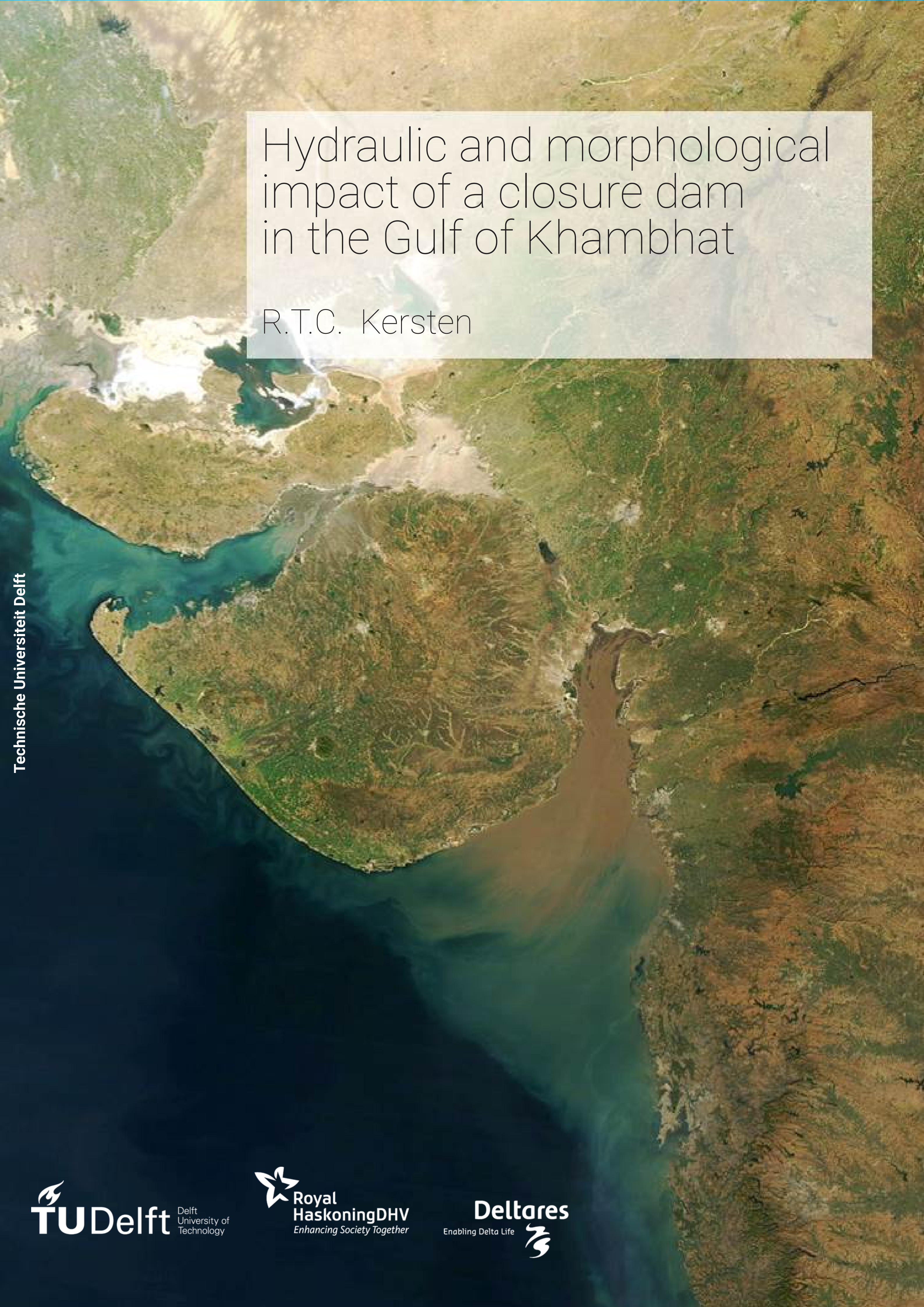

Hydraulic and morphological impact of a closure dam in the Gulf of Khambhat

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Technische Universiteit Delft

TU Delft Delft University of Technology

Royal HaskoningDHV Enhancing Society Together

Deltares Enabling Delta Life

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by

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Preface

This thesis concludes the Master of Science program in Hydraulic Engineering at Delft University of Technology. The research was conducted during seven enjoyable months at Royal HaskoningDHV, one of the leading engineering and project management consultancies in the Netherlands.

In the fall of 2017, Royal HaskoningDHV set up an interdisciplinary research team in collaboration with three universities to revive the Kalpasar project. This project focuses on a closure in the Gulf of Khambhat in India, which aims at the creation of the world's largest fresh water reservoir. Before starting this thesis, I worked together with two other students from the TU Delft on an integral part of the project. During four energetic and insightful weeks we gathered as much information as we could on the case study. Subsequently, we divided the technical challenges of the project into three categories, which will be covered separate MSc theses. This report focuses on the impact of the closure on the hydrodynamics and the large-scale morphology in the gulf.

During my study, I gathered a great amount of knowledge and skills that came together in this final project. Looking back, one could have foreseen my interest in coastal engineering already twenty years ago, when my parents made me unbelievably happy with truck full of sand as a birthday present. At present, my main interest lies in large-scale coastal engineering projects with a significant impact on social aspects as well as on the environment.

The realization of this thesis has been made possible by a great number of people. First of all, I would like to thank my committee for their guidance throughout the past months. Prof. Wang, I am very grateful for your inspirational ideas and insights during the meetings. Filip, you have been a great daily supervisor, thank you for enthusiasm and for the time you invested in me. Your guidance with the Delft3D modelling, writing of the report and other aspects of writing a thesis definitely were of great help. Michel, many thanks for providing the opportunity to work on this multidisciplinary topic. Your guidance of the team, positive mindset and they way you put my thesis in the perspective of a larger project is much appreciated. Dirk-Jan, thank you for sharing your years of experience and for making me zoom out and consider practical aspects that would otherwise be forgotten. Mark, many thanks for the detailed feedback on my report, you have taught me a lot on setting up a research methodology and writing a scientific report.

I would like to acknowledge Royal HaskoningDHV and especially the department of Rivers & Coasts, for providing an excellent working space and learning environment. Many thanks to my fellow graduates and temporary colleagues, for the inspirational chats and for occasionally being a very welcome distraction. Besides, I would like to thank Deltares for providing and helping me with the Delft3D model.

Lastly, I want to thank the people who supported me during the last years. To my friends here in Delft: many thanks for the great times we've had, I hope many will follow. In particular, I want to thank my parents, Theo and Trees, and brothers, Thijs and Kees for the great support and love. Last but not least, thank you Ana for your patience and for believing in me. You always know how to make me laugh.

René Kersten
Delft, June 2018

Summary

Tidal basins are highly dynamic environments with a complex behavior that is often disturbed by human activities. Considering that tidal dynamics have a direct impact on surrounding engineering infrastructures, adjacent coastlines, nature environment and socio-economic human activities, it is crucial to know the impact of human interventions on these dynamics. This research focuses on the closure of the Gulf of Khambhat in India, which aims at the creation of a fresh water reservoir in the gulf by partly closing the current estuary with the Kalpasar dam. The most recent design of the closure concerns a 30 km dam from the eastern bank near Aladar to the western bank near Bhavnagar. This closure will significantly reduce the total basin area. Consequently, major and morphodynamic changes are expected in the basin.

The Kalpasar project has been on the Indian Government's agenda since 1986. Royal HaskoningDHV was involved in the pre-feasibility study, which was presented in the late 1990s. Since then, the existence of a detailed report study has not been confirmed and the status of the announced feasibility studies by the Indian government is unknown. The main objective of this research is to investigate the morphodynamic response at the seaward side of the dam after the closure.

A process-based morphodynamic model has been developed to study this response. Deltares and NIOT have provided a two-dimensional (2DH) numerical model of the Gulf of Khambhat to study the tidal propagation in the basin. After calibration and validation of the hydrodynamic predictions, the model has been extended to a morphodynamic model in order to perform morphological calculations. Several adaptations have been made to improve the hydrodynamic simulations of the model; the main contributing factor was the new initial bathymetry. An extensive spin-up simulation has been performed to gather this. To deal with introduced model artefacts, the model results are compared to the reference case. Therefore, two almost identical simulations are performed: the only difference is that one run contains the Kalpasar dam while the other does not. This way, the relative effect of the dam is determined. Moreover, the morphological results have to be interpreted qualitatively, since the predictive skill of the model has not yet been determined.

Model results show an overall increase of the tidal range in the basin after the closure, which will have effect up to 100 km from the dam. Close to the dam, the range will initially increase from 7.88 to 10.25 m, and up to 10.50 m after 96 years. Besides, the tidal signal switches from being ebb-dominant to flood-dominant. The velocities around the dam become negligible and the velocities at the main western channel significantly decrease. The eastern channel remains the main channel of the gulf, although its maximum flood- and ebb-velocities also decrease. As a consequence of the hydrodynamic changes, the basin will start importing sediment, directly becoming a sink. On the long term, the area up to 40 km southward of the dam partly fills in. The eastern side of the main channel will also accrete, although its western side will erode over the years.

The implementation of the dam will have negative impacts on several locations at the study area. Four vulnerable locations are identified, namely Dahej (India's largest LNG-terminal), Hazira (container terminal), Surat (> 6 million inhabitants) and Alang (largest ship wrecking worldwide). All of these locations will become prone to flooding because of the increased maximum water levels. Moreover, sedimentation at the approach channels of the ports of Dahej and Hazira may hinder their accessibility. The increased water levels at Alang may lead to the suspension of heavily contaminated sediments from these beaches. Furthermore, coastal erosion might be a problem for the entire study area, if the ebb-tidal delta is not large enough to balance the sand hunger of the basin.

Relocating the dam is not an effective measure to prevent the negative impacts. Maintenance dredging activities will probably be required to maintain the accessibility of the ports. Moreover, major infrastructural changes will be needed to prevent floods. It is recommended to execute follow up studies with more detailed tools to determine the exact response at these locations. More accurate and up-to-date hydraulic and bathymetric data is required to develop these tools. To this end, it is highly recommended to partner with local parties like the Government of Gujarat, the EAG and local universities.

Contents

1
INTRODUCTION

1.1. BACKGROUND

1.1.1. GENERAL INTRODUCTION

Tidal basins are highly dynamic environments with a complex behaviour. Human activities may add more complexity to the natural processes of basins, as they often disturb the situation of dynamic equilibrium (Elias, 2006, Stive and Wang, 2003). Estuaries have high environmental, social and economic values; considering that tidal dynamics have a direct impact on surrounding engineering infrastructures, adjacent coastlines, nature environment and socio-economic human activities, it is crucial to know the impact of human interventions on the dynamics (Wang et al., 2012).

This research treats the closure of the Gulf of Khambhat in India, which aims at the creation of a fresh water reservoir in the gulf by partly closing the current estuary with a dam, see Figure 1.1. This closure will significantly reduce the total remaining basin area. Consequently, major hydrodynamic and morphodynamic changes are expected in the basin. A similar case is for example the closure of the Zuiderzee in the Netherlands, see Figure 1.2, which reduced the tidal basin area and caused major changes in the Wadden Sea (Wang et al., 2009). Furthermore, other closures are currently planned at estuaries with similar extreme tidal conditions, e.g. in Russia and Canada, where dams will be built to generate tidal energy. For these projects it is also of great importance to build up knowledge on possible effects of a closure dam on the hydrodynamics and morphology.

Figure 1.1: The Gulf of Khambhat

Figure 1.2: Closure of the Zuiderzee by the Afsluitdijk

1.1.2. THE KALPASAR PROJECT

In the Gulf of Khambhat, which is embraced by the Gujarat main land and the eastern coast of Saurashtra peninsula, a yearly volume of 30,000 Mm^3 of waters flow into the sea. Consequently, this water can no longer be used to mitigate the severe shortage of drinking and irrigation water in Gujarat.

The Gulf of Khambhat project (or *Kalpasar*) aims at the creation of a fresh water reservoir in the Gulf of Khambhat, by the construction of a dam connecting the east and west bank of the Gulf. The run-off from the rivers Sabarmati, Mahi, Dhadhar and Narmada will be stored in the reservoir, together with the waters from the Saurashtra rivers discharging into the Gulf of Khambhat. The stored waters are to be used for irrigation, water supply and industrial requirements in the Saurashtra region. Several designs have been investigated the last decades (Kalpasar Department, 2009). The most recent design from the state of Gujarat concerns a 30 kilometres earthen dam from the eastern bank near Aladar to the western bank near Bhavnagar as can be seen in Figure1.4. A considerable part of the gulf will be cut off because of the closure. The dam will drastically change the hydrodynamic conditions in the gulf on both sides of the dam.

This thesis is part of a broader interdisciplinary project regarding the closure of the Gulf of Khambhat in India. The official project is called 'Kalpasar, a lake that fulfils all wishes' and has been on the Indian Government's agenda since 1986. Their vision is to create one of the largest freshwater lakes at sea in the world. It will mainly provide water for agricultural, industrial and domestic use in the region of the peninsula Saurashtra located in the state of Gujarat, which suffers from severe water shortages (Figure1.3).

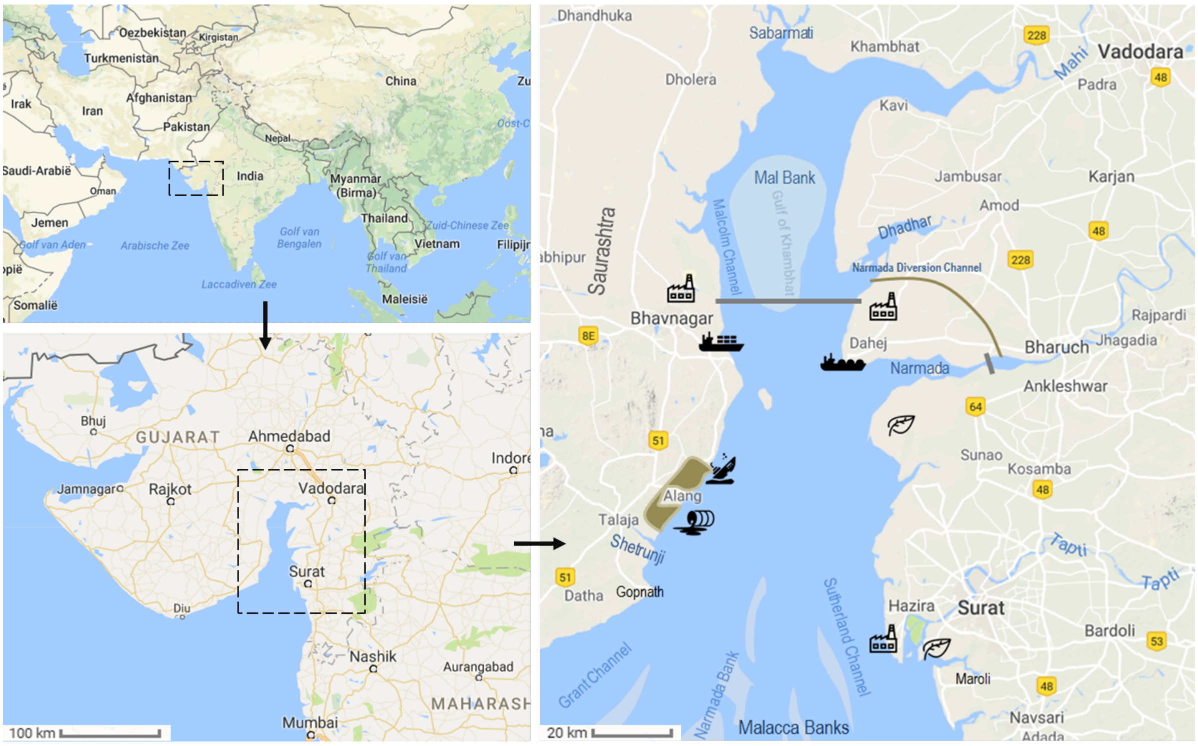


Figure 1.3: Project area - Upper left: India, down left: state of Gujarat & region Saurashtra, right: General map of th Gulf of Khambhat, showing the most relevant features.

Royal HaskoningDHV was involved in the pre-feasibility study, which was presented end 90s. Since then, the existence of a detailed report study has not been confirmed and the status of the announced feasibility studies by the Indian government is unknown. An Expert Advisory Group (EAG) consisting of international experts, has been installed to guide and coordinate the preparation of the feasibility report. Except for a few adjustments in the design, Royal HaskoningDHV suspects that no real progress has been made since the pre-feasibility study.

In 2017, Royal HaskoningDHV decided to initiate a cooperation with three Dutch universities (Delft University of Technology, University of Amsterdam and University of Maastricht) to set up an interdisciplinary research team to revive the project with new insights and techniques. The objective of the team is to develop a business case which can generate attention to the project, identify opportunities and threats and attract investors. This thesis is part of the interdisciplinary research and focuses on the hydrodynamics and morphology. The scope is elaborated further on in this chapter. Besides the previously mentioned actors, the World bank has always been involved in the Kalpasar project. They also have an interest in the new research team and therefore will partly support the project as well.

1.1.3. STUDY AREA

The Gulf of Khambhat is located in the North-West of India and is part of the Gujarat state. The gulf, part of the Arabic Sea, is about 100 kilometres long and between 25 to 50 kilometres wide as can be seen in Figure 1.3. The North-East part of the gulf is a large estuary of the rivers Sabarmati, Mahi, Dhadhar and Narmada, as can be seen in Figure 1.4. The latter discharges the most water into the sea: this river has a huge water resources potential of about 41,000 m^3/s with an average annual flow of more than 90% during monsoon. Furthermore, a number of small rivers and creeks discharge into the gulf and more to the south, the Shetrunji and Tapi rivers enter the gulf. South of the line Gopnath-Hazira, the estuary is bordered by the Malacca Banks which can be considered as the outer delta of the estuary. The outer delta is intersected by several tidal channels which are the ebb and flood dominated channels for the filling and emptying of the estuary by the semi-diurnal tide. South of the Malacca Banks there is a sea area with water depths ranging from 20 to 50 m as a transition zone to the deep Arabian Sea.

Figure 1.4: Study area

	LAT	LONG
A	21° 49' 15"	72° 40' 00"
B	21° 49' 15"	72° 12' 50"
C	21° 51' 56"	72° 08' 23"

Table 1.1: Coordinates new dam

1.1.4. DESIGN OF THE DAM

The minutes of the EAG meeting in 2009 show that the decision is made to not further continue with the old design; namely the southern dam alignment (Kalpasar Department, 2009). This alignment is indicated by a thin purple line in Figure 1.4, going from the eastern coast near Ghogha to the western coast near Alibet. An extensive chapter about this old alignment and reasoning for a new alignment can be found in the Source:Project Proposal report. As stated before, the final design is to realize the northern alignment in the Gulf of Khambhat. The most recent and likely final design of this dam is drawn in purple in Figure 1.4, the coordinates of the significant points are given in Table 1.1.

The progress of the new northern alignment design happens parallel to the design of the Bhadbhut Barrage project. The main functions of this stand-alone project are: controlling salinity ingress and deterioration of ground water quality in upstream area, storage of fresh river water for meeting domestic and industrial water supply and flood protection of 17 low lying villages on left bank of the river (Kalpasar Department, 2017). While the government appointed the Bhadbhut Barrage project as a stand-alone project (Shah, 2008), it cannot be treated separately from the Kalpasar project since they have a significant impact on each other. Since the registration phase for the tender of this project closed in September 2017, the project will have direct impact on the hydrodynamics and morphological conditions, and these effects may interfere with the effects of the dam. Part of the Bhadbhut Barrage project is the Narmada Diversion Canal that redirects a part of the fresh water basin the the Kalpasar Project.

1.2. PROBLEM STATEMENT AND RELEVANCE

Although the Kalpasar Department expected major changes caused by the closure dam, its exact hydrodynamic and morphological impact is yet unknown. This was one of the reasons for the Kalpasar Department, State of Gujarat and India's Government to initiate a collaboration with Royal HaskoningDHV and to request this company for consult.

The lack of knowledge about the impacts in combination with the location of the dam makes this research a highly relevant study. The Kalpasar project area is namely on several aspects a highly dynamic area and the project includes many stakeholders. Partly closing an estuary with an original tidal range of 8 to 11 meters results in a potential high impact on the vulnerable intertidal areas (Haskoning, 1998a). Besides, the study area contains a range of industries that have shown a strong growth over the last decade: container terminals, salt industry, copper industry, agricultural hinterland, and one of the leading LNG ports of India are stationed in or near the gulf (Ocean Imaging, 2013). Another noteworthy area houses world's largest ship breaking yard, at the west bank of the gulf. This yard contains broad beaches with highly contaminated materials. A combination of the latter and the presence of the adjacent cities Bhavnagar (600,000 inhabitants), Surat (6.3 million) and Bharuch (170,000) results in a area where the closure will have a significant impact on social, economical and nature environmental scales.

The study on the morphodynamic impact of the closure of Khambat has high priority at the moment, since the current design is not yet labelled as the final design. It is of great importance to test the impact of the design, on both short term and long term before this happens. Moreover, depending on the results, this provides opportunities to improve it and to adapt it into a design with a more favourable outcome on the considered aspects. This makes the hydrodynamic and the related morphological changes the most important aspect of assessment and improvement of the design at this moment. To this end, the focus of this study will be on these aspects.

Coastal phenomena and their hydro- and morphodynamics span a large range of time and spatial scales. Previous research has shown that these two scales are closely coupled; the larger the spatial scale of a feature, the larger the timescale in which significant changes occur (Dronkers, 2005). Figure 1.5 provides an overview of the scales for several coastal phenomena and the blue marked area shows the scope of this research within these scales.

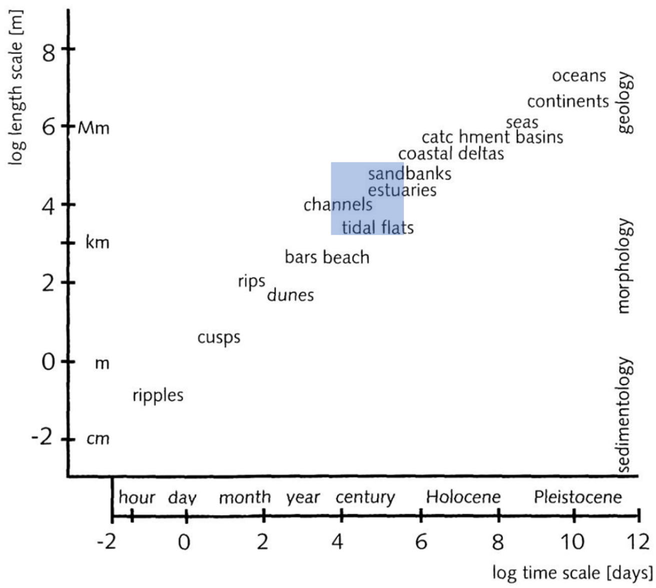


Figure 1.5: Scope of the research within the time and spatial scales of coastal phenomena. Adapted from Dronkers (2005)

This thesis is one of the five final reports of the interdisciplinary research. The content of the other reports is described in the Technical Project Proposal (Kersten et al., 2017). After completion of the five projects, Royal HaskoningDHV will work on a business case integrating the results. On an academic level, the outcomes of this research enable a comparison of the Khambat case with other former closures. Previous research on closures in the Netherlands has provided rules of thumb to obtain a general idea on the morphodynamic consequences of a closure. However, given the differences in size, bathymetry and hydrodynamic activity, the response of the Gulf of Khambat may be different. A comparison between cases with varying conditions is necessary to establish a domain in which these rules of thumb may be valid.

1.3. RESEARCH OBJECTIVE AND QUESTIONS

1.3.1. OBJECTIVE

The main objective of this study is to investigate the changes at the seaward side of the dam after the closure in terms of hydrodynamic conditions as well as the corresponding morphological response. This is done by comparing the future development of the basin without a closure with the future development after implementation of the dam. To this end, a two-dimensional numerical model of the Gulf of Khambhat – which is based on the Delft3D code – is tested and improved (sub-goal). The results of the used model help to get insight in the morphodynamic response and can be used to identify impacts of this response. It is expected that the improved morphodynamic Delft3D-model is sufficiently reliable to provide conclusions on the large-scale morphodynamic changes.

1.3.2. MAIN QUESTION

The research question that follows from the research objective is:

> *What is the impact of partly closing off the Gulf of Khambhat with the Kalpasar Dam on the hydraulics, morphodynamics and user functions of the remaining tidal basin?*

1.3.3. SUB QUESTIONS

To find an answer to this question the following sub-questions are defined:

(1) *What are the present conditions without dam concerning hydrodynamic forcing, sediment properties and bathymetry?*

(2) *How does the original hydrodynamic Khambhat-Delft3D model perform and what adaptations are required to investigate the morphodynamic response of the gulf?*

(3) *What is the change of the tidal conditions and what will be the effect on the hydrodynamic forcing?*

(4) *What are the short and long term morphodynamic responses of the system?*

(5) *What are the threats of the hydrodynamic and morphodynamic responses and what possible mitigation measures should be studied in the future?*

1.4. METHOD AND THESIS OUTLINE

In order to reach the objective and find an answer to the research questions, the research methodology is divided in three main phases, namely: a literature review, testing and adapting the Khambhat-Delft3D model and the model study and synthesis of the results. Figure 1.6 provides an overview of the report structure in relation to the research phases and the research questions.

Part 1: Literature review

This study starts with the literature review. During this part background information is gathered about the Kalpasar Project and research is done about the initial conditions within the study area. To gather more knowledge about the morphodynamic response of a closure in general, reference cases and the theory that is used to describe these interventions is studied. The largest part of the literature review is processed in Chapter 2. Sub-question (1) can be answered after the literature review is completed.

Part 2: Testing and adapting the Khambhat-Delft3D model
Deltares and *NIOT* (*National Institute of Ocean Technology*, an autonomous society under the Indian Government's Ministry of Earth Sciences), have been working on a two-dimensional (2DH) numerical model of the Gulf of Khambhat to study the tidal propagation in the basin in a previous study. This model is a hydrodynamic model and demands to be calibrated and validated. Moreover it should be extended to perform morphological calculations. The second part of this research consists of testing the performance of the Khambhat-Delft3D model and adapting it if needed. This is done in close cooperation with *Deltares*. The set-up of the so-called *initial (hydrodynamic) model* is described in Chapter 3. Its calibration and validation are discussed in Chapter 4. Chapter 5 explains the performed adaptations to convert it into a morphological model. After this part of the research sub-question (2) can be answered.

Part 3: Model study and synthesis
With the morphodynamic model a study is performed to answer sub-questions (3) and (4). Here the hydrodynamic and morphological response of the closure are researched for short (~1 year) and long time-scales (~100 years). A top down approach is chosen: first the overall response of the gulf will be identified, before determining its impact on small scale areas. Moreover the hydrodynamic changes have to be determined first, after which the corresponding sediment fluxes are studied. The fluxes eventually lead to sedimentation-erosion patterns, which determine the new morphology after the closure. The model results are presented in Chapter 6.

The morphological response of the Gulf of Khambhat after partially closing the basin may have a negative impact on the adjacent areas. Examples are increased flood risk, infilling of navigation channels and erosion of the adjacent coastlines. The obtained hydrological and morphological results are translated into potential future threats in this part. After the definition of these threats possible mitigation measures are defined. An extensive study on these measures is not within the scope of this research. However, based on the outcomes, recommendations for further research on these measures may be given. The translation of the model results to potential future treats is discussed in Chapter 7 of this thesis.

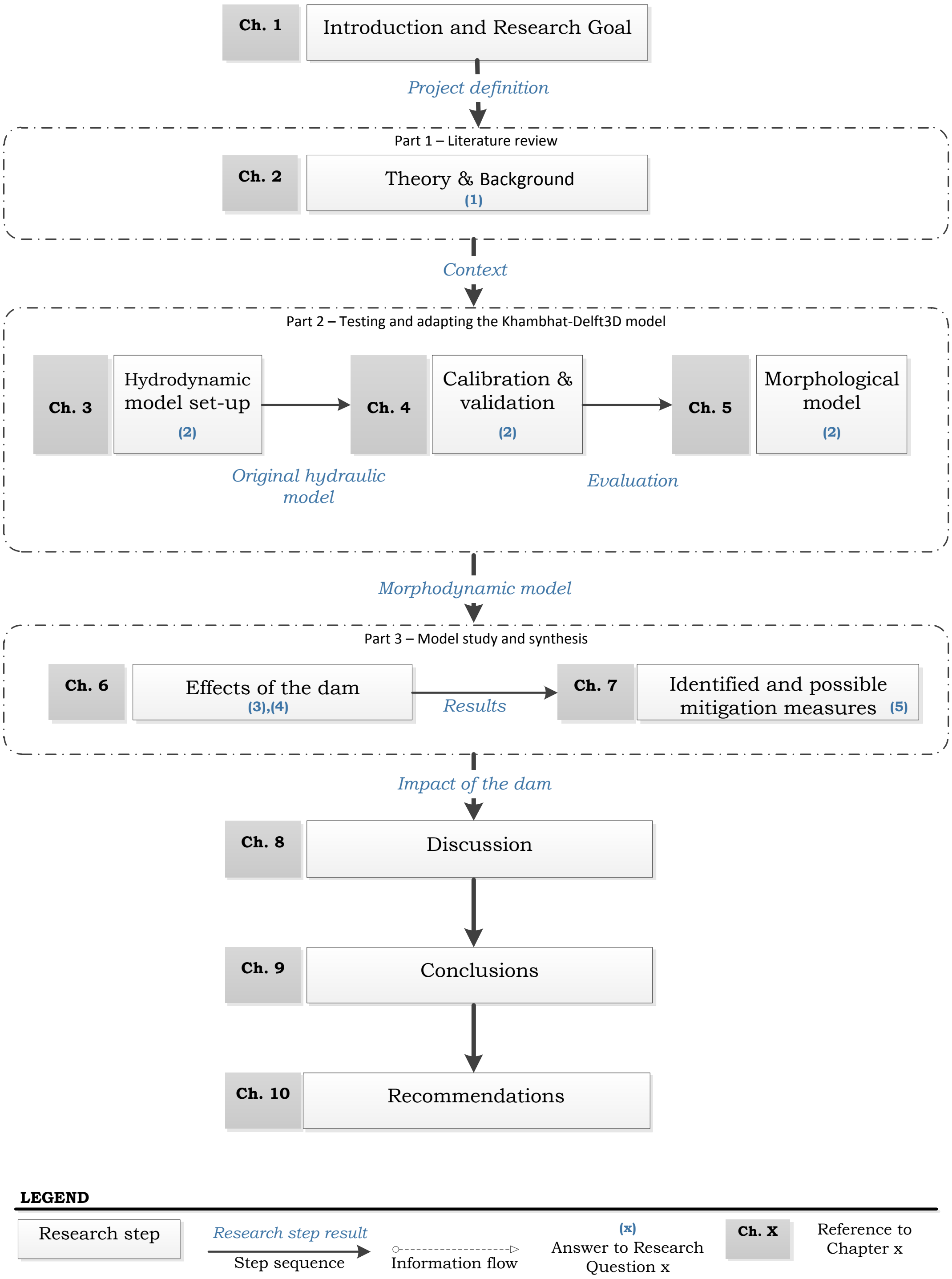


Figure 1.6: Report structure with research steps

2

THEORY AND BACKGROUND

2.1. INTRODUCTION

This chapter contains the main findings of a literature review on theoretical background information on tidal basins, hydrodynamics and sediment transport, as well as general information on the present conditions of the study area. The first part contributes to an understanding of the methods and theoretical concepts in this report. This is mainly related to the interpretation of the results of Chapter 6 and the comparison of these results with the theory. In the second part of this chapter an answer is found on sub-question one: *'What are the present conditions without dam concerning hydrodynamic forcing, sediment properties and bathymetry?'*.

2.2. THEORETICAL BACKGROUND

2.2.1. TIDAL BASINS

Tidal inlets are openings along coastlines connecting the sea to tidal basins, which are maintained by tidal currents (Eelkema, 2013). Essential for an inlet is the tidal variation in the open sea; the tide is the engine that determines most of the occurring features of the inlet and the basin it connects to (Bosboom and Stive, 2015). A tidal basin system is usually subdivided in four main elements, namely: a back-barrier basin, an inlet gorge, an ebb-tidal delta and the adjacent coastlines. The main morphological units of the basin are the (ebb- or flood-)channels and shoals. The dynamic coupling between ebb-tidal delta, inlet gorge and back-barrier basin tends to remain in (dynamic) equilibrium to the large-scale hydrodynamic forcing, individually as well as collectively (Elias, 2006).

Three distinct types of tidal basins can be discerned (Carter, 1988): *Tidal lagoons* are basins that are enclosed by wave-shaped barrier islands or spits. The presence of the barriers limits the wave penetration (Bosboom and Stive, 2015). Water flows into the lagoon with the flood and out during the ebb through passes or inlets in between the barrier islands. In the absence of barrier islands, *tidal bays* are more open to the deep water of the ocean or sea. *Estuaries* are tidal basins that experience a (strong) fresh water run-off. However, unlike river mouths, the water motion is controlled more by the tides than by the river discharge. Depending on the degree of mixing between the saline seawater and the fresh water from upstream, an estuary may be classified as stratified, partially mixed or mixed.

From a morphological point of view, tidal inlets form highly dynamic systems, which are interlinked with the adjacent coast and the basin to which they give access (Bosboom and Stive, 2015). Their natural morphodynamic behaviour often interferes with unnatural constrains, such as coastal defenses, and with the effects of human utilisation. The behaviour of tidal basins is dynamic on both time and spatial scales. These two scales are closely coupled; the larger the spatial scale of a feature, the larger the timescale in which significant changes occur (Dronkers, 2005). These time scales have been introduces earlier in Figure 1.5. De Vriend (1991) specified this coupling of time scales for tidal inlets, also including the respective forcing conditions, see Figure 2.1. As explained in Chapter 1 the main focus of this thesis is of time scales of 1-100 years, focusing on the changes of the tidal basin characteristics as a whole and its main channels and shoals.

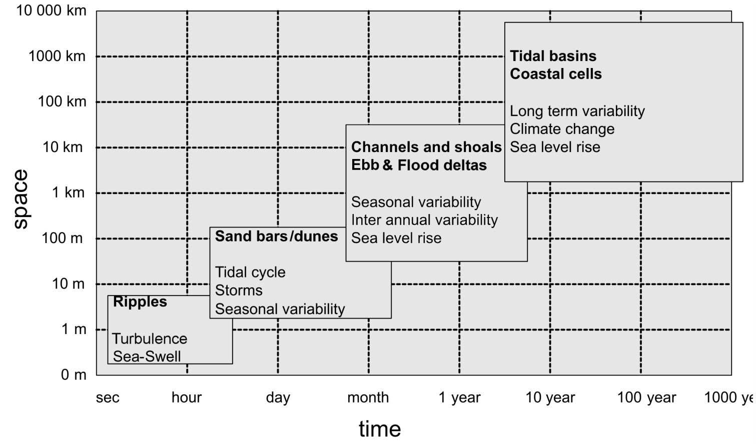


Figure 2.1: Components of tidal inlets and their respective forces in temporal and spatial scales. Retrieved from Tung (2011) based on De Vriend (1991)

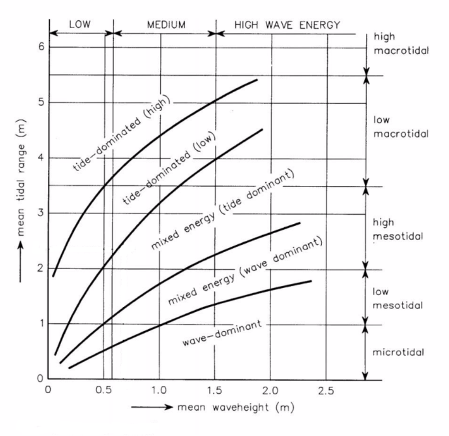


Figure 2.2: Hydrodynamical classification according to Davis and Hayes (1984), retrieved from Bosboom and Stive (2015)

In the inlet of a tidal basin, wave and tidal influences are combined. The tidal range outside the inlet mainly depends on the ocean tides and their interaction with the continental shelf (Bosboom and Stive, 2015). Three tidal ranges can be distinguished based on the mean spring tidal range, namely: micro-tidal, meso-tidal and macro-tidal. The wave conditions are independent of the inlet, since they are generated further seaward (note that dis does not hold for the wave penetration inside the basin, since this does depend on the exposure of the basin). Wave energy may be classified as low, medium or high, depending on the mean significant wave height. Hayes (1980) and Davis and Hayes (1984) established a tidal inlet classification based on the tidal range outside the inlet and the seaward generated wave conditions, distinguishing five inlet classes. This classification is shown in Figure 2.2.

A useful tool to analyse the relation between the depth of the channels in a tidal basin and the extent of the flats is the so-called hypsometric curve. These curves depict the (wetted) surface basin area as a function of the bed level. By including the high water and low water lines, the intertidal area can be analysed. Figure 2.3 shows the hypsometric curves for two types of basins: the left plot is representative of a situation with shallow channels and large intertidal storage areas, while the right plot represents deep channels and small intertidal areas.

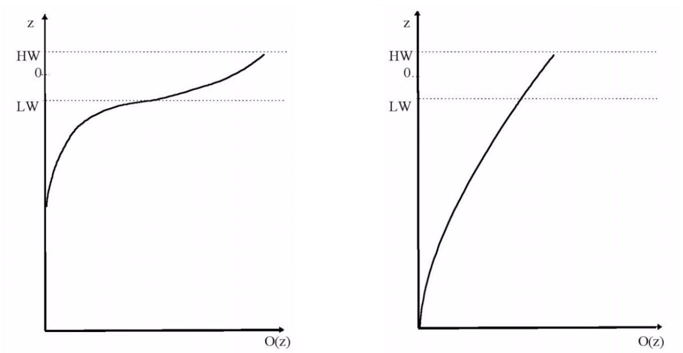


Figure 2.3: Hypsometric curves for two types of tidal basin: the left plot represents a situation with shallow channels ans large intertidal storage areas, the right represents the opposite (Bosboom and Stive, 2015)

2.2.2. EMPIRICAL RELATIONS BETWEEN THE ELEMENTS

Several empirical relations have previously been found that describe the stability of the morphological units of the tidal basin. The geometry of the basin and the tidal range determine the tidal prism, which is the total amount of water flowing through the inlet per tidal cycle (Eelkema, 2013). This same tidal prism in turn determines the size of other elements of the basin.

The volume of sand stored in an ebb-tidal delta has empirically been related to the tidal prism in the inlet and to lesser extent the wave conditions at sea. This relationship was first derived for the outer deltas in the USA by Walton and Adams (1976) and reads:

$$V_{od} = C_{od} P^{1.23} \tag{2.1}$$

In which:

V_{od}	sand volume stored in the outer delta	[m^3]
C_{od}	empirical coefficient	[m$^{-0.69}$]
P	tidal prism of spring tide in the inlet	[m^3]

Figure 2.4 shows that the coefficient is dependent on the wave climate, in such a way that for the same tidal prism the volume in the ebb-tidal delta is smaller for more energetic waves (Bosboom and Stive, 2015).

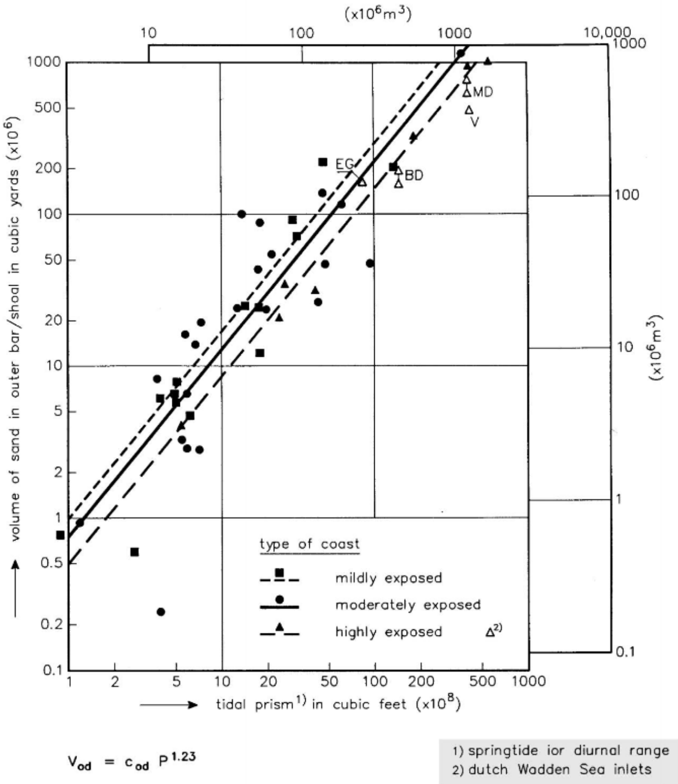


Figure 2.4: Empirical relationship between volume of sand in the outer delta and the tidal prism.

From literature it is known that also a distinct relation exists between the size of a cross sectional profile of a tidal inlet and the volume of water passing that cross section (e.g. O'Brien, 1969; Johnson, 1973; Jarret, 1976). More recent investigations show that such a relation not only holds for the cross sections of tidal inlets, but for any cross section of a tidal channel (Bosboom and Stive, 2015). Such a relationship can be described by:

$$A_{MSL} = C_A P_{AB} \tag{2.2}$$

In which:

A_{MSL}	the equilibrium flow area in a certain cross-section AB of the basin, below MSL	[m^2]
P_{AB}	the tidal prism landward of the cross-section AB under consideration	[m^3]
C_A	empirical coefficient	[m^{-1}]

These empirical A-P relationships are applied widely, because of their simplicity and practical engineering value. However the $A-P$ relationships are not universally applicable and vary over different regions of the world (Stive et al., 2012).

Eysink (1990) found the following relationship holds for the total basin channel volume, which holds when the flood-tidal delta spans the entire basin area:

$$V_C = C_V P^{3/2} \tag{2.3}$$

In which:

V_C	equilibrium total channel volume, below MSL	[m^3]
P	tidal prism landward	[m^3]
C_V	coefficient	[m$^{-3/2}$]

From the previous equations it is possible to deduce a relationship between the area of the tidal flats and the total basin area:

$$A_f = A_b - A_{ch} = A_b - \frac{V_c}{D_c} \approx A_b - \alpha\frac{P\sqrt{A_b}}{D_c} \approx A_b - \beta\frac{H_m}{D_c}A_b^{3/2} \tag{2.4}$$

In which:

A_f	flats area (the area above MSL	[m]
A_{ch}	horizontal area covered by the channels	[m]
α, β	constants of proportionality	[m^{-1}]
D_c	characteristic channel depth	[m]
H_m	mean tidal range	[m]

2.2.3. SEDIMENT TRANSPORT

Net or residual sediment transport is often related to asymmetries in the tidal signal. Tidal waves are strongly deformed when reaching the shallow area of a basin. This tidal distortion may either strengthen or weaken the magnitude of the maximum flood flow compared to the maximum ebb flow (flood- versus ebb-dominance) and causes an asymmetry between the durations of the slack water as well (Bosboom and Stive, 2015).

The residual transport rates of coarse sediment are mainly determined by the vertical asymmetries of the tide. Flood-dominance causes a larger influx than outflux of sediment leading to a net landward directed near bed transport. Likewise, ebb-dominance induces seaward directed sediment transport. Figure 2.5 shows four tidal signals composed of M2 and M4 tidal current constituents. The upper left signal shows flood dominance, while the lower left signal shows ebb-dominance.

Fine sediment is transported as suspended load. Sediment particles sink to the bottom around slack tide, when the hydrodynamic conditions are calm. Consequently, differences in the currents around slack water after the flood and ebb periods cause net sediment transport of fines. This slack water asymmetry is represented by the right two plots of Figure 2.5. The lower right figure shows a situation in which the high water slack (flow reversal from flood to ebb) is longer than the low water slack. So, the sediment concentration is higher during the flood period and residual sediment transport occurs in flood direction (Wang et al., 1999).

2.2.4. CLOSURES

Human interventions or other large scale disturbances in and around tidal inlet systems can have far reaching consequences on the behaviour of tidal inlets and the basins and coasts which they connect (Eelkema, 2013, Stive and Wang, 2003).

From the theoretical principles of wave propagation, it is well known that a man-made barrier placed in the path of a wave results in a reflected wave travelling in the opposite direction. The summation of the two oscillatory motions results in an anti-node at the barrier and a node at a distance of a quarter of the wave length away from the barrier, see Figure 2.6. This leads to a higher water level and an increase of the velocity at the

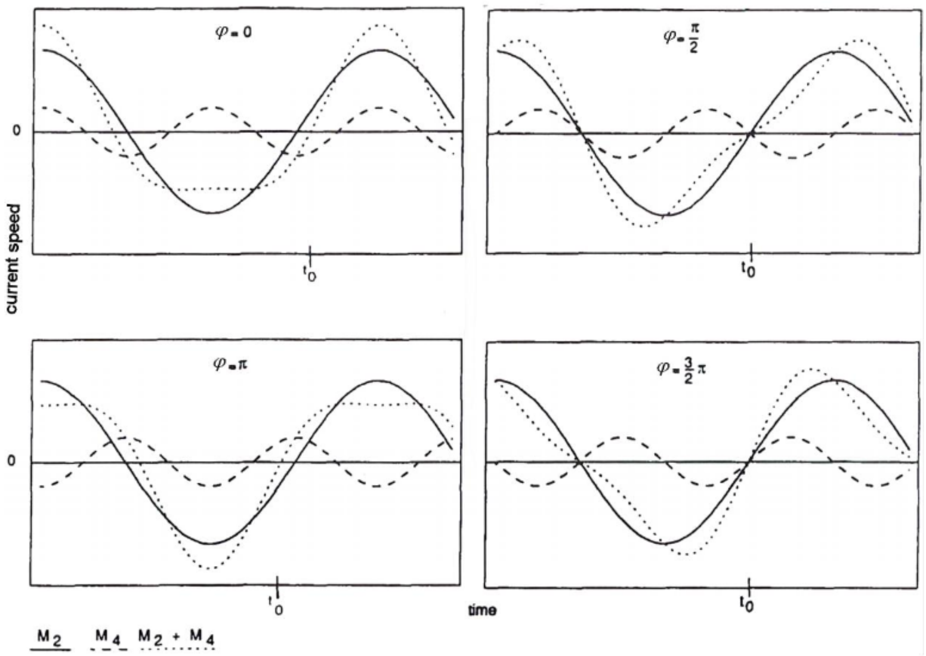


Figure 2.5: Currents of M2 and M4 tidal constituents, leading to tidal asymmetries, (Bosboom and Stive, 2015)

barrier, while there is a reduction in the amplitude and increase in the velocity at the anti-node.

The previously given empirical relationships (equations 2.1-2.4) can help in understanding the large-scale morphological response to changes in hydrodynamic equilibrium. Figure 2.7 shows the potential effect of the closure of a part of a basin. The closure results in a reduction of the channel volume (V_{MSL}) and of the tidal prism (P). Consequently, also the volume of the outer delta decreases (V_{OD}). A new equilibrium will arise at the equilibrium lines for the prism $P - \Delta P$. In this figure, the channel volume is a m^3 too big and the outer delta is b m^3 too big. The change in prism has a larger effect on the equilibrium channel volume than on the equilibrium volume of the outer delta. If the volume of the outer delta is not sufficient for the adaptation of the channels (so if $a - b > 0$), the remaining part will have to be supplied from outside (Bosboom and Stive, 2015). This may result in erosion of the adjacent coasts.

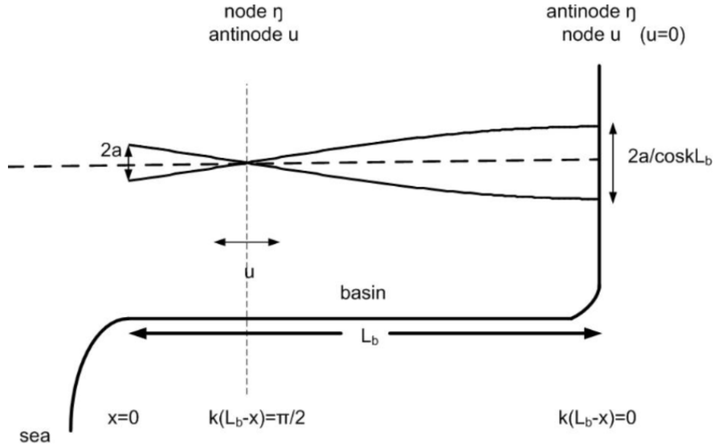


Figure 2.6: Standing wave (Bosboom and Stive, 2015)

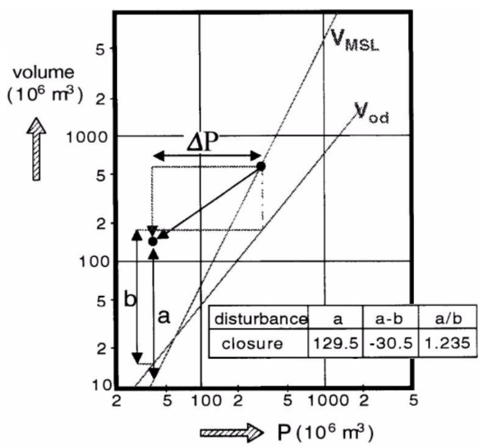


Figure 2.7: Effect of the closure (Bosboom and Stive, 2015)

2.3. BACKGROUND INFORMATION ON THE STUDY AREA

2.3.1. BATHYMETRY AND SEDIMENTOLOGY

The Admiralty Chart in Figure 2.8, shows an estuary with an outer delta, the Malacca Banks, with a complicated system of channels, bars, shoals and banks. The bed levels in the channels show large differences, ranging from about 14 m or less down to 50 m below Chart Datum (CD). North of the Malacca Banks the number of channels reduces and the remaining channels are deeper. The central main channel has depths of about 25 m in the wide lower part of the Gulf. In front of the Narmada river, the gulf is narrowed by the rocky Piram Island and the rock outcrops off Kuda point, see Figure 1.3. The main channel deepens east of Piram Island to depths over 40 m. The channel running between Piram Island and Kuda Point reaches depths over 50 m and locally even to 97 m. North of Piram Island de depths in the channels decrease again and the main channels are separated by Mal Bank in the northern half of the estuary. North of Mal Bank the main channels join again and run towards the Sabarmati and Mahi rivers. More offshore depth contours are presented in Figure A.1.

The bathymetry presented in Figure 2.8 is relatively old: lead-line surveys of 1837-1857 and 1927-1928, to the north of Dahej. The maps show that central parts of the Gulf between Dahej and Hazira were sounded between 1963 and 1973. More recent soundings in the mouth of Tapi river, in the area due west of Lakhigam and west of Mal Bank indicate considerable changes in bathymetry and a dynamic behaviour of the bottom. Malcolm Channel has migrated eastwards over a distance of a few kilometres, Mal Bank is largely eroded, a new channel (Dholera Channel) has developed along the bank west of Mal Bank and a new sand bank has emerged between the new channel and Malcolm Channel. Sounding and satellite images showed serious bank erosion of the west bank near Dholera. The situation west of Dahej showed only relatively minor changes (Klaassen, 1999).

The considerable changes in bathymetry are not surprising, considering the high flow velocities in the area, which cause high sediment transport per tide, particularly during spring tides, which are capable of generating high mobility of bed and rapid changes in bathymetry. The suspended sediment concentrations are relatively high (Haskoning, 1998a). Most seems to be silt and very fine sand. Measurements on suspended sediment at the surface, mid-depth and near bottom in Malcolm Channel in March and April 1999 showed sediments contents generally ranging between 1 and 14 g/l with the lowest observed content of 0.25 g/l during a neap slack water. The high sediment concentrations occur during maximum flow and spring tide. All the measurements of sediment concentration were carried out in connection with the development of ports. So all these measurements are near the coast where there are shallow depths. Sediments at this location are re-suspended in the wide inter-tidal zone, resulting in high concentrations. No measurements are available in the main Gulf and it is desirable to obtain such data for the Kalpasar Project as these are likely to show lower values and consequently lower morphological impact.

The bulk of the suspended sediment consists of clay, 2 – 20 μm. The silt and fine sand fraction, 20-200 μm, generally amounts to roughly 10 to 20% of the total content. The bed of the Gulf of Khambhat south of the Malacca Banks generally consists of mud. The shallow and exposed banks of the Malacca Banks consist of sand, whereas the bed of the tidal channels in that area consists of mud, sandy mud and in some places at the north-east side of the Malacca Banks of clay, coarse sand with broken shells and/or pebbles. Going north, the bed of the Gulf becomes sandier, particularly on the eastern side. The banks along the main tidal channels are sandy, whereas the tidal flats along the rivers and creeds discharging into the Gulf are muddy. Bed samples of the bed of the channels and tidal flats between Mal Bank and the west coast of the Gulf are taken by a bottom grab or a drop corer in a site investigation originates from the end 90s. They showed fine silty sand, 5 or 25% of fines smaller than 75 μm, or fine sand, less than 5% smaller than 75 μm. Only three samples in a row across the deep part of Malcolm Channel were different and showed ‘highly plastic sandy clayey silt, medium plastic sandy clay and fine clayey sand’. This probably indicates old deposits which are now being eroded by the migrating channel. In Appendix B an overview is given of the boring locations in the gulf and the results of the borehole investigations and cone penetration test. In Table 2.1 the $d10$, $d50$ and composition of the ten boring samples of the upper soil layer is given. Haskoning (1998b) contains an extensive geo-technical report of the area.

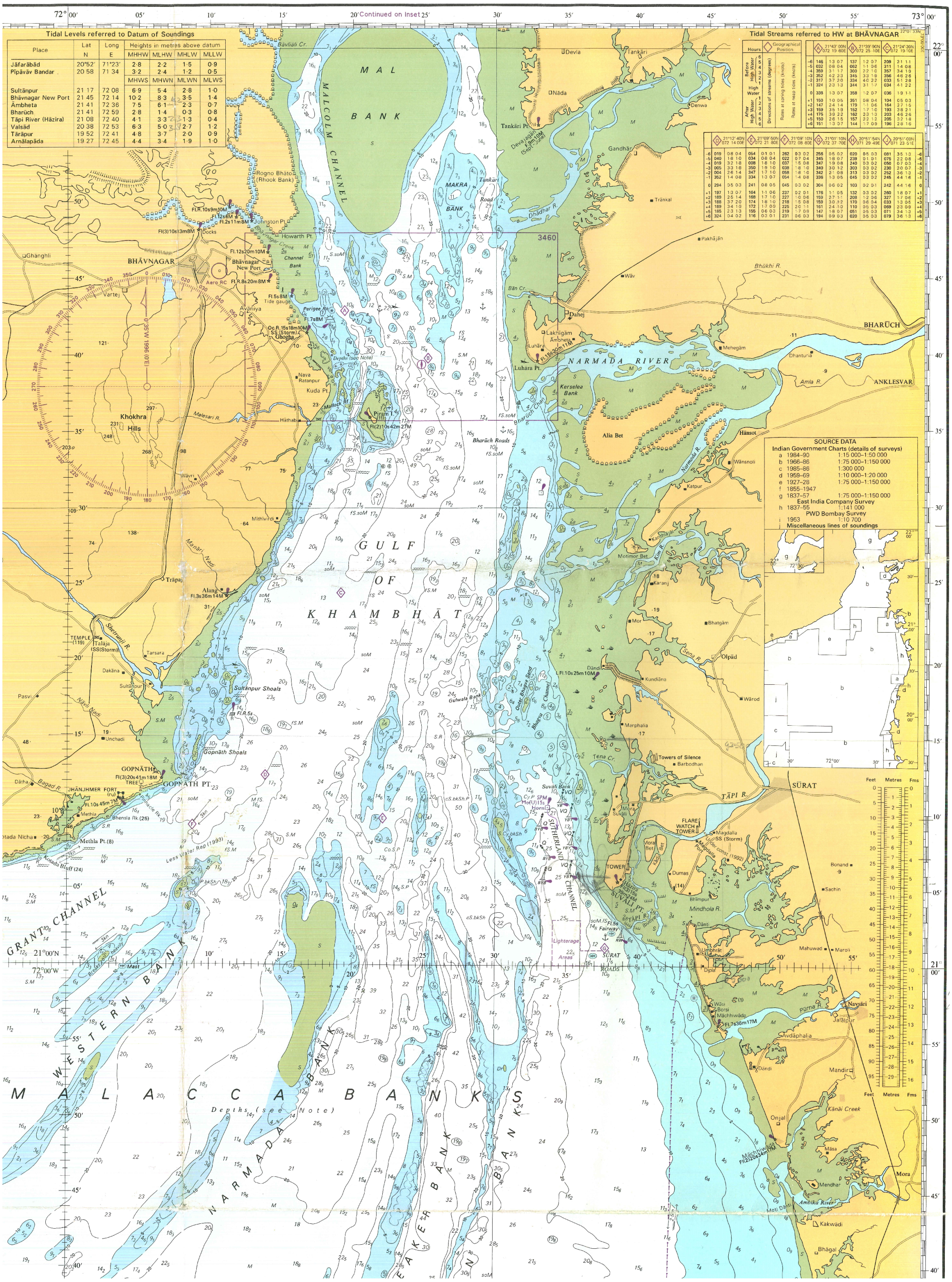


Figure 2.8: Admiralty Chart 1486 (BritishAdmiralty, 1980)

Sample		KB1	KB2	KB3	KB4	KB5	KB6	KB7	KB8	KB9	KB10
d10	[mm]	0.049	0.085	0.094	0.052	0.002	0.051	0.052	0.046	0.088	0.292
d50	[mm]	0.170	0.120	0.150	0.110	0.030	0.110	0.080	0.100	0.210	0.540
sand	[%]	85	92	95	85	83	88	77	76	92	90
silt	[%]	15	8	5	13	7	12	20	22	8	5
clay	[%]	0	0	0	2	10	0	3	2	0	0
gravel	[%]	0	0	0	0	0	0	0	0	0	5

Table 2.1: Overview of the $d10$, $d50$ and sample composition of the upper layer (Haskoning, 1998b)

2.3.2. TIDES AND CURRENTS

The tidal wave enters the gulf from the south. It shows a strong amplification running north, due to the funnel shape of the gulf and due to its relative length compared with the length of the tidal wave, which causes reflection (Sathish Kumar and Balaji, 2015). At the tidal station Jafarabad, to the south-west of the gulf, the mean tidal range amounts to 0.7 m (neap tide) to 1.9 m (spring tide), whereas it increases to 4.8 m and 8.8 m respectively at the station Bhavnagar south of Mal Bank. The tidal range gradually decreases again in the relatively shallow rivers discharging into the gulf. The tidal amplitudes at various points along the gulf coast are available at minor harbours (Table 2.2).

The tidal currents are proportional to the tidal range. Flow velocity indication show maximum ebb end flood velocities of 2 to 2.5 knots (1 to 1.25 m/s) south of the Malacca banks (Figure 2.8). In the channels in the Malacca banks this increases to about 3 knots (1.5 m/s) and south of Mal Bank maximum flow velocities may reach a velocity of 3.8 m/s during flood and 2.8 m/s during ebb (flow measurements off Lakhigam village, near Dahej). Flow measurements in Malcolm Channel showed maximum velocities of about 1.5 m/s during neap tide and 2.5 m/s (flood) to 2.9 m/s (ebb) during a spring tide. In Appendix C several maps are included that show the tidal propagation of the M2, K1, S2 and O1 constituents.

Location	MHWS	MHWN	MLWN	MLWS	MSL
Simar	2.2	1.9	1.4	0.7	1.6
Mitihivirdi	8.6	6.9	3.7	2.0	5.3
Bhavnagar	10.2	8.3	3.5	1.4	6.1
Dahej	8.8	7.0	3.2	1.4	5.1
Hazira	7.4	6.0	3.1	1.7	4.5
Umargaon	5.4	4.3	2.4	1.3	3.4

Table 2.2: Tide levels at minor ports in Gulf of Khambhat [m] (Klaassen, 1999)

2.3.3. RIVER RUN-OFF

Fresh water flow into the gulf arrives through the Narmada, Mahi, Sabarmati and Tapi rivers. The mean annual discharge rates are:

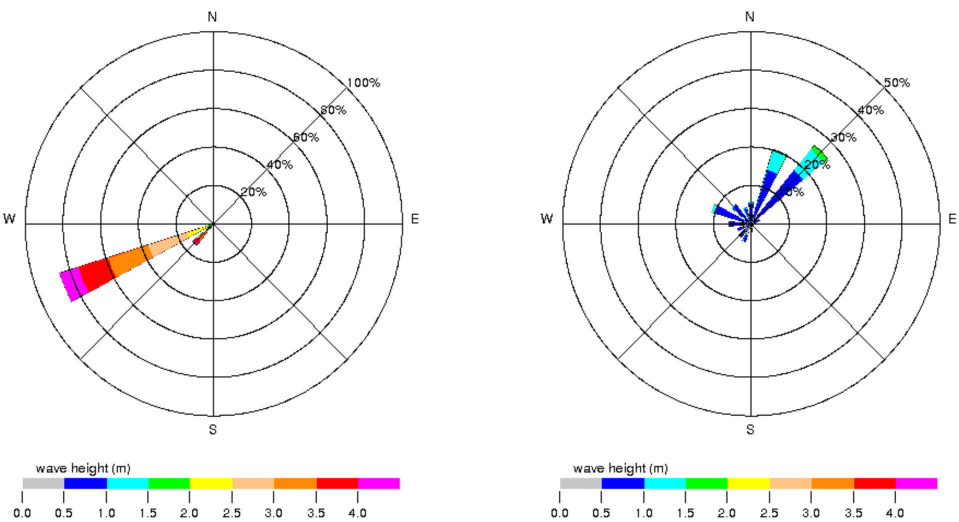
- Narmada 1400 [m^3/s]
- Mahi 375 [m^3/s]
- Sabarmati 120 [m^3/s]
- Tapi 570 [m^3/s]

Considering that the rainfall in the monsoon period (June-September) is typically about three times higher than in the non-monsoon period, it can be assumed that the mean river discharge in the monsoon period is about three times higher than in the non-monsoon period. Maximum river discharge can be considerably higher. It can be easily recognized, that the tidal flow dominates in the Gulf, and consequently, the vertical fresh and salt water layers in the gulf are well mixed (Bosboom and Stive, 2015).

2.3.4. WAVE CLIMATE AND CYCLONES

The wave climate in the Gulf of Khambhat is largely determined by locally generated wind waves, although the gulf is open to the long waves from the Indian Ocean and the Arabian Sea. Figure 2.9 gives an indication of the two dominant wave conditions. Subfigure (a) shows the wave rose during the monsoon season, which lasts from June till September, and in subfigure (b) the wave rose of the calm season is shown. Rose diagrams showing the directional distribution of wave height and wave period in the deep sea throughout the year are given in Appendix C, new data can be found in Figure C.7 and the two pages after. Wave measurements carried out at Hazira with a wave rider buoy, shown that there is a steady 2 to 3 m wave action during the monsoon, see Figure D.1. The corresponding wave periods are shown in Figure D.2, from which it would be seen that the deep sea swell of 8 seconds and higher (as opposed to local seas generated by the local winds) form 40 to 50% of the wave data in Hazira. More northwards into the gulf, the local wind generated waves become more dominant.

The western shoreline of the gulf is naturally more protected than the eastern foreshore, and the wave disturbance decreases with decreasing distance from the northern boundary. The design conditions for the wave action arise from the cyclonic movements, which dominate in the pre- and post-monsoon periods of May and November. These cyclones attack the west coast at a frequency of once a year, but they generally turn westwards of the Gulf, attacking primarily the western shoreline of the Saurashtra (Figure E.1). From this figure it can be seen that only three cyclones have entered the Gulf of Khambhat in a data series extending over 115 years.



(a) July (b) January

Figure 2.9: Wave height rose diagrams

3

INITIAL HYDRODYNAMIC MODEL SET-UP

3.1. INTRODUCTION

This chapter describes a two-dimensional numerical model of the Gulf of Khambhat. *Deltares* and *NIOT* have been working on a two-dimensional (2DH) numerical model of the Gulf of Khambhat to study the tidal propagation in the basin during a previous study (Giardino et al., 2014). This model is a basic hydrodynamic model that makes use of the FLOW-module of Delft3D. This chapter is split-up into six sections: in Section 3.2 a conceptual description of the Delft3D model is given. In Sections 3.3 to 3.6 the initial model set-up is discussed. The outcomes of this chapter and the two chapters hereafter lead to an answer for the second sub-question *'How does the original hydrodynamic Khambhat-Delft3D model perform and what adaptations are required to investigate the morphodynamic response of the gulf?'*.

3.2. CONCEPTUAL DESCRIPTION OF DELFT3D

Delft3D is a physics based non-linear model that may be used as a tool to solve hydro- and morphodynamic problems. This model is used in a depth averaged approach (2DH) to resolve the flow equations. Delft3D could also be used to perform 3D calculations, but this is not feasible in this study because of the extensive computational times involved. Moreover, 2D hydrodynamics are sufficient to capture the relevant processes. The initial hydrodynamic model of this study only made use of the FLOW-module (version 4.03.01). Later on, test simulations have been performed including the WAVE-module. To perform morphodynamic calculations, not only the hydrodynamics, but also sediment transport has to be resolved. Although this chapter deals with a model consisting of the FLOW-module only, a conceptual description is provided of all parts, since they will all be treated throughout the report. For a detailed description of Delft3D and its applications for coastal morphological modelling is referred to Deltares (2014a), Deltares (2014b) and Lesser (2009).

The hydrodynamic module of Delft3D, Delft3D-FLOW, solves the Navier-Stokes equations for an incompressible fluid, under the shallow water and the Boussinesq assumptions (Deltares, 2014a). Since the hydrodynamic equations are solved in 2D mode, the vertical momentum equation is reduced to the hydrostatic pressure relation. This assumption is valid when vertical accelerations are small compared to the gravitational acceleration. The horizontal differential equations are solved by using a staggered grid and finite difference Alternating Direction Implicit method (ADI), which splits each time-step in two parts: the first half to solve implicitly in x direction and the second half to solve implicitly in y-direction (Schuurman, 2015). The solution of this scheme is implicit, which means that there are no numerical restrictions for the chosen time step or grid size (Lesser, 2009). Nevertheless, the accuracy of the model results decreases with increasing time step and grid size.

The WAVE-module of Delft3D is used to simulate wave propagation. This can be done together with the FLOW-module or as a stand-alone module (Deltares, 2014b). The WAVE-module uses SWAN to simulate the evolution of random, short-crested waves. To this end, waves are described by using the 2D wave action density spectrum. The numerical scheme that is used to calculate the wave propagation is also implicit, making it unconditionally stable regardless of the water depth.

The online sediment part of Delft3D-FLOW may be used to calculate sediment transport simultaneously with the flow calculations. This also computes sedimentation/erosion rates and bevel changes. The sediment transport rates in each grid cell depend on sediment transport capacity generated by the flow conditions and the sediment properties. Simulations may be performed in morphostatic mode, in which the bottom is fixed . This is valid when changes in the bed topography occur on much larger time scales than the time scales involved with the adaptation of the flow, so also when the morphological change is relatively small in the period of modelling. In morphodynamic models the bottom morphology is dynamically coupled into the system; bottom changes are taken into account and act as a feedback loop, influencing the flow and transports.

3.3. GENERIC MODEL CONTENTS

All information for a flow simulation is stored in an input file, also known as Master Definition Flow file (MDF-file). To execute a flow simulation for a specific area various kinds of information is needed, such as the extent of the model area, the bathymetry etc. The various kinds of information are stored in separate, so-called attribute files. Deltares provided eight attribute files, shown in Table 3.1, and one MDF-file. In the MDF-file only a reference is made to these files instead of including all data in the MDF-file itself. In the .mdf file for instance, the definition of which and where results of the simulation need to be stored for later inspection is included.

Table 3.1: Overview of attribute files

Extension	**Description**
.bca	Flowboundary conditions (astronomic)
.bnd	Open boundaries
.dep	Bathymetry
.dis	Discharges rates
.enc	Grid enclosure
.grd	Curvilinear grid
.obs	Observation points
.src	Discharge locations

The results of a Delft3D-FLOW computation are in this case stored in two types of output files:

- History file: <trih-runid.def> and <trih-runid.dat>
- Map file: <trim-runid.def> and <trim-runid.dat>

The history file contains results of all computed quantities in a number of defined grid points at a defined time interval. The map-file contains results of all quantities in all grid points at a specified time interval. The interval time for the initial model is 1 minute.

3.4. COMPUTATIONAL GRID AND MODEL BOUNDARIES

The model schematisation uses the curvilinear staggered grid shown in Figure 3.1. This type of grid requires that grid cells are only approximately rectangular and approximately the same size as neighbouring cells. This flexibility compared to a true rectangular grid allows the construction of flexible and computationally efficient computational grids that can follow the shape of gently curving shorelines. This grid has a length of about 350 km with 254 grid cells in M-direction (cross-shore) and 128 grid cells in N-direction (longshore) and was run in depth averaged mode. The grid size ranges approximately between 3000 x 5500 m at the sea boundary, down to about 100 x 100 m in the upstream part of the gulf. The grid size at the proposed location of the dam, as stated in Figure 1.4, is around 1600 x 650 m.

The open boundary at sea is defined outside the gulf at a depth of about 300 m to reduce the number of relevant tidal components, see Figure 3.2. Moreover, this reduces the interaction of the propagating and

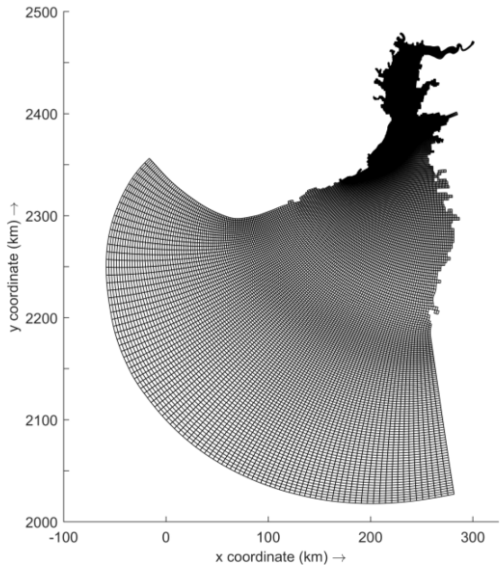


Figure 3.1: Spatial coverage of the Delft3D grid

Figure 3.2: Model domain

reflected tidal wave at the open boundary. The boundary is divided in 17 segments with each their specific settings of the type of open boundary and related astronomic components. Besides the boundary in the south (East1 till East17), the nine observation points (names) and the rivers (dots) are shown in Figure 3.3. The four rivers in the northern part of the gulf are imposed as discharge points.

3.5. FORCING

The astronomic tidal conditions at the open boundary were based on the TOPEX/Poseidon Global database (Giardino et al., 2014). In particular, 13 astronomic components were used to force the sea boundary: M2, S2, N2, K2, K1, O1, P1, Q1, MF, MM, M4, MS4, and MN4. In Table 3.2 the amplitude and phase of the largest four components are shown for each segment of the open boundary. The type of boundary conditions that are imposed in the model are mainly Riemann. Riemann gives more control over the velocities and discharges within the model. The exact reason for the choice of this boundary condition within this model is not yet clear, but it could be for the reason to push a little impulse in the system, what is not possible with the choice of the water level as boundary condition. Besides, Deltares often uses Riemann boundaries as they appear to be less reflective than water levels boundary. Of course, with water level boundaries you have a bit better control on the water levels you impose. For a more detailed argumentation of this choice, reference is made to Deltares (Giardino et al., 2014).

3.6. INITIAL BATHYMETRY

The bathymetry data of the Gulf were collected by the National Institute of Ocean Technology (NIOT, India). Figure 3.4 shows the bathymetry of the study area. The bathymetry of the tidal channels and mudflats is improved in Section 4.3.3.

Table 3.2: Essential astronomic components

	Amplitude [m]				**Phase [deg]**				
	M2	K1	S2	O1	M2	K1	S2	O1	Type of b.c.
East1	0,67	0,36	0,25	0,18	154,0	336,1	187,1	338,0	Water level
East2	0,31	0,17	0,12	0,08	332,1	148,9	2,1	152,2	Riemann
East3	0,31	0,18	0,12	0,09	333,9	143,1	6,2	145,9	Riemann
East4	0,42	0,20	0,14	0,09	329,9	135,2	2,4	138,4	Riemann
East5	0,37	0,20	0,13	0,09	328,2	132,8	5,9	134,5	Riemann
East6	0,30	0,13	0,10	0,06	324,7	125,3	354,9	130,9	Riemann
East7	0,31	0,10	0,09	0,05	315,7	119,9	345,6	130,6	Riemann
East8	0,42	0,14	0,13	0,07	312,3	115,5	347,8	124,4	Riemann
East9	0,63	0,16	0,21	0,07	308,1	87,2	337,0	102,4	Riemann
East10	0,31	0,11	0,09	0,06	309,5	131,7	347,1	138,4	Riemann
East11	0,29	0,11	0,09	0,05	314,5	130,0	354,5	134,9	Riemann
East12	0,36	0,11	0,10	0,06	317,5	126,0	353,8	130,6	Riemann
East13	0,39	0,11	0,11	0,06	320,6	123,2	355,9	127,3	Riemann
East14	0,39	0,11	0,12	0,05	324,0	118,6	357,2	122,7	Riemann
East15	0,44	0,12	0,14	0,06	328,2	124,3	2,2	128,2	Riemann
East16	0,60	0,15	0,19	0,07	331,7	127,0	6,6	131,1	Riemann
East17	0,83	0,22	0,29	0,11	337,8	146,3	14,6	148,7	Riemann

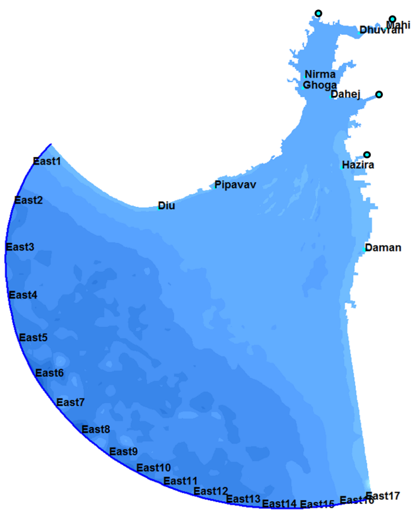


Figure 3.3: Boundary conditions

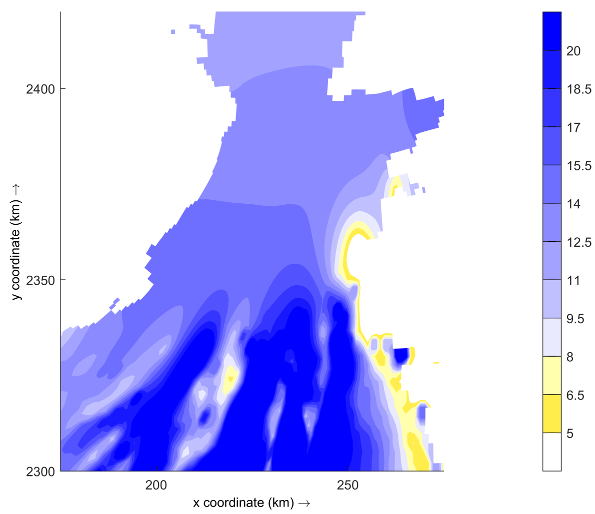


Figure 3.4: Initial bed level in meters

4

CALIBRATION AND VALIDATION OF THE HYDRODYNAMIC MODEL

4.1. INTRODUCTION

A determination of the performance of the initial model is needed to answer the first part of sub-question two: *'How does the original hydrodynamic Khambhat-Delft3D model perform and what adaptations are required to investigate the morphodynamic response of the gulf?'* The reason for this is threefold; most importantly, we have to know whether the outcomes of the model are in line with reality. Besides, it gives a better understanding of the computational model and the working of this model schematisation in particular. The final reason is to get a better understanding of the estuary system of the Gulf of Khambhat. The first part of sub-question 2 is answered in this chapter.

4.2. MODEL PERFORMANCE

In numerical modelling, it is important to check the model results with real-life observations. In this thesis this is valid as well: to predict the morphological change of the south part of the dam after a closure the model first needs to be able to model the hydro- and morphodynamics correct in the initial case. To calibrate the initial hydrodynamic model a set of measured data is needed, the toolbox 'Tide Stations' of Delft Dashboard is used for this cause. Delft Dashboard is a Matlab based open source model interface, to quickly set up models for i.e. Delft3D-FLOW. The toolbox makes use of IHO stations, from each of the stations one can view and download water level time series. The International Hydrographic Organization (IHO) tidal data bank consists of over 4000 tide gauge stations scattered all around the globe, most of which are in coastal regions (Qi, 2012). In this section the focus is at the hydrodynamic conditions as the tidal range and tidal current.

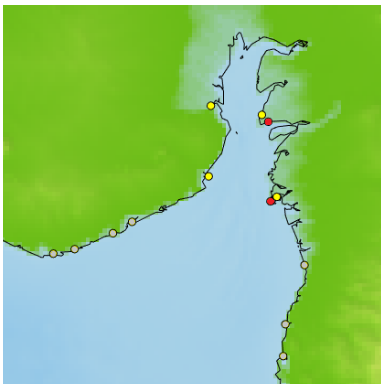


Figure 4.1: All tidal stations in the Gulf, marked red and yellow if within study area. The stations used for comparison with the numerical modal are marked red

Table 4.1: IHO stations, read clockwise starting in the southern left corner

Name station
Sultanpur (GULF OIHO)
Bhavnagar IHO
Dahej Bandar IHO
Ambheta IHO
N.W. Hazira (TAPTIHO)
Hazira (2ND)

4.2.1. OBSERVATION POINTS

The initial model includes nine observation points, these points are used to monitor the time-dependent behaviour of one or all computed quantities as a function of time at a specific location, i.e. water elevations, velocities and fluxes. The observation points are shown before in Figure 3.3 and are located at cell centres of the grid, i.e. at water level points. The observation point of the numerical model have to be at the exact same location as the IHO station to check the different conditions. With the initial model this wasn't the case. With Delft Dashboard the coordinates from the IHO stations in the northern part of the Gulf are used to adjust or add stations in the initial model. Before output is retrieved from Delft Dashboard the time-series are filtered for certain astronomical constituents to match the thirteen tidal components from the initial model. meter metre behaviour

4.2.2. TIDAL RANGE

As shown in Figure 4.1 the tidal stations within the study area are marked red and yellow. Not all time-series from the six stations are equally valuable what has to do with the location of the station. For example the station 'Dahej Bandar IHO' is at a location, close the the land boundary, with a restricted depth. This specific circumstance ensures that the tidal signal is not representative any more in case the bed level changes in time within the model predictions. More or less the same holds for 'Sultanpur (Gulf OIHO)', 'Bhavnagar IHO' and 'N.W. Hazira (TAPTIHO)'. The stations left over for comparison with the numerical modal are 'Ambheta IHO' and 'Hazira (2ND)', marked red. The measured tidal signals for the three stations do not all show the same agreement with the calculated one with the model, as can be seen in Figure 4.2. The calculated signal for Hazira, the most offshore station, is one-on-one in line with the measured tidal signal at this location. The two calculate signals more northern in the gulf do not show this agreement. Although the shape of the semi-diurnal matches the measured signal quite well, sub-figure (b), the tidal range does not seem to be amplified enough. In Section 4.3 this difference will be analyses in more detail and a solution is presented.

4.2.3. STRENGTHS OF THE MODEL

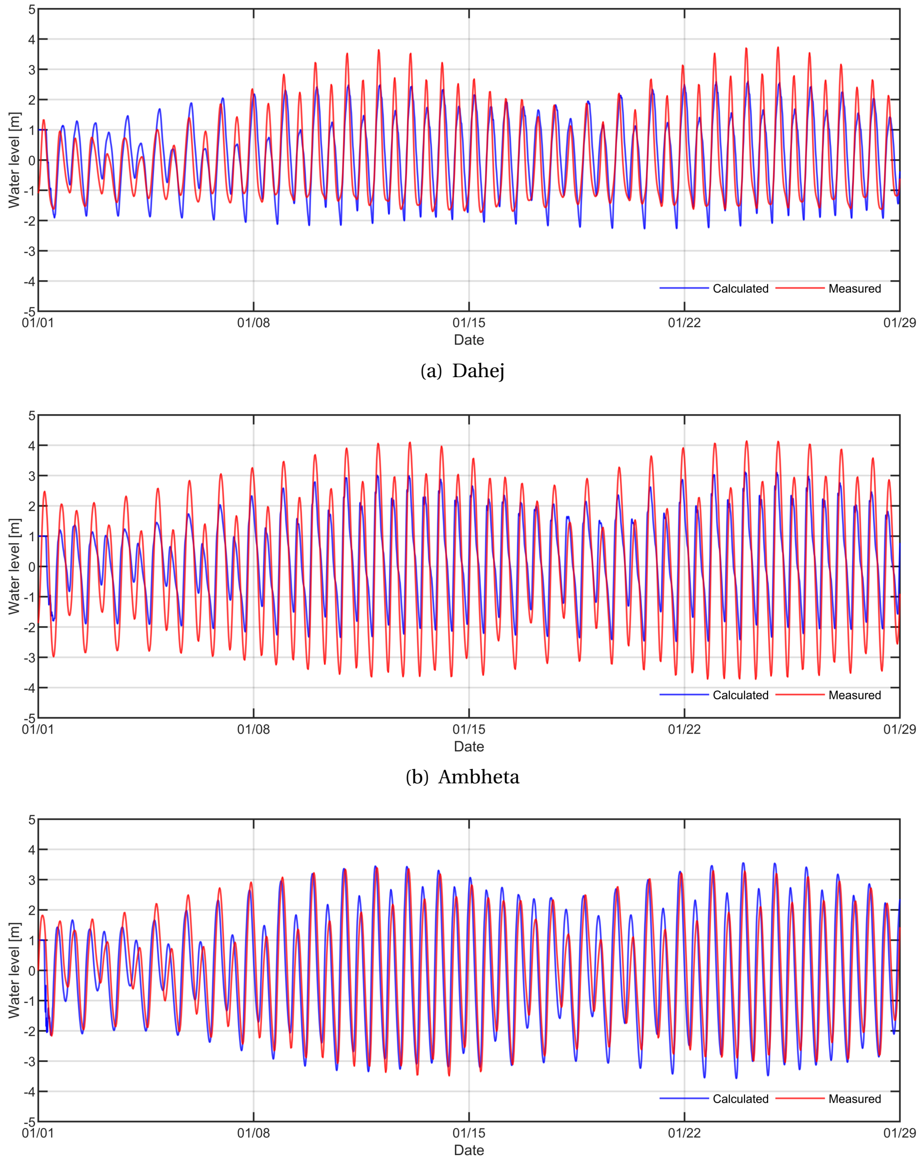
- First, the remark should be made that the initial model was basic but clean and clear (consisting of only eight files), which made it suitable to extend. Considering the limited amount of offshore data on the tidal components, a large model domain was required to include all of the tidal components and to reproduce the water motion correctly.
- The model covers a large area, starting offshore of the ebb-tidal delta and reaching the northern land boundary. This makes it an excellent tool to obtain a general idea of the hydrodynamic response after the closure. Besides, is has more than acceptable computational times, as it takes about 16 minutes to calculate the one month of hydrodynamics of a hundred years (with a MorFac of 0).
- At last, the shape of the simulated tidal signal is in good agreement with the the measured semi-diurnal tide.

4.2.4. LIMITATIONS OF THE MODEL

- The large coverage of the model also has its downsides. To maintain an acceptable computational time, the grid has to be relatively coarse (3000 x 5500 m offshore and 1600 x 650 m near the dam). This makes it impossible to thoroughly study the local changes of small individual morphological units in the next phase, especially offshore. However, this does not restrict the analysis of this research, since the focus is on the large-scale changes in the gulf.
- The main forces acting on a hydro-morphological model for coastal regions are tides, wind, waves and gravitational circulations. However, in the initial model, only the effect of the tidal forcing is taken into account. Is this a limitation of the model schematisation if you want to simulate all processes as realistically as possible. Nevertheless, this is not the purpose of this research. The hydrodynamic forcing that will mainly change because of the closure will be the tide. Moreover, the study is a strongly tide-dominated basin, in which the wave (and wind) influence remains limited. Density driven currents will mainly play a local role at the river mouths. So, is is assumed to be valid to only account for the tidal influence.
- The initial bathymetry as shown in Figure 3.4 clearly has its shortcomings. From the southern boundary, around the fictional 2350 km line, till the northern boundary of the study area, the bottom file

(probably) is simplified in a way that led to a lost of valuable data. This can have major implications to the hydrodynamic and the morphodynamic behaviour of the study area. For this reason, this bathymetry has later on been improved, as explained in Section 4.3.3.

- The current model is not able to represent the tidal signal that is measured within the gulf sufficiently accurate to answer the research questions. The correction and improvement of this signal is elaborated in Section 4.3.



(a) Dahej

(b) Ambheta

(c) Hazira

Figure 4.2: Tidal stations Dahej, Ambheta and Hazira

4.3. CALIBRATION OF THE TIDAL SIGNAL

In Section 4.2, it became clear that the initial model is able to simulate the hydrodynamics within the Gulf of Khambhat. At the end of the previous section a list is made of the strengths and limitations. The first goal of this section is to solve those limitation. After this is happened the model in total needs to be optimized. As stated in Section 4.2.2 the tidal range is underestimated by the model in comparison with the IHO stations. In this report the IHO stations in first instant are assumed as the 'truth', no other water level time-series are available. The difference between the two signals therefore we seek in the model part of the comparison an can have multiple causes. An overview of these possible causes is shown in Table 4.2, in the next the steps to the final outcome and conclusions are being treated.

Table 4.2: Overview of i.a. possible causes and solutions for the underestimation of the tidal by the model in the North of the study area

Tidal range in Dahej underestimated by model				
Possible causes	Inaccurate boundary conditions	Amplification (shoaling) due to the decrease of width and depth (convergence)	Partial reflection at the landward and of the gulf of estuary	Damping due to bottom friction
Possible solutions	Derive new B.C's within Delft Dashboard	Improve bathymetry input (1) inadequate depth data (2) Island Priam missing (convergence)	Improve bathymetry input	Test Manning's values
Outcome	See Figure 4.3	Contact NIOT to get updated model (Incl. updated and bathymetry and sediment data)	**New bathymetry file created in C-Map and Delft Dashboard**	See Figure 4.4
Conclusion	No adjustment needed	No reaction	**More accurate results in modelling the tidal range**	Calibrating model possible by tweaking the n-value
Discussion	-	Possible that NIOT has more recent data	-	Not the preferable solution because the unrealistic value for n

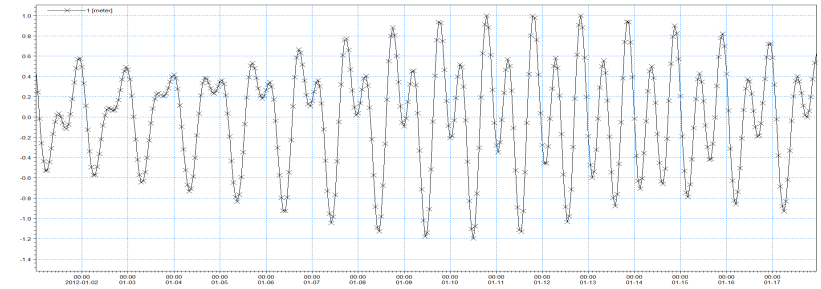
4.3.1. TESTING THE OFFSHORE TIDAL SIGNAL

The parameters within the model can be changed in many ways but if the input files do not represent the reality well enough the final tidal amplitude at one of the observing points can hardly match the measured tidal signal. The primary check therefore is located at the source part of the problem, in this case the astronomic tidal conditions. The outcome of this check can be seen in Figure 4.3. Although there is a small difference between the predicted tidal signal from the global tidal model of MIKE Zero and the calculated signal by the Delft3D model, this can be excluded as a possible cause for the underestimation of the model of the tidal range.

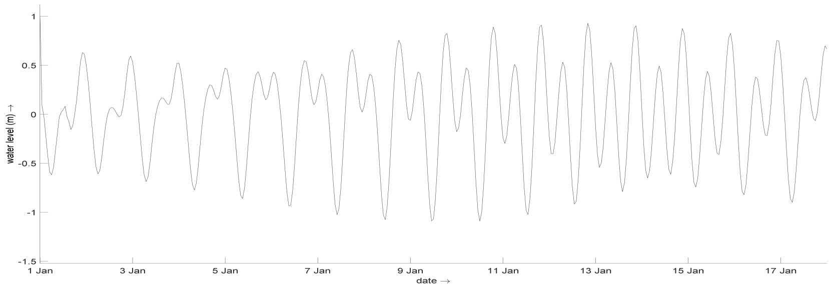
4.3.2. BOTTOM FRICTION

The second possibility for the underestimated tidal range by the model could be caused by the damping due to bottom friction, see column five of Table 4.2. The bottom roughness of the gulf is computed according to Manning. In this formulation the Manning coefficient n, must be specified, a typical value is 0.02 $\mathrm{s/m^{1/3}}$. The higher this value the higher the roughness and consequently the more friction is caused by the bottom. With the current settings the bottom roughness of the gulf is uniform with $n = 0.016$ in both the U and V directions. A simulation is preformed to test the impact with different values of n, the results are shown in Figure 4.4.

As expected a lower value of n, what means an lower roughness, causes less damping resulting in a larger tidal range. Since the tidal range is underestimated by the model, a larger value of n is required than originally chosen. This is where the problem arises. The already lower value of 0.016 in comparison with 0.020 can be explained by the d_{50} values found at the top layer of the bed. The value of 0.012, which increases the tidal range but still not enough, can be seen as unrealistic in this case.



(a) Measured



(b) Calculated

Figure 4.3: Predicted and modelled offshore tide level at southern sea boundary

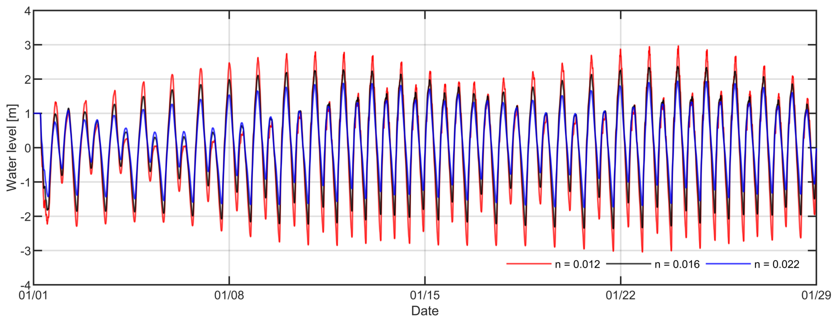


Figure 4.4: Waterlevel in Dahej for different values of Manning's coefficient - $n = 0.012$ (Blue), $n = 0.016$ (Black) and $n = 0.022$ (Red)

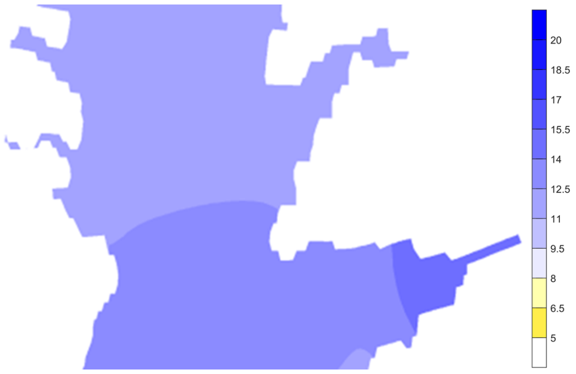
4.3.3. BATHYMETRY

One of the limitations of the model is the initial bathymetry as stated in Section 4.2.4 and shown in Figure 3.4. In columns three and four of Table 4.2 an improved bathymetry file is marked as a possible solution. Together with Deltares much effort is put into restoring the contact with the NIOT to speak with them about the hydrodynamic model or get an updated version of the model. In the paper of the model it is namely stated that the model is in good agreement with respect to the tidal measurements (Giardino et al., 2014). Unfortunately, it did not lead to a result that is marked as the conclusion of column 2 as well.

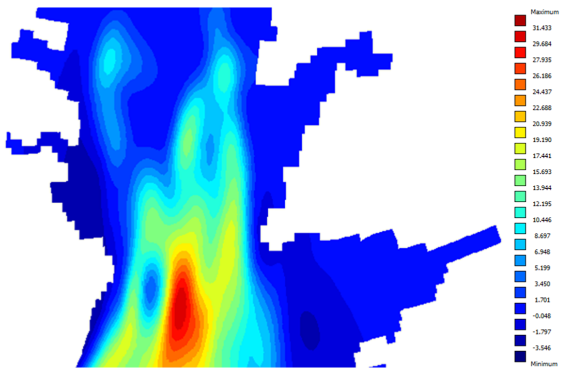
Finally, with the use of C-map, Delft Dashboard and Delft3D-RGFGRID a new bathymetry is assembled for a more realistic representation of reality. In Figure 4.5 both bathymetry files are visualised for the northern part of the gulf. Especially the update of the more defined depths at the river mouths and the channels and flats in the center stand out.

4.4. ADDITIONAL ADAPTATIONS OF THE INITIAL MODEL

Besides the aforementioned adaptation, several other adjustments have been made to the initial hydrodynamic model. First of all, more rivers have been added together with their mean annual discharge and sediment input. The final model contains seven rivers, namely the rivers: Narmada, Tapi, Mahi, Sabermati, Saurashtra North, Saurashtra South, Dhadhar.



(a) Initial

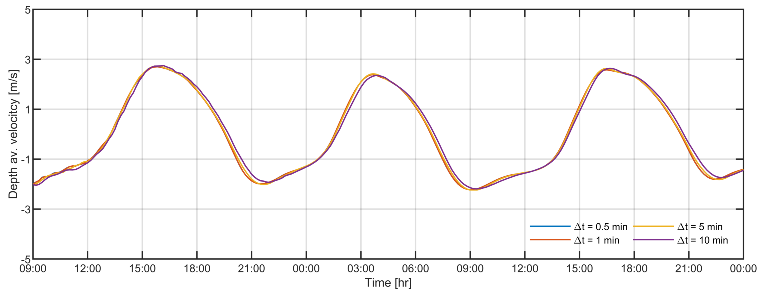


(b) New

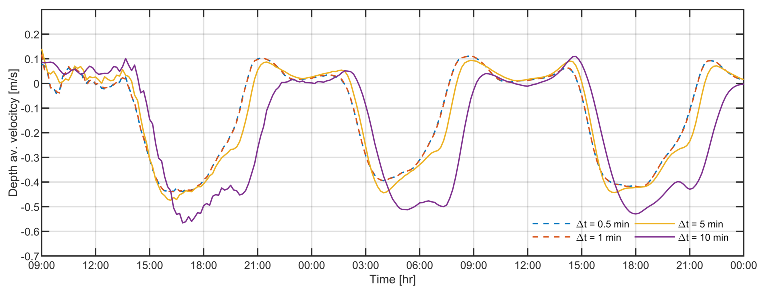
Figure 4.5: The initial- and new bathymetries, showing clear differences. The bed values are indicated in meters [m].

Many observation points have been added to the Khambhat model schematisation for several purposes. In the northern part of the gulf, approximately 10 observation point are added to investigate the tidal propagation in detail and to determine the correctness of the represented tidal signal. In addition, around 200 observation points are created along a line going from north to south along the center of the gulf. This is done to analyse the tidal envelope in the main flood- and ebb-direction.

Calibration runs have been performed with different values for the computational time step Δt. Figure 4.6 shows the results of this calibration of the tidal signal for simulations with different Δt. At first sight it seems as if all four signals of the y-component of the depth averaged velocity are nearly identical. However, slight differences have been noticed when increasing the time step from 1 minute to 5 minutes. This is also observed in the x-component of the velocities, although for this component the signals start to deviate when using a time step of 10 minutes. For this research it is decided to impose a Δt of 1 minute, although using a Δt of 5 might also be valid.



(a) y-component



(b) x-component

Figure 4.6: Depth averaged velocity for the time steps t=0.5, 1, 5 and 10 minutes

5

EXTENDED MORPHODYNAMIC MODEL

5.1. INTRODUCTION

The goal of this chapter is to prepare the model for the final application: the morphodynamic simulations. During this chapter an answer is given on the second part of sub-question two: *'How does the original hydrodynamic Khambhat-Delft3D model perform and what adaptations are required to investigate the morphodynamic response of the gulf?'*. To investigate which exact adaptations are needed the hydrodynamic model first will be made morphological ready by adding basic files for the sediment an morphological characteristic. This can be read in Section 5.2. In Section 5.3 the basic morphology model is tested and changes are implemented. In Section 5.4 morphological spin-up times are applied to make the model ready for the simulation of the gulf with and without dam. After the morphodynamic model is ready, a list of model settings is presented in Section 5.5. With these settings the model results of Chapter 6 are obtained.

5.2. MORPHOLOGY AND SEDIMENT SETTINGS

To turn the hydrodynamic model into a morphodynamic model two modules, captured in the .sed-file and .mor-file, have been added. The functionality sediments within the Delft3D-FLOW module includes the transport of suspended sediments (cohesive and non-cohesive), bed load and optionally the updating of the bathymetry. One can define the sediment and morphology characteristics at the start of a simulation. Within the sediment input file one can find sediment fractions and other input quantities have to be defined. In the morphological input file parameters for the morphodynamic computation are defined. In the .mor-file basic setting are applied. The most important summarized in Table 5.1. Note that these settings are not the settings of the initial hydrodynamic model schematisation, but the outcome of this chapter.

MorFac

The *Morphological Acceleration Factor* (MorFac) approach for morphodynamic up-scaling makes the simulation of long term coastal evolution possible within reasonable timescales. Bed level update in Delft3D is carried out via the sediment continuity equation. One of the complications in carrying out morphological projections on the basis of hydrodynamic flows is that morphological developments take place on a time scale several times longer than typical flow changes (Deltares, 2014a). To enable reasonably fast computations the MorFac approach multiplies the bed levels computed after each hydrodynamic time step by a factor, see Figure 5.1. The significantly up-scaled new bathymetry is then used in the next hydrodynamic step.

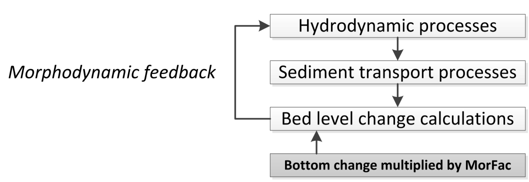


Figure 5.1: General structure of coastal morphodynamic models and the MorFac concept. Based on Ranasinghe et al. (2009)

The initial MorFac was set on '0', the model was only used to perform morphostatic simulations for which the bottom is assumed to be fixed. This is however not a valid assumption when performing simulations at time-scales for which the bottom may significantly change. In Figure 5.2 the cumulative erosion/sedimentation patterns are shown for a morphological runtime of 12 years with at MorFac of 1, 12 and 24. Considering the total computation time versus the increasing error related to the use of high MorFac values, the choice is made for a MorFac of 12.

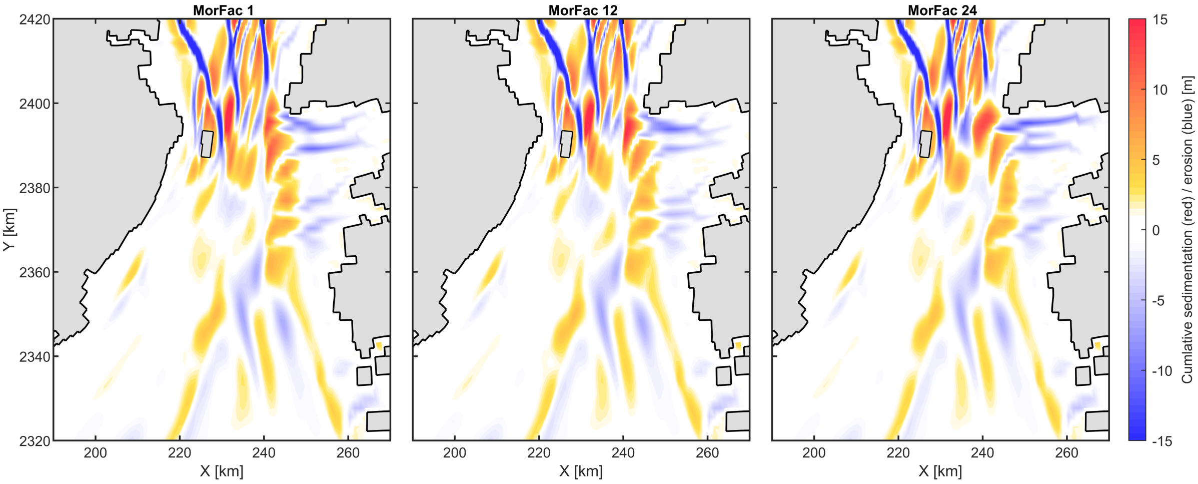


Figure 5.2: The cumulative sedimentation/erosion patterns for a morphological time of 12 years for a MorFac of 1, 12 and 24

5.3. CALIBRATION OF MORPHOLOGICAL MODEL

During several test simulations with the initial settings for the .mor-file, insight is gained on the evolution of the bed over time. The output bathymetry maps show many deep and narrow channels. These patterns in the bathymetry are not as expected as they are not observed in comparative bathymetry maps of different sources. In this section an extra analysis of this result is executed to calibrate the .mor-file settings and preform feasible morphodynamic calculations in the next phase of the thesis. Several settings have influence on the shape and the depth of the channels. The setting that will be treated here are the transport formula, the spiral flow, the bed slope effect Ashld and Bshld and the values of AlfaBn and AlfaBs.

As elaborated in Deltares (2014a), the bed load transport is affected by bed level gradients. Two bed slope directions are distinguished: the slope in the initial direction of the transport: referred to as the longitudinal bed slope, and the slope in the direction perpendicular to that: referred to as the transverse bed slope, see Figure 5.3. One of the options to prevent the channels to become too deep is to boost this transverse bed gradient factor AlfaBn, in addition, increasing the AlfaBn often gives numerical stability as well. In this case is chosen to set it to 50 (1 is default). The longitudinal bed slope will be kept at its default value of 1.

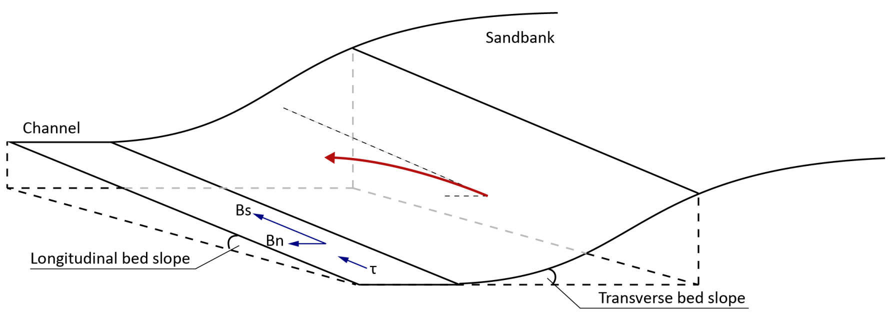


Figure 5.3: Schematisation of the bed slope effect

The longitudinal bed slope results in a change in the sediment transport rate as given by Koch and Flokstra (1980) as extended by Talmon et al. (1995). By default, the formulations of Van Rijn et al. (2001) are applied for the suspended and bedload transport of non-cohesive sediment. With the Delft3D feature called *Sediment transport input file* extra sediment transport relations for non-cohesive sediment can be added. By creating a sediment transport input file .tra one can use another formula, the formula overrules the default formula. Chosen is for the Engelund-Hansen transport formula by adding to the .mdf file the keyword 'TraFrm' with value '#eh.tra#' (Deltares, 2014a). The reason for this is that this transport formula limits the continuous deepening of the main channels, which is a model artifact.

Another parameter that has effect on the bed slope is the Ashld. By lowering this value the effect becomes larger and the slope decreases. The default value of this parameter is 0.7, after different tests the choice is made for a value of 0.2 (Schuurman et al., 2018). With this value bathymetry shows most agreement with the reality concerning the amount of channels, the depth and the width of the channels. The channels stay dynamic active.

In the initial setting the spiral flow is enabled. This means that in a bend of the channel a spiral flow can arise where the sediment from the outside bend erodes and is deposed at the inner bend. This i.a. causes relative steep slopes shown in Figure 5.2. At the most channels this has only little influence since this effect only occurs in the bends, at coastal regions this effect mostly is not used during modelling.

Another characteristic of the model that tends to make the channels deeper is the absence of *armouring* (Ferdowsi et al., 2017). With different sediment fraction within the model armouring of the bed layer normal acts, a phenomena whereby the bed typically has an 'armoured' layer of coarse grains on the surface, which acts to protect finer particles underneath from erosion. With only one sediment fraction, this behaviour will not occur. The initial sediment thickness is set to 10 m. See Chapters 8 and 10 for further advises on this topic.

Waves are not included in the final model used in this thesis. Further reasoning for choice and a summary of the preformed work can be found in Appendix F.

5.4. SIMULATION MORPHOLOGICAL SPIN-UP

In Sections 5.2 and 5.3 the extensions of morphological model settings are prescribed, now the model is almost ready for its purpose. The last step before the model can simulate the situation with and without dam for a certain time span is to apply a morphological spin-up time. This spin-up time will give the bathymetry time to respond on the hydrodynamic forcing. If this spin-up time is not applied one couldn't reason from the results if, for instance, the change in bed level is caused by the implementation of a dam or that this appearance would happen anyway.

As stated, the primary goal of this simulation is to obtain a bathymetry that is more or less in equilibrium. The time span that is required to reach this point is unknown prior to the simulation. Chosen is for a simulation time of 8 years with a MorFac of 12, which represents a morphological time span of 96 years. The hypothesis is that the bed will adjust slowly and that this adjustment will reduce over time. The water level at t=96 will probably differ from the level at t=0 as result of the changing bed level.

5.4.1. CROSS-SECTIONS AND OBSERVATION POINTS

To determine the behaviour of the movement of sediment over the gulf multiple cross-sections are implemented all the simulations, see Figure 5.4. With this cross-section the computational results can be monitored as a function of time over a certain line. Most of the sections are perpendicular to the in- and outflow direction of the tide. The observation points that are used in Chapter 4 and 3 originated from the original hydrodynamic model and are mainly used for the calibration and validation of the tidal signal. In Figure 5.5 the observation points are shown that will be use in Chapter 5 and 6. The points form line with the grid coordinates m=1:255, n=69. The individual observation points that will be used most are at the crossings of this line with the cross-sections: Dam m=68,n=69; Dahej m=80, n=69; River m=94, n=69; Alang m=107, n=69; Neutral m=116, n=69; Hazira m=125, n=69.

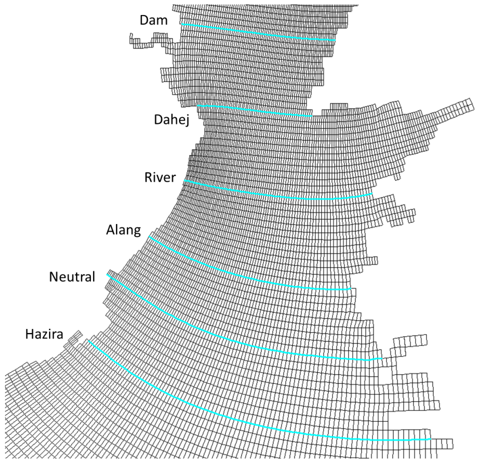


Figure 5.4: Cross-sections within study area

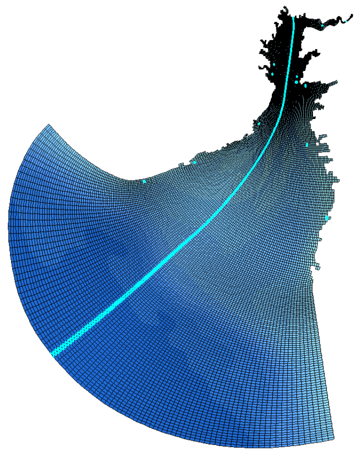


Figure 5.5: Observation points

5.4.2. CUMULATIVE AND INSTANTANEOUS TOTAL TRANSPORT

To investigate the evolution of the bed during this simulation the mean total transport is chosen as starting point, it gives inside of the general behaviour of the sediment transport in the gulf. In Figure 5.6 the cumulative total transport at cross-section Alang is given. From this simulation a few things can be observed. The first notable event is that after 1,5 years (18 morphological years) the cumulative total transport seems to strives towards an equilibrium state with a constant directional coefficient. The second point is that the change in slope of the cumulative total transport around the same year can be appointed to the available amount of sediment, or better said, the lack of available amount of sediment. The formed main channels at this moment reach the bottom of the bed layer of 10 m as described in Section 5.2. After the process of further deepening stops the channels tend to get wider for a moment after that the widening process stops as well.

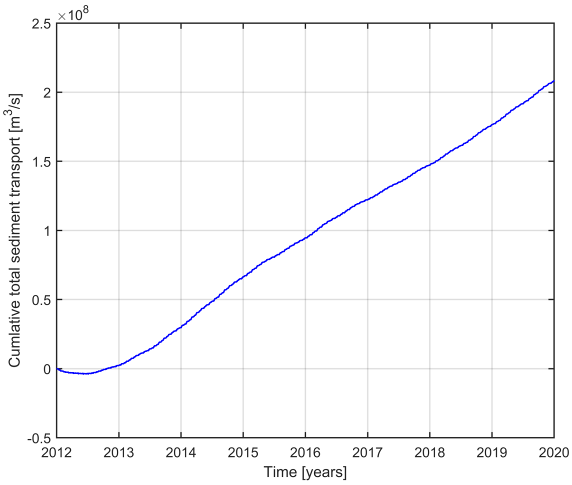


Figure 5.6: Cumulative total transport at cross-section Alang

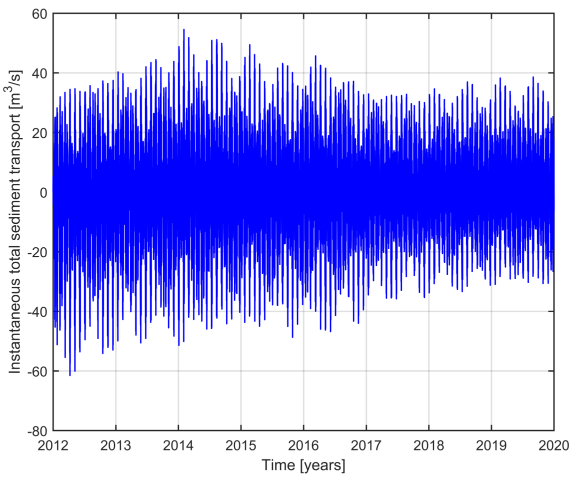


Figure 5.7: Instantaneous total transport at cross-section Alang

The instantaneous total transport over the same cross-section is shown in Figure 5.7. From this figure can be noted that the amplitude of the instantaneous total transport over cross-section Alang decreases over time, which suggests that the flow velocities lower as well. This is caused by the decrease of the tidal range of 1 m over the entire simulation. The decreasing tidal range over time is a combination of two changes between the start and the end of the simulation. The first change is that the forcing conditions change over time. From t=0 to t=96 the depth at m254, n69 decreases from 78,83 to 79,59 meters. With the Riemann boundary condition this difference causes a change in the water level signal of 0,05 meters, see Figure 5.8. During the same 96 years the bathymetry changes as well. The combination of the two changes result in a different propagation of the incoming tidal wave over time as can be seen from the onshore water level.

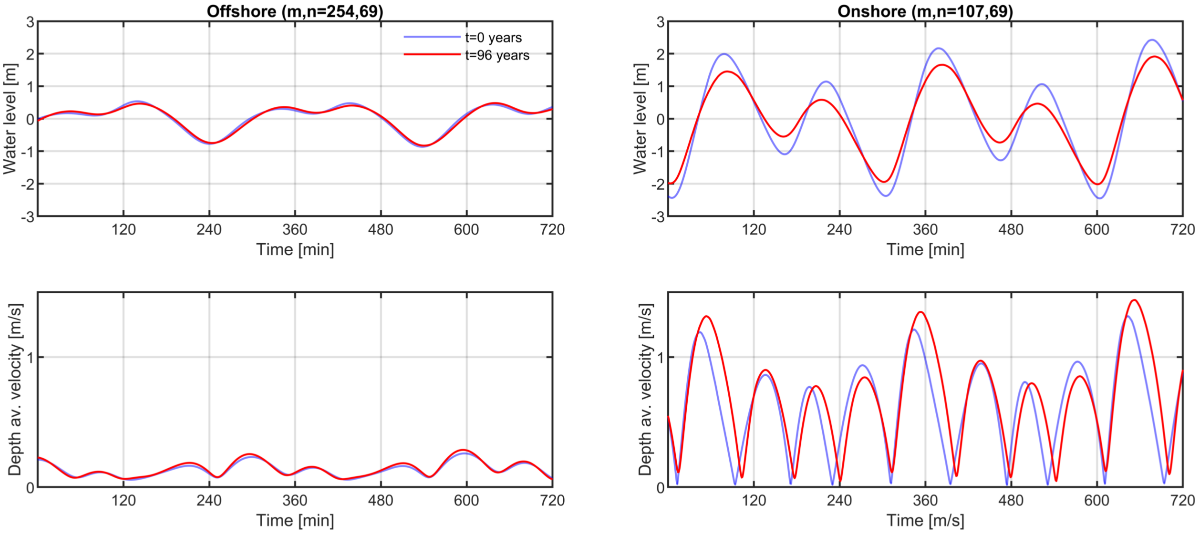


Figure 5.8: Water levels and depth averaged velocities for t=0 and t=96 years at the seaward boundary of the domain (offshore) and near Alang (onshore)

5.4.3. BED LEVEL CHANGES AND DISTRIBUTION

The cumulative total transport rates described in the previous section lead to bed level changes in the study area. The sedimentation and erosion rates over the spin-up simulation are shown in Figure 5.9. These are slip-up in three equally long periods to analyse the change of the patterns in time. The main channel in the centre of the gulf seems to become stable after 64 years. However, this is an introduced model artifact and it does not necessarily represent reality. Once the erosion rates cause full erosion of the initial layer, which has a thickness of 10 m, no more sediment can be eroded.

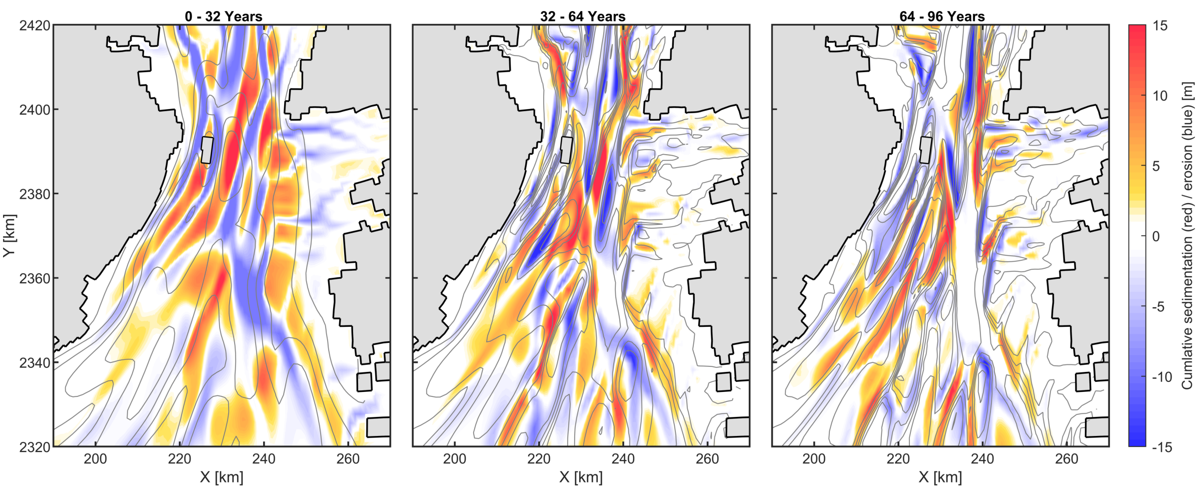


Figure 5.9: Cumulative sedimentation erosion for different time spans of the spin-up simulation

The cumulative and instantaneous total transport of the spin-up simulation gives inside in the general behaviour of the sediment transport in the study area. It is a strong tool to get an impression of the ongoing processes over a larger area. However, since the transports are calculated over a cross-section there is no clear insight in what happens at the characteristics of the area as the channels and flats. In Figure 5.10 the 5, 50 and 95 percentile of the bed level distribution of the study area is shown. From this figure can be concluded the flats increase slightly in the first 30 years and from there stay constant to the end of the simulation. The 5 percent lowest grid cells of the study area.

To get an even better picture of the evolution of the channels versus the flats, a distinction is made between the data points that are above and below MSL. In Figure 5.11 the difference of bed level of the data points above MSL with the previous time step is set against the time. The 5, 50 and 90% lines show a decrease of difference over the first 10 years, after that the band with between these lines is about 0.2 m. The 5, 50 and 90% lines of the data points below MSL show the same behaviour; remarkable is the larger difference in band with over the simulation in comparison with the top sub-figure. It can be concluded that the channels tend to strive to an equilibrium state as well but remain their dynamic behaviour.

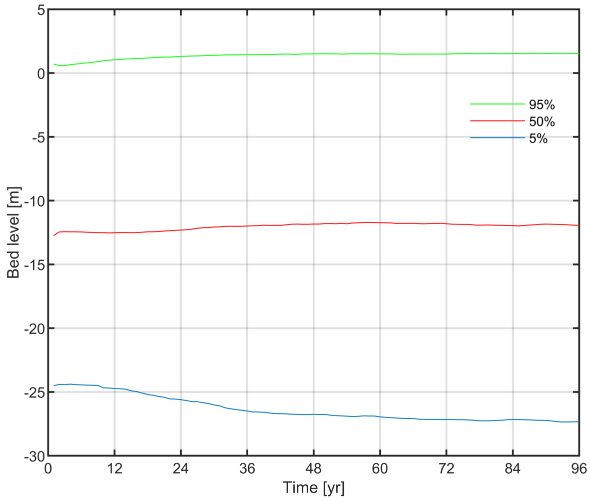


Figure 5.10: The 5, 50, and 95 percentile of the bed level distribution for the simulation with dam (m=69-120). All bed levels are included

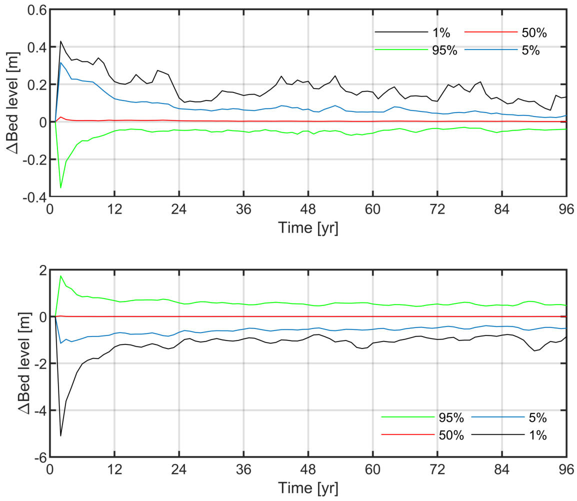


Figure 5.11: The 1, 5, 50, and 95 percentile of the bed level difference for the simulation with dam (m=69-120). Bed levels >0 (top) bed levels <0 (down)

5.5. MAIN MODEL SETTINGS

Table 5.1: Summary of the main model parameter settings. Based on Elias (2006)

Module	***Parameter***	***Value***	***Description***
Flow	Δt	30	Computational time step [s]
	ρ_w	1025	Density of water [kg/m^3]
	ρ_a	1.25	Air density [kg/m^3]
	Roumet	Chezy	Type of bottom friction formulation [-]
	Ccofu	60.0	Uniform bottom roughness in u-dir [$m^{1/2}/s$]
	Ccofv	60.0	Uniform bottom roughness in v-dir [$m^{1/2}/s$]
	Vicouv	1.0	Uniform horizontal eddy viscosity [m^2/s]
	Dicouv	0.5	Uniform horizontal eddy diffusivity [m^2/s]
	Dryflc	0.1	Threshold depth for drying and flooding [m]
	CSTbnd	yes	Boundary condition [-]
Transport	MorFac	12	Morphological scale factor [-]
	MorStt	1,440	Spin-up interval for start of morphological changes [min]
	Thresh	0.1	Threshold sediment thickness [m]
	BedUpd	true	Update bed level during flow run [-]
	MorUpd	true	Update bathymetry during FLOW simulation [-]
	CmpUpd	true	Update bed composition during flow run [-]
	EqmBc	true	Equilibrium sed. con. profile at open boundary [-]
	DensIn	false	Include effect of sediment on water density [-]
	AksFac	1	Van Rijn's reference height factor [-]
	RWave	2	Estimated ripple height factor [-]
	Rouse	false	Set equilibrium sediment concentration to Rouse profiles [-]
	AlfaBs	1	Streamwise bed gradient factor for bed load transport [-]
	AlfaBn	50	Transverse bed gradient factor for bed load transport [-]
	Sus	1	Current-related reference concentration factor [-]
	Bed	1	Current-related transport vector magnitude vector [-]
	SedThr	0.1	Minimum water depth for sediment computations [m]
	ThetSD	1	Factor for erosion of adjacent dry cells [-]
	HMaxTH	0.1	Max depth for variable THETSD [m]
	IopKCW	1	Flag for determining Rc and Rw [-]
	RDC	0.01	Rc in case IopKCW = 2 [-]
	RDW	0.02	Rw in case IopKCW = 2 [-]
	Espir	0.0	Calibration factor spiral flow [-]
	ISlope	3	Flag for bed slope effect [-]
	AShld	0.2	Bed slope parameter Koch & Flokstra [-]
	BShld	0.5	Bed slope parameter Koch & Flokstra [-]
	Upw.Bed.L	True	Numerical scheme for bedload
	Max.Water.d	True	Use maximum of water depth
	D_{50}	162	Median grain diameter [μm]
	TraFrn	eh.tra	Sediment transport formula [-]
	Cref	1,600	Reference density for hindered settling calculations [kg/m^3]
	IopSus	0	Sediment size depends on local flow and wave conditions
	Name	SedimentNC	Name of sediment fraction
	SedTyp	sand	Must be "sand", "mud" or "bedload"
	RhoSol	2,650	Specific density [kg/m^3]
	CDryB	1,600	Dry bed density [kg/m^3]
	IniSedThick	10	Initial sediment layer thickness at bed [m]
	FacDSS	1	Initial suspended sediment diameter [-]

6

Effects of the dam

6.1. Introduction

This chapter presents the results of model simulations of the study area for the current situation and for the future situation of the gulf, in which the dam is implemented. The set-up of this analysis is more or less the same as the spin-up simulation in Section 5.4 of Chapter 5. This simulation served to bring the bathymetry towards a dynamic equilibrium. The final bathymetry and hydrodynamic conditions at the end of the spin-up served as a starting point for a simulation with the dam, the main simulation of this chapter. Model simulations introduce inaccuracies and errors in the results due to model artifacts. To cope with these introduced errors, an extra simulation is performed with the same settings as the previous simulation, but without the dam. A comparison between both simulations serves to determine the relative effect of the dam.

This chapter is divided in three main sections - hydrodynamics (Section 6.2), morphodynamics (Section 6.3) and sediment budget (Section 6.4) - to answer sub-questions three and four: *'What is the change of the tidal conditions and what will be the effect on the hydrodynamic forcing?'* and *'What are the short and long term morphodynamic responses of the system?'*.

6.2. Hydrodynamics

6.2.1. Introduction and expectations

Figure 6.1 shows a simplified representation of a 1D wave motion that can be extended in principle to the three dimensional real world situation of the Gulf of Khambhat. Knowing that the magnification of the tidal range at the barrier and the changes in the velocity field are strongly dependent on the three dimensional geometry, this needs to be modelled in order to quantify the changes. Nevertheless, it can be generally concluded that the introduction of a dam in an estuary or gulf would result in a reduction of velocities over a substantial area downstream of the dam (Bosboom and Stive, 2015). The tidal range in converging estuaries is affected by three dominant processes: *a)* amplification (or shoaling) due to the decrease of the width and depth in landward direction, *b)* damping due to bottom friction and *c)* partial reflection at the landward end of the gulf or estuary, whereas bathymetry convergence produces continuous reflection along the entire length (Giardino et al., 2014). In case of man-made artificial closure the tidal range might be largely amplified.

6.2.2. Tidal signal

To answer the third sub-question a clear interpretation of the conditions is required; the vertical rise and fall of the water level is called the *vertical tide* or simply *tide*. The *rising period* is the time it takes for the water level to get from the lowest elevation to the highest elevation, *the falling period* is the time it subsequently takes to reach the lowest level. The corresponding horizontal movement back and forward is the *horizontal tide* or tidal current. When it is said that the (vertical) tide is *flood-dominant* this refers to a shorter rising period than falling period. Vice versa *ebb-dominance* indicates a shorter falling period. Flood dominance is also used to indicate the direction of net sediment transport as result of asymmetries of the horizontal tide. Generally speaking we may state that we have net flood transport for $u_{max,\,flood} > u_{max,\,ebb}$, and net

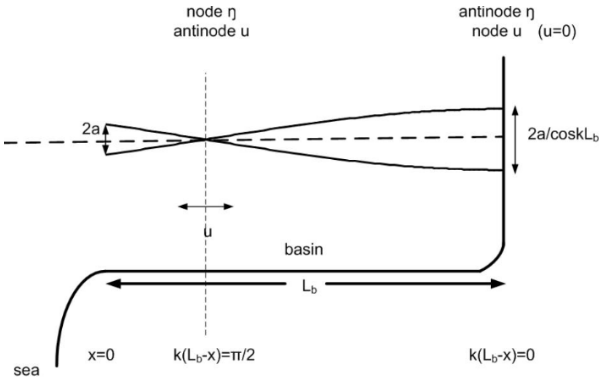


Figure 6.1: Standing wave (Bosboom and Stive, 2015)

ebb transport in the reverse case. So, by analysing the tide one could say, in general, something about the morphodynamic system. This is explained in detail Section 2.2.3.

Situation without dam

In Figure 6.2 an overview is given of the tidal signals for the situations with (continuous lines) and without dam (dotted lines) at observation points *Alang* and *Dahej* at the begin of the simulations. The locations of the observation points are on the crossings of the line observations points of 5.5 and the cross-section of Figure 5.4. The tidal range increases with decreasing distance from the northern edge of the gulf, caused by the three processes mentioned in Section 6.2.1. The magnitude of the tidal current is maximum 2.2 m/s at Alang and 3.0 m/s at Dahej. Besides, it is worth mentioning that the $u_{\text{max, flood}} > u_{\text{max, ebb}}$ at Alang, which indicates that there is probably net transport in flood direction. Close to the dam the opposite is the case, here $u_{\text{max, ebb}} > u_{\text{max, flood}}$, which indicates net transport in ebb direction. Over time the signal at Dahej changes, the signal remains ebb dominant but not as strong as the initial situation. The signal at Alang changes from flood dominant to slightly ebb dominant over time. In Figure 6.3 the overview is given for the same observation points but now at the end of the simulations, after 96 years. The tidal range remains approximately the same during the simulation for both locations. We observe a slight decrease in flood velocities and a slight increase in ebb velocities at Alang. At Dahej both velocities tend to slightly decrease, but the differences are minimal.

Situation with dam

In comparison with the situation without a dam, the initial tidal range increases in both observation points for the situation with dam. This increase is observed largest at the observation point close to the dam. The magnitude of the tidal current is maximum 2.4 m/s at Alang and 1.4 m/s at Dahej. The maximum current speed during ebb and flood are changing in this new situation. The $u_{\text{max, flood}} > u_{\text{max, ebb}}$ at Alang what indicates net flood transport. Close to the dam the same holds. At the end of the simulation, see Figure 6.3, we observe a slightly different situation: the tidal signal at Dahej has become strong flood dominance. At the same time the signal at Alang became less flood dominant. Not all of the conclusions can be made of Figure 6.2 and 6.3, the more general trends can be noticed from Figure G.1 and G.2.

6.2.3. TIDAL ENVELOP

For each of the observation points introduced in Figure 5.5, the highest high water and the lowest low water values are plotted for the first and last three morphological years, hereafter referred as 'initial' and 'final', of the 96 year simulation. As starting point the initial tidal envelop without dam is taken, the tidal range for this particular situation is 7.88 m. The change in the tidal range is largest close at the dam with an increase of 2.62 m. The highest high water increases with 1.61 m at this location for the situation with dam after 96 years, the decrease of the lowest low water near the dam is relatively smaller with a maximum decrease of 1.01 m. The influence of the dam on the tidal range decreases with increasing distance from the dam. The initial tidal envelops of both simulations show a remarkable deviation of the low water levels at the area between 80 and 100 km from the dam. This is because the initial bathymetry of these simulations contains a large shallow shoal at this location, for which the water levels cannot reach the expected low water levels. The figure also shows that the shoal is probably eroded after 96 years, which also holds for both simulations.

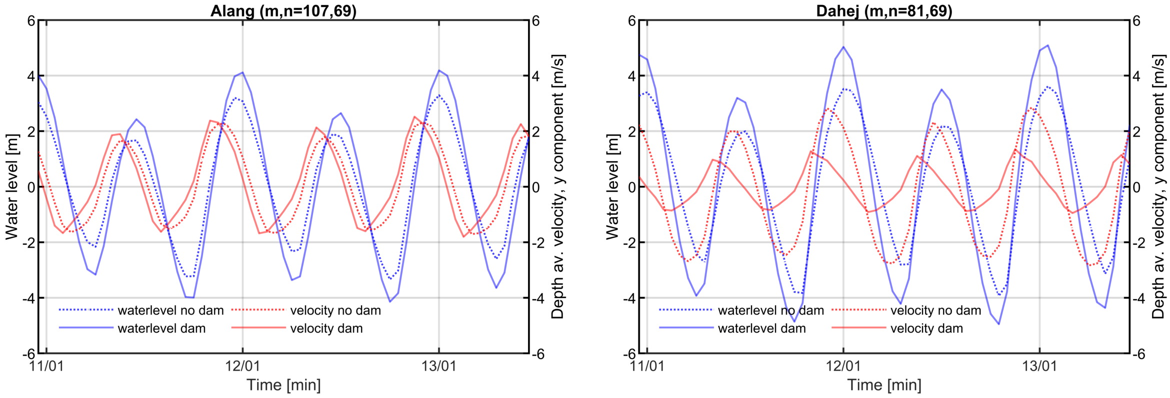


Figure 6.2: Water levels and the depth average velocities (y-component) for the observation points Alang and Dahej at the beginning of the simulation. A positive y-velocity indicates flood direction.

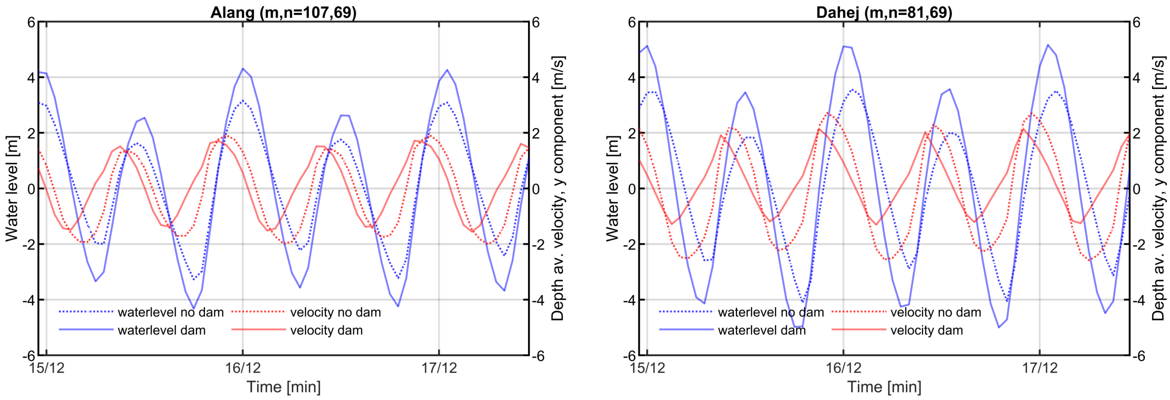


Figure 6.3: Water levels and the depth average velocities (y-component) for the observation points Alang and Dahej at the end of the simulation, after 96 years. A positive y-velocity indicates flood direction.

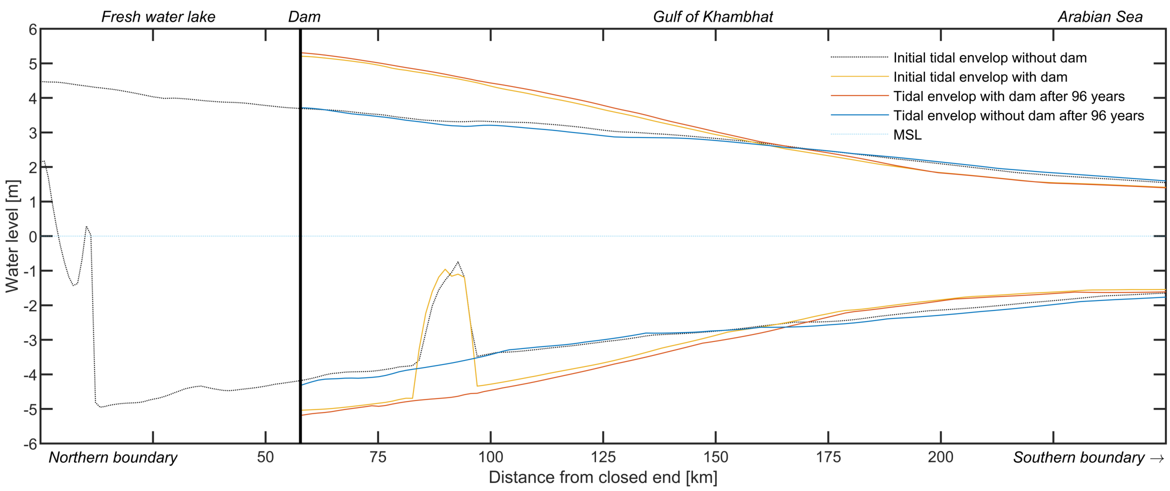


Figure 6.4: Influence of the closure of the Golf of Khambhat on the tidal envelop

6.2.4. CURRENT PATTERNS AND BED SHEAR STRESS

A change in tidal propagation goes hand in hand with a change of the current patterns. Moreover, the current velocities cause bed shear stresses, according to the relation $\tau \sim u^2$. Figure 6.5 provides insight in what the change of the tidal signal means for the current patterns bed shear stresses in the study area. Besides, the tidal signal is indicated for the observation point Alang, indicated with a black dot. The snapshots indicate the different current patterns at characteristic moments of the tidal motion. The arrows in the figures indicate the magnitude and the direction of the depth averaged flow. In the background the corresponding bed shear stresses are shown. Especially in the channels the current velocities and bed shear stresses reach high values of 3-4 m/s and 9-10 N/m^2.

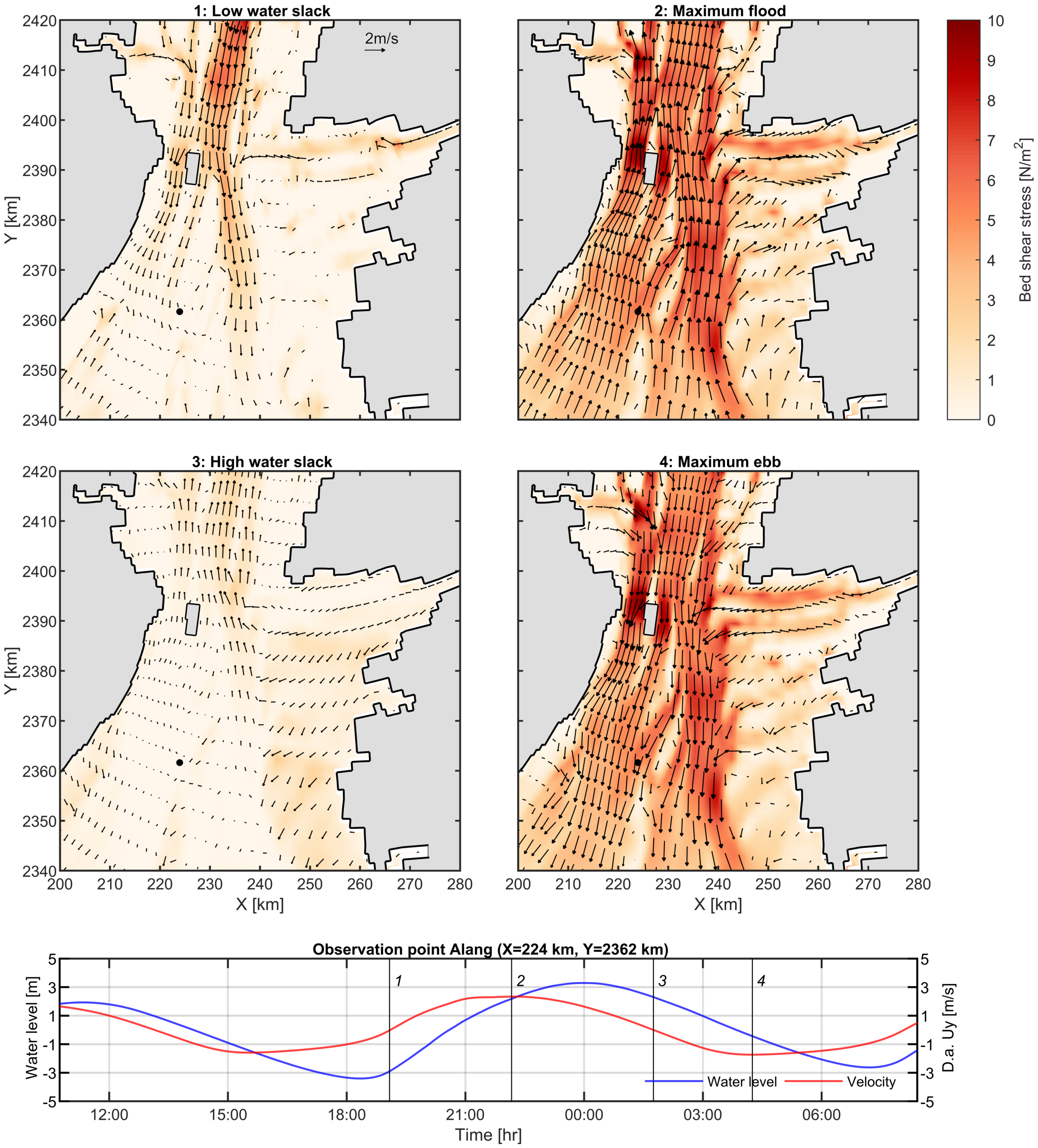


Figure 6.5: Current patterns and bed shear stresses of four moments during one tidal cycle without dam. A positive y-velocity indicates flood direction.

At Alang, the tidal range increases with the implementation of the dam and subsequently, the corresponding flow velocities also sightly increase. From Figure 6.6 one can distinguish a long and strong current of in- and outflow of the tide during maximum flood and maximum ebb. Around the altitude of Y=2400 km, the distance between the eastern and the western coastline is the smallest. This in combination with the Piram Island, forms a constriction of the estuary. Therefore, this is the location with the highest flow velocities. In the situation with dam the width of the constriction has not changed, but the amount of water that moves in and out of the imaginary cross section along this altitude decreases significantly. As a result the flow velocities and the bed shear stresses also decrease. Consequently, the main channel at the eastern side of the basin decreases in length. The observed velocities around the dam at the location of the former channels become negligible.

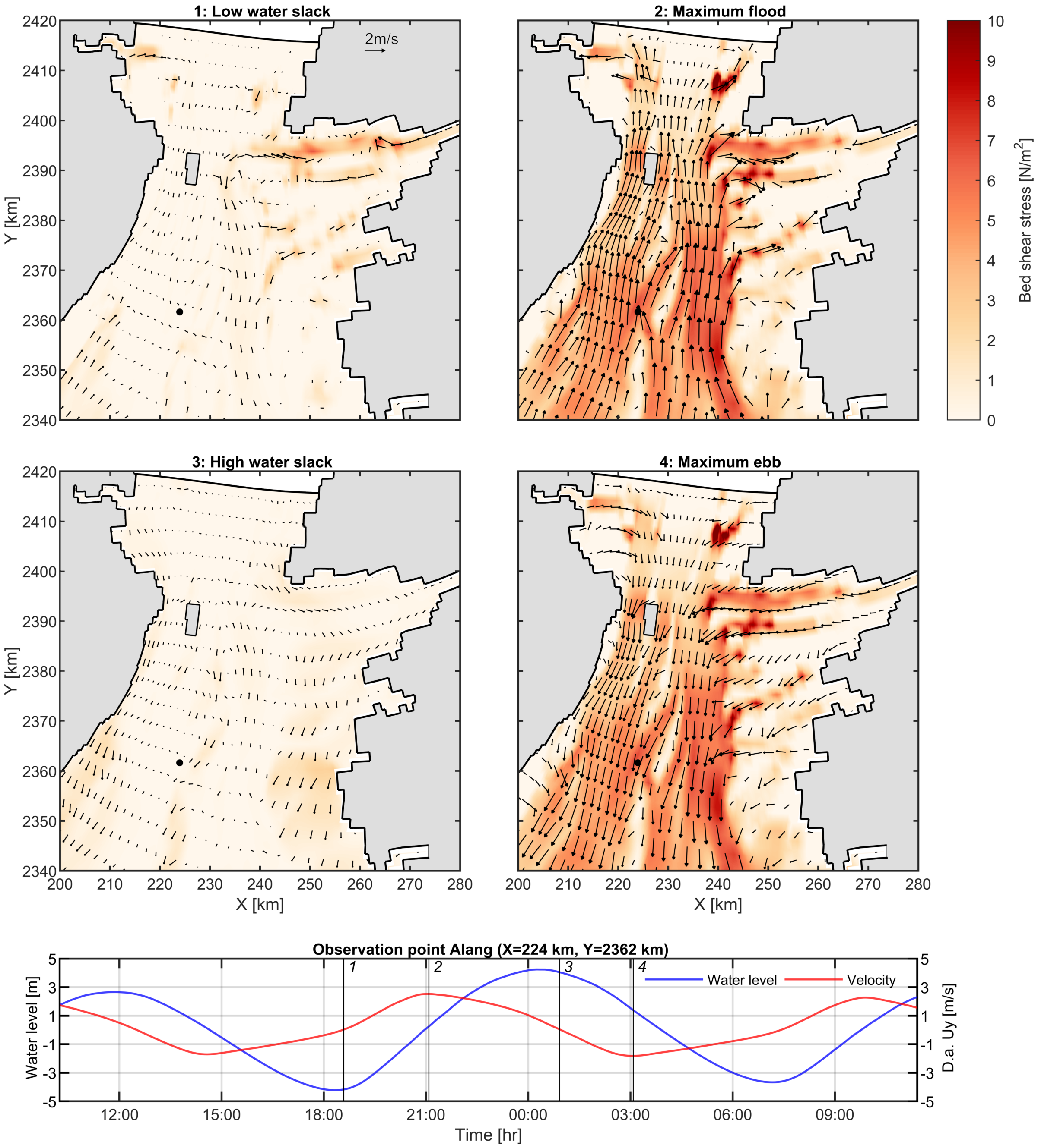


Figure 6.6: Current patterns and bed shear stresses of four moments during one tidal cycle with dam. A positive y-velocity indicates flood direction.

6.3. MORPHODYNAMICS

6.3.1. INTRODUCTION AND EXPECTATIONS

As described in the previous sections, the implementation of the dam will cause a direct change of the hydrodynamics of the study area, such as an overall increase of the tidal range and a locally increase of the tidal currents. This change will have an impact on the morphology. While the morphology changes, the tide - being dependent on the water depth - responds to the adjusted bed levels. As a result the sediment transport rates change and this again affects the development of the morphology. This feedback between the hydrodynamic processes and morphology is named *morphodynamics*.

It is now clear what the meaning is of morphodynamics, but in what spatial scales are we interested and what can be stated as short and long term in morphological time scales? The scope of this research has earlier been defined in Section 1.2, along with the problem statement. The spatial scale is generally determined by the dimensions (in m) of a particular morphological element; it indicates the extent of the element (Bosboom and Stive, 2015). For example: a whole tidal inlet system, comprising of a flood basing, an inlet gorge and an ebb or outer delta with dimensions varying between 50 to 700 km^2. In this study we define the study area as the area from the dam upto 75 km southwards, which is around the altitude of Hazira.

To place the study area in the perspective of the spatial scales defined in Figure 1.5. The Gulf of Khambhat has a total length of 250 km and a varying width of 250 km in the south to 25 km in the north. Within this estuary the main morphological elements are present, e.g, ripples, dunes, tidal flats, channels, sandbanks and tidal deltas. Changes in this system as a whole will probably take centuries to a Holocene. The aforementioned study area were the focus is on during this study is thus smaller and located in the northern part of the gulf, just above the outer delta. Short term changes of this area are therefore estimated at years to decades and long term changes at decades to centuries.

6.3.2. SEDIMENT TRANSPORT RATES

The current patterns and bed shear stresses induce sediment transport. Residual transport rates eventually result in morphological changes of the study area. This section focusses on the *mean total transport*, or *net transport* patterns. These give insight in the direction and magnitude of the sediment transport at the end of the simulations, so after 96 years.

Figure 6.7 shows the net transport patterns for the simulation without dam (left) and with dam (right). The white arrows indicate the magnitude and direction of the transport rates. The initial bathymetry is plotted underneath, which is the same for both simulations. This way, the sediment patterns at the individual morphological units may be distinguished.

In the situation without dam the rivers act as a sediment source. Sediment transport takes mainly place at the channels, with maximum depth averaged net transport rates of around $3*10^{-4}$ m^3/s/m. The net transport is primarily in ebb direction, so sediment is mainly leaving the estuary. This implies that in general the estuary may act as a sediment source for the ebb tidal delta or adjacent coastlines. Note that sediment transport not only takes place at the area around the future dam: the northern part of the estuary also shows significant transport rates.

After implementation of the dam, the area north of the barrier is almost fully closed off. Implementation of sluices will allow water from the closed lake to be discharged towards the sea, but the tidal wave will no longer propagate into this area. The sluices are not implemented in the model, since these will only operate in case of extremely high water levels at the lake. So, they are mainly a flood protection measure during extreme events.

Because of the dam, the upstream rivers will no longer act as a sediment source. Again, transport mainly takes place at the channels, although the net transport rates are now smaller with maximum depth averaged values of around $1*10^{-4}$ m^3/s/m. Moreover, the predominant transport direction is onshore (flood direction). Apparently, the channels are too deep for the new situation and tend to accrete. The required sediment will most likely originate from the ebb-tidal delta. Whether this source is large enough remains uncertain.

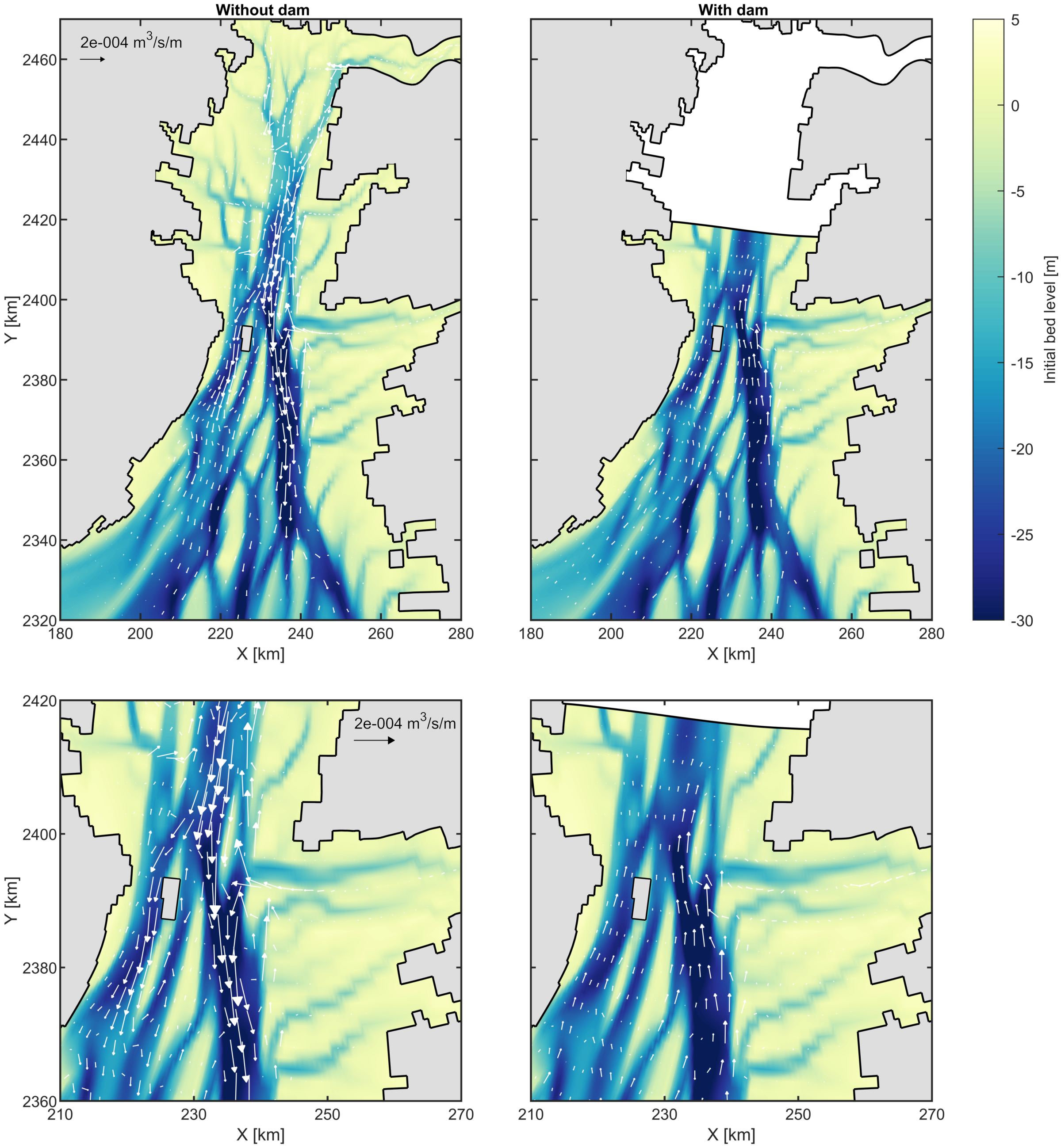


Figure 6.7: Mean total transport patterns for the northern part of the gulf (the top sub-figures) and the area just in front of the dam (the lower sub-figures). The left plots show the situation without dam and the right plots the situation with dam. The white arrows indicate the magnitude and direction of the transport rates. The initial bathymetry is plotted underneath.

6.3.3. SEDIMENTATION AND EROSION PATTERNS

Spatial gradients in transport result in mean total transport rates, causing sedimentation or erosion. Note that the mean total transport is calculated over the entire simulation, while the sedimentation/erosion patterns are analysed over short and long term time scales. Again, two situations are distinguished, one without dam and one with dam, to enable the analysis of the relative results as well.

In Figures 6.8 and 6.9 the simulation results (with and without dam) are divided into three periods: 0-32 years, 32-64 years and 64-96 years. This enables the analysis of the response during different parts of the simulation. For each sub-figure the cumulative sedimentation and erosion patterns are shown over the timespan, whereby the depth contours at the beginning of the each period are shown. The values of these depth contours are shown in Appendix H.

Without dam

The situation without dam, see Figure 6.8, shows a predominant erosion of the main channels, which matches the net offshore directed transport patterns of Figure 6.7. The rate of the bed level changes decreases in time and after some decades the main channels seem to have reached an equilibrium. Note that bed level changes occur over the entire area, so also at the northern and southern boundaries. The eastern part of the gulf, where the channels are significantly more shallow, shows much smaller bed level changes. This is in line with the relatively small flow velocities and transport rates shown in Figures 6.5 and 6.7.

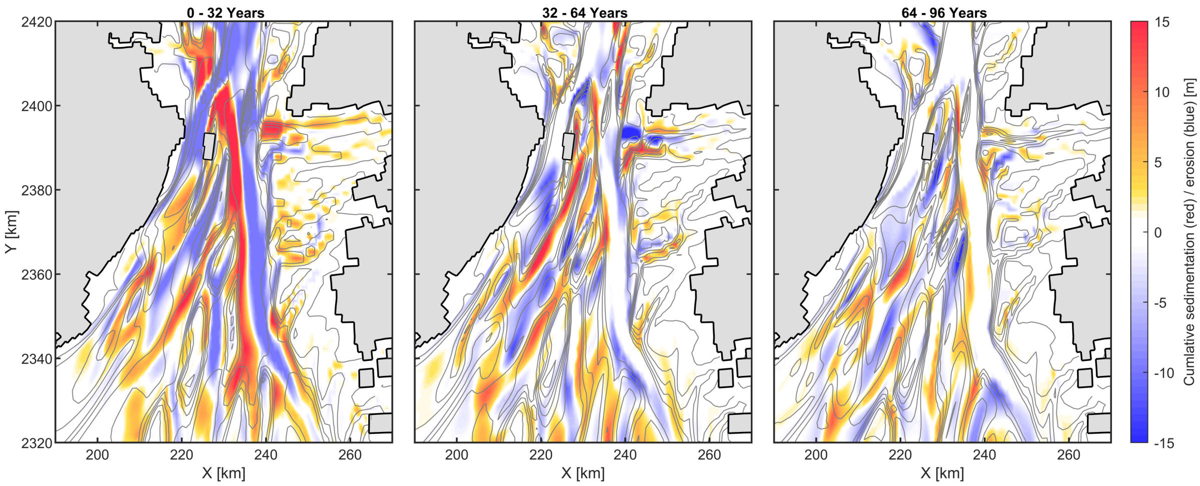


Figure 6.8: Cumulative sedimentation/erosion patterns of different timespans for the simulation without dam.

With dam

The morphodynamic response of the gulf for the simulation with dam is, as expected, different. The erosion of the main channel in the middle of the figure is remarkable: initially, this response seems similar to the one for the situation without dam. However, one should remember that the transport patterns are in opposite direction. Closer to the dam the bed level changes show a clear process of infilling: the former main channel at the location of the dam, was most likely mainly formed by the strong intertidal current towards the northern part of the gulf. Now, it is blocked off by the implementation of the dam. This closure causes a instant infilling of the smaller channel in the left upper corner in front of the dam, and the initial infill of the main channel from the south. In the next time-span (32-64 years) this infill continues closer to the dam and at the same time the deepening of the channel in the middle of the figure has stopped. The reason for this can be found in the set-up of sediment layer thickness. With a thickness of 10 m the bottom of this layer is reached within 25 years. During the last period (64-96 years), the area closest to the dam fills in.

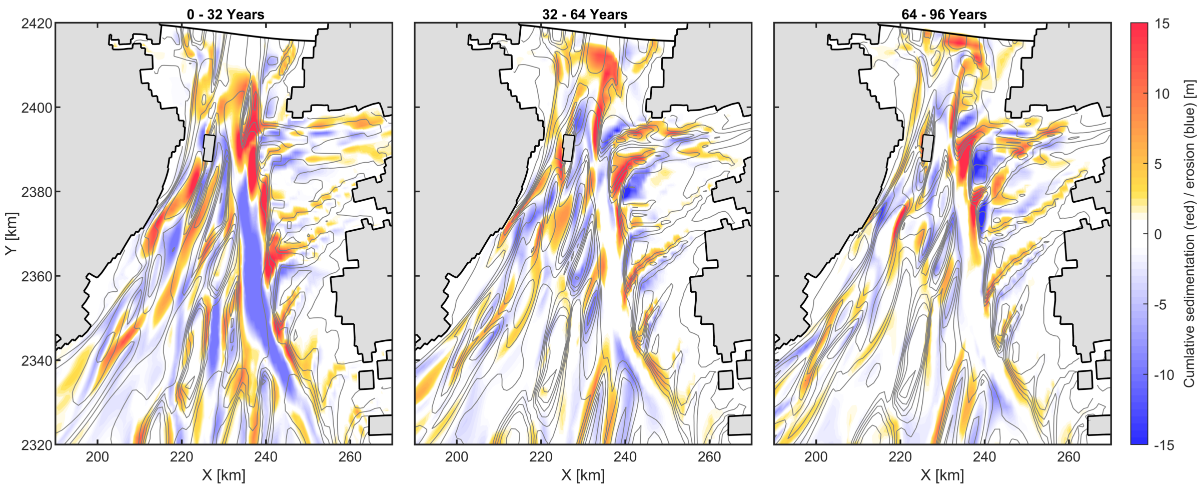


Figure 6.9: Cumulative sedimentation/erosion patterns of different timespans for the simulation with dam.

Concluding, we observe that the area with a distance of 20 to 40 km of the dam accretes first, before sedimentation is observed near the dam. This is explained as follows: the required sediment to infill the areas originates from the offshore areas and from the Narmada river. This sediment reaches the areas around Y ≈ 2350 km first.

Relative sedimentation and erosion

Figure 6.10 shows the cumulative sedimentation/erosion patterns for the total 96 years of the simulation with dam (left) and the relative cumulative sedimentation/erosion patterns for the total period (right). The latter shows the difference between the simulation with and without dam. Model simulations introduce inaccuracies and errors in the results due to model artifacts. To cope with these introduced errors, it is important to also study the relative effect of the dam instead of only the absolute effect. Note that the results should be interpreted qualitatively and not quantitatively. The reason for this is that the model simulations contain to many uncertainties to say something about the exact final bed levels. However, the information on sedimentation or erosion patterns is valuable to understand the overall response.

The overall patterns of both plots of Figure 6.10 are similar, but the rates are stronger for the relative case. This means for instance, that the main channel will erode even more than initially expected. Likewise, the area around the dam will accrete significantly more. East of the the main channel an elongated area of sedimentation is visible. This is because the channel for the situation with dam is narrower than the channel for the situation without dam. So the east bank is wider, but note that this is not necessarily a separate bar.

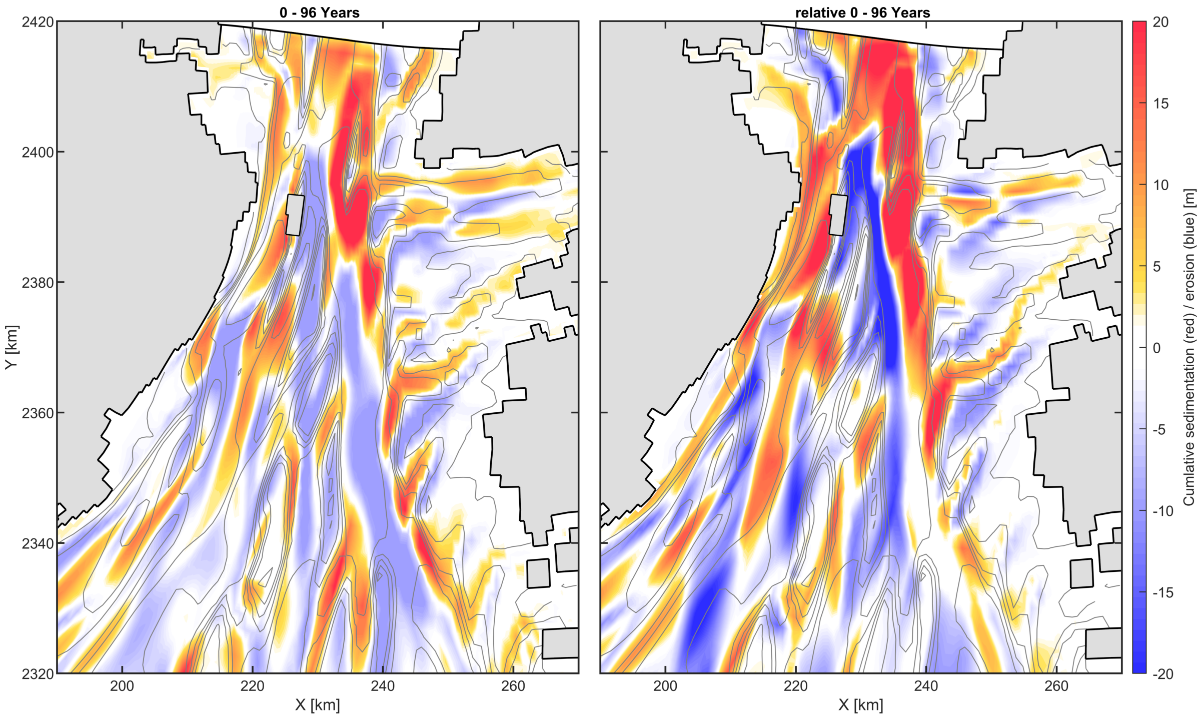


Figure 6.10: Left: cumulative sedimentation/erosion pattern for the total 96 years of the simulation with dam. Right: relative cumulative sedimentation/erosion pattern for the total 96 years between the simulation with and without dam.

6.3.4. PREDICTED BED LEVELS AND CHANNEL BEHAVIOUR

The calculated bed level changes result in a new topography of the Gulf of Khambhat. This section treats the characteristic bathymetries for three moments of the simulations: at t=32, t=64 and t=96 years. Again, first the results without implementation of the closure are treated after which the effect of the dam is discussed.

Without dam

Two main observations of morphological changes are distinguished from Figure 6.11:

- The main channel becomes deeper, but reaches its maximum depth of around -35 m within the first period. This is also supported by the results of Figure 6.8. One may interpret this as if the morphological unit is able to reach an (dynamic) equilibrium state within a few decades. However, this might not be the case, as it could also be a model artifact. This is elaborated in more detail in Chapter 8.
- The southwestern part of the gulf seems to be the most dynamic area; the alternation between channel (and bar) formation and deformation is namely visible for the entire simulation.

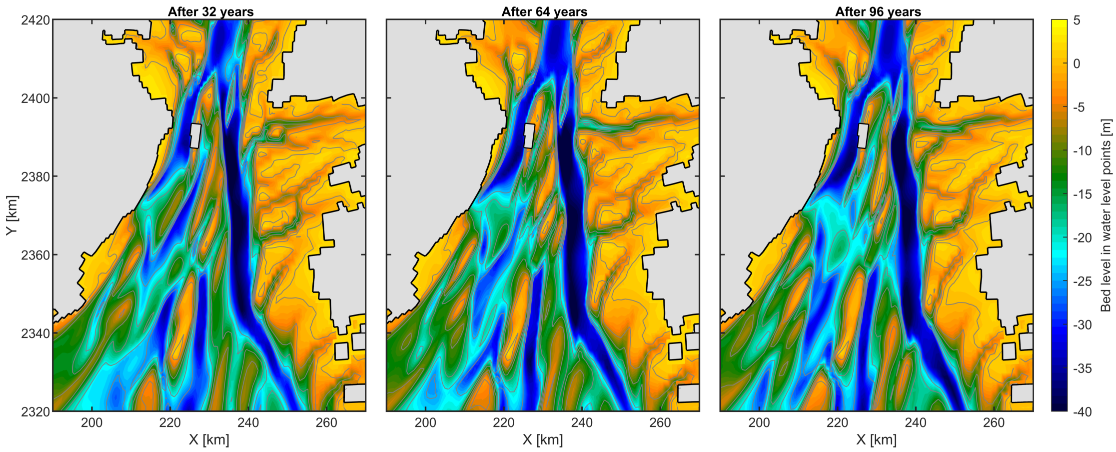


Figure 6.11: Bed levels with respect to MSL at different moments for the simulation without dam.

With dam

Figure 6.12 shows the bed levels for the situation with dam. Three main observations stand out:

- The area in front of the dam clearly fills in during the simulation: to this end, the existing channel seems to become narrower at first. Similar to the results of Figure 6.9 this plot shows that the area with a distance of 5 km and less from the dam starts to accrete strongly after six decades.
- The main channel in the middle of the gulf preserves its location after implementation of the dam. It final depth is, however, still unclear: the simulation results suggest that the channel does not become any deeper than 35-40 m, but this may be the result of the model settings, see Chapter 8. In the situation without dam another main channel is present at the western part of the gulf. This channel will fill in for a large part after constructing the dam.
- It is worth mentioning that the channels that discharge the outflow of the Narmada river keep their dynamic character in which the location of the bifurcation changes. Their development is different for the situation without dam, although they remain dynamic.

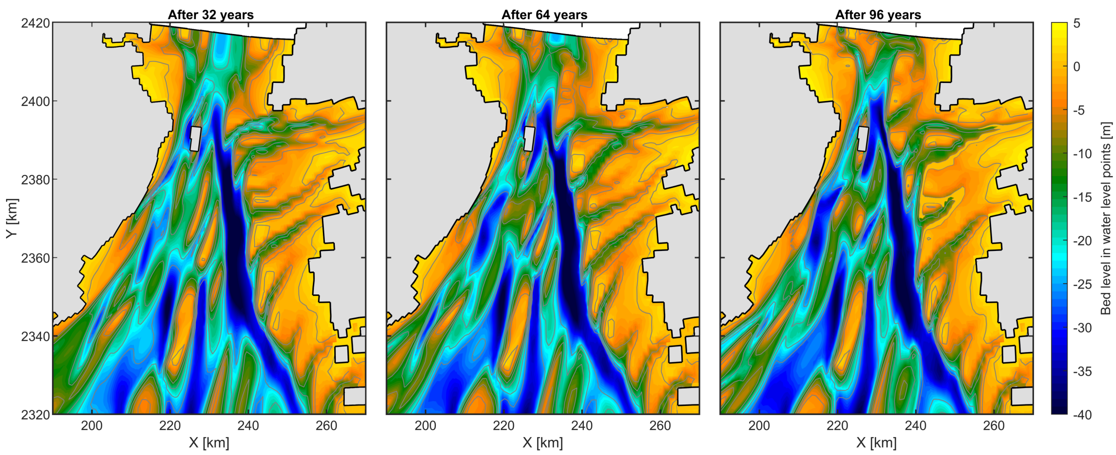


Figure 6.12: Bed levels with respect to MSL at different moments for the simulation with dam.

Figure 6.13 shows the morphological evolution of the entire study area by indicating the percentiles of the area that contain a minimal certain bed level. In other words: the 95% line indicates that after 72 years 5% of the area has a minimal hight of 2m. This also shows that 50% of the area becomes more shallow during the simulation. On the other hand, the most deep points become even deeper.

Besides the retrieved insight on the overall morphological evolution, it is interesting to get a better picture of the evolution of the channels and flats. To analyse this, a distinction is made between the data points that are above and below MSL. In Figure 6.14 the difference of bed level of the data points above MSL with the previous time step is set against the time. The 5, 50 and 90% lines show a decrease of difference over the first 10 years. After that, the bandwidth between these lines is about 0.2 m. The 5, 50 and 90% lines of the data points below MSL show the same behaviour; remarkable is the big difference in band with over the run in comparison with Figure 5.11. It can be concluded that the channels tend to strive to an equilibrium state as well but remain their dynamic behaviour.

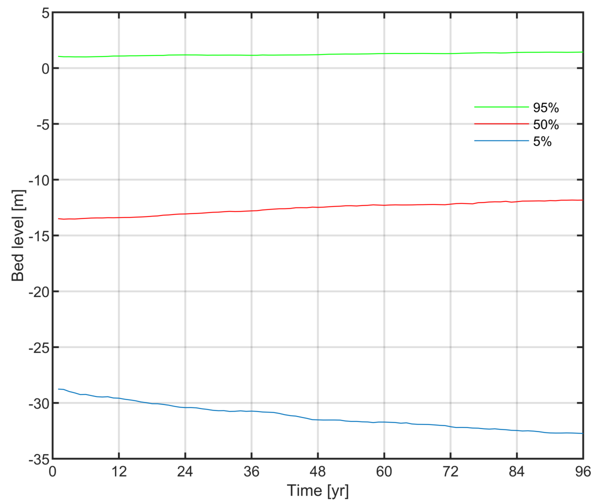


Figure 6.13: The 5, 50, and 95 percentile of the bed level distribution for the simulation with dam (m=69-120). All bed levels are included

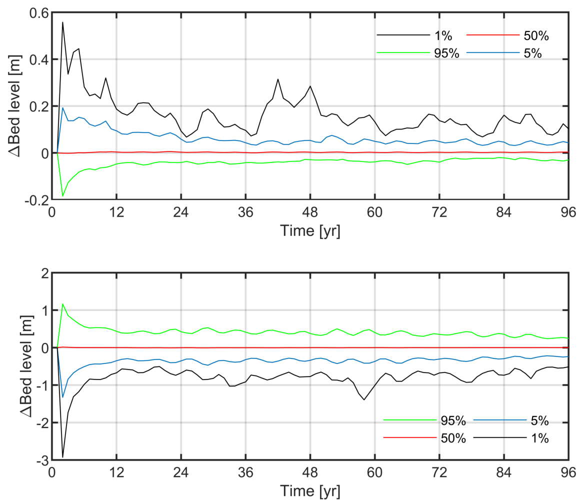


Figure 6.14: The 1, 5, 50, and 95 percentile of the bed level difference for the simulation with dam (m=69-120). Bed levels >0 (top) bed levels <0 (down)

6.3.5. HYPSOMETRY

As explained in Section 2.2.1, hypsometric curves can be used to analyse the bed level distribution over a tidal basin. These curves depict the surface basin area as a function of the bed level. Figure 6.15 shows the hypsometric curves for several periods after implementation of the dam. These curves are generated with the predicted bed levels. Again, it stands out that most of the changes take place in the first decades after construction of the dam. The areas with depths from -5 m to -45 m are most active, which represents the dynamic behaviour of the channels. The total area with depths of -30 m to -45 m significantly increases, showing the ongoing deepening of the deepest channels.

By zooming into the upper bed levels of a hypsometric curve and plotting the high water and low water lines, one can identify the intertidal area. This is done in Figure 6.16 for the initial situation (without dam) and the final situation, 96 years after constructing the Kalpasar dam. Note that not only the bed levels change during the simulation, but also the tidal range and thereby also the highest high water (HHW) and lowest low water level (LLW). The total intertidal area in the gulf increases because of the closure dam. The model simulations predict an increase of approximately $0.37*10^9$ m^2. Two main reasons are identified from Figure 6.16: first of all, the tidal range increases, as explained in Section 6.2.3 Secondly, the hypsometric curves become less steep between the bed levels of 5 m and -5 m over the years.

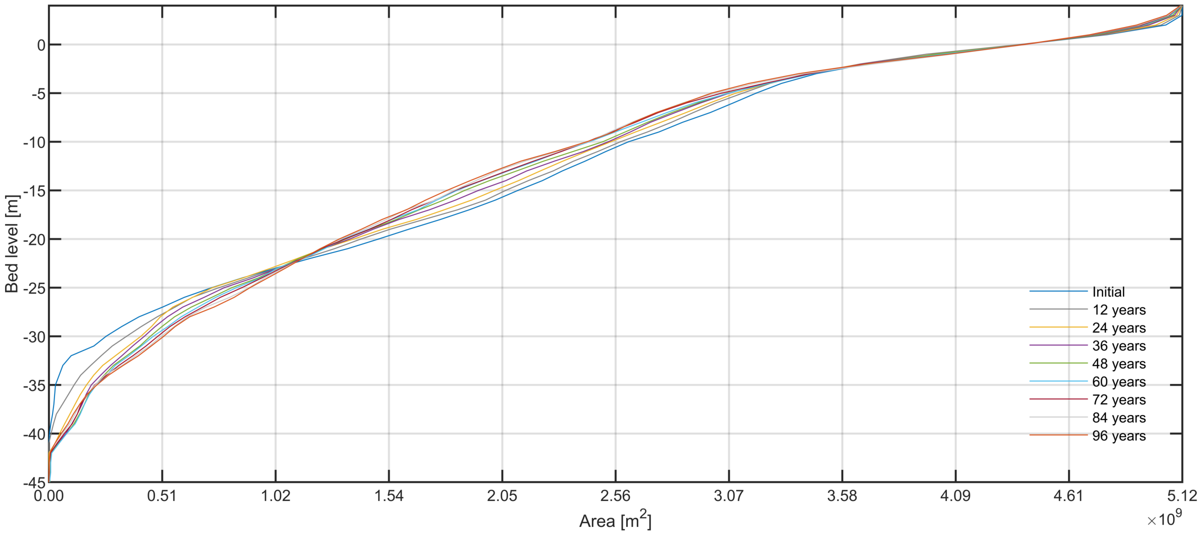


Figure 6.15: Hypsometric curve for the simulation with dam

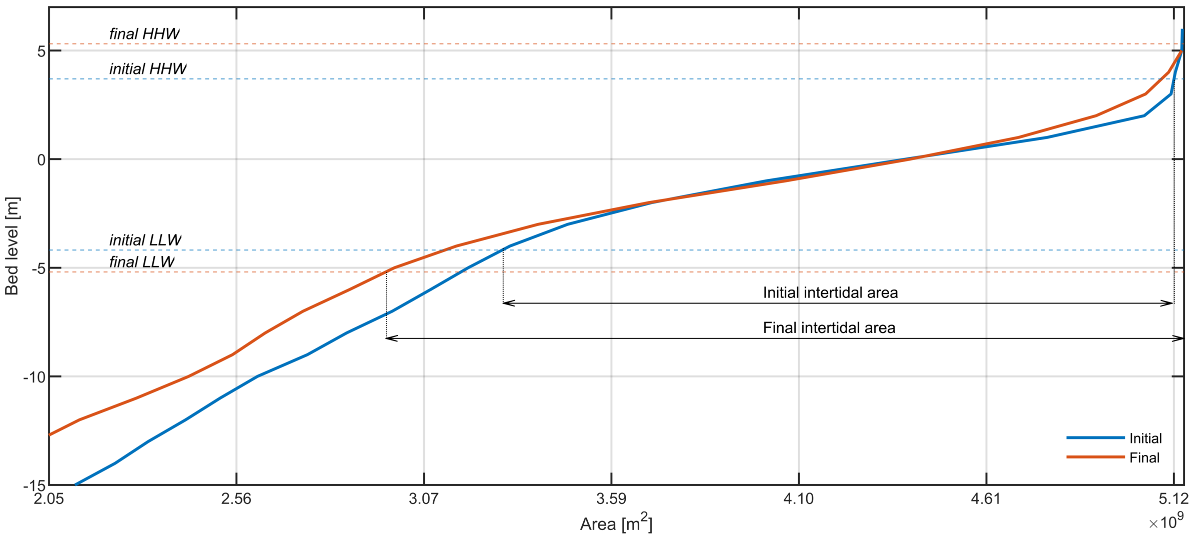


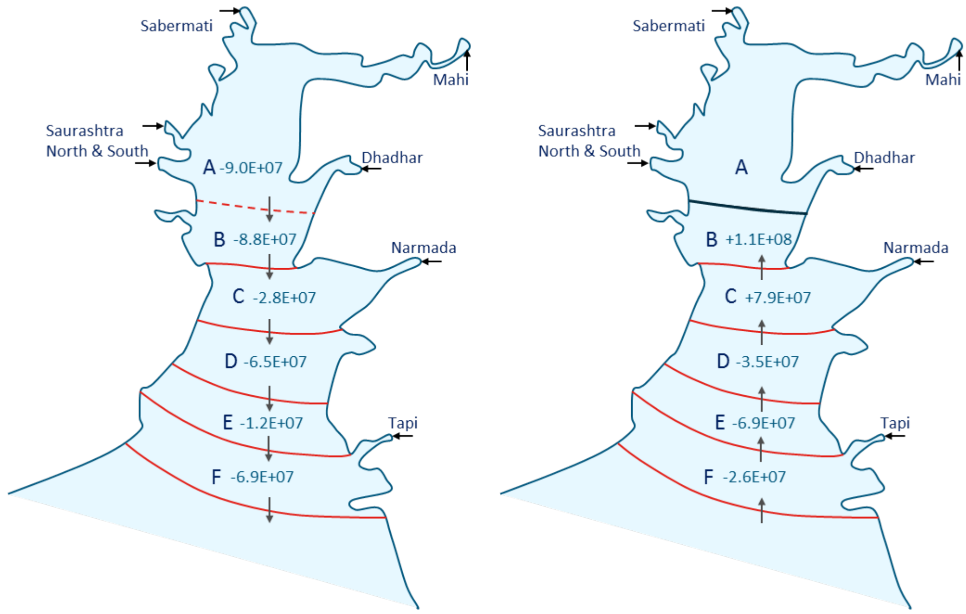
Figure 6.16: Outtake of the initial and final (after 96 years) hypsometric curves, showing the intertidal areas

6.4. CONCEPTUAL MODEL OF THE SEDIMENT BUDGET

The previous section has shown the sedimentation and erosion patterns of the sediment that are predicted by the model. These qualitatively calculations are, at this stage of the research, not without risk given the large number of uncertainties. For instance, with the large model domain the tidal forcing is well included but at the same time it is hard to make predictions with a high certainty at a specific location. In this section therefore the attention is on the quantitative effects of the dam. Thereby, previous results are combined to formulate a more general conceptual model of the total response of the gulf.

As mentioned it is important to get insight in the ability on different size scales to see on which level the model can be used for actual predictions, this because the local effects can be strongly dependent of the set-up of the model. To predict with a higher certainty, the study area in this section is split-up into a number of smaller areas. With the use of the cumulative total transports over the cross-sections between the area we will be looking will be the average deposit in each of these areas. By looking at larger area in stead of one grid location one loses some accuracy in the prediction but increases the certainty of the model result.

The area's are classified based on the locations of interest which will be discussed in more detail in Chapter 7. In Figure 6.17 the area's A, B, C, D, E and F and shown. Each area can be seen as an element whereby transport



(a) Without dam (b) With dam

Figure 6.17: Sediment budget of the study area for the area's A-F, given in m^3 for 96 (morphological) years. Calculated by the cumulative total transports over the cross-sections (red). Sediment inflow by rivers included.

can take place over the boundaries of the element. The left and right bank are assumed as a closed boundary and the rivers as an source of sediment. By looking at the cumulative total transport over the cross-sections which are imposed at the borders of the area's and at the river inflows, it becomes clear if there is a net import or export over the area. Note that the arrows only give information about the direction of the cumulative total transport over the cross-sections, not about the magnitude. The number in the middle of each area gives the netto sum of the fluxes of each area. It is good to mention that this way of presenting doesn't give insight in intern movement of channels of shoals.

Another way to approach the net import of export of the different area's is to look at the difference between the bed level at the begin and the end of the simulation. By averaging the bed level over the width of the gulf one could obtain a 2D impression of the bed level evolution over the gulf after the implementation of the dam. The results are shown in Figure 6.18.

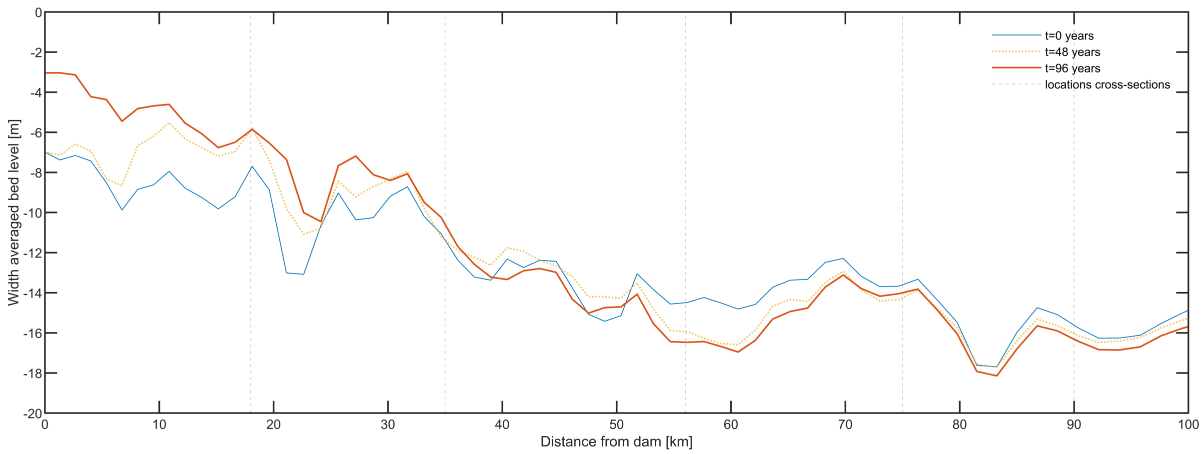


Figure 6.18: Bed level evolution over time for the simulation with dam. The continuous lines represent the bed level at t=0, t=48 and t=96 years, the dotted lines show the location of the cross-sections of Figure 6.17.

7

Potential threats and mitigation measures

7.1. Introduction

In this chapter an answer is given to sub-question 5: *'What are the threats of the hydrodynamic and morphodynamic responses and what possible mitigation measures should be studied in the future?'*. As discussed in the previous chapter, the implementation of the dam will change the tidal conditions in the Gulf of Khambhat (south of the dam). Consequently, the sediment transports in that area will change as well. As a result the dynamic equilibrium between the hydrodynamic forces shaping the bed of the gulf and the present bathymetry is disturbed and the nature will respond with morphological changes in the tidal area south of the dam. These changes will continue until a new dynamic equilibrium is achieved between the changed hydrodynamic conditions and the bathymetry of the remaining part of the the gulf. As stated before, it is anticipated that the total adaptation of the sea bed downstream of the dam will take a long time, but locally the initial response may occur rather fast with possible negative effects on navigation or coastline developments. These effects on the study area are discussed in the following sections.

7.2. Vulnerable locations and potential threats

The study area is introduced in Chapter 2, this area is chosen as such for several reasons. The most important one is the multi-functional use of the area for industry, navigation and coastal development. Within this chapter the focus is on the four most economically and socially important locations of the area: Dahej, Alang, Surat and Hazira.

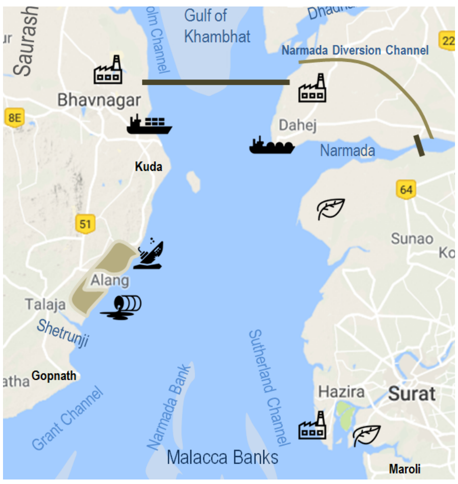


Figure 7.1: General map, retrieved from Google Maps (Google Maps, 2018)

7.2.1. LNG TERMINAL DAHEJ

Indias only Liquid Chemical Port Terminal has two of the three LNG terminals in the country. The present facilities at Dahej contain five jetties and the berths in Dahej are located in a patch. The approach to the port of Dahej is either through the Sutherland Channel, see Figure 7.1, the easternmost channel through the Malacca Banks, or through the Grant Channel, which is the most western channel through the banks. The Grant Channel is the deepest.

The major impact of sedimentation after implementation of the dam will be felt near the entrance of the port of Dahej. The model results presented in Chapter 6 show that the Sutherland channel will partly accrete, as it will become narrower while the east bank will grow. As explained, these results ought to be interpreted qualitatively, so the exact final bed levels are not known thus it is uncertain whether the sedimentation results in unacceptable maintenance dredging volumes. However, it is likely that the sedimentation of the access route will reduce the accessibility of the port.

Besides sedimentation, flooding plays may be a threat for this area as well. In the past flooding of this area mainly occurred when high tide coincided with high discharges of the Narmada river in August and September. The implementation of the Bhadbhut Barrage (dam in the Narmada river mouth, as explained in Chapter 2) changes this situation. High discharges will now be guided through the Narmada Diversion Channel towards the future fresh water lake north of the Khambhat dam. Nevertheless, this does not imply that flooding of the port area is no longer an issue: reflection of the tidal wave against the dam causes a maximum water level increase at Dahej of 1.61 m, as shown in Figure 7.2. The port infrastructure (jetties, structures, etc.) is not designed for the new highest water levels. This may have economically disastrous consequences in the future. The area around the port, which is usually less protected against high water levels, now becomes even flood prone.

Not only the higher high water causes a larger risk in the future but the lower low water as well. Due to the dam the lowest low water decreases with approximately 1 m. So, the minimal depth in front of Dahej will definitely decrease, especially when considering the expected sedimentation. A detailed study on the exact final bed levels near the entrance is required to determine whether the port will still fulfill the requirements on the minimal depth for the draught of the LNG vessels.

7.2.2. SHIP WRECKING ALANG

Alang is a town in the Bhavnagar district in the state of Gujarat. In the past three decades, its beaches have become a major worldwide centre for ship breaking (Hossain, 2006). The shipyards recycle approximately half of all ships salvaged around the world. The yards are located 50 km south-east of Bhavnagar. Large supertankers, car ferries, container ships, and ocean liners are beached during high tide, and as the tide recedes, hundreds of manual labourers move onto the beach to dismantle each ship, salvaging what they can and reducing the rest to scrap. The yard contains broad beaches with highly contaminated material. Due to the increase of the water levels at these beaches, the contaminated sediment is likely to be brought into suspension. Consequently, the water quality in the gulf will deteriorate.

7.2.3. SURAT AND THE CONTAINER TERMINAL OF HAZIRA

The Tapi river surroundings are highly developed areas (Kalpasar Department, 2009), with the industrial area of Hazira extending from the mouth of the river to the city of Surat 12 km upstream. This industrial complex is located on reclaimed area from the Tapi flood plain and has little free-board when the high tide coincides with the flood waters let out of the Ukai reservoir. Any increase in tidal high water would require the setting up of protective flood levees. Similarly the city of Surat is located on the banks of the Tapi and was subject to floods on regular basis until the construction of the Ukai Dam which has substantial flood storage. The protective levees around Surat would therefore require raising, to account for the increase in tidal high water. Just as the port of Dahej the current port infrastructure of Hazira is not designed to deal with the higher high water levels, for example the quay walls of the current container terminal.

7.2.4. OVERALL COASTAL EROSION

Model results show that the basin will act as a sink of sediment after the closure. The ebb-tidal delta will act as the first source of sediment to will in the areas that are now too deep in the basin. If this source is not sufficient, adjacent coastlines will erode to provide the required sand. Note that major sediment sources are closed off by the dam, since six rivers do no longer directly flow into the basin. Moreover, because of the increased highest high water level waves may be able to reach the steeper slopes at the coastlines that surround the gulf. This would result in erosion of a higher part of the coastal profile (Bosboom and Stive, 2015). Consequently a steep cliff would be created and the eroded sediment would be deposited at the lower levels of the profile (Bruun, 1954). This leads to regression of the coast and valuable land may be lost.

7.3. POSSIBLE MITIGATION MEASURES

As discussed, the implementation of the dam may have a significant negative impact on several locations at the study area. Large changes in the coastal zone will always go hand in hand with (negative) effects. It is definitely worth the effort to critically discuss the current design and to attempt to prevent or mitigate its negative effects. To prevent a negative impact, changes may be made on the *loads-side* of the situation, which consists of the hydrodynamic loads that change because of the closure, or changes be made on the *resistance-side*. The latter consists of taking measures to mitigate the threats caused by the new hydrodynamics.

7.3.1. RELOCATE DAM

The only way to generally adapt the hydrodynamic-loads is to adapt the design of the dam, especially its location. As stated in Section 1.1.4, the current design is the outcome of an iterative design process that has been going on for decades. Therefore, it is assumed that the design is not likely to be changed. However, with the aforementioned negative effects in mind it is still interesting to consider if a change in the current design would have an effect on the impacts of this design. To investigate the effect of the location of the dam in the gulf on the hydrodynamic conditions, two alternative locations are tested. Both have a parallel orientation to the dam in the current design. One has a distance from the original dam design of about 15 km inland and the other of about 15 km seaward.

In Figure 7.2 an overview is given of the tidal envelops for the different design options. The locations of the dam designs are shown in the left part of the figure. The tidal envelop for each of those locations is plotted in yellow, blue en red. On the top of the figure the locations of the areas of interest are indicated.

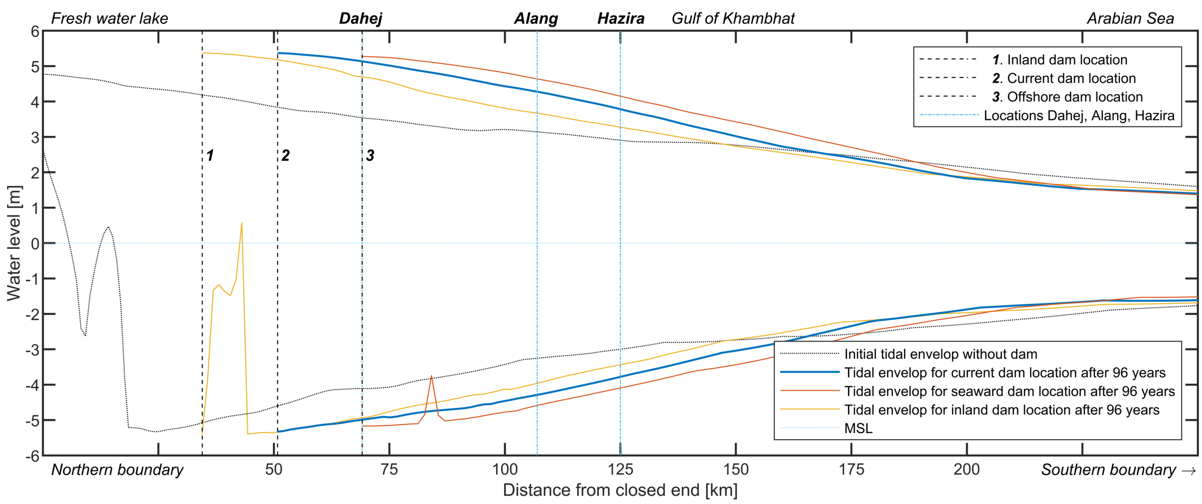


Figure 7.2: Cumulative sedimentation and erosion pattern for the simulation with dam

Regardless of the relocation of the dam, the overall shape of the tidal envelop will remain the same. The maximum and minimum water levels directly in front of the dam stay the same as well. The convex shape of the envelop decreases slightly by moving the dam more northwards. In combination with the lowering of the high water levels, by moving the dam dam more northwards the water levels for all vulnerable areas will lower.

By shifting the dam 15 km inland the high water level at the most important location, Dahej, decreases with 0.62 m. The lowest water level does not seem to change. The water level decrease of more than half a meter seems quite large, however one should consider that the highest high water level will still increase with almost

2 m in the most favourable situation. Moreover, changing the dam location is a major change of the design, that would require a completely new study on the dam to be built. In addition, relocating the dam in landward direction is not an option, since the location of the dam is now based on the minimum rewuired area of the fresh water lake which is needed to counteract the drought problem (Kersten et al., 2017). Besides, because of the minor relative effect on the tidal envelop of a possible relocation of the dam, the expected effect on the morphological changes will be small. Relocating the dam in seaward direction would solve the sedimentation problems at the port of Dahej. In this situation Dahej would namely be located within the closed-off lake. To enable navigation towards the port, locks would have to be implemented in the dam. This may be a relatively costly solution. A cost-benefit analysis is needed, which considers the new design of the dam, the locks and flooding.

7.3.2. DREDGING

The approach of the port of Dahej could be hindered by the expected sedimentation in the approach channel and near the port entrance. The model results presented in this thesis do not provide sufficiently reliable information on the expected final bed levels. So the exact amount of superfluous sediment to be dredged remains unclear. Considering the distinct and strong sedimentation patters at these areas, and the length of the approach channels, the dredging activities are expected to be expensive.

7.3.3. INFRASTRUCTURAL CHANGES

The infrastructure that surrounds the gulf requires major changes to cope with the flood risk introduced by the new hydrodynamic conditions. Large parts of the coastline may need (heightening of the existing) levees for instance. Port infrastructures such as quay walls and other equipment should also be adapted to the new loads as the design water level of these structures is probably much lower.

8
Discussion

This chapter provides a discussion on four levels. First, the methodology is revised and the choices and assumptions in the project definition and in the Delft3D model schematisation are discussed. After this, an additional interpretation of the model results is given. Subsequently, the results of this research are compared to the theory and reference projects. Finally, this research is put into perspective, linking it to the previously executed multidisciplinary technical proposal.

8.1. The research method

8.1.1. Project definition

Initially, the Kalpasar Project of Royal HaskoningDHV was intended to contain five main parts of which one was formulated as follows: “Hydraulics, morphology and water quality issues." This part contains several broad topics and it is not feasible to investigate each of them in detail within the timespan of a MSc thesis. Because of the educational background of the writer of this thesis, it was decided to focus on the effects south of the dam, and to leave a.o. the water-quality issues out of the scope. However, it must be noted that the effects on the closed-off lake is an interesting and essential issue, which should be studied soon. This concerns both the research on the water quality as on the morphodynamic response of the bed. This is elaborated in the recommendations of Chapter 10.

The topic of the hydraulic and morphological response of the system is still too broad. Therefore, a top down approach was chosen in which first, the overall response of the system was determined, after which locations are identified that require further research. This is also done for practical reasons: first of all, there is a lack of detailed data, which hinders detailed small-scale analyses. Furthermore, a basis hydrodynamic model was available at the beginning of this research and it was a logical choice to build on it.

8.1.2. Numerical model

The used morphodynamic model, which is an extended version of the initial hydrodynamic model, provides several opportunities for studies on the gulf. First, the remark should be made that the initial model was basic but clean and clear (consisting of only eight files), which made it suitable to extend. The revised version is now able to reproduce the tidal motion inside the basin quite well. Considering the limited amount of offshore data on the tidal components, a large model domain (that covers several data points) was required to include all of the tidal components and to reproduce the water motion correctly.

Because of the implemented extension, the model is now also able to reproduce sediment transport and morphological changes, which provides several opportunities for morphodynamic studies. Note that due to several assumptions, the results may only be interpreted qualitatively. For insights in quantitative results, a more detailed approach and better data are necessary as elaborated in Chapter 10.

The model, covers a large area, starting offshore of the ebb-tidal delta and reaching the northern land boundary. This makes it a useful tool to obtain a general idea of the large-scale morphodynamic response after the closure. Besides, is has more than acceptable computational times, as it takes about 32 hours to calculate the evolution of a hundred years (with a MorFac of 12). The large coverage of the model also has its downsides. To maintain an acceptable computational time, the grid has to be relatively coarse (3000 x 5500 m offshore and 1600 x 650 m onshore). This makes it impossible to thoroughly study the local changes of individual morphological units, especially offshore. As a rule of thumb, a morphological unit should be covered by at least 8 grid cells to study its behaviour. So channels and shoals that are smaller than around 5 km (in width and length) cannot be researched.

Another assumption is implied in the depth-averaged approach. 3D-processes, like estuarine circulation, tend to be relevant in estuaries. However, this will mostly be the case near the river mouths, where the fresh water meets the saline water from the sea.

Several adaptations are possible to improve the reliability of the model results. As explained, the current lack of data, which is often also outdated, makes it difficult to build an up-to-date realistic model. The implemented initial bathymetry for instance, is mainly composed out of several data sources of which the correctness is doubtful. To cope with this error, an extended morphological spin-up run simulation has been performed. It would be even better to gather detailed bathymetry data in the future. Higher detail modeling requires both a finer grid as well as a more detailed bathymetry.

The calibration of the hydrodynamic boundary conditions could be developed to an absolute optimum. This especially holds for the long-term astronomical constituents of the tide. This requires the hydraulic data from NIOT and the analitical of the water motion, as descibed by Giardino et al. (2014).

The improved model only contains one sediment fraction with a median grain size of 0.162 mm, which is the calculated average value of several bed samples within the study area. The standard deviation of all the grain sizes within the samples has a value of 0.142 mm, which is quite large. At one location grain sizes of 0.030 mm were found, while the largest grains had a median size of 0.540 mm. This shows the importance of the implementation of several sediment fractions in the model. Consequently, the model results will be more realistic, as for instance armouring effects cannot be simulated yet. At this moment, only ten sediment samples are available for an area of 100*100 km, which is insufficient to accurately model the sediment distribution.

Each simulation produces an extensive amount of output data. The time interval of the 1D results (history file, or trih file) is set to 5 minutes for practical reasons. Smaller time intervals would enable a more precise analysis of the output water level and velocities.

8.2. INTERPRETATION OF THE MODEL RESULTS

Numerical models always go hand in hand with a simplification of reality. This is also the case for the Khambhat model. Consequently, it is important to interpret the model results qualitatively: the model is an excellent tool to determine the overall response, but the exact predicted bed level changes could still deviate from reality. Regardless of this, we can learn a lot about the large processes that have an impact on the area. To use the model wisely, expert judgement is needed: during this research a reference case (without dam) is simulated and the results are compared with past trends that can be found in bathymetry maps. This way, it was found that the model predicts an ongoing erosion of the channels (also in the case without the dam), creating unrealistic depths. While bathymetric maps show that the main channel has depths of around 20-30 m (see Figure 2.8), the model predicts ongoing erosion creating much deeper channels. To cope with this, calibration runs are performed. The only measure that turned out to work, was setting a maximum erosion value of 10 m. With this, the channels are forced towards an equilibrium depth of around 35 m. Nevertheless, this forced model artifact has to be kept in mind while interpreting the results.

To wisely deal with the introduced model artifact, the model results have to be interpreted compared to the reference case. Therefore, two almost identical simulations were performed: the only difference is that one run contains the Kalpasar dam while the other does not. This way, the relative effect of the dam is determined, as explained in Section 6.10 for instance. Now, most of the artificial model artifacts are filtered out.
The top down approach has served to identify potentially vulnerable areas, namely: the port at Dahej, the ship wrecking in Alang and the terminals at Hazira. Moreover, overall coastal erosion may become a problem

if the estuary requires more sediment than the outer delta can deliver. The identification of these areas is based on large-scale trends.

During the execution of this research, a new future policy for the Narmada river is accepted by the government (Kalpasar Department, 2017). In this thesis simulations are performed with constant discharge values from the river. However, in the future the river will be dammed by the Bhadbhut barrage, and water will only be released sporadically. Sediment that originates from the river will accumulate in front of the barrage (river side) (HaskoningDHV, 2010). Sporadically, the gates of the barrage will be opened, quickly flushing the accumulated sediment (*flush regime*).

To determine the consequences of the Kalpasar dam, all other forcing factors that may vary in the future are not taken into account in the model. This implies, that the effect of (relative) sea level rise has not been determined, as it is not within the scope of the research. Yet it is stated that this will certainly influence the morphodynamics of the basin on the long term, unless the expected infilling of the basin is able to keep up with sea level rise. However, this is unlikely since only the northern part of the basin will fill in, while the remaining part is erosive.

8.3. COMPARISON WITH THEORY AND REFERENCE PROJECTS

In Chapter 2, a literature review is summarised, which contains theoretical knowledge on tidal basins, sediment transport and closures. This chapter contributed to an understanding of the methods and concepts of the thesis. In this section, the model results are compared to the theory to identify the similarities and differences. Hereby, it is explained whether this case fits into the domain to which some theories are valid and why this is the case.

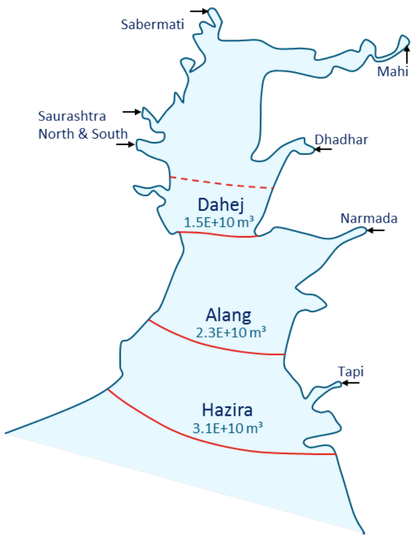
If we look at the hydrodynamic classification of tidal basins as established by Davis and Hayes (1984), it is remarkable that the domain for which this classification is established does not cover the studied case of the Gulf of Khambhat (see Figure 2.2): after implementation of the dam, the tidal range will often exceed the value of 8 m. The classification suggests that the basin will then be tide-dominated and the model results confirm this. Simulations where waves are included show that the wave influence on the hydrodynamics and morphodynamics remains limited in comparison with the influence of the tide.

The morphological response of the basin after construction of the closure dam corresponds with the expected changes based on the new tidal conditions in the basin. In Section 2.2.3 it was explained that net sediment transport is often related to asymmetries of the tidal signal. A flood-dominant signal leads to basin infilling, while ebb-dominance will result in overall sediment export in case of coarse sediment (sand). The simulation results are in agreement with this theory, showing that the sediment transport in the basin is largely determined by asymmetries (skewness) of the horizontal tide.

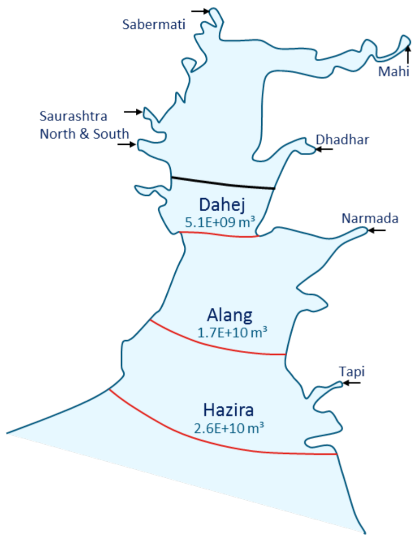
As explained in Section 2.2.2, several empirical relations exist that describe the stability of the morphological units of a basin. When a dynamic equilibrium situation is disturbed because of a man-made closure, morphological adjustments will take place until the system adapts itself towards a new equilibrium state. One of the aforementioned empirical relations concerns the relation between the tidal prism and the ebb tidal delta, which was first derived for outer deltas in the USA, see equation 2.1. This equation relates the volume of the outer delta to the tidal prism and to a coefficient that is dependent on the wave climate. Previous studies show that this relation also holds for Dutch tidal basins, such as Borndiep, Marsdiep and Vlie (Bosboom and Stive, 2015). It would be interesting to determine whether this relation also holds for the case of the Gulf of Khambhat. However, it is not clear what the exact volume of the outer delta is, which hinders this analysis. Moreover, to determine the tidal prism of the basin first the offshore borders of the basin have to be determined, since the relatively exposed gulf does not have a clear inlet or mouth in between barrier islands for instance.

Nevertheless, a first estimate of the tidal prisms at several locations of the basin is shown in Figure 8.1. This figure shows the volumes of water that flow in and out during a (mean) tidal cycle through the marked cross-sections at Dahej, Alang and Hazira. Because of the Kalpasar dam, the tidal prism near Dahej will reduce with 64.8%. This reduction will decrease with increasing distance from the dam: at 26.2% at Alang and 15.3% at

Hazira. From the decrease in tidal prism, it is expected that the volume of the ebb-tidal delta will also decrease. If we look at the simulated sediment budget of Figure 6.17 we see that the seaward part of the gulf indeed does erode. Whether the exact relation of equation 2.1 also holds for this case, remains unstudied.



(a) Without dam



(b) With dam

Figure 8.1: Tidal prisms at several location for the situation without dam and directly after constructing the dam

The former Haringvliet and Grevelingen estuaries in the Southwest Netherlands have both been closed for tidal flow by the Dutch Delta Works (Wang et al., 2009). The Haringvliet was closed off by sluices that only allow fresh river water flowing out of the estuary, thus the basin became a fresh water reservoir. Because of the disappearing of the tidal flow, accumulation of fluvial sediment occurred in the closed-off basin. At that time, the quality of the fluvial sediment was poor, resulting in the current presence of polluted sediments in the bottom of the basin. This forms an environmental problem (Wang et al., 2009). The Kalpasar dam may have a similar effect on the closed-off basin in the Gulf of Khambhat. Although this dam does not contain sluices, it will allow the fresh water to flow into the sea in case of high water levels in the basin. The tidal flow will also be completely absent. Given the facts that water pollution of the rivers that flow into the basin is already a severe problem (Katakwar, 2016) and that the water temperatures are significantly higher that in The Netherlands, pollution in the basin is likely to be a future problem.

8.4. LINK WITH THE INTERDISCIPLINARY RESEARCH PROPOSAL

As explained in the introduction of this report, this thesis is part of a larger interdisciplinary project that is the a result of a collaboration between Royal HaskoningDHV and three Dutch Universities. The objective of this project is to develop a business case to generate attention to the project and identify opportunities and threats. The result of the kick-off phase was an interdisciplinary technical research proposal in which several key factors have been identified. A key factor determines the feasibility of the project and the extent of success or failure of these factors are crucial. The formulated key factors are: keeping costs low, generating a high revenue and mitigating environmental risk (Kersten et al., 2017). Mainly the latter is directly linked with the outcomes of this thesis. The model results show that the change in hydrodynamics and morphodynamics after implementation of the dam will increase the flood risk and may cause sedimentation problems in several areas. Moreover, coastal erosion might be a problem. Now, it is crucial to determine the exact impact of these risks and especially which mitigation measures are most suitable, to successfully generate the business case. In addition, it is necessary to account for the economical and social aspects of the project as defined in the research proposal (Kersten et al., 2017).

9

CONCLUSIONS

In this chapter the answer is given to the main question of this research: *'What is the impact of partly closing off the Gulf of Khambhat with the Kalpasar Dam on the hydraulics, morphodynamics and user functions of the remaining tidal basin?'*. This question can be split up into several parts. In this chapter each sub-question is answered separately.

What are the present conditions without dam concerning hydrodynamic forcing, sediment properties and bathymetry?

Gulf of Khambhat is an inverted funnel shaped basin on the west coast of India. It has a surface area of several hundred square kilometres and it is one of the dynamic natural basins and having high tidal range. The entire gulf is relatively shallow compared to the Arabian Sea, with a maximum water depth of about 30 m. The complex geography of the gulf amplifies the tidal range to about 10 m, while the tidal currents are about 3 m/s.

The bed samples taken in the study area originate from the end 90s. They are composed of mainly fine silty sand and fine sand. Near the Malacca Banks mud is found. Several bathymetry maps are found of the Gulf of Khambhat. However, the correctness of most of the maps is doubtful. For instance: the official Admiralty Standard Nautical Charts, normally worldwide considered as reliable, is assembled of six different sets of data, originating between 1837 and 1990.

How does the original hydrodynamic Khambhat-Delft3D model perform and what adaptations are required to investigate the morphodynamic response of the gulf?

Deltares and *NIOT* have provided a two-dimensional (2DH) numerical model of the Gulf of Khambhat to study the tidal propagation in the basin. This model is a basic hydrodynamic model that makes use of the FLOW-module of Delft3D. Thirteen Astronomic components were used to apply the forcing at the sea boundary. At this open boundary the type Riemann boundary conditions are imposed at 16 segments, at one segment the condition water level is imposed. The rivers in the model are set as a discharge; localised discharges of water at a certain position in the grid (respectively m, n).

Two out of three measured tidal signals at the study area do not show a good agreement with the calculated signals of the model. The calculated signal for Hazira, the most offshore station within the study area, is actually one-on-one in line with the measured tidal signal at this location. However, the northern two calculated signals in the gulf do not show this agreement. Although the shape of the semi-diurnal tide matches the measured signal quite well, the water level does not seem to be amplified enough. Before converting the model into a morphodynamic tool, the hydrodynamic model needed to be calibrated and validated. The strong parts of the model are kept unchanged while the weaker points require extra attention. Several settings have been changed to this end.

The revised version is able to reproduce the tidal motion inside the basin quite well. To this end, the initial bathymetry has been adapted, at the river boundaries the conditions have been changed into water level boundary conditions, and extra rivers have been added. It is concluded that the new bathymetry was the main contributor to the improved tidal signal. This bathymetry is obtained by first combining data of C-map and Delft Dashboard and implementing this as an initial bathymetry in the model. Subsequently, this has been smoothened with an extensive spin-up simulation. Two files have been added to the to model to extend it from a hydrodynamic to a morphodynamic model. The sed-file contains the sediment properties: the final sediment fraction used as input of Delft3D is a d_{50} of 0.162 mm. This is an averaged value of the top layers of the different sediment samples. With the mor-file the sediment transport properties are defined. Sediment transport rates are calculated with the formula of Engelund Hansen, and bed level changes are upscaled with a MorFac of 12. Because of the implemented extension, the model is now also able to reproduce sediment transport and morphological changes, which provides several opportunities for morphodynamic studies. Note that due to the several assumptions, the results may only be interpreted qualitatively. For insights in quantitative results a more detailed approach and better data are necessary.

What is the change of the tidal conditions and what will be the effect on the hydrodynamic forcing?

To deal with the introduced model artifacts, the model results are interpreted compared to the reference case. Therefore, two almost identical simulations are performed: the only difference is that one run contains the Kalpasar dam while the other does not. This way, the relative effect of the dam is determined. The implementation of the dam causes a significant change of the tidal conditions. The tidal range increases to an extend of about 100 km southwards of the dam. Close to the dam the tidal range increases with 2.4 m, from 7.88 m to 10.25 m, and after 96 years even to 10.50 m. The highest high water level increases, from the situation without dam: +3.70 to +5.21 after the initial response to +5.31 m after 96 years. For the lowest low water these levels are respectively: -4.18 m, -5.04 m and -5.19 m.

As expected, the maximum current speed during ebb and flood change as well. Close to the dam the initial maximum speed becomes 1.5 m/s northwards and 1.0 m/s southwards. Seawards the initial maximum speed becomes 2.5 m/s northwards and 1.75 m/s southwards. In the case without dam those are respectively 2.25, 2.75 and 2.0, 1.75. For both locations holds that $u_{max,\ flood}>u_{max,\ ebb}$, what indicates an net flood transport where there is an net ebb transport in the situation without dam at almost the entire study area. During the simulation of 96 years the maximum current speeds changes, both northwards and southwards. Close to the dam tide becomes more flood dominant, more seaward the tide becomes less, but still, flood dominant.

Overall the tidal range increases with the implementation of the dam. The observed velocities around the dam at the location of the former channels become negligible. The velocities at the main western channel significantly decrease, and subsequently so to the bed shear stresses. The large eastern channel remains the main channel of the gulf, although it maximum flood- and ebb-velocities also decrease.

What are the short and long term morphodynamic responses of the system?

The short term morphodynamic response of the system shows two main distinct developments. After the implementation of the dam the study area becomes flood dominant and starts importing sediment directly. The area of 10 to 50 km in southward direction of the dam shows the most clear sedimentation. Subsequently, the existing channel becomes narrower at first. At the same time, the main channel becomes deeper, but reaches its maximum depth of around -35 m within approximately 30 years.

On the long term, the area upto 40 km southward of the dam partly fills in. The area in front of the dam clearly fills in during the simulation: the area with a distance of 5 km and less from the dam starts to accrete strongly after six decades. The southwestern part of the gulf seems to be the most dynamic area. The alternation between channel (and bar) formation and deformation is visible for the entire simulation. The main channel in the middle of the gulf preserves its location after implementation of the dam. Its final depth is, however, still unclear: the simulation results suggest that the channel does not become any deeper than 35-40 m, but this may be the result of the model settings. When looking at the relative response of the system one could even conclude that the eastern side of the channel will accrete. The channels that discharge the outflow of the Narmada river keep their dynamic character, in which the location of the bifurcation changes.

What are the threats of the hydrodynamic and morphodynamic responses and what possible mitigation measures should be studied in the future?

The implementation of the dam may have a significant negative impact on several locations at the study area. Four vulnerable locations are identified, namely Dahej, Hazira, Surat and Alang. These are the most important locations of the area on economic and social point of view. Accretion of the bed near the LNG terminal of Dahej, is very likely to hinder the accessibility of the approach channel. Besides, flooding may be a threat because of the increased maximum water levels. The jetties are not designed to withstand the new highest water levels. The latter also holds for the quay wall of the container terminal at Hazira. Near Hazira, the city of Surat is located on the banks of the Tapi river. The increase in tidal range will cause an increase in maximum water levels at this city, for which the levees need to be raised. Due to the increase of the water levels at these beaches of the ship wrecking Alang, heavily contaminated sediment will be brought into suspension. Consequently, the water quality in the gulf may deteriorate.

The basin will act as a sink of sediment after the closure. The ebb-tidal delta will act as the first source of sediment to fill in the areas that are now too deep in the basin. If this source is not sufficient, adjacent coastlines will erode to provide the required sand. Moreover, because of the increased highest high water level waves may be able to reach the steeper slopes at the coastlines that surround the gulf. This would result in erosion of a higher part of the coastal profile. Concluding, coastal erosion is likely to be a problem after construction of the dam.

Relocating the dam is not an effective measure to prevent the negative impacts. Maintenance dredging activities will probably be required to maintain the accessibility of the ports. Moreover, major infrastructural changes will be needed to prevent floods.

10

RECOMMENDATIONS

In this chapter, recommendations for further research are presented, which follow from the results, discussion and conclusions of this research. First, recommendations are given on the usage and improvement of the Khambhat Delft3D model. Subsequently, recommendations are given on further studies about the Gulf Khambhat.

10.1. THE KHAMBHAT DELFT3D MODEL

- The model that has been used to obtain the results of this research is a useful tool to get an idea of the general morphodynamic response of the gulf as a consequence of the closure. The results of a simulation with dam have to be interpreted relatively to a reference case without a dam, in order to minimize the introduced model artifacts. Note that the model is not suitable for small-scale studies of specific locations or morphological units (e.g. shoals and channels). These studies would require an increase of the local grid resolution and bathymetry detail by nesting fine grids for instance.

- Several improvements can be made to the model by adjusting its input. This research only accounts for one sediment fraction, namely sand with a median diameter of 0.162 mm. Data was found of ten bed samples, which showed a great variety in sediment size. However, this could not be implemented in the model, since the amount of data was too limited to create an initial sediment distribution map. Model results are likely to be more realistic when implementing the sediment variations. To this end, first more data needs to be gathered on the sediment distribution in the study area. The same holds for the bathymetry: a detailed map of the current bathymetry is required to improve the initial bathymetry of the model.

- Ideally, the morphological predictions of the model would be calibrated and validated. An extensive sensitivity study on several model parameters would lead to more accurate model results. However, bathymetric data of several years is needed to do this and this data has not been found yet. It is not clear of this data exists, but according to Giardino et al. (2014), *NIOT India* has recently measured the bed levels in the Gulf for instance. Therefore, it is recommended to look into the potential data sources on this.

- NIOT India has an improved version of the hydrodynamic model that has been used in for this research (Delft3D-FLOW). As stated in the paper of Giardino et al. (2014) the model of NIOT can well represent the tidal amplification at the measuring stations. Unfortunately, this model was not available for this study, but it is highly recommended to use the Delft3D-FLOW NIOT model for further research. This model can be coupled to the morphodynamic part that has been developed during this research.

- This study has mainly focussed on the tide as a hydrodynamic driver, since this is the forcing mechanism that will mainly change because of the closure. For a better representation of reality, it is advised to also implement surge levels and wind- and wave-forcing.

10.2. FURTHER RESEARCH ON THE GULF OF KHAMBHAT

- It is highly recommended to partner up with other parties during further studies on the closure of the gulf. Deltares, for instance, already did a quite specific study on a jetty in the Narmada delta near Dahej. Moreover, it is expected that local parties have much more data of the study area. The Government of Gujarat and the EAG (Expert Advisory Group) are main stakeholder with a lot of political power and a large network. They probably know, who has the most accurate and up-to-date data. Moreover, local universities also have ongoing research about the gulf.

- Several locations have been pointed out as vulnerable areas because of the closure, namely: Hazira, Dahej, Surat and Alang. Many will be prone to flooding and coastal erosion is also likely to be a problem because of the sand hunger of the basin. Besides the accessibility of several ports may be hindered because of large sedimentation rates at the entrance channels. The morphological model used in this study is not accurate enough to study the exact response at these locations. Therefore, it is recommended to execute follow up studies with more detailed tools. It is for instance desirable to make a proper inventory of the potential loss of valuable land due to coastal erosion. To this end, it is recommended to create local morphological models with much finer grids and to nest them in the large-scale model that covers the entire gulf.

- Note that this study only covers the morphological response of the system downstream of the dam. However, major changes are also expected at the upstream part. Cases as the closures of the Haringvliet and the Grevelingen show that the water quality of the new lake will probably be poor (Wang et al., 2009). This also depends on the water quality of the river run-off and industrial waste water that will be disposed in the lake. It is advised to do a follow-up study on potential new water-quality problems. Moreover, this part of the dam will also experience morphological changes. The tidal force, that is probably the main mechanism to build up the intertidal flats, will disappear. Locally generated waves will still remain and will erode the flats. So as a first estimate, it is expected that the intertidal areas will flatten out and a large part may even disappear (Wang et al., 2009). However, it is recommended to study this with a morphodynamic model.

- Besides construction of the Kalpasar dam, another part of the Kalpasar Project is the *Bhatbut Barrage project*. This project involves the damming of the river mouth and the flood plains of the Narmada river. The river discharge will be reduced so does the source of sediment, what has a large impact on the area. Therefore, the flush regime of the dam needs to be studied further.

- The Gulf of Khambhat is frequently affected by tropical cyclones. These extreme events may be disastrous of they coincide with the new maximum water levels after implementation of the dam. Therefore, it is recommended to do a follow up study on this. This does also hold for tsunamis. The consequence of sea level rise in combination with the new tidal range should also be studied.

Bibliography

BMT ARGOSS. Waveclimate.com: The on-line offshore climate assessment system.

Bosboom, J. and Stive, M. J. (2015). *Coastal Dynamics 1: lecture notes CIE4305*. Delft Academic Press - VSSD.

BritishAdmiralty (1980). Admiralty Chart 1486.

Bruun, P. (1954). *Coast erosion and the development of beach profiles*. U.S. Beach Erosion Board, [Washington].

Carter, R. G. (1988). *Coastal environments : an introduction to the physical, ecological, and cultural systems of coastlines*. Academic Press.

Davis, R. A. and Hayes, M. O. (1984). What is a Wave-Dominated Coast? *Developments in Sedimentology*, 39:313–329.

De Vriend, H. J. (1991). Mathematical modelling and large-scale coastal behaviour. *Journal of Hydraulic Research*, 29(6):727–740.

Deltares (2014a). Delft3D-FLOW, User Manual.

Deltares (2014b). Delft3D-WAVE. Simulation of short-crested waves with SWAN. User Manual. Hydro-Morphodynamics. *Delft3D Modeling Suite*, pages 1–226.

Dronkers, J. (2005). *Dynamics of Coastal Systems*, volume 25 of *Advanced Series on Ocean Engineering*. WORLD SCIENTIFIC, Singapore.

Eelkema, M. (2013). *Eastern Scheldt inlet morphodynamics*. PhD thesis, Delft University of Technology.

Elias, E. (2006). *Morphodynamics of Texel Inlet*. Phd, Delft University of Technology.

Ferdowsi, B., Ortiz, C. P., Houssais, M., and Jerolmack, D. J. (2017). River-bed armouring as a granular segregation phenomenon. *Nature Communications*, 8(1):1363.

Giardino, a., Elias, E., Arunakumar, a., and Karunakar, K. (2014). Tidal modelling in the Gulf of Khambhat based on a numerical and analytical approach. *Inchoe014*, 2014(Figure 1):5–7.

Haskoning (1998a). Pre-feasibility study report Volume 1: Executive Summary, Main Report. Technical report, Haskoning - Consulting Engineers and Architects.

Haskoning (1998b). Pre-feasibility study report Volume 2: Hydraulic Conditions, Geotechnical Conditions, Dam Design, Tidal Power. Technical report, Haskoning - Consulting Engineers and Architects.

HaskoningDHV, R. (2010). Narmada Barrage Project. Technical Report Annexure 8.

Hayes, M. O. (1980). General morphology and sediment patterns in tidal inlets. *Sedimentary Geology*, 26(1-3):139–156.

Hossain, M. (2006). Ship Breaking -Towards Sustainable Management Ship Breaking Activities and its Impact on the Coastal Zone of Chittagong, Bangladesh.

Kalpasar Department (2009). EAG report - Gulf of Khambhat Development Project (W.R.). Technical report, Kalpasar Department.

Kalpasar Department (2017). Expression Of Interests for Bhadbhut Barrage. Technical report, Kalpasar Department.

Katakwar, M. (2016). Narmada river water: Pollution and its impact on the human health. *International Journal of Chemical Studies IJCS*, 66(42):66–70.

Kersten, R., de Jong, H., and Rajeev, D. (2017). Project Proposal: Kalpasar, India. Technical report, Delft University of Technology, Royal HaskoningDHV, Delft, Netherlands.

Klaassen, G. (1999). Specific Studies - Volume V. Technical report, Haskoning - Consulting Engineers and Architects.

Koch, F. and Flokstra, C. (1980). *Bed level computations for curved alluvial channels.* Delft Hydraulics Laboratory, Delft, Netherlands.

Lesser, G. (2009). *An Approach to Medium-term Coastal Morphological Modelling.* Phd, UNESCO-IHE Institute for Water Education.

Ocean Imaging (2013). Corporate Profile. *Ocean Imaging.*

Qi, S. (2012). *Use of International Hydrographic Organization Tidal Data for Improved Tidal Prediction.* Phd, Portland State University.

Ranasinghe, R., Swinkels, C., Luijendijk, A., Bosboom, J., Roelvink, D., Stive, M., and Walstra, D.-J. (2009). Morphodynamic upscaling with the MorFac Approach. pages 1–7.

Sathish Kumar, S. I. I. o. T. B. and Balaji, R. I. I. o. T. B. (2015). Tidal Hydrodynamics along Gulf of Khambhat, West Coast of India. *Elsevier*, page 8.

Schuurman, F. (2015). *Bar and channel evolution in meandering and braiding rivers using physics-based modeling.* Phd, Utrecht University.

Schuurman, F., Ta, W., Post, S., Sokolewicz, M., Busnelli, M., and Kleinhans, M. (2018). Response to peak discharge in braiding Yellow River. *Earth Surface Processes and Landforms*, 1662(March):1648–1662.

Shah, T. S. E. K. D. (2008). Minutes of the 6th meeting of the Expert Advisory Group (EAG). Technical report, Kalpasar Department.

Stive, M., Tran, T., and Nghiem, T. (2012). Stable and unstable coastal inlet cross-sectional behaviour. In *International Conference on Estuaries and Coasts.* Hydraulic Engineering Department, Delft University of Technology.

Stive, M. and Wang, Z. (2003). Morphodynamic modeling of tidal basins and coastal inlets. *Elsevier Oceanography Series*, 67:367–392.

Talmon, A., Struiksma, N., and Van Mierlo, M. (1995). Laboratory measurements of the direction of sediment transport on transverse alluvial-bed slopes. *Journal of Hydraulic Research*, 33(4):495–517.

Tung, T. T. (2011). *Morphodynamics of seasonally closed coastal inlets at the central coast of Vietnam.* PhD thesis, TU Delft.

Unnikrishnan, A., Shetye, S., and Michael, G. (1999). Tidal propagation in the Gulf of Khambhat, Bombay High, and surrounding areas.

Van Rijn, L. C., Roelvink, J. A., and Ter Horst, W. (2001). Approximation formulae for sand transport by currents and waves and implementation in DELFT-MOR.

Walton, T. and Adams, W. (1976). Capacity of inlet outer bars to store sand. In *Fifteenth Coastal Engineering Conference Proc*, pages 1919–1937, Honolulu.

Wang, Z., de Ronde, J., van der Spek, A., and Elias, E. (2009). Responses of the Dutch coastal system to the (semi-)closures of tidal basins.

Wang, Z., Hoekstra, P., Burchard, H., Ridderinkhof, H., De Swart, H., and Stive, M. (2012). Morphodynamics of the Wadden Sea and its barrier island system. *Ocean and Coastal Management*, 68:39–57.

Wang, Z. B., Jeuken, C., and Vriend, H. J. D. (1999). Tidal asymmetry and residual sediment transport in estuaries.

List of abbreviations

Abbreviation	*Meaning*
2DH	two-dimensional in the horizontal plane
3D	three-dimensinal
ADI	alternating direction implicit (method)
CD	Chart Datum
d.a.	depth averaged
EAG	Expert Advisory Group
HHW	highest high water
IHO	International Hydrographic Organization
LLW	lowest low water
LNG	liquefied natural gas
MDF	master definition flow file
MDW	master definition wave file
MHHW	mean high high water
MHW	mean high water
MHWN	mean high water neap
MHWS	mean high water spring
MLLW	mean low low water
MLW	mean low water
MLWN	mean low water neap
MLWS	mean low water spring
MorFac	morphological acceleration factor
MSL	mean sea level
NIOT	National Institute of Ocean Technology

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APPENDICES

A

BATHYMETRY AND HYDROGRAPHIC CHARTS

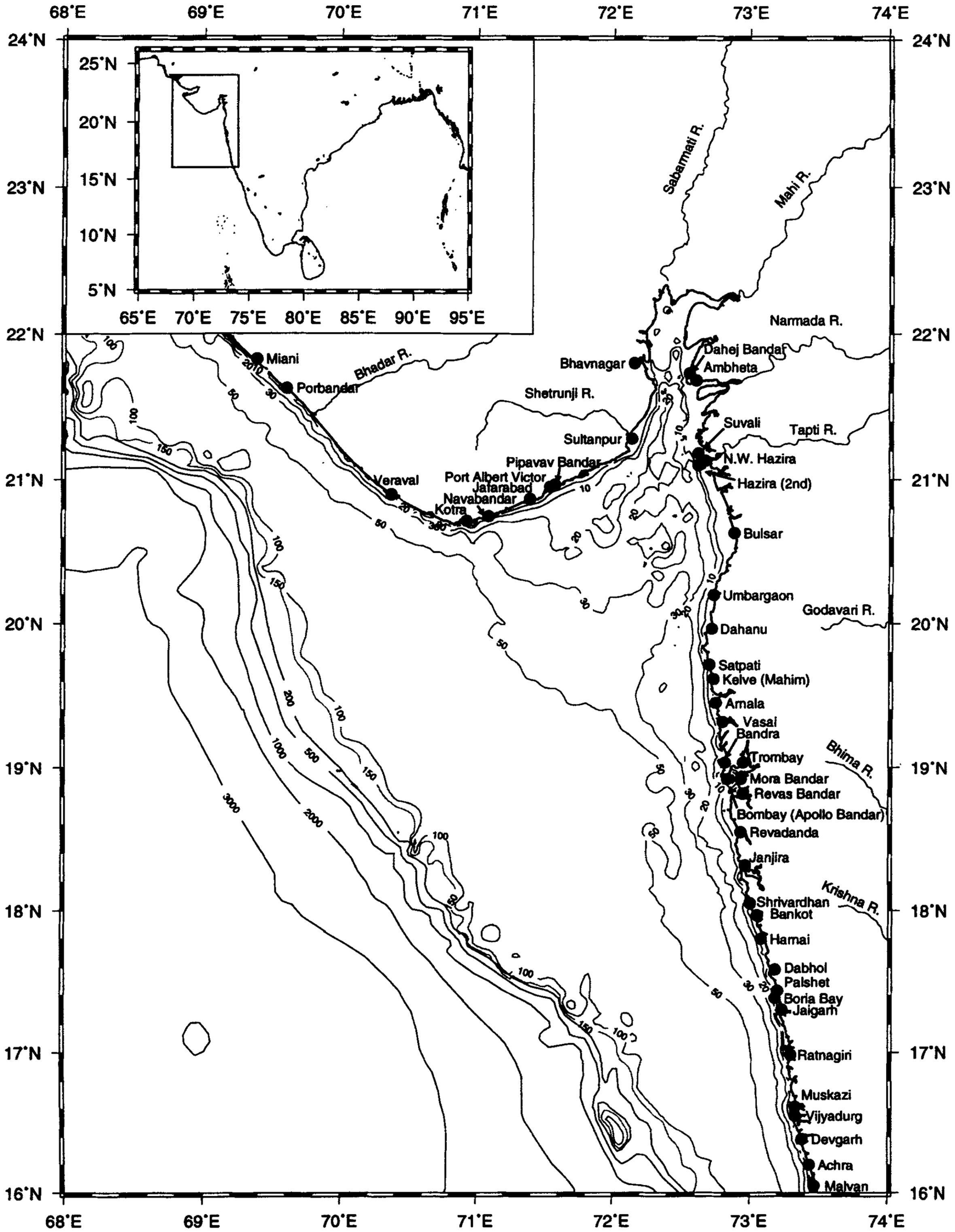


Figure A.1: Map of the Gulf of Khambhat, Bombay High, and surrounding areas (Unnikrishnan et al., 1999)

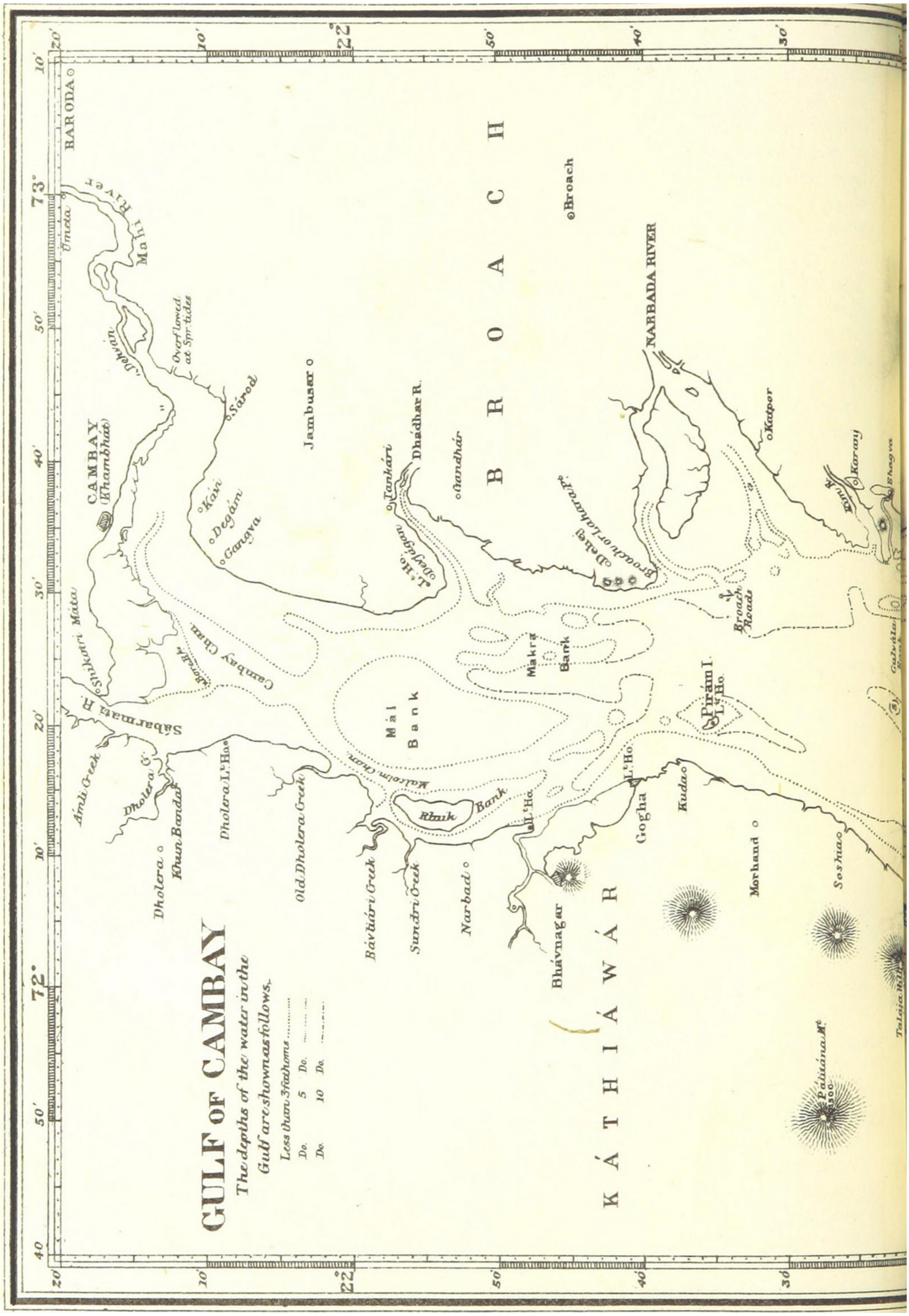


Figure A.2: Indian Naval Hydrographic Chart 208 - North (Klaassen, 1999)

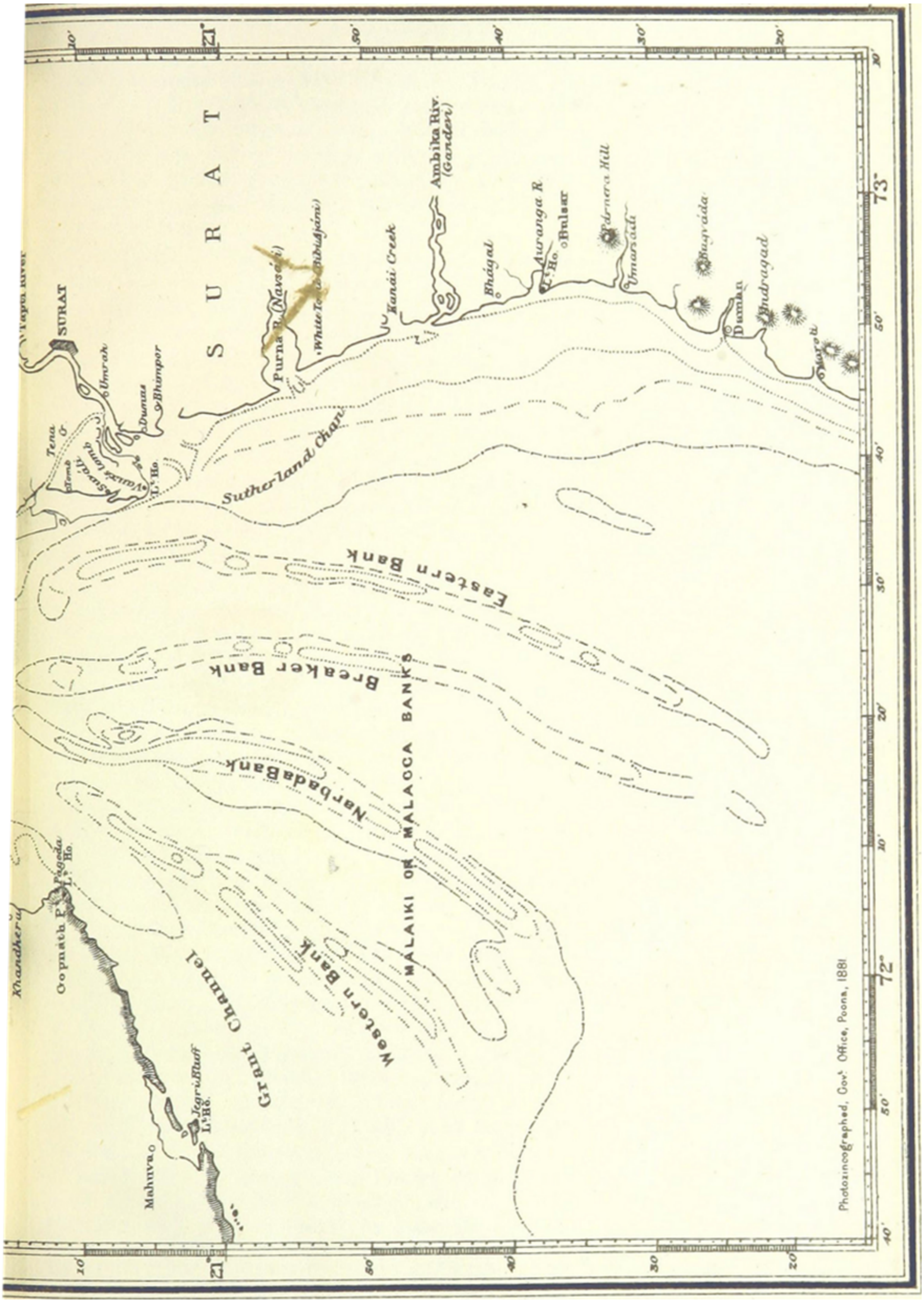


Figure A.3: Indian Naval Hydrographic Chart 208 - South (Klaassen, 1999)

B
Bed samples

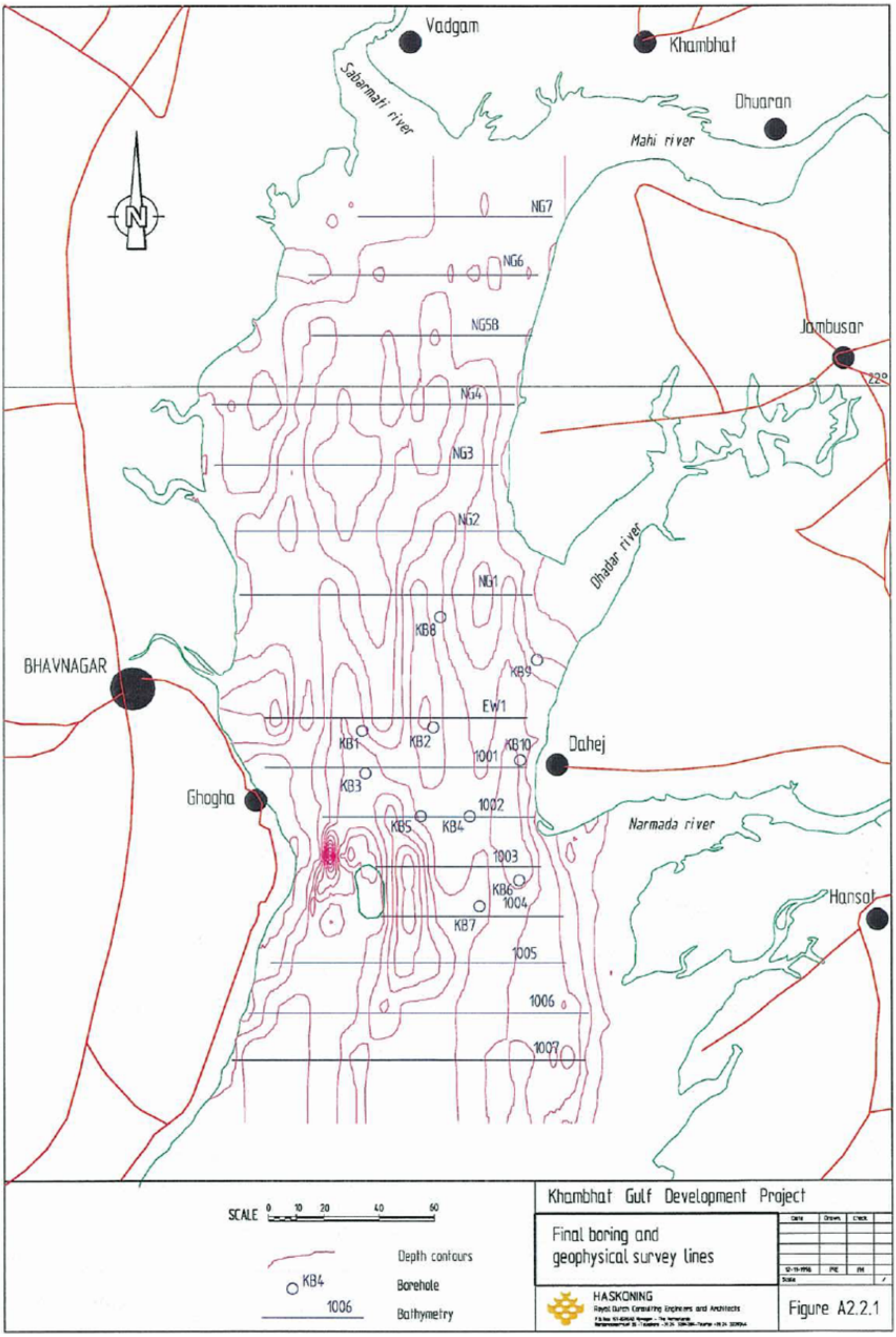


Figure B.1: Final boring and geophysical survey lines (Haskoning, 1998b). The dots indicate the locations of the boreholes of Figures B.2 and B.3.

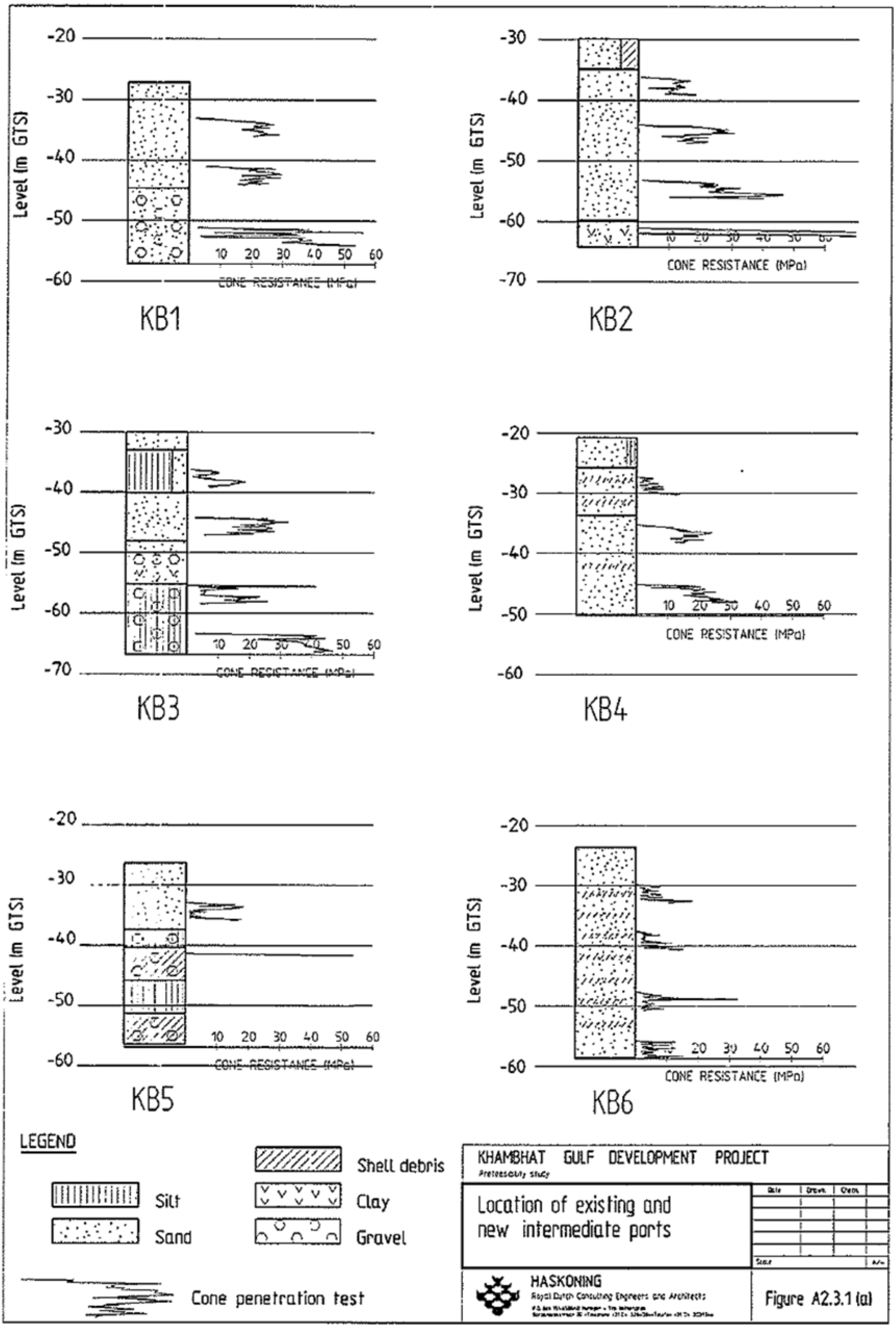


Figure B.2: Results borehole investigations and CPT testing (1) (Haskoning, 1998b)

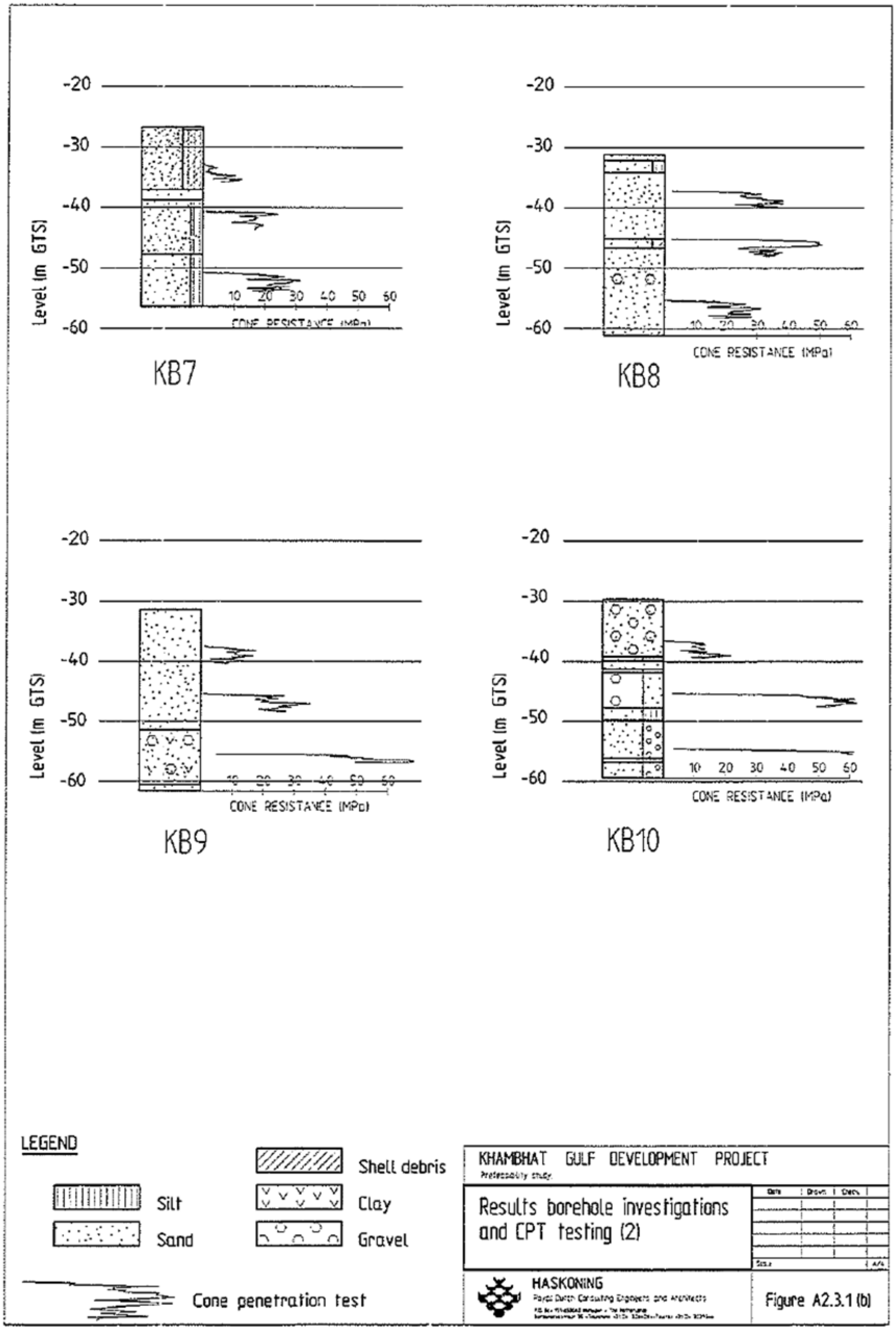


Figure B.3: Results borehole investigations and CPT testing (2) (Haskoning, 1998b)

C

Tides and wave climate

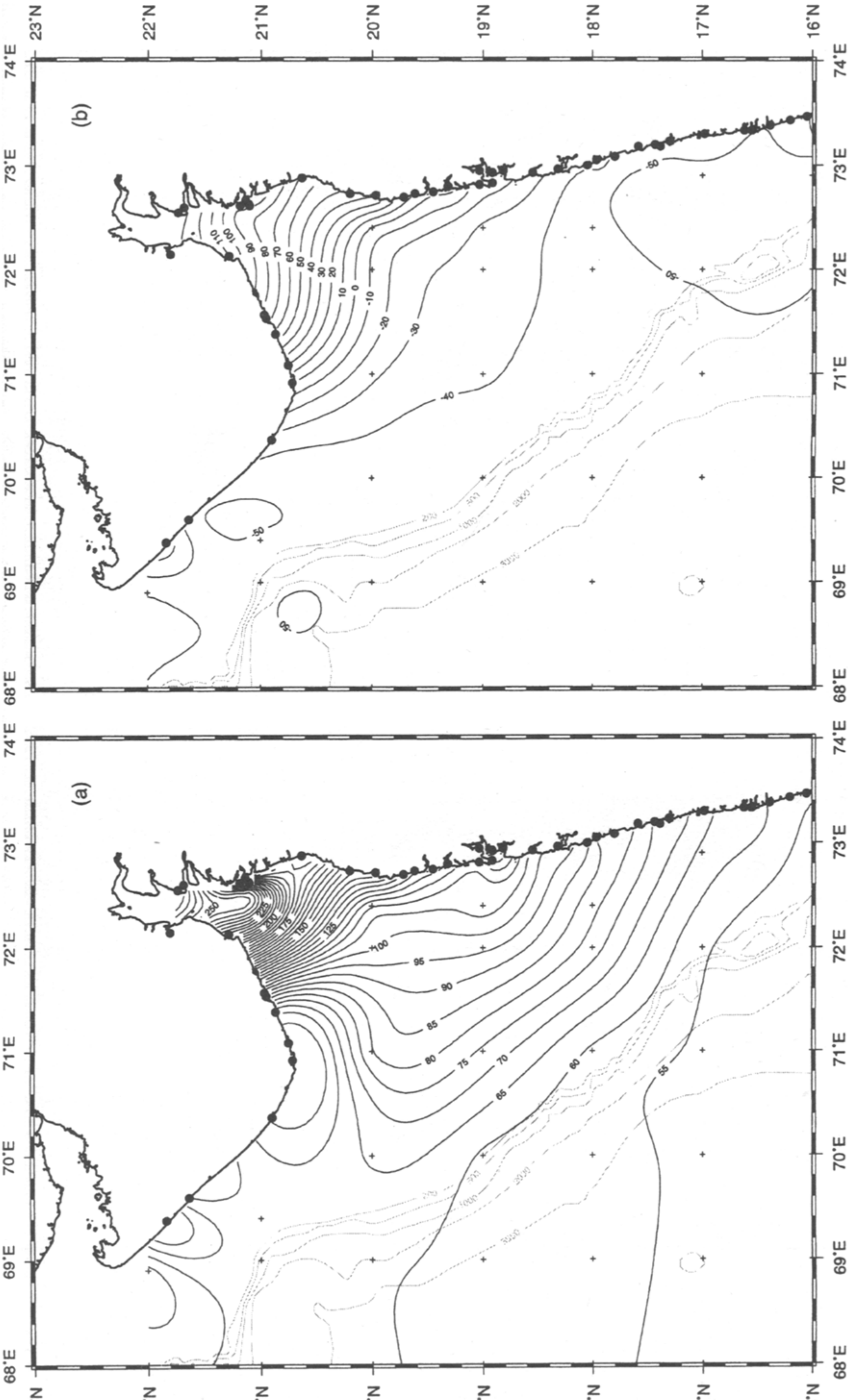


Figure C.1: (a) Amplitude (cm) and (b) phase (degrees) of tidal constituent M2 (Unnikrishnan et al., 1999)

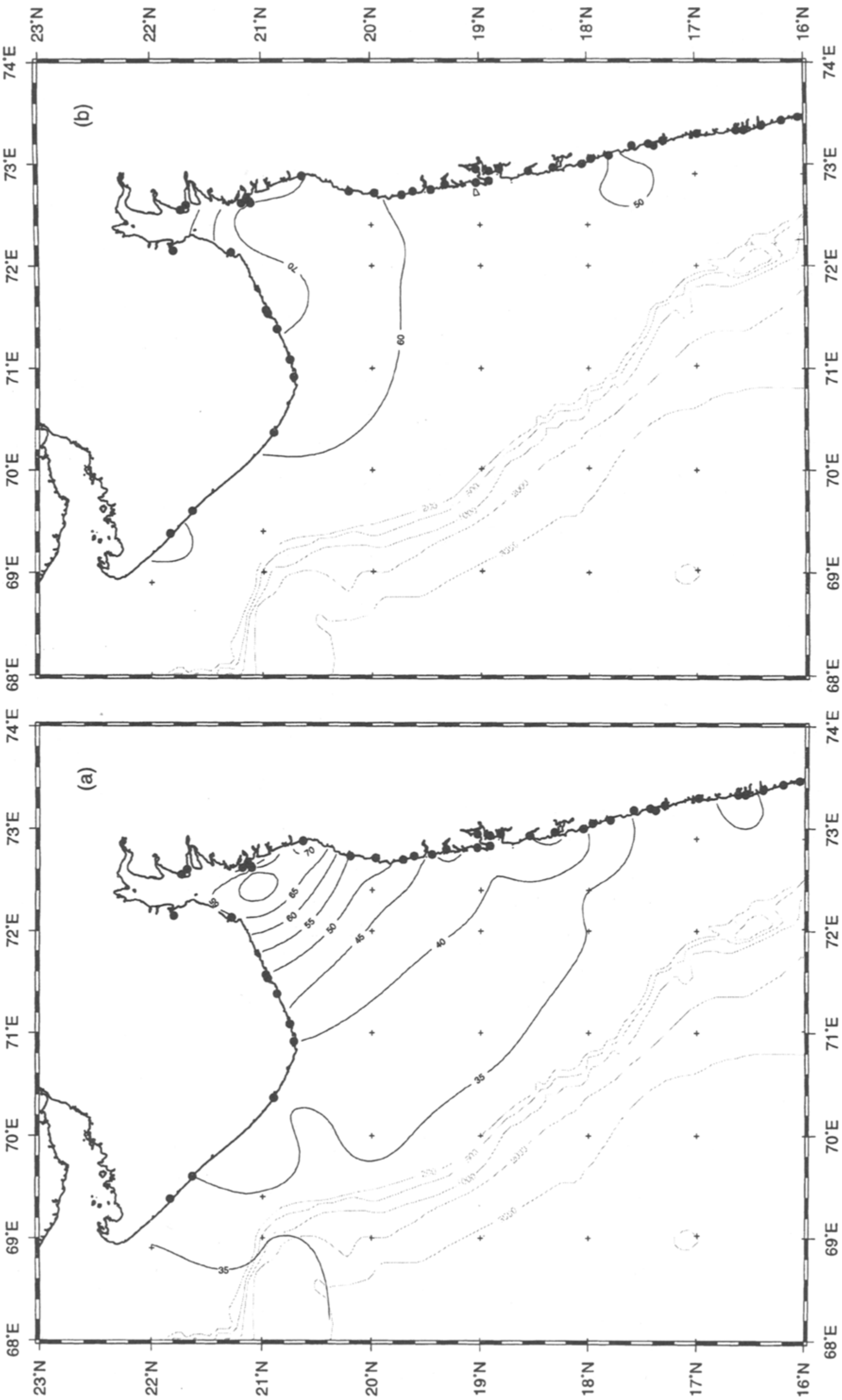


Figure C.2: (a) Amplitude (cm) and (b) phase (degrees) of tidal constituent K1 (Unnikrishnan et al., 1999)

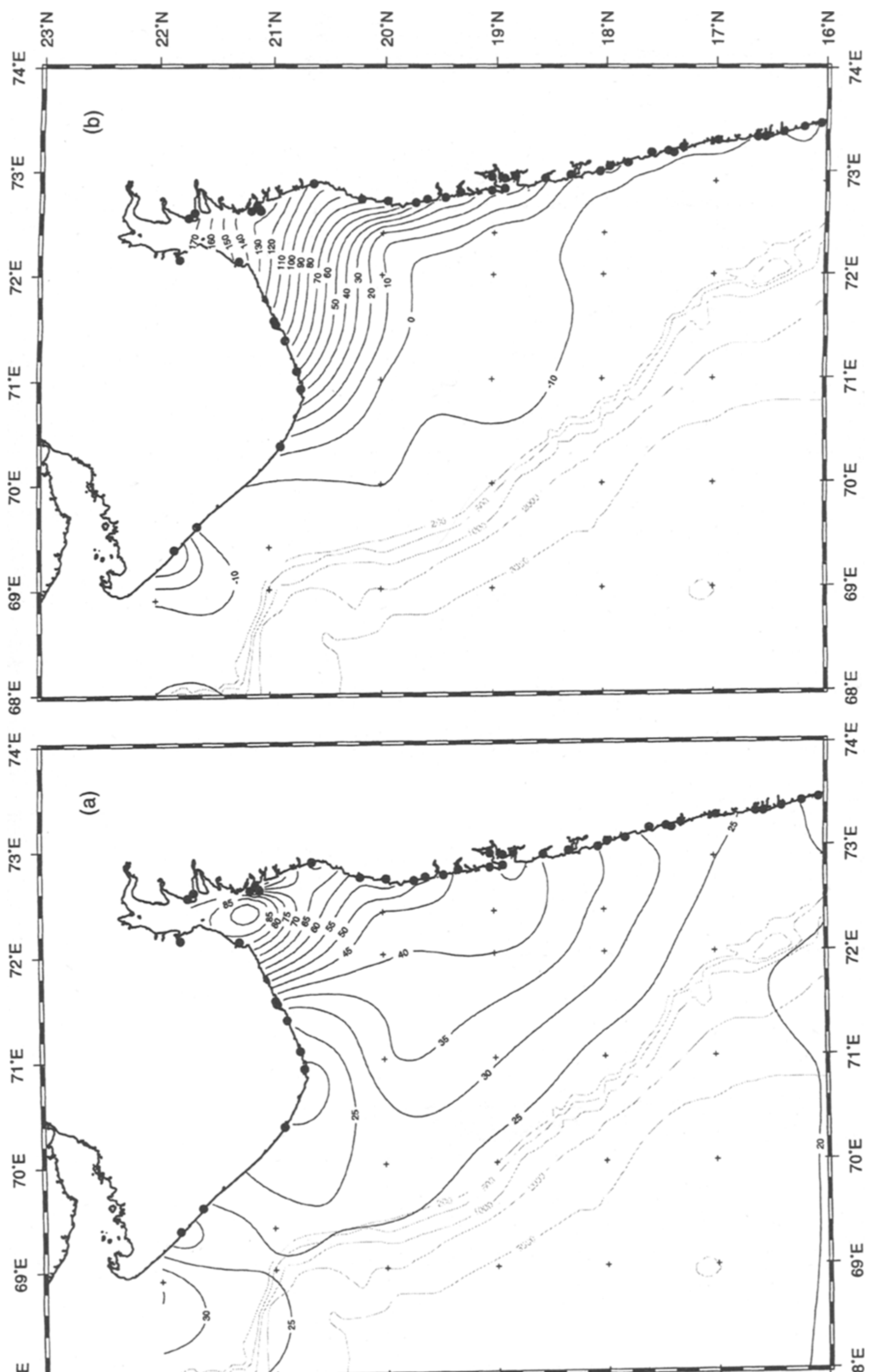


Figure C.3: (a) Amplitude (cm) and (b) phase (degrees) of tidal constituent S2 (Unnikrishnan et al., 1999)

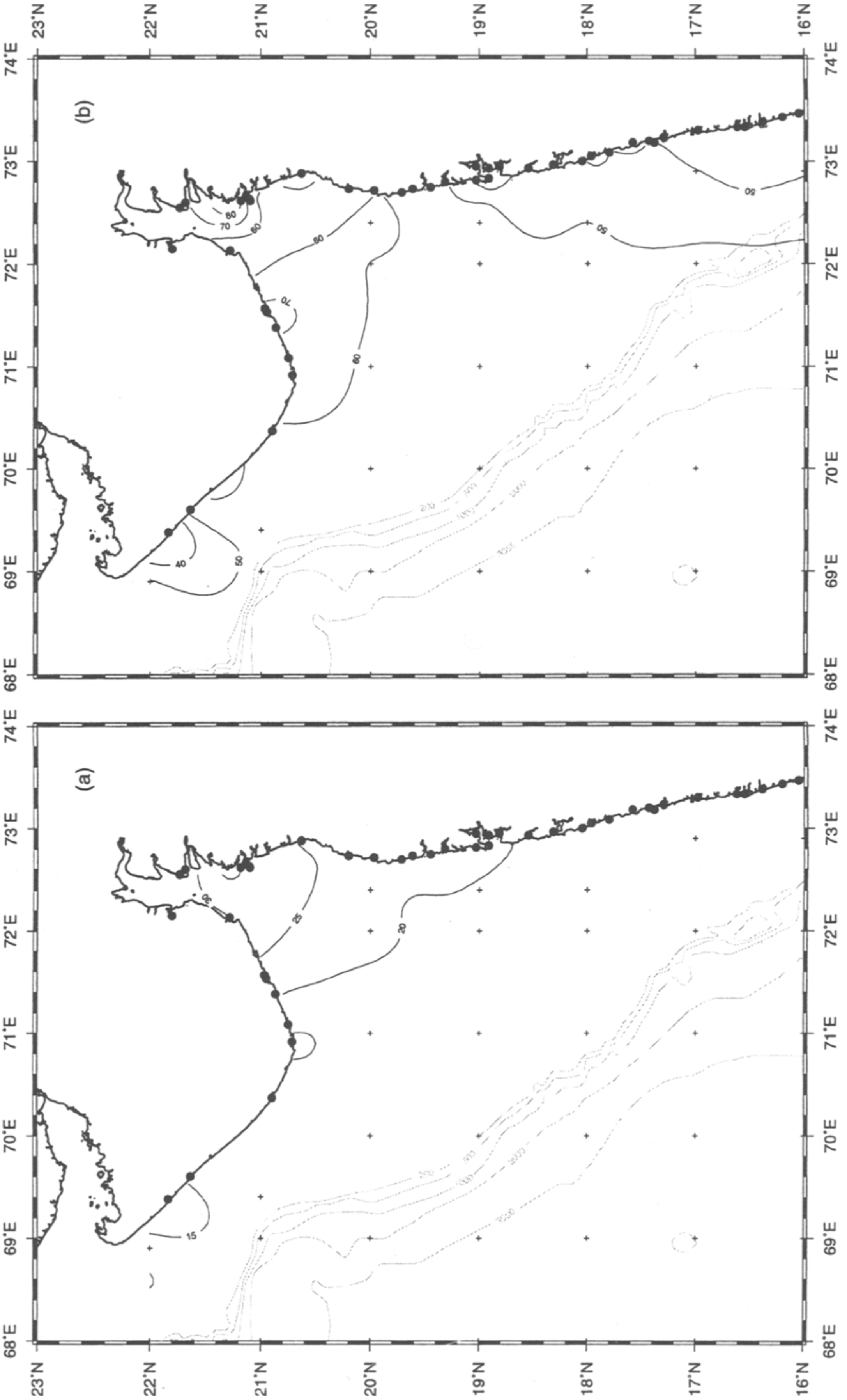


Figure C.4: (a) Amplitude (cm) and (b) phase (degrees) of tidal constituent O1 (Unnikrishnan et al., 1999)

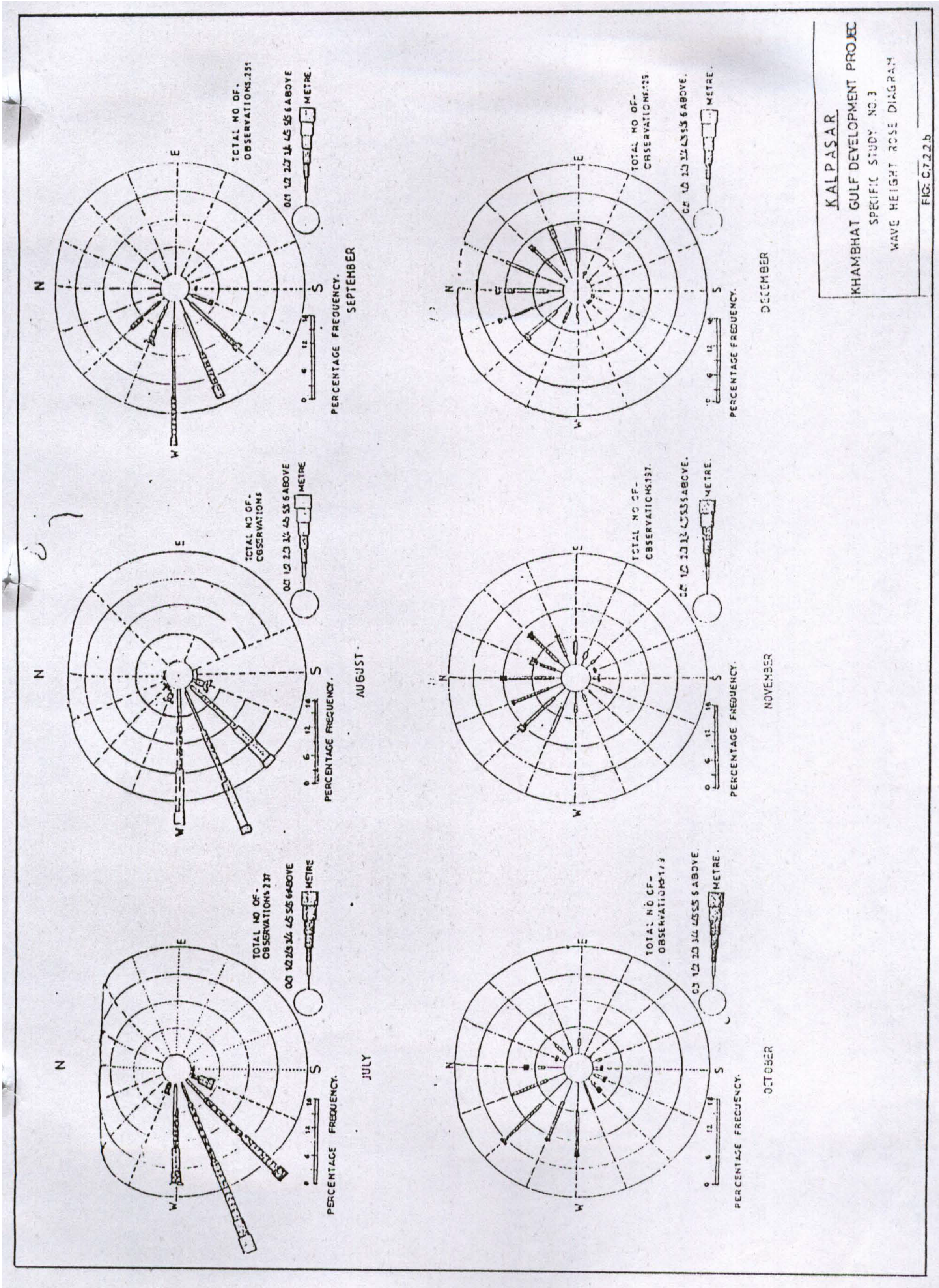


Figure C.5: Wave height rose diagram (Klaassen, 1999)

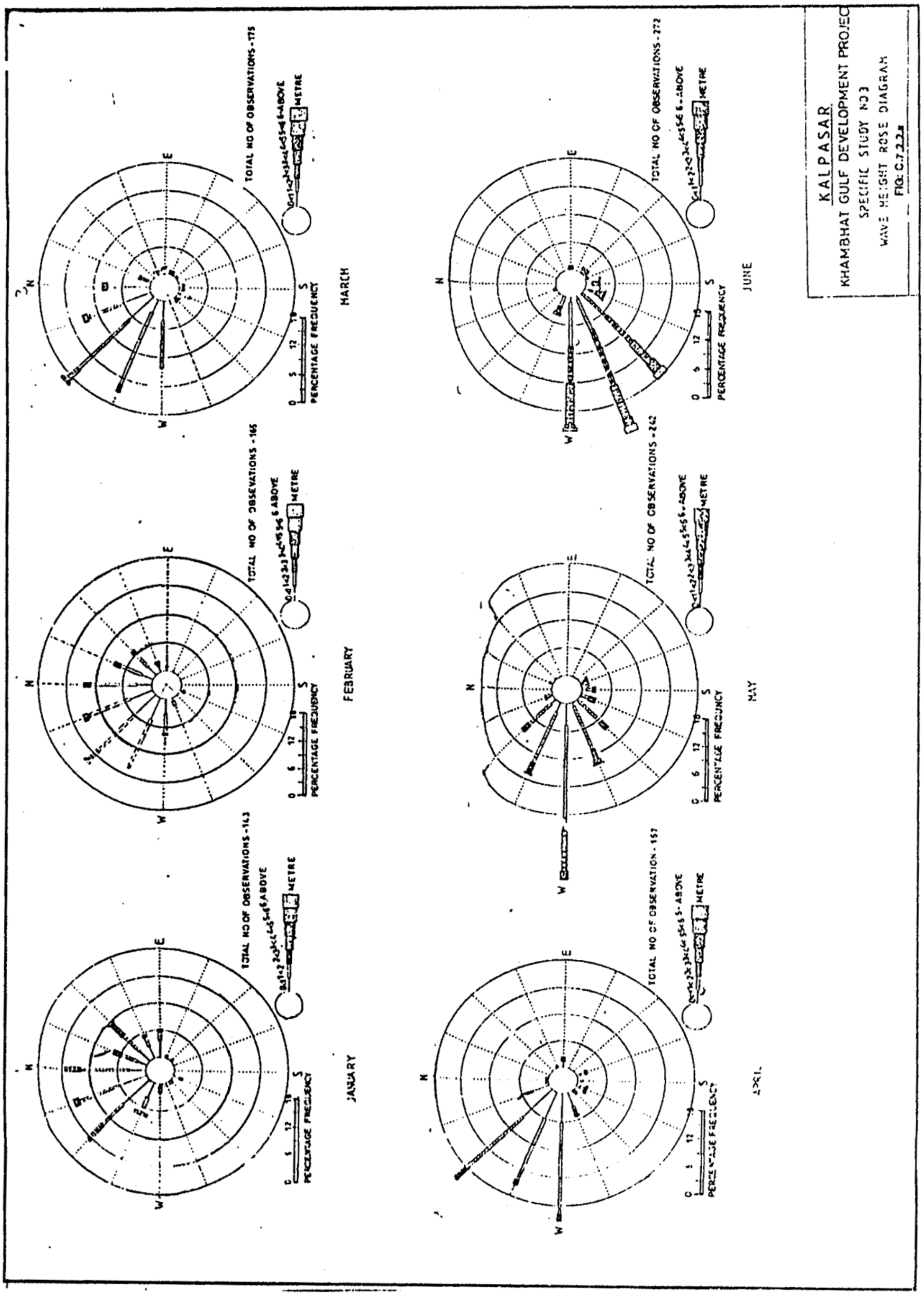


Figure C.6: Wave height rose diagram (Klaassen, 1999)

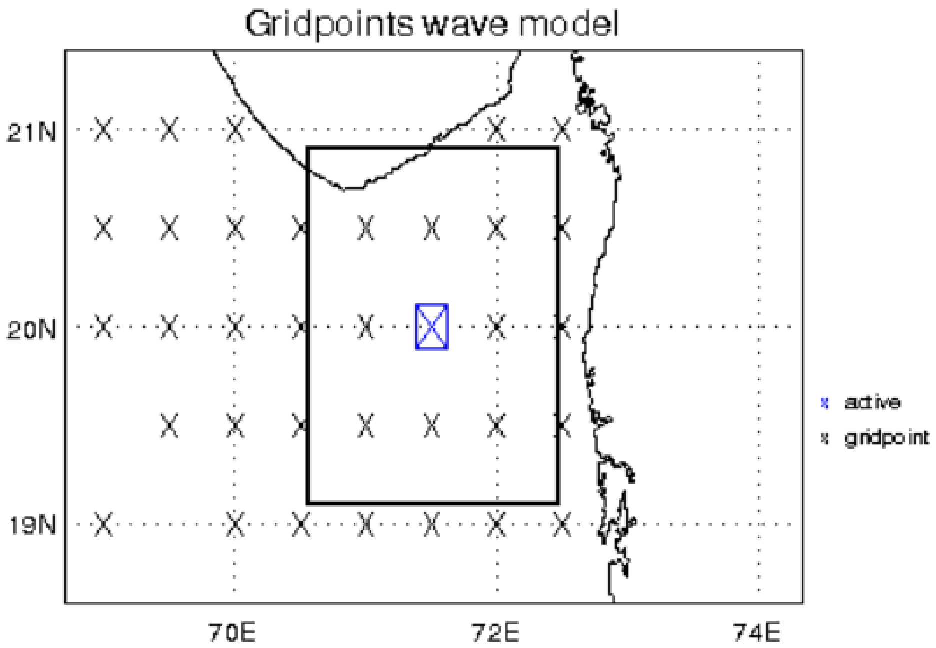


Figure C.7: Grid point wave model at sea (BMT ARGOSS)

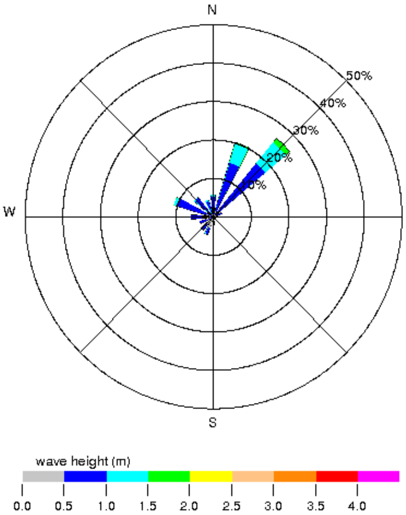
Table C.1: Location grid point (BMT ARGOSS)

Offshore location	20° 00'N, 71° 31'E
Offshore model point	20° 00'N, 71° 30'E
Size of offshore area for satellite data	200 x 200 km

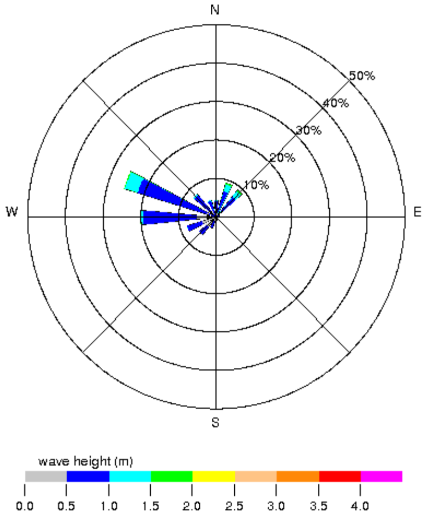
Model output point is 20° 00'N, 71° 30'E
First and last year analysed 1992-2016
Variables are wave height (m) and wave direction (deg)
Data source is wave model
Results are based on 6200 model records
Direction convention is "coming from"

Warning:

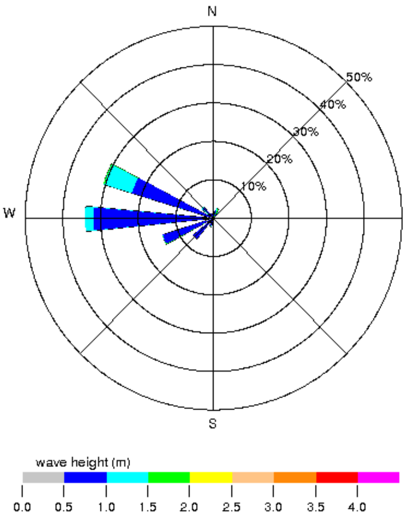
Tropical storms are known to occur in this area. These storms are not properly represented in the wind and wave climate data on this page. Tropical storms and their effects should always be analysed separately based on data of storm tracks and intensity. This data is not included in the waveclimate.com database.



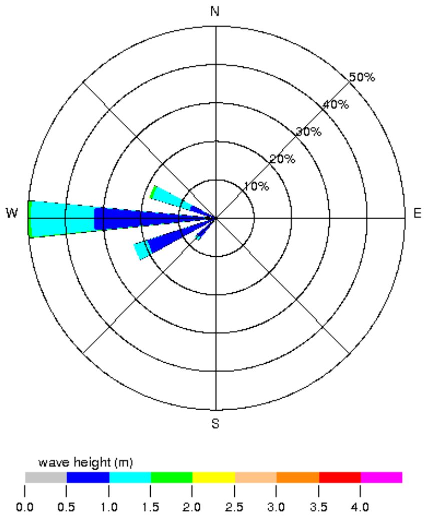
(a) January



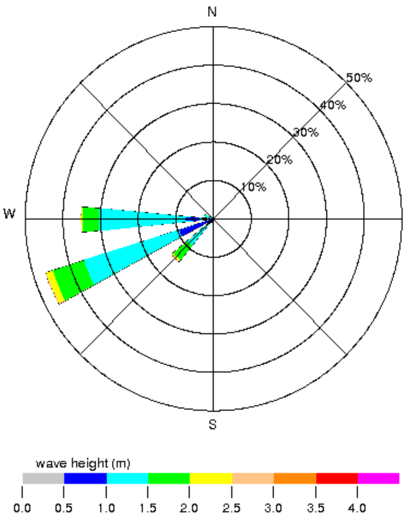
(b) February



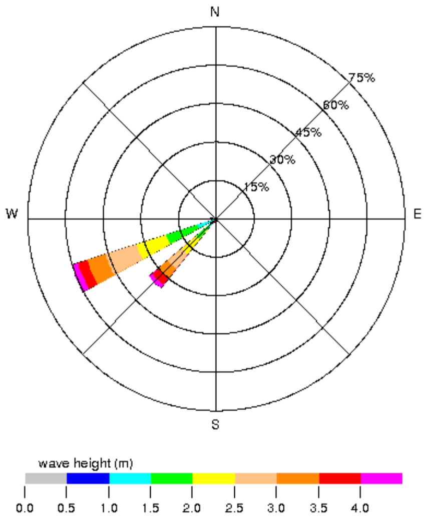
(c) March



(d) April

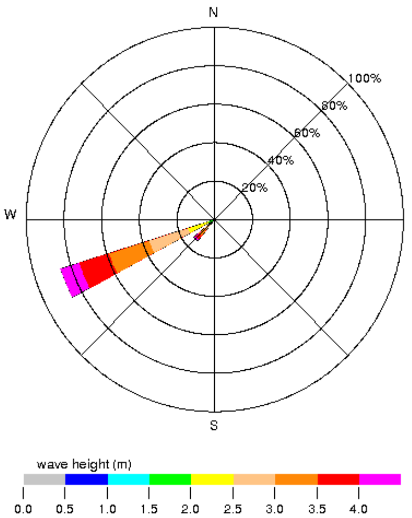


(e) May

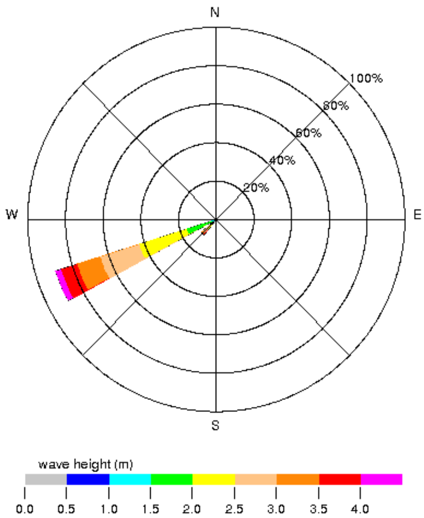


(f) June

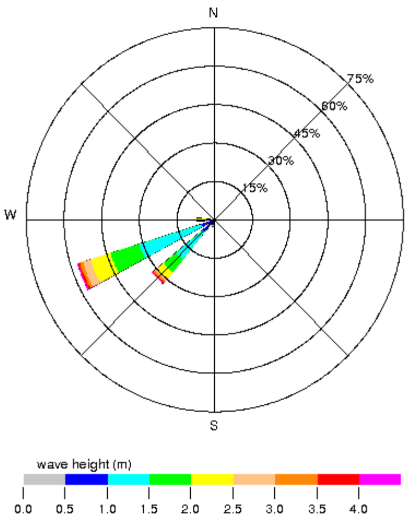
Figure C.8: Wave height rose diagrams January - June (BMT ARGOSS)



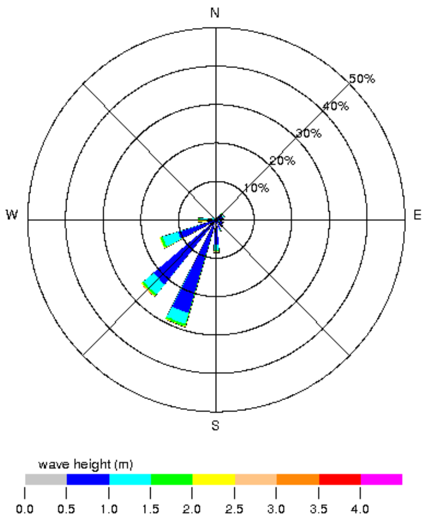
(a) July



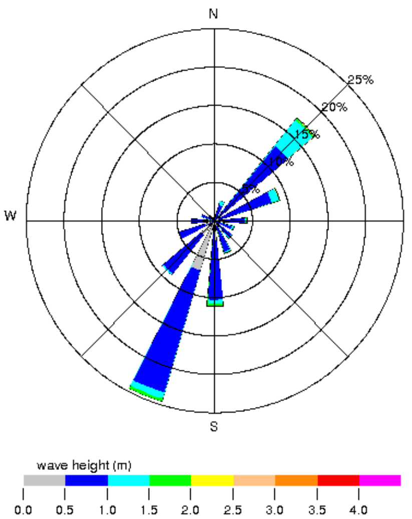
(b) August



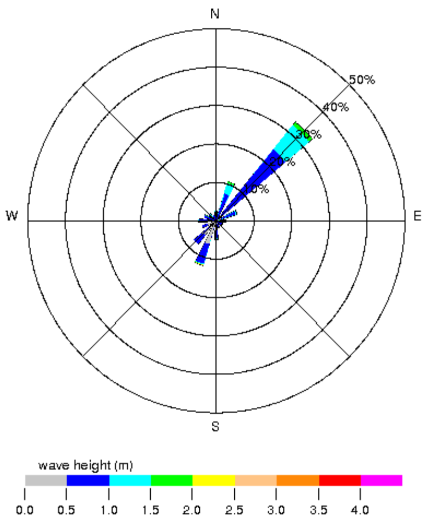
(c) September



(d) October



(e) November



(f) December

Figure C.9: Wave height rose diagrams July - December (BMT ARGOSS)

D

LOCAL WAVE CLIMATE AT HAZIRA

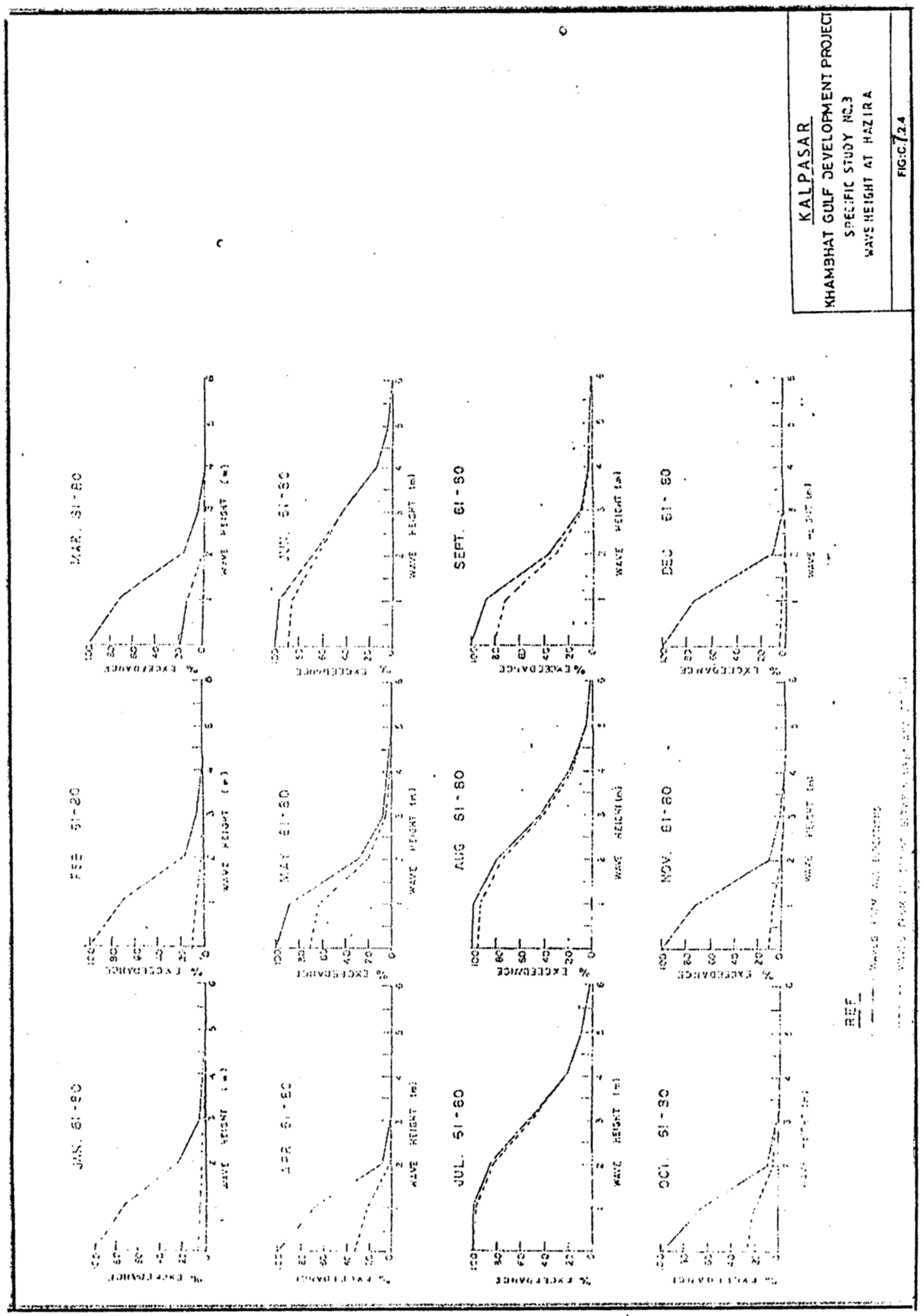


Figure D.1: Wave height at Hazira (Klaassen, 1999)

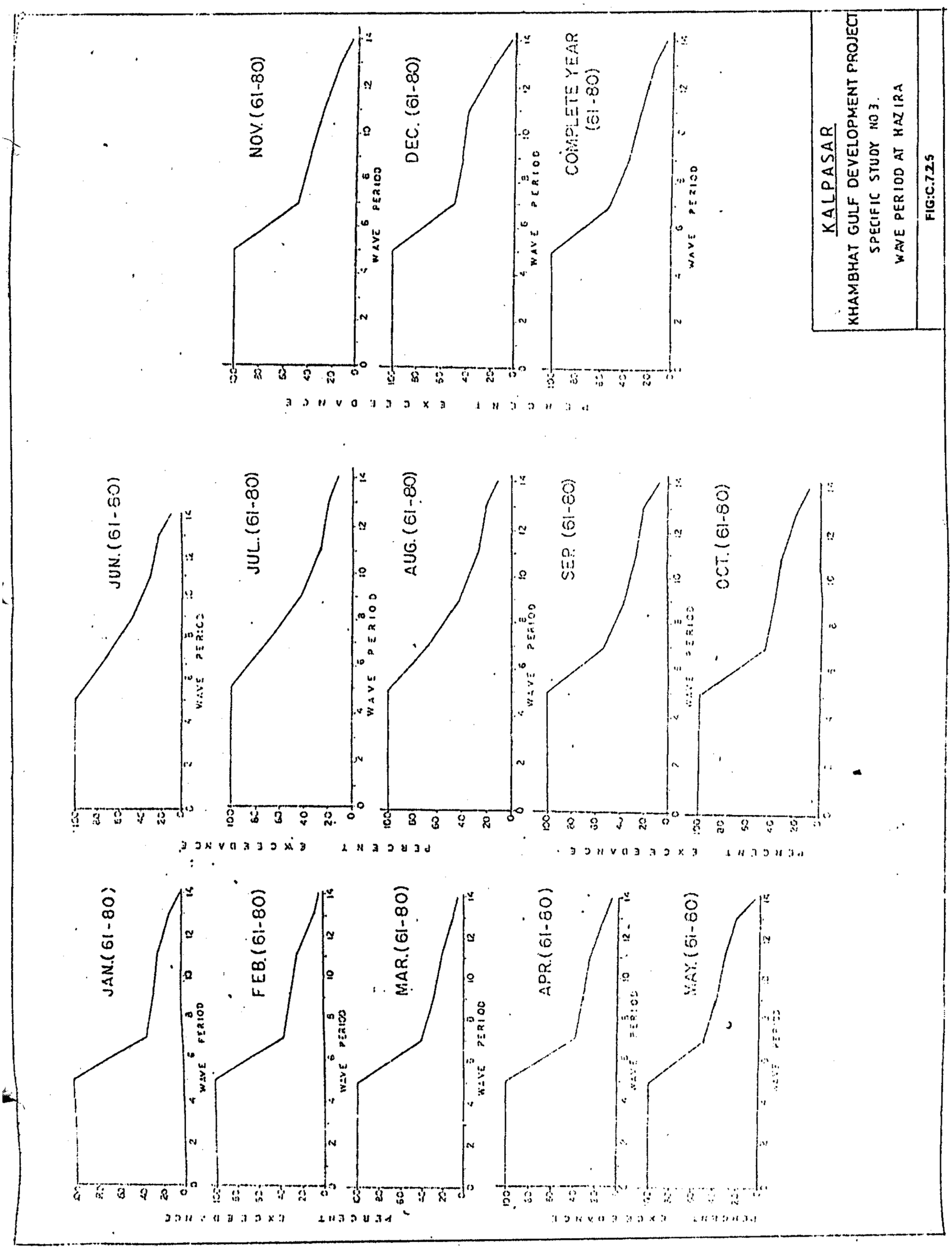


Figure D.2: Wave height at Hazira (Klaassen, 1999)

E

Cyclonic paths in Gulf of Khambhat

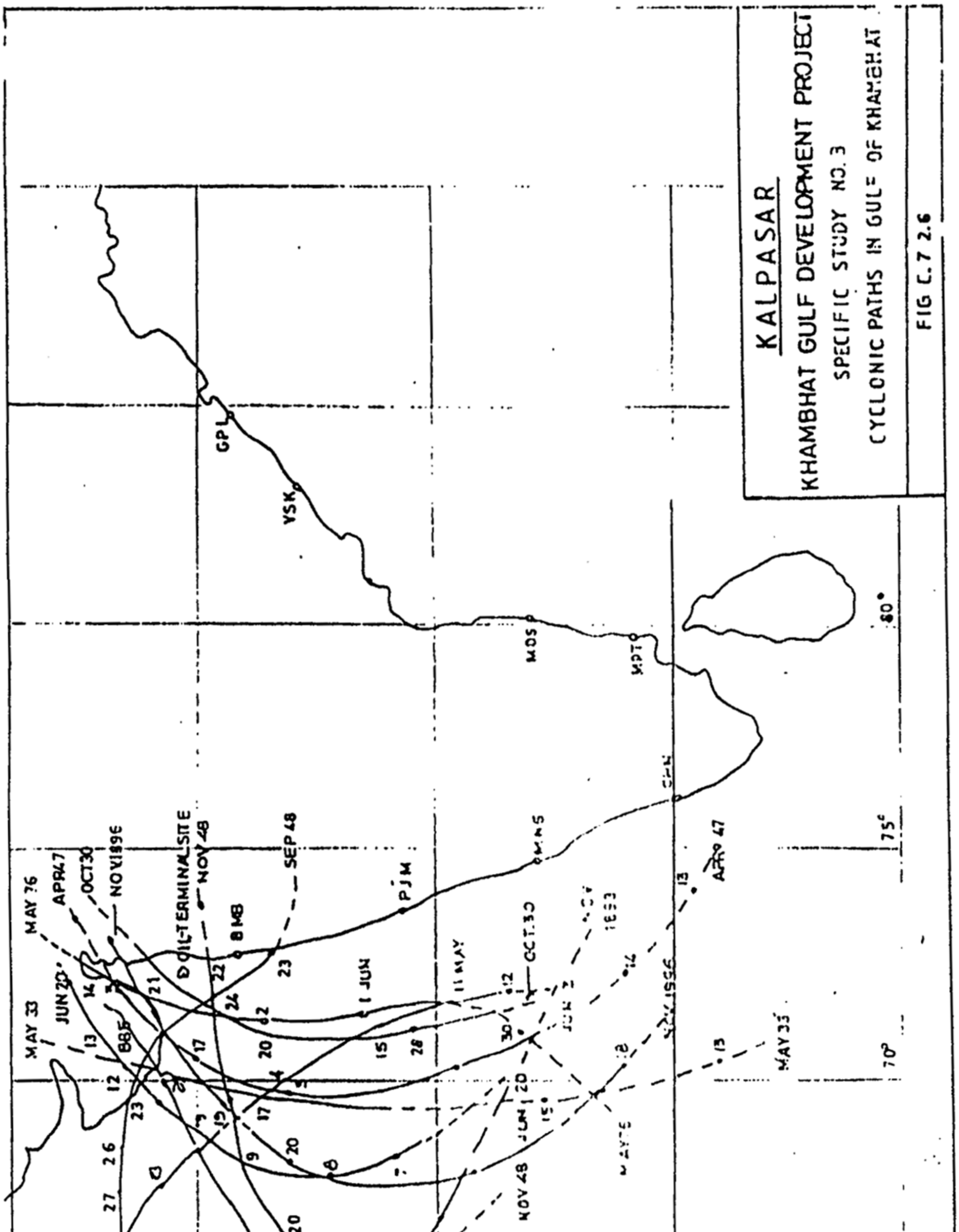


Figure E.1: Cyclonic paths in Gulf of Khambhat (Klaassen, 1999)

F

MODELLING WAVES

The forcing in an estuary like the Gulf of Khambhat exists, besides the component tide, out of the main components wind and waves and river inflow. The waves do not directly cause a net flow in the study area in a way that the tide does, but they induce up-stirring of bed material in the shallower parts. Subsequently, the tidal flow moves the suspended material. To represent reality in a most realistic way, the forcing like wind should be included in the model.

After researching the wind and wave climate the choice is made to run simulations for different scenarios. For these scenarios a lot of effort is put in the on-line wind-wave coupling. After computing several test runs the decision is made to only use a constant wave field in terms of a *wavecon* file, i.a. for computational time reasons. In Table F.1 the used settings are shown for the normative scenario. The results of this simulation are shown in Figure F.1. What can observed from this simulation is the effect of the waves on the mean total transport. This is done my subtracting the simulation without waves from the simulation with waves. From the figure it becomes clear that the influence of the waves is present, in the order of 0.3-3 kg/s/m, and mainly concentrated at the shallow area's in the north part of the gulf. Our interest is at the south part of the dam where the waves still cause some net total transport but to a lesser extent.

However, in the end the decision is made to disregard the use of waves in this model. There are several reasons that underlie this choice. First, the wave forcing does not change with the implementation of the dam as we look at the change of the system by the dam. Secondly, as showed in Figure F.1 the influence of the waves is small, if not negligible when considering the large-scale response of the system. Besides, with the choice for the Engelund Hansen transport formula it is not possible to include waves in the model. Moreover, one of the most important considerations to let the wave forcing out of the model, is that the flow- wave coupling that is used to simulate the tide and waves significantly increases the computational times.

Note that the importance of the waves in front of the dam will probably increase after its construction. Model results (see Chapter 6) show that the area just south of the dam will encounter strong sedimentation. For smaller depths, the waves will be more effective in stirring up the sediment. Moreover, their relative influence will be larger in those places where the influence of the tide becomes less.

Table F.1: The wavecon settings

u10 [m/s]	u10d [deg]	H_s [m]	Hs,d [deg]	Tm [s]	Tp [s]
7.5	258	2.5	247	8.2	10.1

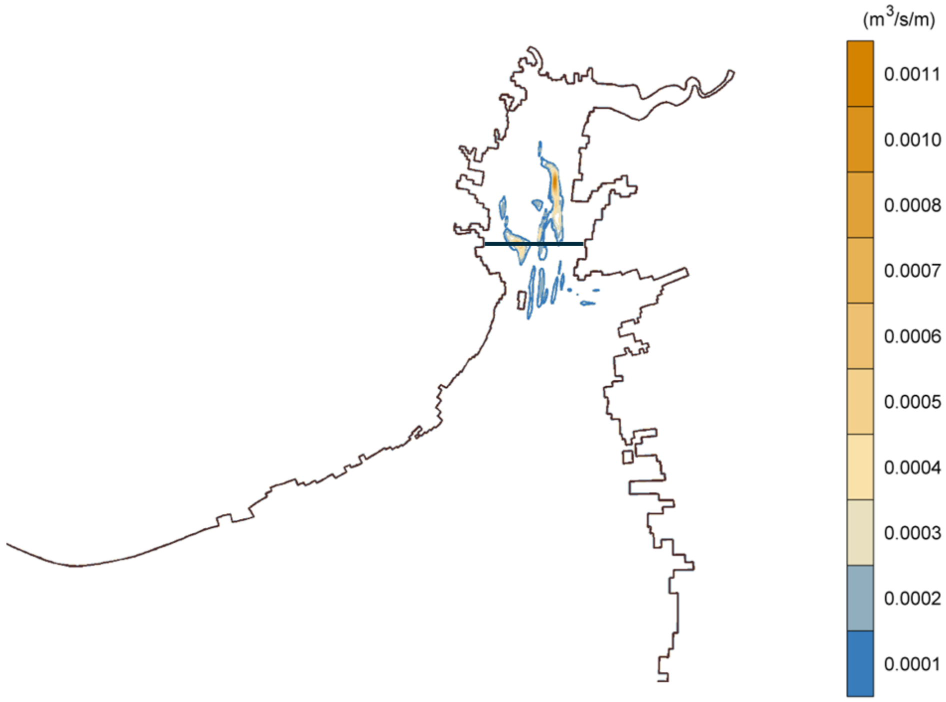
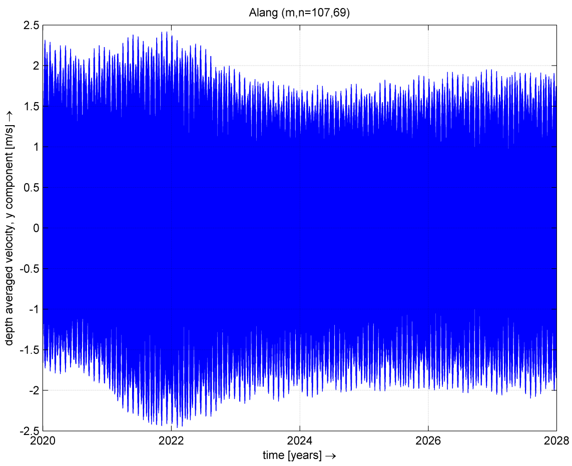


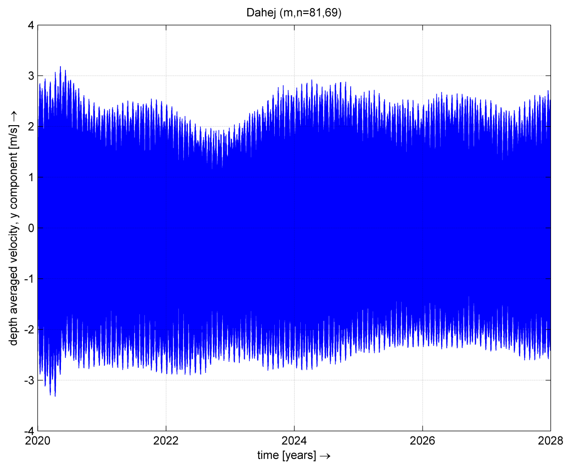
Figure F.1: Mean total transport difference with and without waves. The future location of the dam is marked with a black line.

G

Depth averaged velocities

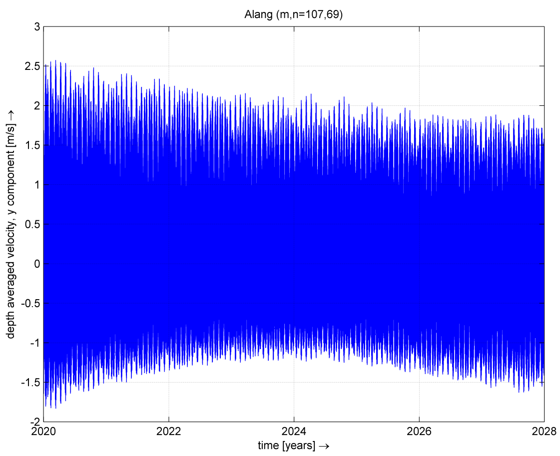


(a) Alang

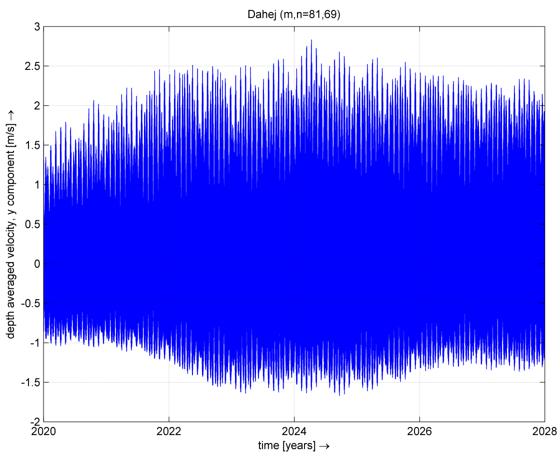


(b) Dahej

Figure G.1: Depth averaged velocities, y component. Simulation without dam



(a) Alang



(b) Dahej

Figure G.2: Depth averaged velocities, y component. Simulation with dam

H

DEPTH CONTOUR MAP

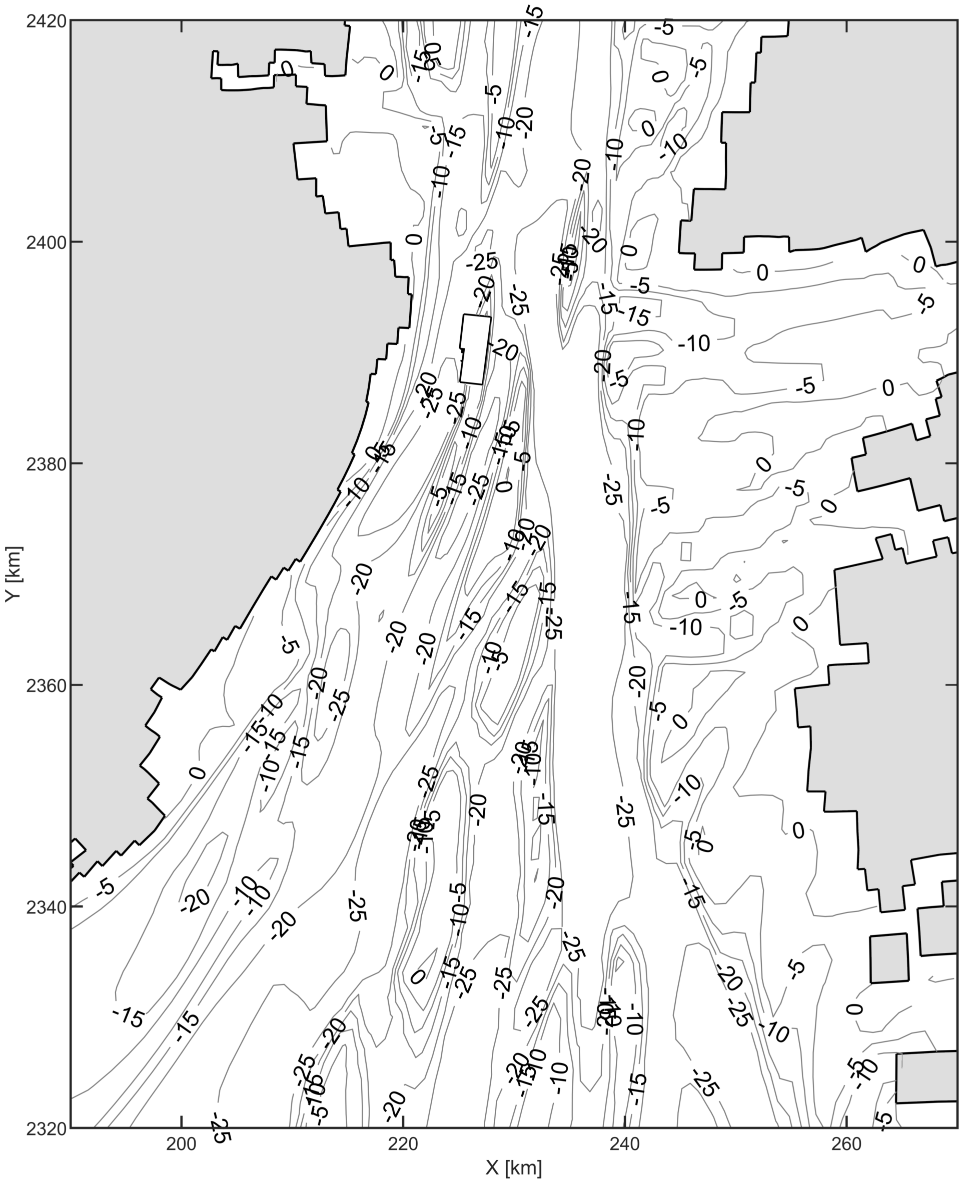


Figure H.1: Depth contours of the initial model bathymetry (after the spin-up simulation) and corresponding bed levels