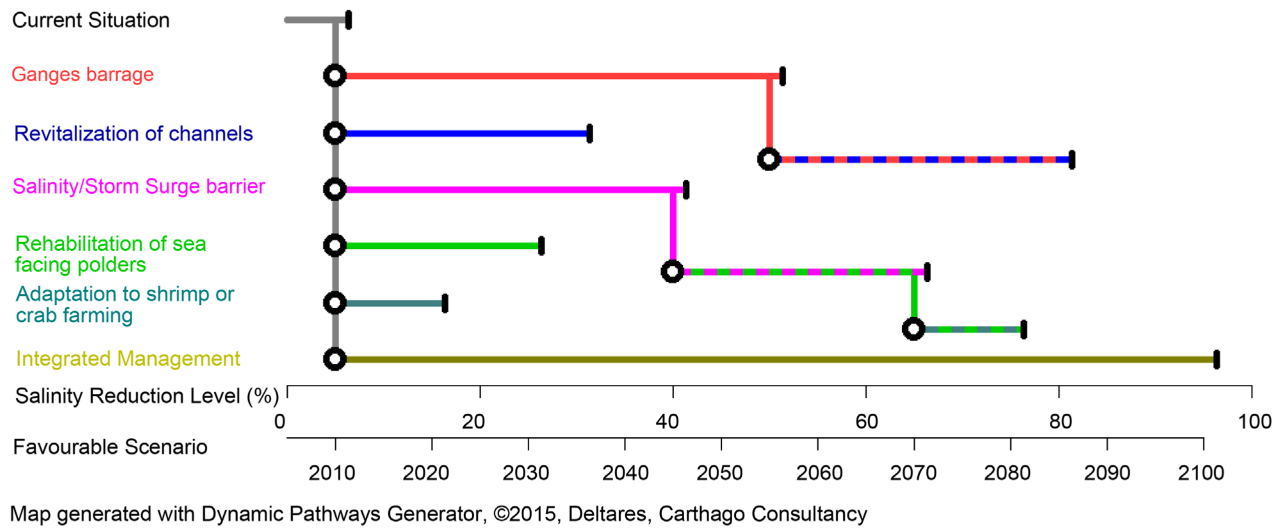

Figure 13. Adaptation pathway for augmenting fresh water flow to diminish surface water salinization.

3) Salt-water sea barriers to regulate dry season flow; large salinization barriers may be constructed in the large river mouths to the sea. This may be not feasible for the river mouths flowing into the Sundarbans, because of environmental concerns. This measure may be of greater use in the Baleswar and Tetulia river mouths or offtakes, when climate change, sea level rise and uncertain dry season flows may increase salt pressure.

4) Rehabilitating sea facing polders and water infrastructures; current polder infrastructure need rationalization considering the impact of climate change. This may effective to surface reduce water salinity levels.

5) Adaptation to shrimp or crab farming; diversifying cropping patterns, including a cycle of aquaculture or complete transition to aquaculture is considered the autonomous adaptation action of the current population. Water salinity levels can be handled with this type of land use.

5.3. Disaster Risk Management

Among all the disasters in this region, 75% originate from weather-climate extremes [46]. Disaster risk management strategies both are aimed at enhancing sustainability, resilient societies and human security. Disaster risk reduction offers opportunities for "bottom-up" strategies for adaptation to current climate variability and climate extremes. In this respect, disaster risk reduction can promote early adaptation to climate risks and impacts. There are a number of pathways to address disaster risk are depicted in **Figure 14**:

1) Constructing sea dykes; more strengthened and heightened sea dyke could be constructed in the area to address the devastating impacts of cyclonic and tidal floods, storm surges, wave thrust, etc. Moreover, rationalization of the coastal polders and existing dykes could be constructed in the region. This measure may manage disaster risk in the area, as such, it is estimated that, the adaptive tipping point can be reached after 2050. After that period, it requires another measures like storm surge barrier or estuary closure to achieve more management of disaster

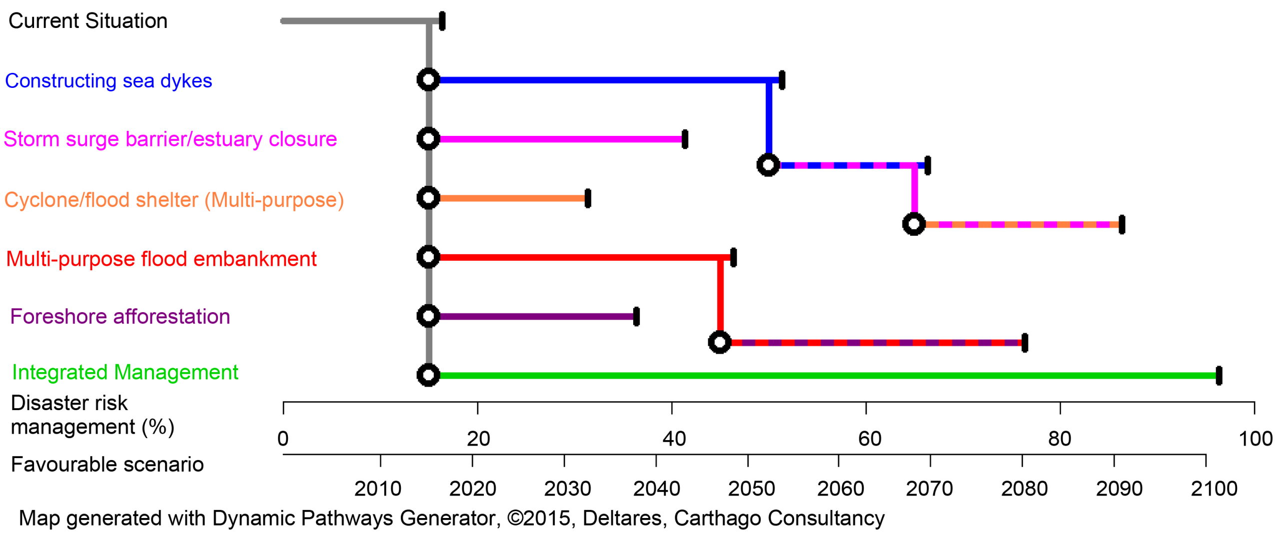

Figure 14. Adaptation pathways for disaster risk reduction in the study area.

risks.

2) Strom surge barrier or estuary closure; as the country setup a national target to achieve developed country status by 2041, for which lots of economic activities will further go on in the coastal region. But due to the climate change extreme flood event may come. So the economic strongholds, major urban cities need higher level of protection. For this reason, construction of storm surge barriers, estuary closures, water control infrastructures as well as strengthening and/or maintenance of the existing structures is needed at economic priority zones, major urban cities etc. This integrated development may ensure disaster risk management and may reach to its tipping point after 2060.

3) Multi-purpose flood embankment; constructing new embankments and/or strengthening existing embankment for multi-purpose use (e.g., as roads, shelters etc.) may serve to reduce disaster risk in the study area and may stretch to its tipping point after 2040, afterwards, it may require another measures like afforestation or green belt development.

4) Foreshore afforestation or green belt development; foreshore plantation component, if expanded, could have contributed towards creating an effective buffer against the impact of cyclones and storms. The afforestation or green belt can be developed along the banks of the embankments and it might serve to reduce disaster risk and the tipping point would be achieved after 2080.

6. Assessment Framework

Developing and designing adaptation strategies for the study area requires making choices and co-relations among various interests in a complex environment. This process involves a lot of complexity that is related to uncertainties, many stakeholders involved, sometimes conflicting interests and the complexity of the natural system that in characterized by many interconnections.

This process of developing and later assessing is supported by an assessment framework. The assessment framework consists of a comprehensive set of indicators [47]. A rapid assessment tool is used to support an interactive process in which the assessment is performed jointly. The rapid assessment uses the methodology of Multi-criteria Decision Analysis [48].

The aim of the assessment framework is to assess the performance of strategies in order to provide the basis for re-designing and improving the strategies. The focus is on supporting the design process by cooperating explicit and stimulates discussions on the relative importance of indicators. Rather than choosing among single adaptation options, the aim is to develop a coherent set of different alternatives in order to be able to make an integrated assessment of climate change related adaptation strategies. This way the development of potential strategies can be supported.

For better understanding, the measures have been divided into two categories; optimized water and water steers, delineated in Table 3. When the measures are to be taken in order to regulate the natural flow of water and optimized the benefit of water to future development, then it is reserved for the optimized water block. On the other hand, when the water plays the leading role and all development measures are taken in compliance with the flow of water, then those measures are grouped as water steers.

While formulating and afterwards assessing measures with respect to the

Table 3. Measures assembled in optimized water and water steers groups.

Optimized Water	Water Steers
Strategic dredging of Gorai-Modhumati-Passur	Restoration of peripheral rivers
Constructing Ganges barrage and ancillary works	Pumping out water from water logged areas
Retention of water control structures	Integrated Management of Drainage Congestion
Optimized use of polders	Tidal River Management (TRM) for 10 years
Connectivity among wetlands and floodplains	De-polderization in selected areas
Building salinity barrier/storm surge barrier	Restoration of Beels
Deep well development	Groundwater artificial recharge
Water treatment facilities	Arsenic filtering
Increase surface water storage	Salt resistant crop farming
Coastal green belts	Adaptation to shrimp to crab
Rehabilitate polders and water infrastructures	Non-farm income activities
Constructing sea dykes	Regional connectivity
Erosion control in the study area	Foreshore afforestation and protect Sundarbans
flood embankment on right bank of Ganges	Sediment management of the basins
Multi-purpose embankment from Jalangi to Muladi	Flood proofing and preparedness
Construct sea port and economic zones	Develop flood hazard and risk map

identified issues and problems, three criteria were taken into account: Impact (expected amount of people affected by the project), Efficiency (social benefits are higher than the social costs) and Risk (technical complexity of the project). These three criteria had been scored 1 - 9 against some indicators and a comprehensive calculation had been conducted to prioritize the measures. The selected or prioritized measures then assessed and shown in the radar charts as shown in Figure 15.

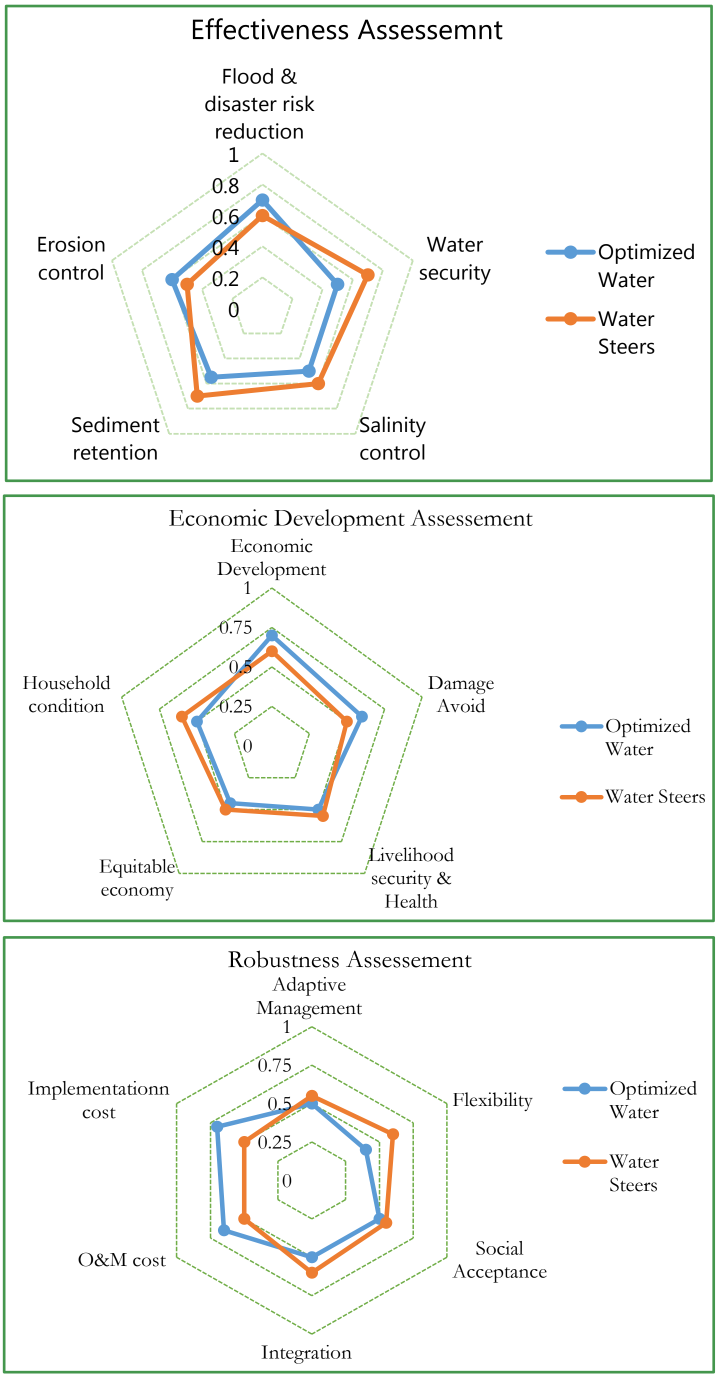

Figure 15. Assessment framework for testing measures with respect to indicators.

Concerning the overall score, the strategies perform very similarly. The Optimized Water strategies and corresponding measures outperforms on the Effectiveness Assessment and Economic Development Assessment framework. On contrary, the Water Steers strategies and corresponding would be much less costly to implement and outperforms on many implementation indicators on Robustness Assessment framework.

7. Conclusions

The suggested strategies and possible measures for the study area intent to improve living condition, sustainable agricultural and aqua-cultural production, as well as maintain environmental sustainability. The above adaptation pathways represent a sequence of measures to achieve a set of predefined goals under changing external conditions, such as climate, socio-economic factors or other developments. For the short term, the strategy includes revitalizing surface water supply sources from the Ganges as much as possible. For the coast, the construction of the Ganges barrage to restore the freshwater flow through the Gorai and other rivers would be profitable, certainly with respect to drinking water and salinization in the Sundarbans. Current FCD/I infrastructure needs to be rationalized and modernized, as insufficient maintenance and changing exogenous conditions (*i.e.*, upstream development, climate change, etc.) have led to a substantial degree of malfunctioning. A main aspect to be solved is management, which needs innovative forms of institutions.

The unique largest Mangrove forest, the Sundarbans, desires to be protected by national laws and programs and should be managed to maintain its unique characteristics. Some polders on the northern border of the Sundarbans should be investigated to restore the area to historical proportions, which will improve environmental sustainability, as well as the natural wave attenuation capacities of Mangroves in times of storm surges.

Last, but not least, the tidal rivers are part of an extensive network for transport of goods and people over water. Several measures need to be taken to improve navigation potentials by excavation/dredging and adapted cargo facilities. This will decrease pressure on the yet exhaustive use of the water system as a whole.

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Conflicts of Interest

The authors declare no conflict of interest.

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