Ministry of Water Resources

Bangladesh Water Development Board

Coastal Embankment Improvement Project, Phase-I (CEIP-I)

Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone (Sustainable Polders Adapted to Coastal Dynamics)

Component 5a: Reconstruction of the Polder at different coastal zones including their phasing and construction program

5A-3: Conceptual Design of 5 Polders

July 2022

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Long Term Monitoring, Research and Analysis of Bangladesh Coastal Zone
Office: Flat #3/B, House #4, Road #23/A, Banani, Dhaka 1213, BANGLADESH Phone +880 1307 693299

Memo No: CEIP/LTMRA/0722/190 24 July 2022

Project Management Unit
Coastal Embankment Improvement Project, Phase-I (CEIP-I)
Pani Bhaban, Level-10
72, Green Road, Dhaka-1205

Attn: Mr. Syed Hasan Imam, Project Director

Dear Mr Imam,

Subject: Submission of updated report "D-5A:3 Conceptual Designs of 5 Polders"

It is our pleasure to submit herewith five copies of the updated Report ***"D-5A:3 Conceptual Designs 5 Polders"***. The earlier version of the report was submitted on 22 May 2022. The comments received from the World bank are addressed in this updated version of the report.

It may be mentioned that the soft copy of the report together with the updated LTM Tracker containing comment-response table were emailed to you on 20 July 2022.

Thanking you,

Yours sincerely,

Dr Ranjit Galappatti
Team Leader

Copies: Engineer Fazlur Rashid, Director General, BWDB
Dr. Zia Uddin Baig, ADG (Planning), BWDB
Dr Kim Wium Olesen, Project Manager, DHI
Ms. Sonja Pans, Deltares Project Manager
Mr Zahirul Haque Khan, Deputy Team Leader
Mr AKM Bodruddoza, Procurement Specialist
Swarna Kazi, Sr. Disaster Risk Management Specialist, World Bank

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ACRONYMS AND ABBREVIATIONS

BDP2100- Bangladesh Delta Plan 2100

BDT- Bangladesh Taka

BWDB- Bangladesh Water Development Board

CBA- Coast Benefit Analysis

CC- Concrete Cement

CEGIS- Centre for Environmental and Geographic Information Services

CEIP- Coastal Embankment Improvement Project

CEP- Coastal Embankment Project

DEM- Digital Elevation Model

EIA- Environmental Impact Assessment

FIAT – Flood Impact Assessment Tool

GBM- Ganges Brahmaputra Meghna

GIS- Geographical Information System

IGDCZ- Interactive Geo Database of the Coastal Zone

IPCC- Intergovernmental Panel for Climate Change

IPSWAM- Integrated Planning for Sustainable Water Management

IWM- Institute of Water Modelling

LGED- Local Government Engineering Department

MoWR- Ministry of Water Resources

MSL- Mean Sea Level

ppt- parts per thousand

PV- Present Value

PWD- Public Works Datum

RCP- Representative Concentration Pathways

SFINCS- Super Fast Inundation of Coasts

SLR- Sea Level Rise

SWRM- South West Region Model

TRM- Tidal River Management

ToR- Terms of Reference

US$- United States Dollar

VoSL- Value of a Statistical Life

WL - Water Level

WMA- Water Management Association

WMG- Water Management Group

1 Introduction

1.1 Scope of work

Based on the data and model results from the different Components, the Project will prepare an investment plan to improve the resilience of the communities living in Bangladesh’s 139 polders to hydro-meteorological events. In order to do so, measures and strategies need to be defined and evaluated. This cannot be done in one step for all polders. Therefore, 5 pilot polders were selected that will be used as intermediate step under Component 5A. This will serve as a pilot program for a conceptual design for future polder development. These 5 polders are considered more or less representative for the polders in the different sub-regions of coastal Bangladesh. Due consideration is given to: climate change, subsidence, possible land heights, land use, economic activities, infrastructure needed for water management and water management policy, drinking water facilities (especially in salt water conditions) for long term sustainability.

The report has a special chapter on management plans, specifically focused on the different operational management for the polders. Note that institutional water management issues, such as participatory water management, are not highlighted in this report. The reason is that these issues apply to all polders in a similar way and are therefore elaborated in a special report (Component 6.2+6.3 Polder Management Plan).

1.2 Selection of 5 polders

The selection of 5 polders was made out of the 139 coastal polders and used the following criteria (see CEIP-I, 2021):

- Selected polders are to be representative for each zone of hydro-morphological characteristics
- Availability of data/ information for polders
- Degree of vulnerability against bank erosion, storm surge, drainage congestion, flood, salinity, subsidence etc.
- Opinion of the stakeholders including local BWDB officials, local inhabitants and economic activities
- Water management issues
- At least one CEIP-I polder and one BlueGold polder to be included in the shortlisting

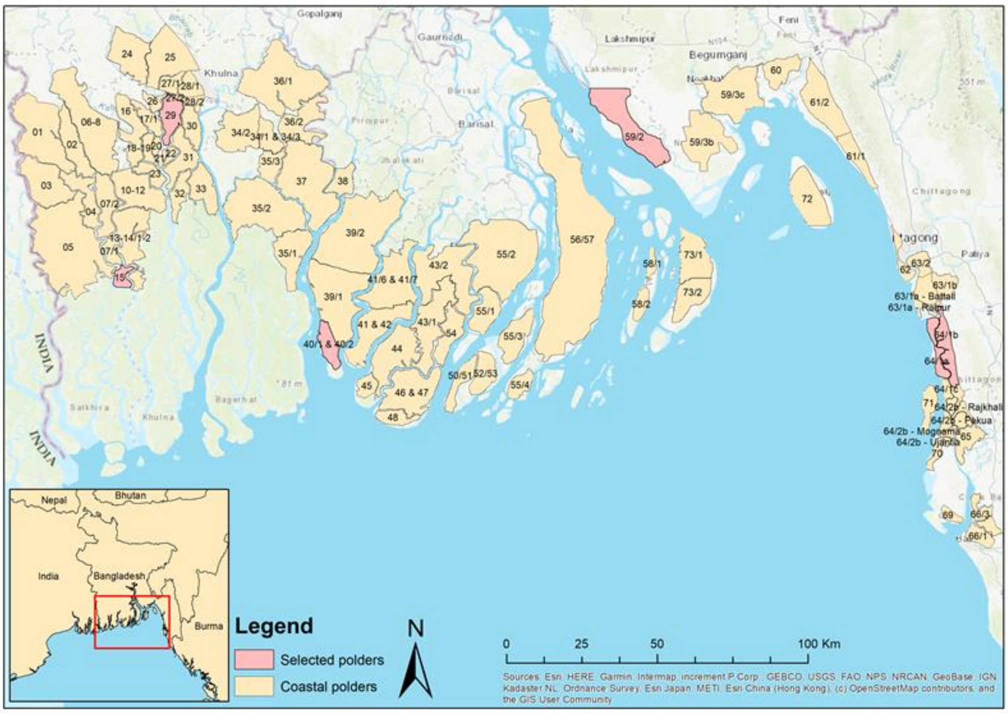


Figure 1-1 Map with locations of the 5 study polders

Table 1-1 basic data of 5 selected polders

Polder Name	Gross Protected Area (Ha)	Cultivable Land				Main Project Feature				Polder population*	Remarks
		Total (Ha)	Crop (Ha)	Shrimp (Ha)	Salt (Ha)	Embkt. (km)	No. of Regulators	No. of Flushing Inlet	Drainage Channel (km)		
15	3,441	2,925	900	2,025	0	27	5	0	0	31,788	CEIP-1 Project
29	8,218	6,570	6,570	0	0	49	11	81	39	53,268	Blue Gold project
40/1	2,105	1,684	1,684	0	0	23	28	24	14	12,200	
59/2	21,255	20,000	20,000	0	0	82	40	0	91	372,047	
64/1a&b	13,750	11,800	11,190	380	280	111	57	0	102	268,910	

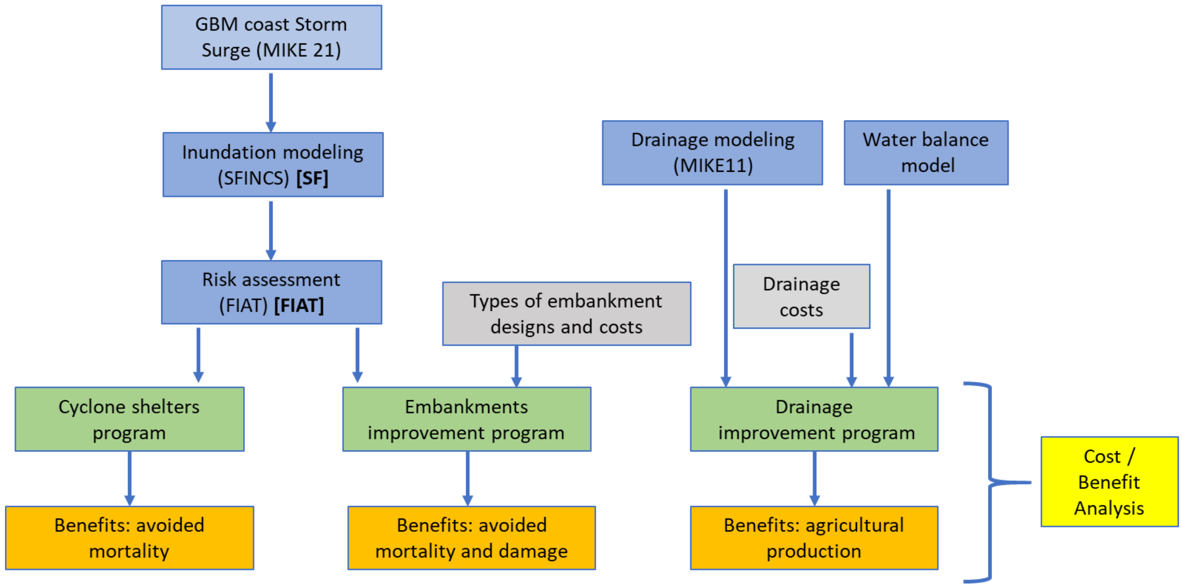
*Note: Population of each polder in 2011 was estimated from the population density in each union. Total population of each union in 2001 was projected to the year 2011 with growth rate of 2001 population census.

Table 1-2 Key characteristics of the 5 selected polders

Polder Name and district	Coastal Region	Peripheral River	Key Characteristics
Polder 15 (Satkhira)	South-West Coastal region	Kobadak River and Kholpetua River	➢ Very little freshwater flow from upstream river (Ganges) ➢ Influenced by strong tidal action, salinity problem is acute. ➢ Peripheral river sedimentation is a major problem; which creates drainage problem. People inside coastal polder experiencing prolonged water logging. ➢ River bank erosion problem. ➢ Vulnerable to cyclonic storm surges.
Polder 29 (Khulna)	South-West Coastal region	Lower Bhadra River and Teka Hari Teli Gang	
Polder 40/1 (Barguna)	South-Central Coastal region	Baleswar River and Bishkhali River	➢ Polder embankment is facing river erosion problem. ➢ Vulnerable to cyclonic storm surges. ➢ Large mangove forest present
Polder 59/2 (Noakhali)	South-East Coastal region	Shahbazpur Channel (East)	➢ Morphologically active place: land accretion and erosion ➢ Severe river erosion due to thalweg migration. ➢ Vulnerable to cyclonic storm surge. ➢ Some area subjected to prolonged waterlogging due to encroachment and land reclamation by closing of tidal creeks.
Polder 64/1a+b (Chittagong)	Eastern Hilly region	Sangu River, Jalkadar Khal and Open Sea	➢ Vulnerable to cyclonic storm surge. ➢ Prone to flash flood due to steep gradient of river and intense rainfall. ➢ Erosion around Sangu River

1.3 Approach

This report will present the development opportunities and risk profile of the 5 selected polders that will serve to illustrate the approach the project will take to formulate the investment plan for the total of the polders of Bangladesh. The approach is to develop an investment strategy with a reasonable degree of detail for the 5 polders, for which field investigations have been conducted under the project. The lessons learned in the formulation of the investment plan for the 5 polders in the current report will form the basis to develop a more general approach that will be used in the formulation of the investment plan for the polders for which only basic data are available.



For the 5 polders field survey information is used in a storm surge model to determine the risk profile. Then, the SFINCS model is used to calculate inundation maps under different return periods. Storm surge characteristics are taken from the storm surge modelling as previously reported by IWM (IWM, 2018). Based on the inundation maps the FIAT model is used to calculate damages to infrastructure, including loss of production (businesses, agriculture), people affected and mortality. This is also done for different return periods. Based on the FIAT model a risk profile is made for each of the polders. Details of the SFINCS and FIAT calculations can be found in Annex C to this Report. Based on the risk profile, the proposed interventions and associated costs, a cost benefit analysis (CBA) is made.

Interventions are not only proposed for reducing storm surge damage, but also for improved drainage, improvements for agriculture and investments to reduce mortality (cyclone shelters). Benefits are calculated based on difference in risk profile between the reference situation and the situation with proposed investments. Additional benefits are calculated based on improvement in agricultural output and reductions in mortality due to the construction of cyclone shelters, that constitute in reduction of mortality from flooding (cyclone shelters are elevated buildings) and reductions in mortality from excessive winds during cyclones. Details on investments; what, how, when, costs, etc. are provided in paragraph 2.1 and chapters 3, 4, 5, 6 and 7.

Based on the risk profile for the different aspects in the risk profile investments are proposed at polder level that will meet the economic requirements as calculated in the Cost Benefit Analysis (CBA). The evaluation in the CBA is made on the Benefit/Cost-ratio (B/C-ratio). Costs and benefits are discounted with a 12% interest rate. Future population growth and economic development are assumed to develop according the Shared Socioeconomic Pathways scenario 2 (SSP2 - middle of the road) (Riahi et al., 2017). Details on benefit calculations are provided in paragraph 2.2.

1.4 Setup of the report

In the next chapter the methodology and the way costs and benefits are calculated are explained. In the chapters 3 to 7 each polder will be described in terms of its present problems, future changes in boundary conditions and design options and measures. Each Chapter ends with an estimation of the costs and benefits of the measures.

Chapter 8 elaborates on the operational plans in general and specific operation issues for each polder separately.

Chapter 9 provides a conclusion in terms of key development directions for the 5 polders. It concludes with general remarks on the economic evaluation of the development opportunities for these polders.

Annex A provides the method and results of the Drainage analysis, whereas Annex B provides details on the typical designs for the different types of embankments used in the investment plans. Annex C provides the methods and results of the cyclone risk assessment.

2 Costs and Benefits

This chapter outlines the conceptual designs that are proposed for the different investments that serve to determine the investment costs for the interventions for the 5 polders. The designs are based on the risk profile of the polder and the information that is obtained from the different models. The conceptual designs are developed using the design characteristics that follow from the boundary conditions. However, these designs are a first draft, that need to be further detailed in a full feasibility study and a consequent detailed design. The design presented in this report are just a first indication of what types of interventions are needed for the different polders based on the current boundary conditions. Consequently, also costs for the implementation of the design are just a first estimate.

In this chapter the manner is also presented in which the benefits from the different interventions is determined. Similar to the costs, also the benefits are a first assessment, based on modelled effects of the interventions.

2.1 Costs of interventions

2.1.1 Embankments

For the design of the embankments use is made of 5 conceptual designs that are made for the different environments that exist for the polders in Bangladesh. The different designs vary according to storm surge level, typical wave height and the situation on the water side of the embankment, notably the presence of a land in front of the embankment and the presence of protective vegetation to reduce wave energy. Figure 2-1 provides the 6 types of designs proposed in this report. Annex B provides more details on the designs.

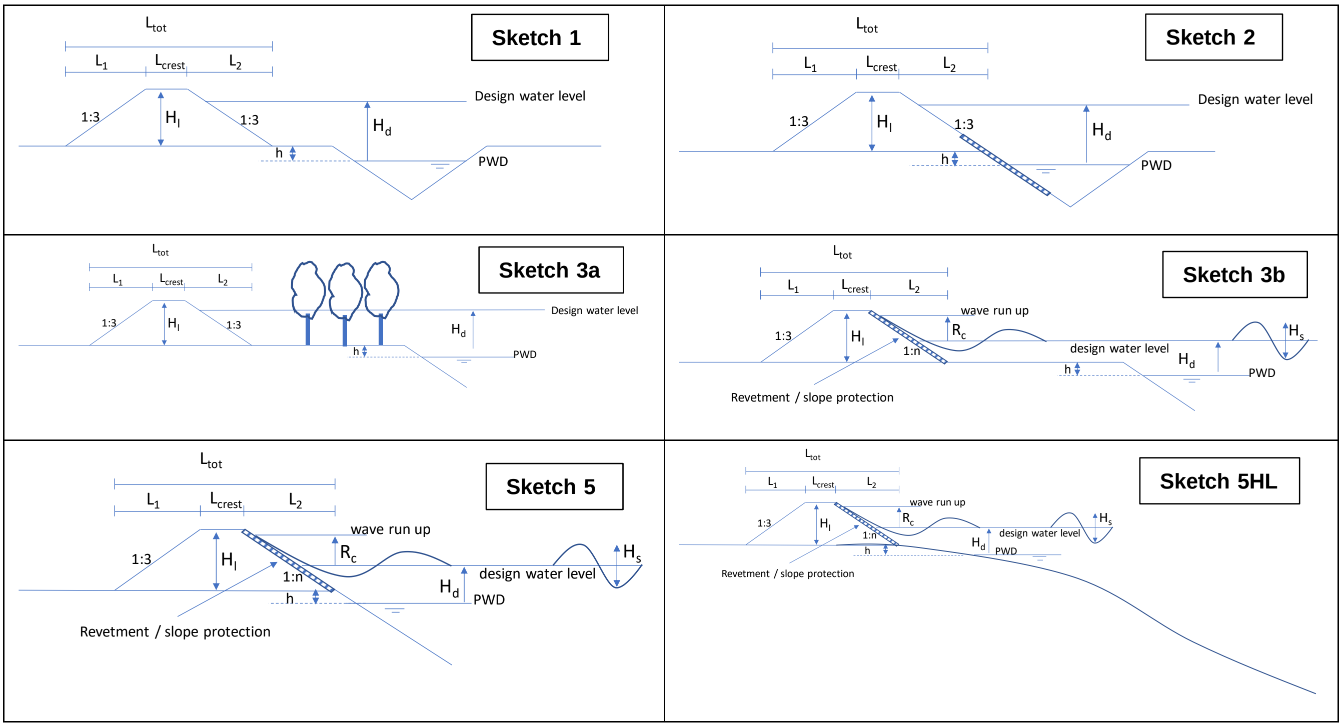


Figure 2-1 Conceptual designs for embankments for polders in Bangladesh

The actual dimensions of the embankments are a function of polder elevation and storm surge level as provided in the IWM storm surge model (IWM, 2018). Based on these dimensions the costs for the different types of embankments per each individual polder are determined. The Table 2-1 provides some costs for embankments for each design type under varying conditions for average polder height, storm surge level and wave action. Costs are based on the designs as presented in Annex B and unit costs as used in the Coastal Resilience study (Deltares, 2020) that are updated to current prices. It is assumed that embankments are constructed at the same locations as current embankments, i.e. new embankments are constructed “on top of” the old embankment. Note that although costs for land acquisitions is part of the cost estimate for the embankments, these costs are found to be very high. At this point the costs for future land acquisition is therefore a point of concern for the overall cost estimate for embankments.

Table 2-1 Cost of typical embankment designs for polders in Bangladesh

Description Embankment	Cost (USD/km)
Sketch 1, Narrow channel with foreland	
Type1_1	337.500
Type1_2	427.500
Sketch 2, Narrow channel without foreland	
Type2_1	1.507.500
Type2_2	1.597.500
Sketch 3a, river bank with foreland, no wave action	
Type3A_1	78.750
Type3A_2	153.750
Sketch 3b, river bank with foreland and wave action	
Type3B_1	315.000
Type3B_2	727.500
Type3B_3	395.000
Type3B_4	821.550
Sketch 4, River bank, no foreland with wave action	
Type4_1	907.500
Type4_2	1.072.500
Type4_3	991.800
Type4_4	1.227.800
Sketch 5, Sea defence, no berm	
Type5A_1	3.387.500
Type5A_2	3.857.500
Type5A_3	3.593.750
Type5A_4	4.233.750
Sketch 5, Sea defence, no berm, high loading	
Type5B_3	6.590.000
Type5B_4	7.400.000
River Bank Protection Work	8.250.000

2.1.2 Drainage system rehabilitation

The rehabilitation of the drainage system is done through two interventions: excavation of the khals in the polder to improve drainage flows to the drainage structures (sluices) and the reconstruction or rehabilitation of the drainage structures. For reconstruction the design as used in the CEIP I project is used. The costs are taken from the feasibility study for CEIP II. The costs for reconstruction are USD 350,000 for the rehabilitation of a structure (mostly replacement of the gate) and for minor repairs on the concrete an average cost of USD 25,000 is used. For the replacement of the gates it is recommended to use composite gates, which recently have been tested in Bangladesh. The advantage of the composite gates is the reduced need for maintenance and the increased lifespan, especially in conditions with saline water. The excavation of the khals is assumed to be a volume of 3 m^3/m – 5 m^3/m, which at current prices is estimated to be USD 75,000/km, see also Table 2-2.

Table 2-2 Cost for excavation of Khal/km and rehabilitation/reconstruction of drainage structures

Description	Unit Cost (USD)
Khal excavation (km)	75,000
Regulator Rehabilitation (#)	25,000
Regulator Reconstruction (#)	350,000

2.1.3 Cyclone shelters

Based on the cost estimate that was made within the “Coastal resilience project” (Deltares et al., 2020) the average cost of a multipurpose cyclone shelter with a capacity of 1,250 persons is US$ 600,000 (the report cites several sources from Bangladesh like documents from MDSP[1] and ECRRP[2]). Added to the cost of the cyclone shelter there is a need for an average of 1km of access road, in order to secure easy access during heavy storms, which would cost around US$150,000. This brings the total costs for a cyclone shelter at US$ 750,000.

2.2 Benefits from interventions

2.2.1 Basic principles in the Cost Benefit Analysis

The investments that are proposed for the 5 polders are subject to a cost benefit analysis (CBA). In this paragraph the basic principles that are used in this CBA are explained. The general approach within the CBA is that investments are compared with the discounted benefits over the anticipated lifespan of the investments, which for all investments is put at 30 years. The investments and discounted benefits are compared in a Benefit / Cost ratio (B/C-ratio). Because of the uncertainties in the assessment of the investment costs and the determination of the benefits (at this point not all benefits are known, nor can these be accurately calculated), investments are judged economically feasible when the B/C-ratio is between 0.8 – 1.2. Below a B/C-ratio of 0.8 investments are not considered to be economically feasible and investments should be reconsidered. Redesign of investments could be done by only investing in economically feasible components, e.g. constructing embankments at a lower safety level, only construction of cyclone shelters, or only rehabilitation of the drainage system. Investments that have a B/C-ratio of more than 1.2 are considered to be very economically feasible, e.g. because current risk profile is very high. Investment in these polders should receive priority in programming of investments, as the significant benefits can be obtained from interventions in these polders. . As budget in Bangladesh is a constraint, a discount rate of 12 % is used. This discount rate, in combination with the used SSP2 scenario for economic and population growth results in a net discount rate of around 6 %. This rate is adequate to substantiate economic viability of investments when B/C-ratio is above the threshold. Based on these points of departure an economic evaluation has been conducted for the investments as proposed for the 5 polders.

In the CBA the following points of departure have been used;

- Discount rate of 12%
- Economic evaluation of technical lifespan of investments of 30 years
- All investments are considered to be done in year 0
- Full benefits are assumed to occur from year 1
- Economic and demographic developments are considered to follow the SSP2 scenario (Riahi et al., 2017)
- Effects of climate change and subsidence are considered to occur linear over time between current and 2050
- Value of a statistical life (VoSL) is US$ 205,000 (Viscusi and Masterman, 2017)

2.2.2 Embankments

The benefits from embankments are formed by the increase in safety level in the polders from protection against storm surges and resulting floods. Risk profiles of the polders are made from flood maps based on the current

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[1] Based on WB Project brief (2019), mentioning 3268 existing shelters plus 552 newly constructed shelters of MDSP.

[2] World Bank, 2018, Implementation completion and results report, Emergency 2007 cyclone recovery and restoration project

situation for different events with different return periods. Risk profiles are made both for the current situation under current storm surge levels and for storm surge levels in 2050. Storm surge levels are taken from the study by IWM from 2018 (IWM, 2018). The risk profiles of all polders are considered to currently have a safety level of 1/10 years. New investments are considered to bring the safety level of the polders to 1/50, gradually declining to 1/25 in 2050 due to subsidence and climate change. The reduction in damages from the increased safety level are considered to be the benefits from the embankments. In the calculation of the risk profile the coverage with cyclone shelters in the polder plays a role in the definition of the "evacuation fraction", the percentage of the population in the polder that is considered to find refuge in a cyclone shelter from floods, as cyclone shelter are elevated buildings. The evacuation fraction is divided into 3 classes 25%, 50% and 75%, meaning that with increasing coverage the calculated mortality in a polder will be decreased with the evacuation fraction. Coverage in cyclone shelters and assumed evacuation factions are provided in Table 2-3. For instance, a polder that has a modelled mortality risk of 10 persons a year and a coverage of cyclone shelters with 60%, will be assigned an evacuation fraction of 50% which will lead to a risk of 5 persons a year. However, changes in evacuation fraction are attributed to the cyclone shelters, not to the embankments.

Table 2-3 Coverage in Cyclone Shelter to evacuation fraction

Coverage in CS	Evacuation fraction
0 – 25%	25%
25% - 75%	50%
> 75%	75%

2.2.3 Khals and drainage structures

The excavation of khals and the rehabilitation, or reconstruction, of drainage sluices have the objective to improve the drainage and water management in general of the polders. Improved drainage and water management will contribute to improved agricultural yields. Improved yields are translated into increased income for the agricultural sector. In order to determine the benefits of khal excavation and sluice rehabilitation a certain increase in income from the increase in yields is assigned to these works. Currently the average yield for a rice crop in the polders is below 2 T/ha paddy. Improved agricultural practices could increase the yield with an average of 1 T/ha. However, although improved drainage will contribute to the increase in yield, more aspects are required. Drainage is a very important factor in the effectiveness of fertilizer application. However, next to drainage also the correct timing and the quantity of fertiliser applied is very important in the overall effect on crop yields. In order not to over-estimate the effect of the drainage a 25 % increase in crop yield has been assumed. Therefore 25% is used as a fraction of the increase in yield that is attributed to the investments. The increase in valued through the price of paddy of BDT 24,000 per ton, over a period of 30 years, equaling US$ 855/ha. This is used as the overall benefit from the improvements in drainage systems per hectare for all of the polders.

2.2.4 Cyclone shelters

The benefits from cyclone shelters consist of three parts; firstly, they provide shelter from the wind and flying debris caused by cyclonic winds, and secondly, they provide a place of refuge in case of inundations due to their elevated positions and multi story construction. Additionally, cyclone shelters in Bangladesh have a double function as schools. Also, the schooling function is valued as a benefit. All services provided by the cyclone shelter are attributed to the number of new shelters. Furthermore, the value of the benefits from the function as a place of refuge in the case of flooding is dependent on the original coverage in the polder as explained in paragraph 2.2.2. When additional cyclone shelters are constructed in a polder that already has a coverage of more than 75% of the population no additional benefits are attributed from the service as a refuge in the case of flooding. Furthermore, it is assumed that in time the quality of housing in a polder will improve, resulting in a smaller fraction of the population being dependent on cyclone shelters. For this reason the required number of cyclone shelters is determined by 33% of the population needing access to a cyclone shelter, while in 2050 only 25% of the population is in need of shelter in a cyclone shelter. The value of the different services is determined through the reduction in mortality and the Value of Statistical Life (VoSL). Reduction in mortality in the flood risk calculations are based on the results from the FIAT model and the possible change in evacuation fractions as illustrated in Table 2-3. Reduction in mortality from the service of refuge from cyclonic winds is taken from the "Coastal Resilience study" (Deltares et al., 2020), that determine the overall reduction of mortality from cyclone shelters to be from 1% of the exposed population to 0.05% of the exposed population. In this study we assume the protection against cyclonic winds to be 1/3 of the improvement, i.e. 0.0167% of the additionally protected population.

The benefits from education services are taken from the PAD document of the World Bank (WB, 2014) in which a grade 5 education is valued at in increased annual income of US$ 172/year. Assuming 236 pupils per shelter and 5 year in education this would provide an annual benefit of US$ 8,152.

3 Polder 15

3.1 Present situation and problems

Polder 15 has a relatively high population density (10 persons/ha), is located remotely (51 km from Satkhira) and in a high salinity area. Land use in the polder consists mostly of shrimp culture (Ghers). It was observed during the field visit (on 8 June 2020) that the 5 existing sluices are not fully functional for proper drainage and have deteriorated due to long use and saline water. Local people are constructing cross dams to store the water which creates water logging problem in the polder (CEIP-I, 2021). Manually operated tube-wells have been installed through horizontal boring pipe on embankment by the Gher owners for lifting water from the river to fulfil their demand of water inside the polder (CEIP-I, 2012).

Bank erosion from the Kobadak river is a main problem for the embankments. Many segments of the embankment have been damaged by wave action and eroded due to river flow. The CEIP-I Feasibility Study Report (CEIP-I, 2012) advised to protect about 15 km of embankments by afforestation on the foreshore area and several sections to be strengthened by bank and slope protection works. Note that Polder 15 is one of the CEIP-1 polders for which currently a feasibility design is ongoing.

Polder 15 also has a high cyclone risk. During cyclone AILA the embankment was overtopped, causing the polder area to be submerged by 1 to 1.5 m of surge water. About 75 people died, damage occurred & breaches formed at several places on the embankment. The polder area has remained under saline water due to damaged embankment since AILA (CEIP-I, 2012). In 2020, Polder 15 was affected severely by cyclone AMPHAN. A breach on the embankment had occurred and caused severe flooding.

Land use is dominated by shrimp production, as in many polders in the southwest region. Around 15% of the land is settlement, 10% for crops (mostly Aman rice) and the rest (75%) is aquaculture. The main cultivated species in this region is marine tiger shrimp (*Penaeus monodon*), locally called *bagda*. Apart from *P. monodon* also the giant fresh water shrimp (*Macrobrachium rosenbergii*), locally called *golda*, is a prominent species , but it is practiced more in the south central region (Bagerhat, Patuakhali). Shrimp *(P. monodon*) farming in the south eastern area rotates with salt production and some rice farming though in the more saline areas only shrimp are farmed (Azad et al., 2008). The cultivation of the shrimp has not come without environmental and social problems. Traditional rice farmers complained that the aquaculture owners modified the water system to their benefit and caused salinity in the polders to rise which resulted in damages to crops due to increased salinity of the water.

Table 3-1 Basic data of Polder 15

gross area (ha)	average elevation (m)	perimeter (km)	pop (2011)	pop density (#/ha)	erosion (km)	distance to main town (km)	salinity current	salinity future	shelter capacity
3,441	1.0	27	34,766	10.1	22	51	25.2	26.6	2,975

Parameter	**description**
Embankment	Main rivers Kobadak and Kholpetua: storm surge plus waves, river erosion
Embankment efficiency	**moderate**: >1,287 people per km
Salinity	**very high**: > 25 ppt
Waterlogging	Although whole polder has waterlogging (see Figure 3-5)), this may cause no problem because most of the polder is under shrimp culture.
Subsidence	land subsidence for West Ganges Region is relatively **low** (~2.5mm/y)
Distance to district capital	51 km to Satkhira **Remote polder**
Outside water level	Tides, surges, monsoon water levels: Determines embankment heights and drainage potential
Cropping intensity	
Cyclone risk	**high** economic risk; **Low** mortality risk

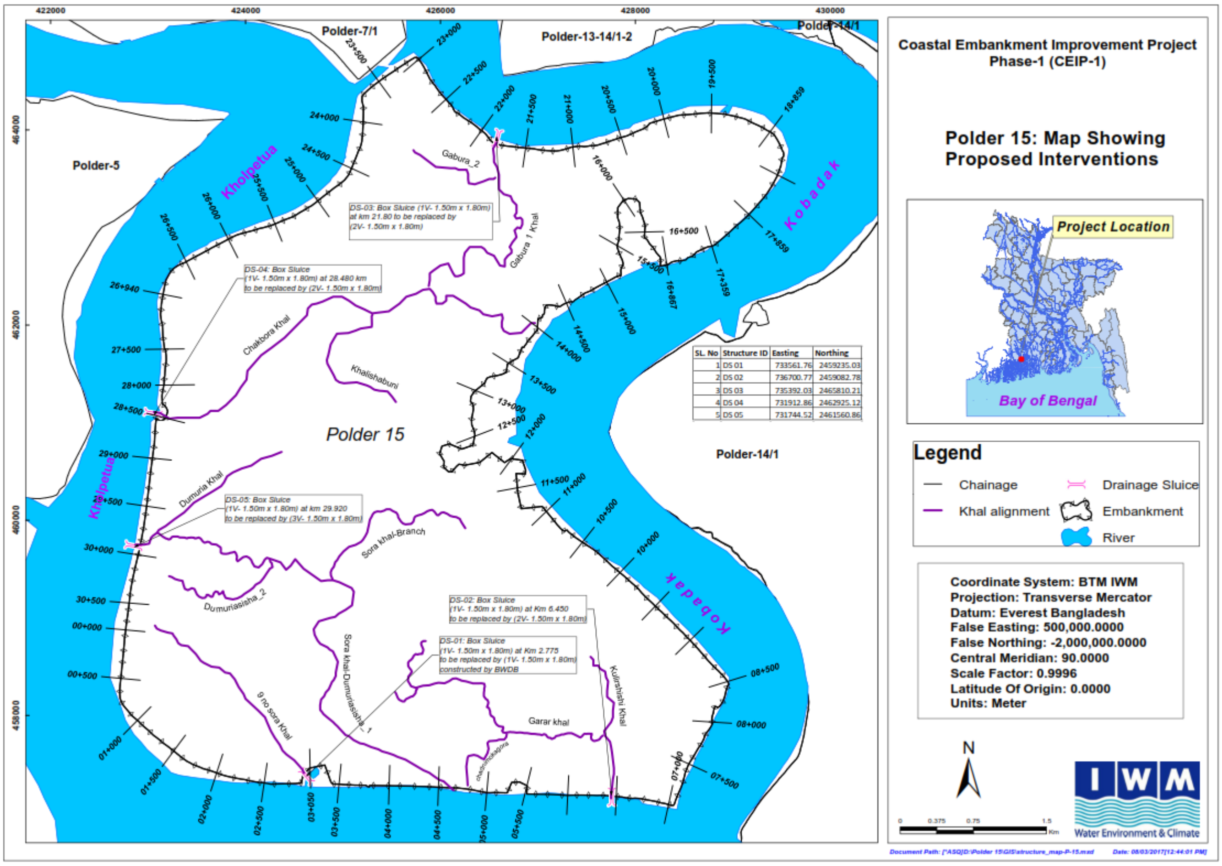


Figure 3-1 Map of Polder 15

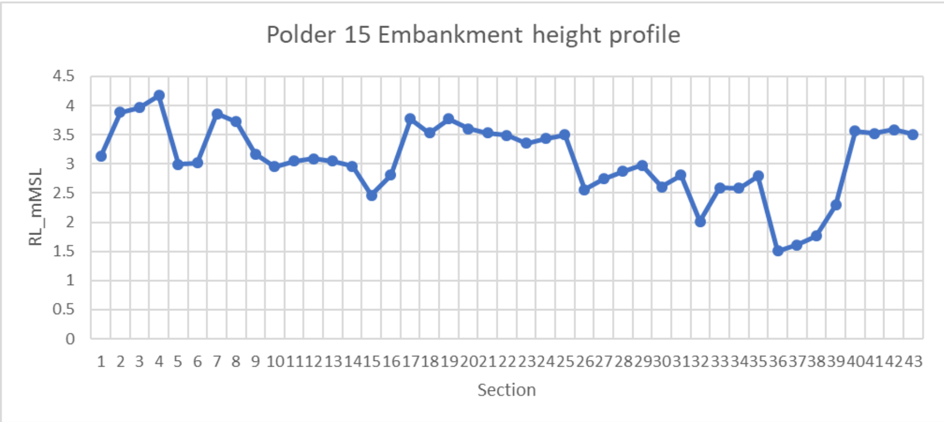


Figure 3-2 Current embankment profile

The general socioeconomic situation in the polder is as follows: the great majority of the population is engaged in the fisheries sector, in one way or another. Labourers work in the shrimp farms, whereas women and children from poor families are engaged in shrimp fry collection. During the winter season, people suffer from unemployment in the area and many migrate to other areas of the country to work in brick making and construction work. Other economic activities in the polder besides shrimp farming are small businesses, rice cultivation and fishing.

The majority of the population is poor, and mostly lives in katcha houses. The people build houses with an increased plinth height to avoid water entering their homes. Because the residence areas of the villages are congested, many houses are built at the river side of the embankment, which make them very vulnerable during disaster.

Figure 3-3 Land use in Polder 15 (ghers and Aman rice field)

Figure 3-4 Housing conditions in Polder 15

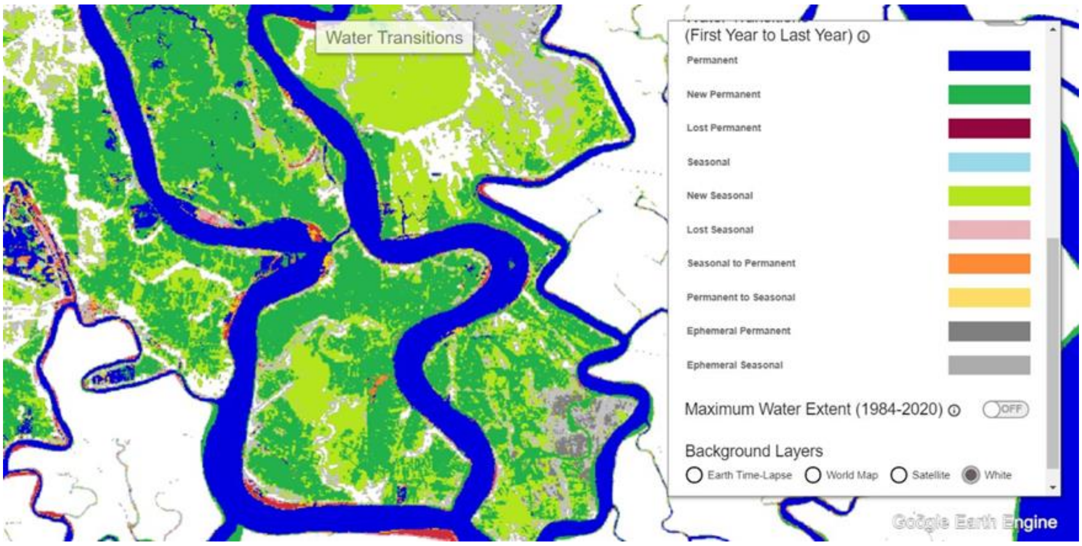


Figure 3-5 Flooding and drying map for polder 15 over the period 1984 – 2020, retrieved from http://global-surface-water.appspot.com/map. 'New permanent' refers to areas that were dry before 1984 but became permanent water bodies.

3.2 Future changes in boundary conditions

Precipitation: an increase rainfall is expected after 2070 during the monsoon (in the order of 4 to 9% relative to the year 2020). A decrease in rainfall during the winter months is projected after 2100 (in the order of -11%). Annual maximum daily precipitation is likely to increase after 2070 with 8 to 18%.

Subsidence: around 7 - 10 cm in 2050.

Cyclone frequency and intensity: Increase in cyclone frequency is found to be inconclusive, however, wind intensity is projected to increase with 4 – 8 %. The storm surge model developed by IWM (2018) has used an increase in wind speeds of 8%.

Salinity: is expected to increase somewhat. But is already quite high. Situation could change significantly if the Ganges Barrage is constructed and predominant farming system of shrimp culture is reduced or abandoned.

Sea Level Rise: SLR used in the risk modelling is 30 cm in 2050

3.3 Polder design options and measures

3.3.1 Embankments

There is a need to restructure/improve the existing embankments. As the current embankment profile shows (Figure 3-2), it has not a uniform height and at its lowest point is only 1.5 m above mean sea level. The many tubes (20 inches) which are dug into the embankment for letting water in an out of the ghers weaken the embankment. It is mentioned that there are more than 500 of these pipe sets on the embankment throughout the polder.

Erosion control: bank (400m) and slope (4.44 km) protection works are advised for several sections of the embankments. (CEIP-I, 2012)

Afforestation: At several locations there is significant space between the toe of the embankment and the riverbank (up to 70-80m), at which locations mangroves could develop. Some 20 ha of foreshore afforestation has been identified (CEIP-I, 2012).

Table 3-2 presents a summary of embankment improvements.

Table 3-2 Proposed embankment improvements Polder 15

Embankment improvements	length
re-sectioning (upgrade to design crest level of 4.5m PWD)	23.92 km
Construction of retired embankment	6.86 km
Bank protection works	400 m
Slope protection works	4.44 km
Afforestation	20 ha
Land acquisition	21.95 ha

Source: CEIP-1 Feasibility Study (2012)

The embankments for polder 15 are classified as “Intermediate” type of embankments, while combined storm surge levels and waves result required embankments “Type 3A” (Figure 3-6) and “Type 3B” (Figure 3-7), depending on the characteristics of the embankments and its surroundings (details on the embankments design and costing can be found in Annex B). At locations of possible wave attack and locations that suffer from scour from river flow it is advised to include a stone or Concrete Cement blocks (CC) embankment that will protect the embankment from erosion. Depending on storm surge, average polder elevation and presence and magnitude of the wave attack the dimensions of the embankment and construction costs are determined (details can be found in Annex B).

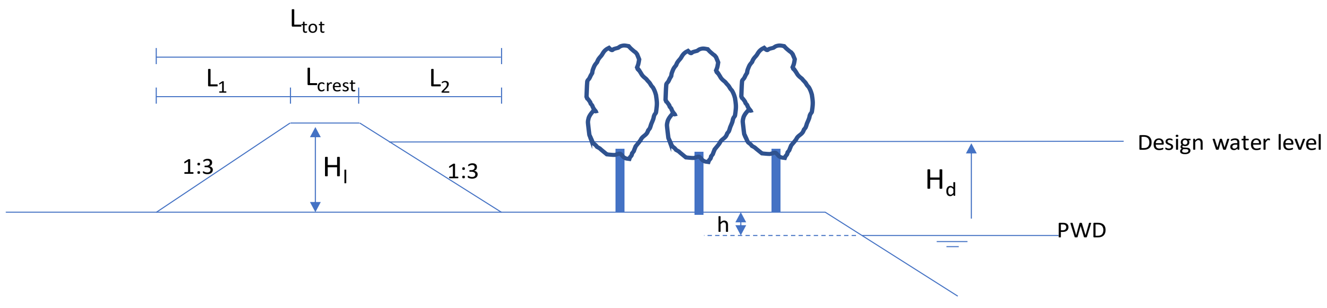


Figure 3-6; Embankment “Type 3A”

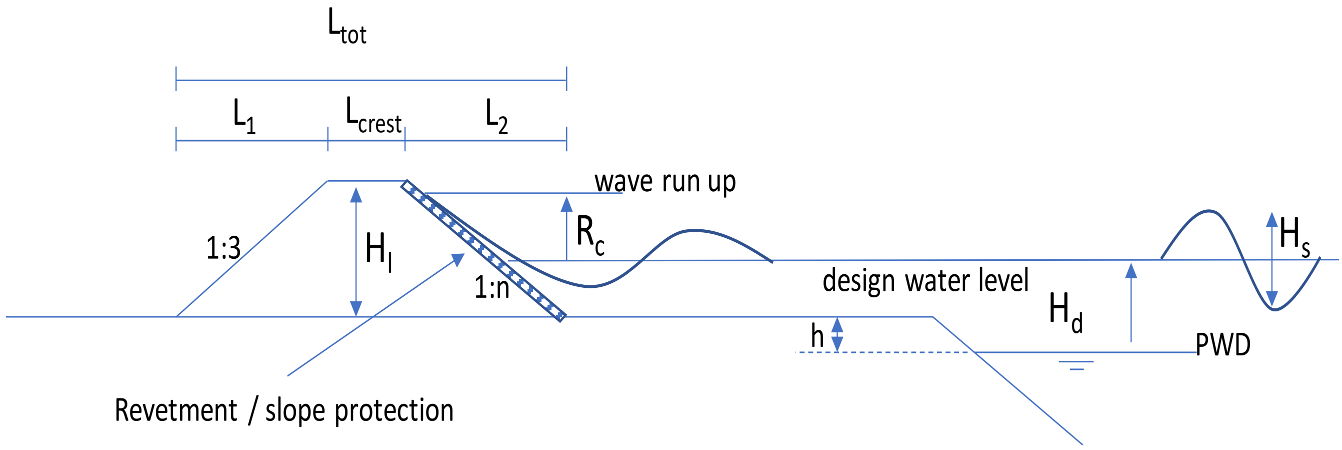


Figure 3-7; Embankment “Type 3B”

3.3.2 Sediment management

Tidal River Management (TRM) to restore sediment deposition in the polder is not needed when aquaculture will remain the main land use, hence waterlogging is not a serious problem.

3.3.3 Water management

The intensive shrimp culture activities cause high salinity in the polder surface and groundwater and is seriously limiting the agricultural potential. If in future the freshwater flow from the Ganges would improve, a more diverse land use could be envisaged. Besides shrimp production as a monoculture, for instance a combination of rice and shrimp could be feasible. The bottom of ghers act as a nutrient sink and these nutrients can be utilized by the rice plants. Also, a polyculture with mullet and mud crab could be practiced in brackish and saline water environments. In any case, the water management in Polder 15 is not so much about drainage, but more on providing the optimal mix of fresh and salt water to diversify aquaculture production.

Drainage conditions:

Currently there are 5 regulators with a total opening of 14.7 m^2. Average regulator opening is 2.94 m^2. However only one regulator seems operational (Table 3-3). The current drainage window is approx. 17 h per 24h. With 7.5 cm subsidence and 20.8 cm SLR in 2050 the drainage window will be reduced to 15.5 h (Figure 3-9).

Table 3-3 Regulator data for Polder 15

SL no.	Structure ID	Structure Type	No. of vent	Vent information				Condition
				Barrel length	Height (m)	Width (m)	m^2	
1	DS_01	Box	1	4.9	2	1.5	3	Good
2	DS_02	Box	1	3.6	2	1.5	3	Bad
3	DS_03	Box	1	3.6	2	1.5	3	Bad
4	DS_04	Box	1	3.6	1.8	1.5	2.7	Bad
5	DS_05	Box	1	3.6	2	1.5	3	Bad

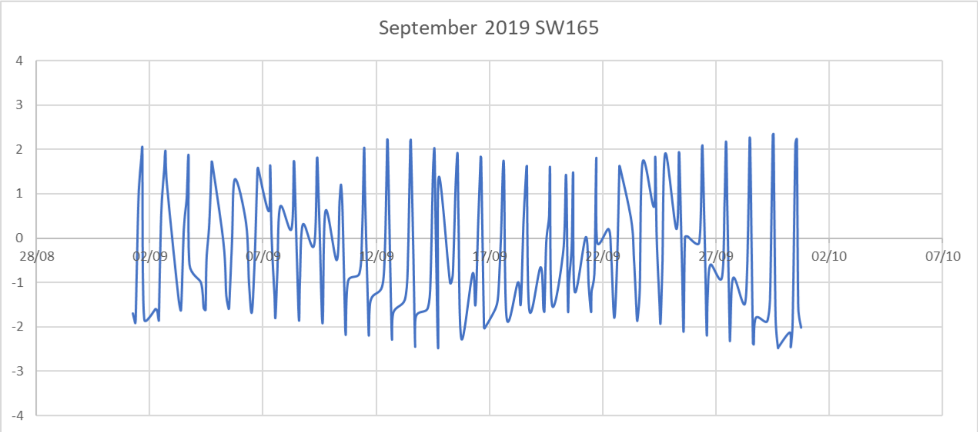


Figure 3-8 Water levels for station SW165 during the month of September 2019

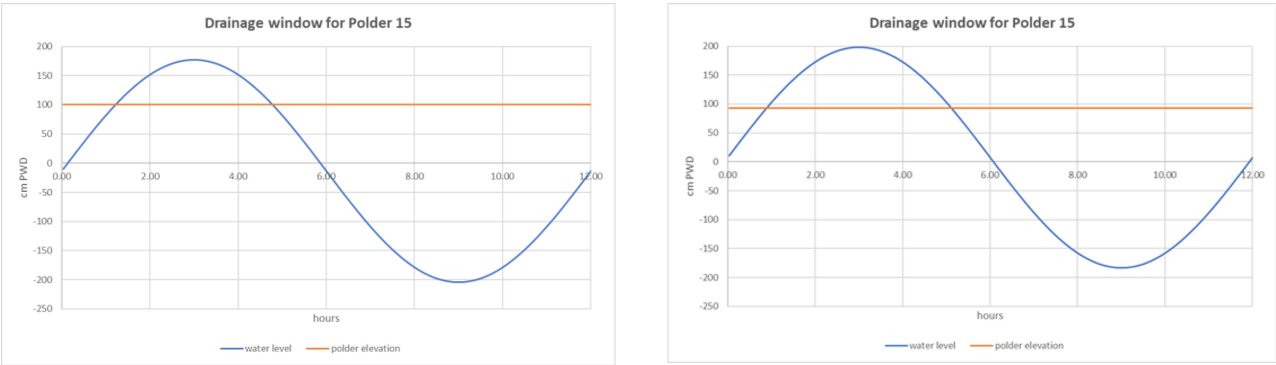


Figure 3-9 Drainage window (left: current, right: future) for Polder 15, based on average monsoon water level station SW165

The water balance model results (see Annex A) show that in wet and extremely wet years the existing drainage system is not able to keep the polder dry. But also during average years, there are 15 days with more than 20 cm of water on the fields. In wet years this increases in the future to 113 days and this accumulates to water levels of 1 m and more. This condition can be explained by the fact that the calculation assumes only one active regulator.

Also, the detailed drainage modelling exercise (IWM, 2022) reveals that polder 15 is vulnerable to water logging problem even in a 1 in 10-year return period design rainfall event without climate change. For more extreme conditions (1 in 25 and 1 in 50 year rainfall conditions) more than 80% of the polder is inundated with more than 30 cm of water.

From the survey conducted in 2021 it was observed that 4 out of the 5 existing regulators are in bad condition (see Table 3-3).. Should all 5 regulators work effectively (not shown in the graphs), the waterlogging conditions would be reduced significantly. For instance, under average rainfall conditions, water would be on the fields for only 2 days instead of 15. But in an extreme wet year the polder would still be waterlogged for 129 days. The detailed model results (IWM, 2022) show that only if the capacity of the 5 regulators is increased significantly (from one vent to up to 4 vents per regulator), the polder can achieve 88% of flood free area.

Future conditions (sea level rise, subsidence and increased monsoon rainfall) do not change the drainage situation much. Also, a reduced khal efficiency does not show a great effect on the water balance results. Both are clear indications that the number and capacity of the drain regulators is the limiting factor.

Should the polder be kept mainly for aquaculture, there is no need to improve the drainage capacity. However, there would be a need to improve the capacity to regulate the water conditions to optimize the salinity level for the shrimp or integrated shrimp-rice culture. For example, in the Shyamnagar district there are already signs that salinity in the dry season is too high for even producing salt water shrimp (Talukder et al., 2015).

It is advisable to use a water and salt balance model that simulates the storage and movement of water and salt amongst three stores in the polder: a shallow transient groundwater lens sitting on top of an underlying saltier groundwater, the soil, and canal and ponds which may store and drain water (and hence salt) from the polder (Mainuddin et al., 2021).

3.3.4 Disaster management

Using the storm surge inundation model SFINCS and the Flood Impact Assessment Tool FIAT, an estimation has been made of the cyclone storm surge risk for each polder. Details of the method and results can be found in Annex C. The risk after embankment improvement has been calculated by assuming an embankment with a safety level of 1 in 50 years under current climate conditions and 1 in 25 years in 2050. The risk profile is presented in three categories; damages (to houses, agriculture and businesses), people affected and annual mortality.

The present economic risk with the current embankment is rather high, about 2 million US$ per year (which is around 580 US$/ha per year) (Table 3-4). This comes down to an average safety level of one in 10 years (see Figure 3-10). The mortality risk due to cyclones is also high: 27 people per year. After improving the embankments, the economic risk will significantly be reduced. But the mortality risk does not reduce because casualties only occur with cyclones of 1/50 to 1/100 year probability. Both economic and mortality risk will rise in the future due to increasing cyclone hazard and sea level rise. The mortality risk will then be higher as under present conditions. This would warrant a sufficient number of cyclone shelters and early warning. There are only four cyclone shelters and the current shelter capacity is only around 10% of the polder population, which may be considered too low.

Table 3-4 Risk assessment Polder 15

15	Initial risk (no embankment)			Risk with existing embankment			Risk after embankment improvement		
	Damages USD/year	People affected per year	Mortality per year	Damages USD/year	People affected per year	Mortality per year	Damages USD/year	People affected per year	Mortality per year
Present	$4,225,512	3,106	44	$2,051,135	1,140	27	$706,003	500	25
2050	$4,402,750	3,250	66	$3,080,734	1,883	43	$1,391,242	996	42

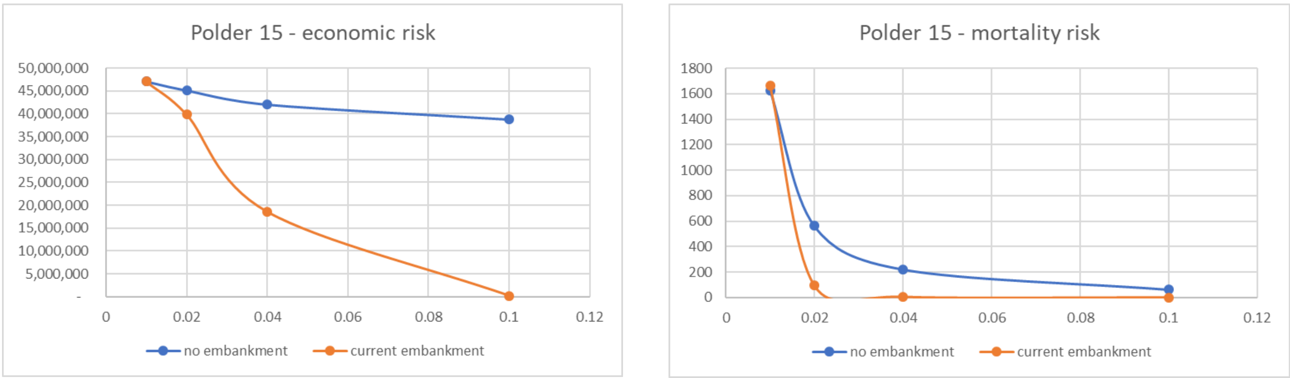


Figure 3-10 Risk profiles Polder 15 without and with current embankment (current conditions)

3.4 Cost and benefits of measures

3.4.1 Cost

Based on the above inventory of interventions a total cost estimate has been made, as presented in Table 3-5. The basis of the cost estimate are the unit prices developed for the conceptual designs that have been made for the proposed interventions. The unit prices used in the cost estimates use the specific boundary conditions of Polder 15 as described above.

Table 3-5 Cost estimation polder 15 (million US$)

Measure	**units**	**Costs (million US$)**
embankment re-sectioning (km)	23.92	8.5
retired embankment (km)	6.86	
bank protection (m)	400	23.8
slope protection (m)	4.44	
new and rehabilitation of regulators	5	1.4
khal excavation (km)	19	0.5
(new) cyclone shelters	7	5.3
Total		**39.5**

With an average shelter capacity of 1,250 people, a current population estimate of 38,866 (growth since 2011 as per SSP2 scenario) and assuming that 33% of the population should to be able to take refuge in a shelter, the total shelters needed in 2020 is 9 ((33% x 38,866)/1250). There exist 2 shelters, so 7 new shelters have to be constructed. It is assumed that future population growth does not require additional shelters as also housing conditions will improve over time.

3.4.2 Benefits

The benefits for Polder 15 consist of risk reduction from embankments, risk reductions from cyclone shelters and improved agricultural yields from improved drainage. For Polder 15 the present value[3] (PV) of the benefits are presented in Table 3-6. Based on the total costs of US$ 39.6 million and total benefits of US$ 61.2 million the investments for Polder 15 have a B/C-ratio of 1.0, which makes the proposed investments for Polder 15 feasible

[3] The present value presented in the table is the value today of a discounted number of annual benefits over a period of 30 years

from an economic perspective, especially as a very large part of the investments is in the estimated length of riverbank protection to a value of US$ 23.8 million, which is 60 % of total investments. A small reduction in length will improve the economic feasibility of the investments for Polder 15.

Table 3-6 Benefit table for polder 15

Benefit Category	**PV Benefits (million US$)**
Flood risk reduction	28.0
Risk reduction from Cyclone Shelters	7.1
Agricultural benefits	2.9
Total	**38.1**

4 Polder 29

4.1 Present situation and problems

Polder 29 has a moderate population density and is located close to Khulna (10 km). Salinity is moderately high. Large parts used to be poorly drained and have relatively high soil salinities (see figures 3-6 and 3-7). Problems include lack of fresh water, river erosion and a high cyclone risk (shelter capacity is very low). Note that local people alleged that there was no major storm surge flooding in Polder 29 during Aila (2009) and Sidr (2007) (CEGIS, 2016).

The cropping pattern as based on the statistics of the Upazilla Batiagata is as follows: large area is under single crop (T. Aman), whereas a substantial part has a double crop with T. Aman in Kharif 2 and Boro during Rabi season (see for details Box 1).

Box 1: Crop practice in Gajendrapur (Polder 29)(Source: Mita et al., 2017)

As Aman is a rain-fed crop and cultivated in monsoon, sluice gate is kept opened during June-July (Ashar) to December-January (Poush/Magh), during harvesting season of Aman, to fulfil additional water requirement apart from rainfall. To avoid internal conflict, farmers prefer cultivating high land before the low land. Therefore, irrigation is done in high land earlier thus extra water can flow in low land. Thus, low land got enough moisture prior to irrigation and deficiency in moisture is filled up by irrigation. Boro, the main dry season crop is sowed in the field during January-February (Magh) and harvested in May-June (Jeistha). Farmers irrigate field with groundwater in shallow depth locally known as boring, which can be referred as shallow tube well. Groundwater is used because salinity concentration of surface water (river, canal) is so high that it cannot be used in irrigation. Sluice gate is kept closed during (January- February) Magh/Falgun to Jeistha (May-June) to prevent salinity intrusion. Brinjal, Cauliflower, Cabbage, Bitter gourd, Okra, Bit, Pumpkin, and Sesame are cultivated in high land round the year, mainly in Boro season. Water is applied to the vegetable field from groundwater by shallow tube wells and deep tube wells. A water availability rating chart was developed in the group discussion where the local farmers spontaneously rated the water availability for irrigation purpose round the year. From Poush to Boishakh surface water quality degrades as salinity increases and the sluice gate is kept closed. During this period, farmers cultivate Boro by lifting groundwater by shallow tube well.

Polder 29 was one out of nine polders selected for the Integrated Planning for Sustainable Water Management (***IPSWAM***) project implemented by BWDB and IPSWAM project staff between 2004 and 2011. This project followed the Guidelines for Participatory Water Management (Ministry of Water Resources, 2001) that stipulated local stakeholder participation in any water management project. During this project IPSWAM helped create village level Water Management Groups (WMGs) and 1 polder level organization, the Water Management Association (WMA). WMGs are locally known as water committee and the WMA is called central or polder committee. These water management organizations (WMOs) were meant to represent the interests to local stakeholders, provide feedback on engineering design as well as labour for earthworks through Labour Contracting Societies and take over the responsibility of operation of sluice gates and minor maintenance after the project has completed (Dewan & Das, 2012).

Polder 29 is a ***Blue Gold*** Polder. The Blue Gold program since 2013 has conducted various interventions for rehabilitation of the polder which have apparently removed the existed drainage and water logging problems (see Box 2 for a description of the situation at the start of the Blue Gold Program). The various interventions done under Blue Gold program have been re-sectioning of the existing embankment, repairing of drainage/flushing sluices, repairing of drainage outlets and re-excavation of drainage canals, etc. Still considerable water management issues remain because of silting up of several peripheral rivers (see Figure 4-10, showing dead rivers to the north and northeast of the polder).

The major embankment problem at present in the Polder as observed during the field visit (June 2019) was erosion at the Bhadra River along right bank at Chandghar and Baroaria. Probably due to development of a bar at the middle of Bhadra river which made the flow area constricted on the side channels. As a result, the near bank velocity along the right bank of Bhadra river at Baroaria is increased and caused bank erosion. Precautionary protective work by geobags is also been done under Blue Gold program at Chandghor and other places, but they are not enough (CEIP-I, 2021).

Box 2: Drainage congestion before the start of Blue Gold in Polder 29 (Source: CEGIS, 2016)

Drainage congestion has been identified as the major problem inside the polder. Almost all the khals inside the polder, which are directly connected to the peripheral rivers, suffer from tremendous drainage congestion. Some of the severely affected khals are Aro khal, Asannagar khal, Mora Bhadra khal, Bokultola khal, Telikhali khal etc. During monsoon and post-monsoon periods, these khals cannot cope with the increased rainfall occurrences, leading to moderate to severe drainage congestion problems. Such drainage congestion problems mostly affect the agriculture and production sector. Due to the reduced drainage capacity of khals, rainwater often inundates agricultural fields for a period of 4 to 5 days, and affects the Kharif-II crops.

The reason for drainage congestion problems is two-fold. In the khals which are connected to Ghengrail, drainage congestion problems have been induced by a gradual sedimentation in the Upper Bhadra River, which resulted in an increased bed level. For this reason, water from the khals could not pass properly to the parent river (Upper Bhadra), leading to gradual siltation of khals and drainage congestion problems. This is a reason why most of the sluice gates placed along the eastern periphery of the polder have been non-functional. On the other hand, the khals connected to the Ghengrail River have mostly been silted up because of the damaged sluice gates placed at the khal openings. Some of the gates (Aro khal, Asannagar khal etc.) became non-functional due to poor maintenance, leading to siltation adjacent to the khal openings. Local people opined that, no prolonged water logging situation exists inside the polder, however, minor rainfed inundation exists at some areas as already discussed above.

Table 4-1 Basic data Polder 29

gross area (ha)	average elevation (m)	perimeter (km)	pop (2011)	pop density (#/ha)	erosion (km)	distance to main town (km)	salinity current	salinity future	shelter capacity
8,218	1.02	49	59,072	7.2	13	10	9.9 – 10.3	12.6	825

Parameter	**description**
Embankment	Lower Bhadra River and Teka Hari Teli Gang: storm surge plus waves, river erosion, coastal erosion
Embankment efficiency	**moderate**: 1,206 people per km
Salinity	**moderately high**: 10-12 ppt
Waterlogging	waterlogging is apparent in the north and the south part of the polder, which was not there in 1984 (see Figure 4-5).
Subsidence	land subsidence for West Ganges Region is relatively **low** (~2.5 mm/y)
Distance to district capital	10 km to Khulna **Not a remote polder**
Outside water level	Tides, surges, monsoon water levels: Determines embankment heights and drainage potential
Cropping intensity	**170%** (based on entire Upazilla statistics) (mostly double crop rice)
Cyclone risk	**high**

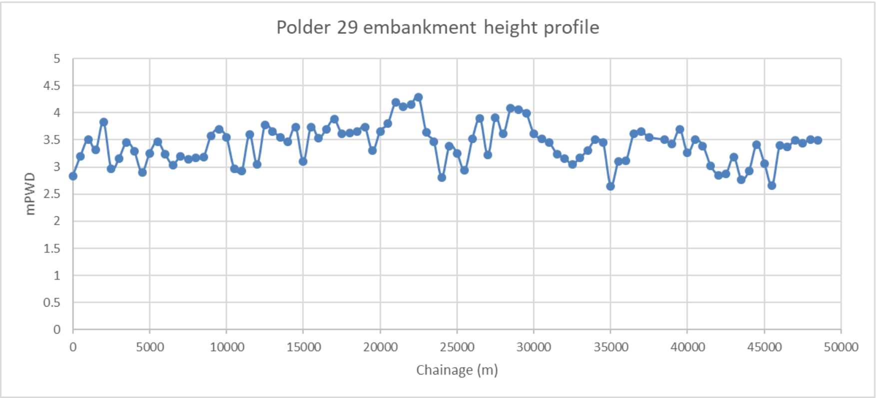


Figure 4-1 Polder 29 embankment height

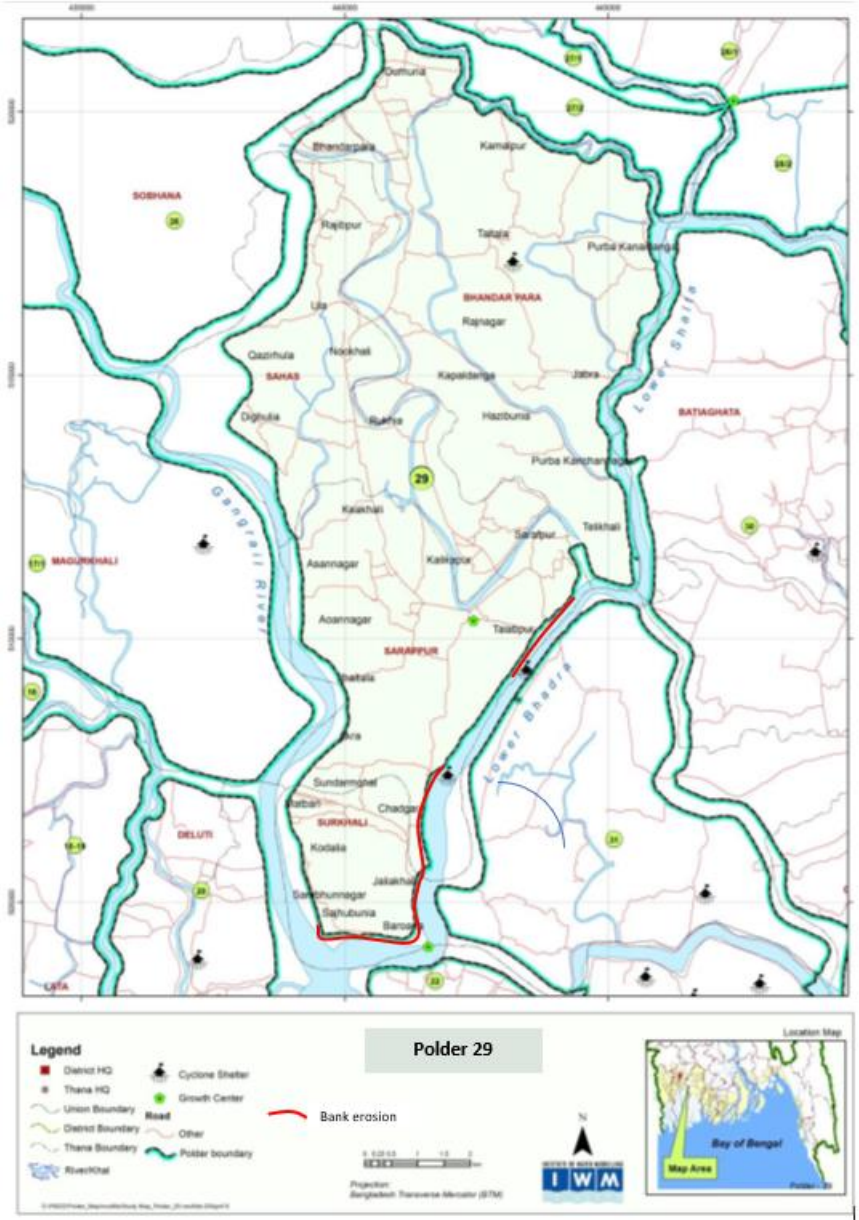


Figure 4-2 Map of Polder 29

Figure 4-3 River bank erosion and siltation problem in the Polder 29

Figure 4-4 Aquaculture practices in Polder 29

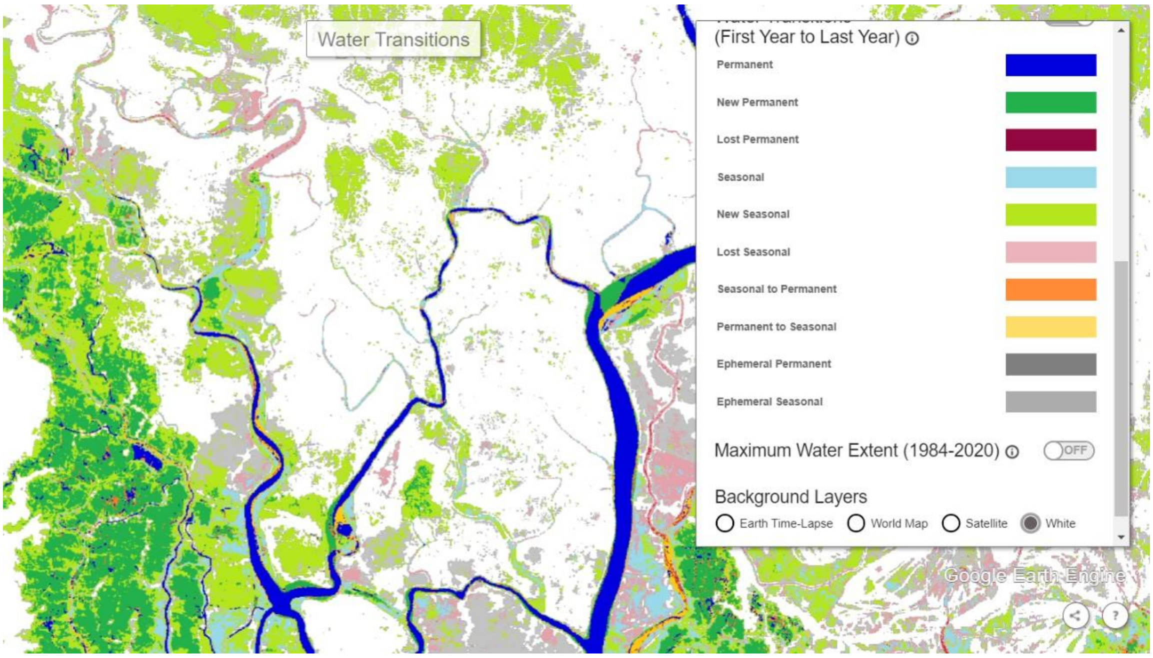


Figure 4-5 Flooding and drying map for polder 29 over the period 1984 – 2020, retrieved from http://global-surface-water.appspot.com/map . 'New permanent' refers to areas that were dry before 1984 but became permanent water bodies.

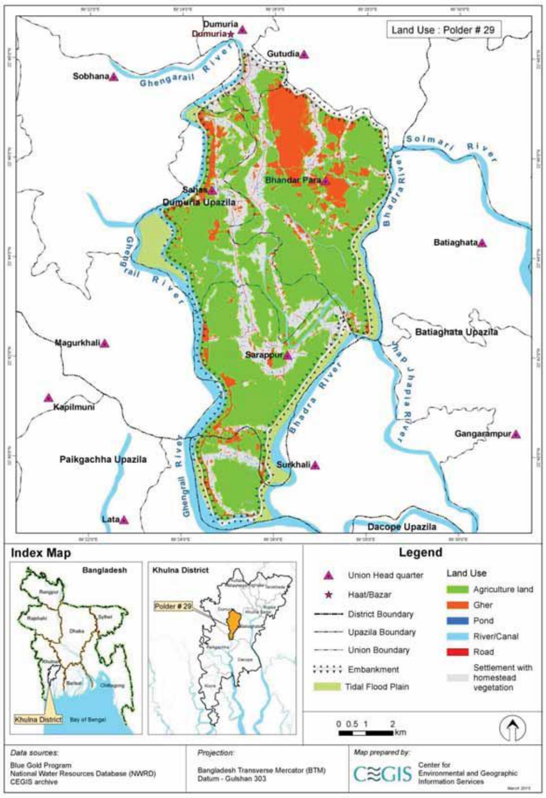


Figure 4-6 Land use Polder 29 (CEGIS, 2016a)

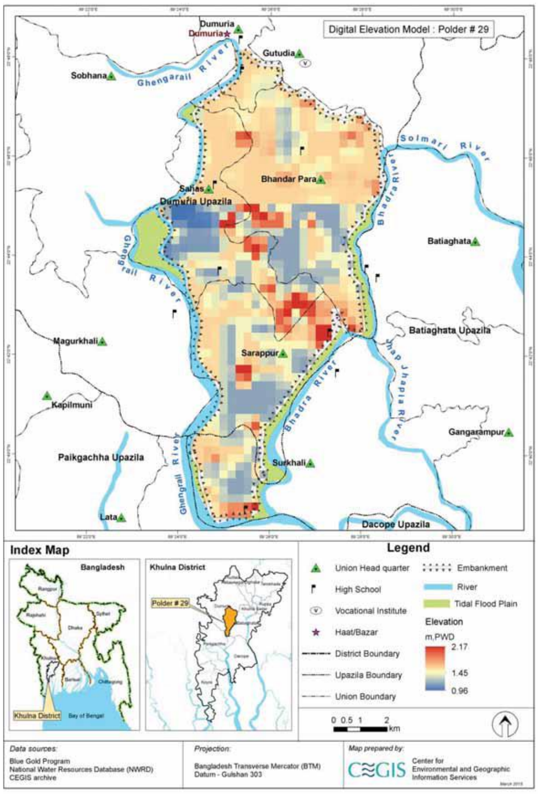


Figure 4-7 DEM Polder 29 (CEGIS, 2016a)

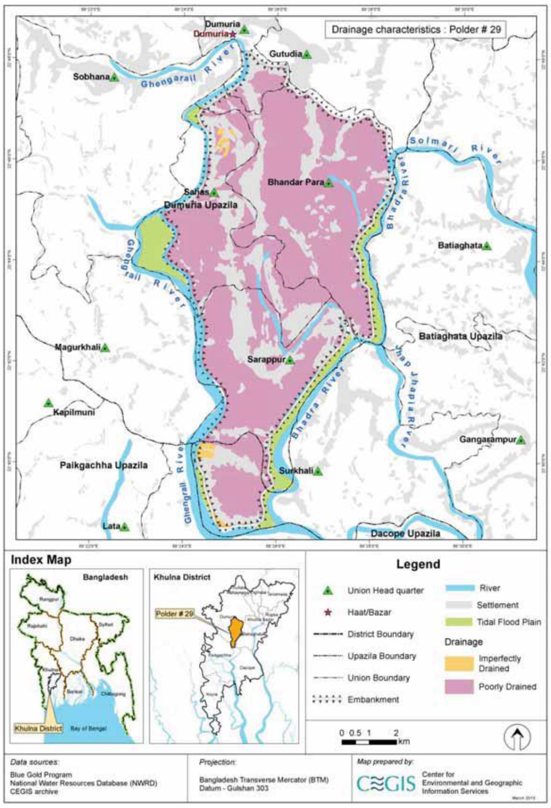


Figure 4-8 Drainage characteristics Polder 29 (CEGIS, 2016a)

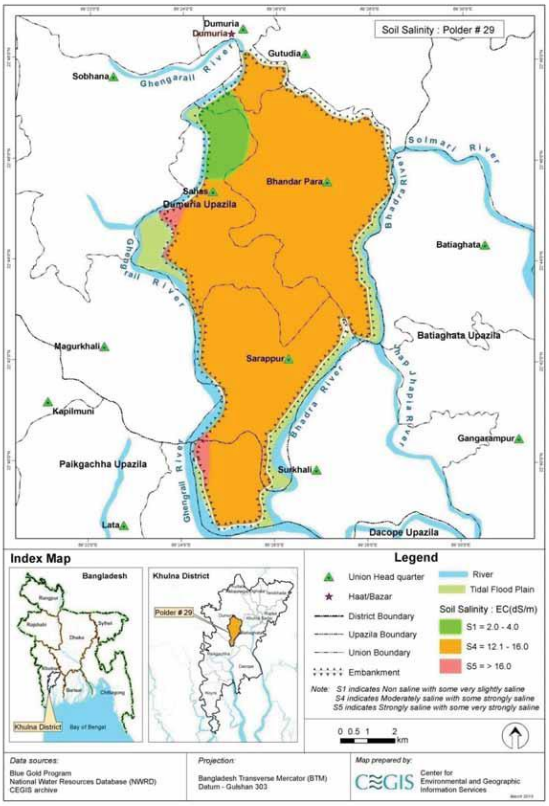


Figure 4-9 Soil Salinity Polder 29 (CEGIS, 2016a)

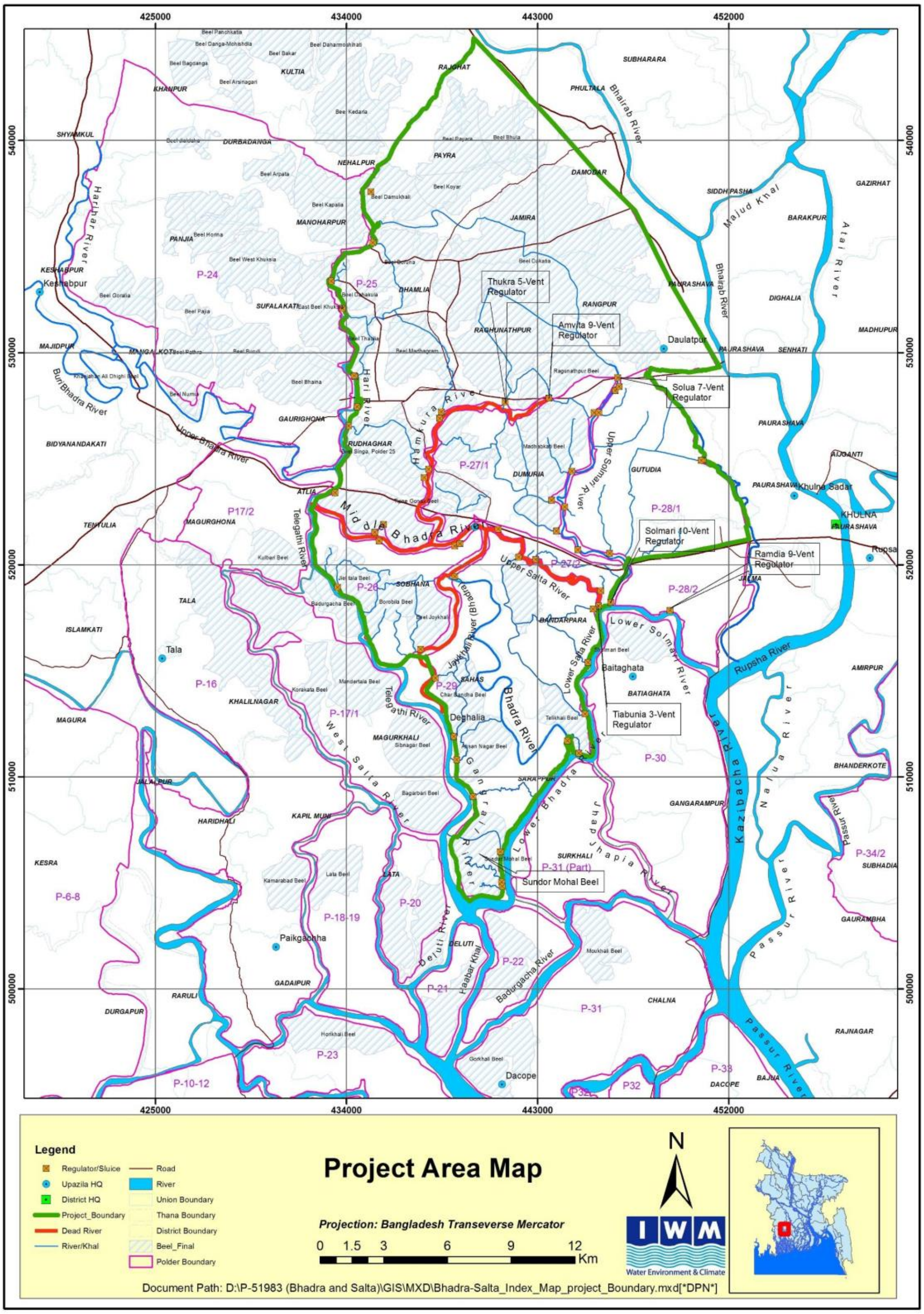


Figure 4-10 Map showing the silted up rivers north and west of Polder 29

4.2 Future changes in boundary conditions

Precipitation: an increase rainfall is expected after 2070 during the monsoon (in the order of 5 to 12% relative to the year 2020). A possible decrease in rainfall during the winter months is projected after 2100 (in the order of -7%). Annual maximum daily precipitation is likely to increase after 2070 with 7 to 10%.

Subsidence: around 10 cm in 2050.

Cyclone frequency and intensity: Increase in cyclone frequency is found to be inconclusive, however, wind intensity is projected to increase with 4 – 8 %. The storm surge model developed by IWM (2018) has used an increase in wind speeds of 8%.

Salinity: is expected to increase somewhat. But is already quite high. Situation could change significantly if the Ganges Barrage is constructed or Gorai offtake improved.

Sea Level Rise: SLR used in the risk modelling is 30 cm in 2050

4.3 Polder design options and measures

4.3.1 Embankments

Bank erosion is serious problem along some parts of the embankment. Several studies were conducted to solve the erosion problem along lower river Bhadra near Chandghar (IWM, 2016; Mosselman, 2016; Mosselman, 2017; Mathiesen, 2018). Groynes are not necessarily the best solution to bank erosion. Trends in the science of river training move away from groynes, since longitudinal structures are often more favourable (Mosselman, 2017).

The most appropriate measure for emergency bank protection is a revetment. Revetments based on geobags have been shown to be successful at other locations in Bangladesh. An auxiliary measure could be to dredge sediments from the recently accreted land on the opposite side of the river and to dump this along the bank at Chandgar. This would be a truly nature-based solution according to the philosophy of Building with Nature. However, as the new land has been developed into usage immediately, this option may not be feasible for social and political reasons. Ideally this type of solutions would be anticipated earlier, allowing timely administrative arrangements (Mosselman, 2017).

Due to progressing erosion, the flood embankment of Polder 29 had to be retired and shifted inland. The process of the construction of the retired embankment is slow due to limited funds resulting in limited construction power but also by administrative hurdles as land acquisition. In the case of Polder 29, the retired embankment alignment affected a school, which complicated and prolonged the land acquisition and therefore construction process. The emergency protection works implemented by the Blue Gold Program comprised two parts: (i) a 6m wide underwater apron consisting of 3 layers of 250kg geobags along 950m of bankline and (ii) an above low water level protection of 1.5 layers of placed 250kg geobags on the slope along 111m (Mathiesen, 2018).

Table 4-2 presents a summary of embankment improvements. As part of the Blue Gold program re-sectioning works along the peripheral embankment is proposed to be carried out in the selected locations which are found damaged. The proposed crest width is 4.27m, with side slopes of 1(V): 3(H) on river side and 1(V):2(H) on country side. The design elevation of the crest of the embankment is at 4.27 m +PWD. A total of 16.16 km of embankment will be re-sectioned along the chainage 0.00 to 1.00, 1.86 to 5.00, 5.98 to 7.50, 21.7 to 22.0, 23.6 to 24.02, 31.155 to 35.80, 37.00 to 41.317, 44.30 to 45.34 (CEGIS, 2016a).

Retired embankment is proposed to be constructed at two eroded locations of Baroaria and Jaliakhali along the chainage 22.00 to 23 and 26.40 to 27.30. The total length of which is 1.9 km and proposed crest width is 4.27 m with side slopes of 1(V): 3(H) on river side and 1(V):2(H) on country sides. The design elevation of the crest of the embankment is at 4.27 m +PWD (CEGIS, 2016a).

Table 4-2 Proposed embankment improvements Polder 29

Embankment improvements	length
Re-sectioning (upgrade to design crest level of 4.27m PWD)	16.16 km
Construction of retired embankment	1.9 km
Bank protection works	950m
Slope protection works	111m
Afforestation	p.m.
Land acquisition	p.m.

The embankments for Polder 29 are classified as “Intermediate” type of embankments, while combined storm surge levels and waves result required embankments “Type 3A” (Figure 4-11) and “Type 3B” (Figure 4-12), depending on the characteristics of the embankments and its surroundings (details on the embankments design and costing can be found in Annex B). At locations of possible wave attack and locations that suffer from scour from river flow is advised to include a stone embankment that will protect the embankment from erosion. Depending on storm surge, average polder elevation and presence and magnitude of the wave attack the dimensions of the embankment and construction costs are determined (details can be found in Annex B).

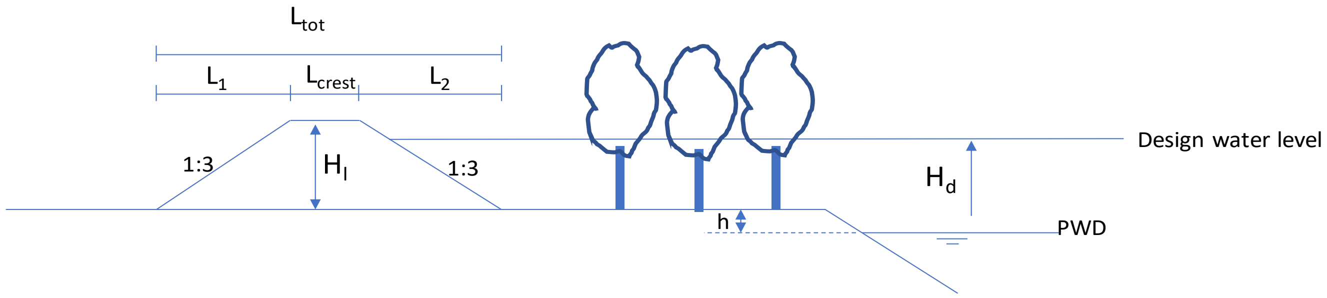


Figure 4-11; Embankment “Type 3A”

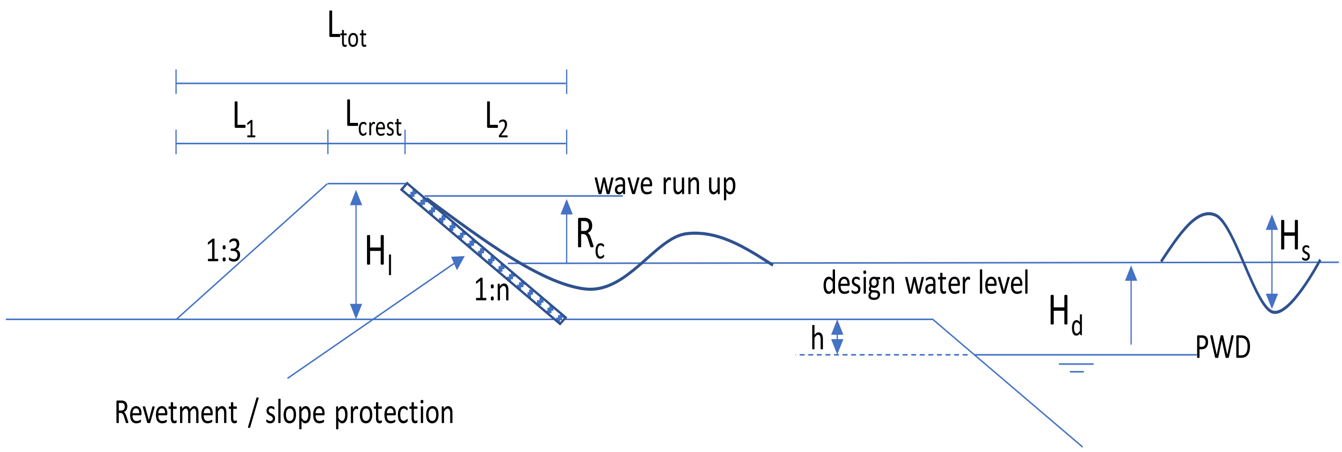


Figure 4-12; Embankment “Type 3B”

4.3.2 Sediment management

The Study TRM for the Bhabodah area of Jessore identifies several beels in the vicinity of Polder 29 as proposed TRM basins (for instance in the Upper Bhadra River Basin). A study by IWM analysed the option of using TRM at Madhugram Beel connecting the Hamkura river and to alleviate siltation of this and related “dead” rivers.

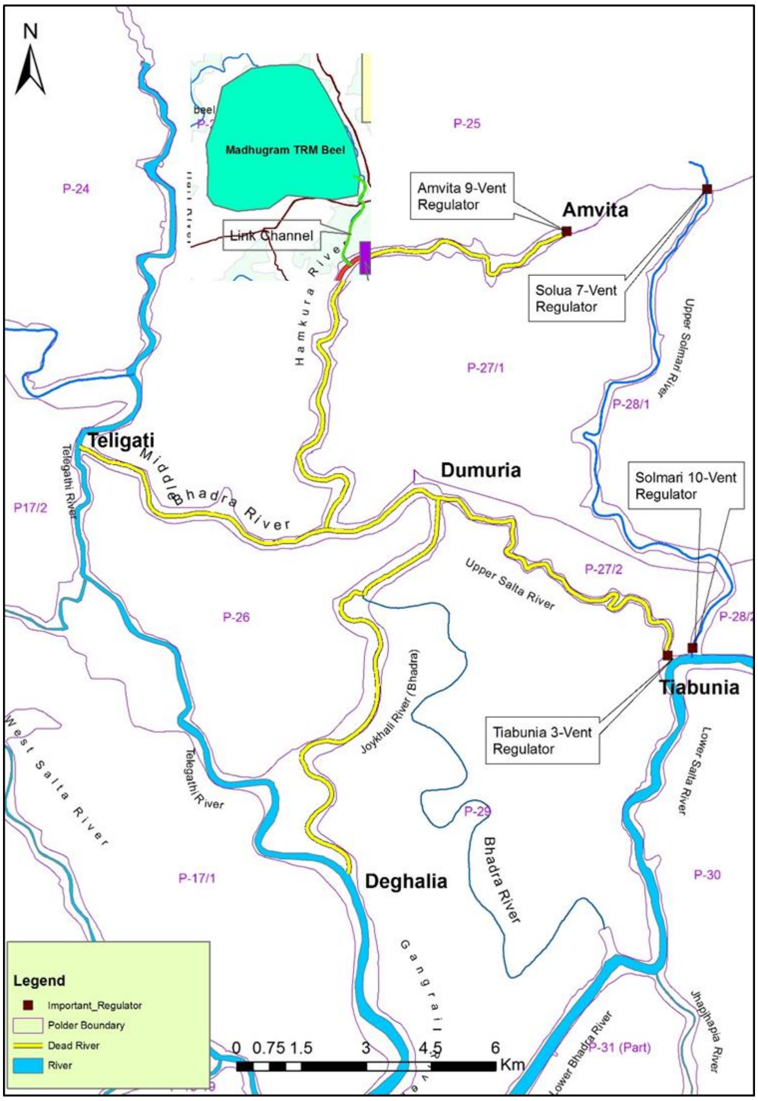
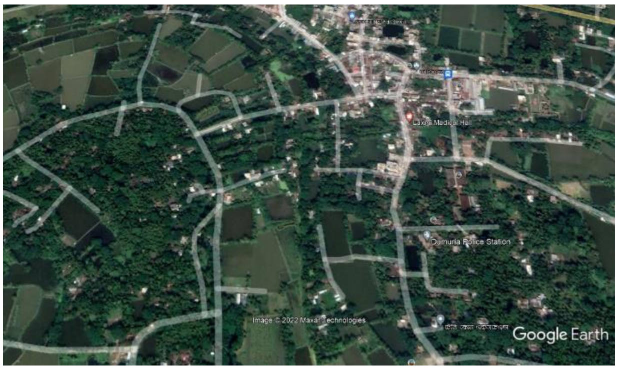


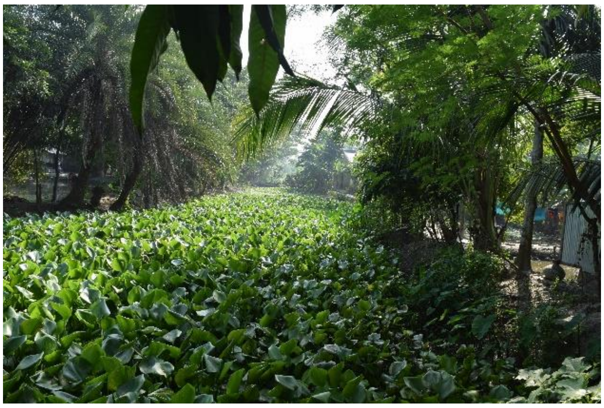
Figure 4-13 Proposed TRM plan for Madhugram Beel

Since 2018 dredging activities took place to revive the Upper Salta and Joykhali rivers. On the satellite pictures (Figure 4-14), in 2017 the Joykhali could not be seen, whereas in 2021 the river is clearly visible. The question remains how long it takes before the rivers are silted up again.



Satellite Image of Joykhali River in 2017

Satellite Image of 2021



Joykhali at Dumuria Bazar Point in 2017

Joykhali River dredging in 2018 at the same point

Joykhali River in December 2021 at the same point

The confluence of Joykhali and Upper Salta- December 2021

Figure 4-14 Dredging of the Joykhali river

4.3.3 Water management

Drainage conditions

Table 4-3 show the regulator data for Polder 29. There are 12 working vents/pipes (besides three that are damaged or silted up) with a total opening of 38.81 m^2. Average regulator opening is 3.23 m^2. Khal length is 93 km.

Table 4-3 Regulator data for Polder 29

	Structure Name	Type	No of Vent	Vent Width	Height	No of Pipe	Pipe Dia	Condition
1	Kalakhali Sluice Gate	Box	1	1.5	1.8			Good Condition
2	Bokultola Sluice Gate (S-1)	Box	1	1.5	1.8			Good Condition
3	Kanchan Nagar Sluice Gate (S-2)	Box	2	2	1.3			Good Condition
4	Telikhali Sluice Gate (S-3)	Box	2	2	1.2			Fully Damaged
5	Telikhali Sluice New	Box	2	1.5	1.8			Good Condition
6	Agunkhali Drainage Outlet	Drainage Outlet				1	0.9	Siltation on both side
7	Jaliakhali Sluice Gate	Box	1	0.9	1.2			Siltation on both side
8	Rutmara Gate (Baroarw)	Pipe Sluice				3	0.9	No Siltation
9	Rutmara Gate	Box	1	1.5	1.8			Good Condition
10	Sumbonagar Gate	Box	1	0.9	1.2			Good Condition
11	Bhadra Outlet	Outlet				1	0.6	Good Condition
12	Sluice Gate (S-6)	Sluice Gate	1	1.5	1.8			Good Condition
13	Asanagar Sluice	Box	1	0.9	1.2			Good Condition
14	Chatchatia Sluice (S-7)	Box	2	1.5	1.8			Good Condition
15	Golaimari Sluice (S-7A)	Box	1	0.9	1.2			Good Condition

The polder drains into the two peripheral rivers: Bhadra river and Ghengrail river. The two rivers originate from the Sibsa River System and are directly fed by the oceanic tides. During the monsoon period the drainage period is limited because the high tide exceeds the average polder elevation (see Figure 4-15 and Figure 4-16). This results in a drainage window of 12.1 hrs per day. In 2050 this could reduce to 10.5 h per day (considering 7.5 cm subsidence, 20.8 cm SLR).

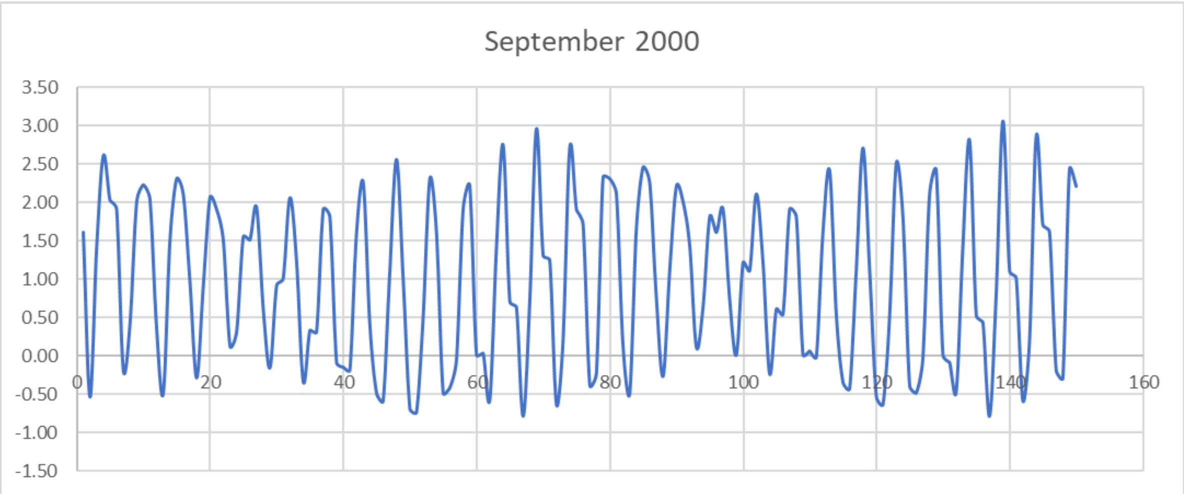
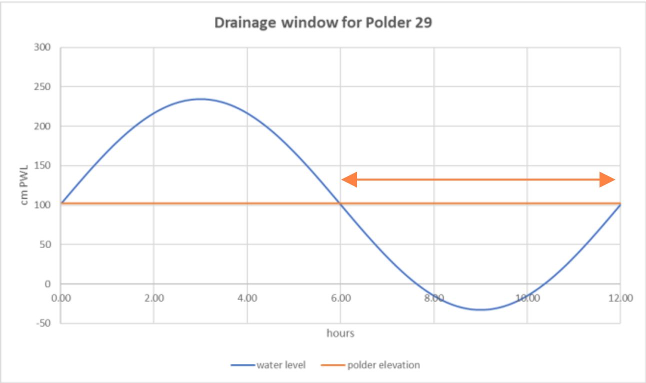


Figure 4-15 Water levels for station SW28 during the month of September 2000



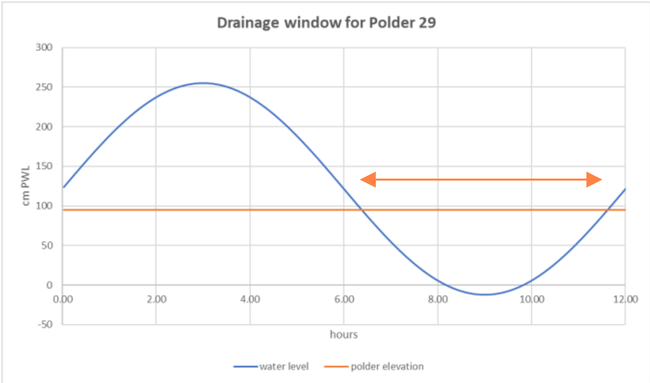


Figure 4-16 Drainage window (left: current, right: future) for Polder 29, based on average monsoon water level station SW28

Results from the water balance model show good drainage potential under an average and wet year. But an extreme wet year would cause significant long duration waterlogging (80 days of which 37 consecutive). Although the surface area per khal is relatively small (on average 88 ha per km khal), the length per regulator is relatively long (7.2 km). Detailed drainage modelling (IWM, 2022) shows that significant areas (approx. 45% of the polder) suffers from inundation during an average year. This is mainly located at the northern part of the polder, where also most of the fishponds (ghers) are found.

Khal efficiency seems to have no effect on the drainage. Although this looks counterintuitive, the reason is that the regulator drainage capacity is the limiting factor. With 12 regulators and a capacity of 3.23 m^3/s each the drainage capacity is 3.4 million m^3 per day. Furthermore, the polder can be drained only 12 hours per 24 hours, because of the tide. Therefore only 1.7 million m^3 can be drained per day. This equals 21 mm on the field. Hence, a daily rainfall of more 29 mm (compensating for 3 mm evaporation and 5 mm infiltration) would already cause some drainage congestion.

In the future with sea level rise and subsidence, the drainage window will reduce to 10.5 hours per day. Combined with a predicted rainfall intensity increase, this will cause more waterlogging, especially in extreme wet years (133 days consecutive, i.e. a long-term flood condition).

From the lessons learned in the Blue Gold program (BGP) it can be concluded that investments in water infrastructure pays off. Only 9% WMGs reported ‘bad’ or ‘very bad’ water management condition compared to 59% WMGs prior to BGP. Improvement in infrastructure included re-excavation of khals, and khal cleaning, sluice repairs, new / repaired culverts, better sluice operation and repaired embankments (Blue Gold, 2019).

If the Ganges barrage or improved Gorai offtake reduces the salinity problem, this polder can become a major agricultural production centre with a market close to Khulna. Polder 29 is located within the GDA (Ganges Dependent Area) and bears high sensitivity towards the proposed Ganges Barrage. The most significant impact of the barrage on Polder 29 would be the reduction of surface water salinity in its adjoining river system. Dry season water use may be benefited tremendously, and more surface water irrigation is expected to increase inside the polder. This would eventually enhance the production and food security of the area (CEGIS, 2016a).

Drinking water supply

A study by Roman et al. (2021) gives insight in the water supply situation of Polder 29. Figure 4-17 shows the water infrastructure. Of the 2,103 surveyed households, 58% used deep tube wells as their main source of drinking water, with 13% using shallow tube wells, 11% depending on pond sand filters, 9% using one of the three piped systems, 7% purchasing water from informal vendors, and 2% using rainwater.

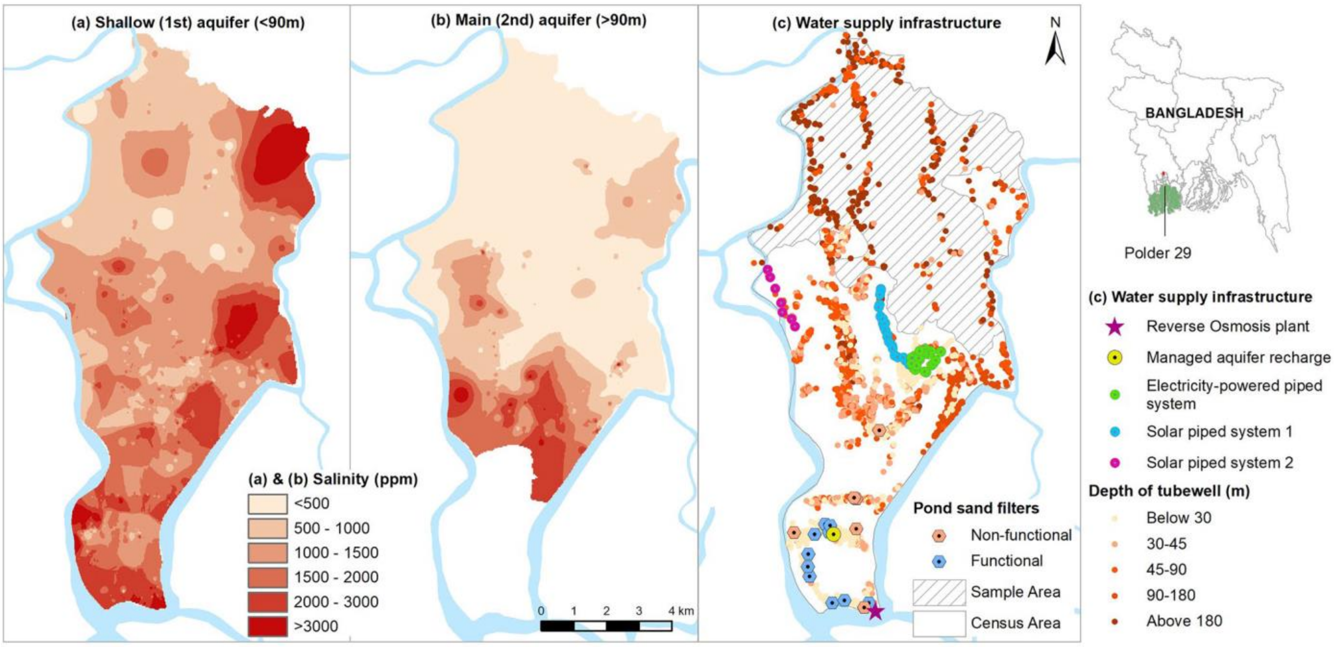


Figure 4-17 Maps of Polder 29 showing locations of (a) salinity measures in the shallow (first) aquifer, (b) salinity measures in the main (second) aquifer, and (c) censed and sampled drinking water supply infrastructure (Source: Roman et al., 2021)

Using a spatial optimization technique, the authors analysed different options for improvement. The solution that maximizes access for the greatest number of people is focused upon deep tube wells for the population without access to low-salinity drinking water in the north of the model domain. This portfolio includes 30 deep tube wells in the north, 5 piped systems close to the high/low salinity boundary, 2 piped systems in the high salinity region, and 1 desalination plant in the south. The “maximize welfare” solution has higher capital investment toward the south including seven desalination plants and three piped systems close to the high/low salinity boundary and other two piped systems from desalination in the south (Roman et al., 2021).

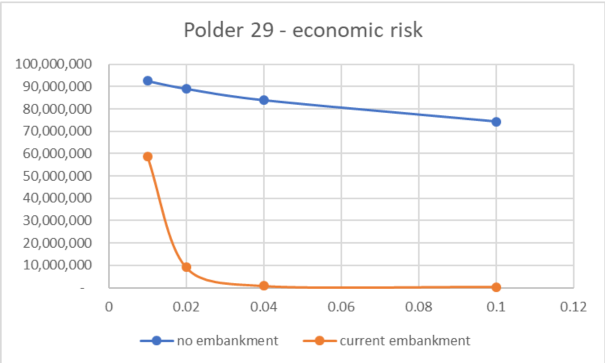
4.3.4 Disaster management

Using the storm surge inundation model SFINCS and the Flood Impact Assessment Tool FIAT, an estimation has been made of the cyclone storm surge risk for each polder. Details of the method and results can be found in Annex C. The risk after embankment improvement has been calculated by assuming an embankment with a safety level of 1 in 50 years under current climate conditions and 1 in 25 years in 2050.

Although the cyclone risks are high under natural conditions, the current embankment already provides a safety level around 1 in 25 year (Figure 4-18). Bank improvements will only slightly reduce the risk and they will increase again in 2050 (Table 4-4). Especially the mortality risk increases considerably to 84 casualties per year. This would warrant a sufficient number of cyclone shelters and early warning. Current shelter capacity is only around 1.4% of the polder population, which may be considered much too low.

Table 4-4 Risk assessment Polder 29

29	Initial risk (no embankment)			Risk with existing embankment			Risk after embankment improvement		
	Damage USD/year	People affected per year	Mortality per year	Damage USD/year	People affected per year	Mortality per year	Damage USD/year	People affected per year	Mortality per year
Present	$8,313,801	5,590	53	$1,057,041	374	1	$881,647	339	1
2050	$9,085,612	6,312	204	$4,444,953	2,323	84	$2,735,271	1,899	84



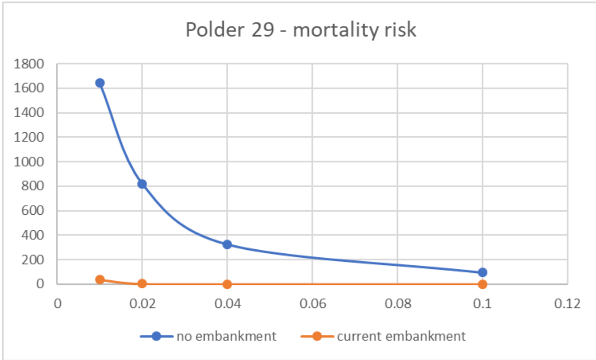


Figure 4-18 Risk profiles Polder 29 without and with current embankment (current conditions)

4.4 Cost and benefits of measures

4.4.1 Cost

Based on the above inventory of interventions, a total cost estimate has been made, as presented in Table 4-5. The basis of the cost estimate are the unit prices developed for the typical designs that have been made for the proposed interventions. The unit prices used in the cost estimates use the specific boundary conditions of Polder 29 as described above.

Table 4-5 Cost estimation polder 29 (million US$)

Measure	**units**	**Costs (million US$)**
embankment re-sectioning (km)	16.16	15.4
retired embankment (km)	1.9	
bank protection (m)	950	12.2
slope protection (m)	111	
new regulators (no.)	1	0.6
khal excavation (km)	93	2.3
new cyclone shelters (no.)	17	12.8
Total		**39.5**

With an average shelter capacity of 1,250 people, a current population estimate of 77,778 (growth since 2011 as per SSP2 scenario) and assuming that 33% of the population should to be able to take refuge in a shelter, the total shelters needed in 2020 is 17 ((33% x 77,778)/1250). It is assumed that future population growth does not require additional shelters as also housing conditions will improve over time.

4.4.2 Benefits

The benefits for Polder 29 consist of risk reduction from embankments, risk reductions from cyclone shelters and improved agricultural yields from improved drainage. For Polder 29 the PV of the benefits are presented in Table 4-6. Based on the total costs of US$ 43.3 million and total benefits of US$ 40 million the investments for Polder 29 have a B/C-ratio of 0.9, which makes the proposed investments for Polder 29 almost feasible from an economic perspective. However, as a large part of the investments are to the estimated quantity in riverbank protection (US$ 12.2 million) a small reduction in total length in embankments needing protection will result in an economic feasible investment for Polder 29.

Table 4-6 Benefit table for polder 29

Benefit Category	PV Benefits (Million $)
Flood risk reduction	19.3
Risk reduction from Cyclone Shelters	13.7
Agricultural benefits	7.0
Total	**40.0**

5 Polder 40/1

5.1 Present situation and problems

Polder 40/1 is situated on the southern-most tip of the coastal area and is therefore a bit isolated (distance to Barguna 23 km). The foreshore is very wide and long, where mangrove forest was planted. It has a low population density and moderate salinity. Waterlogging seems absent, but the main problem is erosion due to cyclonic storm surges. The polder was severely damaged during the Cyclone SIDR in 2007. Near Rohita the embankment was destroyed, after which a retired embankment was built. Unfortunately, the stretch in Padma Hat area is currently under erosion attack, which prompted BWDB to execute emergency protective works using geo-bags.

The cropping pattern in the polder, using statistics of Upzilla Pathargatha, is as follows: majority of land is under double cropping, with T. Aman during Kharif 1 and mostly pulses during Rabi. Kharif 2 season mostly fallow.

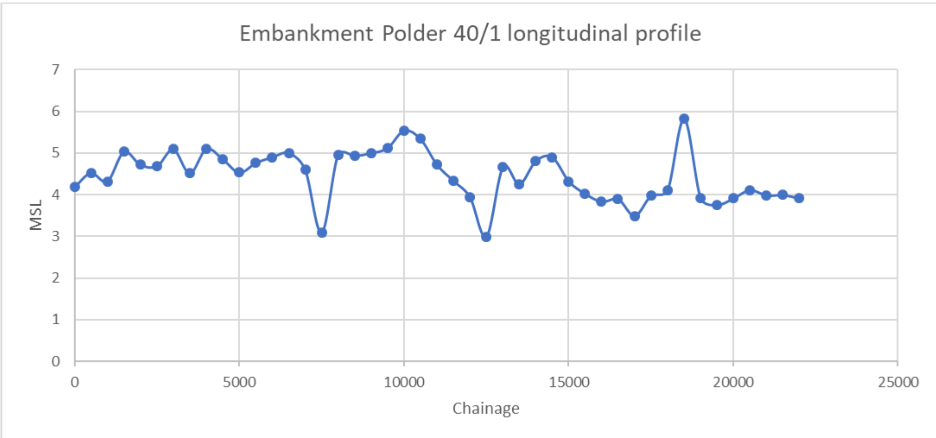


Figure 5-1 Polder 40/1 embankment height

Table 5-1 Basic data for Polder 40/1

gross area (ha)	average elevation (m)	perimeter (km)	pop (2011)	pop density (#/ha)	erosion (km)	distance to main town (km)	salinity current	salinity future	shelter capacity
2,105	1.56	23	12,200	5.8	-	23	6.3	8.3	8,250

Parameter	**description**
Embankment	Baleswar and Bishkhali River: storm surge plus waves, river and coastal erosion
Embankment efficiency	**Low**: 530 people per km
Salinity	**moderate**: 6.3-8.3 ppt
Waterlogging	currently no waterlogging problem (see Figure 5-4)
Subsidence	land subsidence for Ganges Tidal Flats Region is medium (~ 5 mm/y)
Distance to district capital	23 km to Barguna **Remote polder**
Outside water level	Tides, surges, monsoon water levels: Determines embankment heights and drainage potential
Cropping intensity	**203%** (based on entire Upazilla statistics) (mostly double crop rice/pulses)
Cyclone risk	**Moderate**

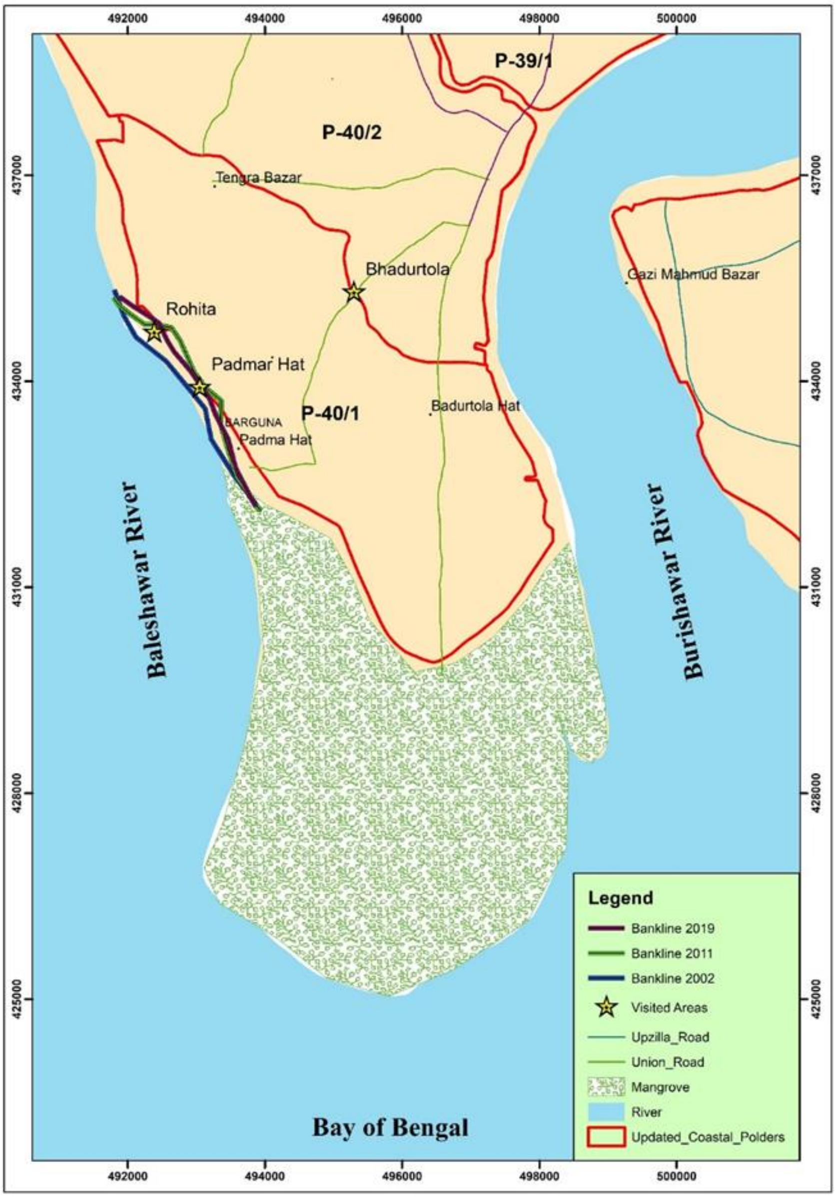


Figure 5-2 Map of Polder 40/1

Figure 5-3 Interior and coastal landscape of Polder 40/1

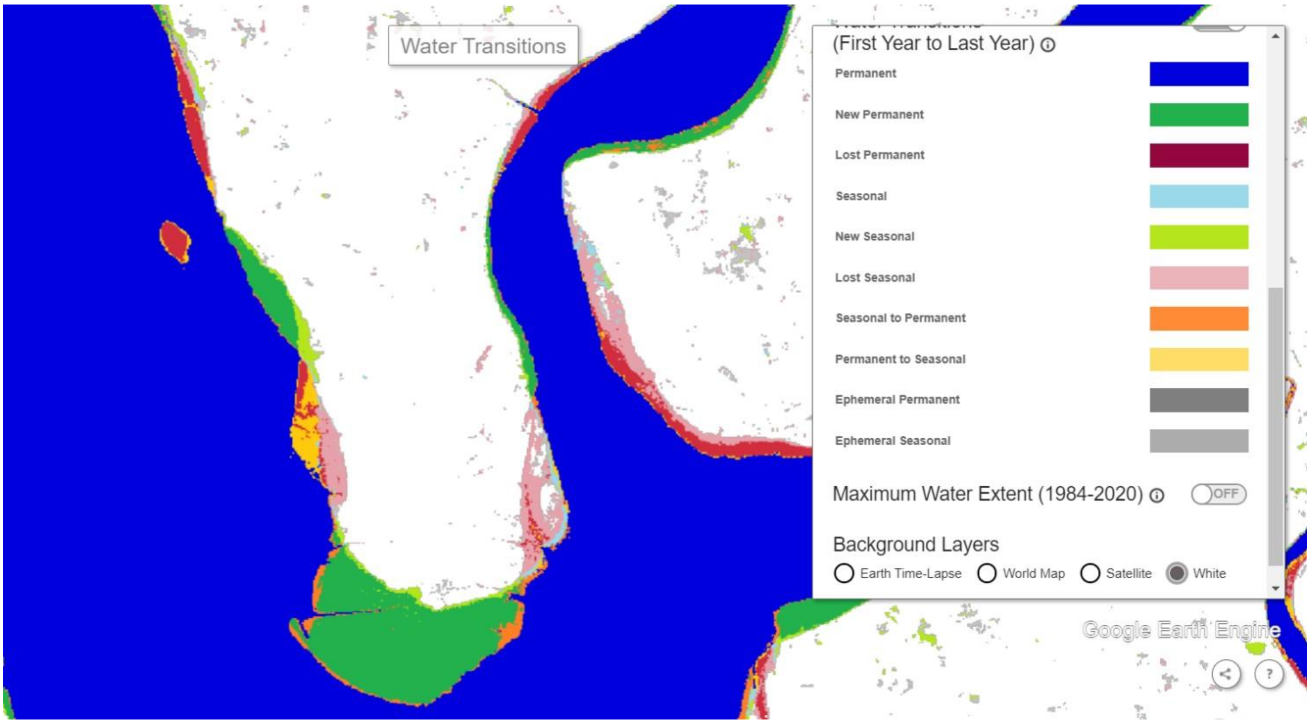


Figure 5-4 Flooding and drying map for polder 40/1 over the period 1984 – 2020, retrieved from http://global-surface-water.appspot.com/map. 'New permanent' refers to areas that were dry before 1984 but became permanent water bodies.

5.2 Future changes in boundary conditions

Precipitation: an increase rainfall is expected after 2070 during the monsoon (in the order of 4 to 9% relative to the year 2020). A decrease in rainfall during the winter months is projected after 2100 (in the order of -14%). Annual maximum daily precipitation is likely to increase after 2070 with 7 to 14%.

Subsidence: around 10 cm in 2050.

Cyclone frequency and intensity: Increase in cyclone frequency is found to be inconclusive, however, wind intensity is projected to increase with 4 – 8 %. The storm surge model developed by IWM (2018) has used an increase in wind speeds of 8%.

Salinity: is expected to increase somewhat. Situation could change if the Ganges Barrage is constructed.

Sea Level Rise: SLR used in the risk modelling is 30 cm in 2050

5.3 Polder design options and measures

5.3.1 Embankments

Based on the survey (Figure 5-1) there is roughly 5 km of embankment below 4 m MSL. This should be re-sectioned to get it up to the level of the remaining embankment. Furthermore, there is an estimated 3 km stretch of embankment between Rohita and Padmar Hat that needs to be protected from erosion through bank protection.

5.3.2 Sediment management

Tidal River Management (TRM) is not necessary. The polder is situated close to the sea with deep and wide rivers. There is also no waterlogging. Long term macro-scale sediment modelling suggests growth of the inter- and supratidal land on the seaside. This will promote mangrove development and – in the far future – a potential for new occupation. Meanwhile, the current mangrove should be protected and used as an asset for eco-tourism.

5.3.3 Water management

Drainage conditions

Table 5-2 shows the regulator data for Polder 40/1. There are 5 working regulators/pipes with a total opening of 26.6 m^2. Average regulator opening is 5.3 m^2. Total length of khals is 15.4 km

Table 5-2 Regulator data for Polder 40/1

	Structure Name	Khal Name	Type	No of Vent	Vent Width	Height	Total opening	Condition
1	Sluice Gate	Haritana 2	Box Sluice	1	2	1.62	3.24	Siltation on Both Side
2	DS-1	Jintola	Box Sluice	1	1.5	1.998	2.997	Good Condition
3	DS-2	Padma Khal	Box Sluice	1	1.5	2.2	3.3	Good Condition
	Structure Name	**Khal Name**		**No of pipes**	**Pipe ø**	**Height**	**Total opening**	**Condition**
4	DS-4	Koralia	Pipe Sluice	3	0.9	-	7.63	Good Condition
5	R-4-DS-5	Badurtola	Pipe Sluice	3	1	-	9.42	Good Condition

The polder drains into the Baleshawar and Burishawar rivers. During the monsoon period the drainage period is limited because the high tide exceeds the average polder elevation (see Figure 5-5 and Figure 5-6). This results in a drainage window of 16.2 hrs per day. In 2050 this could reduce to 13.3 h per day (considering 15 cm subsidence, 20.8 cm SLR).

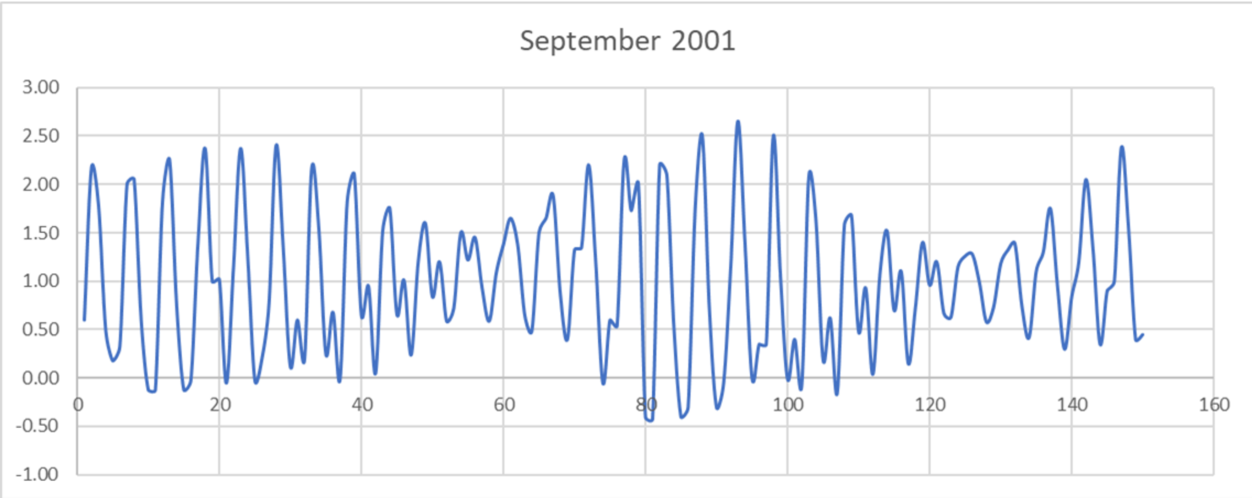


Figure 5-5 Water levels for station SW39 during the month of September 2001

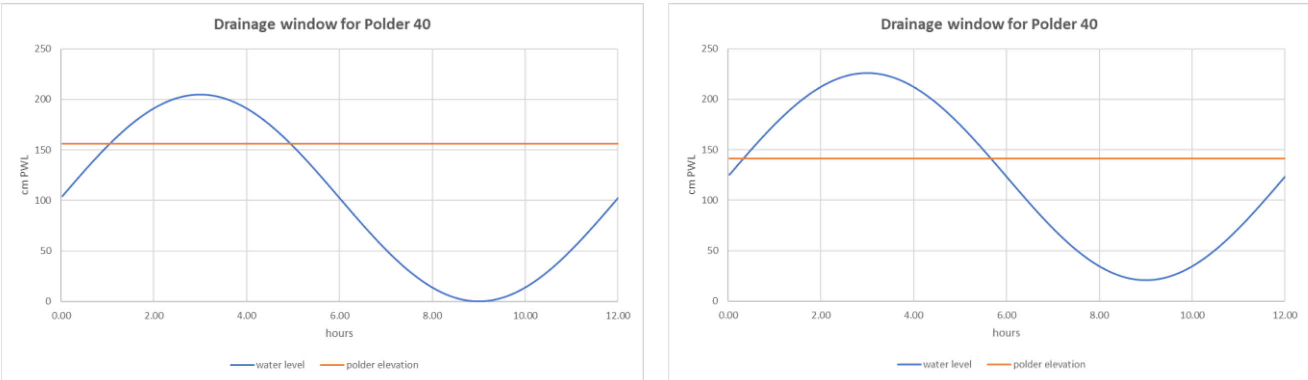


Figure 5-6 Drainage window (left: current, right: future) for Polder 40/1, based on average monsoon water level station SW39

Under the assumed conditions of the drainage infrastructure, Polder 40 shows excellent drainage potential, even if only 25 % khal efficiency is assumed. Only during extreme wet conditions problems could arise in the future (2050). Part of the explanation is a relatively short khal length per regulator (3.1 km) and a relatively good drainage capacity at the polder outlets: it can drain 73 mm/day, which is the highest of all 5 polders, despite of a drainage window of 16 hours per day. Also, in the future (2050) drainage potential remains good.

Detailed drainage modelling (IWM, 2022) shows a relatively good performance, with almost 80% polder area flood free under normal conditions. Deep inundation occurs in the southernmost corner of the polder, where local drainage conditions appear poor. Upgrading the existing regulators results already in an acceptable drainage performance under climate change conditions, even without excavating existing khals, as the detailed drainage model exercise shows.

5.3.4 Disaster management

Using the storm surge inundation model SFINCS and the Flood Impact Assessment Tool FIAT, an estimation has been made of the cyclone storm surge risk for each polder. Details of the method and results can be found in Annex C. The risk after embankment improvement has been calculated by assuming an embankment with a safety level of 1 in 50 years under current climate conditions and 1 in 25 years in 2050.

The current mortality risk due to cyclones is moderately low: 7 people per year but could increase almost 5-fold to 32 by the year 2050 due to climate change (Table 5-3). The economic risk is rather low (0.3 million US$ per year, which is around US$142 per ha per year), thanks to the existing embankment, which effectively reduces the damage of a 1 in 10 year storm surge to zero (Figure 5-7). After improving the embankments, the economic risks will be reduced half. However, the risk will rise again in the future due to increasing cyclone hazard and sea level rise. The high mortality risk would warrant a sufficient number of cyclone shelters and early warning. Current shelter capacity is about 70% of the polder population, which may be considered more than sufficient.

Table 5-3 Risk assessment Polder 40/1

40/1	Initial risk (no embankment)			Risk with existing embankment			Risk after embankment improvement		
	Damage USD/year	People affected per year	Mortality per year	Damage USD/year	People affected per year	Mortality per year	Damage USD/year	People affected per year	Mortality per year
Present	$878,144	124	11	$300,932	33	7	$134,839	20	6
2050	$895,411	134	49	$652,523	95	43	$269,860	41	32

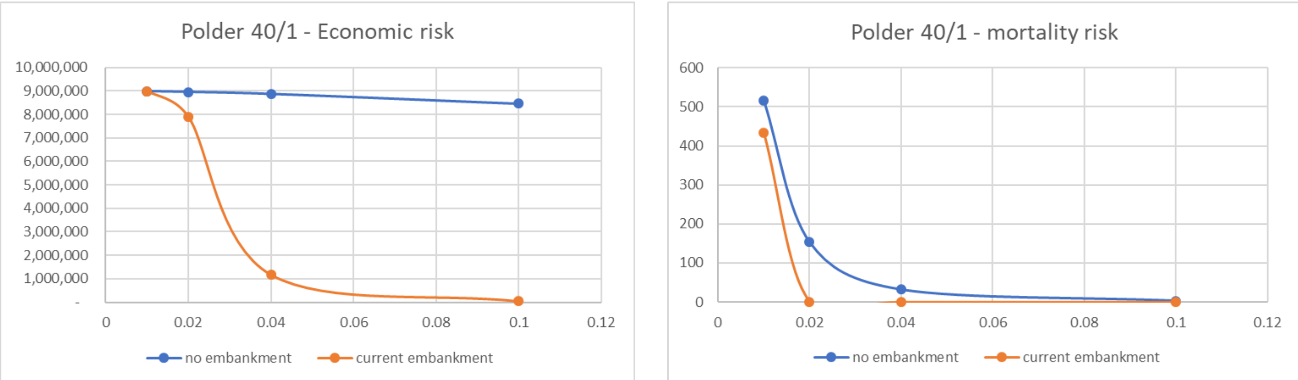


Figure 5-7 Risk profiles Polder 40/1 without and with current embankment (current conditions)

5.4 Cost and benefits of measures

5.4.1 Cost

Based on the above inventory of interventions a total cost estimate has been made, as presented in Table 5-4. The basis of the cost estimate are the unit prices developed for the typical designs that have been made for the proposed interventions. The unit prices used in the cost estimates use the specific boundary conditions of Polder 40/1 as described above. As the embankment within Polder 40/1 are largely protected by mangrove forests, the embankments need less height due to the fact there is no wave attack and less slope protection against waves. This make the average unit costs for the embankments in Polder 40/1 significantly less than for other polders. However, there is some uncertainty as to the required height of the embankments and needed slope protection. This makes it more difficult to provide exact investment for embankments. Therefor for Polder 40/1 a bandwidth is provided for the costs for the embankments (and in the next paragraph for the B/C -ratio).

Table 5-4 Cost estimation polder 40/1 (million US$)

Measure	**units**	**Costs (million US$)**
embankment re-sectioning (km)	23	5.4 – 8.2
retired embankment (km)	0	
bank protection (m)	3000	
slope protection (m)	3000	
land acquisition (ha)	3	
new/rehabilitate regulators (no.)	5/23	2.3
khal excavation (km)	15.4	0.4
new cyclone shelters (no.)	0	0

Measure	units	Costs (million US$)
Total		**8.1 – 10.9**

The embankments for polder 40/1 are classified as "Marginal" and "Intermediate" type of embankments, while combined storm surge levels and waves result required embankments "Type 1" (Figure 5-8), "Type 3A" (Figure 3-6) and "Type 3B" (Figure 5-10), depending on the characteristics of the embankments and its surroundings (details on the embankments design and costing can be found in Annex B). At locations of possible wave attack and locations that suffer from scour from river flow is advised to include a stone embankment that will protect the embankment from erosion. Depending on storm surge, average polder elevation and presence and magnitude of the wave attack the dimensions of the embankment and construction costs are determined (details can be found in Annex B).

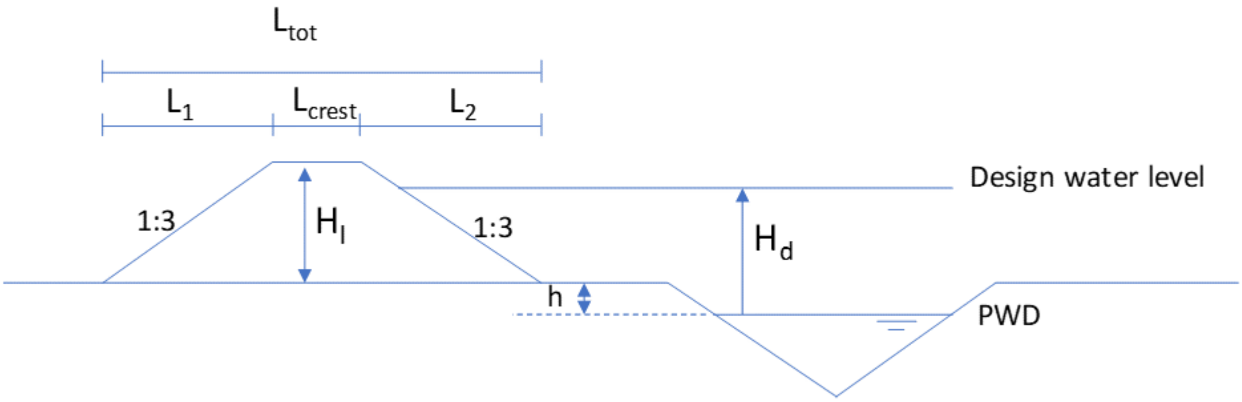


Figure 5-8; Embankment "Type 1"

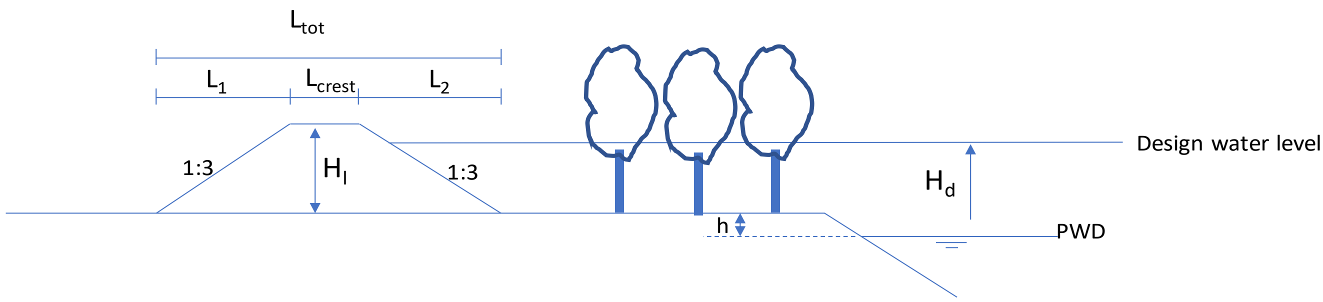


Figure 5-9; Embankment "Type 3A"

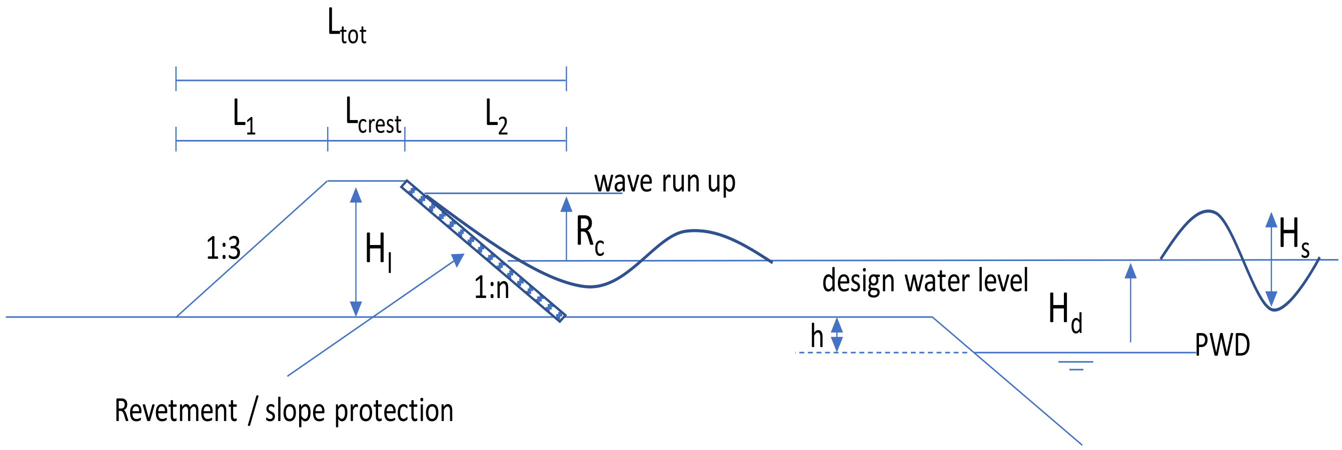


Figure 5-10; Embankment "Type 3B"

5.4.2 Benefits

The benefits for Polder 40/1 consist of risk reduction from embankments and improved agricultural yields from improved drainage. For Polder 40/1 the PV of the benefits are presented in Table 5-5. Based on the total costs of US$ 8.1 - – 10.9 million and total benefits of US$ 8.7 million the investments for Polder 29 have a B/C-ratio of between 0.8 – 1.0, which makes the proposed investments for Polder 40/1 feasible from an economic perspective.

Table 5-5 Benefit table for polder 40/1

Benefit Category	PV Benefits (Million $)
Flood risk reduction	6.9
Risk reduction from Cyclone Shelters	0
Agricultural benefits	1.8
Total	**8.7**

6 Polder 59/2

6.1 Present situation and problems

Polder 59/2 has a high population density and is not isolated (distance to Noakhali 17 km). Lying next to the Meghna river there is always freshwater available and no salinity problem. However, the same river causes serious river erosion. As can be seen from the map (Figure 5-1), large parts of the land area were lost to the river over the past decades. Protection work has been carried out during 2016 -17 and 2017 – 18 in the severe eroded areas. Parts of the protection works of 600m at the tail end of Ramgati and 3000m at Kamal Nagar have been implemented and the performance is satisfactory except areas at terminal points (CEIP-I, 2021). From the field visit in February 2020 it was known that around 36 km bank protection work was recommended by placing CC blocks in different phases in different sections. So far 5.5 km protection work in four different sections have been completed/being completed. As known, a DPP was submitted for the rest of the area to be protected.

Currently the polder has a high cyclone risk, and it is projected to increase significantly in the future.

The cropping pattern in the polder, using statistics of Upzilla Ramgati, is as follows: majority of land is under double cropping, with T. Aman during Kharif 1 and pulses/soybean during Rabi. Also, substantial triple cropping with Soybean – T. Aus – T. Aman.

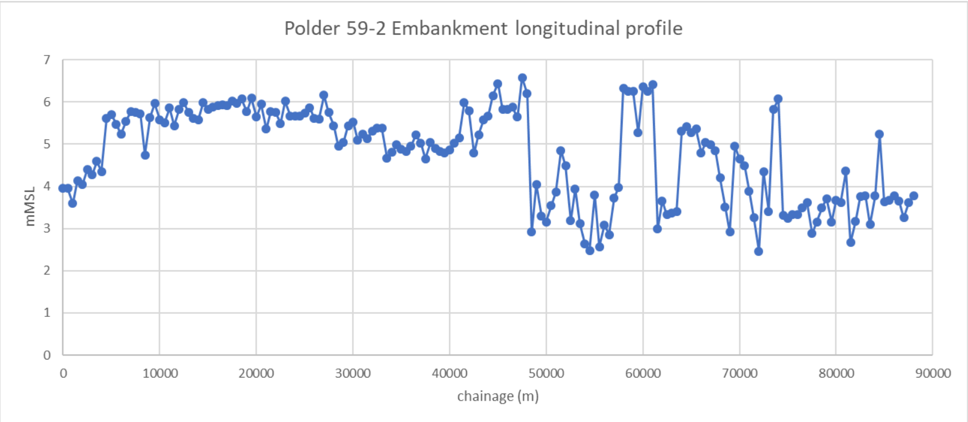


Figure 6-1 Polder 59/2 embankment height

Table 6-1 Basic data of Polder 59/2

gross area (ha)	average elevation (m)	perimeter (km)	pop (2011)	pop density (#/ha)	erosion (km)	distance to main town (km)	salinity current	salinity future	shelter capacity
21,255	3.10	82	372,021	17.5	4	17	0	0	105,525

Parameter	**description**
Embankment	Meghna River: storm surge plus waves, river erosion Shahbazpur Channel
Embankment efficiency	**High**: 4,537 people per km
Salinity	**Absent**: 0 ppt
Waterlogging	No permanent waterlogging (see Figure 6-4), but serious temporary waterlogging.
Subsidence	land subsidence for Meghna Region is **medium** (~5 mm/y)
Distance to district capital	17 km to Noakhali **Not a remote polder**
Outside water level	Tides, surges, monsoon water levels: Determines embankment heights and drainage

Cropping intensity	**228%** (based on entire Upazilla statistics) (mostly double crop rice/pulses)
Cyclone risk	**High**

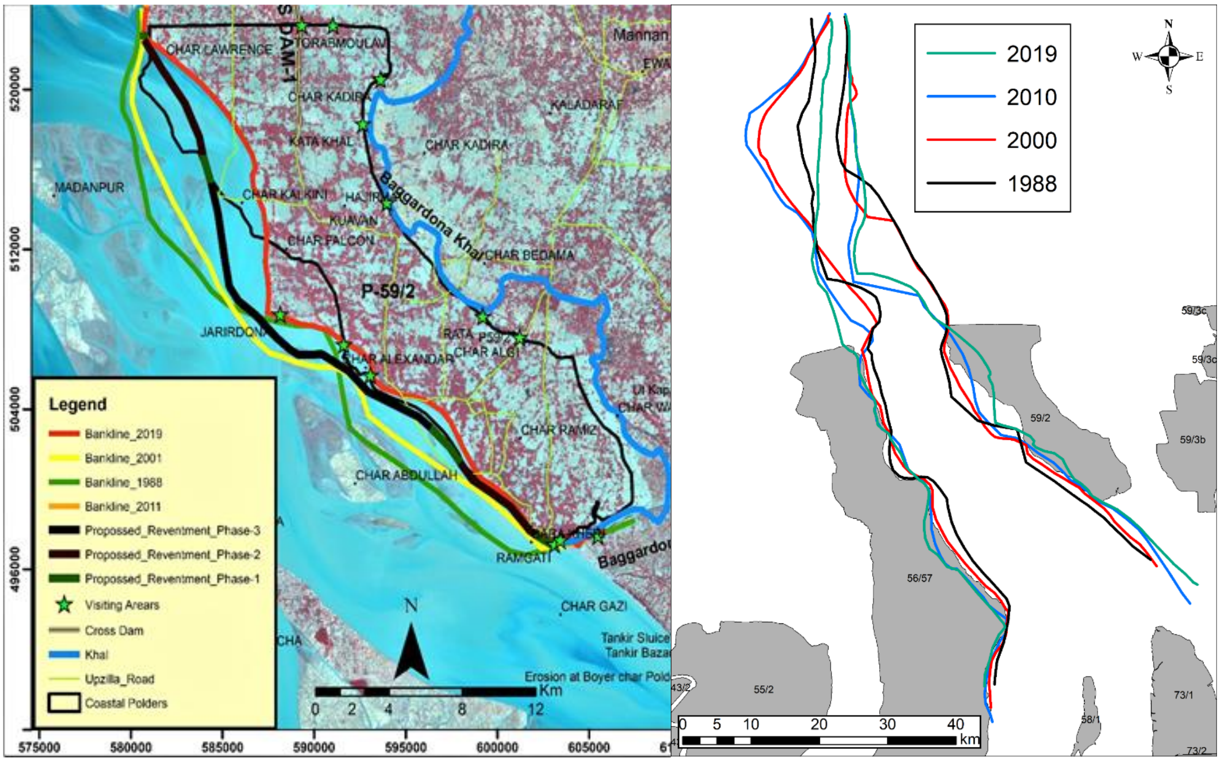


Figure 6-2 Map of Polder 59/2 (left) and river bank history in the middle Meghna (right)

Figure 6-3 Riverbank erosion (left) and khal sluice (right) in Polder 59/2

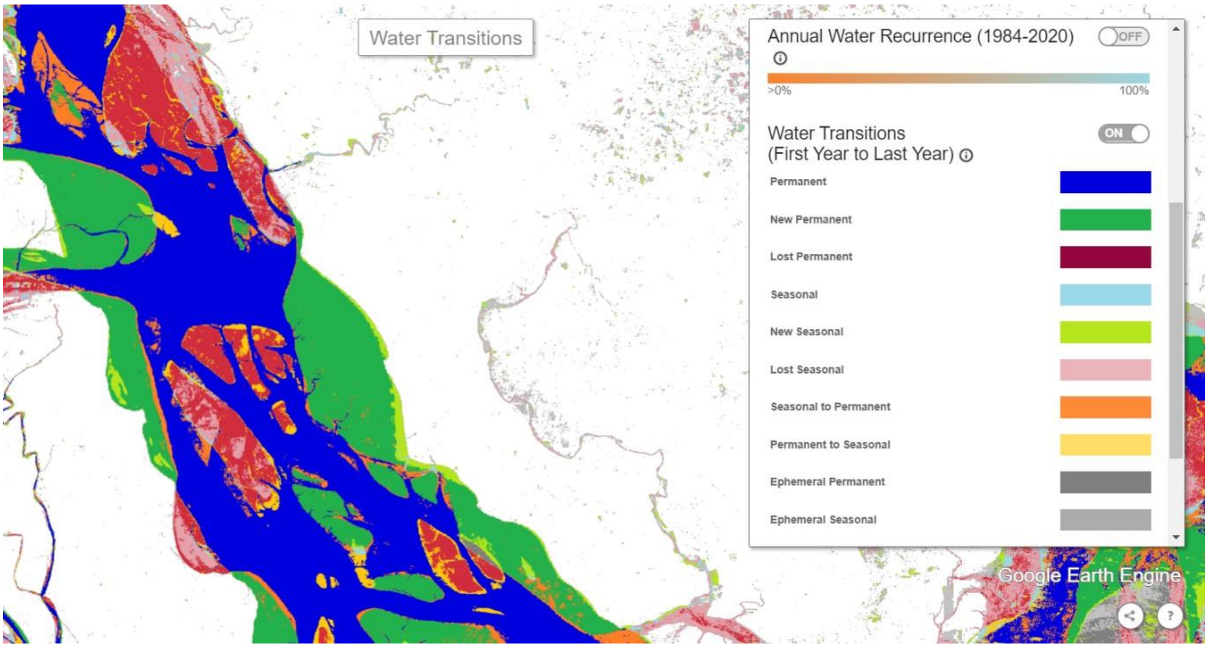


Figure 6-4 Flooding and drying map for polder 59/2 over the period 1984 – 2020, retrieved from http://global-surface-water.appspot.com/map. 'New permanent' refers to areas that were dry before 1984 but became permanent water bodies.

6.2 Future changes in boundary conditions

Precipitation: an increase rainfall is expected after 2070 during the monsoon (in the order of 5 to 10% relative to the year 2020). A decrease in rainfall during the winter months is projected after 2100 (in the order of -16%). Annual maximum daily precipitation is likely to increase after 2070 with 10 to 19%.

Subsidence: 15 cm in 2050

Cyclone frequency and intensity: Increase in cyclone frequency is found to be inconclusive, however, wind intensity is projected to increase with 4 – 8 %. The storm surge model developed by IWM (2018) has used an increase in wind speeds of 8%.

Salinity: the polder is adjacent to the Meghna river, hence there is abundant freshwater available.

Sea Level Rise: SLR used in the risk modelling is 30 cm in 2050

6.3 Polder design options and measures

6.3.1 Embankments

Erosion from Meghna river remains a big problem. Erosion rates are up to 200 m/year near polder 59/2. An important observation is that the erosion rates are mostly constant (i.e. not accelerating or slowing down) until a sudden large-scale realignment takes place.

Dredging may be used to reduce the bank erosion. Near Polder 59/2 the bank erosion is the result of deflection of tidal and river water by accreting channel or mouth bars. One way of alleviating bank erosion is therefore to dredge the channel bars and mouth bars and dispose the sediment close to the eroding banks.

Furthermore, there is a new/improved revetment proposed along the Meghna estuary of about 36 km of which 5.5 km has been finished. The principle design for Polder 59/2 is illustrated in Figure 6-5.

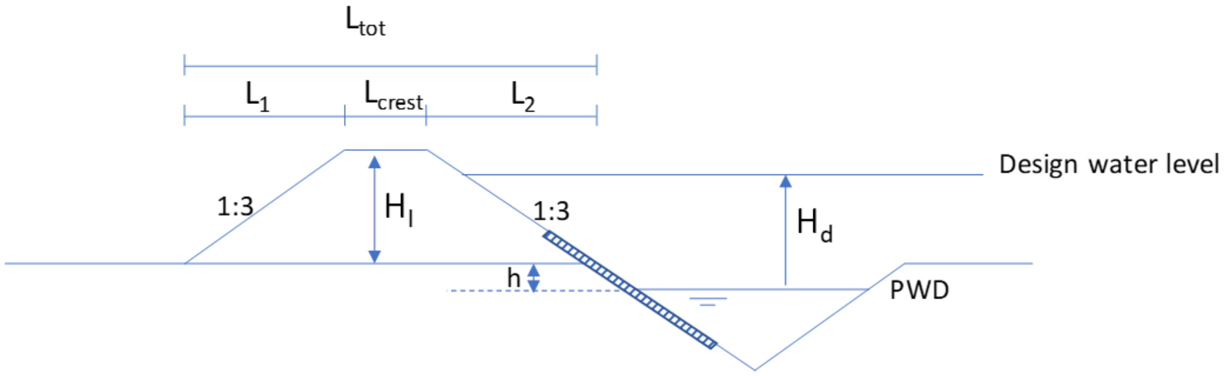


Figure 6-5 Typical design for embankments for Polder 59/2

6.3.2 Sediment management

There is no need for Tidal River Management (TRM). The Meghna river is deep and wide. The Polder is still relatively high (average +3mPWD).

6.3.3 Water management

Drainage conditions

Table 6-2 and Table 6-3 show the regulator data for Polder 59/2. There are 20 regulators/pipes with a total opening of 100.8 m^2. Average regulator opening is 5.04 m^2. Total length of khals is 131 km.

Table 6-2 Regulator data for Polder 59/2 (pipe)

	Structure Name	Khal Name	No of Pipe	Pipe Dia	Total opening	Remarks
1	Ratachora	Ratachora Khal	6	0.9	15.27	No siltation/scour
2	Kata Khal Drainage Sluice	Tulatuli Khal	1	0.9	2.545	No siltation/scour
3	Char Kadira Sluice		2	0.9	5.089	Siltation on both side
4	Chowdhury Bazar Sluice		4	0.9	10.18	Siltation on both side
5	Chouroibati Sluice		2	0.9	5.089	Siltation on both side
6	Tumchar Drainage Sluice		1	0.9	2.545	Siltation on both side
7	Tumchar Sluice DS-5		1	0.9	2.545	Siltation on both side
8	Chowdhury Bazar DS		1	0.9	2.545	Siltation on both side
9	Char Afjal Sluice		1	0.9	2.545	Siltation on both side

Table 6-3 Regulator data for Polder 59/2 (box)

	Structure Name	Khal Name	No of Vents	Width	Height	Total opening	Remarks
10	Jorirdona Sluice		4	1.5	1.8	10.8	Siltation on both side
11	Islamgonj Sluice Gate		1	1.5	1.8	2.7	Siltation on both side
12	Jorirdona Sluice-01		4	1.5	1.8	10.8	Siltation on both side
13	Sluice DS	Moshar Khal	2	2	2.3	9.2	Siltation on both side
14	Kuarvon Nagar Sluice		1	1.5	1.8	2.7	No siltation/scour
15	Jorirdona Sluice-02		3	1.5	1.8	8.1	Siltation on both side
16	Jorirdona Sluice-03		1	0.9	1.2	1.08	Siltation on both side
17	Nowakhola Gate		1	0.9	1.3	1.17	Siltation on both side

18	Nazar Patoway Sluice		1	1.5	1.8	2.7	Siltation on both side
19	Aswini Khal Sluice	Aswini Khal	1	0.9	1.2	1.08	Siltation on both side
20	Rogunathpur Sluice	Rogunathpur	1	1.2	1.8	2.16	No siltation/scour

The polder drains into the Lower Meghna River, Jarirdona River and Bhullar Khal through the drainage regulators. Based on the water level station SW278 in the Meghna river (Figure 6-6) the drainage window for the regulators on the west side of the polder is almost uninterrupted (23 h per day) (Figure 6-7). In 2050 this could reduce to 17.3 h per day (considering 15 cm subsidence, 20.8 cm SLR). No data are available for the other rivers on the east side of the polder (the water balance model assumes the same as on the west side).

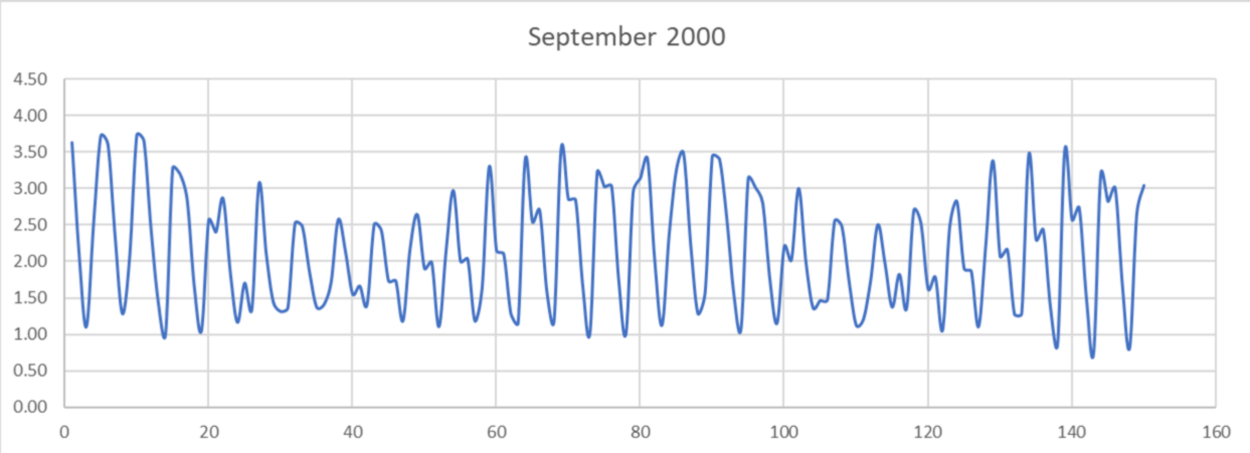


Figure 6-6 Water levels for station SW278 during the month of September 2000

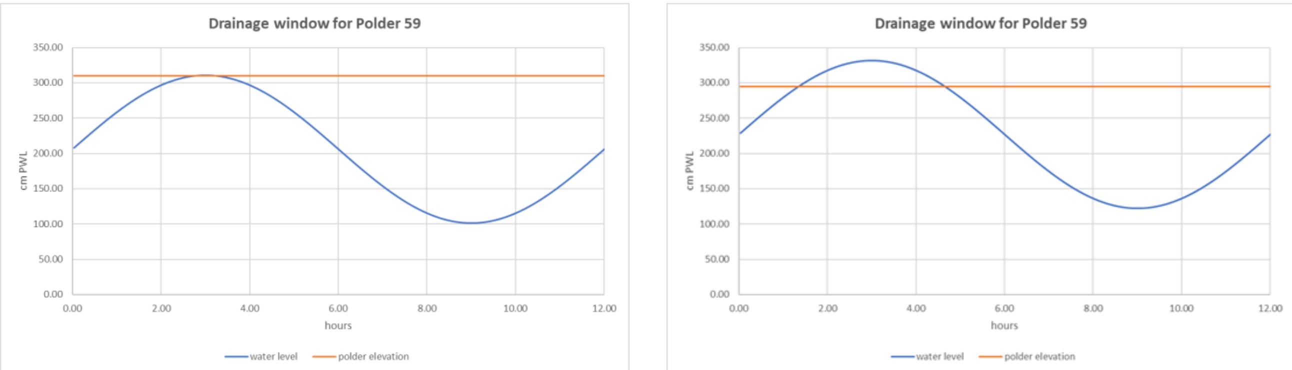


Figure 6-7 Drainage window (left: current, right: future) for Polder 59/2, based on average monsoon water level station SW279 (Meghna river)

Polder 59 performs quite satisfactorily in the model, should 100% khal efficiency now and in the future be guaranteed. With 50% efficiency prolonged waterlogging is expected in extremely wet years and with 25% efficiency, waterlogging duration will also occur in wet years. The performance is partly dominated by the khal infrastructure: the length per regulator is relatively long (6.6 km) and surface area per km khal is high (162 ha).

In reality (based on field visits), most of the regulators are not functioning effectively and cannot be closed. This means that during high tides the water flows into the khals. Also, many khals need to be excavated. These issues result in many places with local waterlogging, as it can take many days and sometimes up to one month to drain water after heavy rainfall.

Most inundation areas are located in the eastern part of the polder due to less conveyance capacity of the peripheral Jarirdona khal. The western part is mostly flood free as here the internal drainage channels are directly connected with the Lower Meghna River and water can flush easily during the ebb tide.

In the detailed drainage model (IWM, 2022), a combination of 9 new regulators, increasing the opening of three regulators and khal excavation could result in 72% flood free area for a 1 in 25 rainfall under climate change conditions.

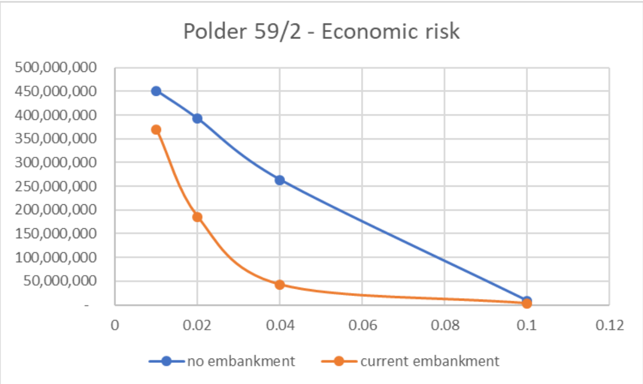
6.3.4 Disaster management

Using the storm surge inundation model SFINCS and the Flood Impact Assessment Tool FIAT, an estimation has been made of the cyclone storm surge risk for each polder. Details of the method and results can be found in Annex C. The risk after embankment improvement has been calculated by assuming an embankment with a safety level of 1 in 50 years under current climate conditions and 1 in 25 years in 2050.

Current embankments have a safety level of around 1 in 10 years (Figure 6-8), which result in a high economic risk of 10 million US$ per year (around 470 US$ per ha per year) (Table 6-4). After embankment improvement the economic risk will be halved. But the mortality risk will hardly be reduced and the embankments in 2050 will not prevent that this risk will be an order of magnitude higher than current. This would warrant a sufficient number of cyclone shelters and early warning. Current shelter capacity for over 100,000 people may be considered more than sufficient presently but may need to be enlarged in 2050 to account for population growth.

Table 6-4 Risk assessment Polder 59/2

59/2	Initial risk (no embankment)			Risk with existing embankment			Risk after embankment improvement		
	Damage USD/year	People affected per year	Mortality per year	Damage USD/year	People affected per year	Mortality per year	Damage USD/year	People affected per year	Mortality per year
Present	$23,449,699	16,743	239	$10,125,768	6,622	24	$5,547,265	4,759	21
2050	$34,128,060	26,567	1,565	$20,805,969	14,681	555	$12,600,104	10,628	548



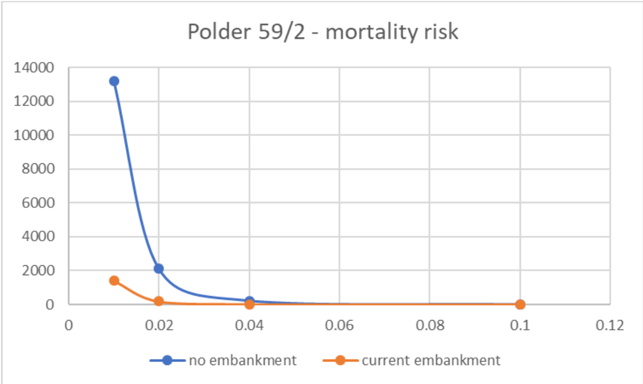


Figure 6-8 Risk profiles Polder 59/2 without and with current embankment (current conditions)

6.4 Cost and benefits of measures

6.4.1 Cost

Based on the above inventory of interventions a total cost estimate has been made, as presented in Table 6-5. The basis of the cost estimate are the unit prices developed for the typical designs that have been made for the proposed interventions. The unit prices used in the cost estimates use the specific boundary conditions of Polder 59/2 as described above.

Table 6-5 Cost estimation polder 59/2 (million US$)

Measure	units	costs (million US$)
embankment re-sectioning (km)		46.0
retired embankment (km)	0	
Slope protection (m)	30,500	
Bank protection (m)	10,000	90.3
Dredging Megnha shoal	??	
new/rehabilitate regulators (no.)	20/20	7.5
khal excavation (km)	131	3.3
new cyclone shelters (no.)	52	39
Total		**186.1**

With an average shelter capacity of 1,250 people, a current population estimate of 489,826 (growth since 2011 as per SSP2 scenario) and assuming that 33% of the population should to be able to take refuge in a shelter, the total shelters needed in 2020 is 129 ((33% x 489,826)/1250). There exist 77 shelters, so 52 new shelters have to be constructed. It is assumed that future population growth does not require additional shelters as also housing conditions will improve over time.

6.4.2 Benefits

The benefits for Polder 59/2 consist of risk reduction from embankments, risk reductions from cyclone shelters and improved agricultural yields from improved drainage. For Polder 59/2 the PV of the benefits are presented in Table 6-6. Based on the total costs of US$ 186.1 million and total benefits of US$ 183.2 million the investments for Polder 59/2 have a B/C-ratio of 0.98, which makes the proposed investments for Polder 59/2 feasible from an economic perspective. However, as a large part of the investments are to the estimated quantity in riverbank protection (US$ 90.3 million) a reduction or increase in total length in embankments needing protection will result in a different economic feasibility for the investments for Polder 59/2. Furthermore, the change from riverbank protection to an option with dredging can again change both the costs and benefits for the investments. Due to the large uncertainties surrounding the investments for Polder 59/2 more insight is required into future requirements for riverbank protection and/or dredging.

Table 6-6 Benefit table for polder 15

Benefit Category	PV Benefits (Million US$)
Flood risk reduction	121.6
Risk reduction from Cyclone Shelters	43.3
Agricultural benefits	18.2
Total	**183.2**

7 Polders 64/1a and 64/1b

7.1 Present situation and problems

Polder 64/1 has a high population density, is not isolated (good road to Chittagong) and has a salinity problem. According to local people the low land area faces water logging problems due to silted up drainage khals and for 2-3 days during flash flood conditions. The embankment at the sea side of the polder is partly damaged. Flash floods are a special risk for these polders (CEIP-I, 2021). Note that there is no water management organization in the polders.

Polder 64/1a is situated in the Easter Hilly region of Bangladesh in the Upazilas of Banshkhali of Chattogram district and is surrounded by Sangu River (north), Jalkador Khal (east) and Bay of Bengal (west) (Figure 7-2). The total length of Jalkador Khal is about 31 km. The existing condition of the peripheral embankment is good in most of the portion of the Eastern side. The embankment of polder is brick soiling and partially paved. The embankment at the sea side of the polder is kancha and damaged in the salt farming areas due to movement of salt carrying tractors. Hence, part of the embankment of Polder 64/1a needs to be repaired and maintained. Sea dike and slope protection construction work has been ongoing from Moulobipara to Khankhanabad (4800m) and Gondamara to oufall of Jalkadar Khal (1900m). Only the erosion prone areas in the sea side has been protected. The construction has been implemented by BWDB.

During the field visit of the IWM team in July 2019, some encroachment of khals was observed as well as deposition of silt upstream of sluices. The important Jalkador khal between the two polders is narrow and silted up at the northern part, but wider and deeper in the south. Hence, excavation of the northern part of the khal, as well as some internal khals is required to improve drainage. A second field visit (October 2020) observed that most of the 25 sluices are functioning. Some of them need to be replaced. Local people use the sluices for drainage and flushing for fish, salt cultivation and agriculture, though some are not designed to serve several purposes.

Polder 64/1b is situated east from the Jalkador Khal and is further surrounded by the Sangu River in the north and the Banshkhali Upazila road to the east (Figure 7-4). The major problem at present in the polder as observed was erosion at the Sangu River along left bank at Sangu Bridge to outfall of the River. According to BWDB, 5 km along left bank of Sangu River at Hajigaon to Eshorbabur Hat is under threat of erosion. Around 60-200 m has been eroded since 2004-2016.

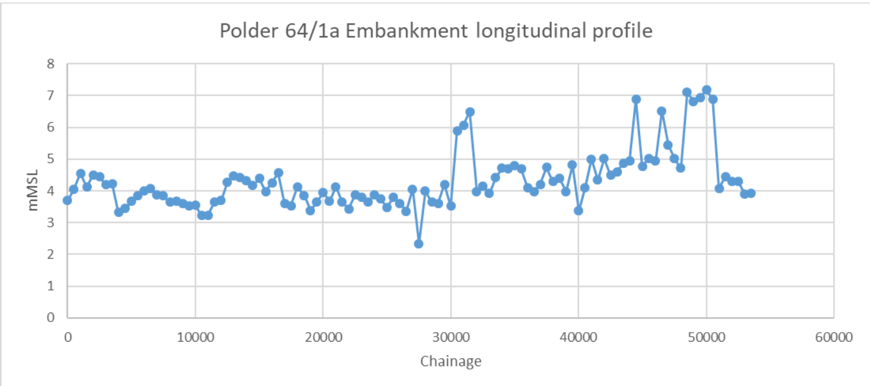


Figure 7-1 Polder 64/1a embankment height

The cropping pattern in the polder, using statistics of Upazilla Baskhali, is as follows: majority of land is under double cropping, with T. Aman during Kharif 1 and Boro or vegetables during Rabi. Also, a substantial part is under triple cropping, with Boro – T. Aus – T. Aman. Also worth mentioning is a rather wide diversity of other crops growing, such as spices, potato, fruits, tomato, beetle leaf etc.

Surface water salinity is rather high, as the Jalkadar Khal is in open connection to the sea in the south. In the north it gets water from the Sangu river, which is brackish. Measured salinity in the surface water ranges from

4.96 ppt to 20.6 ppt in the khals inside the polder. Groundwater salinity ranges from 0.09 ppt to 0.38 ppt (see Figure 7-3). Local people use tube well and well water for drinking and domestic uses. Due to high salinity the surface water cannot be used for irrigation. Groundwater extracted by deep tube wells is used for irrigation.

The cyclone risk is high, as storm surges can reach very high levels. Over the past decades many shelters have been built so that their capacity is very high.

Table 7-1 Basic data of Polder 64/1a+b

gross area (ha)	average elevation (m)	perimeter (km)	pop (2011)	pop density (#/ha)	erosion (km)	distance to main town (km)	salinity current	salinity future	shelter capacity
13,750	2.34	111	268,910	19.6	2	25	1-20	increase	103,735

Parameter	**description**
Embankment	Sangu River, Jalkadar Khal and Open Sea: Storm surge plus waves, coastal erosion
Embankment efficiency	**High**: 2,422 people per km
Salinity	**High**
Waterlogging	waterlogging is a problem and mainly confined to the southern part (see Figure 7-6). But also in other parts temporary waterlogging occurs.
Subsidence	land subsidence for Chittagong Region is around 2.5 mm/y
Distance to district capital	25 km to Chittagong, but a good road connection. **Not a remote polder**
Outside water level	Tides, surges, monsoon water levels: Determines embankment heights and drainage potential
Cropping intensity	**222%** (based on entire Upazilla statistics) (mostly double crop rice/rice and vegetables)
Cyclone risk	**very high**

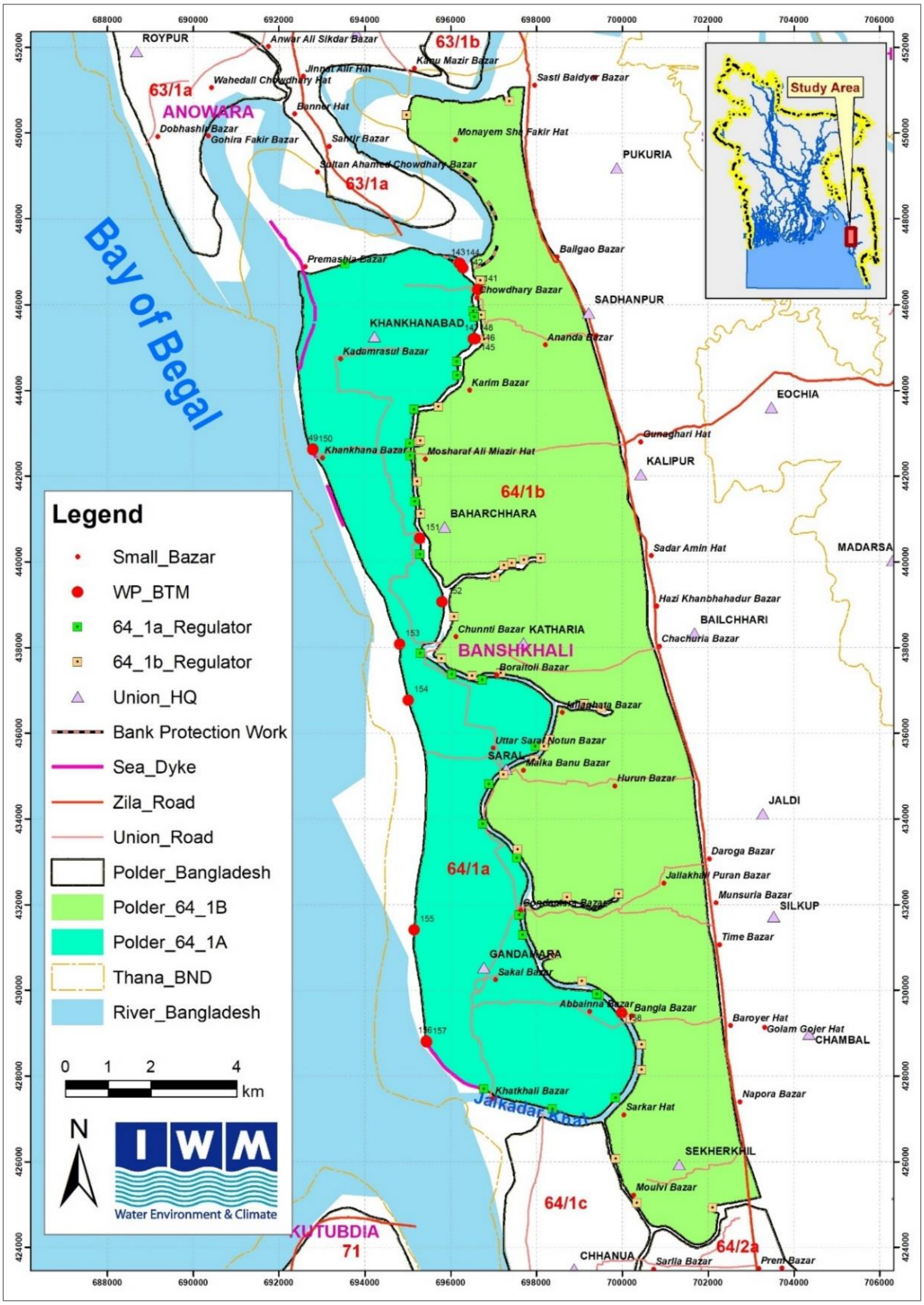


Figure 7-2 Map of Polder 64/1a+b

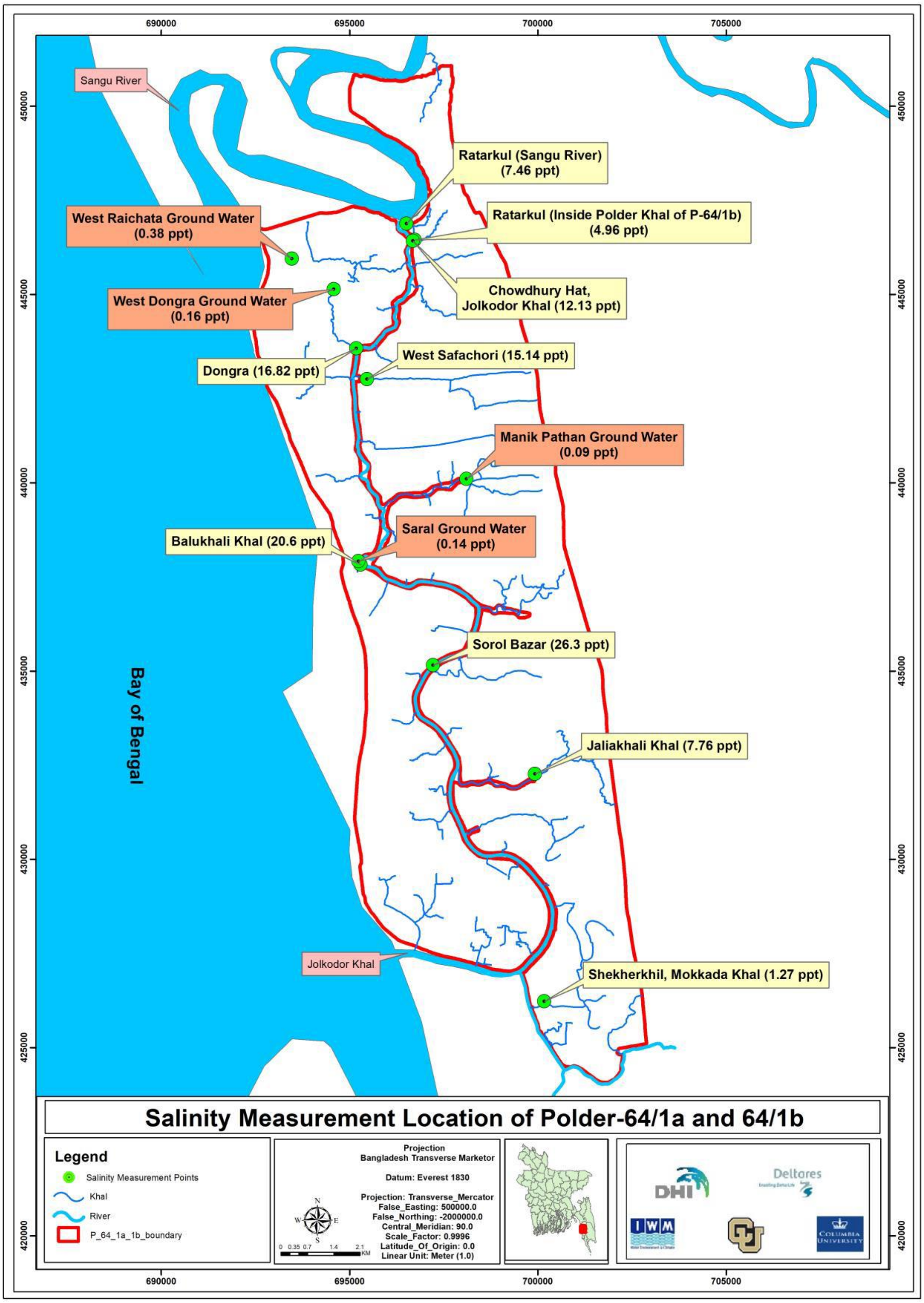


Figure 7-3 Salinity measurements in March 2022 in Polder 64/1a+b (Source: IWM)

Figure 7-4 Coastline and sea dike of Polder 64/1a

Figure 7-5 Agricultural landscape Polder 64/1a

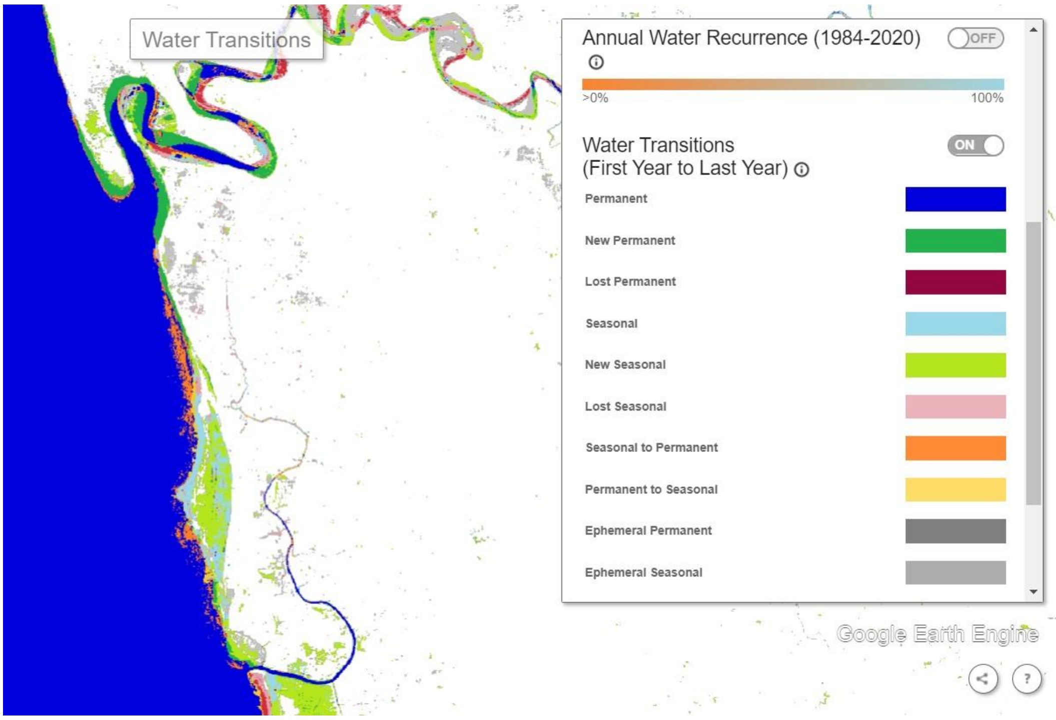


Figure 7-6 Flooding and drying map for polder 64/1a+b over the period 1984 – 2020, retrieved from http://global-surface-water.appspot.com/map. 'New permanent' refers to areas that were dry before 1984 but became permanent water bodies.

7.2 Future changes in boundary conditions

Precipitation: an increase rainfall is expected after 2070 during the monsoon (in the order of 5 to 9% relative to the year 2020). A decrease in rainfall during the winter months is projected after 2100 (in the order of -15%). Annual maximum daily precipitation is likely to increase after 2070 with 10 to 13%.

Subsidence: unknown. Assumed 2.5 mm/year.

Cyclone frequency and intensity: Increase in cyclone frequency is found to be inconclusive, however, wind intensity is projected to increase with 4 – 8 %. The storm surge model developed by IWM (2018) has used an increase in wind speeds of 8%.

Salinity: higher sea level will cause more salinity intrusion in the Jalkadar khal.

Sea Level Rise: SLR used in the risk modelling is 30 cm in 2050.

7.3 Polder design options and measures

7.3.1 Embankments

There is ongoing work to strengthen the sea dike with slope protection (CC blocks). Large parts of the current embankment are in a rather poor state and need repair/improvement. Considering the exposure of the coast to potentially large storm surges (more than 6 m high) and the likely future increase in cyclone risk, it would be rational to strengthen and heighten the embankments along the sea coast.

There is a large foreshore at most places and coastal erosion seems absent. Therefore, no additional erosion prevention measures are needed along the sea side. There is some river erosion from the Sangu River that requires attention. Typical designs for the embankments for Polder 64/1A & 1B are presented in Figure 7-7 and Figure 7-8.

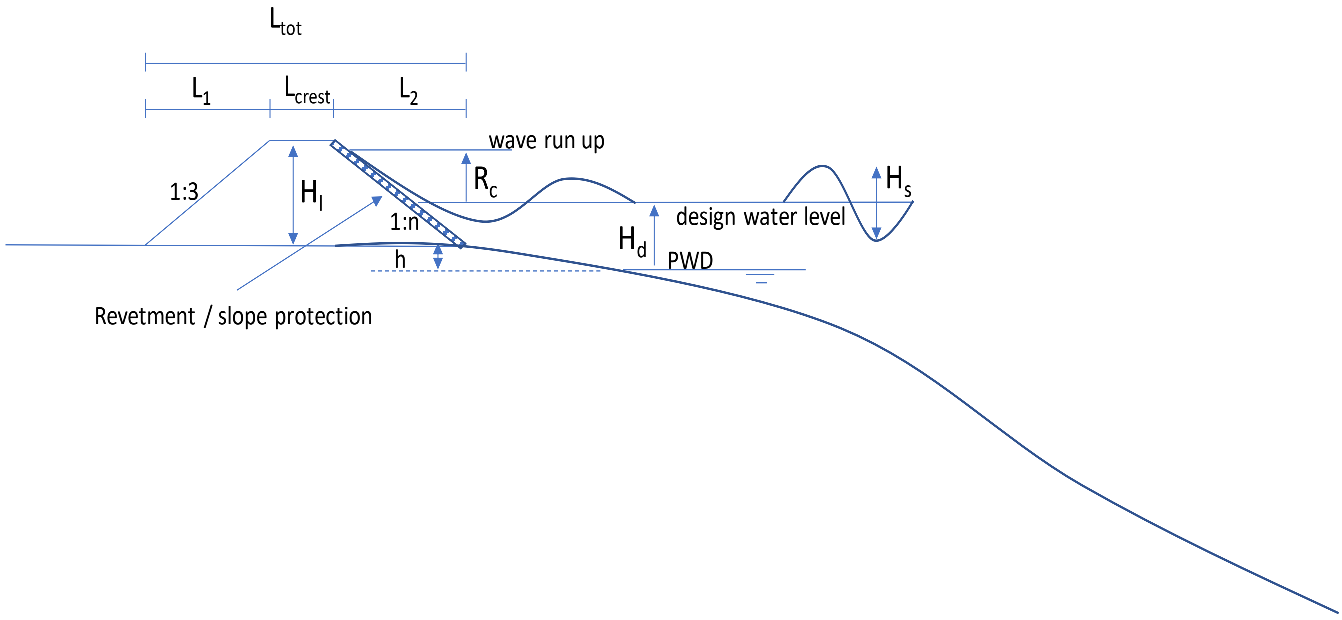


Figure 7-7 Typical design for sea defence embankment for Polder 64/1A

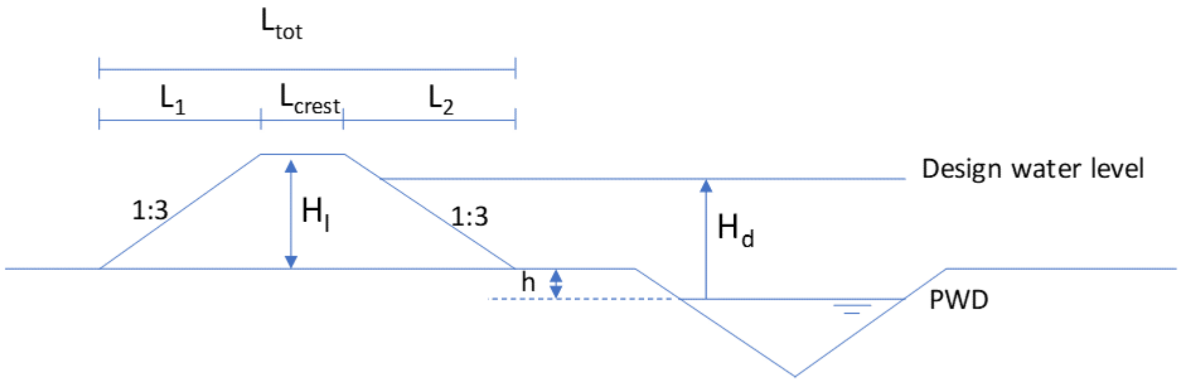


Figure 7-8 Typical design for intermediate embankment for Polder 64/1A and 64/1B

7.3.2 Sediment management

There is no need for TRM (no silting peripheral rivers).

7.3.3 Water management

Drainage conditions

Table 7-2 shows the regulator data for Polder 64/1a and 1/b. There are 50 regulators, most of which are working, with a total opening of 79.08 m^2. Average regulator opening is 1.58 m^2. Total length of khals is 117 km.

Table 7-2 Regulator data for Polder 64/1a and 1b

	Structure ID	No. of Vent	Vent Width (m)	Vent Height (m)	Total opening
	641/a				
1	DS_1	1	1.52	1.82	2.7664
2	DS_2	1	0.47	0.6	0.282
3	DS_3	2	0.6	0.76	0.456
4	DS_4	4	0.59	0.75	0.4425
5	DS_5	1	0.96	1.22	1.1712
6	DS_6	1	0.93	1.18	1.0974
7	DS_7	1	0.93	1.18	1.0974
8	DS_8	2	0.93	1.18	1.0974
9	DS_9	2	0.71	0.9	0.639
10	DS_10	1	0.91	1.12	1.0192
11	DS_11	1	0.91	0	0
12	DS_12	1	0.94	1.2	1.128
13	DS_13	1	0.9	1.21	1.089
14	DS_14	1	0.91	1.22	1.1102
15	DS_15	1	1.5	1.8	2.7
16	DS_16	1	0.71	0.91	0.6461
17	DS_17	1	0.91	1.22	2.13
18	DS_18	2	0.91	1.21	1.1011
19	DS_19	2	0.91	1.21	1.1011

	Structure ID	No. of Vent	Vent Width (m)	Vent Height (m)	Total opening
	64/1b				
20	DS_1	1	1.52	1.83	2.7816
21	DS_2	1	0.91	1.22	1.1102
22	DS_3	4	0.83	1.06	0.8798
23	DS_4	3	0.83	1.06	0.8798
24	DS_5	4	0.71	0.91	0.6461
25	DS_6	1	0.71	0.91	0.6461
26	DS_7	7	1.14	1.45	1.653
27	DS_8	1	0.91	1.22	1.1102
28	DS_9	1	1.52	1.82	2.7664
29	DS_10	1	1.19	1.52	1.8088
30	DS_11	1	0.91	1.22	1.1102
31	DS_12	2	1.67	2.13	3.5571
32	DS_13	1	0.71	0.91	0.6461
33	DS_14	1	1.52	1.83	2.7816
34	DS_15	1	0.91	1.22	1.1102
35	DS_16	1	0.59	0.76	0.4484
36	DS_17	1	0.95	1.21	1.1495
37	DS_18	2	1.67	2.13	3.5571
38	DS_19	1	0.71	0.91	0.6461
39	DS_20	1	0.91	1.22	1.1102
40	DS_21	1	1.52	1.83	2.7816
41	DS_22	1	0.91	1.22	1.1102
42	DS_23	1	0.91	1.22	1.1102
43	DS_24	2	1.52	1.83	2.7816
44	DS_25	2	1.67	2.13	3.5571
45	DS_26	1	1.52	1.82	2.7664
46	DS_27	1	1.52	1.82	2.7664
47	DS_28	1	1.5	1.8	2.7
48	DS_29	1	1.5	1.8	2.7
49	DS_30	1	0.94	1.2	1.128
50	DS_31	1	1.82	2.31	4.2042

Both 64/1a and 64/1b drain into the Jalkadar Canal, which flows in between them (except for some sluices that drain into Sangu river). Based on the nearest water level station SW176 along the coast (Figure 7-9) the drainage window for the regulators is almost uninterrupted (23.1 h per day) (Figure 7-10). In 2050 this could reduce to 19.1h per day (considering 7.5 cm subsidence, 20.8 cm SLR).

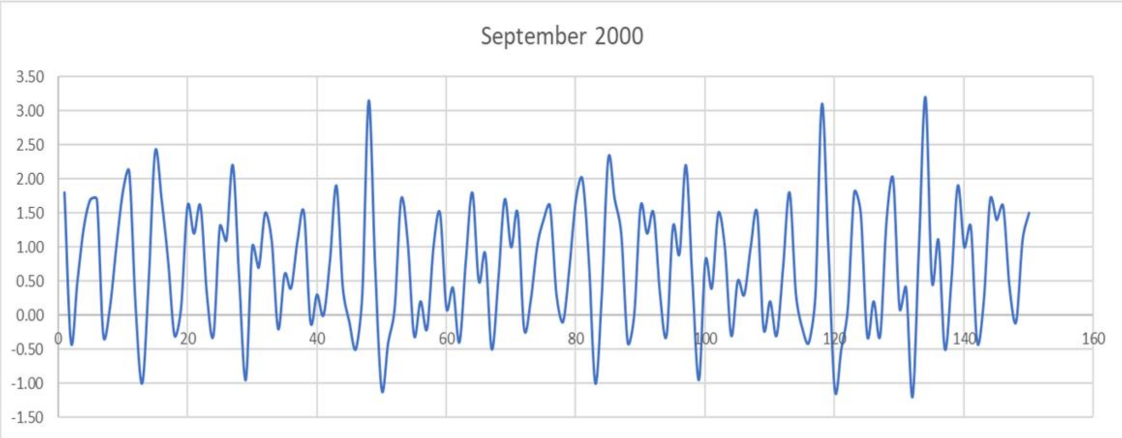


Figure 7-9 Water levels for station SW176 during the month of September 2000

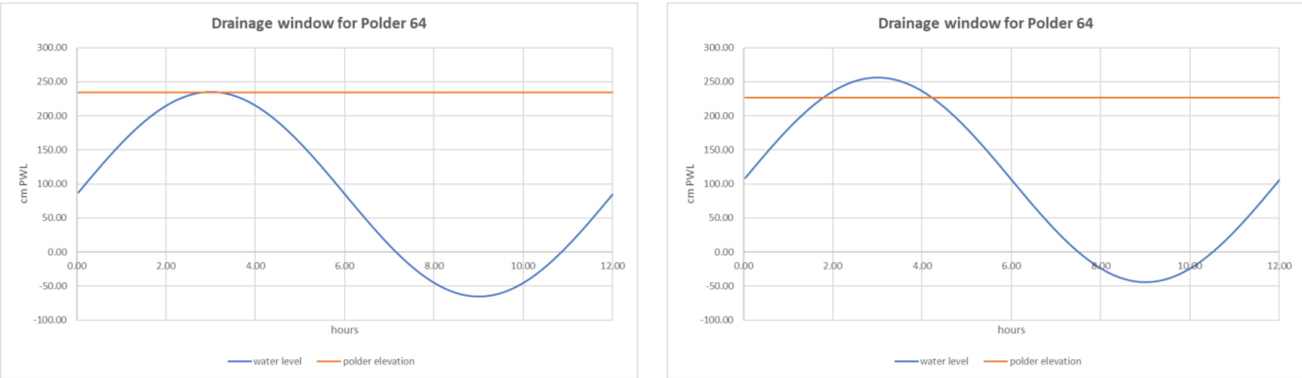


Figure 7-10 Drainage window (left: current, right: future) for Polder 64/1a and 1b, based on average monsoon water level station SW176

Of all studied polders, Polder 64/1a+b shows the best and almost perfect drainage model results under all conditions and scenarios. With 50 regulators and a relatively short khal length per regulator (2.3 km) the drainage infrastructure seems sufficient for now and in the future, although the drainage window would reduce from 23 to 19 hours per day.

However, in reality, water logging problem exists at different locations of both the polders. There are water logging problems at Premasia, Dongra, West Dongra, West Raichata and Gondamara of polder 64/1a and at West Safachori, Shekherkhil, Ratarkul and Manikpara of polder 64/1b. Local people demanded the water logging problem can be resolved by the dredging the countryside khal and peripheral khal. They also demanded for gates with larger vents and increased number of vents so that the gates can easily flush out the water (Field visit March 2022).

The detailed drainage modelling (IWM, 2022) showed that for a 5 days cumulative rainfall with a 1 in 10 year return period the current arrangement would still keep 85 to 95% of the polders flood free. However, this will reduce significantly under climate change conditions. Therefore, additional measures to improve drainage, esp. improving the functioning of khals are needed.

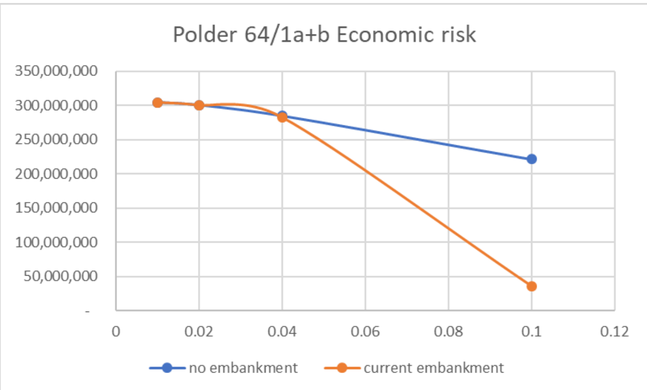
7.3.4 Disaster management

Using the storm surge inundation model SFINCS and the Flood Impact Assessment Tool FIAT, an estimation has been made of the cyclone storm surge risk for each polder. Details of the method and results can be found in Annex C. The risk after embankment improvement has been calculated by assuming an embankment with a safety level of 1 in 50 years under current climate conditions and 1 in 25 years in 2050.

The current embankments cannot prevent that the economic risk is very high (21 million USD per year, which is around 1500 USD per ha per year) (Table 7-3). Also, the mortality risk due to cyclone surge is very high: 2,117 persons per year. Figure 7-11 shows that the current embankment does not reduce the cyclone risk for people. The reason is that most of the risk exists due to a storm surge with a 1 on 50 to 1 in 100 years return period which would inundate the polder with several meters of water. This risk could double in the year 2050 due to climate change, even with improved embankments. It would warrant a sufficient number of cyclone shelters and early warning. Current shelter capacity for over 100,000 people may be considered more than sufficient presently but needs to increase in 2050 to account for population growth.

Table 7-3 Risk assessment Polder 64/1a+b

64/1	Initial risk (no embankment)			Risk with existing embankment			Risk after embankment improvement		
	Damage USD/year	People affected per year	Mortality per year	Damage USD/year	People affected per year	Mortality per year	Damage USD/year	People affected per year	Mortality per year
Present	$27,062,607	23,123	2,225	$21,431,009	18102	2,117	$4,558,941	3,876	1,410
2050	$29,059,340	25,125	5,424	$27,853,622	23640	5,260	$9,149,402	7,779	4,119



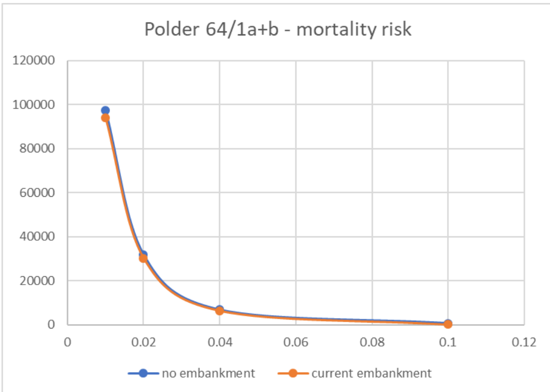


Figure 7-11 Risk profiles Polder 64/1a and 64/1b without and with current embankment (current conditions)

7.4 Cost and benefits of measures

7.4.1 Cost

Based on the above inventory of interventions a total cost estimate has been made, as presented in Table 7-4. The basis of the cost estimate are the unit prices developed for the typical designs that have been made for the proposed interventions. The unit prices used in the cost estimates use the specific boundary conditions of Polder 29 as described above.

With an average shelter capacity of 1,250 people, a current population estimate of 300,620 (growth since 2011 as per SSP2 scenario) and assuming that 33% of the population should to be able to take refuge in a shelter, the total shelters needed in 2020 is 80 ((33% x 300,620)/1250). There exist 71 shelters, so 9 new shelters have to be constructed. It is assumed that future population growth does not require additional shelters as also housing conditions will improve over time.

Table 7-4 Cost estimation polder 64/1a+b (in million US$)

Measure	Units P64/1a	Units P64/1b	Costs P64/1a (million US$)	Costs P64/1b (million US$)
embankment re-sectioning (km)	58	53	169.1	21.8
retired embankment (km)	0			
slope protection (m)	7,000			
bank protection (m)	3,000	450	26.8	3.7
new/rehabilitate regulators (no.)	0/24	0/33	0.6	0.8
khal excavation (km)	36	78	0.9	2.0
new cyclone shelters (no.)	0	9	0	6.8
Total			**186.1**	**35.0**

7.4.2 Benefits

The benefits for Polder 64/1a+1b consist of risk reduction from embankments, risk reductions from cyclone shelters and improved agricultural yields from improved drainage. For Polder 64/1a+1b the PV of the benefits are presented in Table 7-5. Based on the total costs of US$ 186.1 million and total benefits of US$ 262.1 million the investments for Polder 64/1a have a B/C-ratio of 1.3, which makes the proposed investments for Polder 64/1a very feasible from an economic perspective. For Polder 64/1b the total costs of USD 35 million and total benefits of US$ 474.2 million the investments for Polder 64/1b have a B/C-ratio of 13.5, which makes the proposed investments for Polder 64/1b extremely feasible from an economic perspective. The high B/C-ratio is predominantly based on the flood risk profile of the polder, which has a significant decline in mortality rate resulting from the new embankments. This is caused by the high storm surge calculated for this stretch of the coast, which according to the flood risk model can inundate the entire polder 64/1b.

Table 7-5 Benefit table for Polder 64/1a+1b (million US$)

Benefit Category	PV Benefits Polder 64/1a (million US$)	PV Benefits Polder 64/1b (million US$)
Flood risk reduction	257.2	460.4
Risk reduction from Cyclone Shelters	0	7.0
Agricultural benefits	4.9	6.8
Total	**262.1**	**474.2**

8 Management Plans

8.1 Operational plan

The operational plan for water management should distinguish three levels in the temporal and three levels in the spatial domain. At the spatial domain we have the Catchment, Sub-catchment and Fields level (see Figure 8-1). Timewise, the planning of operation is divided into three parts: Seasonal Water Management Plan; Weekly Operation Targets and Day-to-day Operation.

At the catchment scale, the water levels in the primary or main khals can be managed with a sluice and should ideally serve the interests of all stakeholders in that catchment, i.e. farmers, fishermen, shrimp farmers and others. In the seasonal water management plan the objectives for the operation of each sluice is determined. In the wet season drainage will usually get priority while in the dry season, conservation of fresh water inside the polder becomes the predominant factor. The plan needs to be prepared well ahead of the cropping season so that critical farm operations can be carried out in line with the plan. The seasonal water management plan basically consists of ideal water levels and discharges in the khals and sluices.

By comparing the parameters in the Seasonal Water Management Plan with the actual field conditions, operation targets on a weekly basis should be set. These targets should maintain the desired water levels and primary and secondary khals and should enable the farmer to arrive at suitable field conditions.

Daily structure operation requirements involve manipulation of gates or pumps to maintain water levels in the channels as laid down in the operation target. For polders with a limited drainage window caused by tidal movement, this requires 24 hours attendance of the gates.

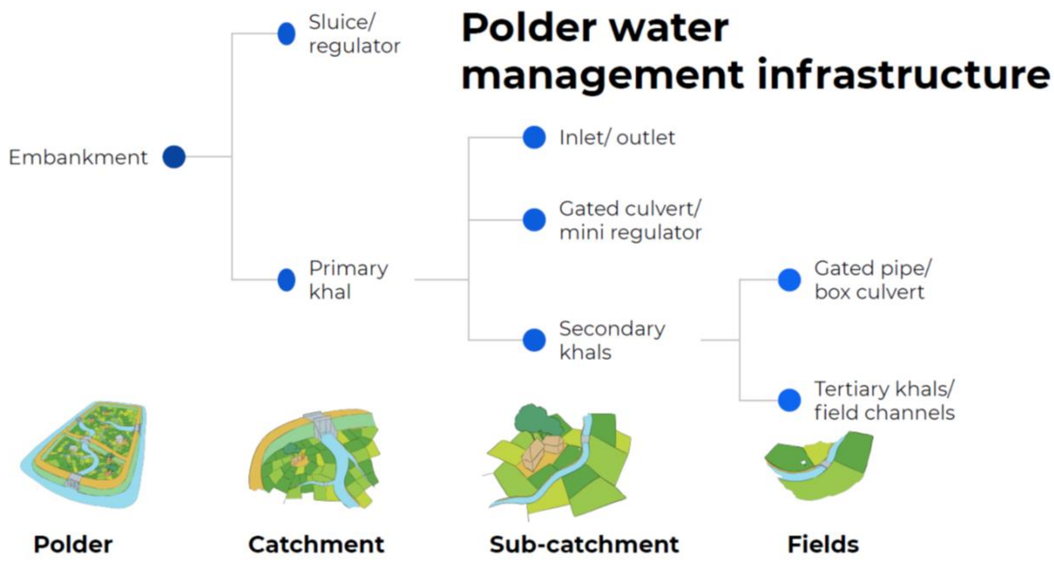


Figure 8-1 Different scales of polder water infrastructure (Source: Blue Gold).

Although in theory the catchment plan should benefit the field conditions, in reality this is often not the case. Many secondary and tertiary khals have cross dams in place to help to store water for a small group of people (e.g. for irrigation purposes or fish cultivation) living next to the khals. This reduces the connectivity of the sub-catchments and hampers drainage and irrigation for significant portion of lands. Would sluice operation be optimised, it would not have any effect on these more interior areas. Therefore, good maintenance is indispensable for a sound operation.

8.2 Specific operation issues for each polder

Polder 15

Polder 15 suffers from high saline water, because most of the area is under gher operation. Operation of the regulators is often done by or under control of the gher owners. With opposing needs, an optimal operation system would take into account the interest of both farmers and gher owners to achieve a fair distribution. Therefore, there is a need for change in the regulation of the operation.

Productivity and profitability in brackish water aquaculture can be increased significantly through diversification and better water management. For instance, shrimp-Tilapia in the dry season and carp-catfish in the wet season showed higher profitability than monoculture of shrimp (Kabir et al., 2015).

Preliminary experiments with growth of vegetables and fodder on dikes also suggests it is possible to integrate vegetable production on dikes in the wet season and support livestock by growing grass on the dikes (Kabir et al., 2015). Also, a combination of shrimp and fish with a rice crop is feasible. A possible cropping pattern is given in Table 8-1.

Table 8-1 Combined paddy / shrimp / fish cropping pattern

Crop	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Aman paddy								■	■	■	■	■
Fish/shrimp		■	■	■	■	■	■					
Vegetables*						■	■	■	■	■	■	■

* on homestead lands

The productivity of rice in ghers used for shrimp culture is often hampered by salinity, submergence and water stagnation as a result of high rainfall and lack of drainage. Improving drainage management is the key to improving yield and yield stability of aman crops in shrimp ghers, to enable better leaching of salt prior to rice establishment, and to maintain a suitable water depth for the rice crop throughout the season (Rahman et al., 2015).

Polder 29

Water logging, salinity and poor water management is a key problem in this polder hampering agricultural improvements. However, in theory it is possible to produce 8 to 9 t/ha of rice per year in medium salinity areas of the coastal zone of Bangladesh by growing a modern, short duration, salt tolerant aus variety, followed by a modern aman variety (Ritu et al., 2015). But in order to unlock this potential better water management is required that reduces the salinity problem and optimises paddy growth. This includes the separation of lands of higher and lower elevation with small levees to prevent accumulation of water in lower lying lands, and for the ability to drain (Ritu et al., 2015).

Besides the in-polder drainage improvements, on the longer term the gravity drainage to the rivers will become a problem due to relative sea level rise. Already in 2050, the drainage window will be reduced to an estimated 10 hours per day. Pumped drainage will inevitably become necessary.

Polder 40/1

In this polder, improvement of irrigation and drainage could increase the agricultural crop output. To unlock the production potential, improvements in surface water irrigation are required. Using pumps (such as axial flow pumps) could easily bring agricultural land under rabi season cultivation (Qureshi et al., 2015).

Polder 59/2

There are relatively few structural water management problems in this polder. Freshwater is abundant and external drainage conditions are good. But the internal drainage system needs to be revitalized (khal excavation and removal of cross dams, repairing regulators etc.).

Polder 64/1a+b

These two polders require revitalization of the drainage system (especially khal excavation). High external salinities are a problem for the dry season and makes surface water irrigation unfeasible. The only option is to use groundwater, although this also has its limitations (groundwater salinity up to 0.4 ppt).

8.3 Maintenance plan

There are broadly speaking three types of maintenance: routine maintenance, periodic maintenance and emergency works. The routine or **preventive maintenance** activities are needed to keep the water infrastructure in order. This includes simple activities that can be done by local people, such as maintaining a good vegetation cover on embankments, cleaning, painting and greasing of regulator mechanics and cleaning of khals from aquatic weeds and floating debris.

Periodic maintenance intends to bring the components of the hydraulic infrastructure back to its design standard. The works are more expensive than preventive maintenance and have the character of repair works and are identified during the field assessment at (more or less) regular intervals.

Emergency works cover unforeseen interventions that require immediate actions to protect the polder as a whole or a part thereof from the adverse effects of flooding or uncontrolled saline intrusion etc. associated with damage of lives and properties. This type of work requiring immediate attention includes the closure of an embankment breach, the repair and replacement of flap gates, or the construction of cross dams over canals if structure fails.

Details of maintenance plans, monitoring and suggestions for improved O&M can be found in report Component 6.2+6.3 Polder Management Plan.

9 Conclusions

9.1 Key development directions for the polders

9.1.1 Polder 15

Polder 15 is situated in the high salinity zone of Satkhira in the South-west coastal region. It is therefore an example of a high salinity polder type. The intensive shrimp culture activities cause high salinity in the polder surface and groundwater and is seriously limiting the agricultural potential. In the future, sea level rise will increase salt intrusion. If the Ganges Barrage would be constructed there could become more freshwater available. But this is considered only a long-term option. Recent history suggests that ***aquaculture seems the most viable option for economic development. However, a more diverse cropping pattern (polyculture, rice - shrimp etc.) is needed for a sustainable and more equitable development.***

The water management in Polder 15 is not only about drainage, but also on providing the optimal mix of fresh and salt water to diversify aquaculture production. It therefore is recommended to develop a water and salt balance model that enables to provide advice on the optimal water management of the polder.

Drinking water supply in Polder 15 is a critical issue because of high salinity levels of surface and groundwater. This will probably become worse due to sea level rise. Therefore, investments are needed to ensure all inhabitants have access to safe and affordable drinking water. ***A combination of rainwater harvesting and Pond Sand Filters should be complemented with Reverse Osmosis desalination plants as a targeted government intervention.***

Cyclone risk remains high and therefore warrants the ***upgrading of the coastal embankments***. Besides significant re-sectioning of the entire embankment also some bank and slope protection works are needed. Even so, the mortality risk remains significant and would require additional disaster management measures, such as an ***increase in the number of cyclone shelters and last mile early warning (e.g. through SMS)***.

9.1.2 Polder 29

Polder 29 is an example of a polder with intermediate salinity conditions. It also suffers from some waterlogging problems due to the siltation of khals and reduced drainage potential to some of the adjacent rivers. ***A catchment wide plan for river restoration***, encompassing polders 25, 26, 27, 28 and 29, has been studied and implementation is underway. Middle Bhadra, Joykhali and Upper Salta rivers have been excavated already.

In the future this solution may be hampered due to new siltation and increased tidal water levels that further reduce the already limited drainage window. ***Pumping may be required in the (distant) future***. As part of the Blue Gold project already some drainage improvements have been executed, not only on the primary, but also on the secondary and tertiary drainage infrastructure which have proven to successfully reduce water logging conditions. In the south a relatively new waterlogged area seems to have evolved, which could benefit from TRM.

This polder can become a major agricultural production centre with a market close to Khulna, provided that the drainage conditions improve, and salinity levels would decrease. ***Restoration of the Gorai flow would be highly recommended.*** A reduction of surface water salinity in its adjoining river system would in the dry season promote surface water irrigation and enhance the production and food security of the polder. Also, several in-polder management strategies are available to manage salt, such as subsurface field drainage, groundwater management (lowering of salty groundwater tables), and the management of the canals and ponds to maximise the export of salt from the polder and minimise its import. The increased rain in some climate change scenarios might lead to more waterlogging problems, with adverse impacts on crop production. But field drainage for salt management is also likely to be effective for waterlogging management.

Parts of Polder 29 suffer from insufficient drinking water supply because of high groundwater salinity. This will probably become worse due to sea level rise. Therefore, investments are needed to ensure all inhabitants to safe and affordable drinking water. ***A combination of rainwater harvesting and Pond Sand Filters should be complemented with Reverse Osmosis desalination plants as a targeted government intervention.***

The economic risk of cyclone storm surges is not very high as current embankments have a safety level between 1 in 10 and 1 in 25 years. Even so, the risk will rise considerably due to climate change and would therefore call for embankment improvement in the future. This however, would not prevent mortality risk to rise significantly and will require additional disaster management measures. ***Approx. 20 additional cyclone shelters are recommended***. There are local bank erosion problems (near Chandgar) that require revetments based on geobags and possibly dredging sediments from recently accreted land on the opposite side of the river and to supplement the excavated sediment along the bank at Chandgar.

9.1.3 Polder 40/1

Polder 40/1 is an example of a moderately freshwater polder with rice cropping during the Kharif season and pulses in the Rabi season. It is situated on the southern-most tip of the coastal area and is therefore a bit isolated (distance to Barguna is 23 km). The foreshore is very wide and long, where mangrove forest was planted. Economic development opportunities are limited, due to the remoteness of the polder and the relatively low population density. Even so, ***agricultural production could be promoted by the use of surface water irrigation with low cost pumps.***

The current mangrove area will likely expand on the long term and could become an ***asset for developing eco-tourism and will help protecting the embankments from wave attack.***

Waterlogging is practically absent and should not cause problems in the future. Part of the explanation is a relatively short khal length per regulator (3.1 km) and a relatively good drainage capacity at the polder outlets. Even with sea level rise there is probably enough drainage window in 2050 for sufficient drainage capacity.

The economic risk of cyclone storm surge is relatively low, which makes costly embankments economically difficult. Mortality would increase in 2050, even with 1/25 year safety embankments, which would warrant additional disaster management measures. However, no new shelters are needed since the capacity is already quite high.

9.1.4 Polder 59/2

Polder 59/2 is a freshwater polder due to the nearby Meghna river. At the same time this river produces the biggest problem of this polder, which is riverbank erosion. ***Besides bank protection over a long distance, the other potentially effective measure would be to dredge the channel bars and mouth bars*** and dispose the sediment close to the eroding banks, thus changing the thalweg of the river away from the bank. The feasibility of this measure should be carefully studied.

Waterlogging is a serious problem. The performance is partly dominated by the khal infrastructure: the length per regulator is relatively long (6.6 km) and surface area per km khal is high (162 ha). Thanks to the relatively high elevation the drainage window currently is 23 hours but would reduce to 17 hours per day due to sea level rise and 15 cm subsidence. But malfunctioning regulators cause water flowing inside the polders and silted khals also cause waterlogging.

Both mortality risk and economic risk due to cyclonic storm surges are high, which are significantly reduced by upgraded embankments. However, future conditions (2050) would double the economic risk and increase the mortality risk with one order of magnitude. Therefore, ***additional disaster management measures are required***. Although currently sufficient, in 2050 50 new shelters are considered necessary.

9.1.5 Polders 64/1a and 64/1b

Polders 64/1a and 64/1b have good connections to the city of Chittagong. Designed primary drainage conditions (number and size of regulators and khals) is good. With 50 regulators and a relatively short khal length per regulator (2.3 km) the drainage infrastructure seems more than sufficient for now and in the future, although the drainage window would reduce from 23 to 19 hours per day. Local waterlogging exists however due to silted up khals which require continuous maintenance. Relative high surface water salinity levels are a constraint for irrigation in the dry season.

Due to its location on the eastern part of the Bay of Bengal, ***the polder has one of the highest cyclone risks***. Current embankments reduce this risk to a certain extent, but an upgrade would significantly reduce the economic risk. The mortality risk, however, will remain extremely high, even with a new embankment. Therefore, and because of population growth, an additional 18 cyclone shelters in 2050 would be needed.

There is ongoing work to strengthen the sea dike with slope protection (CC blocks). Large parts of the current embankment are in a rather poor state and need repair/improvement. Considering the exposure of the coast to potentially large storm surges (more than 6 m high) and the likely future increase in cyclone risk, ***it would be rational to strengthen and heighten the embankments along the sea coast.***

9.2 Economic evaluation

Table 9-1 presents the summary of the economic evaluation as described and calculated in the preceding chapters for the pilot polders. All proposed investments show a B/C ratio equal to or higher than 0.8, which is sufficiently high in order to study the measures more in detail and make pre-feaibility studies for these investments.

Table 9-1 Summary economic evaluation

Polder No	Gross Polder Area (Ha)	Total Costs (million US$)	Total Benefits (million US$)	B/C Ratio
15	3,441	39.5	38.1	1.0
29	8,218	39.5	40.0	1.01
40/1	2,105	10.9	8.7	0.80
59/2	21,255	186.1	183.2	0.98
64/1A	5,750	186.1	262.1	1.3
64/1B	8,000	35.0	474.2	13.5

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Annex A: Drainage analysis

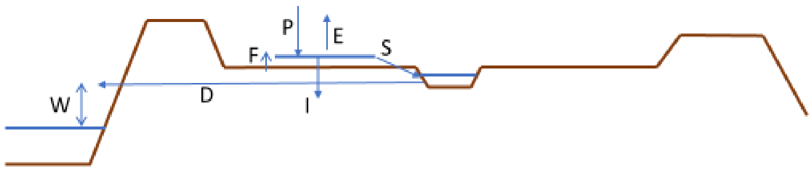
Method

A drainage analysis has been performed by using a water balance method. It is implemented in an Excel workbook. The water balance uses the following information:

Component / parameter	**Values and dimensions**	**Data source / remarks**
Total area of polder		IGDCZ
Khals	Khal length	Survey of IWM
	Average width (10m assumed) Average depth (2m assumed)	In reality many khals are silted up and are partly blocked. Therefore, the model used three scenarios: 100% efficiency, 50% efficiency and 25% efficiency
Outlet structures (regulators)	the number of actual working outlet structures per polder	Survey of IWM
	an average cross-section area per vent has been assumed, using the actual vent dimensions	Survey of IWM
Evaporation	a universal evaporation of 3mm per day is assumed for all polders	EIA-Report Polder 43-2b mentions average 100 mm/month in summer (~ 3 mm/day).
Infiltration	a universal infiltration of 5 mm per day is assumed for all polders	EIA-Report Polder 43-2b mentions average 160 mm/month in summer (~ 5 mm/day).
Drainage window	The drainage window is determined for each polder as a relation between the average polder elevation and average tidal cycle during the month of September of the nearest tidal gauge.	Polder elevation from IGDCZ Tidal water levels from IGDCZ
Rainfall	Three rainfall scenarios are used: average year, wet year and extreme wet year	The rainfall data is the same for all polders.

A water balance is calculated for each daily time step by subtracting the drained, evaporated and infiltrated volume from the total rain volume of that day plus what was on the field from the previous day. The volume that is not drained is then translated into a level of the water that remains on the field. This volume is considered the starting situation for the next day. The model runs for 184 days, using three different hydrological years: and average (normal) year, a wet year (roughly one in 10 years) and an extremely wet year (roughly one in 25-50 years).

Each day that has a water level of more than 20 and more than 60 cm is added to the total of the monsoon season. Also, the number of cumulative days with more than 20 and 60 cm, respectively, is summed up.



The formula is as follows:

$$F_i = P_i - E_i - I_i + F_{i-1} - S*MIN(D_W, D_K*k)$$

in which:

i = Day
F = Water volume on field
P = Precipitation volume in one day
E = Evaporation volume in one day
I = Infiltration volume in one day
D_W = Daily drainage capacity based on the regulators and drainage window
D_K = Daily drainage capacity based on maximum khal hydraulic conveyance
k = Khal efficiency percentage
S = Surface runoff fraction to khal (assumed to be 1)
W = Drainage window, percentage of time per day that gravity drainage is possible

Hence, the drainage capacity of the polder is either limited by the drainage window or by the khal drainage capacity. It is further assumed that each regulator is linked to a khal with the same length. The length is determined by the total khal length divided by the total number of regulators. The polder elevation is assumed to be uniform over the polder (bucket approach).

The daily drainage capacity for each khal is dependent on its size, hydraulic resistance (roughness) and slope. It is calculated using the following formula:

$$Q = \frac{K * A * R^{2/3} * S^{1/2}}{n}$$

in which:
Q = flow rate
A = cross sectional area of flow
R = hydraulic radius (cross-section area divided by wetted perimeter)
S = slope of the channel at the point of measurement
n = surface roughness
K = constant dependent upon units

In our model the uniform khal parameters are: A = 20; R=14; n=0.05. Hence the calculated maximum Q is only dependent on the length of the khal and the slope.

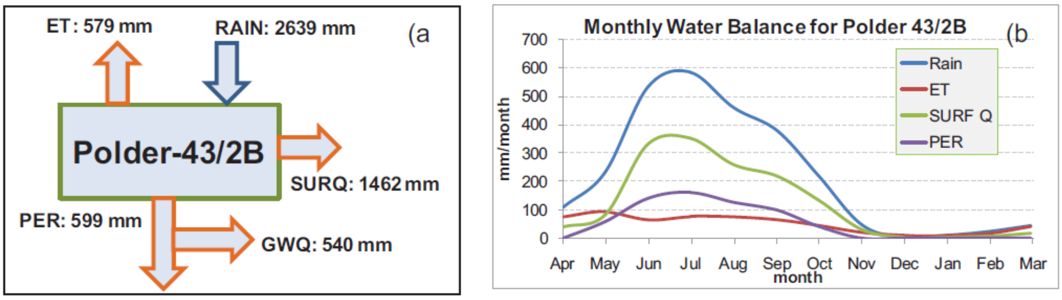
The drainage capacity of the regulators is taken as the total of regulator vents per polder times the average vent cross-section area. The drainage window is estimated as follows: from a nearby water level station the average flood and average eb level is determined for the month of September. Based on these an idealized sinusoid curve is prepared for a 12-hour cycle. Then the time period in which the water level is lower than the polder level is calculated, times 2 (for a diurnal tidal regime).

Rainfall
For the three different hydrological years (average, wet and extremely wet) three years have been selected.

Year	maximum 1 day	maximum 3 days	maximum 5 days	est. return period
average (2006)	158 mm	211 mm	283 mm	< 2yr
wet	164 mm	344 mm	477 mm	4-10 yr
extremely wet	337 mm	509 mm	645 mm	25-50 yr

Evaporation and infiltration
Polder 43/2B is used as reference for evaporation and infiltration. CEGIS (2016b) mentions:

> "Input to the water balance is rainfall while losses occur through evapotranspiration and percolation and as water contributing to stream flow through surface runoff. The annual actual evapotranspiration of the area is 579 mm which is 22% of the annual rainfall. The evapotranspiration is maximum during April and May and is about 100 mm per month. The evapotranspiration rate is minimum during December to January. The percolation rate in the polder area is 599 mm per year which is 23% of the annual rainfall. The percolation rate follows similar trend like rainfall and the maximum rate is 160 mm per month. After losses of water through evapotranspiration and percolation, the remaining portion contributes to stream flow as overland flow and lateral (subsurface) flow. Around 55% (1462 mm) of rainfall contributes to stream flow through surface runoff while the lateral flow is negligible".



Note: Rain - Rainfall; ET - Evapotranspiration; PER - Percolation; SURQ - Surface Runoff

Figure: Water balance for Polder 43-2b (Source: CEGIS, 2016b)

Drainage parameters

		Polder number				
	unit	**15**	**29**	**40**	**59**	**64**
Polder area	ha	3441	8218	2105	21255	13750
Khal length	km	19	93	15.4	131	117
Average width	m	10	10	10	10	10
Average depth	m	2	2	2	2	2
Total khal surface	ha	19	93	15.4	131	117
Total khal volume	m^3	380,000	1,860,000	308,000	2,620,000	2,340,000
Surface area per km khal	ha	181	88	137	162	118
Length per regulator vent	km	3.8	7.2	3.1	6.6	2.3
Slope of khal (height difference)	m	1	1	1	2	1
Drainage regulators (vents)	#	5	13	5	20	50
Av. Drainage capacity per vent	m^3/s	2.94	3.15	5.3	5	1.58
Sea level rise in 2050	m	0.208	0.208	0.208	0.208	0.208
Subsidence in 2050	m	0.075	0.075	0.15	0.15	0.075
Drainage window (current)	h/day	12.1	12.1	16.2	23	23.1
Drainage window (2050)	h/day	10.5	10.5	13.3	17.3	19.1
Drainage window change	%	-13%	-13%	-18%	-25%	-17%
Rainfall increase 2050	%	10%	10%	10%	10%	10%

Results

The results of the drainage analysis for the 5 polders are shown in the Figures below. For each polder three graphs show the rainfall and field water level under current climate conditions and for three different hydrological years (average, wet and extremely wet). Another three graphs show the same for the year 2050 ("future climate"), assuming a 10% rainfall increase scenario, a sea level rise under RCP 8.5 and subsidence. All graphs assume the current drainage conditions and a 100% khal efficiency (i.e. no siltation or cross dams). The last three bar charts show the number of days per monsoon with water on the field (20 and 60 cm, respectively) under three different khal efficiencies (100, 50 and 25%). Each bar chart shows both current and future boundary conditions and three types of hydrological year (average, wet, extremely wet).

Polder 15:
The results show that in wet and extremely wet years the existing drainage system is not able to keep the polder dry. But also during average years there are 15 days with more than 20 cm of water on the fields. In wet years this increases to 113 days and this accumulates to water levels of 1 m and more. This condition can be explained by the fact that the calculation assumes only one active regulator. From the survey conducted in 2021 it was observed that 4 out of the 5 existing regulators the condition is bad. Should all 5 regulators work effectively (not shown in the graphs), the waterlogging conditions would be reduced significantly. For instance, under average rainfall conditions, water would be on the fields for only 2 days instead of 15. But in an extreme wet year the polder would still be waterlogged for 129 days.

The bar charts show that future conditions do not change the drainage situation much. Also, a reduced khal efficiency does not show a great effect. Both are clear indications that the number and capacity of the drain regulators is the limiting factor.

Polder 29:

This polder is showing good drainage potential under an average and wet year. But an extreme wet year would cause significant long duration waterlogging (80 days of which 37 consecutive). Although the surface area per khal is relatively small (on average 88 ha per km khal), the length per regulator is relatively long (7.2 km).

Khal efficiency seems to have no effect on the modelled drainage. Although this looks counterintuitive, the reason is that the regulator drainage capacity is the limiting factor. With 13 regulators and a capacity of 3.15 m^3/s each the drainage capacity is 3.5 million m^3 per day. Furthermore, the polder can be drained only 12 hours per 24 hours, because of the tide. Therefore only 1.8 million m^3 can be drained per day. This equals 22 mm on the field. Hence, a daily rainfall of more 28 mm (compensating for 3 mm evaporation and 3 mm infiltration) would already cause some drainage congestion.

In the future with sea level rise and subsidence, the drainage window will reduce to 10.5 hours per day. Combined with a predicted rainfall intensity increase, this will cause more waterlogging, especially in extreme wet years (147 days consecutive, i.e. a long-term flood condition).

Polder 40:
Under the assumed conditions of the drainage infrastructure, Polder 40 shows excellent drainage potential, even if only 25 % khal efficiency is assumed. Only during extreme wet conditions problems could arise in the future (2050). Part of the explanation is a relatively short khal length per regulator (3.1 km) and a relatively good drainage capacity at the polder outlets: it can drain 73 mm/day, which is the highest of all 5 polders, despite of a drainage window of 16 hours per day.

Polder 59:
Polder 59 performs quite satisfactorily, should 100% khal efficiency now and in the future be guaranteed. With 50% efficiency prolonged waterlogging is expected in extremely wet years and with 25% efficiency, waterlogging duration will occur in wet years. The performance is partly dominated by the khal infrastructure: the length per regulator is relatively long (6.6 km) and surface area per km khal is high (162 ha). Because its relatively high elevation, polder 59 can drain 23 hours a day, which in 2050 could be reduced to 17 hours due to sea level rise and subsidence.

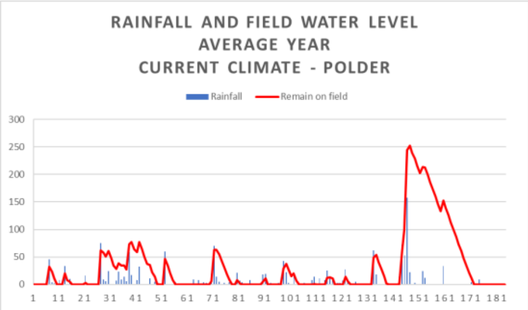
Polder 64:
Of all studied polders, Polder 64/1a+b shows the best and almost perfect drainage potential under all conditions and scenarios. With 50 regulators and a relatively short khal length per regulator (2.3 km) the drainage infrastructure seems sufficient for now and in the future, although the drainage window would reduce from 23 to 19 hours per day.

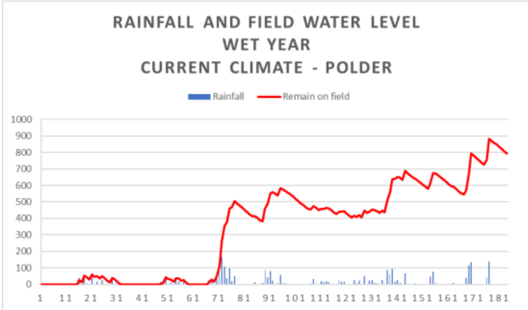
Conclusions
The simple water balance model shows that there are many factors that may affect the drainage capacity in a polder, such as the ratio of khal length and surface to be drained, the number of regulators and the drainage window (determined by the tide and polder elevation). In some modelled cases the internal (khal) drainage is limited, but more often the external drainage through the regulators is the limiting factor.

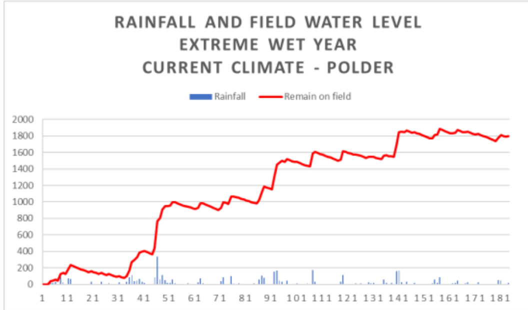
Limitations
It should be noted that the waterlogging pattern of the polder is much more complicated than can be simulated by a water balance model, which assumes that the polder has a uniform terrain. In reality, even an average of 20 cm water could result in many parts of the polder suffering of much deeper water, while other areas remain dry.

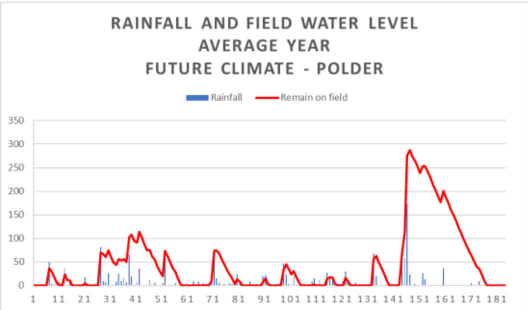
The model also assumes that all khals can still drain water to the regulator over its entire length, even with 25% efficiency. In reality, some khals are completely blocked by cross dams or clogged culverts, which will result in zero drainage discharge. In such cases it does not help to increase the drainage capacity at the polder boundaries.

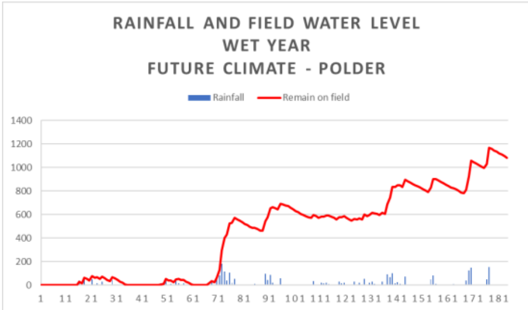
Estimation of the drainage window has been based on water level observations from September 2000. For some locations in the rivers (esp. for Polder 15 and Polder 29) it is most probable that highwater levels have increased. It is advised to update the drainage window for these polders with more recent data.

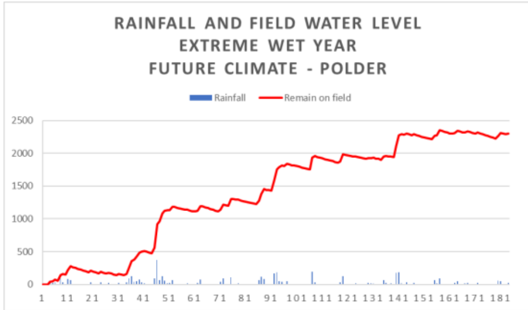




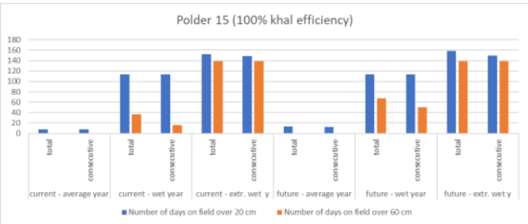


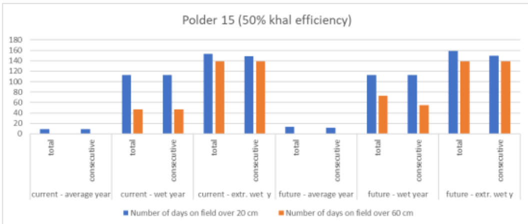


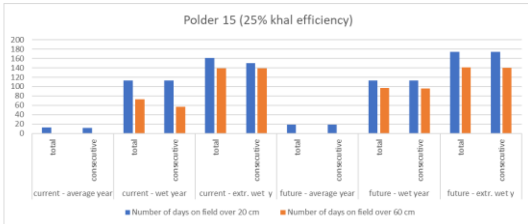




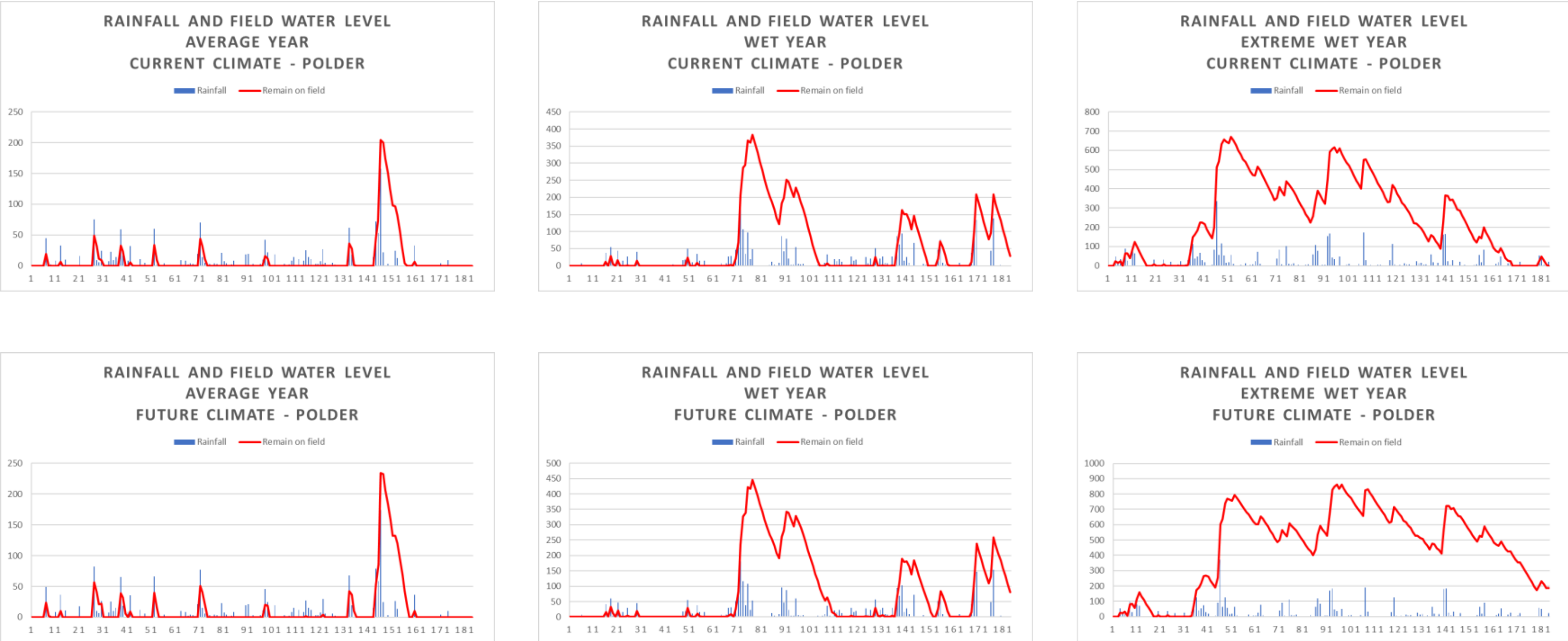
Polder 15 (current drainage capacity – 100% khal efficiency assumed)



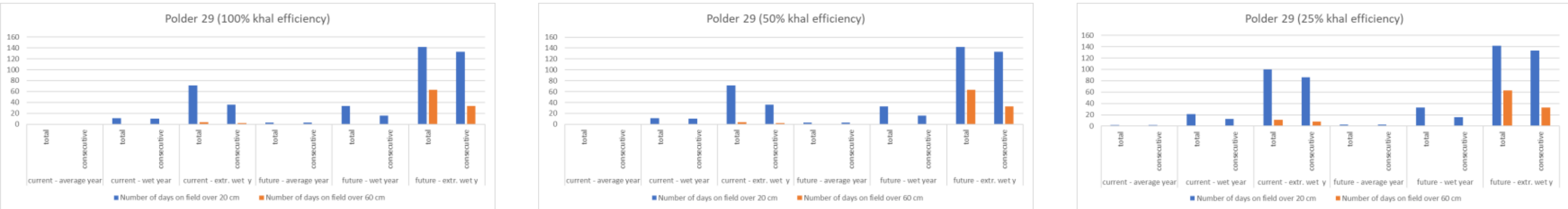




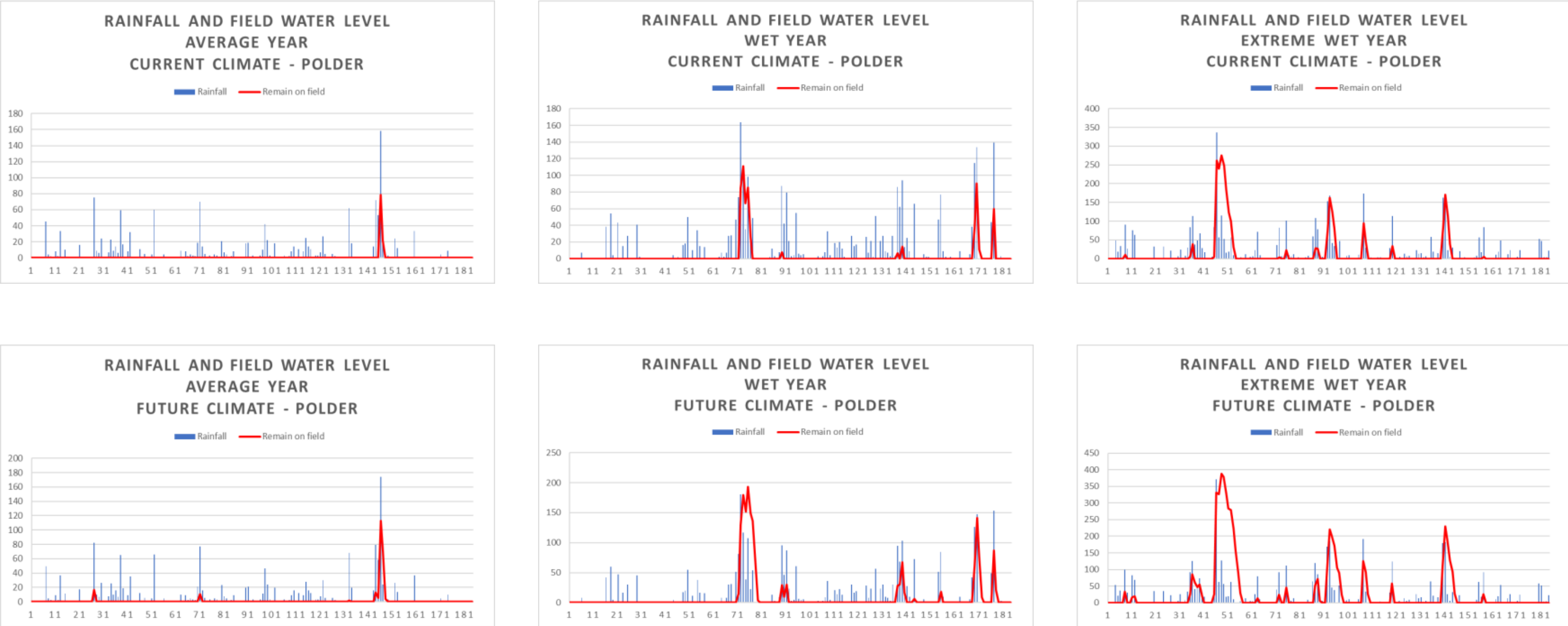
Polder 15 number of days with water on field (current drainage capacity - various khal efficiencies assumed)



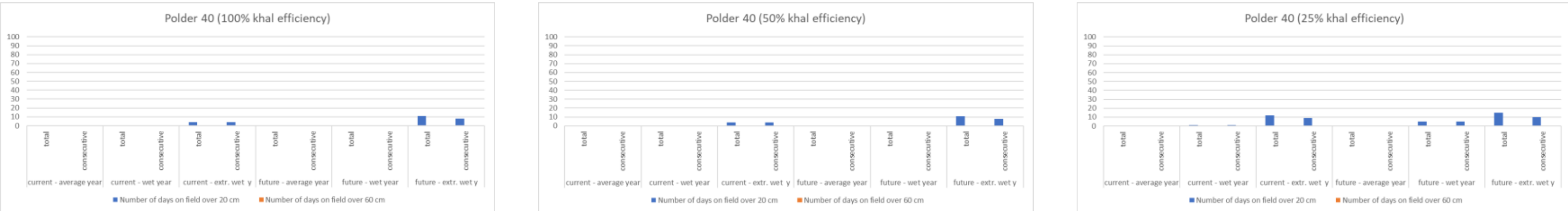
Polder 29 (current drainage capacity – 100% khal efficiency assumed)



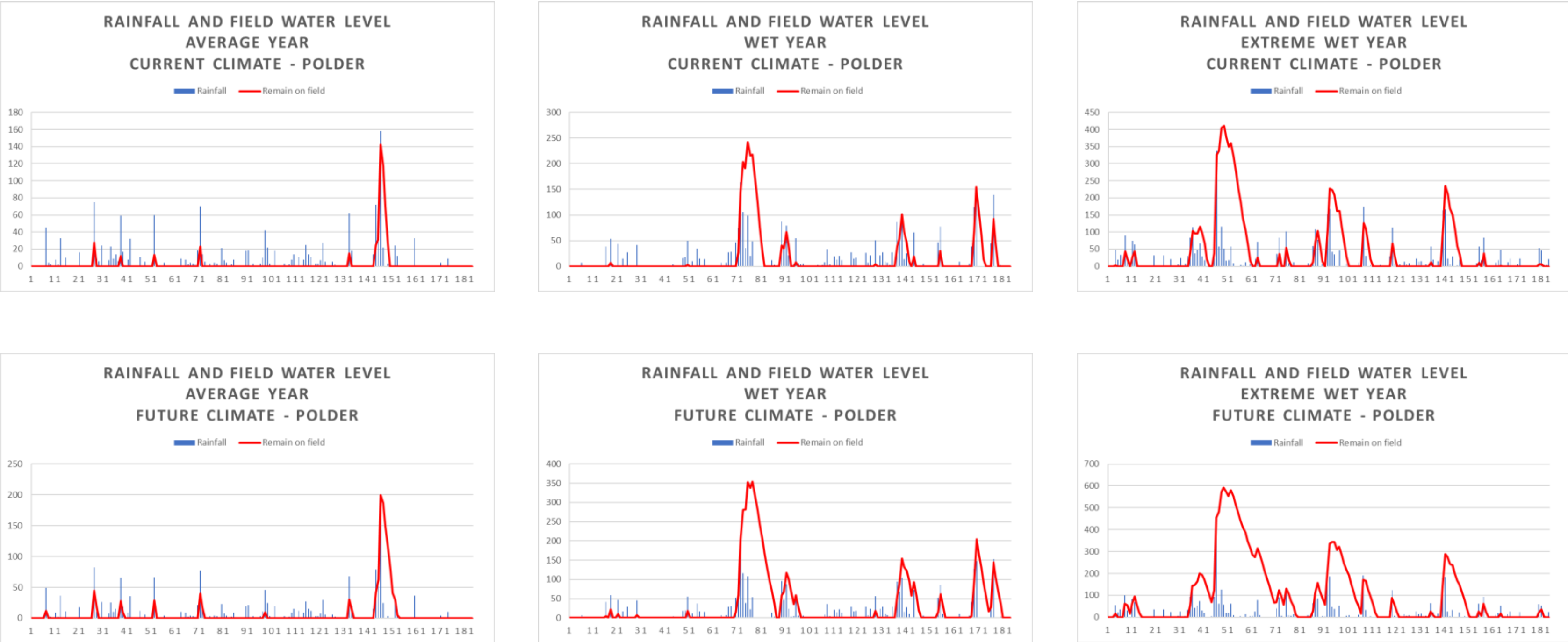
Polder 29 number of days with water on field (current drainage capacity - various khal efficiencies assumed)



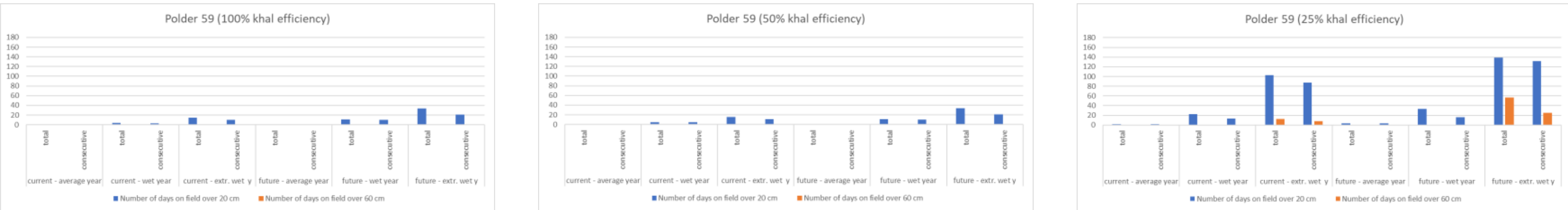
Polder 40 (current drainage capacity – 100% khal efficiency assumed)



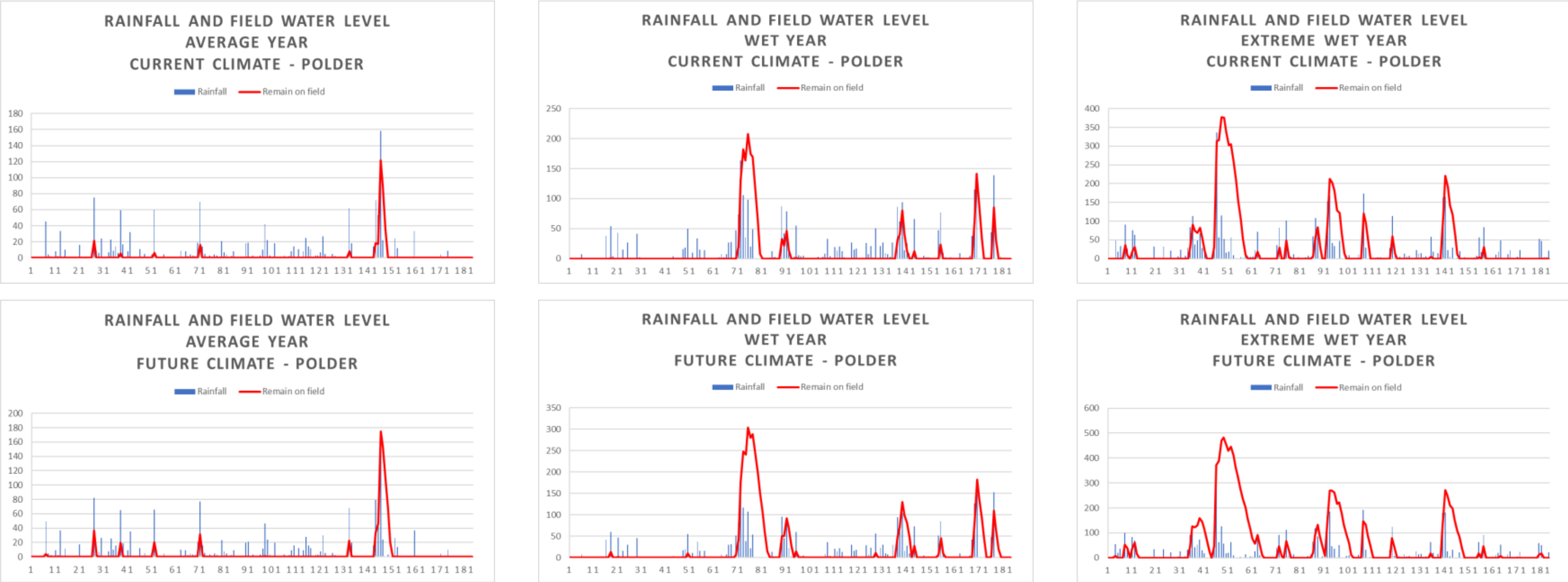
Polder 40 number of days with water on field (current drainage capacity - various khal efficiencies assumed)



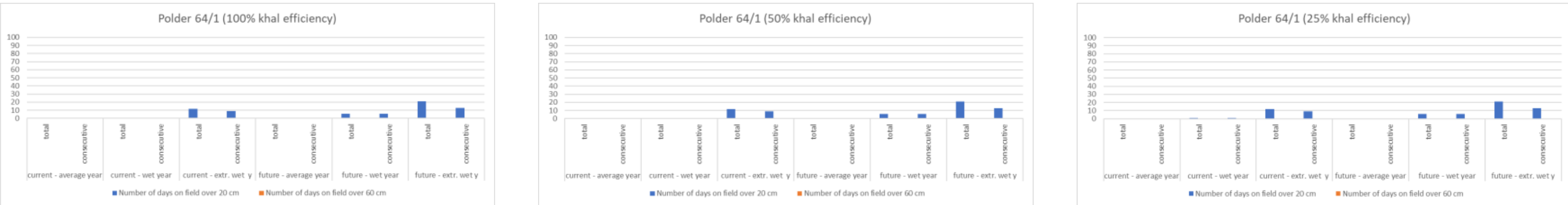
Polder 59 (current drainage capacity - 100% khal efficiency assumed)



Polder 59 number of days with water on field (current drainage capacity - various khal efficiencies assumed)



Polder 64/1 rainfall and field water level graphs (current drainage capacity - 100% khal efficiency assumed)



Polder 64/1 number of days with water on field (current drainage capacity - various khal efficiencies assumed)

Annex B: Principle design sketches dike improvement Bangladesh

Introduction

Along the coast of Bangladesh and more inland along the river systems that form the Bangladesh delta several polders have been created in the past. To improve the safety against flooding of the polders an evaluation of the water retaining systems has been made and several measures to improve safety against flooding are elaborated. One of these measures is improving the dikes around the polders. This memo describes a series of principle sketches of improved dike cross sections. Based on these sketches a first impression of the consequences of dike improvement in this area can be elaborated.

The differences between the different the different elaborated cross sections follow from differences in loading conditions and bathymetry of the foreshore. It should be noted that subsoil conditions can have a strong influence on the required geometry of a dike. For example, low sub soil strength might result in low bearing capacity and therefore stability issues. Internal erosion processes, like piping, might weaken sub soil strength and as such induce failure during a high-water event. At the moment of writing this memo, little to no sub soil related information is available. However, a visual inspection of the protection system of one of the polders shows that besides the height of the dikes and levees, foreshore erosion due to wave action or river scour represents the main failure mechanism. Stability issues and / or internal erosion, either through the dike body or in the subsoil was not observed. It should be noted that these mechanisms could become relevant when upgrading the existing structures such that it can withstand higher water levels.

A proper dike reinforcement design should deal with all relevant failure mechanisms. Due to the absence of subsoil information, the resistance against the different failure mechanisms is not elaborated here. The principle sketches, discussed in this memo, cannot be seen as a design of the required dike reinforcement. Instead the principle sketches are meant to provide an educated impression what the dimensions of the dike reinforcement could be. Since raising a dike also requires widening the base, in order to secure stability issues, conflicts with land ownership and the presence of buildings on or the present dike might emerge. The principle sketches are meant to acquire a first approach in the footprint of the improved dike system and will be the input for a budget estimate required to realize the improved safety against flooding.

Construction material

At this early stage of designing the dike reinforcement, the construction material is assumed to be produced by locally dredged material. At this moment no specifications of the locally dredged material are available and the applicability of this material for dike construction is unknown. When using dredged material for dike construction, the following issues are relevant:

Liquidity;

When the material is too wet, the material volume will considerable shrink upon drying. This volume reduction will lead to considerable cracking when the initial water content is above the liquid limit of the material. It is obvious that considerable cracks in the dike body should be avoided. The liquidity index, I_l, and consistency index, I_c, is a measure for the liquidity of the material:

$$I_l = \frac{w - PL}{I_p}, \quad I_c = \frac{LL - w}{I_p}$$

In which:

- I_l = liquidity index
- I_c = consistency index
- w = water content
- PL = plastic limit
- I_p = plasticity index, $I_p = LL - PL$
- LL = liquid limit

It should be noted that the liquidity index is the inverse of the consistency index, I_c. Typically, after dredging, the water content will be beyond the liquid limit and $I_l > 1$. In that case the material should allow to dry until the water content is sufficiently dropped and $I_l < 0.25$, $I_c > 0.75$, before it is used as a construction material. For the core of the dike $I_c > 0.6$ can be used. Drying clay means that the dredged material should be placed in ridges of 0.5 – 1.0 m high and is allowed to dry for several weeks or months before used as construction material.

Ability to densify

To improve material properties like stiffness and strength, resistance against erosion and reduce development of cracks, the material should be densified when building the dike. For optimum densification, the material should not be too wet, see text above. For clayey material, the densification should be done by using a static load.

Typically, silts and sands in Bangladesh contain mica. Mica is recognised as the shiny thin plates that are present between the sand grains. The presence of the flaky mica particles between the spherical sand particles will cause bridging and other complex behaviour at microscopic level. As such micaceous sands are known for their problematic densification abilities. Before the material is used for construction material the properties of the material and the ability for densification should be tested.

Erodibility

Sand and silty material will easily erode when in contact with water. When the construction material contains a high silt or sand fraction erosion problems are to be expected. Regarding shore protection, a revetment or other protective constructions will be built. However, the material should contain at least enough resistance against erosion due to rainfall. Consequently, the construction material should contain a sufficiently high clay fraction.

The consequences of these issues above are that the dredged material might not be used directly in the same cross section. Instead mining locations should be found where the right material can be found and / or processing of the material is required before it is applied for construction. Construction alternatives in which the dike body is constructed of an erodible material, sand, protected by a clay cover will not be considered. Since the main failure mechanism, observed in the field, is erosion due to waves and river scour, high resistance against erosion is favoured for the entire construction.

Principle sketches

In total 5 principle sketches are derived for the different loading conditions that can be found in the Bangladesh delta. The loading conditions will be discussed in the description of the principle sketches below. The principles sketches are developed on the following rules:

- The daily mean water table is taken at PWD 0 m.
- The ground level fluctuates between PWD + 1.0 m and PWD + 2.0 m. The dimensions in the principal sketches are elaborated for both values.
- The loading contains a combination of storm surge and wave action. The raised water level due to the storm surge are referred in the principle sketches as Design Water Level. The design wave action is represented by a significant wave height at deeper water, H_s.
- The relevant storm surge levels and significant wave heights are taken from the CEIP technical report on *Storm Surge, Wave, Hydrodynamic Modelling and Design Parameters on Drainage System and Embankment Crest Level, Volume-III: Package-3, Appendix-B: Storm Surge and Monsoon Water Level*, March 2018.
- The crest width is taken as 3 m in all sketches. In case of severe wave action, a wider crest might be beneficial in improving the probability of failure due to erosion by wave action.

- The inner slope in all sketches are taken at 1(V):3(H). This is an engineering estimate to create a slope which is sufficiently stable for typical construction materials. For low quality construction material and large construction height for example the sea defence Figure and Figure, the slope might be built shallower.
- The slope angle of the outer slope is selected in combination with dike height and expected wave action during design conditions. Wave overtopping should be kept to a minimum unless the inner slope is protected to withstand the expected amount of wave overtopping. The expected amount of wave overtopping during design conditions is estimated following the Overtopping Manual[4] and the computer program PCOverslag.
- According to the overtopping manual an unprotected inner slope should not be loaded with overtopping discharge more than 0.1 l/s/m. A high-quality grass cover can withstand an overtopping discharge of 5 l/s/m. The freeboard presented for the sketches below is based on an overtopping discharge of 1 l/s/m. Consequently, it is assumed that the inner slope is protected by at least a low-quality grass cover.
- In cases where no severe wave action is expected during design conditions, the outer slope angle is selected as 1(V):3(H).
- An additional freeboard of 0.5 m is added. This freeboard accounts for settlement due to added weight, setting of the dike body, general land subsidence and inaccuracies in construction. Due to lack of sub soil information a settlement prediction cannot be made, and 0.5 m is a rough estimate. When organic soils are present in the sub soil settlement, larger than 0.5 m, is to be expected. Regarding settlement it should be noted that:
    - Dikes are already present, so the sub soil is already pre-loaded and not full cross section, as presented below in the principle sketches can be considered as a new loading.
    - Soft soil is expected more inland, where due to reduced wave conditions dike heights are also reduced. The larger dikes are required at the coast where the sub soil contains more stiff sands and silts.
- Due to the additional freeboard the overtopping discharge during design conditions at the start of the life cycle of dike will be smaller than 1 l/s/m/, for which the overtopping freeboard is determined. During its lifetime, the dike will settle and the expected overtopping discharge will increase to 1 l/s/m.

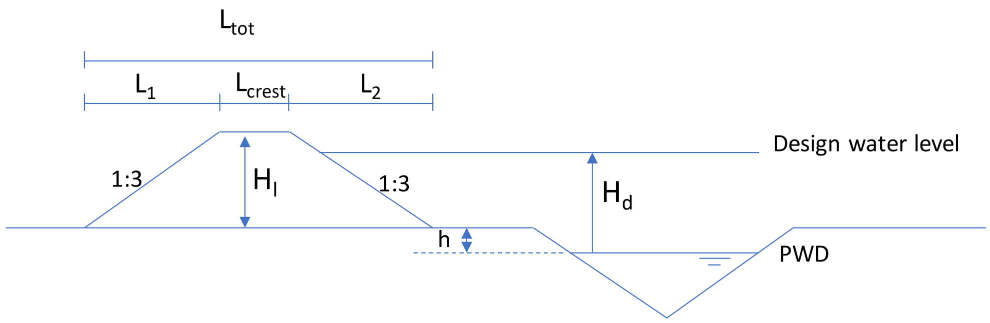
The different sketches are discussed below:

<u>Sketch 1, Narrow channel with foreland</u>

Specifications:

- Some polders are separated by relatively narrow channels.
- During extreme events the water level might rise considerably.
- Wave action and currents are absent or insignificant.
- Daily water levels are within the channel; Under daily conditions the dikes remain dry
- An example of this situation is the channel between polder P45 and P44, with design conditions given for points 39 and 50 in the appendix B of the technical report *Storm Surge, Wave, Hydrodynamic Modelling and Design Parameters on Drainage System and Embankment Crest Level*

[4] EurOtop, Manual on wave overtopping of sea defences and related structures, second edition 2018, www.overtopping-manual.com



Figure, Sketch case 1, narrow channel with foreland

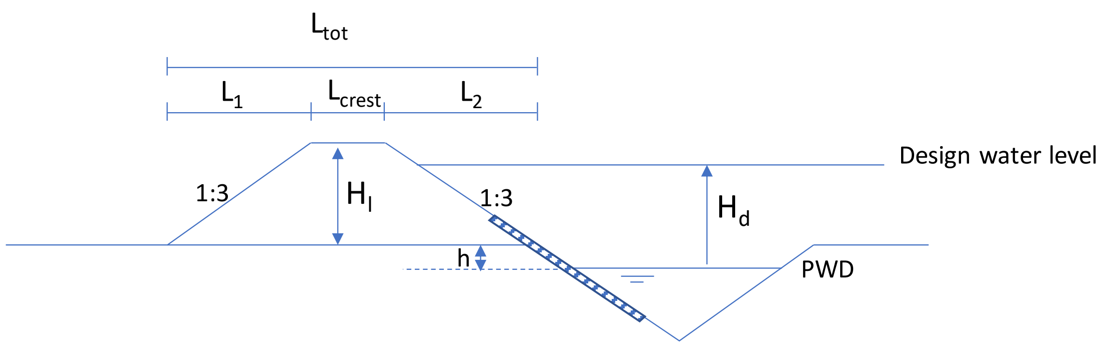
Parameter	Symbol	Unit	Set 1	Set 2
ground level relative to mean sea level	h	[m]	1.0	2.0
design water level relative to mean sea level	H_d	[m]	5.5	5.5
crest level relative to ground level	H_l	[m]	5.0	4.0
length polder side slope	L_1	[m]	15	12
length river side slope	L_2	[m]	15	12
crest width	L_c	[m]	3.0	3.0
total length dike body	L_{tot}	[m]	33.0	27.0

Due to the absence of wave action and strong currents erosion will be limited. A good grass cover or similar protection will suffice to withstand erosion due to rainfall and occurrence of design water level.

<u>Sketch 2, Narrow channel without foreland</u>

Specifications:

- Basically equal to sketch 1,
- During extreme events the water level might rise considerably.
- Wave action and currents are absent or insignificant.
- No foreland presence; dike directly retains water also during daily conditions.



Figure, Sketch 2, Narrow channel without foreland

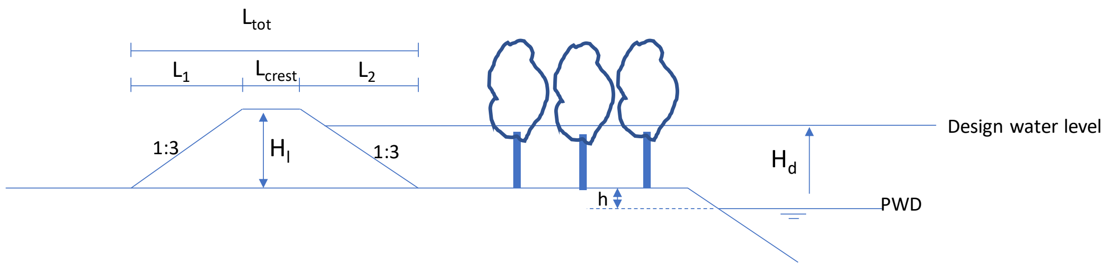
Parameter	Symbol	Unit	Set 1	Set 2
ground level relative to mean sea level	h	[m]	1.0	2.0
design water level relative to mean sea level	H_d	[m]	5.5	5.5
crest level relative to ground level	H_l	[m]	5.0	4.0
length polder side slope	L_1	[m]	15	12
length river side slope	L_2	[m]	15	12
crest width	L_c	[m]	3.0	3.0
total length dike body	L_{tot}	[m]	33.0	27.0

Due to the absence of wave action and strong currents erosion will be limited. Above the water table, a good grass cover or similar protection will suffice to withstand erosion due to rainfall and occurrence of design water level. Around the water level is stone revetment is required.

Sketch 3, along the riverbank

Specifications:

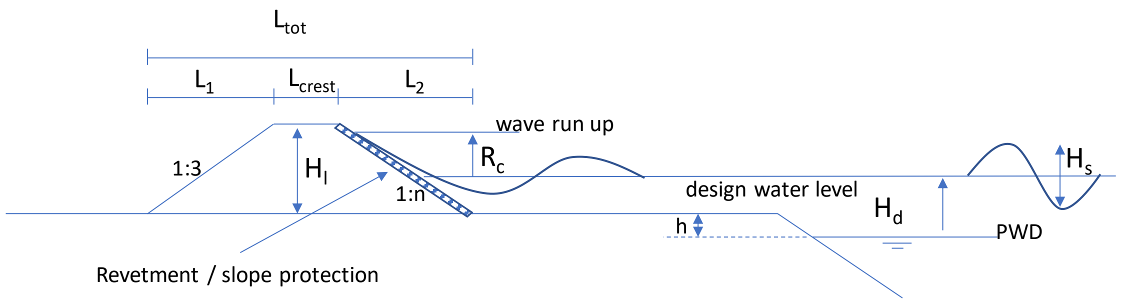
- Along the riverbank
- Foreland typically above daily water levels
- No scour erosion. (sketch 4 includes the conditions with scour)
- if dense mangrove forest is present wave action at the dike will be negligible. Therefore, two options: with and without wave action



Figure, Sketch case 3a, river bank with foreland, no wave action

Parameter	Symbol	Unit	Set 1	Set 2
ground level relative to mean sea level	h	[m]	1.0	2.0
design water level relative to mean sea level	H_d	[m]	2.75	2.75
cfrest level relative to ground level	H_l	[m]	2.25	1.25
length polder side slope	L_1	[m]	6.75	3.75
length river side slope	L_2	[m]	6.75	3.75
crest width	L_c	[m]	3.0	3.0
total length dike body	L_{tot}	[m]	16.5	10.5

When the mangrove is absent, waves will reach the dike and additional height might be required to minimise the amount of overtopping. Large waves will break when reaching the foreland, reducing wave impact on the dike. The level of impact reduction depends on the length and elevation of the foreland. The table below provides the dimensions for two different slopes in combination with different elevations of the foreland and a foreland length of 50 m.



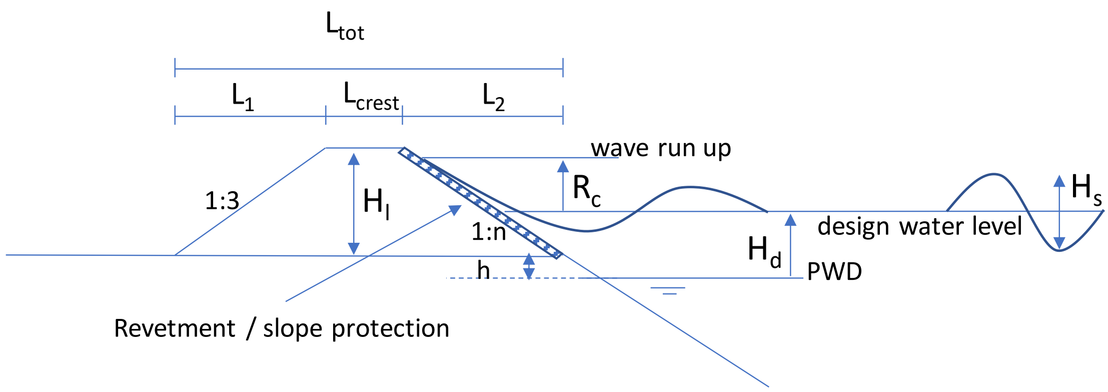
Figure, Sketch case 3b, river bank with foreland and wave action

Parameter	Symbol	Unit	Set 1	Set 2	Set 3	Set 4
ground level relative to mean sea level	h	[m]	1.0	2.0	1.0	2.0
steepness outer slope	n	[-]	3	3	4	4
design water level relative to mean sea level	H_d	[m]	2.75	2.75	2.75	2.75
significant wave height	H_s	[m]	1.5	1.5	1.5	1.5
Freeboard, to reduce overtopping to q_c =1 l/s/m	R_c	[m]	2.25	0.81	1.65	0.81
crest level relative to ground level	H_l	[m]	4.5	2.0	3.9	2.0
overtopping discharge at design conditions	q_c	[l/s/m]	0.25	0.07	0.16	0.07
length polder side slope	L_1	[m]	13.5	6.0	11.7	6.0
length river side slope	L_2	[m]	13.5	6.0	15.6	8.0
crest width	L_c	[m]	3.0	3.0	3.0	3.0
total length dike body	L_{tot}	[m]	30	15	30.3	17

<u>Sketch 4, Riverbank with scour</u>

Specifications:

- Along the riverbank
- Foreland is under attack from river scour
- In the sketch the presence of the foreland is neglected



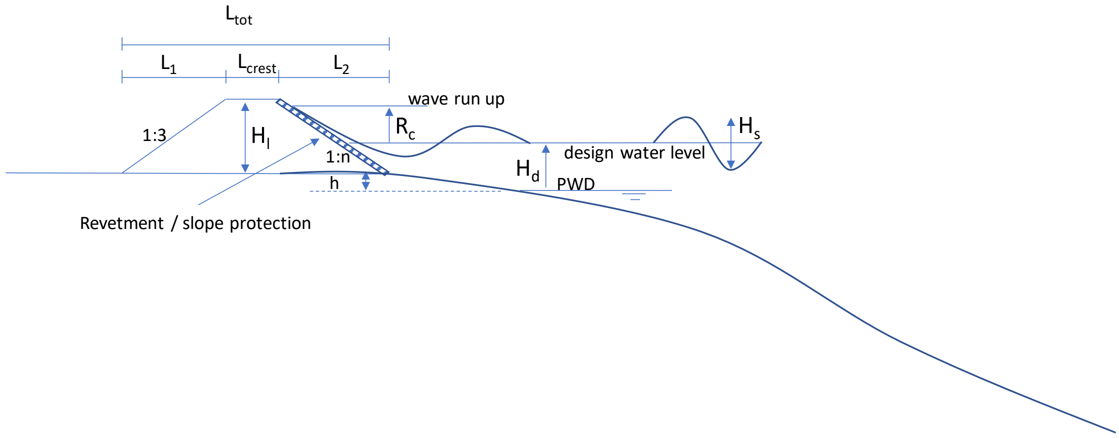
Figure, Sketch case 4, River bank, no foreland with wave action

Parameter	Symbol	Unit	Set 1	Set 2	Set 3	Set 4
ground level relative to mean sea level	h	[m]	1.0	2.0	1.0	2.0
steepness outer slope	n	[-]	3	3	4	4
design water level relative to mean sea level	H_d	[m]	2.75	2.75	2.75	2.75
significant wave height	H_s	[m]	1.5	1.5	1.5	1.5
Freeboard, to reduce overtopping to q_c =1 l/s/m	R_c	[m]	3.25	3.25	2.35	2.35
crest level relative to ground level	H_l	[m]	5.5	4.5	4.6	3.6
overtopping discharge at design conditions	q_c	[l/s/m]	0.32	0.32	0.25	0.25
length polder side slope	L_1	[m]	16.5	13.5	13.8	10.8
length river side slope	L_2	[m]	16.5	13.5	18.4	14.4
crest width	L_c	[m]	3.0	3.0	3.0	3.0
total length dike body	L_{tot}	[m]	36.0	30.0	35.2	28.2

<u>Sketch 5, Sea defence</u>

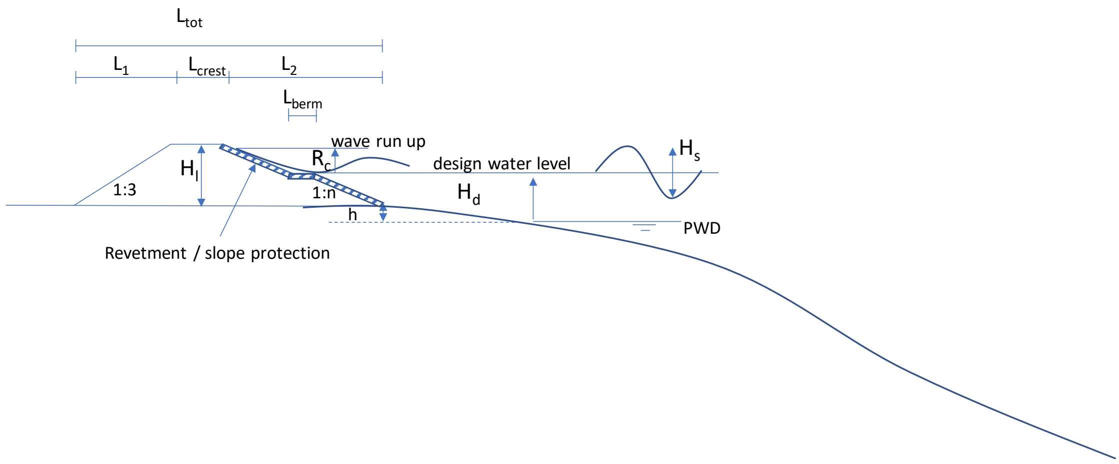
Specifications:

- Direct wave attack from the sea
- Sandy coast
- Due to large wave loads and storm surge, two solutions have been elaborated;
    - Protected slope
    - Protected slope with spilling berm



Figure, Sketch case 5, Sea defence, no berm

Parameter	Symbol	Unit	Set 1	Set 2	Set 3	Set 4
ground level relative to mean sea level	h	[m]	1.0	2.0	1.0	2.0
steepness outer slope	n	[-]	5	5	7	7
design water level relative to mean sea level	H_d	[m]	4.0	4.0	4.0	4.0
significant wave height	H_s	[m]	4.0	4.0	4.0	4.0
Freeboard, to reduce overtopping to q_c =1 l/s/m	R_c	[m]	6.10	6.1	4.25	4.25
crest level relative to ground level	H_l	[m]	9.5	8.5	7.75	6.75
overtopping discharge at design conditions	q_c	[l/s/m]	0.6	0.6	0.4	0.4
length polder side slope	L_1	[m]	28.5	25.5	23.25	20.25
length sea side slope	L_2	[m]	47.5	42.5	54.25	47.25
crest width	L_c	[m]	3.0	3.0	3.0	3.0
total length dike body	L_{tot}	[m]	79	71	80.5	70.5



Figure, Sketch case 5, Sea defence, with berm

Parameter	Symbol	Unit	Set 1	Set 2
ground level relative to mean sea level	h	[m]	1.0	2.0
steepness outer slope (below and above berm)	n	[-]	5	5
design water level relative to mean sea level	H_d	[m]	4.0	4.0
significant wave height	H_s	[m]	4.0	4.0
Freeboard, to reduce overtopping to q_c =1 l/s/m	R_c	[m]	4.7	4.7
crest level relative to ground level	H_l	[m]	8.2	7.2
overtopping discharge at design conditions	q_c	[l/s/m]	0.45	0.45
berm length (outer slope berm)	L_{berm}	[m]	10	10
length polder side slope	L_1	[m]	24.6	21.6
length sea side slope	L_2	[m]	51.0	46
crest width	L_c	[m]	3.0	3.0
total length dike body	L_{tot}	[m]	78.6	70.6

Case 5 is also elaborated for more severe loading conditions, storm surge of 7 m and significant wave height, at deep water, of 5 m. The dimensions are elaborated according to the sketches given by the figures above.

Parameter	Symbol	Unit	Set 1	Set 2
ground level relative to mean sea level	h	[m]	1.0	2.0
steepness outer slope	n	[-]	7	7
design water level relative to mean sea level	H_d	[m]	7.0	7.0
significant wave height	H_s	[m]	5.0	5.0
Freeboard, to reduce overtopping to q_c =1 l/s/m	R_c	[m]	5.5	5.5
crest level relative to ground level	H_l	[m]	12	11
overtopping discharge at design conditions	q_c	[l/s/m]	0.5	0.5
length polder side slope	L_1	[m]	36.0	33.0
length sea side slope	L_2	[m]	84.0	77.0
crest width	L_c	[m]	3.0	3.0
total length dike body	L_{tot}	[m]	123	113

Parameter	Symbol	Unit	Set 1	Set 2
ground level relative to mean sea level	h	[m]	1.0	2.0
steepness outer slope (below and above berm)	n	[-]	7	7
design water level relative to mean sea level	H_d	[m]	7.0	7.0
significant wave height	H_s	[m]	5.0	5.0
Freeboard, to reduce overtopping to q_c =1 l/s/m	R_c	[m]	4.7	4.7
crest level relative to ground level	H_l	[m]	11.2	10.2
overtopping discharge at design conditions	q_c	[l/s/m]	0.48	0.48
berm length (outer slope berm)	L_{berm}	[m]	10	10
length polder side slope	L_1	[m]	33.6	30.6
length sea side slope	L_2	[m]	88.4	81.4
crest width	L_c	[m]	3.0	3.0
total length dike body	L_{tot}	[m]	125	115

Annex C: Risk Calculations

A.1 Introduction

This Appendix describes the modelling methods for analyzing the current and future risk to flooding from a storm surge for a selection of 5 polders for which in the main report Conceptual Designs have been made. A flood inundation model called SFINCS was used to do the hazard modelling. For the risk analysis the FIAT-Accelerator software was used.

A.2 Hazard modeling

A.2.1 SFINCS model

SFINCS is a rapid state-of-the-art coastal inundation model (Leijnse et al., 2020). SFINCS (Super-Fast Inundation of CoastS) includes the effects of tides, storm surge, wave set-up and wave run-up. It applies the simplified approximation of the momentum balance equations described in Bates et al. (2010) with added capability of modelling waves by including advection and a generating-absorbing boundary condition. SFINCS is on average two orders of magnitude faster than traditional coastal flood models (Leijnse et al., 2020). It can therefore be run at higher horizontal resolutions and/or larger areas, which allows for a more accurate representation of coastal topography in the model. The shorter computational time will make it possible to run many scenarios, needed to carry out a probabilistic risk assessment for current and future time horizons.

A.2.2 Data

In this section, an introduction is given to the data necessary for setting up a SFINCS model. In order to estimate the probability of the selected polders to flooding, both terrain elevation and hydrodynamic conditions (such as water levels) during extreme events are needed for each polder.

A.2.2.1 Topography

In the absence of a proper local DEM, the topography is estimated using the MERIT DEM, which is a high accuracy global DEM based on both the SRTM3 v2.1 and AW3D-30m v1 DEMs. After removing multiple error components from these existing DEMS, the MERIT DEM reaches ~ 90m horizontal resolution at the equator (Institute of Industrial Sciences, 2018). The resulting topography for each of the polders is provided in Figure 0-1 to Figure 0-5. Ideally the currently existing embankments would be included in the model explicitly to ensure a best representation of the actual state but required data regarding the actual heights and extends of the embankments is not available in sufficient detail. Nevertheless, while using the MERIT DEM to estimate the topography of the polders, elevations of the embankments are (partly) captured as well in this topography data. It should be noted however that due to the ~ 90m horizontal resolution, this approximation of the embankment heights may not be fully accurate and could result in an underestimation of the actual embankment height, and therefore an overestimation of the flooding.

A.2.2.2 Boundary conditions

In an earlier stage of the Coastal Embankment Improvement Phase (CEIP-1), hydrodynamic modelling is used to quantify hydrodynamic conditions in the Bangladesh' coastal zone, which is elaborately described by IWM (2018a, 2018d). Storm surge was determined by performing an extreme value analysis (EVA) on the water levels obtained from hindcasting a total number of 19 historic cyclones with a process-based storm surge model (Bay of Bengal model), forced by the astronomic tide, river discharge, and meteorological conditions during the cyclones. The EVA provided 10, 25, 50, and 100-year return periods for the maximum attained storm surge during cyclonic storms in meters above PWD (Public Works Datum). The cyclone modelling was performed with a phase shift in the tidal components as well, to consider an unfavorable tidal phasing with respect to the moment of the cyclonic surge (i.e. the worst-case scenario of high tide during the cyclone is covered). An additional water level set-up due to wind-driven waves during the cyclonic events was assessed using a wave model. Using an approach similar to the EVA on the water levels, the 10, 25, 50, and 100-year return periods of the significant wave height (H_s) was obtained.

Additionally, extreme water levels due to monsoonal flooding (i.e. high river discharge) were determined as well, by applying a freeboard computation on the monsoon-driven water levels which were modelled with a validated one-dimensional river model capable of translating upstream river discharge to water level over the whole GBM delta (South West Regional Model). The various models provided the necessary data on strategically chosen points covering the coastal zone of Bangladesh.

Within the CEIP-1 project, maximum storm surge and wave heights are not only calculated for the different return periods, but also considering scenarios with and without the effects of climate change. Within the project, the effects of climate change for the area of interest were approximated with a 50 cm sea level rise in 2050 and an increase of the windspeeds with 8%. In this flood risk analysis, we applied the same projections as used by CEIP-1 for modelling climate change.

Each of the selected polders is surrounded by at least one of the strategically chosen points (see Figure 0-1-Figure 0-5), from now on referred to as observation points (IWM, 2018c). Maximum storm surge and wave heights for each of these observation points are presented in Table 0-1 and Table 0-2. However, only the values shown in black could be derived directly from the published reports **(**Table B3.1 to B3.5 & B5.1 to B5.4 in Appendix B of IWM (2018a, 2018b)**).** The values for the significant wave height in the case of no climate change were not available and were estimated using the quadratic relationship between wave height and wind speed**:** $H_s \sim u_{wind}^{\;2}$ **.** Since wind speeds are assumed to increase with 8%, wave heights without climate change are expected to be a factor $1/1.08^2 = 0.86$ lower. Peak periods associated with the return periods are not provided in literature but were estimated using (Van Rijn, 2011): $T_p = 6H_s^{\;0.33}$

Table 0-1 Maximum storm surge in meters above PWD at the observation points. Source: Table B3.1-B3.5 of IWM (2018b)

		WITHOUT CLIMATE CHANGE STORM SURGE (M) FOR DIFFERENT RETURN PERIODS (YEARS)				WITH CLIMATE CHANGE STORM SURGE (M) FOR DIFFERENT RETURN PERIODS (YEARS)			
POLDER	**Point ID**	**10**	**25**	**50**	**100**	**10**	**25**	**50**	**100**
15	**1**	2.49	3.07	3.52	3.96	2.77	3.28	3.65	4.03
15	**2**	2.54	3.15	3.61	4.07	2.77	3.31	3.7	4.1
15	**3**	2.49	3.09	3.54	4	2.74	3.21	3.55	3.89
29	**10**	2.45	2.97	3.36	3.76	2.97	3.53	3.95	4.36
29	**11**	2.36	2.82	3.17	3.52	2.83	3.32	3.69	4.05
40-1	**34**	2.76	3.74	4.46	5.18	3.51	4.86	5.85	6.84
40-1	**35**	2.99	4.09	4.9	5.71	3.83	5.41	6.59	7.75
40-1	**37**	2.99	4.11	4.94	5.76	3.96	5.67	6.93	8.19
40-1	**105**	2.79	3.79	4.53	5.27	3.49	4.7	5.6	5.49
40-1	**106**	3.02	4.15	4.98	5.81	3.8	5.2	6.23	7.26
40-1	**107**	2.79	3.79	4.53	5.26	3.57	4.83	5.76	6.69
40-1	**108**	2.74	3.7	4.41	5.12	3.46	4.63	5.5	6.36
59-2	**65**	3.32	4.34	5.1	5.85	3.92	5.03	5.85	6.66
59-2	**67**	3.16	4.22	5	5.77	3.74	4.79	5.56	6.33
64	**89**	4.14	5.31	6.17	7.03	4.89	6.21	7.19	8.16

64	**90**	3.97	5.08	5.9	6.72	4.69	5.95	6.88	7.81
64	**91**	3.84	4.91	5.7	6.48	4.55	5.75	6.64	7.52

Table 0-2 Maximum wave heights in meters at the observation points. Values without climate change in red are derived within this study. Source: Table B5.1-B5.4 of IWM (2018b)

		WITHOUT CLIMATE CHANGE WAVE HEIGHT (M) FOR DIFFERENT RETURN PERIODS (YEARS)				**WITH CLIMATE CHANGE WAVE HEIGHT (M) FOR DIFFERENT RETURN PERIODS (YEARS)**			
POLDER	**Point ID**	**10**	**25**	**50**	**100**	**10**	**25**	**50**	**100**
15	**1**	0.41	0.57	0.72	0.88	0.48	0.67	0.84	1.03
15	**2**	0.34	0.49	0.62	0.75	0.4	0.57	0.72	0.88
15	**3**	0.35	0.50	0.63	0.76	0.41	0.58	0.73	0.89
29	**10**	0.24	0.33	0.42	0.51	0.28	0.39	0.49	0.6
29	**11**	0.22	0.32	0.40	0.49	0.26	0.37	0.47	0.57
40-1	**34**	1.49	1.99	2.31	2.61	1.74	2.32	2.69	3.04
40-1	**35**	1.51	2.04	2.39	2.71	1.76	2.38	2.79	3.16
40-1	**37**	1.78	2.55	3.09	3.58	2.08	2.98	3.6	4.17
40-1	**105**	1.56	2.07	2.38	2.67	1.82	2.41	2.78	3.11
40-1	**106**	1.45	2.04	2.43	2.80	1.69	2.38	2.84	3.27
40-1	**107**	1.23	1.83	2.26	2.68	1.44	2.14	2.64	3.13
40-1	**108**	0.92	1.47	1.92	2.39	1.07	1.72	2.24	2.79
59-2	**65**	2.30	3.21	3.81	4.36	2.68	3.74	4.44	5.08
59-2	**67**	2.53	3.26	3.70	4.10	2.95	3.8	4.32	4.78
64	**89**	3.22	3.95	4.39	4.77	3.76	4.61	5.12	5.56
64	**90**	3.37	4.11	4.55	4.93	3.93	4.79	5.31	5.75
64	**91**	3.46	4.33	4.86	5.32	4.03	5.05	5.67	6.21

A.2.2.3 Subsidence

To account for possible subsidence, the value of 1 cm / y as in the CEIP-1 embankment designs (BWDB, 2012) is used. Since the future climate conditions are derived for 2050 this gives a total subsidence to be included of 0.3m.

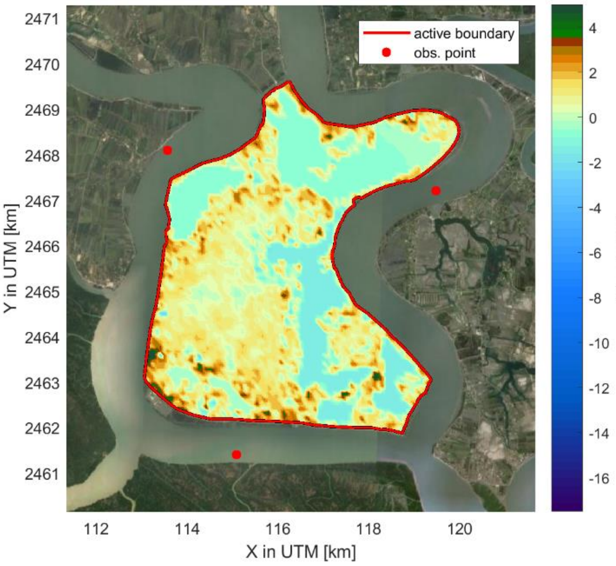


Figure 0-1 Elevation with respect to PWD for polder 15

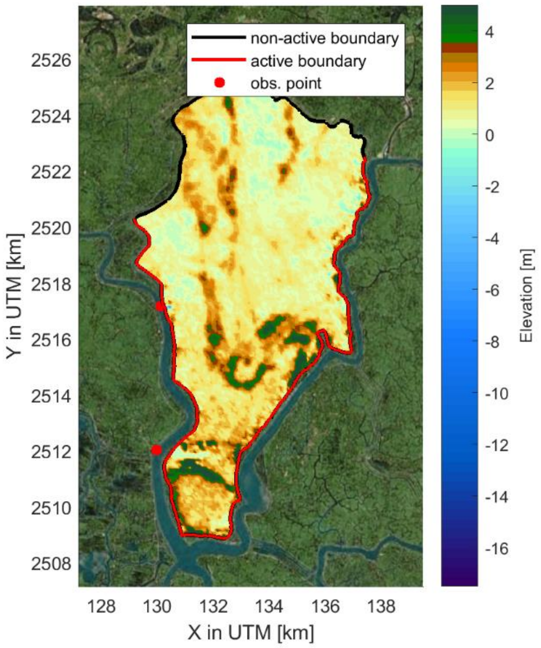


Figure 0-2 Elevation with respect to PWD for polder 29

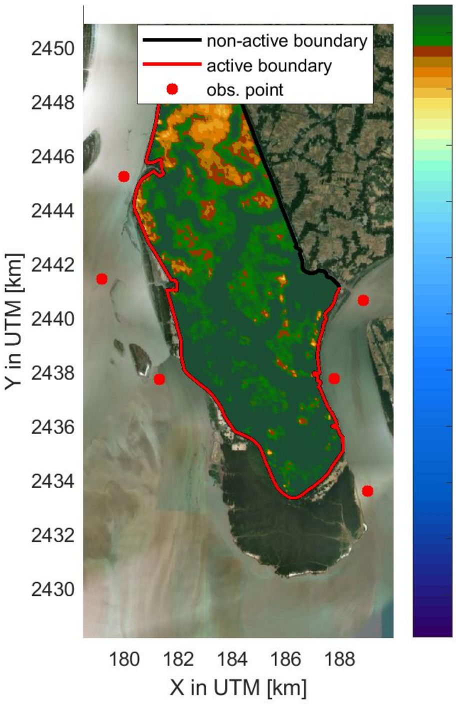


Figure 0-3 Elevation with respect to PWD for polder 40-1

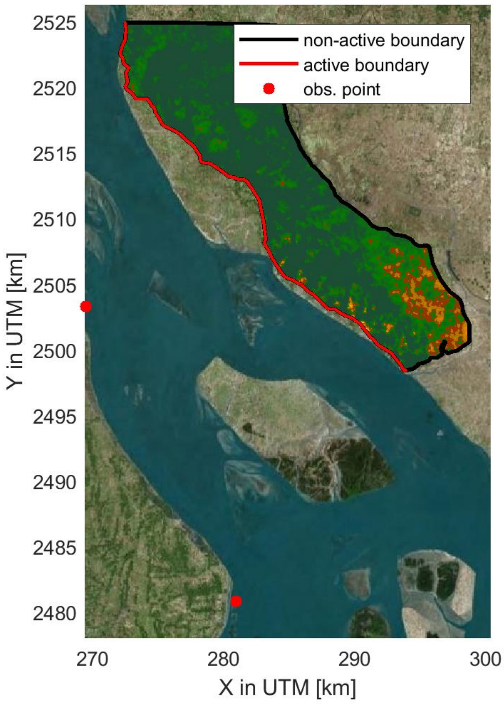


Figure 0-4 Elevation with respect to PWD for polder 59-2

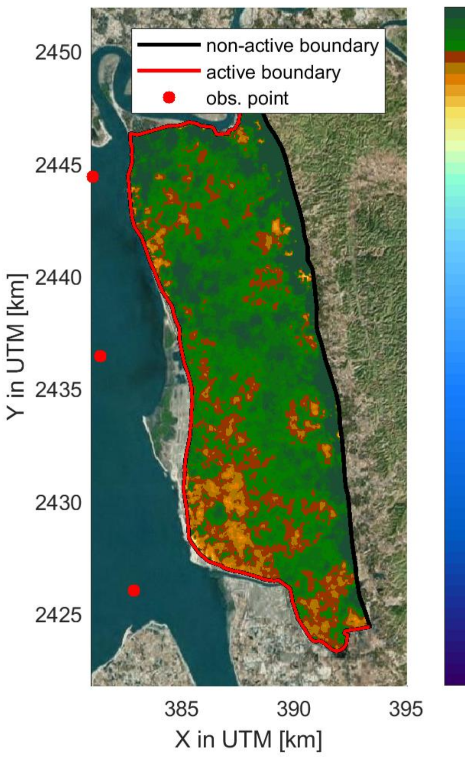


Figure 0-5 Elevation with respect to PWD for polder 64/1a and polder 64/1b

A.2.3 Modelling approach

A flood inundation model was set-up for each polder to estimate the extent of flooding under extreme surge levels and wave heights determined in CEIP-1 (see Table 0-1Error! Reference source not found. and Table 0-2). The SFINCS model is used for this purpose. The SFINCS model does not account for morphological changes and therefore only overtopping is considered, i.e. no breaching or other bank failure is modelled. A model is set-up covering the area of the specific polder, with a numerical grid of 20 m grid cells. The extent of the numerical grid is limited to the extent of the topo-bathymetric data available. The vertical reference level of the models is PWD. Since the MERIT DEM is defined with respect to the geoid, a correction was applied to express the topography in PWD as well. Mean sea level (MSL) around Bangladesh is defined at 1.1m above the geoid EGM1996 according to the global Mean Dynamic Topography model MDT-CNES-CLS18 (Aviso, 2018), whereas PWD is MSL-0.46m. Combining the latter gives that PWD is 0.64m above the geoid, which was used to correct the MERIT DEM to PWD.

The models are set-up with open (active) boundaries along the main river banks and along the Bay of Bengal where the storm surge and waves are forced. The (relatively) small canals that surround the polders are assumed not to play a role considering inundation and since no boundary conditions are derived for these small canals these are therefore modelled as closed (inactive) boundaries. For the same reason, the small canal between polder 64/1a and 64/1b is neglected, and these polders are modelled as one. All models get input from the closest observation points (Figure 0-1 - Figure 0-5). Using linear interpolation these values are forced along the active boundary of the SFINCS models.

The forcing of the water levels is described as a 48 hour sinusoidal signal which reaches the maximum surge level indicated in Table 0-1 after 1 day (e.g. 1/25 year storm for polder 15 in Figure 0-6). An additional wave signal is described as a signal of random fluctuations, that is made using a JONSWAP spectrum[5] using the wave height and peak periods from the previous section (see Table 0-2). The same methodology is followed as in Schrijvershof (2020).

The models were consequently run for a set of simulations (10, 25, 50, and 100-year return periods) with and without the influence of climate change and land subsidence (i.e. relative sea level rise). This gives a total set of 8 simulations per polder.

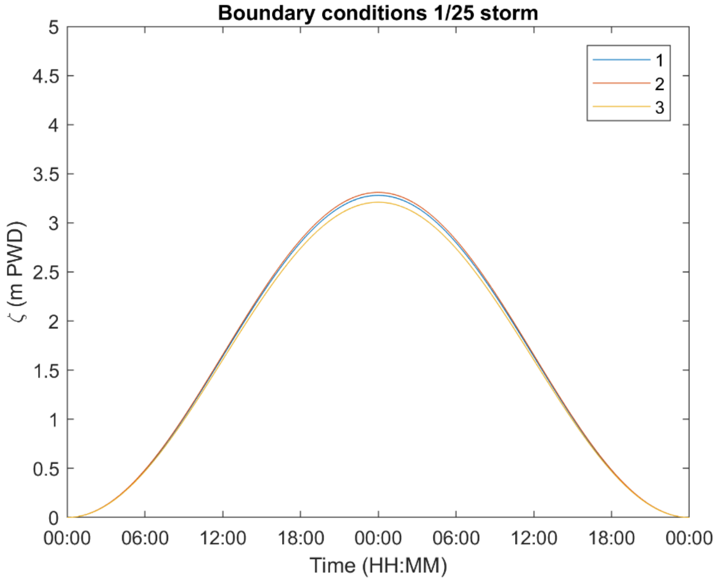


Figure 0-6 Boundary condition of 1/25 year storm for the three different observation points around polder 15 (Point ID in legend).

A.2.4 Results

For each polder, 8 different inundation scenarios have been modelled using the SFINCS model. In this chapter, general trends between the different scenarios will be discussed taking polder 40/1 as an example. Furthermore, differences between the polders will be highlighted by comparing the 25-year return period including climate change for each polder.

A.2.4.1 Polder 40/1

The results of the most distinctive scenarios for polder 40/1 are provided in Figure 0-7 to Figure 0-10. For each scenario a map is presented which indicates the maximum water depth reached at each location during the storm. Although the magnitude between the different polders may vary, the general trends between the different scenarios show similar results for all polders. At first, it should be noted that the influence of relative sea level rise is already visible for relatively small storms with a 10-year return period (Figure 0-9). The inundation is minimal for a 10-year return period storm without relative sea level rise (Figure 0-7). The maximum inundation is found while considering a 100-year return period storm and accounting for relative sea level rise. Scenarios in between the two extremes often result in partial inundation (clearly visible in Figure 0-8), i.e. higher land remains dry whereas low lying land is inundated. The maximum water depths in the presented flood maps are very much dependent on the local topography.

[5] The JONSWAP spectrum is an idealized wave spectrum that describes the energy distribution over different wave frequencies. The JONSWAP spectrum is widely used as design spectrum for to model waves during storm conditions (Hasselmann et al., 1973).

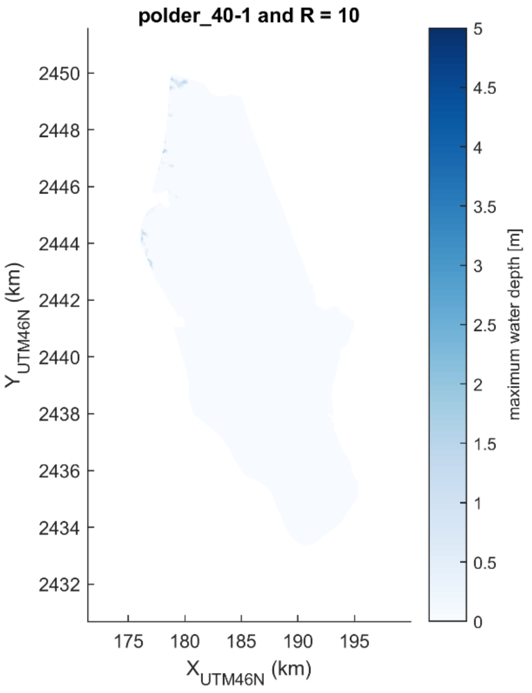


Figure 0-7 No relative SLR and R=10 years

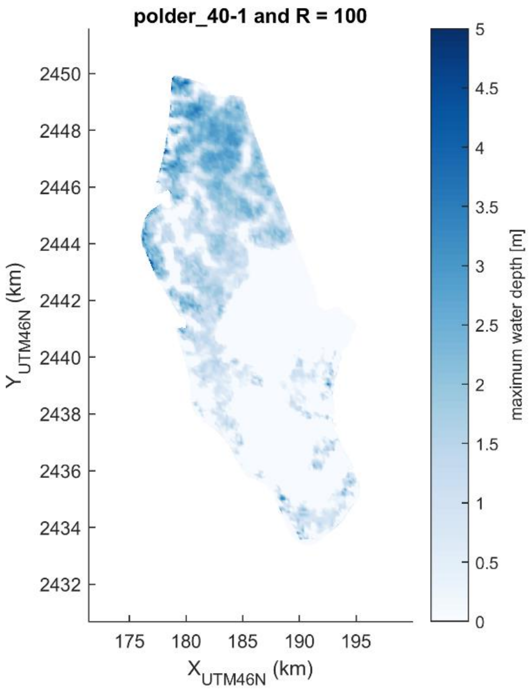


Figure 0-8 No relative SLR and R=100 years

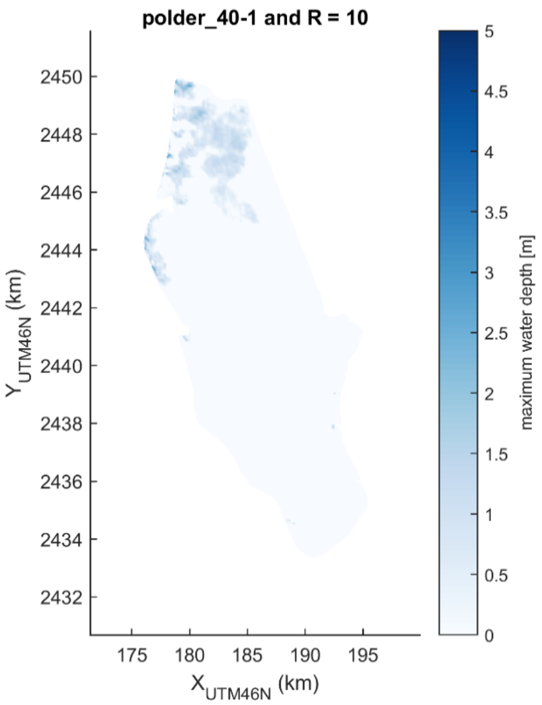


Figure 0-9 With relative SLR and R=10 years

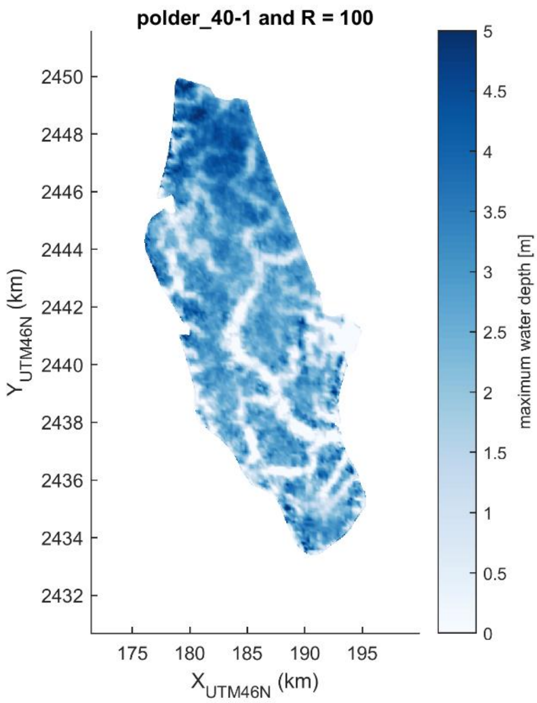


Figure 0-10 With relative SLR and R=100 years

A.2.4.2 All polders

Since the embankments proposed during the CEIP-1 project were designed to withstand conditions with a 25-year return period in 2050, the expected flooding for the 25-year return period including the effects of relative sea level rise are also presented below. In Figure 0-11 to Figure 0-15 it can be seen that almost all polders are susceptible to inundation. In polder 15, some low-lying areas may reach depths up to 5 meters during a storm surge of 4m+PWD. Also, in the polders 29 and 40/1, relatively large depths may be reached, especially near the embankments. Nevertheless, computations also show that polder 59/2 is relatively safe for flooding and also polder 40/1 has a large area which remains dry during storms. Although these results provide some first insights of what areas are prone to flooding, it should be noted that by not specifically taking into account the embankments this might result in an overestimation of the flooding, especially when embankments are partially not captured in the MERIT DEM. These findings are quantitatively visualized in Table 0-3 which shows the relative area of the polder for which the maximum water depth exceeds 0.5 m.

Table 0-3 Percentage of polder for which maximum water depth exceeds 0.5 m, where the background color indicates the vulnerability to flooding from safe (green) to susceptible (orange)

		With relative sea level rise				Without relative sea level rise			
Polder	**Area (ha.)**	**10**	**25**	**50**	**100**	**10**	**25**	**50**	**100**
15	3,236	96,1%	97,5%	98,0%	98,2%	92,4%	96,3%	97,5%	98,0%
29	7,996	88,4%	92,9%	95,0%	96,6%	75,3%	84,9%	89,2%	92,3%
40/1	6,855	7,9%	41,3%	69,7%	89,9%	0,3%	6,6%	20,4%	44,1%
59/2	24,916	1,6%	5,3%	38,7%	93,1%	0,4%	2,3%	5,0%	27,4%
64	15,080	59,0%	93,5%	96,1%	97,2%	11,8%	61,1%	91,0%	95,2%

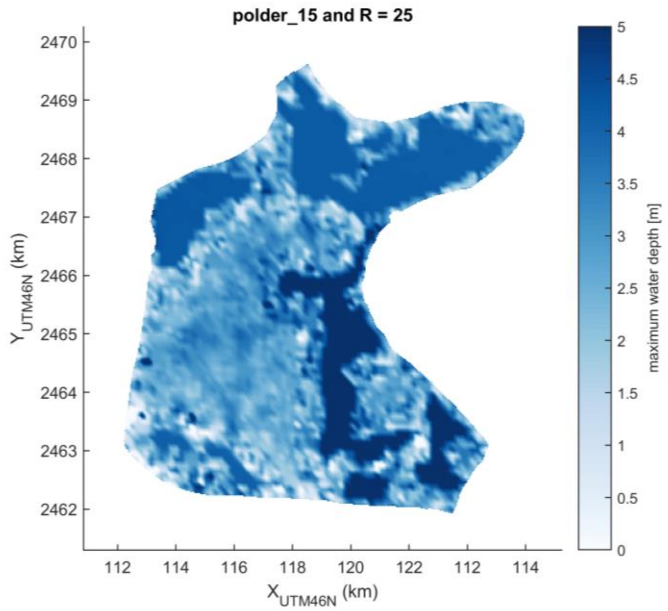


Figure 0-11 25-year return period for polder 15, including relative sea level rise

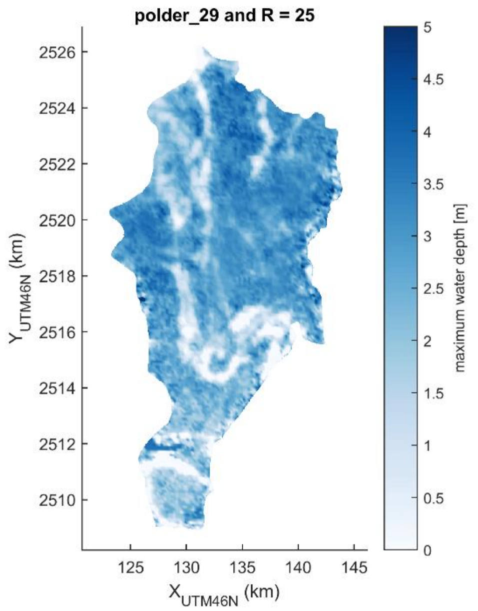


Figure 0-12 25-year return period for polder 29, including relative sea level rise

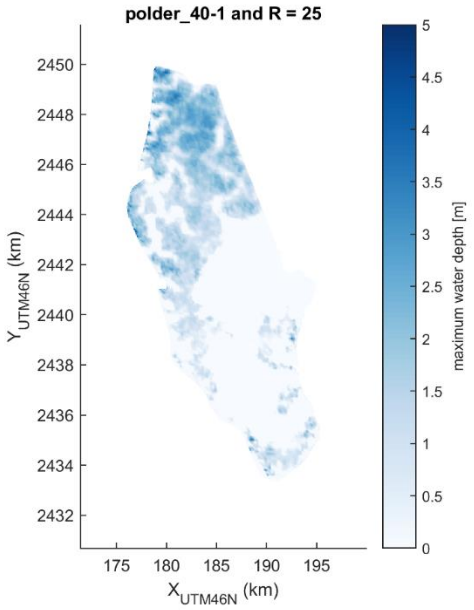


Figure 0-13 25-year return period for polder 40/1, including relative sea level rise

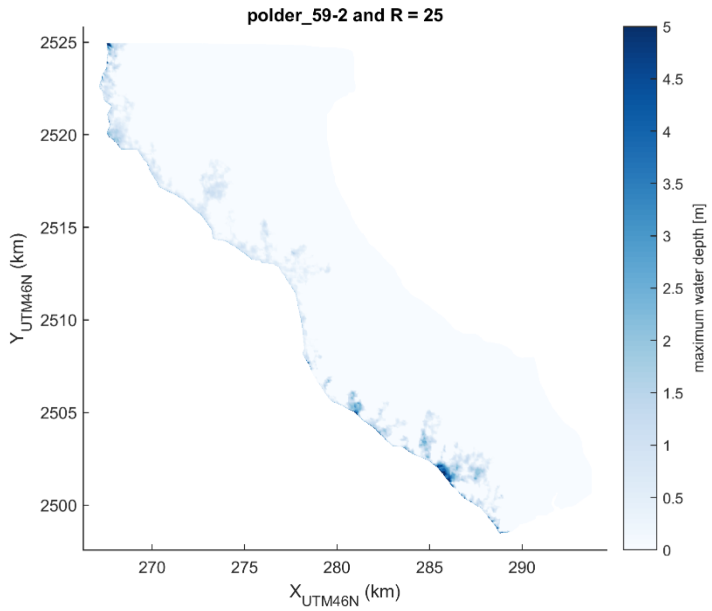


Figure 0-14 25-year return period for polder 59/2, including relative sea level rise

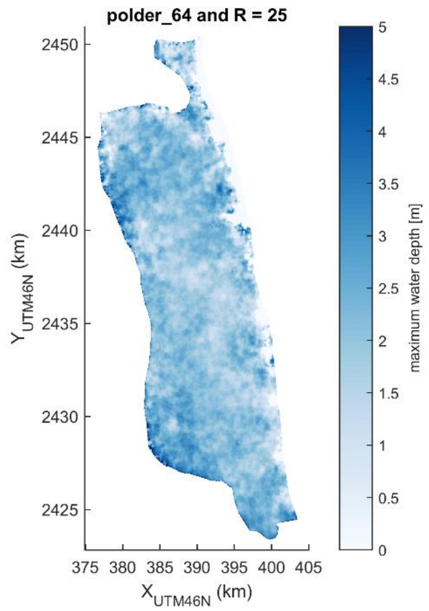


Figure 0-15 25-year return period for polder 64, including relative sea level rise

A.3 Risk modelling

A.3.1 Introduction

The goal of the risk analysis is to assess the risk reduction (i.e. reduction in annual direct impacts to exposed assets and people in the polders) resulting from the improvement of embankments up to a safety level of 1:25 year in 2050. For this purpose, the Delft- Flood Impact Assessment Tool (D-FIAT, Slager et al., 2016) is used. D-FIAT is an open source toolset for building and running impact models, based on the unit-loss method. The tool requires input for a flood impact assessment; inundation maps, exposure maps, damage functions and maximum damage (Figure 0-16). The risk analysis is quantitative and expresses direct and indirect damages of houses, infrastructure and production in monetary values as well as mortality.

D-FIAT has been applied at several flood risk studies around the world due to its flexible modelling scheme and its computational speed. The tool estimates economic damages and impacted assets by linking hazard information (water depth maps) to exposure maps (object maps) via vulnerability functions (damage functions) for different types of assets using the flow diagram presented in Figure 0-16. The results of the tool are available as (monetary) damage (impact) per flood return period (associated to the probabilities of exceedance). Finally, the tool integrates the damage-probability curve and the Expected Annual Average Losses (EAAL) to obtain total risk.

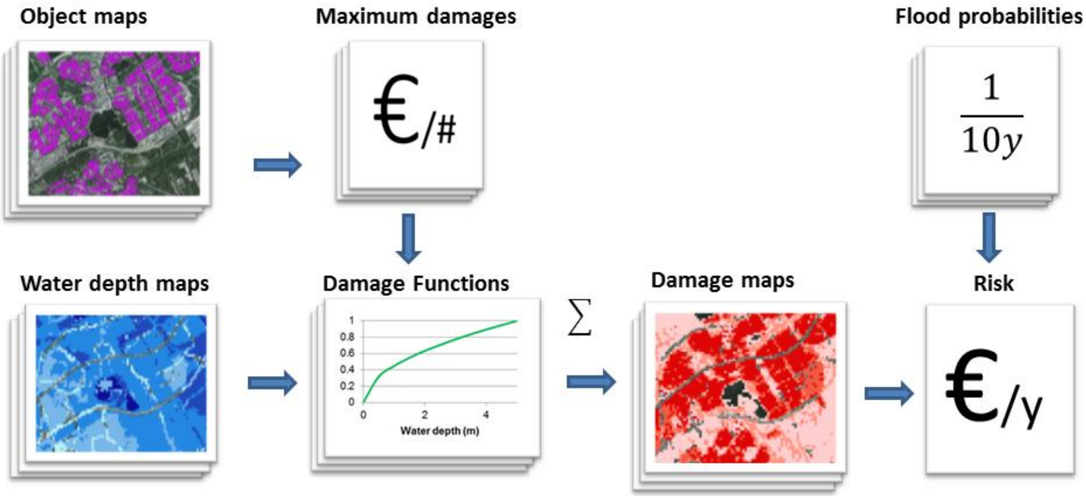


Figure 0-16 Overview of damage and risk calculations in Delft-FIAT.

For each polder one impact model was set-up, using the inundation results corresponding to the different scenarios (4 return periods with and 4 return periods without relative SLR), as well as the exposure maps and damage functions (see next section). For the risk reduction due to (new) embankments it was assumed that all damages and mortality are zero for return periods lower than the design safety level of these embankments.

A.3.2 Damage categories and vulnerability

Three types of exposed assets were analysed:

- Residential buildings (consisting of the following types: Pucca house, Semi-Pucca house, Kutcha and Shanty types)
- Businesses and services infrastructure
- Agriculture

Furthermore, the flood impact includes affected people and mortality due to flooding. Seven different vulnerability functions were used which are combined (multiplied)with the maximum damage values in Table 0-4:

- 4 functions for structural damage of different types of residential building categories (Figure 0-17)
- 1 function for damage to crops (agricultural damage; Figure 0-17), and
- 2 functions for the estimation of affected people by flooding (threshold of 10 cm; Figure 0-18) and flood mortality (Figure 0-19)

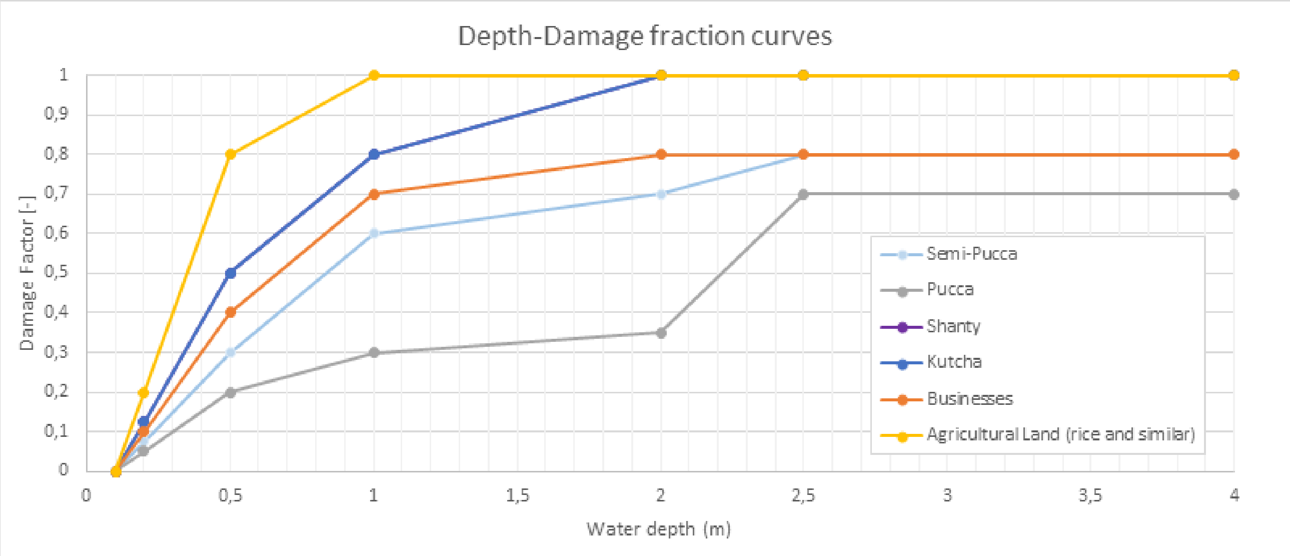


Figure 0-17 Damage functions for houses and agriculture

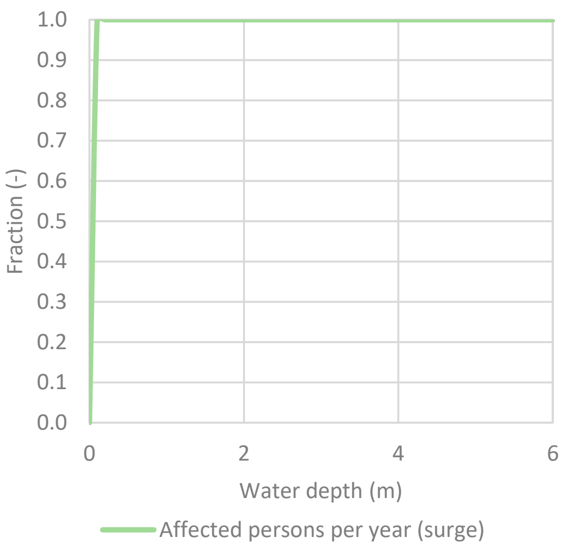


Figure 0-18 Vulnerability function for affected people (threshold 0.1m)

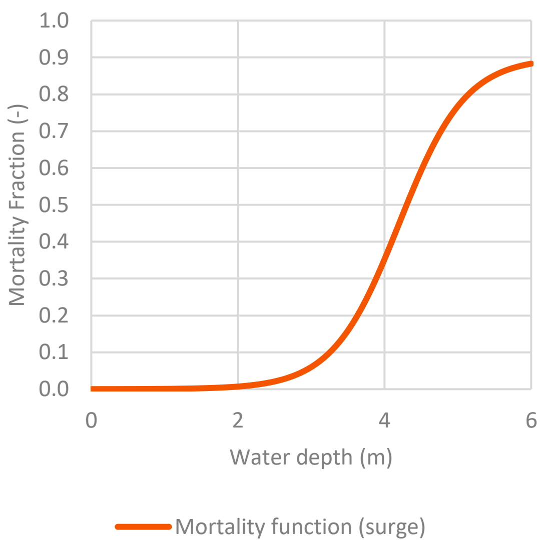


Figure 0-19 Function for flood mortality. Source: Adapted from Jonkman, 2007.

Table 0-4 Maximum damage per asset analysed. Values are multiplied by damage fraction to obtain depth-damage curves.

Asset	Maximum Damage	Building type distribution**
*Pucca House**	880,000 BDT/house	8%

*Semi-Pucca House**	261,500 BDT/house	84%
*Kutcha House**	115,000 BDT/house	1%
*Shanty House**	30,000 BDT/house	7%
Business and services	25% of total residential assets	
Agriculture	442,800 BDT/ha	--
Affected people	1 person	--
Mortality	1 person	--

Sources: *see table 5; ** GOB (2008)

The maximum damage of residential buildings has been estimated using the replacement costs for houses that were assessed under the Resettlement Action Plan of CEIP-1 (RAP Report - CEIP, 2018). Because the RAP assessment only provides costs per square feet of the different house types, an average cost per house type has been approximated by using an average size of each house type (see Table 0-5).

Table 0-5 Replacement costs for houses

House type	cost per sq ft*	average cost per sq ft	average size* (sq ft)	average cost per house
Pucca	1100	1100	800	880,000
Semi-pucca	475 – 570	523	500	261,500
Katcha	242-525	384	300	115,200
Kuregor (hut)	100-200	150	200	30,000

* Source: RAP Report - CEIP(2018)

Damage for agriculture is based on added value from agriculture as provided by BBS (2019), which is BDT 221,400 per ha/crop. Damages to businesses and services is based on value of residential houses in the polder and set at 25 % of total residential value. Next to direct damages, there is also indirect damages for agriculture and businesses. For agriculture indirect damages are assumed to be 100 % of direct damages, assuming a gradual return to normal production in 1 – 3 years after the flood event. For businesses and services, the indirect damages are assumed to be 80 % of direct damages, which is based on international experiences and calculations from The Netherlands as described in De Bruin et al (2014). More information on Delft-FIAT can be found at https://publicwiki.deltares.nl/display/DFIAT/Delft-FIAT+Home .

Table 0-6 Other type of damages (Businesses)

Other Type of Damages	Factor over all residential damages (sum of 4 categories)
Business damages	0.25
Business interruption (indirect damages)	0.2

A.3.3 Exposure data

A.3.3.1 Population and houses

The number of residential units in the polders was calculated from the World Settlement Footprint (WSF) dataset[6] and a reported average household size of 4 people (CEIC data, 2016). The WSF dataset has estimations of population (2015) per grid cell of 20m x 20m. The total number of people per grid cell was divided by the household size to obtain the number of residential units.

[6] World Settlement Footprint 2015- available at: https://urban-tep.eu/puma/tool/?id=574795484&lang=en

A.3.3.2 Land use

For agriculture a land use map was used (see Figure 0-20) by rasterizing to the same resolution of the flood maps (20x20m) and georeferenced the map to UTM 46N.

Detailed maps of each polder are provided in figures 3-6 to 3-11.

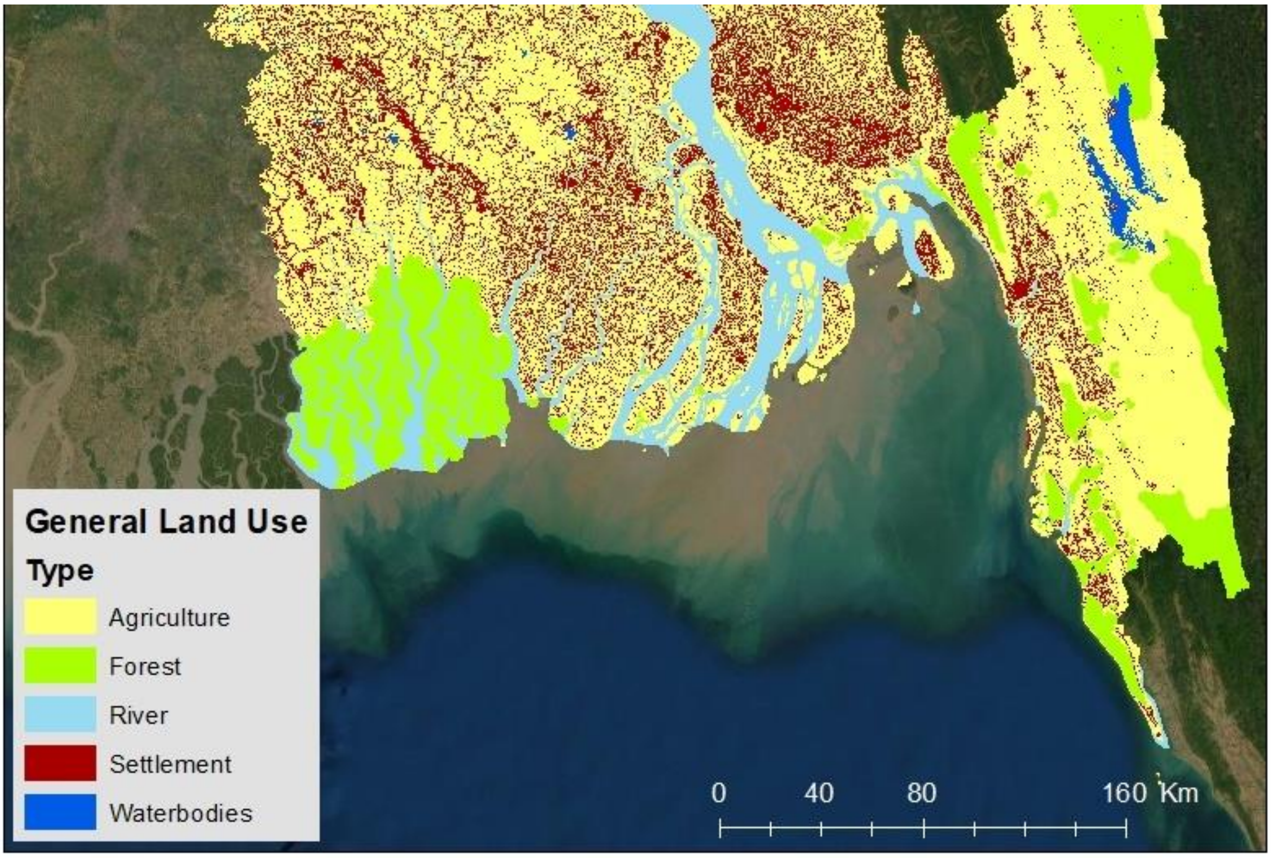


Figure 0-20 Coastal part of the land use map (original projection GCS_Everest_1830)

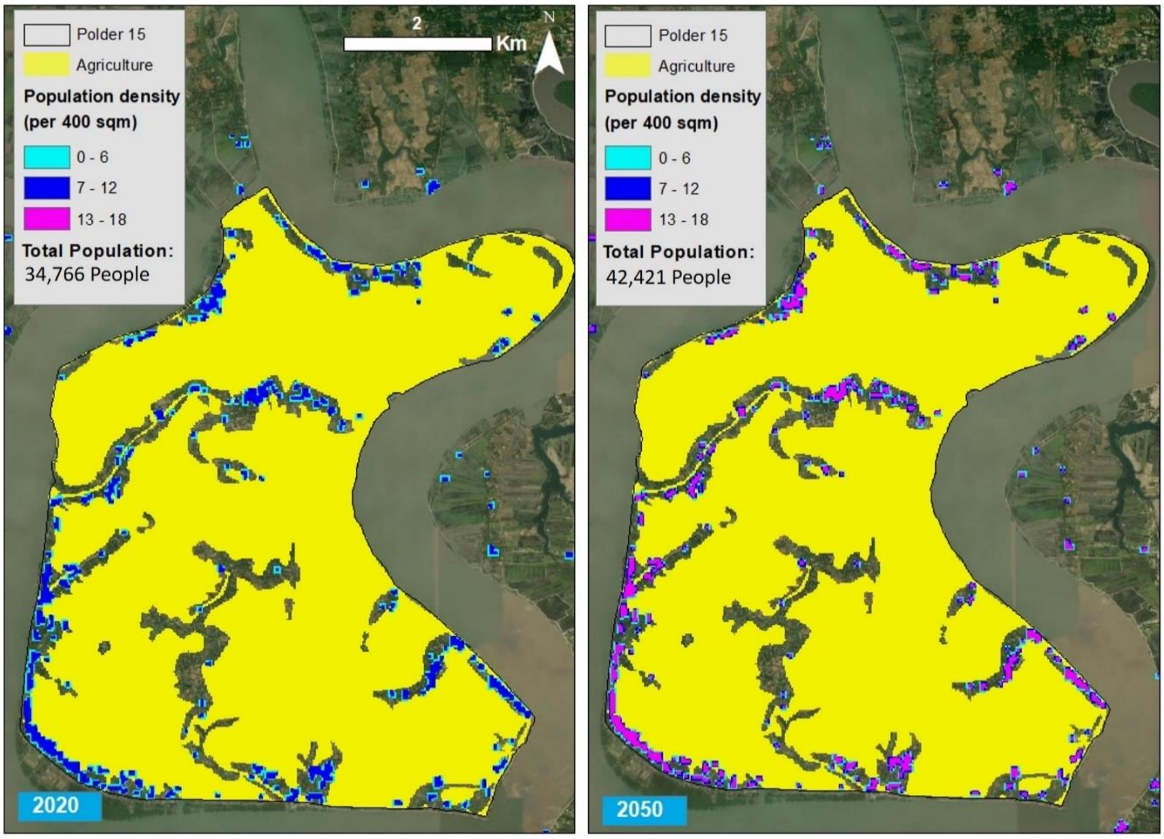


Figure 0-21 Land use and Population density Polder 15 (current and projected)

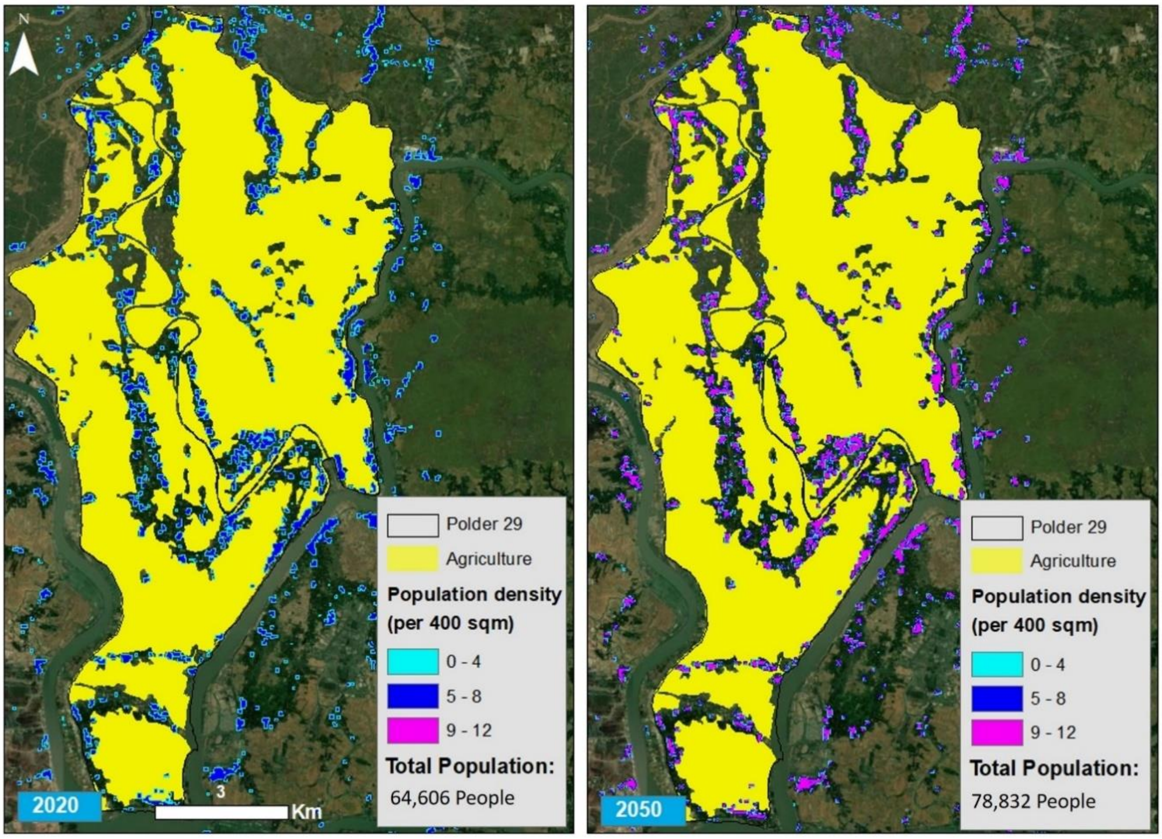


Figure 0-22 Land use and Population density Polder 29 (current and projected)

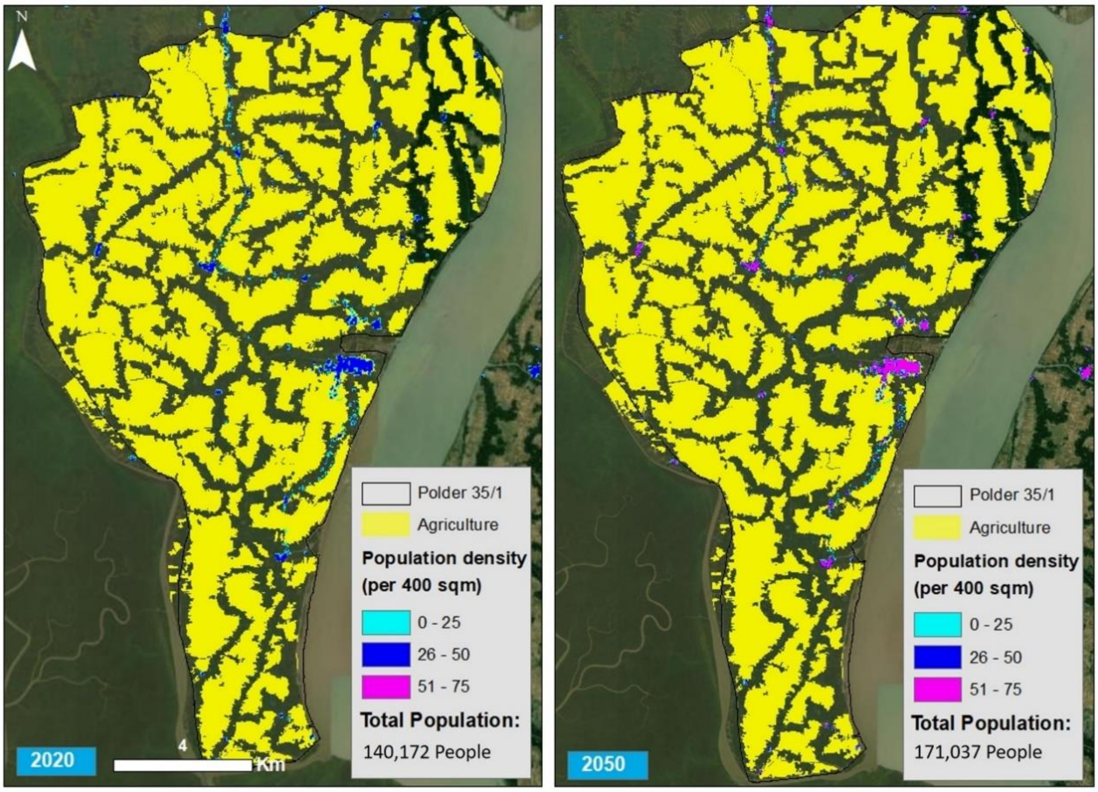


Figure 0-23 Land use and Population density Polder 35/1 (current and projected)

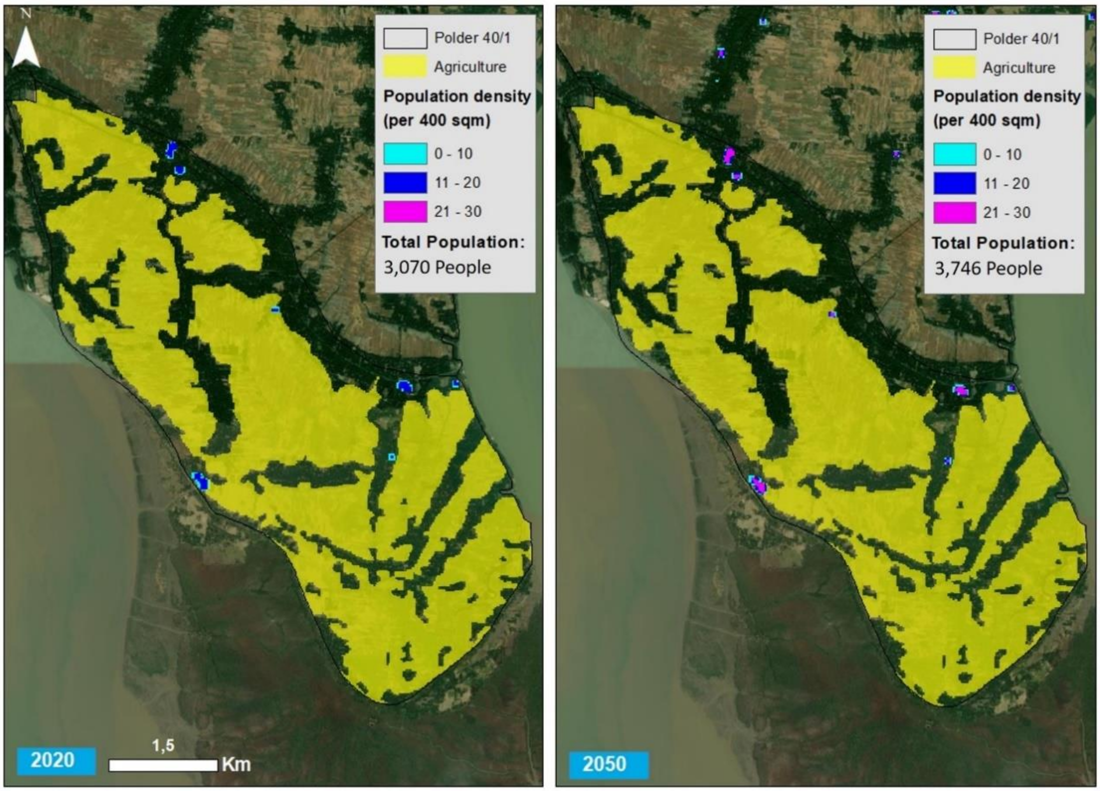


Figure 0-24 Land use and Population density Polder 40/1 (current and projected)

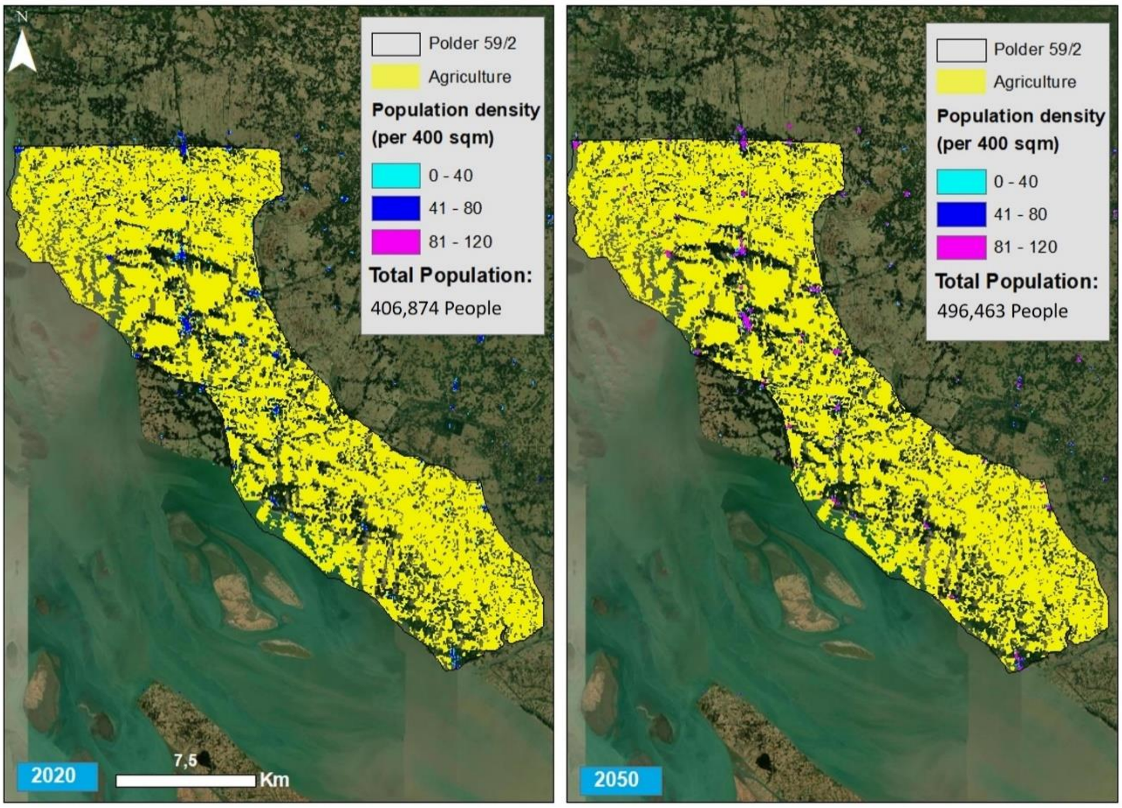


Figure 0-25 Land use and Population density Polder 59/2 (current and projected)

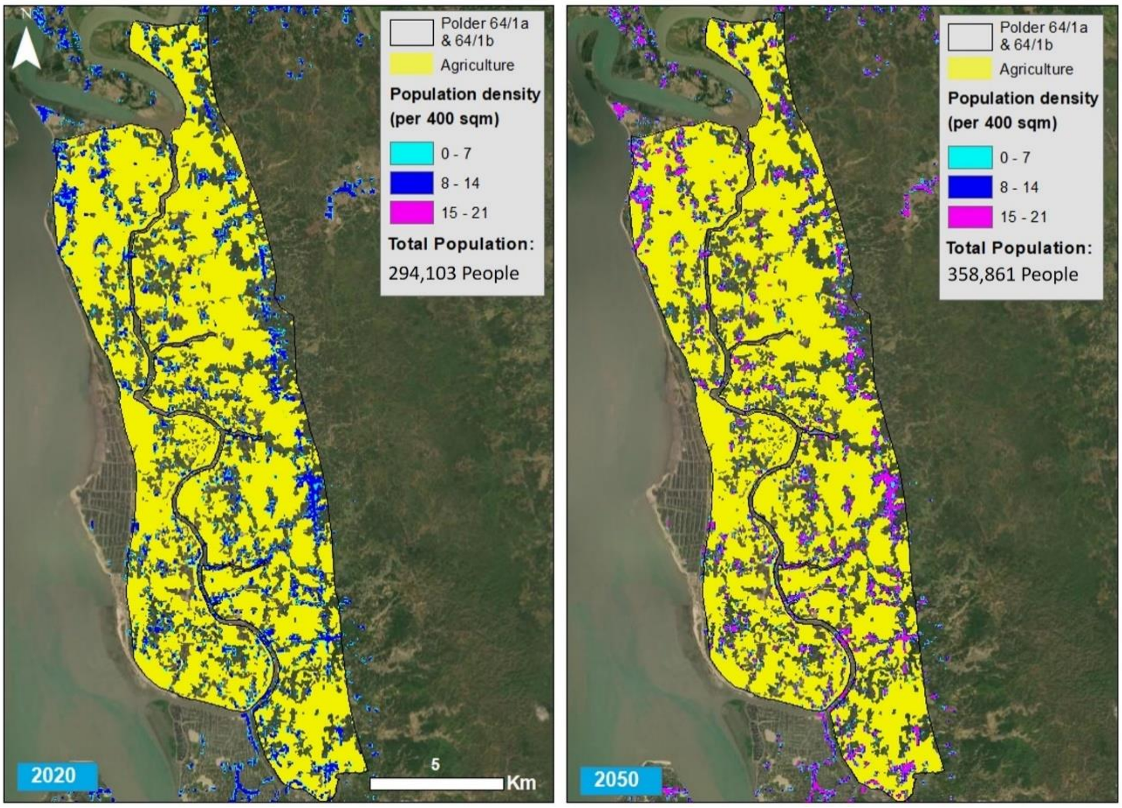


Figure 0-26 Land use and Population density Polder 64/1a and 1b (current and projected)

A.3.4 Assumptions and limitations

The following assumptions were made in computing the risks for the polders:

- A threshold of 10 cm of water depth was used as an indicator of affected people by flooding.
- The risk estimation was based on 2018 prices.
- Risk for residential houses only considered structural damages. Damage to content was not considered due to lack of detailed data[7].
- The method to calculate direct annual damages does not reflect differences in risk resulting from inequalities between population. Differences in income lead to differences in social vulnerability, as the loss of the same monetary value of an asset (such as a house) has a different social welfare value.
- The method assumes a risk neutral approach in which equal values are assigned to low probability/high consequence and high probability/low consequence events. This means that risk aversion is not included in the analysis.

[7] Global assumptions (e.g. Huizinga et al, 2017) often consider that damage to content represent 50% of the structural damage

A.4 References

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Annex D: Comments of World Bank and Responses from the Consultants

Comments and Responses

PDF page	Short reference to report text/figure	Comments of World Bank	Responses from the consultants
	General	'- The presented report provides for 5 polders a (straightforward) analysis of the cost and benefits of polder rehabilitation of the existing polder layout. However, it was expected that this report would come with some new ideas/options how the future polders could look like based on the insights from the modeling etc. E.g. what about lumping different polders together, what are different polder options? are those more cost-effective? This may warrant a discussion between Consultants and BWBD/WB how this could be enhanced. '- Various comments to Polder 15 also hold for the other polders; please check these carefully when revising;	Based on the current models it is not possible to suggest specific large scale systemic (e.g. joining of polders, closing side channels) interventions. Before this type of interventions can be suggested effects in respect to tidal prism and sediment flows should first be assessed. This has not been modelled so far, and are therefor not included in the proposed interventions for the polders. Interventions are currently geared to reduction of the risk impact on the polder, the improvement of the drainage situation and exposure to cyclonic winds. Furthermore, a recommendation to separate "saltwater cultures", i.e. shrimp aquaculture, from fresh water cultivation due to the negative impacts of aquaculture of shrimp farming. However, this is not so much a suggestion for interventions as one of land use planning.
15	Cost table Table 2-1	The costs presented here are the total cost (including design/contingencies etc.) for an entire new embankment based on the sketches provided? Typically, there is an existing embankment that is simply raised and/or add slope protection is added. The assumption later on is that the starting point is a 1/10yr protection level (so there is an existing embankment). How has this been factored in? Also, the translation of the design sketches into costs is not very clear; maybe include in the text which unit cost numbers have been used for earthworks, bank protection etc.?	The starting point for the costs estimate is an existing 1/10 embankment. Costs are for the additional works to be done. Explanation added to the tekst.
16	Cost table Table 2-2	Khal costs are per kilometers, others are per unit I think	units added in table
16	Maintenance costs	The section on costs does refer the capital costs; maintenance costs assumptions?	These are investment costs
17	Assumptions CBA	Discount rate 12% => include why this has been chosen (typical for BD?); also interventions implementation in 1 year and full benefits after 1 year seems quite optimistic, maybe make a note about this?	As budget in Bangladesh is a constraint, a discount rate of 12 % is used. This discount rate, in combination with the used SSP2 scenario for economic and population growth results in a net discount rate of around 6 %. This rate is adequate to substantiate economic viability of investments when B/C-ratio is above the threshold. Text added.

PDF page	Short reference to report text/figure	Comments of World Bank	Responses from the consultants
18	2.2.3	What is the rationale for the assumption of 25% efficiency for the drainage infra investments to the agri benefits? Why not 50% or 10%? I understand that an assumption must be made but this number should somehow be justified.	Indeed the 25 % is an assumption. Drainage is a very important factor in the effectiveness of fertilizer application. However, next to drainage also the correct timing and the quantity of fertiliser applied is very important in the overall effect on crop yields. In order not to over-estimate the effect of the drainage a 25 % increase in crop yield has been assumed. Explanation added
18	2.2.3	Paddy is mentioned but what about shrimp culture and the benefits of the drainage network for this type of economic activity? Aquaculture also uses the drainage system (but in a different way), right?	Drainage has a completely different role in aquaculture. No specific benefits are used for this sector, only a general proxy for paddy cultivation.
18	2.2.4	Cyclone shelters are also built generally for cattle (400-500?); see https://reliefweb.int/report/bangladesh/cyclone-shelters-livestock-too; should that be factored in as well (or are the benefits relatively small?)?	Indeed shelters are also used for cattle. However benefits are relatively small and have not been factored separately for cyclone shelters (they are part of the agriculture damages in the FIAT model.
21	Fig 3-2	Can this figure be redrawn with the km on the horizontal axis so that it can be referenced to the figure of the polder? The sections are undefined.	Unfortunately for polder 15 this is not readily available. However, in the modelling the proper embankment height has been used.
22	3.2	Cyclone intensity and frequency: what is stated here seems in contradiction to the meteo/hydro report Deliverable 4C; that report suggests that - if at all - the most severe TCs may increase in intensity and frequency; suggest to align this better	Increase in cyclone frequency is found to be inconclusive, however, wind intensity is projected to increase with 4 – 8 %. The storm surge model developed by IWM (2018) has used an increase in wind speeds of 8%. Text added
22	3.2	Sea level rise?	Sea Level Rise: SLR used in the risk modelling is 30 cm in 2050. Text added
	Fig 3-10	Hor axis legend missing; it would suggest to present this as function of return period, not frequency, so that damage curves goes up to the right.	
	Chapter 3-7	Please consider comments above also for the other chapters/polders where relevant	consistency checked

PDF page	Short reference to report text/figure	Comments of World Bank	Responses from the consultants
76	Chapter 9	The conclusions indicate that economic justification of rehab/increase in protection level of Polder 40/1 is difficult whereas the chapter says something different	The proposed investments for polder 40/1 have a B/C-ratio of 0.8 (1.0 with lower end costs) making the investments economically viable (just). This is the conclusion in chapter and conclusions?