Cochin Estuary
Morphological Modelling
And
Coastal Zone Management

Technische Universiteit Delft

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Preface

Before you lies the thesis report "Cochin Estuary, Modelling and Coastal Zone Management" for finishing my study Civil engineering at Delft University of Technology. This report is drafted on behalf of the section Hydraulic Engineering.

This project started a year ago when I was requested to do a morphological research of the Cochin estuary within the framework of the Imcoz-project, a joined project from Delft University of Technology and Cochin University of Science and Technology.

An exciting project began with a field trip to unknown India, where the support of the people was overwhelming. Special thanks go to Dr. Radhakrishna who supported me with advice and information during my stay. Also I would like to express my thanks to the whole staff of the faculty of marine sciences for their information and assistance to my project. I would like to thank my Indian fellow students for the kind way they took care of me.

For the Dutch part of my project I would like to thank Mr. Z.B. Wang and Mr. M. van Helvert for their support with the Estmorf model. I would like to thank the members of my committee, prof.dr.ir. M.J.F. Stive, Dr.ir. Z.B. Wang and Dr.ir. B. Enserink for their support and advise concerning the project. Special thanks go out to Ir. T.J. Zitman for his great support throughout the project and of course I would like to thank my friends, family and girlfriend for their support and putting up with me during the last few months of my thesis work. I would like to end with a Dutch phrase:
"Het is mooi geweest."

Marten Strikwerda

Summary

A study is made of the morphological development of Cochin estuary keeping socio economic consequences of possible interferences in mind. The Cochin area profits from its favourable position in connecting sea and land. This causes also problems, large volumes of dredged material, environmental pollution because of excessive use and a population pressure.
The estuary has as characteristic that it is a tropical estuary; this means that large changes occur over the seasons, from extensive droughts in the pre-monsoon to flooding in the monsoon. Because of the micro-tidal character the estuary would be expected to be small, but the large river discharges during monsoon keep the cross-sectional areas in shape.
After the analysis of the current situation the following objectives were formulated. The morphological development of the estuary is investigated with support of some existing software, the applicability of the then constructed model had to be investigated. After finishing the model it would be put to use to solve some actual cases that implemented some coastal zone management.

Subsequently an existing software package was selected, the Estmorf model. This software qualifies the best for the processes that are investigated. This Estmorf model operates on the basis of the theory that an entire estuary is in equilibrium when the concentration over the entire estuary is constant. It is a semi-empirical model in which the hydrodynamic part is based on process-based equations and the morphological part on empirical formulas that connect the tidal prism with a certain cross-sectional area.
After the choice for Estmorf the geometry of the Cochin estuary was implemented. Calibration and validation of the model is done with the help of tidal data. When the data were analysed it became apparent that some data are lacking or not available in the order of detail needed. This lack of data leads to an extensive sensitivity analysis in which the different parameters are investigated for their importance on the end results. It became clear that actually more bathymetric data are needed to get a more accurate model. Since these are not available the different branches have a coarse schematisation, which limits the applicability of the model. Morphological calibration is done with the help of dredging data. Since no morphological history is available it is assumed that the current situation is the equilibrium situation. Because of the lack of data, a sensitivity analysis is performed. From this analysis it becomes clear that morphological history can severely change the results of the model. Because of the Thanneermukkon bund two separate models are made. This also has the advantage to see what the two seasons influence is on the morphology of the estuary. Through this it is found that the dry season is quite unstable because a small tide has to keep large cross-sectional areas open.

With this morphological model some cases are studied. The first case concerns stratification in the Cochin harbour area, where a density current enters the harbour area underneath the freshwater discharge. Since stratification plays an important role in the sedimentation pattern of the Cochin estuary, it is investigated if it is possible to represent this stratification in the Estmorf model, which is constructed for well-mixed estuaries. Two approaches are studied, implementing a higher diffusion coefficient in the stratified area and a higher boundary concentration. It is found that the first approach has the advantage of a variable implementation area where the second one has the advantage that the effect is much more local.
The second case concernes the expansion of the harbour. There are different ways to expand the Cochin harbour. The existing harbour may be expanded or an additional harbour may be built outside the estuary to be less dependent on the morphological development of the estuary, but this may give a new impact on the coastal morphology. Deepening of the harbour areas brings about an increase in maintenance dredging. This increase in dredging fades in the long term because

under impulse of the dry season the tidal prism grows fast, which widens the cross-sectional area. Also an additional harbour was considered which means the current harbour channels can be shallower. The gain in lowering the dredging volume is not as high as expected, but the additional harbour may cause large economical profit for the area.
The third case concerns the mining of sand from the estuary. Since sand is a scarce good in the Keralan region new sources have to be found. The mining can be done inside the estuary if enough intervals are given for the estuary to restore itself. If this is not the case legislation prohibits any sand mining.
From this report it can be concluded that modelling such a complicated system with the available data limits applicability of such a model to a great extent, but it also teaches us something about the value of particular data. When further in depth research is required extensive data are needed about the hydraulic boundary conditions (river discharge data and tidal data).

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Chapter 1: Introduction

1.1 Background

The importance of tidal basins around the world

In lowlands all around the world tidal basins are found. These basins were developed over a long period of time especially during the Holocene when sea level was rising and estuaries are still developing through natural causes, sea level rise and bottom subsidence, and human interference. These areas play an important role in the human environment because these are places where the sea is connected with the hinterland. This connection can be direct through a river or indirect through a tidal basin or an estuary. These areas have a tendency of drawing a lot of activity, thereby causing large numbers of people to move towards the small area near the sea. Because of this more than half the world population lives in a coastal area and are facing the difficulties as well as the benefits of living near the sea. In 2025 even 75 % of all people is expected to live in coastal areas.[1] Observing this more and more attention is being placed on the coastal region and its physics. Tidal basins are getting more and more important as a connection between land and sea.
An estuary is characterised by the outflow of a river where the tide of the sea or ocean plays an important part in the dynamics of the water flow. There are lots of different tidal basins each with their own characteristics, because of their balance between waves, tides and river discharge.

A tropical estuary

As mentioned in the previous section each tidal basin has its own characteristics, but tropical basins have some common features. During monsoon or rain time as it is called in other regions around the world, coastal zones have suddenly to cope with large quantities of water that have to be discharged through the coastal zones. These large discharges give the estuary a stratified character, where salt wedges are an important dynamical component in determining the morphology of such a basin. Also, large seasonal differences are a typical feature of a tropical estuary. These large seasonal variations give different problems in dealing with such estuaries because the tidal basin can undergo large seasonal variation and so can the whole of the coastal system. These changes can severely confront the people living around such an estuary with large problems as floods or collapsing of banks.

1.2 Objective

In the Southwest of India the green state, Kerala, is located. This state harbours the city of Cochin. Cochin is situated at an estuary connected with the Arabian Sea. This estuary is an example of a tropical estuary with its problems and opportunities. The harbour of Cochin brings a lot of economic fortune to the city of Cochin and the water makes sure millions of people can live here from fishing and paddy crop farming. But at the same time the sea also brings about a lot of problems like coastal erosion and pollution.
This report in general deals with the problems concerning the morpho-dynamic system in the estuary of Cochin and a few specific coastal zone problems are dealt with, which have a direct connection with the morpho-dynamics of the system. Issues that need urgent solving like environmental problems concerning the disappearance of the estuary and its bio-diversity and

[1] www.WNF.nl

economic opportunities for the Keralan region, like the building of new docks or even whole terminals.
This complicated morphological system is nowadays not well modelled and so the dynamics of this estuary are not yet completely understood. There are a lot of estuarine systems modelled nowadays, but tropical estuarine systems with typical features like monsoon and high river discharges are rarely modelled in a morpho-dynamical sense.
One of the main problems for Cochin and most of the estuarine areas in the tropical hemisphere is the high population pressure. The available land will be used for multiple reasons and this sometimes provides problems, because some of the land used for housing should actually be left free because this land is not in a static equilibrium with the sea. Flooding of coastal areas with retrieving coastlines is the consequence.
This project is started within the framework of the IMCOZ project. This project is a mutual effort of the Cochin University of Science And Technology and Delft University of Technology to start up a coastal zone management institute at Cochin University to provide the future Indian students with more knowledge on the subject of integrated coastal zone management. This project may be seen as a case for future Indian students, that they may use to get a better understanding of the forces, which are in play when the morphological development of the estuary is discussed.

1.3 Reader guide

First this report presents an analysis of the general theory concerning estuaries and the modelling of estuaries. This is handled in section 2.1. In section 2.2 the current situation in Cochin is discussed with the help of a situation sketch and a problem analysis for the area. After this analysis, the objectives of this thesis are formulated. Also by the meaning of the problem analysis, some cases that will be treated later will be generated.
In chapter 3 the Estmorf model is presented. Its use is explained and a review is given of how the model was developed. In chapter 4 the construction of the model starts. First a hydrodynamic model is constructed with the help of the Sobek-software, subsequently this hydrodynamic model is implemented in the Estmorf software to make the morphological model. Also a sensitivity analysis is done to present some statements on the qualitative behaviour of the estuary. In chapter 5 some cases are treated with the help of the model. These cases deal with the expansion of the Cochin harbour and the mining of sand out of the estuary. Here also a connection will be made with the coastal zone management. In chapter 6 the conclusions from this research are drawn and some suggestions for follow-up research will be made.

Chapter 2: Analysis

2.1 Introduction

In this chapter the information that is needed to start of with the thesis is presented. That is why the general theory about estuaries and the part of estuaries in coastal engineering is discussed. Also the current situation in Cochin and the origination of the estuary is discussed. The analysis of the problems that are currently present are treated and when all this information is combined the thesis objectives are set.

2.2 General theory

In this section the theory about estuaries and the modelling of estuaries will be treated. First the main characteristics of an estuary and some important terminology will be treated, thereafter the modelling of an estuary will be treated.

2.2.1 Estuarine features

Estuaries are defined as semi-enclosed water bodies, connected to the sea, within which seawater is measurably diluted by freshwater(R.W.G. Carter, 1988). There are many different tidal basin, of which the estuary is one, with its specific characteristics.
An estuary can be considered to be tide dominated in general because the barrier islands tend to exclude the wave energy, tide dominated means the morphology of the estuary is predominantly determined by the tide.
This does not mean the whole coastal system has to be tide dominated. If there would be no or negligible freshwater discharge the tidal basin would be called tidal bays or tidal lagoons.
Estuaries are originated by the invasion of the sea of non-marine land by the rising sea levels.
Tidal basins are characterised by a basin, an outer delta and an inlet. The shape of these characteristics are defined by the wave and the tidal climate. The estuary plays an important role in the whole of the coastal system since there is a balance of sand load between the estuary and adjacent shorelines. This can be seen in Figure 2.1.

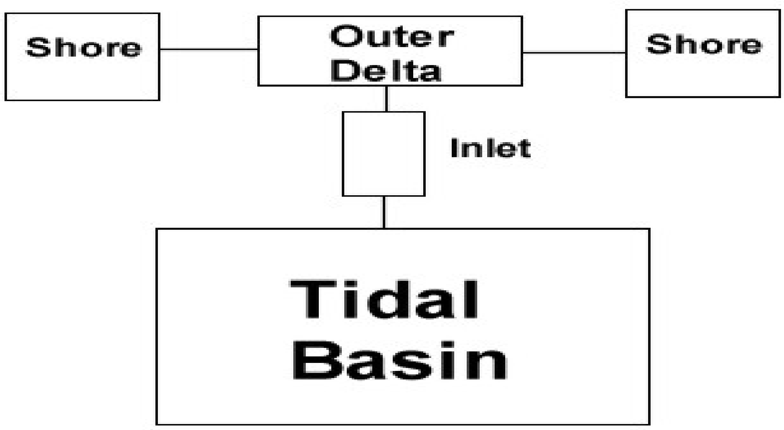


Figure 2.1 Estuary system

Inside the basin the current is diverted into separate channels. The channels in the basin are divided by flood channels and ebb channels because of this distinction especially the area around the inlet will get a specific shape with several channels. A flood channel is a channel where the volume water passing through during flood is larger than the volume water passing during ebb. If an inlet is tide dominated the outer delta will contain a large volume of sand. The outer delta is the volume of sand in front of the inlet. The inlet can also be defined as wave or tide dominated this is determined by Figure 2.2.

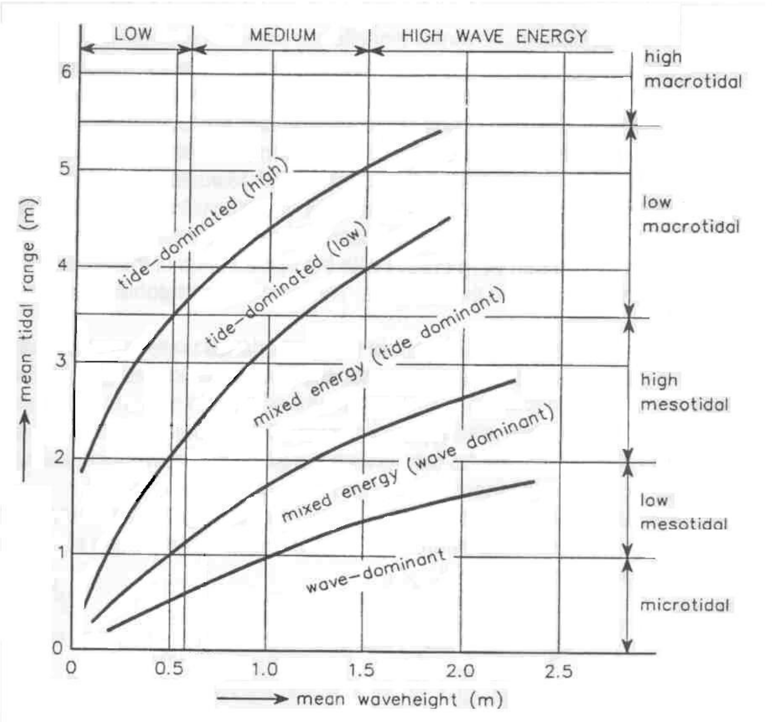


Figure 2.2 Determining the system

The shape of the inlet is also determined by the character of the tidal propagation through the ocean, is this a standing wave or a propagating wave. This is determined by the large-scale oceanographic environment. The tide is generated at the southern hemisphere and propagates from there to the northern hemisphere. Because of the Coriolis force the currents have a tendency to bend to the right on the northern hemisphere and left on the southern hemisphere. The overall pattern is determined by this force and the global circulation pattern.

The internal shape of an estuary is predominantly determined by the tide because the waves normally don't really progress through the estuary. Important features are the tidal dominance and the tidal prism. Because speed and sediment transport don't have a linear relation but an exponential one. Because of continuity by low river discharges the volume of water going in an estuary has to be equal to the volume flowing out of the estuary. This can mean that because of daily inequality in the tide the time it's ebb is longer than the time it is flood. This can give a flood-dominated estuary, because higher velocities are needed to get the same volume of water in a shorter period in the estuary, and will normally transport sediment into the estuary. Another aspect that determines the dominance of an estuary is the phase of the discharge and the water depth, in phase gives a more ebb-dominated estuary, because the same volume of water has to be through a smaller cross-sectional area.

The tidal prism is the volume of water what flows in or out of the estuary during one ebb or flood period or half a tidal cycle. The tidal prism is especially important for the cross-sectional area of channels and the inlets. The tidal prism is sensitive for human interference, especially reclamation, because this decreases the tidal prism. Even worse though are the reclamations with soil from inside the system. Since the system needs more sand for filling up the channels and for the sand that was taken out of the system for the reclamation and has to be replaced. Sand has to be transported from somewhere else, which can be the coastline.
The littoral drift and the discharge out of the inlet determine if an inlet is stable at its location or that it is moving and how sand can pass the inlet. This gives valuable information how sediment is transported over the inlet and it gives an indication on how the movement of the tidal inlet is in general. Bruun(1978) gives the following relation (the notation in Bruun is different, this is the notation as copied from "Coastal inlets and tidal basins", 2002):

$r = \frac{P}{M_{max}}$ in which P = Tidal prism and M_{tot} = the total littoral drift.[2]

If r is small the inlet is a typical bar passing inlet and can have an unstable, moving character. A large r gives the inlet a flow by-passing character and most of the time a stable inlet.
To determine if an inlet is stable in the cross-sectional area and if it is closing or widening, one can use Escoffier. This method compares the critical velocity of erosion with the cross-sectional area of the inlet, this is also the basic principal for a lot of the empirical models. This critical erosion velocity is not the velocity that the sediment starts to move but that more sediment is picked up than put down. If v_{cr} is bigger than the actual velocity the inlet will have a tendency to become smaller if the actual velocity is smaller the inlet will have a tendency to grow, see Figure 2.3. The velocity in the inlet is most dependent on the tidal prism and the river discharges.

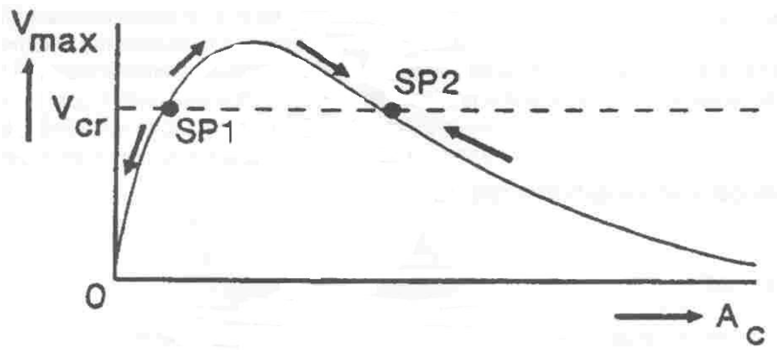


Figure 2.3 Escofier

The water movement in an estuary is determined by the interaction between river discharge and the tidal prism. Especially in a tropical estuary with large seasonal differences this can give three situations:
The river discharge is much larger than the tidal influx. This will mean the estuary will exist predominantly out of fresh water and at peak discharges depending on the shape of the estuary even a total flush of the saltwater can occur. The tidal propagation into the estuary will be effected in the way that it will be smaller than in the case of lesser discharge.
The river discharge equals the tidal influx. Now a stratified situation will occur in which the heavier salt water will flow underneath the lighter fresh water.

[2] See Bruun 1978 page 248

The river discharge is much smaller than the tidal influx. There will be a well mixed estuary with salt intrusion far upstream in the estuary and with the tidal propagation far upstream the estuary.

2.1.2 Modelling of estuaries

Modelling is a reflection of reality wherein the aspects of interest are represented as good as possible. Important is to consider that a model is not reality itself and the results have to be handled with care. It is important to consider what actually is the use of the model. Modelling of estuaries is a recent developed science because of the difficult dynamic processes involved in estuarine development. Since the beginning estuarine modelling has gone through a rapid development. A quick overview of this development is given in this section.

Empirical modelling

In empirical modelling predictions are done on the basis of empirical relations. These empirical relations are based on comparing existing data with the data available at the site of interest. Important quantities in empirical models are the tidal prism and the areas of flats and channels. The determination of an equilibrium cross-sectional area related to the tidal prism is one of the equations. This relation depends on the theory of Escoffier, which says that every inlet has one equilibrium cross-sectional area. These cross-sectional areas are of course not constant because of different types of sediment, flow patterns, etc.

$$A_c = c_A P$$

With A_c = The cross-sectional area of the inlet below MSL
c_A = Coefficient of proportionality, dependent on the local qualities
P = Tidal prism

Another relation is the relation between the area of the basin related to the area of flats:

$$A_f = A_b - A_{ch} \approx A_b - \alpha \frac{P\sqrt{A_b}}{D_{ch}}$$

with A_f = Flat Area
A_b = Basin Area
A_{ch} = Channel Area
α = Coefficient
D_{ch} = characteristic channel depth

There are many more relations comparing the tidal prism with one of the other quantities, for example the outer Delta and the channel volume.
Also a time component can be inserted into the empirical modelling, this is done by comparing an estuary with a similar estuarine system and define an equilibrium state out of this comparison. By doing this the time can be found out that the system needs to get to its equilibrium state. One has to be ware of the fact that changes always take time and the equilibrium state is constantly changing.

Semi empirical models

Because the dynamics of the sediment movement are still not fully understood and more research needs to be done in this field, an approach has been developed in which water movements are process-based modelled and the morphological development are represented in empirical relations based on the prior development of the estuary.
The first basin model of this type was Di Silvio's basin model developed for the Venice lagoon in 1989. This is the first concept including an equilibrium concentration to determine the equilibrium state of the estuary. This basin model is an 1-dimensional model which means it is important to think large since two-dimensional flow-patterns are not included. The equilibrium concentration means that if the concentration is equal at all places in the estuary the dispersion of sediment through the water will stop and the system is in equilibrium, which means the contours are set. These contours are split up in the total area of flat and the total area of channels in the basin. Because the road to equilibrium takes a long time in estuarine development the boundary condition have presumably changed, by human interference or natural development. The system is therefor constantly on the move.
In the Di Silvio model the equilibrium concentration is determined by the concentration in the sea. This is off course not the measured concentration but a representative concentration for the 1-dimensional model. This concentration is a given constant for the model.
From the equilibrium concept as presented above at Delft Hydraulics some models have been developed, beginning with van Dongeren's (1992) basin concept, which parted the basin area in a number of pieces. In 1994 Karssen and Wang have started to develop the model Estmorf. This long-term semi empirical model for morphological development also assumes an overall equilibrium concentration for the basin. But by parting the basin in smaller pieces each part gets an individual temporary equilibrium concentration which changes after a number of morphological time steps, when the morphology and bathymetry also changes. The model is purely developed for the internal basin and because it is developed by Delft Hydraulics under supervision of Rijkswaterstaat for the Dutch situation, it's primarily for well mixed tidal basins where secondary flows play a minor part.
Because the coastline plays an important role in the overall system of the sand balance, Delft Hydraulics also developed a model, which represents the system as a whole. This model gives a balance between the basin, the inlet, the outer Delta and the coastline. This kind of model is particularly useful in case of determining the sources of coastal erosion or accretion. This model is called ASMITA it also takes as starting-point an equilibrium concentration. This model gives a long-term prediction of the development of the coastal system.

Process based models[3]

This is the newest generations of models; these models try to make a prediction fully based on process equations. These models require high detailed data collection and a large computation time. Although with the new generation of computers the computation time has become smaller, these models are not undisputed, especially for long-term calculations. The disadvantages formulated before are the lack of exact knowledge of the process and there by the impossibility of formulating process based formulas. It's not even sure if the formulas for these processes can ever be formulated, nevertheless these models can give a good insight in the sediment movement in the short term. Therefore there are the ISE-models, the Initial Sedimentation Erosion models. These models assume present situation, obtained by detailed measurements and implement all known process based formulas on this situation, which gives a general overview in the sedimentation and erosion pattern. Because the bathymetry and thereby also the water motion are not changed in the model, this kind of models can only provide you with an initial pattern.

[3] Vriend, H.J. de (2002), Coastal inlets and Tidal basins

The newest models are the Medium-Term Morpho-dynamic models, these models do adjust the bathymetry and thereby the water motion after large enough changes because of sedimentation or erosion. These models are therefore fit for longer-term calculations, but bear in mind that the result may not be taken without any reserve.

Model choice

The choice of a model depends on a lot of things, the most important one of course is what do we want to model, which exact physical relations are important for the area of interest of our project. Which tool can help us in achieving our objectives? Except that also availability, the order of detail of data and the computational resources determine the model.
These aspects have to be kept in mind when proceeding through the process and analysing the data, because each model has its own limitations and its own strength.

2.3 The Cochin estuary

2.3.1 Situation sketch

The Area of Cochin

Cochin (9°45'N and 76°17'E) or as it is now officially called Kochi is a city situated in the South-western part of India in the state of Kerala. It is a corporation of multiple cities that are situated around the inlet of the Cochin estuary also known as the Vembanad Lake. It is situated at the Arabian Sea and since the 13th century an important economic centre in this area, after the deviation of the Periyar River that first had his outlet near Azhikode. After Bombay it is the second city on the western coast of India and also possesses the second harbour of the western coast.
Kerala is a green state from the south most point of India to 560 kilometres up north. Surrounded by two natural boundaries, the Arabian Sea and the Western Ghats, Kerala has developed in a unique way, due to the moderate climate and the heavy rains during the southwest monsoon. This southwest monsoon is from June until August and comes with a lot of heavy showers. Almost 6 million people populate Cochin and its suburban and the whole province of Kerala is populated by approximately 32 million people on approximately 40000 km² (Ramachandran, Balchand, Enserink 2002). So this is a densely populated area with a population density of 800 people per square kilometre. Especially the coastal area is densely populated because the Western Ghats are partly protected reservations for wildlife. In the Cochin metropolitan area the population density is as high as 3281 persons per square kilometre (Menon, 2000).
The economy of this area depends on trading, fishing and the cultivation of rice and rubber. Cochin is the economic centre of the area. It 's a cooperation of the cities of Ernakulam, fort Kochi and Mattanchery. In Ernakulam the most important economic districts are situated. The harbour is partly located in Ernakulam and also some terminals are on Willingdon Island. Plans are made for additional harbours at Vallarpadom and Vypeen Island. This already indicates the importance of the sea in the Cochin Area. In appendix 2.1 maps of Cochin and Kerala are included with its most important topographic sites.

The estuary of Cochin

The total area of the backwater system in Kerala is 300 km² of which the Vembanad Lake is the largest with nowadays an area of 130 km^2. The estuary has four connections with the Indian Ocean/Arabic Sea. The northerly connection, Azhikod, is at the mouth of the Periyar River. This

connection takes care of half the discharge by the Periyar River, but has no real influence of tidal inflow (Chandramohan, 2002). The other half flows to the more southern gull near Cochin. This is also the approach channel for the harbour of Cochin. In the southern part of the Periyar river is a bund preventing salt water intrusion upstream in the Periyar. So during dry season the total volume of water is being diverted through the northern entrance, see Appendix 2.1 for maps.
The inlet near Cochin discharges half of the discharge of the Periyar River and almost the whole discharge for the other five rivers, the Muvattupuzha, the Meenachil, the Manimala, the Pamba and the Achakoil, who let out their water on the Vembanad Lake.
In the Area near Andhakaranazhi there is a seasonal opening, which is used as a fishing harbour. This opening will only open during monsoon and has a small effect on the water movements in the whole of the estuary.
The most southern entry near Allepey, the Thottapally spillway, is an artificial outlet, which doesn't function as well as expected, because the dimensions are too small to discharge the water that was supposed to get through. It should be noticed that their has been built a dam, called the Thanneermukkon bund in the Vembanad lake for the water household. This dam was finished in 1976. The dam is closed during dry season, preventing the salt water from flowing into the Kuttanad agricultural area, but opened during monsoon, because then the large discharges of the four rivers south of the Cochin gut can be let through. When the dam was built it closed of 69 km^2 from the backwaters hydraulically during dry season. The artificial outlet is a part of the fresh water project for the Kuttanad region, which started in 1955 to get more than one harvest period. During the wet season 10 % of the discharge from the three most southern rivers flows trough this southern outlet. The problems with this artificial agricultural area are still very actual. Since the opening regime of the bund is quite unclear, the farmers in the Kuttanad region can still only harvest once a year. Also this area is presented with large environmental problems since the polluted soil caused by the agricultural pesticide can't pass through the bund and piles up in the southern part of the Cochin estuary.

Development of the backwaters of the Vembanad Lake

The estuary of Cochin in contrary to a lot of other estuaries is of relatively recent nature. It became in its characterising shape during 14^{th} century when a great flood closed the Periyar Rivers outlet and opened the Cochin gut (Gopalan 1983).
When in the last century the estuary was at its largest, it accounted for almost 365 km^2. In the end of the 19^{th} century the state government decided to stimulate the cultivation and the reclamation of land in the backwaters. This practice was stopped in the early 1900's when people started to think there was a connection between the land reclamation and the higher siltation rates at the harbour area. The estuary had then shrunk to an area of 312 km^2. The practice for agricultural reasons resumed in 1912 when the reclamation of the Kuttanad region begun. This involved an area of 52 km^2 until 1931 and an area of 13.25 km^2 between 1941-1950. Another 51 km^2 was reclaimed throughout the area for paddy cum shrimp farms between 1900 and 1970 and after 1970 until 1984 there was another area of 8 km^2 reclaimed. Also private users have reclaimed 15 km^2 of land throughout the years for housing or different private uses. Nowadays only 130 km^2 backwater is left of what once was 365 km^2.

Development of the Cochin harbour area

The harbour was exploited from the day the Periyar river changed its course and has developed steadily into the twentieth century. Then in front of the inlet in the Cochin harbour area there was a built up of a large sand bar, presumably the outer delta. In the early 1920's sir Robert Bristow took the decision for dredging an approach channel through this sand bar that was forming and growing 1.6 kilometres out of the coast and was only 3 metres under the lowest possible sea level

(Chart Datum). There was decided that a 4.65 kilometres long approach channel would be built 10.7 metres deep and 137 metres width (Mathew, T.K.1993).
The development of this sandbar is in contradiction with the expected reduction of the tidal prism as a consequence of the land reclamation, because a reduction of a tidal prism normally means the outer delta will become smaller. On the contrary the theory of Bruun expects a tendency to a bar passing mechanism if the relationship between the Tidal prism and the total littoral drift becomes smaller, see paragraph 2.1. This can explain why the bar in front of the estuary inlet becomes larger. Also some changes in the water movement could have caused the prism to grow, while the area decreased. One should think here of the occurrence of a standing wave or less friction because of the dammed flows.
The dredged material from this entrance channel was used to reclaim Willingdon Island, also a channel was dredged on the west side of Willingdon Island, the Mattanchery channel. In the 1950's also on the eastside of the Willingdon Island a channel was dredged, the Ernakulam channel, because of this siltation rates inside the harbour rose. After a large revising operation in the early 1980's of the harbour where the channels where broadened and deepened to make way for larger ships the siltation of the harbour area took a drastic switch. Where at first the dredging activities inside the harbour area predominantly concerned the Mattanchery channel now the Ernakulam channel became the main area of dredging, also the dredged volumes went up, see Table 2-1.

Channel	Percentage 1970	Percentage 2000	Dredged volume 2002
Matt. Channel	28 %	20 %	$432*10^3$ m^2
Ern. Channel	2 %	29 %	$324*10^3$ m^2
Approach Channel	70 %	51 %	$764*10^3$ m^2

Table 2-1 Dredging volumes throughout the year

This change in dredging percentages cannot only be attributed on the new depths of the channels but also on the change at the bifurcation point south of Willingdon Island where the southern part of Willingdon Island was reclaimed.
The channels in there present shape are shown in Table 2-2. These channels are being dredged throughout the year with the exception of the rough season at the start of monsoon. Still there are plans for deepening and widening the Channels even more, but from recent research it became apparent that this deepening is bound to a maximum (Menon, 2002). This maximum has given the signal to find different solutions for the extension of the harbour, like building harbour docks outside of the inlet.

Channel	Depth (m) compared to Chart Datum	Width (m)
Approach Channel	12,8	170
The Gut	14	430
Ernakulam Channel	11,9	400
Mattanchery Channel	9,8	300

Table 2-2 Dimensions Channels Cochin Area

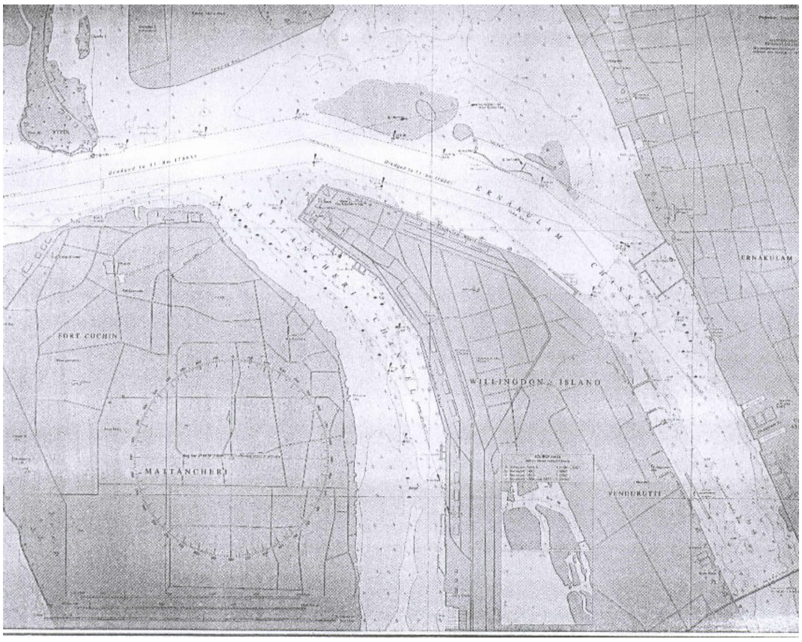


Figure 2.4 Cochin harbour area

Water movement on the seaside

The Cochin system is a micro tidal system with a tidal amplitude of 0.35 meters on average and a maximum of 0.55 meter, see Figure 2.5. This indicates a small tidal prism but the large bay area still gives a large tidal prism. The tide is of mixed nature. This means the tide has a strong diurnal component that is especially visible during low tide.

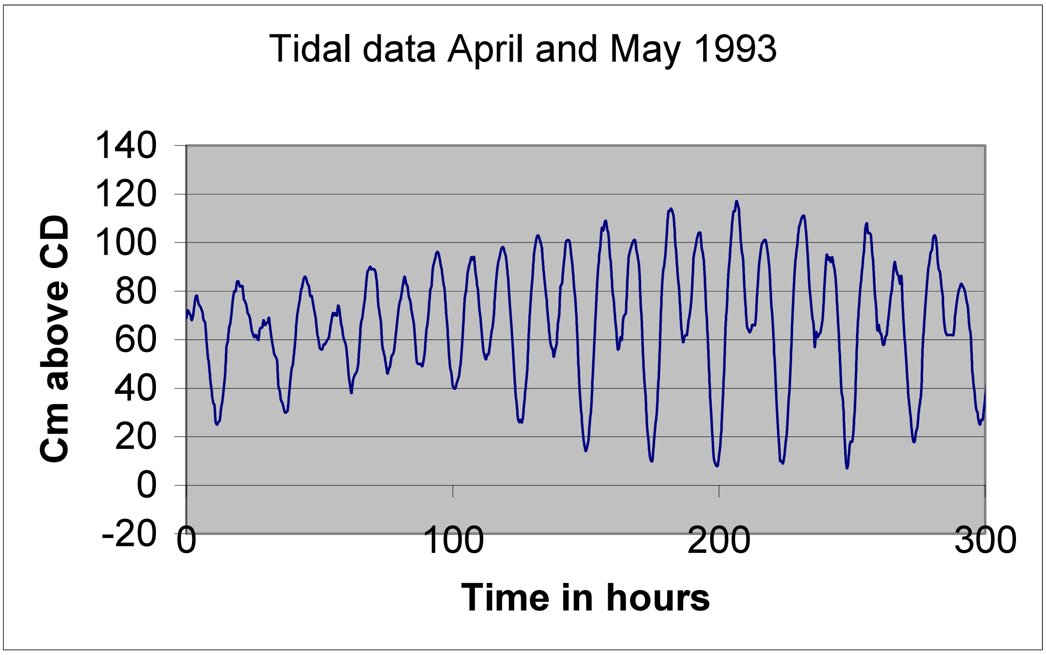


Figure 2.5 Tide in the Cochin harbour

An amphidromic point south of India, which creates a standing wave in the Arabian Sea, determines the water movement in the Arabian in the Cochin Area. An amphidromic point is a point where the amplitude of the tide is zero and where the tidal wave goes around. So this tidal current does not cause a residual tidal current along the Indian west coast (Srinivas, 2002). The overall ocean circulation in this region is predominantly from south to north but varies throughout the year.
The dominant wave direction is from the northwest during the dry season and from the southwest during the wet season. During the wet season, which also brings the highest waves the waves are thus perpendicular on the coast so no residual current is reported then. Inside the estuary there is not much wave energy from the outside is left, there are some reports (Frederic Harris, 1990) that suggest that locally generated waves inside the estuary can contribute to the sedimentation and erosion pattern inside the estuary, but no prove of this interpretation was found in India.
A point of interest in front of the coast of Cochin are the mud banks, which are located around the whole of the west-Indian coast. Nearby Cochin there is one northerly of the approach channel and one on the other side of the approach channel that appear almost every year. It is because of these banks that it is expected that the residual currents in front of the coast are nearly zero. Because these mud banks hardly move and they also absorb almost all of the wave energy. There also used to be some mudbanks in front of the coast south of the Cochin inlet but there have been no more appearances the last couple of years. Sometimes (once every few decades) such a mud bank enters the harbour of Cochin and gives great siltation, but no fixed period is detected in this event. These mudbanks appear most of the time in the monsoon, when the wave climate is vicious enough to get the mud on the bottom in suspension these mudbanks will stay for a week or two then they diminish again until the right wave climate appears again.
The problem with the residual current is that this current is made turbid by two eddies on both sides of the approach channel. This is a common pattern because of the perpendicular orientation of the wave direction in the dominant season. These eddies give a lot of residual current towards the approach channel, which might causes extra siltation in this approach channel.
There is some swell coming from the Persian Gulf. It is expected not to have a great influence on the sediment transport in the estuary but it could considerably attribute to the siltation on the coast outside of the estuary. This has to be investigated further, but is beyond the scope of this research

Coastal morphology

When looking at an estuary one should not forget the entire system of which the estuary is part. If the estuary system needs sand to decrease itself, because the tidal prism has decreased, then first sand from the outer delta is used for this purpose. If that is not possible because of lack of sand, then sand of the shore might be used to fulfil the deficit of sand in the estuary. There are a few reasons that amplify this effect.
If land is reclaimed the tidal prism probably becomes smaller and sand is needed from the outer delta. In Cochin large areas of land have been reclaimed but to enlarge the effect on the coastal system also sand from within the system is used for this purpose, the dredged channels from the harbour area were the supplier for the reclamation of Willingdon Island. This sand is put out of the system and reduces the tidal prism, which has an enlarged effect on the sand balance in the system and can cause coastal erosion in the Cochin area.
Because the sediment flux along the coast is directed from north to south, especially south of the entrance coastal erosion is present on large scales. Of course there are more reasons why this coastal erosion occurs, mudbanks play an important role in this equilibrium because the long shore current is interrupted by these mudbanks The long-shore current is interrupted by these mudbanks because they dissipate the wave energy. This coastal erosion has large effects on the habitat of the Cochin region. Many people have to move when floods arise during monsoon. During dry season this land is most of the time built up again but the residual pattern is erosion.

This erosion can be solved by choosing the right dumping sites for the dredged material from the harbour, but out of environmental point of view the state government does not allow the dredged material to come onshore by sand suppletion. This suppletion can cause the sand volumes on shore to be restored, but the pollution in the sediment causes environmental difficulties.

Water movement in the estuary

In the estuary the water movement differs highly depending on the season. During post monsoon there is in the outlet of the estuary there a strong density current. This current is density driven caused by the fact that the inflow and the outflow are almost equal. The heavier mud-filled silted water flows underneath the clear fresh water coming out of the estuary. It is not exactly clear where the bottom is in this stage because the concentration of particles keeps getting denser going deeper. This thick layer of mud is moving at the bottom from September till December, because then the ebb current is big enough to ensure stratification. Also the weather is fierce enough to cause waves that can get the mud in fluid form. The gorge/inlet of the Cochin estuary is presumably in equilibrium since no dredging has to take place here.
Because of the dam built in the southern part of the estuary, there is a standing wave in the estuary during dry season that ensures large flow velocities in the channels southerly of the gut. The physics of this standing wave come up further in the research. During the wet period the tidal wave is stopped by the large river discharges. This means the maximum flood velocities in the southern channels are much lower.
In the northern part of the estuary there is a small residual current down south, because half the discharge of the Periyar River is going to the Cochin opening. In the south the Muvattupuzha, Meenachil, Manimala, Pamba and Achakoil River make a strong residual current to the north, especially during monsoon. The yearly river discharges are presented in Figure 2.6.The peak discharges of these rivers can be as large as two times the daily mean of the same month and can last for several days. It will be necessary for the rest of the project to find as much possible data about the rivers as can be found.

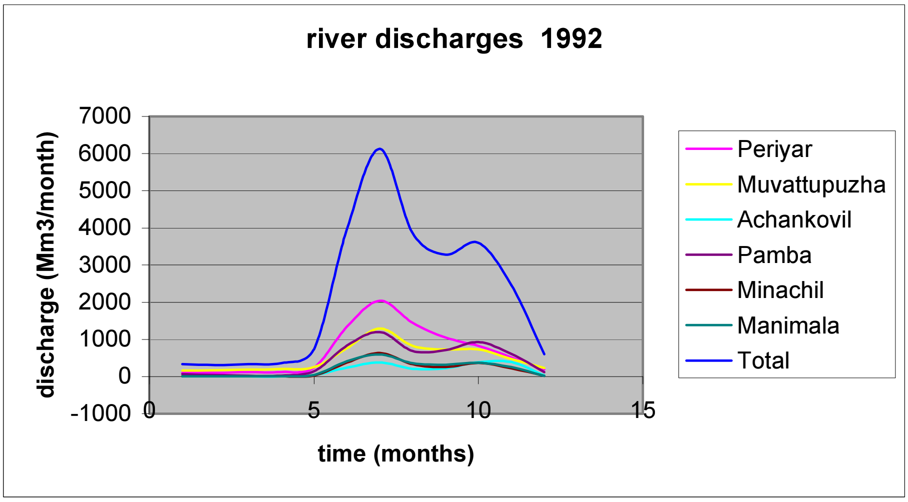


Figure 2.6 river discharge during one year

Textural composition of the sediment in the Cochin estuary

The textural composition of the material in the harbour area changes throughout the year, during pre-monsoon finer fractions can be found in the dredged channels because flow velocities are much lower during pre-monsoon Than during monsoon. These fine fractions are called mud or very fine silt. These sediments originate from the sea. During monsoon when the flow velocities increase the fine fractions are found in the approach channel and more coarser fractions are found in the approach channels. These coarser fractions have a fluvial origin. Throughout the estuary there is a tendency of more finer fractions near the outlet and more coarse fractions upstream. The grain sizes vary with phi is 10 near the outlet and a phi of 2 further upstream. The coarser fractions of the sediment considerably reduced after the construction of the Thanneermukkon bund because this bund traps a considerable amount of the coarser material from the four south most rivers. The clay particles found in the harbour area are mainly kaolinite and partly illite (Chandramohan 2002).

Estuarine features of the Cochin estuary

The Cochin estuary is as most of the estuaries inside a tide dominated estuary, the inlet on the opposite is a wave dominated inlet, also the shape of the estuary with is large and narrow barrier islands indicates that the system is a wave dominated system. Since the estuary has a smaller area then in the beginning of the 20th century, probably the tidal prism also reduced. Because of the length of the estuary this is not a certainty because the estuary is longer than a quarter of the tidal wave length, apparently at the closure of the Kuttanad region by the completion of the Thanneermukkon bund the Tidal prism has become larger. The fact that the outer delta became larger in the beginning of the 20th century can indicate a growing tidal prism, according to:

$$V_o = c_o P^{c_1}$$

with	V_o	=	the volume of sand in the outer delta
	c_o	=	the correlation coefficient situ-determined
	c_1	=	Coefficient close to 1,23

but also as indicated before the change from a stable flow passing estuary to a bar passing estuary can be the reason, because a smaller tidal prism makes r smaller in the formula of Bruun, 1978. Because there are no data available on the textural composition of the material then, no conclusions can be drawn from this fact.
After the dredging of the approach channel and especially the reclamation of Willingdon Island the tidal prism became smaller which can be deduced from the rapidly diminishing depths of the channels inside the estuary(Gopalan, 1993).
The tidal prism in the Cochin area changes enormously throughout the year. During the dry period of the year the Volume of water flowing in and out of the estuary is during spring tide around $50*10^6$ m^3 and during neap tide around $20 *10^6$ (Joseph, 1989). During wet season there is a huge difference between flood discharges and ebb discharges, these can be respectively $45*10^6$ and as high as $140*10^6$. For the empirical relations of the estuary a representative prism is demanded. In literature a prism of $9*10^7$ is customary (Frederic Harris, 1989). According to the discharges a smaller prism would be expected.
The cross sectional area of the inlet is approximately 5000 m^2. The coefficient is not exactly known for the Cochin inlet, but comparing this data with Figure 2.7 with a Tidal prism of $5,0*10^7$ an cross sectional area between 1672 m^2 and 9290 m^2 is expected, so the inlet is expected to be in equilibrium. (Watch out for the units in the figure they are in feet!). This assumption is supported by the fact that the inlet does not need maintenance dredging to keep this cross-sectional area.

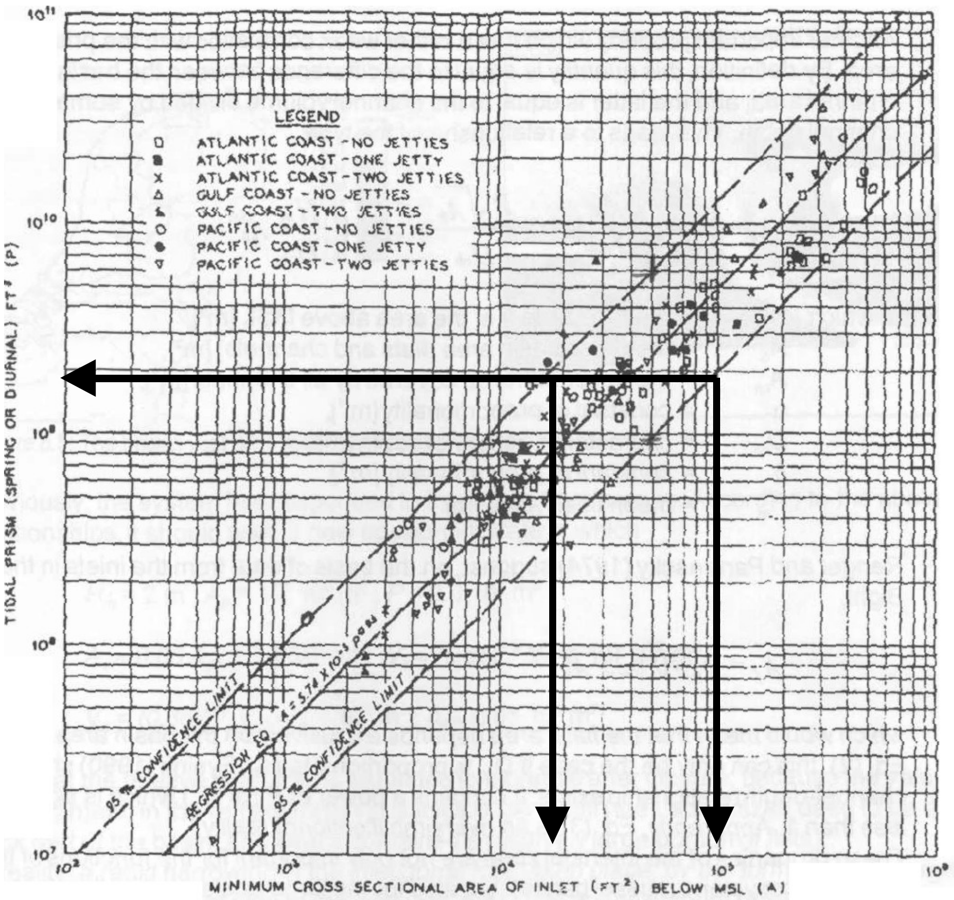


Figure 2.7 Tidal prism compared with cross-sectional area(Jarrett, 1976)

2.3.2 Problem analysis

Dredging

Because of the high siltation rates and the textural composition of the sediment the dredging volumes that need to be dredged from the bottom of the harbour area are very high though the density of this substance is very low (Mathew, 1994). Dredging has taken place in the Cochin area since the 1920's when the first approach channel was dredged, in the beginning only during the dry season maintenance dredging was carried out. When the harbour expanded through the years the dredging activity became larger and since the early 1980's dredging takes place throughout the year. The problems are the cost that are becoming so large the it's hardly comprehensible for the Port Trust. Also the maximum depth for useful dredging has almost been reached (Menon, 2002). Another problem is the dumping of the dredged material, this can give problems with the return of the polluted dredged material on the coast line and a longer journey for the dredgers if the material has to be dumped far away.
Throughout the years the method and place for dumping has altered. In the beginning the material was dumped at 550 meters north and south of the approach channel (Gopinathan, 1971), but research by the Cochin port trust demonstrated that this dumped material returned in the dredged channels and onshore. It was decided to move the dumping sides further up north and south so the material couldn't return to its original place. This process though affected the coastal stability of

the coastline south of the inlet of the Cochin harbour, with fierce erosion as a consequence. As a remedy in the early nineties the dredged material was dumped in the gut and was flushed out during ebb current, which kept the sediment in the system. This Dumping in the inlet created a lot of turbidity around the area what was seen as an insuperable problem for the environment, so this practice was stopped, although there were clear signals that this method prevented any more coastal erosion from happening.
Since then the material is being dumped 5.5 kilometres south and north of the approach channel and the coastal erosion has taken its old form again. This means that during the post and the pre-monsoon there is a building coast and during monsoon there is large erosion with an overall tendency for erosion. On the northern side of the inlet no erosion arises and there is even a matter of accretion, which can maybe be explained by the local currents that still transport the dumped material back to the coast.

Harbour expansion

Since the Indian economy is one of the largest growing economies over the world, the Port Trust decide the harbour has to expand to keep its position in the world market. Nowadays the port handles 12 million tons of cargo. Especially the shipment of liquid bulk is an important market for the Cochin port and plans are made to make a special dock only for the transhipment of this cargo. To allow larger carriers to unload in the Cochin harbour a floating dock in front of the inlet or an additional harbour on Vypeen Island can be constructed.
Because container transhipment is becoming more important over the world, the Cochin Port Trust granted Frederic Harris B.V. in 1989 the assignment to look at the possibilities for an additional container terminal on Vallarpadam Island. In 2003 the central government has granted the funds to start the construction of this additional container terminal. The construction has still to begin. The results of this extra container terminal for the morphological development are still unknown, but additional channels have to be dredged and the present channels have to be deepened. Undoubtedly this will have a large effect on the water flow in the estuary and the discharge distribution at the bifurcation point in the harbour. Another option is to move the container terminal at Vypeen Island together with the oil dock. Then an additional channel has to be dredged in front of Vypeen Island but the channels inside the inlet can remain in the same state or even become a little shallower.

Other socio-economic aspect

An important economical problem in Kerala state is the lack of enough power capacity, this results in numerous power cuts, unexpected as well as half an hour each night. This is off course not very favourable for the regions economic position since everything stops during such a power cut. The main source of electricity in Kerala is appointed by the Indian government, the remaining percentage of power has to be produced by the states itself. In Kerala the main source of electricity are the Hydro-electric power plants. The most power in Kerala is being produced by the Idrukki Power plant, which uses water from the Periyar river in a reservoir. These uses of water affect the water flow inside the estuary because they implement a delay in the release of the precipitation. Especially during monsoon this effect is noticed, since the peak discharge will be much smaller and the sediment movement even more since this is exponentially related. Also because there is a constant flow of fresh water through the estuary, the water is less brackish which influences the bio-diversity of the estuary.
Another problem for the Kerala region is the lack of sufficient construction sand because of restriction of the mining from sand out of the estuary and the coastal region. Because of this restriction this sand is now being won out of the rivers, which gives serious collapsing problems

in these regions, because of which people even have to move. Also the price of the sand becomes too high and this slows down the economic growth.
The soil inside the estuary and in front of the coastline contains a lot of very valuable minerals that are only a small percentage of the soil but could be very profitable for mining. Because of the mining restrictions these minerals cannot be won, which keeps a lot of potential economic profit for the region.
Another important problem mentioned above is the coastal erosion especially for the people who live very near to the shoreline. This coastal erosion is also caused by the dredging regime in the Cochin harbour. The dumping of the material on different places and keeping it in the coastal system could be a solution but the handling of this problem is out of the scope of this thesis, but will be kept in mind when less dredging is possible.

2.4 Thesis Objectives

After this short description of the general theory in case of tropical estuaries and a problem analysis on the Cochin area the major goals for this thesis can be defined. This thesis objective will be bipartite:

1. Developing a morpho-dynamic model for the meso time scale that can help with understanding and dealing with human interference and natural development in the future. By developing the model clearly keep in mind the applicability of the model and find out which characteristics have the most influence on the results of the model.
2. Understanding how some currently present situations effect the morphological development of the estuary by implementing them into the model and give some solutions for a number of coastal zone problems with the model and the knowledge of general coastal zone dynamics in mind.

Chapter 3: Estmorf

3.1 Introduction

In this chapter a description will be given of the Estmorf model used further in the present research, in the previous chapter the selection criteria for the choice of a model was explained and in the present chapter the basic equations of the model are explained. In section 3.4 a short review is given of the development of the Estmorf model and the current state of the model.

3.2 Why the Estmorf model

After the analysis about the problems that arise in the Cochin estuary concerning the morphological development of this area and the objective to give a quantitative analysis of the Cochin estuary, one has to figure out a way to come to this objective. Because the calculation of the morphological development in the scale of detail required in the Cochin estuary by hand is not possible, one soon makes use of available software packages for this kind of problem. With this software package it has to be possible to construct a model to satisfy the requirements of a model as they where put down in chapter 2. It is important to find a software package that is applicable on the Cochin estuary: does the model you develop contain the physical relations you want to investigate and are sufficient data available to set up this model, that contains the right physical relations. In the thesis objectives it was mentioned that the long-term morphological development of the estuary is the point of interest, in this relation long-term means decades. The scale of detail of interest are the large segments of the estuary, this means branches of a few kilometres are the scale of detail that we are interested in. This means that some large-scale empirical formulas cannot give sufficient detail in the development of the estuary, nor in time or in place. Estmorf does own the tools to model on this scale and in contrary to 3-dimensional models needs less detailed field data. Also for the long-term morphological development it is not necessary to implement all kind of small scale 3-dimensional phenomenon, since the scale (geometric and time) doesn't require such detail.

Since Estmorf in principle is able to model the physics in which we are interested and doesn't require the detailed data what in this research is not available, it is the model that will be used. As stated in chapter two the choice also depends on the availability and computational resources. The software package was made available by Delft Hydraulics and the computational resources were made available by the TU Delft.

3.3 Physical relations

The Estmorf model is a semi-empirical model, which simulates the morphological development of a channel network in an estuary.[4] The model is constructed with a hydrodynamic part and a morphological part. The hydrodynamic part makes a process-based calculation of the water movement. This is a 1-dimensional hydrodynamic model, which calculates the water movement by an average flow velocity over the whole cross-sectional area of the channel. It thus primarily calculates water volume shifts and thus is very well able to compare the influence of the tidal component and the river discharge. The hydrodynamic model that is used to describe the water motion with process-based equations is the Sobek model. The morphological calculations of the model are done by the Estmorf part. This part of the model connects the water movement empirically to cross-sectional areas and determines the equilibrium profiles for the different

[4] Helvert van, 2003 p. 1-1

branches. The model calculates the equilibrium profile when the area is in an equilibrium state with the relation.

$$A = c \cdot P$$

with A = Cross-sectional area under MSL
c = Calculated constant when the profile is in equilibrium
P = Tidal prism

This coefficient is first calculated by the model. The user has to determine if the cross-sectional area that is connected with this coefficient is in equilibrium and then leave the coefficient untouched or if the user determines the profile is too narrow/wide, he has to adjust the coefficient accordingly. This means a bigger coefficient for a too narrow profile and a smaller coefficient for a too wide profile. This is done by introducing an equilibrium concentration. The development of a specific area is determined by comparing this equilibrium concentration with the actual concentration. The equilibrium concentration is determined with the help of the global equilibrium concentration and the equilibrium profile. A larger concentration than the equilibrium concentration causes sedimentation, a smaller concentration than the equilibrium concentration causes erosion.
In Estmorf the cross-sectional profile is divided in the channel the low tidal flat and the high tidal flat. The transportation of sediment between different branches will only be through the channel. Only within a branch transport between the flats and the channel is possible. To define these different parts of the cross-section one has to define 7 points of the Cross-section to define the entire profile of the channel. This is shown in figure 3.1

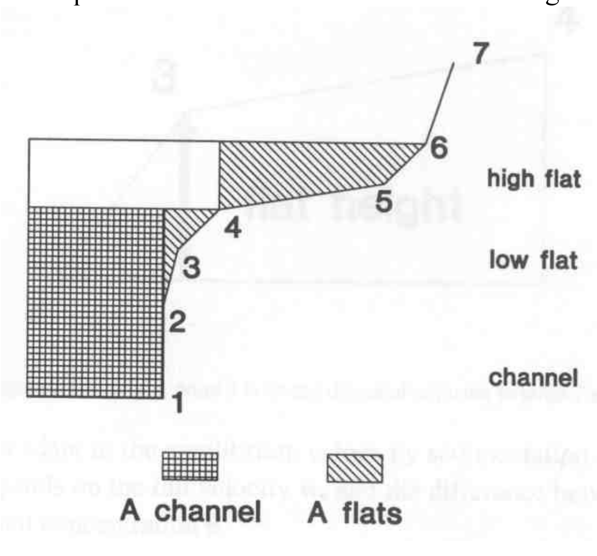


Figure 3.1 The representation of the Cross-sectional area in the Estmorf model[5]

The profile inside the channel has thus no importance for the model. The cross section is divided in a channel area, A_C, a high tidal flat area, A_H, and a low tidal flat area, A_L. The Low tidal flat area is determined by points 2-3-4, the high tidal flat area by 4-5-6, point 7 is an fixed reference point. Erosion or accretion at a certain branch is determined by the local equilibrium concentration according to the formula:

[5] Picture from Helvert van, 2003

$$S = w_S\left(c_e - c\right)$$

with S = Sediment flux
w_s = fall velocity
c_e = equilibrium concentration

This equilibrium concentration depends on the global equilibrium concentration:

$$c_e = c_E\left(\frac{A_{ce}}{A_c}\right)^{n_A}$$

with c_E = global equilibrium concentration
n_A = exponent determined by user
A_c = Cross sectional area
A_{ce} = equilibrium cross sectional area

This equilibrium profile (A_{ce}) is thus determined by the coefficients that were explained above. For the concentrations on the flats a same kind of formulation holds. However this will not be applied at the Cochin estuary because no tidal flats are present there, since all branches are surrounded by quay walls. The coefficient n_A has to be determined by the user and has in general a value between 2-5. This value is based upon the kind of transport formula that is used. For different sizes of grain diameter different formulas are available with different coefficient. Smaller grain sizes give a smaller coefficient.
The timescale of the model is determined by the global equilibrium concentration since this is the parameter that expresses the morphological activity of a certain area. This parameter can only be validated if there is some knowledge of the previous morphological development of the area otherwise the timescale on which the alterations have a tendency of happening is not a reliable factor.
The transport in the main channel is given by a one-dimensional advection diffusion equation. This diffusion coefficient can be used for calibrating the model and including 2-dimensional effects as stratification and waves inside the estuary, although this is off course not a real representation. That is why this coefficient can also be described as the garbage can coefficient. The equation is given by:

$$u\frac{\partial c}{\partial x} - \frac{\partial DA_c \frac{\partial c}{\partial x}}{\partial x} = w_s\left(c_e - c\right) - F_{lc}$$

with D = Diffusion coefficient
F_{lc} = The transversal flux to the low flat

Since the hydrodynamic model already excludes low tidal flats, F_{lc} is in the Cochin estuary model equal to zero. The only thing that changes in the Cochin estuary model is the depth of the different channels, because this is the only way the cross-sectional area can be adjusted.

3.4 A short review of the Estmorf model

The Estmorf model was developed under commission of Rijkswaterstaat to get a better insight in the long-term morphological development in the geometry of estuaries and tidal basins (Karssen, B. 1994). This model was particularly developed for the Western Scheldt and the Friesche Zeegat

and for periods of calculation of 50 to 100 years. These were both well-mixed estuaries and this kind of estuaries are thus the main focus of the model. The model consisted of a combination of the Allersma (1988) model and the equilibrium concentration principle of Di Silvio (1991). The Allersma model couples the sediment transport rate with the channel profile (Karssen and Wang 1991).
Because this model was made for estuaries and tidal lagoons, at first channels without tidal flats were not taken into account. An adjustment had to be made to make sure also channels without tidal flats can be modeled, this is also an interesting adjustment for the current application since the boundaries of the Cochin estuaries channels are mainly solid structures, i.e. quay walls.
Also the hydrodynamic support model changed through the years. First IMPLIC was used, since this was already the hydrodynamic model with which the Western Scheldt was modelled. Now also SOBEK can be used to model the water motion in the estuary.
Within the framework of this project has to be determined whether the model can also give a good long-term description of the morphological evolution of stratified estuaries or if further adjustments to the model have to be made to achieve this.

3.5 Limitations for the Estmorf model

The most obvious limitation for the Estmorf model is the fact that it is a 1-dimensional model, so no 2 or 3-dimensional effects can be directly put into the model. For the mixed estuaries for which this model was constructed this gives less problems than for a case where stratification and thus 2-dimensional flow plays an important role. Since the morphological development of the estuary is determined by empirical relationships the trend can be right, but these empirical formulations are most of the time based on linear 1-dimensional equations. In the case of the Estmorf model it is A=cP, it is not sure of these formulations are correct for highly stratified estuaries since it is not certain that the importance of the stratification is linear with the tidal prism. That's why it is important to find a way to simulate the stratification in the harbor area of the estuary. It at least makes it doubtful that in the equilibrium situation all the empirical coefficients are equal all over the estuary.
Another limitation of the Estmorf model is the fact that this model only includes processes inside the estuary, this is off course a limitation of all models because they have boundaries, but physical processes in the Cochin area like the mud banks cannot be simulated by the model and especially effects of the changes inside the estuary on these mud banks.
Since the Estmorf model has an empirical part in its formulations it is difficult to give absolute certainty about its results, since these empirical formulations have not been calibrated for the local situation and remain constant throughout the process, something what in reality may not be the case.
These limitations kept in mind; one should not forget to look at the results with a critical view to determine how reliable the results are and which marginal comment can be placed by the results.

Chapter 4: : Modelling of the Cochin Estuary

4.1 Introduction

In this chapter the actual model of the Cochin estuary will be explained. Most important is it to procure a model that provides as much possible insight in the process with the available data. The model consists of a hydrodynamic part supported by the Sobek software and described in section 4.2. Its output is used in the second part the sediment transport model supported by the Estmorf model. The hydrodynamic model will first be calibrated with tidal data received from India. Also a sensitivity analysis will be performed, this analysis will focus on the results from the Sobek model. This sensitivity analysis will be carried out to find out which characteristics have the most influence on the results in the model. Another sensitivity analysis has to be done when this hydrodynamic model has been put in the Estmorf software. In section 4.3 the hydrodynamic model will be put in the Estmorf software and also the boundary conditions for this model will be set, after which the first model runs can be done.
In chapter 2 already the applicability and the limitations of several types of software and models were discussed. In chapter 3 it became apparent that only a 1-dimensional model can satisfy the limitations for the Cochin case; this has the advantage that less detailed data is necessary to construct such a model, but the model can give less detail in its results and certain more dimensional phenomena cannot be represented. These limitations have to be kept in mind during the construction of the model but certainly when the cases are implemented in the model in the next chapter.

4.2 The Hydrodynamic Model

As explained in the previous chapter the model consists of a hydrodynamic part and a morphological part. In this section the hydrodynamic model will be constructed, following a certain schedule. The steps of construction are first to give a schematisation that can satisfy the assumed objectives of the model, this has effect on the scale of detail of the model and the area of interest. The model has to be detailed enough to handle the problems that were presented in chapter 2. After schematisation where the limitations of the model become obvious a beginning can be made with calibration and validation. Calibration will be done with the parameter where the most data are available; the validation will be done with same sort of data from different seasons or years. Because the data that were collected don't have the scale of detail that was expected before the visit to India a sensitivity analysis will follow the validation phase. This sensitivity analysis is done to see which elements of the model have the biggest effects on the results of the model. This can be useful information to do some recommendations to any follow-up research and to determine the weaknesses of the model, which have to be kept in mind when making the conclusions.

4.2.1 Data collection

In this section all the data that were procured in India and in Holland will be presented. This is done to give an insight in the data that was used to construct the model that represents the Cochin estuary. First an inventory will be made about the necessary data and the order of detail. The order of detail of the data depends on the order of detail you want to make the model in and vice versa. This means it is more important that the different data sources are of the same order of detail than that all information has to be of great detail, certainly when keeping in mind that only long-term changes are treated. The aspect with the least detailed data is probably responsible for

the accuracy of the model as a whole. The necessary data for the hydrodynamic model is tidal data preferably along more points in the estuary, river discharge data, geometric data of the whole of the estuary and some data to determine the friction inside the estuary.
The tidal data that were obtained was half-hourly water level observations from Willingdon Island; see for the location appendix 2.1. This water level data were registered by a tide gauge. Willingdon Island is close enough to the outlet to say these measurements are equal to the water level outside of the estuary. These data were from 1989-1994. Twelve months spread over the year were put into electronic files to use for calculations. Also data were available for the months June, July and December 2002 and January and February 2003. Also data for these months were provided with hourly water level observations at four different locations along the estuary. These measurements were taken from 6-18h. The order of accuracy of the tidal data on the seaside is very good; the data inside the estuary places us for harder problems. As mentioned in chapter 2 the tide in the Cochin estuary has an important diurnal component, this is difficult to visualize because of the fact that only 12 successive hours of data are available, especially reflection and amplification are hard to discover in the available data. Since the diurnal component has large effect on the reflection and amplification this is a serious absence. A lot of times the maximums of the day are at the boundaries of the available data, 6 am or 6 pm. This gives no insight in the period of the wave inside the estuary.
River discharge data were available as monthly averages for the years 1980-1993. These data are thus hard to combine with the available tidal data. First of all the data are not hourly or daily so no variances within the month can be distinguished. This especially gives problems with the water level observations in the estuary, since these are influenced by the tidal motion as well as by the river discharges. The monthly variations can be big since the monsoon is whimsical in its course and very rainy days can be followed by very calm days.
The bathymetric data from the Cochin estuary were hardly available; values of the bathymetry were available in detail in the harbour area. These measurements where made available by the Cochin Port Trust and read from the admiralty chart, further upstream no data were available. This would be taken care of by a small-scale field survey, but funds that should be available were not available in the end. From the Cochin Water Office some bathymetric measurements necessary for navigation were obtained. These were very global measurements rounded on whole numbers and one measurement per few square kilometres. Geometric values are obtained from the admiralty chart and are thus not of a very detailed scale. One fieldtrip was undertaken to see how the estuary looks in general, hereby it became apparent that quay walls bound the channels of the estuary, see Figure 4.1.

Figure 4.1 Quay walls around the Cochin Estuary

4.2.2 Schematisation

Prior to the set-up of the hydrodynamic model first an inventory was made of the available data that can be used to set-up the model as explained in the previous section. Since the data retrieval in India did not provide the expected material, crude assumptions, regarding some areas of the geometry, bathymetry and the river discharges, have to be made and only an overall sketch of the estuary can be determined. Keeping this in mind too detailed schematization would give an unjust idea of accuracy. Since the Estmorf model only discerns channel area, high and low tidal flats, the inner profile of the channel has no effect in the model. Since all branches in the Cochin estuary are bounded by quay walls these can be modelled as rectangular profiles.
The important physics that are represented in the model is the hydraulic motion inside the estuary, the tidal propagation, the river discharge and the reflection effects on the end of the estuary. Keeping this in mind one should choose boundaries where artificial effects in the water motion are minimized.
The schematization of the estuary is given in Figure 4.2 and appendix 2.1. Focus has been placed on the southern branch of the estuary, because this branch is the largest and the most eminent sites are situated in this branch (i.e. The harbour and the Thanneermukkon bund). The northern branch is not focussed on in the model since the data that were received from that side was minimal; no information of the tidal propagation was available in the northern branch.

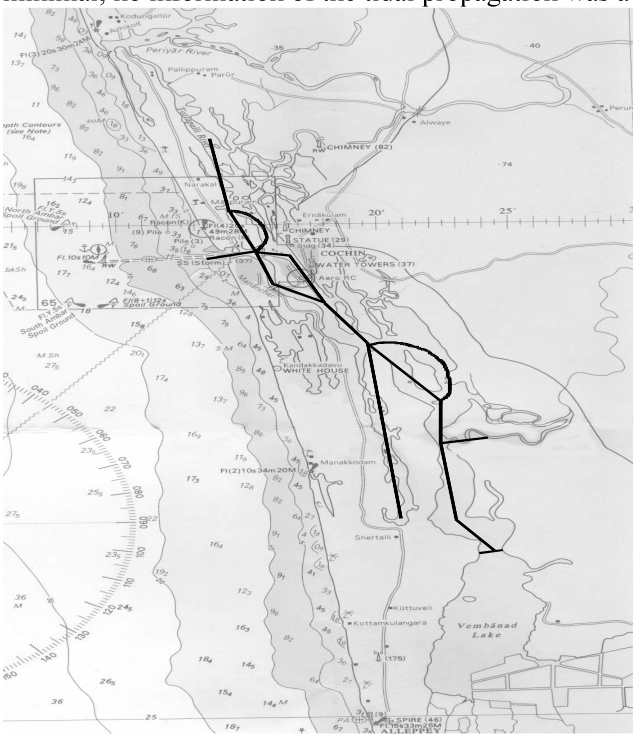


Figure 4.2 schematization estuary of Cochin

Because for some of the side branches little information on their bathymetry was available and they are really shallow they are presented as storage areas. This term should not be seen in the way that a storage area has an equal water level everywhere and there is no flow inside these areas, but it means no main focus is paid on these areas and their main purpose is to model the volume of water they can store. Also no river discharge will go through these branches. The storage areas are represented by dead end areas with no discharge, because no detailed

information is available about their bathymetry mainly attention has been paid on the area of these storage areas and their shape, to see how much water they can store. So no specific attention is paid to their depths. They are also important by determining the tidal prism of the whole of the area.
The boundaries of the modelled area have been determined on the Periyar River and the Thanneermukkon bund. These boundaries are chosen because the area of interest is covered and no artificial reflection effects are implemented in the model, because on these points dams are both in the Periyar as in the Thanneermukkon area. During dry season the tide is reflected on the Thanneermukkon bund, during wet season this doesn't occur. To prevent this from happening in the wet model there is an extra branch south of the Thanneermukkon to make sure this boundary has no reflection effects on the model. Because of the large difference between wet and dry season, different discharges but also different boundary conditions (e.g. the opening or closing of the Thanneermukkon bund), separate models are constructed for the wet and the dry season.
There are five boundaries in the model. The inlet (1)[6] takes care of the inlet of the tide in the model. This is also the boundary that fixes the water level (the downstream boundary). The upstream boundaries are the Muvatthapuzha River (2), the Periyar River (3) and the southern rivers (4) (only in wet season) where a river discharge is given. There are also some closed boundaries without any river discharge, the end of the Aroor storage area (5) and the Thanneermukkon bund (6) (in dry season). Here the discharges are the fixed values in the model; at the dry season model this means the discharge is zero. These points are indicated in the maps of appendix 2.1.

4.2.3 Calibration

In the Calibration phase a first set-up of the model is made, to do this first a rough estimate of the values for the different quantities is made. The calibration is done with tidal data and with qualitative statements known from the analysis of the Cochin estuary as presented in chapter 2. For the roughness a fixed Chezy coefficient is taken, $C=55m^{1/2}/s$, the bathymetry and geometry are taken from the available maps. In this section first a calibration run is made with no river discharge and a semi-diurnal tide.

RUN 1: Calibration run (Tidal amplitude 0.45, no river discharge)

For the calibration of the model a case is chosen with a standard semi-diurnal tide. There is no river discharge and the Thanneermukkon bund is opened. This can be the situation in December just before the bund is closed. 0.45 meter can be seen as high tide for the Cochin estuary and in Chandramohan 2002 some values for the propagation of the amplitude from the tide for the tidal amplitude of 0.45 meter are given, see Table 4-1.This high tide is also chosen because during high tide the tide has a more semidiurnal character.

[6] For these references see appendix 4.1

Station	Distance from sea (m)	Node	Observed levels HW	Observed levels LW	Computed levels HW	Computed levels LW	Observed Tidal Ranges	Computed Tidal Ranges
Gut	0	0	0.45	-0.45	0.45	-0.45	0.9	0.9
Aroor	14200	32	0.36	-0.32	0.36	-0.33	0.69	0.69
Vaduthala	16000	**	0.32	-0.28	0.33	-0.27	0.60	0.60
Thanneer-mukkon	39700	136	0.13	-0.10	0.16	-0.07	0.23	0.23

Table 4-1 Calibration results Cochin estuary7

In this calibration run the model will be set up with an overall friction coefficient, the friction is determined by the coefficient of Chezy. The overall Chezy coefficient was first put on 55 $m^{1/2}/s$. This value is determined by using a value of the Chezy coefficient in correspondence with comparable situations. There are more accurate ways to determine the friction coefficient, but because this coefficient depends on a lot of things, for instance the grain size and the bottom shape, too exact estimates would be worthless, since no data on these characteristics are available. During the calibration it became apparent that the lowering of the tidal amplitude became to severe in the downstream area, so for the harbour area a higher value for the Chezy coefficient was taken because this seemed to give the model better results, this seems in accordance with the fact that the material in the harbour area is much finer than the material further to the south in the estuary. A higher coefficient of the Chezy coefficient means a lower resistance from the bottom. The bathymetry was used as the dependent variable because of its insufficient data. Especially the bathymetry in the southern region has been adjusted throughout the calibration process. This because little detail of data was available for this area, the final values give good results in the Thanneermukkon bund measurement point. In the sensitivity analysis later in this chapter changes in these values will be implemented to see their effects on the model results.
The computed results from the model are also given in Table 4-1. Keeping in mind the available data the model results are quite accurate compared with the observed values. In appendix 4.2 the results of this calibration run are found. Also some qualitative information about the tidal discharges (Chandramohan, 2002) is available since in that research not exactly the same tidal data were used that are used here only the ratios can be used. The ratio between the discharges in the Mattanchery channel and the Ernakulam channel has to be one to two, because two times more volume of water flows through the Ernakulam channel than does through the Mattanchery channel, because Ernakulam channel is much deeper than Mattanchery channel and thus has less bottom friction. The model also represents this ratio correctly.
Another quantitative statement is the Mattanchery channel has to be a flood channel and the Ernakulam channel an ebb channel. As explained before a flood channel is a channel, which has more inflow than outflow for an ebb channel it is the other way around. The model correctly represents this characteristic, see appendix 4.2. Also the cross-sectional area at chart datum, lowest low water, can be compared with the available data and displays a correct image of the estuary.
To characterize an estuary it's useful to know which velocity is higher the flood or the ebb, through the daily inequality of the tide it already seems the flood-velocities are higher than the ebb-velocities, because flood is shorter but more peaked. Apparently also with a standardized semi-diurnal tide the flood velocities are higher than the ebb-velocities. This estuary can be called a flood-dominated estuary in this situation. This means sediment is transported into the estuary; this will be explained later in the sensitivity analysis.

[7] Observed levels originated from Chandramohan 2001

RUN 2: Validation run (real tidal data, River discharge monthly average)

After the calibration run, the validation is done by comparing the model with real tidal data of June and July 2002 retrieved in India, at places along the estuary. These data give hourly water levels along the Cochin estuary. The only problem with implementing these data is the lack of detailed river discharge data. Only monthly average data of the river discharge is available for the years 1980-1993. To implement the river discharge in the model an average is taken for this discharge. So the graphs of the model run and the observed values can only be compared superficially and a more variable pattern can be expected at the real tidal movement upstream of the estuary than the model representation of the tidal movement. The variable water level pattern is of course enhanced by the wind set-up, which is also not implemented in this model. Also the effect of wind set-up or shower oscillations in the harbour area where the external tide was measured are not taken into account. This can be seen in the plot in appendix 4.3. No real adjustments were done on the model during this validation run, since the model results where quite coherent with the observed results, considering the lack of detailed river discharge data. The amplitudes and the phases seem quite correct only the reference level seems wrong, especially in the Thevara case. It can be seen that the first few days there was not much water run off because the reference level in reality is much lower than in the model run. Later during the month the water discharge presumably became larger resulting in a better fit between the model run and reality.

RUN 3: Validation run Thanneermukkon Bund Closed (tidal amplitude 0.45, no river discharge)

During dry season (from January till May) the Thanneermukkon bund is closed and the river discharges are almost equal to zero. This run was performed to see the effect of the Thanneermukkon bund on the system. This bund brings a new physical phenomenon into the model, the standing wave. This wave originates from the reflection of the tidal wave onto the Thanneermukkon bund, because the length of the estuary is not long enough to develop an entire standing wave, so there are no real troughs and nodes. The amplitude at the Thanneermukkon bund does become bigger than when there is no development of a standing wave what happens in the wet season. A total standing wave would exist if the tidal basin was a quarter of the wavelength of the tidal wave. The tidal prism is bigger in this situation than with the bund open because of the effect of the standing wave exceeds the effect of the smaller area. The first fear of the higher siltation rates in the harbour was unfounded as is represented by the model, because velocities in the harbour area are now higher than they were before, see Figure 4.3. This means the tidal prism has become bigger than before the construction of the Thanneermukkon bund.

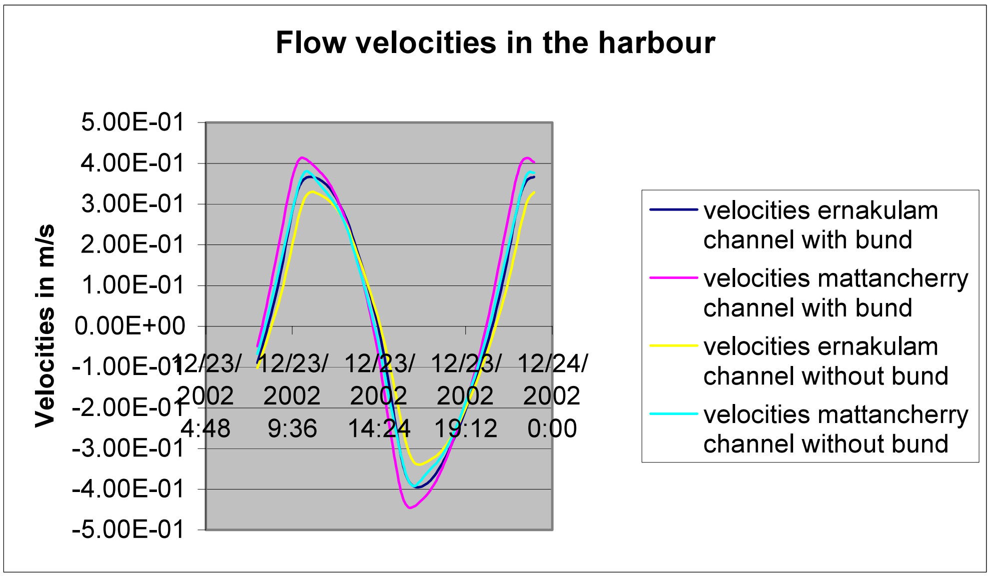


Figure 4.3 flow velocities in the harbour area

RUN 4: Validation run Thanneermukkon Bund Closed (Real Tidal Data, no river discharge)

This run is performed to observe whether the model parameters that were validated with the open bund are also correct for the closed bund. For this run the observed water levels inside and at the inlet of the Cochin area from January and February 2003 were used. Differences in comparison with the dry season real tidal data could occur because of an annual pattern in the dredging activity and siltation. But as seen from the results of this run the values from this model run represent the real situation quite well, see Appendix 4.4. Only the results in Thevara don't seem to coincide with the model results but the reference level seems to be wrong here as can be seen from the earlier runs in this chapter. The results are even better in accordance with observed values than in the wet period; this can be explained by the lack of river discharges in this period, so no big fluctuations in the water level caused by changing weather circumstances are present in the observed model, but the wind set-up or sudden showers can still cause unforeseen fluctuations. This was a problem in the validation in the wet period where large fluctuations occurred, because of the variable river discharge.

4.2.4 Sensitivity analysis

The sensitivity analysis is performed to determine the importance of the different parameters on the results of the model, as said previous in this chapter this is particularly important in this case because the lack of sufficient detail and the high degree of schematization. First the two most important external forces of the water motion are discussed subsequently the geometric parameters (bottom friction, bathymetry). In the end the features of the estuary are discussed with the help of the model.

<u>Tidal amplitude</u>

First in the sensitivity analysis one of the external forces is changed, the seaside amplitude or the period of the tide. This is done to see how the estuary reacts on different tides like there are in reality, because the different values that are taken do all occur in reality. The change in period is

also important to observe because in the Cochin area the diurnal component plays an important role. This change in period occurs in reality when the diurnal tide is dominant during low tide and semi-diurnal tide during high tide. The tides are represented by sinusoidal waves. First these changes are implemented in the wet season model. In this wet season model the river discharges were set on zero to let the tidal amplitude only be influenced by the geometry, like said before this situation can occur during December. These boundary conditions are chosen to prevent the influence of combinations of tide and river discharge have effect on the results. Since the river discharge can change depth and certainly tidal propagation throughout the estuary.
A conclusion is that the amplification factor through the estuary is not equal for all amplitudes but diminishes with growing amplitude. This relation has the form of a power function. The velocities do diminish linearly with decreasing amplitudes. This could be suspected since the discharges decrease linear with the amplitude of the tide. During dry season the amplification factor and the velocity have the same character as during wet season, see Figure 4.4. The power decreasing of the amplification factor has to do with the fact that the southern branches have a strong friction component, because of their shallow character, contrary to the harbour area where the amplification factor is more or less constant and the friction component less eminent.

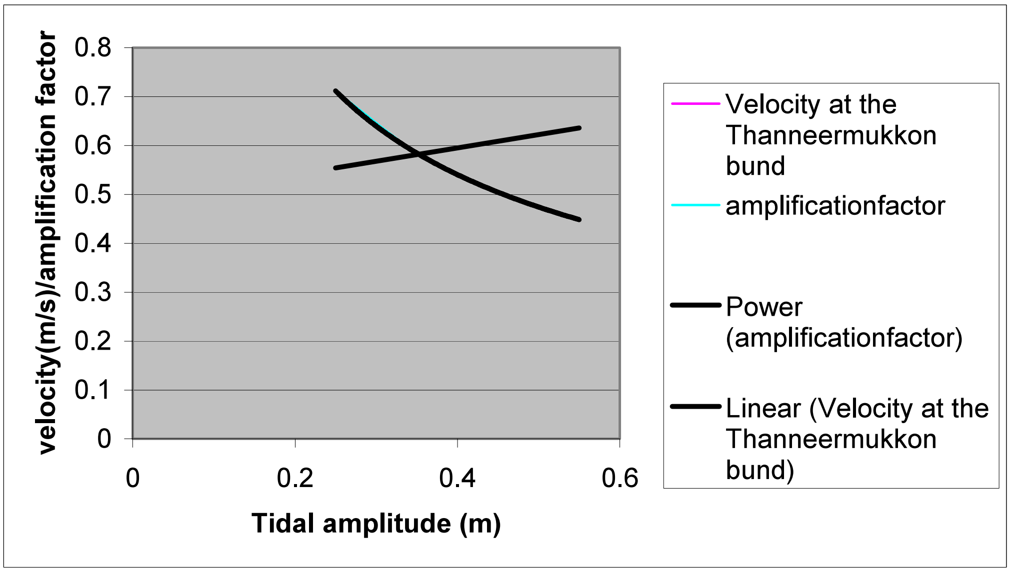


Figure 4.4 Amplification factor and velocity in the Cochin estuary

Now the period of the tidal wave is changed from a semidiurnal to a diurnal period. Also the season is changed to dry season to see the effect of the different period on the reflection on the Thanneermukkon bund. It is interesting to see which period has a more standing wave character and how the amplification factor differs.
To see if a standing wave principle can be expected first the wavelengths of the diurnal and semi-diurnal tidal period are calculated. The average depth in the estuary is taken as 3,5 metres under mean sea level. The wavelength of a shallow water wave is, in a simplified case were the flow area is taken rectangular:

$$L = cT = \sqrt{gd} \cdot T$$

with L = Wavelength
c = Wave velocity
T = Tidal period
d = Average depth (=A/B, in this rectangular case)

This means the length of the semidiurnal wave is 264 km and for a diurnal wave twice as long 529 km. When the Thanneermukkon bund is closed the length of the basin is circa 40 kilometres, a fully developed standing wave arises when the length of the basin is a quarter of the wavelength, this is not the case here. If the Thanneermukkon bund is opened the basin length is 55 kilometres then the semi-diurnal wave could form a standing wave. This doesn't happen because of the geometry of the basin, the end of the basin is namely too shallow and thus because of the friction no fully developed standing wave will exist. With the bund closed the storage area approximation, which is applicable from a basin length of 1/20 of the wavelength, seems more applicable on the estuary. This storage area approximation means that the water level is almost horizontal throughout the basin and the phase difference is almost zero. The model confirms this with little dimming towards the end of the model and a small phase difference near the Thanneermukkon bund. Because a closed bund goes more to a storage area approximation the amplification factor is much higher than during wet season when the bund is opened. With the diurnal tide and the closed bund the tidal prim almost came to its maximum of twice the amplitude times the area of the estuary. This tidal prism was $95{,}12*10^6$ m^3. It seems that the values of $9*10^7$ m^3 or even $141*10^6$ m^3 found in literature[8] is improbable during dry season, because this diurnal tide normally arises during low tide and not at such a high tide with an amplitude of 0.45 meter. The tidal prism during wet season is $86{,}7*10^6$ m^3; this is the average of the flood tide and the ebb tide. With semi-diurnal tide the prisms are $57{,}1*10^6$ m^3 in dry season and $54{,}5*10^6$ m^3 during wet season. Probably the tidal prism for the diurnal tide is much smaller than the values found here since the diurnal tide normally occurs during low tide and the semi-diurnal tide during high tide.
With the calibrating of the model there was not reckoned with the difference in flow pattern during the diurnal tide and the semi-diurnal tide. From the water level measurements across the estuary it became clear that the storage area approximation is even more present than seen in this model simulation. In appendix 4.3 one can see that the real amplitude is bigger during diurnal tide than was calculated by the model. Why this is the case is not obvious, maybe the wind set-up plays a role in this.

River discharge

Another external force of the estuary is the river discharge. In this analysis the effect of the river discharge on the tidal propagation and the velocities in the harbour are checked. The tidal propagation is investigated because the river discharge is expected to have great effects on this propagation. Since the river discharge data are not very detailed and the validating was done with the help of the tidal propagation it is important to see its effect.
Also the velocities in the harbour are investigated because it is interesting to see if total out flushes can still exist besides the deeper channels. In chapter 2 it already became clear that in the past total outflushes of salt water occurred. This means even in the harbour area no salt water is present and the estuary can considered as a fresh water lake. No definite statements can be made on this topic with the help of this model since two-dimensional processes play an important role in the intrusion of salt water. The salt water current flows namely underneath the fresh water into the harbour area. This is important not for the 1 dimensional model but this physic has important effect on the sediment current and the environment since the system is during this out flush is totally ebb-dominated and all the polluted soil can be exported outwards
It's interesting to see that the river discharge when average has hardly any influence on the tidal envelop. This means the effect of the tidal propagation inwards dominates the effect outwards pressure of the tide by the fresh water discharge. This average discharge is taken by averaging out

[8] Frederic Harris B.V. 1989, Chandramohan 2002. In the last report a different definition of tidal prism is seemingly used of the volume of water flowing in and out of the estuary inlet during 1 tidal period.

the monthly discharge data for 1980-1993 and all of these through the Cochin estuary system except for the Periyar where half is taken, because the other half goes through the Azhikode opening. The Thottapally spillway is not taken into account, since its effect is minimal.
The amplitude at the Thanneermukkon bund even increases during low discharge, than when no river discharge was present. This can be explained by the fact that the water level rises because of the river discharge, which procures the lower resistance and thus a higher amplitude at the Thanneermukkon bund. Only when the river discharge is as high as the peak monthly discharge, which can be a situation during very wet years, the discharge effect becomes so big the tidal amplitude decreases significantly to half the amplitude further upstream at the Thanneermukkon bund then it has with no river discharge. From this it can be concluded that the validation with the tidal propagation with average discharge is a just method, because the monsoon during the measurements (June 2002) was an average monsoon. Only at very high discharges the validation is corrupted. This means the amplitudes can be compared during an average monsoon, maybe with the exception of very high discharge weeks that can occur every monsoon. The mean level does change through the river discharge and is harder to represent with so little data.
The velocities in the harbour show a higher ebb-velocity what could be expected, because the river discharge initiates a large ebb current but no disappearance occurs of the flood velocities as sometimes happens with a total out flush of the salt water, when a standardized semidiurnal tide is used with an amplitude of 0.45 meter.
This is tried out with a real tide from June 2002 and a peak discharge. It can be seen that during low tide there are no flood velocities and only ebb-velocities that can explain the total out flush of the salt wedge. During high tide it is seen that there are always flood velocities and thus intrusion of salt water. The velocities that are discussed here are cross-sectional averaged velocities; two dimensional currents patterns are not taken into account, while these are very important when salt-water intrusion is discussed. The results of these runs can be seen in appendix 4.4.

Friction

In these runs the effect of the bottom friction on the results of the model is examined. Since the friction coefficient was not very accurately determined, it is important to investigate its effect on the results of the model. If becomes apparent that differences in this coefficient have great influence on the model results it should be considered to do more detailed research to the bottom roughness in the Cochin area.
For the test with the friction coefficient a comparison is made with an overall friction coefficient of 50, 55 or 60 $m^{1/2}/s$, because of the small grain diameter smaller Chezy coefficients are not expected, also the difference between the friction in the harbour and the friction further upstream are neglected. All these runs are done only in the wet season model, because no big differences are expected between the reactions of the two models on the change in friction coefficients. There are no river discharges in the model runs.
Because the friction plays a more important role in the southern part of the estuary than in the harbour area the adjustment in model results is most obvious in the southern areas with an increase of the Chezy coefficient from 50 to 60 the maximum discharge goes down twenty percent. When the Chezy coefficient goes up from 50 to 55 the discharge goes down ten percent, see Figure 4.5. These numbers indicate that the southern area of the estuary is friction dominated, something that also became apparent when the tidal amplitude was altered. In the harbour area this friction dominance is less apparent but because there is a smaller tidal prism, because of the friction in the southern part, also here the discharges become smaller.

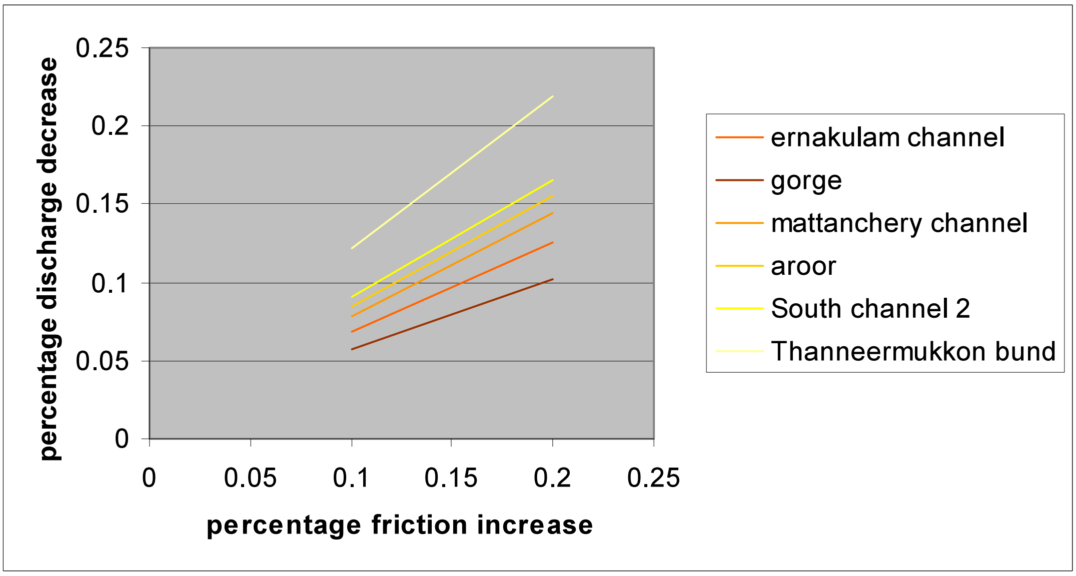


Figure 4.5 Percentage increase friction/percentage decrease discharge

After these runs it can be said that the bottom roughness is very important in the southern part of the estuary. If further research would be done this area is the main interest when the bottom friction/parameter is concerned, this could be expected because this area is much more shallow than the harbour area.

Storage area

In this section the storage areas as they were defined before will be treated, because with these areas we are quantitatively unfamiliar and it will be investigated if effects in these areas have large effects on the results in the areas that we are interested in.
First there will be a test what happens if the depth of the southern storage area, which is only in the wet model, is deepened. It was set in the main model to be 1 meter because no accurate data was available for this area and the most important feature this storage area should have was volume of water storage. In the results of changing the depths in the southern storage area.

Depth Southern Storage area (m under CD)	Amplitude at the Thanneermukkon bund (m)	Total tidal prism (Mm^3)	Ebb tidal prism southern storage area (Mm^3)
1	0.205	54.5	28.8
2	0.204	54.3	29.0
3	0.208	54.2	29.0
4	0.211	54.2	28.9

Table 4-2 Sensitivity analysis Southern storage area

From the table it is seen that difference in depth in the southern storage area has hardly any effects on the results of the model. The results of the prisms never differ more than 1 %. The depth in the southern area is therefore kept on 1 meter below CD.
Also an extra storage area, see maps in appendix 2-1, that sometimes fills during wet season near the south of Willingdon Island will be investigated in this section to see what effect this storage area has on the water movement and especially the tidal prism for the entire area. The additional storage area has a width of 1 kilometre and the length of 3 kilometre, this causes the tidal prism to grow from $54,5*10^6\ m^3$ to $55,8*10^6 m^3$. This is 2,4 %, it is seen that a storage area near the inlet of

the estuary has a large effect on the water movement in the estuary. This means that the storage areas near the Cochin inlet have a higher priority to be investigated than the storage areas further upstream. Since this area is not permanently filled with water and it is not known when it is filled with water it is not taken along in the definite model, but one should bear in mind the large effect of this storage area on the results of the model.

Depths in the southern areas

The analysis of these depths is done because the data that was available for this area was very little. There were only depth measurements every few squared kilometres, which were rounded on whole numbers. Because of the lack of data of this area the profiles in this area where the most adjusted values during the calibrating phase. In these runs one branch a time is made shallower. First the dry season is checked, when the branches are made more shallow the tidal prism grows. This happens because a more shallow profile gives a more standing wave in the southern area and this standing wave is responsible for the larger tidal prism, the results of deepening can be seen in appendix 4.4. For the wet season this argument isn't fulfilled, since then there is a long branch south of these branches, of which the depth prism relation is given in the previous section. It is seen that the A-P curve, the curve that compares the cross-sectional area with the tidal prism, gets more steep when going more south, but it is not yet so that a shallower branch gives a larger prism like in the dry season. Since most branches are already in the steep part of the curve a change in depth would not give a large difference in water movement except for branch South_3, see appendix 2.1, where a small increase has rather large effects on the tidal prism. This can clearly be seen in the Appendix 4.4. From this can be concluded that it is most important to take depth measurements in areas where a change in depth has large effects on the water movement, as is here the case in branch south_3. When a field research is done this area this branch has priority.

Qualitative analysis of the Cochin estuary

Another part of the sensitivity analysis is the determination of the characteristic of the estuary so there can be a qualitative analysis about the estuary and it's development, because it is important to see if some of the features are influenced by the lack of sufficient data or by the limitations of the used model.
The first thing is to determine if the whole system is ebb-dominated or flood-dominated, this can be determined by viewing the sediment flows. This characteristic of the estuary is very important because it decides for a large part the morphological development of an estuary. Because the model doesn't represent any sediment fluxes, the sediment flux has to be related to a parameter that is modelled. The flow velocity is a parameter that is represented by the model, since the sediment flux depends on a higher power of the velocity it can be checked how the sediment flux will be. This velocity is an average flow velocity but assuming the flow pattern throughout the depth has no significant changes because of variances in velocity this value is accepted as a related parameter to the sediment flux.
The fact that the soil has a critical velocity before moving occurs by the water is not taken into account. If the velocity in the gorge and the harbour area is checked the velocity directed outside is higher than inside. This because the water level and the discharge are in phase with each other and the maximum outflow thus coincides with the lowest water level, this effect has thus to be overcome by the higher peaks of the flood velocity to get the expected flood-dominance. In dynamic systems like an estuary the power of the velocity in a formula to roughly check the sediment transport is equal to 3.

$S = au^b$

with a,b = Coefficients
S = Sediment flux
u = Average velocity

To get an impression of the dominance of the Cochin estuary, the hydrodynamic model is used to observe the velocity in the Gorge. The tidal observations from some months from the tidal data from the years 1990-1993 are used. This period is long enough to include all the main features of the tide so that a reliable indication of the type of dominance is obtained.
After these runs it seemed that the system is a flood-dominated system. This means there is from the tidal forcing more influx of sediment than outflux. This can be reduced by the river discharge in wet season because this is always directed outside, but it means that during dry season when the river discharge is almost equal to zero the system is flood-dominated according to the average flow velocity. This is in accordance with the fact that the most of the siltation during dry season inside the harbour comes from the mud originating from the sea. During the monsoon when the average velocity in the gorge is dominated by the river discharge the sediment flux is directed outwards, which is supported by the fact that the highest siltation rates are then in the approach channel. Also can be observed that during low tide when the diurnal component is more dominant, the system is more ebb-dominant and during high tide is more flood-dominated. To clarify why there is siltation inside the harbour during the dry season also the tidal dominance in this area has to be investigated. Also from these runs it seems the dominance in the Ernakulam Channel and the Mattanchery channel is a flood-dominance. The peaks in the flood-dominance is thus high enough to overcome the effect of the in phase being of the discharge and the water level.
The siltation rates are even expected to be bigger than calculated by these model-runs, because the flood-dominance is enhanced. This can be explained with the earlier discussed stratification. During post monsoon a salt wedge is formed which induces a current inwards the harbour area. The two-dimensional flow patterns, especially during post-monsoon when stratification is largest, are proven by the flow velocity data taken by Rasheed (1996), who did current velocity measurements in the harbour area throughout the year. It can be concluded that if any process based morphological development calculations would be done in this area more research has to be done into the field of the 2-dimensional flow and siltation patterns.
From the change in dredging volumes and especially the ratio between the Mattanchery channel and the Ernakulam channel it can be concluded that the Mattanchery channel used to be more of a flood channel than it is now. This will be checked by changing the ratio of the depths of the Mattanchery channel and the Ernakulam channel. This is also interesting when in the future the inner channels are deepened with different ratios as a consequence to see how the dredging volumes will change.
If the Ernakulam channel is made more shallow like how it used to be before 1983 Mattanchery channel has more flood dominance than in the current situation also the tidal prism through Mattanchery channel is in proportion to the tidal prism through the Ernakulam channel. This can explain why there was much more siltation in the Mattanchery channel then in comparison with the present situation. If any changes in the depths of the channels would be made one should keep this in mind.

4.2.5 Summary hydraulic modelling

After the calibration/validation runs and the sensitivity analysis it can be concluded that the model together with the available data form a fair diagnostic tool for to the next step of the project, the morphological modelling. Since the morphological model Estmorf uses a

standardized tide with a constant period, the most important next step is to decide a representative tide and representative river discharge from the hydrodynamic model.
From the sensitivity analysis it became apparent that more research to the bathymetry in the upstream areas needs to be done, because with the data now it was difficult to get a reliable model because changes in these areas have large effects on the results. The bathymetry in the northern area should be measured more accurately to give the model more applicability in this area. Since the Southern storage area is covering quite a large area of the estuary and is responsible for effects like the origination of a standing wave more research in this area would also be useful.
Daily discharge data from the rivers in the area would be useful to better validate the model, because variations within a month were now not represented and made the validation process quite harsh. For the implementation in the Estmorf model this is not very important since an average discharge is needed there.
The friction has large effects on the discharge especially in the southern areas and should therefore be investigated more accurately, because this is a hard parameter to accurately determine this has no priority when a follow-up research is done.
The tidal data was fairly complete, especially for the order of detail in which this research is performed.

4.3 The Morphological model

After finishing the hydraulic model now the second part of the model the morphological model has to be constructed. The Estmorf software that was treated in chapter 3 supports this morphological part.
First the adjustments that have to be made because of the change of software will be discussed, subsequently the data collection concerning the morphological part will be discussed. Thereafter a begin can be made with setting up the morphological model which ends in calibrating the morphological model, since no more data are available there will not be a validating phase in this research, but in the end a sensitivity analysis is done to help us understand which additional data are most important. After this sensitivity analysis the model can be used for some cases in the next chapter.
The hydrodynamic part that was constructed in the Sobek software is used by the Estmorf software as follows; the hydrodynamic calculations from the Sobek model are copied by the Estmorf model, while in the Estmorf model the period, which will be copied, is defined. This can be defined in the Estmorf.inp file, of which is a copy in Appendix 4.5. One can determine if a diurnal or a semi-diurnal tide is dominant. Also all the geometry and the hydraulic conditions are taken from the Sobek model.
The purpose of modelling the Cochin area was to model the development of the estuary in terms of decades and the reaction of the estuary on human interference. Bearing this objective in mind it is useful to repeat the limitations of the Estmorf specifically on the situation at the Cochin estuary.
The physical processes in the sea cannot be represented by the model; especially in Cochin where because of the mud-banks the seaside concentration can change rapidly this should be remembered. So the case that all of a sudden a mud-bank can drift into the estuary cannot be taken into account and also the effect that changes in the estuary have on these mud-banks is not taken into account.
Also variations through the cross-sectional area cannot be physically represented in a 1-dimensional model, like in the Cochin case stratification cannot be modelled directly. A solution how to model these effects has to be found when proceeding with the model. Also one of the cases in the next chapter will be dedicated to this problem.
The model considers one grain-diameter for the entire estuary with one fall-velocity. This is in reality not the case and in the Cochin area the same concentration doesn't mean the same

sedimentation rate because of flocculation inside the harbour area. Bearing these limitations in mind an inventory is given for the necessary and available data for the Estmorf model.
Before implementing the Sobek model in the Estmorf model some small adjustments have to be made concerning the data input and the stability of the program. Also the source code of the Estmorf model does not support the exported files from the Sobek model.
The adjustments are the seven point profiles, wherein the flats are defined, which aren't necessary in the Sobek model, but are in the Estmorf model. The points will be optimized within the Estmorf model itself. Since calculations in Sobek are at first sight stable even with high Courant numbers, for Estmorf this is less obvious, so this Courant number is changed. The Courant number is:

$$c\frac{dt}{dx} = Courant\ number$$

with c = Wave velocity
x = Grid distance
t = Model time step

This Courant number thus says something about the stability of the model. It is important to keep the Courant number small to procure stability of the model and get accurate results without too large numerical errors. Because the calculations in Sobek are much shorter only a few months than in Estmorf, a few decades, the courant number for the Estmorf calculation was brought down from 13 to 4. This was also done because of unstable behaviour of the Estmorf model discussed later in this section.
Another adjustment is the fact that the Estmorf source code cannot read a node to have as a reference a zero, while Sobek thus appoint zero to a node, this has to be changed in some files before the Estmorf model can run. Also in some of the copied files the order of the lines has to be changed to successfully run the Estmorf model.

4.3.1 Data collection and analysis for the morphological modelling

The important parameters for the setup of the morphological model are the morphological development of the estuary during the last few decades, the concentration in the estuary and of course the parameters that were already implemented in the hydraulic model.
First the morphological development of the estuary is checked. This will be done with the help of articles written throughout the years to give an overall view of the development of the estuary. Also dredging data can give a useful indication on the morphological development around the estuary.
Because the model is calibrated on the dredging volumes it is important to see how they were obtained and processed, so the dredging data has to be analysed before it is implemented. Data from 2002 from the local port authorities was obtained. These are daily dredging volumes for several ships, these were not all ships that were working in this area at this time, but from all ships the volume is known so the volumes have been extrapolated to get a total image of the dredging volumes. Each day there are more than 6 maintenance-dredging trips.
The dredging cycle is as follows. First the material is dredged from the Ernakulam Channel, the Mattanchery Channel or the Outer Channel, and then the ship sails to the northern or southern dumping place to dump its dredged material. These dumping places are 5 kilometres out of the coast north and south of the Outer Channel.
The density of the dredged material, which is primarily mud, is quite low at 1.2 times the water density, this because spill from the dredger is not allowed because of turbidity demands. When spill is allowed the lower density mixture can be replaced by a denser mixture increasing the

overall density of the dredged material. It is safe to say that the highest density that is dredged from the bottom of the channel is equal to the density of the soil on the bottom of the harbour area. In the Outer Channel the sand that is available there increases the density to values of 1300 kg/m^3, in the harbour area the value doesn't come above 1250 kg/m^3. This will be said to be the value of the density in the harbour. This density gives the soil a porosity of 0.85. This done by the formula:

$$n = \frac{\rho_k - \rho_g}{\rho_k - \rho_w}$$

with n = Porosity
ρ_k = Grain density
ρ_g = Soil density
ρ_w = Water density

This value for the density is a normal value when dealing with silt and so is the porosity.
During the monsoon not all the time dredging is possible due to the rough weather that can be present in this period. The dredging data will be put in monthly averages because this is the amount that has to be implemented in the dredge file. Also when the annual variation of the dredging was observed it was noted that the dredging is almost constant throughout the year. Since dumping only occurs outside of the estuary no dumping has to be included in the model. First the ratio of dredging trips is made between the outer channel, the Ernakulam channel and the Mattanchery channel. It is seen that 45% of the dredging trips is in the outer channel, 35 % in the Ernakulam channel and 20 % in the Mattanchery channel. When this is compared with the volumes that are dredged from the different channels, 51 % of the total dredged volume comes from the outer channel, 29 % from the Ernakulam channel and 20 % from the Mattanchery channel.
What is note worthily is the fact that during the night the density of the dumped material is much higher than during the day, but the cycle is evenly long, why this is, is not clear, maybe during the day the busier ship traffic hinders the dredging equipment. Since the outer channels are not included in the model these volumes are not taken into account, when the model is made.
The volumes of solid soil that where dredged from the Mattanchery channel and the Ernakulam channel are respectively 27000 m^3/month and 36000 m^3/month. These average monthly totals were calculated by averaging out the annual volume over the months, so no seasonal changes are implemented in these data. In the available data there was also not seen great seasonal variance in the dredging volumes. In the Mattanchery channel compared with the tidal prism relatively more sediment is being dredged. These dredging volumes without porosity mean that a volume of 180000 m^3/month is dredged from the Mattanchery channel and 240000 m^3/month is dredged in the Ernakulam channel. These values are of importance because the input files of Estmorf want the dredged volumes in cubic metres in situ. To give an idea about how much dredging is taken place. These volumes mean an annual siltation of 80 centimetres at the Ernakulam Channel and 128 centimetres in the Mattanchery Channel. These results are subscribed by available literature.[9] Relatively the most dredging is thus in the Mattanchery channel. This means that the equilibrium cross-sectional area in the Mattanchery channel should be much smaller than the actual cross-sectional area. Further the morphological development of the area that is described in literature was already treated in chapter 2. The information lacking is the information on the development since 1983 when the big dredging operations in the harbour area took place. On comparing the data before this date and the scarce data after this date it seems that the siltation process is still continuing but not at the rate before the mayor dredging in 1983. In Table 4-3 a global

[9] Mathew, 1993

comparison of values of depths over the years is given. This is a very global comparison because the real data from 1930 and 1980 were not available but taken from Gopalan, 1983.

Sector	Depth ca.1930	Depth ca. 1980	Depth 2002
South of barrier	8-9	3-3.5	Unknown
Between barrier and Vaikom	8-9	3-4	4-6
Between Vaikom and south Paravoor	7-9	4-5	3-4
Between south Paravoor and Aroor	5-6	3-4	2-4
Between Aroor and Willingdon Island	7-8	7-8	5-7
Cochin harbour area	7-8	dredged depths	dredged depths
Bolgatti to Cherai	3-4.5	2-2.5	1-4
Cherai to Munambam	3-6	2.5-4	2-4

Table 4-3 Maximum depths comparison

Also some data on the concentrations in the Cochin area were needed for the morphological part of the model. This information is needed to determine the range of the equilibrium concentration. Some concentration measurements throughout the estuary were obtained and from the reports of Rasheed (1997) and Ajith (1996) values throughout the year in the harbour area were obtained. The range is determined on 50 mg/l-200mg/l. For Estmorf the volume percentage soil with porosity water is important. Some assumptions have been made for this the weight of only soil is 2650 kg/m^3 and a weight of the bottom including water of 1250 kg/m^3 which gives a porosity of 0,85 as explained above. The range for the equilibrium concentration is then from 0.00013 to 0.00050. This is the way the equilibrium concentration is described in the Estmorf.inp file. From the upstream regions there are some measurements that especially during dry season indicate a much lower concentration.
After these morphological parameters also the boundary conditions in the hydrodynamic model have to be determined. Since the boundary conditions of the water movement are not dominant in the morphological development nor the time scale of the changes, values have to be taken that represent a right tidal prism around the estuary. Important is doing this consequently, because changes in the amplitude during the modelling can have large effects on the morphological development, because then the coefficients are no longer correct since the tidal volume has changed; also the ratio between the tidal amplitude and the river discharge has to be well represented. In the following table the tidal amplitude the river discharge and the initial tidal prism are presented. The tidal prism is calculated in the Sobek model, this can be compared with the values for the tidal prism at high tide found during wet and dry season. Since the semi-diurnal tide is especially dominant during high tide, the choice for a higher tide seems justified.

Period	Tidal amplitude	River discharge	Tidal prism
June-November	0,45	916 m^3/s	54,5*10^6
December-May	0,45	0	57,1*10^6

Table 4-4 Water motion boundary conditions

The higher ebb discharge cannot compensate for the lower flood discharge, so the tidal prism shrinks during the wet season when an average discharge is applied; this is not the case when peak discharges come into play. These figures correspond with the measurements done by Joseph and Kurup, 1989. The river discharge is the average discharge during monsoon with half the Periyar discharge and the whole discharge for the other rivers. The river discharge is set to zero during dry season because only the Muvatthapuzha River has then a discharge through the Cochin inlet, but this discharge is negligible.

4.3.2 Setting up the model

The model that is used here was explained in chapter 3 here only the available data was implemented. The set-up of the model will go as follows; first the initial conditions have to be determined and will be implemented in the model. The morphological history of the area is not yet included in this phase. This part is the same both for the wet season model as for the dry season model. Then both models will be tested on their stability, after which the morphological history is implemented and the calibration phase can start.
When using the morphological model, first the initial conditions have to be determined. The initial hydrodynamic conditions follow from the hydrodynamic model and are discussed above. The initial conditions for the morphological part of the model that have to be determined are the transport formula that is used, the dispersion coefficients and the empirical coefficients for the different branches.
First the transport formula that is used will be chosen, this formula is responsible for the coefficient n_A, Engelund-Hansen the formula for suspended transport gives n_A=4, the Meyer-Peter-Muller Formula for bottom transport gives n_A=2. The value that will be used here is n_A=2, since as explained above the power of the velocity in an estuary is like the Meyer-Peter-Muller Formula 3.
The diffusion coefficients has an order of the distance one water particle travels during half a tide times the average velocity times a coefficient:

$$D = \alpha L u$$

with D = Diffusion coefficient
α = Coefficient between 0-1
L = Normative travel distance for a particle
u = Average velocity of the particles

The coefficient is put on 0,5 after consultation[10], because this value is not really determined for the Cochin area. The Normative travel distance is the distance a particle travels during half a tide this is 10 kilometre in this case. The average velocity is in this case 0,5 m/s, this gives a diffusion coefficient of 2500. This value will be taken for most of the branches with a very low diffusion coefficient in the branches of which one side is closed, i.e. the Thanneermukkon bund and one of the storage areas.
The Estmorf software calculates the empirical coefficients from the formula that connects the tidal prism with the cross-sectional area for each branch. When the program has calculated the coefficients and the water levels, the model is ready for further usage.

The first run will be done with the coefficients calculated by the Estmorf software to check the stability. Initially only the coefficients of the Ernakulam channel are changed since the highest dredging volumes inside the estuary are found here. This is done to see how the model reacts on a minor change in coefficients. When the coefficient is changed the two models (the Estmorf software and the sobek software) have to find a new equilibrium for the whole system. When he Estmorf model changes the cross-sectional area the Sobek model changes the tidal prism this

[10] Wang (2003)

cycle continues till both the Estmorf model and the Sobek model have found a coefficient, where both models satisfy their relation:

$$A = c_1 P^{c_2}$$

Then a new equilibrium is formed. The derivative of the Estmorf graph is the equilibrium coefficient. The derivative of the function drawn by the Estmorf model is a constant, because the Estmorf model works with the empirical formula A=c*P. The coefficient c depends on the tidal period and the critical velocity of the bed material. As an approximation one could say:

$$c \approx \frac{1}{T \cdot u_{cr}}$$

with u_{cr} = Critical flow velocity
T = Tidal period

This means the coefficient is not constant in this area because the diurnal tidal component plays an important rule. This can however have a stable cross-sectional area for the whole time, because if the c gets two times smaller because of the tidal period is twice as long the tidal prism could get two times as big because more time is available to fill the estuary. This is however not the case in the Cochin estuary where as seen before the tidal prim doesn't become twice as big from an increasing tidal period. This means that fluctuations in the cross-sectional area through the month can be expected. Since there is no information on the variance of the cross-sectional area throughout the month this statement cannot be quantitatively checked here, but could give some useful information about the dredging cycle, since the cross-sectional area is expected to be smaller during low-diurnal tide than during high semi-diurnal tide.
In reality the function is not a linear function but more an exponential function with as an asymptote the area of the entire estuary times twice the tidal amplitude. The stable point is the intersection between the two graphs. When the coefficient is changed the Estmorf line gets steeper or less steep. This means a new stable point has to be found, this is the intersection from the new Estmorf line and the Sobek line. In Figure 4.6 the graphs are shown in the initial situation.

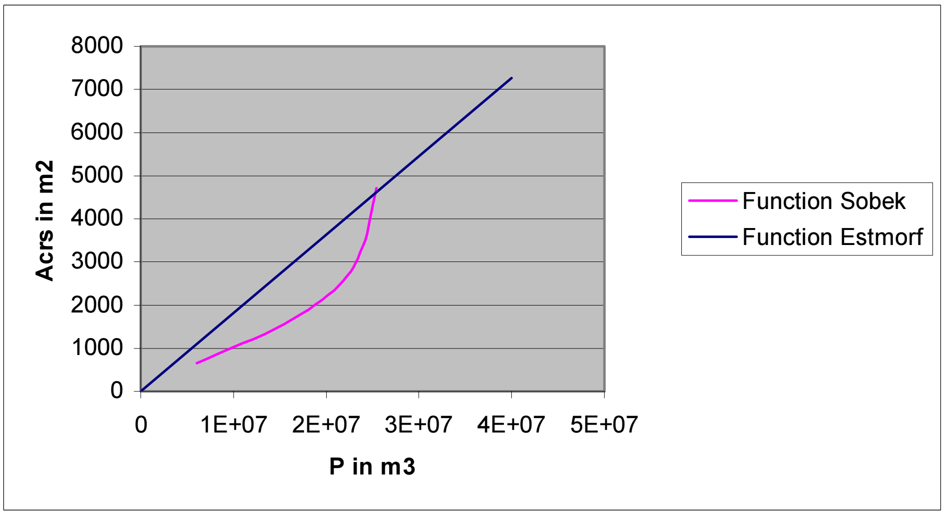


Figure 4.6 Relation cross-sectional area /Tidal prism

The problem with the first few runs when the coefficient of the Ernakulam Channel is decreased in the dry season model is that when T goes to infinity the southern part of the estuary siltates which is not in agreement with the theory presented before. At least when the coefficient is not changed drastically, then the total sedimentation could occur, because the slope of the Estmorf line becomes very flat. But the model also gets complete sedimentation when the coefficients are adjusted slightly. When the morphological activity for the entire model area is raised by increasing the equilibrium concentration, this effect becomes even more apparent. This run in the dry season model is presented in Appendix 4.5.
This effect is not the expected effect nor is it a confirmation of the above-presented theory, so apparently the model doesn't seem to represent the physics correctly. This gives primarily two options the model parameters have to be changed or the estuary is in fact unstable because of an unstable A-P function. This last option means that the estuary is also physically unstable, which can be the case since as stated before the tidal prism is relatively small when the cross-sectional areas it has to keep open are observed.
To check if this unstable behaviour of the Estmorf model comes from the large Courant number in the Sobek model, this number was adjusted as stated in the introduction of this section. Although this gave some small changes in the Sobek output that was implemented in the Estmorf model the last period was not really different nor were the results in Estmorf. The theory behind the model is assumed to be correct, so it is assumed that not a mistake in the model is the reason of the unstable behaviour.
Because the dry season model is still unstable it is checked whether one of the branches has an unstable A-P curve, which would indicate that the estuary during dry season is in reality unstable, This could be the case since in reality there is not only a dry season but also a long season and the instability does not occur on short terms but only in the long term. What an unstable A-P curve means will first be explained here.
As explained before the Estmorf model and the Sobek model have a different relation between the tidal prism and the cross-sectional area. The intersection between these curves is considered the equilibrium situation. When the curve in the Sobek schematisation has an exponential shape it means that with a small disturbance the system goes back to its equilibrium situation, this means this situation is called stable, see Figure 4.7(b). When the shape of the curve in Sobek has a logarithmic shape it means that wit a little disturbance the system or goes to closure or goes to infinite width, this means that in this case the system is called unstable, see Figure 4.7(a). This can be compared with the theory of Escoffier, the unstable situation is the left point or unstable equilibrium point in the Escoffier graph the stable situation is the right point or stable equilibrium point in the Escoffier graph as presented in section 2.2. Since Estmorf defines the equilibrium point without checking the water movement, the place of this point on the A-P curve in Sobek determines its stability. The first thing we do now is to check whether one of the branches in the Cochin estuary has such an unstable branch to explain why the system is unstable. This is done by changing the depths in the Sobek model and thereby calculating the tidal prism. This is of course a first approximation because in the Estmorf model the whole system changes and in these checks the rest of the system remains the same.

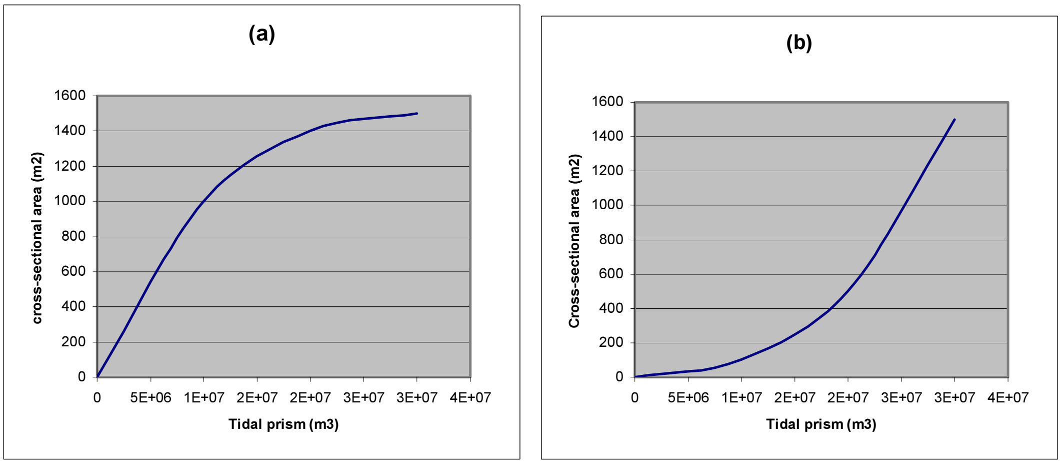


Figure 4.7 Instable A-P curve (a), Stable A-P curve (b)

There were two shapes found of A-P relations in Sobek, the first one is the known exponential curve. This curve is found in the downstream area and thus in the harbour area. The other curve is seen in Figure 4.8; this curve is near dead end branches. The interesting thing is what we have already seen in the sensitivity analysis is that with a deeper profile the tidal prism doesn't always increase but can also decrease. The point where the tidal prism is extreme is probably the depth at which this specific branch contributes most to the existence of a standing wave.

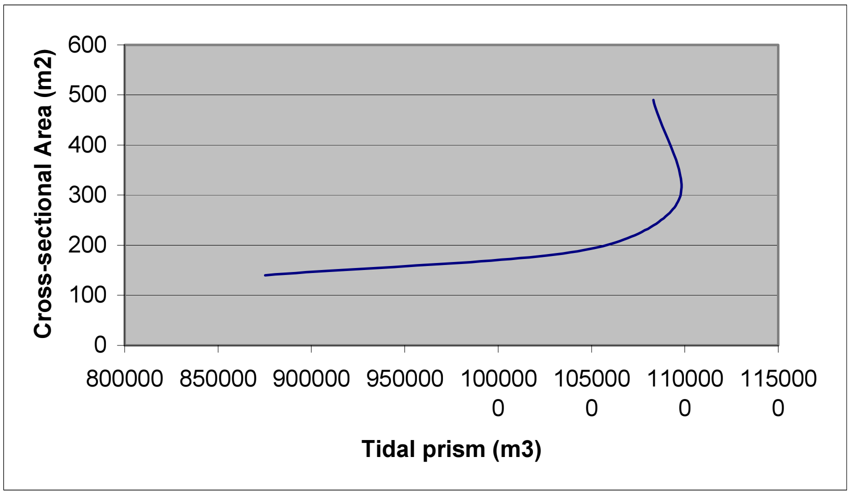


Figure 4.8 The A-P relation in the upstream closed branches in dry season

This is not the shape, which was expected to give instability, and when reflecting on this shape it shouldn't give instability. One of the branches has a shape that could cause this instability. In the Storage area_2 branch the shape of the curve is almost a straight line as can be seen in Figure 4.9. Also the Estmorf curve for this point is added and it can be seen that these two lines almost have the same derivative, so this can explain why a small distortion in this channel can lead to an unstable behaviour, because if the Sobek curve is moved a little to the left the new intersection point will be far away from the current equilibrium point and a small adjustment can have big consequences then. Because this branch seems to be the unstable branch it is turned off for the rest of the calculation. This is a possibility in the Estmorf software. This can be justified as long as the changes in the adjacent branches are not to be big so we can't expect any major changes in this branch either. Also this branch is a storage branch so the representation can be quite

inaccurate. As said before the instability can be also in reality, what is the problem tough is that the instability occurs because of a branch without any serious bathymetric data. Because as seen in the explanation about instability in appendix 4.6 a small increase in depth, which could well be the case makes the model stable again. Also the south_1 branch is just stable but because this branch plays an important role in the hydrodynamics of the estuary it is not switched off and with the fixing of the storage area_2 branch the model reacts stable on small changes.
This check is left with the notion that the dry model on its own has an unstable character. Later in the combined model this stabilized dry part will be implemented because with large changes this instability can have effect quite fast. In appendix 4.6 there will be explained something about the stability of the Estmorf model with the help of an example.

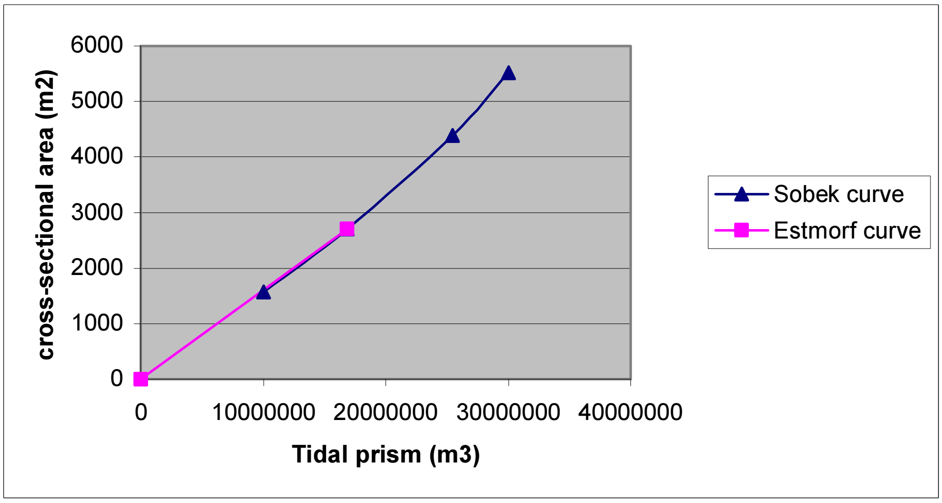


Figure 4.9 The A-P relation for Storage area 2

After the check on the dry model and its behaviour now the wet season model is checked, in contrast to the dry season model the wet season model seems to give stable results. When the depths in the harbour area are changed slightly, made shallower. Also the Southern branches become more shallow what results in a larger tidal prism, see above, and thus in a deepening of the harbour channels. This is a long-term process because first the depths in the harbour area become smaller. Maybe the stability of the wet season model and the instability of the dry season model even each other out and thus make a stable model. As duration for each model 4 years or 96 morphological time steps are chosen. This is an arbitrary choice, but it seems defendable, because it doesn't seem too long to corrupt the sedimentation pattern and not too short to prevent errors with the data-shift and the much higher calculation time. Because the time step is quite long it is determined to keep the storage area_2 turned off during modelling keeping in mind the limitations stated above.
Shifting the data from the one model to the other can be a time-consuming affair as well can be failure sensitive, because mistakes with the shifting of files are readily made. But using the dry-season model and the wet-season model separately could severely damage the results since the water movements will alter according to the profile of the channels. Also with the instability of the dry season model it doesn't seem a good idea to only use this model.

Figure 4.10 Combined morphological model for twenty years

At the first test in a period of twenty years the model seems stable, see Figure 4.10. The same test is done but than changing the model after 192 time steps, this gives errors up to 2% in comparison with the shifting in 96 time steps in the harbour area. It is assumed that a smaller shift time makes the error smaller and although per case treated in the next chapter the time step has to be determined the shift in 96 months seems to give reasonable results.

Now the morphological history can be implemented so it has to be decided which areas of the estuary are in equilibrium and which are not, based upon this fact the coefficients can be altered. The problem arises that some of the areas might be in equilibrium because other areas are artificially kept on a certain depth. This problem occurs because the higher siltation rates in the artificially maintained channels draw sand from adjacent branches. At first this phenomenon is neglected and only at the end of calibration phase this phenomenon will be taken into account. From a qualitative point of view it can be said that the harbour area is in the present situation not in equilibrium, the large amount of dredged volume is a result of this fact. Also if coefficients that are calculated by the model are out of proportion with the other coefficients this is an indication of a non-equilibrium situation. In the Cochin model the last observation at first sight only goes for the Muvatthapuzha branch, since this is a branch that is made purely for modelling reasons only to give the influx from the Muvatthapuzha river it's correct momentum this doesn't seem a problem. Also during the wet season the coefficient gets a more reasonable value, which is in compromise with the fact that the discharge of this river is than larger. After the determination if the models if we can work with the model or not the specific characteristics that determine the morphological development of the Cochin area have to be implemented. These are the dredging volumes, the equilibrium concentration, which determines the morphological development and the morphological timescale. The morphological history can be implemented by changing the coefficients in the Estmorf model. This also has to be done with the help of the dredging data because this is what keeps the current bathymetry in equilibrium.

4.3.3 Calibration

In this section the calibration of the morphological model is explained after the explanation how the model of the Cochin estuary works in the section above.
First the coefficients in the harbour area will be determined, for this run the coefficients in the other branches are kept constant. The coefficients are determined by keeping the cross-sectional area constant when implementing the dredging data. The coefficients that have to be determined concern the Ernakulam channel and the Mattanchery channel. The coefficients will be compared with a cross-sectional area close to the harbour of which it is known to be in equilibrium. The outlet is chosen, because from literature it is known that this cross-section is in equilibrium (also by measurements during the years), the difference is that this coefficient in the harbour has to be distributed evenly over the two channels, because they form a network. The coefficients of the two inner channels are together a little bit smaller than the coefficient of the outlet because without the dredging in the harbour area this cross-sectional area would be a little bit smaller.
Now the ratio between the coefficients in the Mattanchery channel and the Ernakulam channel has to be determined. From the tidal prism one would expect a ratio of 1:2, but because of the relatively large dredging volumes in the Mattanchery channel one would expected a higher ratio, because the profile of the Mattanchery channel is presumably more too wide than the profile in the Ernakulam channel.
When the new coefficients are set for the Mattanchery channel and the Ernakulam channel and the siltation/erosion pattern is the same, that is the ratio, for calibrating the model the equilibrium concentration is used. This equilibrium concentration determines the timescale of the morphological development and thus the time for filling up the dredged channels.
After a value is found for the equilibrium concentration that gives good results in the dredged channels, the coefficients for the adjacent branches have to be determined again, they also will become a little bit smaller, because their current depth is also determined by the dredging in the harbour channels. This procedure has to be done for the wet and the dry model, after which the different coefficients have to be checked if their values can occur compared with the expected values. The final coefficients can be found in appendix 4.5.
What is notable about these coefficient are the rather large coefficients in the southern region, especially if you consider the coarser material in this area, while coarser materials usually are expected to have smaller coefficients because they have a higher critical velocity. Probably the stream (b_s) width in these upstream branches is not the entire width but only a small part of the cross-sectional area, in the rest of the cross-sectional area the current velocity is probably lower.
When the separate models are checked the models will be combined to form one model. This means the results from the wet model will be implemented in the dry season and then this model will run. It is now the task to find out after how much time this change of model has to occur if no big alterations would be in the final results of the model.
The equilibrium concentration for both models is not equal; this seems strange because this undermines the idea that one overall equilibrium concentration causes the equilibrium for the area. On the other hand this could be suspected since the morphological activity inside the estuary is much higher during the dry season than during the wet season. The theory doesn't necessarily say the morphological activity has to be constant throughout the year but throughout the area

4.3.4 Sensitivity analysis

Since no data are available to validate the model, a sensitivity analysis is done directly to check which data are necessary to refine the model if follow up research would be done. The data that will be checked are the data we received, the dredging data, the morphological development but

also some of the results of the model will be checked if one of the assumed coefficient is change, this concerns the diffusion coefficient, the fall velocity and the boundary principles.
First we discuss the actual received data starting with the dredging data.

Dredging data

It was seen during implementing the data that the actual density of the bottom material that determines the porosity can have large effects on the exact volume of the dredged material. The way how this is done in this report assumes a skilful way of dealing with the dredging and a specific method and environmental demands, this means that no spill will be allowed and that as little water as possible is sucked into the dredger. For the time being this method is considered to be used since the results of the density coincide with the expected value. To see what kind of order of effect a change in the results of the model the density of the bottom material is changed from 1250 kg/m^3 to 1300kg/m^3. This means the porosity goes down from 0.85 to 0.82 this means the total volume of dredging goes down from $42*10^4 m^3$ to $35*10^4 m^3$. So an increase of the density of the bottom material of 4 % gives a decrease in dredged bottom volume of 16,7 %. This means that giving this variable a high degree of accuracy in measurement can pay out a lot when comparing the model results.

Concentration

Since the equilibrium concentration is the calibration factor precise measurement of this variable is not necessary. Even though it would be nice to have a certain range in which this coefficient can be. This range is in this research quite big, but it was taken from studies (Rasheed, 1997, Ajith, 1996) that took precise measurements in the area of interest, it is seemingly difficult to make a smaller range and considering the application of this variable also not very necessary to determine the concentration exactly. In this analysis in the stability model it will be checked what doubling the equilibrium concentration from 0.0004 to 0.0008 does with the timescale of a change in the estuary. In this run for one branch the coefficient is changed, this is in the Ernakulam channel. The results for this run are in appendix 4.7. It is seen that the semi-value time from the 2 different runs goes from 24 months to 12 months with the increasing concentration. This decrease in semi value time was expected so the model correctly represents this. Because the equilibrium concentration is not directly in the formula but in a subtraction this relation of doubling the concentration to halving the semi-value time doesn't hold for all values. But if $c_e >> c$ than it does hold this means when fast sedimentation occurs. This check is done another time for $c_E = 0.0002$ and $c_E = 0.0001$ and there also the sedimentation process is twice as fast with the double equilibrium coefficient.

Morphological development

It is very difficult to implement the morphological development of the estuary with such scarce data of the bathymetry through the years, especially in the period after the dredging operations in the early 80's. As we saw before the bathymetry seems somewhat on the over-dimensioned side when we look at it from a morphological point of view. There should be done some exact bathymetric measurements now to compare these values with the measurements over the years, because the maximum depth is known but about the average depth very little is known. Since these data were not available, the assumption that is the most convenient to take is to say that the area is now in equilibrium and thus to give the model not the necessary morphological hind cast. When proceeding with the model in long-term calculations one should keep in mind that a morphological development that was initiated a long time ago can still play a severe part in the current morphological development.

In this sensitivity analysis from the data about the bathymetry in the southern branch it will be tried to make a morphological prediction of its development in the future. To do this some of the coefficients in the southern part will decreased and the effect on the entire model will be checked. This run is done in the wet model with dredging, because no branch in this southern area is fixed in this model and the effect on the dredging in the harbour, will it increase or not, can be taken along.
From this run it seems that a decrease in depths in the southern area causes an increase in depth in the harbour area, this because a decrease in depth in the southern branch causes the creation of a standing wave and thus a higher tidal prism in the harbour area. Also some sediment from the harbour area is used for the higher siltation in the southern areas. In appendix 4.7 one can see the increasing depths in the southern area, these are lines with the highest depths. In the southern branch it is more difficult to see so a different plot is added where it becomes more obvious that they are shallower.
From this analysis it can be concluded that the model is very sensitive for changes of depths in the south by changing the coefficients, since these areas are not very accurately measured and not a lot is known about their morphological development, this is a difficult point in this model. One can say the changes in the model were quite big up to 10% and that the morphological development is probably not this fast, but still if we use table 4.3, it can be said that a decreasing depth of half a meter as in this example is not extraordinary. What can be seen is that on first sight this seems to have a positive effect on the dredging volume, but it should be realised that the equilibrium profiles in the harbour area would have been even smaller if this morphological history was taken along.

Diffusion coefficient

After treating the data and their influence on the results of the model now the coefficients on which normally the model is calibrated are discussed. There are many ways to express the diffusion/dispersion in a model. In this research an assumption is made that the diffusion equals the distance a particle travels with average speed through the estuary, but there are also different theories, which have very different outcomes. To see what kind of effect a change in the diffusion coefficient has, this coefficient is brought down from the now used 2500 to 1250 and the results are compared in the model with the dredging to see how the southern branch react than on an increase of the dredging volume with the different diffusion coefficients. Expected is that the southern branches react faster on the dredging if the diffusion coefficient is higher because the connection between the branches is stronger with a higher diffusion coefficient. This could already be seen in the calibration runs when the dead end branches where the diffusion coefficient was very small did not change at the same velocity as its adjacent branches. It has to be seen if only the speed of the change is different or also the end result, expected is that also the end result is different because with a small diffusion the transport cannot spread from the original location to all places. As can be seen from the results in appendix 4.7 the effect of the less spreading through the estuary is dominated by the effect that the sediment from the seaside spreads less. This is especially clear in the Mattanchery channel, what is a flood channel and which gets a lot of sand from the seaside and which is thus much deeper than in a situation when the diffusion coefficient is twice as large. Since the diffusion coefficient has such a large effect it is important to choose this coefficient carefully, especially since the coefficient in the diffusion formula is quite arbitrarily chosen in this case, but it is sooner too low than too high since normally the value is around 1. To check if a higher coefficient would give very different results, also the diffusion coefficient is put on 5000. Although this is extremely high, it is just used to see its effect on the results. It is seen that this has the opposite effect of halving the coefficient, the harbour area is now much shallower and so are the southern branches. From this it seems that despite distributing the sediment over the estuary the dispersion coefficient is also responsible for the timescale of the morphological change especially for areas near the boundaries.

Fall velocity

The fall velocity was fixed on 0.0003m/s. This value was fixed for the entire area, where as said before this value could differ in reality because of he flocculation in the harbour area of clay particles. This fall velocity determines the morphological timescale since the bottom subsidence or raising is calculated by fall velocity times the concentration difference. A higher fall velocity is thus expected to give a faster morphological change. To see if the model correctly represents this from the initial model without the dredging the fall velocity is increased from 0.0003 to 0.00045 to see how the morphological time scale changes. In appendix 4.7 one can see that increasing the fall velocity with 50% decreases the semi-value time with 50% this could be expected since the bottom rise is directly connected with the fall velocity in the Estmorf model.

The boundary problem

Because the boundaries of the model in the case of the Thanneermukkon or the Aroor storage area in reality don't have a hydraulic connection, these branches have to be modelled as a closed boundary, without sediment transport. In this model the solution is chosen to keep the diffusion coefficient very small in these areas so that the interaction with the adjacent branches is minimized. This does also minimize the connection on the side of the branch on which it is not closed as could be seen in the calibration runs where these branches were much less compliant as its adjacent branch. In this run it is seen what effect a constant diffusion coefficient all over the estuary has when the adjacent branch is being dredged. It is expected that if the diffusion coefficient is small the effects on these branches be very little compared to a big diffusion coefficient. It is seen that with a small diffusion coefficient the dredged area gets deeper much faster because the sediment has to come from much further than when the boundary is open. The whole system gets much deeper when there is dredging while this boundary is closed for sediment fluxes. In appendix 4.7 can be seen that the dredged branch is almost linearly getting deeper when the boundary is closed and has a more logarithmic scale when it is open. Since this was the expected behaviour the method of closing with a low diffusion coefficient seems correct, but as stated before the disadvantage of closing the boundary like this is that also on the other side it doesn't have high interaction. This can also be seen in this example, because Storage area_1 is increased in depth much more when the diffusion is the same overall than with the lower diffusion in this branch, because it is a boundary. This has also been plotted in Appendix 4.7. After concluding this it has to be determined if this method can be used in this model. As with the stability case one should say this method is allowed when the variations in these areas are not too big. When implementing the cases this should be kept in mind.

4.3.5 Conclusion morphological modelling

The conclusion that can be drawn from setting up this model is that constructing such a model with so little data is quite difficult, as can be seen from the sensitivity analysis the morphological history can have large influence on the results of this model. Since only the dredging is implemented as morphological evolution and the rest of the model is considered in equilibrium because of the lack of data, this could affect the results of the model heavily.
The dredging figures are detailed enough for the order of detail of the model and also the diffusion and the fall velocity would not be very different if more detailed data would be

available. Since the equilibrium concentration is kind of the calibrating parameter only the range is of importance and it would have been nice if this range was a little smaller but it is not essential for this model.
Also interesting while constructing this model was the whole instability case in the end this meant that part of the model was "switched off" to go further with modelling. This can only be allowed when small changes are expected in this area; this shall be kept in mind when working further with this model.
When working further with this model one should thus keep in mind its lack of morphological history for large sections of the model. Despite this observation there will be continued using this model in this project while reminding it shortcomings.

Chapter 5: Case studies

5.1 Introduction

In this chapter the model constructed in the previous chapter will be put to use to help give some ideas about the morphological development of the Cochin estuary after a human interference in the system. With the problem analysis in chapter 2 in mind some cases will be generated. One of the objectives for this thesis was to implement coastal zone management in the project through the cases that are generated. This means that with the quantitative analysis produced by the model some socio-economic aspects will be discussed. The influence of the human interference on the socio-economic aspects will be dealt with, with the help of the morpho-dynamic model.
The cases that are generated from the problem analysis should correspond to the level of detail possible in the model. To some extent this limits the freedom to select certain cases, because the model has to be able to represent the physical processes that are present at a chosen case. This order of detail depends mainly on the retrieved field data.

5.2 Generating the Cases

To construct a number of cases, one has to bear in mind the available data and the applicability of the model. With the available data it is not possible to conduct detailed research. Also the time scale on which the model is based, decades, does not allow research on annual variations to determine for example an annual dredging cycle, so only long-term problems can be handled. Keeping in mind the objectives for this thesis, the cases have to be placed in the larger spectrum of the coastal zone management. The cases should therefore not only be generated as if it was a sensitivity analysis of the model, but should have a direct connection with the problem analysis in chapter 2. In chapter 2 a few problems came to light, this will be the main source of the cases that are generated, bearing in mind off course the limitations of the model.
First though a theoretical problem will be treated, because this dynamic plays an important role in the morphology and hydrodynamics of the area. It is noted that in reality large sedimentation rates are found inside the harbour area originated from the sea entering with a density current. Since the Estmorf model was built for well-mixed estuaries and until now was not used in stratified estuaries, it has to be seen if this effect is well represented. Important effects of these stratified estuaries are locally higher grain diameters, because on the boundary of fresh and saltwater the small clay particles flocculate easier and the higher concentrated bottom layer, which flows into the estuary. The fact that there is more sedimentation can be represented in the model by changing the coefficients in the tidal prism equation or changing the equilibrium concentration, but this can't be done locally. In the first case it will be searched if the model can represent this stratification or else how to make the most accurate approximation keeping the limitations in mind. Further theoretical background will be given in section 5.3.
A more applied problem concerning coastal zone management is the wish of the Port Authorities to expand the harbour, since the construction of one terminal should give a small extra dredged channel this seems to detailed for the model to give any useful results, a more pragmatic solution is taken. First all the inner harbour channels will be made deeper, afterwards a solution is chosen to built a harbour outside the estuary and only use the inner harbour for smaller ships, so less dredging has to be taken place inside the estuary, because the more natural depth will be approached. More details about these cases will be given in section 5.4.
Another problem that was observed in the second chapter was the shortage of construction sand, which is an important raw material in a country with a fast growing population. The mining of sand is a problematic point for the Keralan government, since numerous accidents have occurred

in the river areas because of caving soil along the banks. The mining of sand is until now forbidden inside the estuary due to environmental restrictions. In section 5.4 an analysis is given about this situation and some cases will be done with the mining of sand inside the estuary.
Some of the models that were discussed in the problem analysis are not treated because of the applicability or limitations of the model. One of these problems observed in the problem analysis was the detaining of water in reservoirs for hydro-electrical plants, this seems difficult for the model to represent since the influence is marginal and the tidal prism hardly changes. The biggest alteration is the smoothening of the peak discharge during monsoon but this peak discharge is not used in this model. This is thus not a problem at which the model can be of any help and will not be handled any further in the research.
With the problems that were pointed out here one also has to take account of the fact that the estuary is a part of a bigger system. As explained in chapter 2 coastal erosion plays an important role in this system and through the years it seemed that developments in the estuary play an important role in this erosion. So important is to keep in mind especially when large volumes of sand are drawn out of the system that this can have an increasing effect on the coastal erosion. The same goes for a larger tidal prism, which also needs a larger volume of sand in the outer delta.

5.3 Stratification

In the Cochin estuary appears during post monsoon a stratified current or salt wedge in the harbour area. To understand better what happens in the harbour area, there will first be a small introduction on the theory of the stratified currents. Stratified currents arise where the river discharge and the discharge from the tide are more or less equal. There is of course a large transitional area between fully stratified and well-mixed estuaries.
As said in the previous chapters, one of the characteristics of the Cochin estuary is the change of character through the year, from a well-mixed estuary in t he pre-monsoon to a total fresh water reservoir in monsoon, when total flush-outs occur. In between in post-monsoon the estuary gets a stratified character. This means a salt wedge forms in the harbour area, moving the salt water underneath the fresh water. This undercurrent is also called density current.
Normally these density currents occur because of the higher weight caused by the concentration of salt but in Cochin also because the seawater contains a lot of small clay particles. These clay particles flocculate in the harbour area causing higher sedimentation rates than the concentration would suggest and the concentration is also higher in this lower layer than in the upper fresh water layer. The clay particles form a high porosity muddy layer at the bottom. Sice the morphological part of the model was calibrated in the harbour area the results in this area will probably be good, but the higher siltation rates have to be represented with a higher morphological activity. In the Estmorf model this activity is raised by increasing the equilibrium concentration.
The disadvantage of this approach is the fact that for the whole of the estuary the morphological activity has to be increased. This morphological activity is then in the upstream areas higher than necessary. This could corrupt the results, especially the timescale, if adjustments are made in the model in these areas.
For a quantitative analysis of this problem has to be found how much higher the morphological activity is for the harbour area than for the upstream areas. From the sensitivity analysis was made out that at fast sedimentation a twice higher equilibrium concentration causes twice as fast siltation. Assuming it was known how much faster the sedimentation rate or how much higher the concentration is in the harbour than in the upstream areas an alternative equilibrium concentration for these area could be determined. Since no information is available neither on the sedimentation rates upstream nor about the concentrations in the density current, a pragmatic solution path is taken. It is observed that the sedimentation rates are higher in the harbour area than they are in the

rest of the estuary. This is because not the upper freshwater layer in the harbour, which has a connection with the rest of the estuary, determines the sedimentation rate but the lower layer with a higher concentration determines the sedimentation rate. The approach we will take is to find some solutions to locally increase the morphological activity and to check if this approach can work for the estuary and what the results are for these changes. This is thus not a real quantitative representation of the Cochin estuary and will thus not be used further. It is a check how to implement a density current in the Estmorf model. In the Cochin model this is only during a short time of the year (September - December) when this stratification is dominant in the estuary. There will be tested two methods to see if the overall equilibrium concentration can be the same and the morphological activity in the harbour area can increase.
Two approaches are tried to see if the density current can be represented. The concentration on the seaside is increased, since this is the boundary from which the density current enters. The diffusion coefficient in the harbour area is increased to facilitate the sediment at the sea boundary to enter the estuary.
All these runs will be done in the wet season model, since during these months the stratification is present and since this approach is pragmatic and not searching for the real solutions the choice to use only one model can be justified.

Run 1: Higher concentration on the seaside

In this section a run is performed with an increased seaside concentration. This is done to see which effect the increased seaside concentration has on the results of the model and if this is only locally on the harbour area, what we want or for the entire estuary.
The concentration on the seaside is increased because this is the way the higher concentrated density current also enters the estuary in reality. The difference is that in reality this higher concentration is also present in the harbour area but this is not possible to implement in the Estmorf model.
The first run shows an increasing morphological activity, since the morphological development in the harbour area is the most unstable the changes in this area go faster in the beginning. The boundary concentration was increased from 0.00019 to 0.00021.
After this run the seaside concentration is also decreased, which give the expected erosion in the harbour area. The results of these runs can be found in Appendix 5.1.
After the short term results, a long term run is done to see if a new equilibrium is reached an if the effect doesn't spread throughout the estuary instead of changing only the harbour area results. From the long term run can be seen that the increase of the seaside concentration has a very local effect concerning the sedimentation. Only the gorge and its adjacent branches are really affected by this increase and the more upstream branches hardly notice anything of the change in the concentration.

Run 2 : Higher diffusion coefficients in the harbour area

In this run the way the boundaries are closed for sediment transport by putting the diffusion coefficient very low is reversed by giving high diffusion coefficients on the boundary where the sediment transport is much higher than inside the rest of the estuary. This is more a modelling trick than a representation of the real physical processes like in the last approach but this is a way to change the morphological activity locally.
When the diffusion coefficient is increased, the harbour channels get as expected deeper with a decrease of the diffusion the harbour area gets more sedimentation and thus shallower depths, although these changes don't give great alterations.
Also for the diffusion coefficient a long term run is done to determine the effect on the entire estuary. This is also done to compare this approach with the increased boundary concentration to

see which change has the least effect on the rest of the estuary. To give a good comparison a diffusion coefficient is chosen that gave almost the same results in the short term run as the higher concentration of 0.0002, that was 4500. The results of these runs can be found in appendix 5.1.
Compared to the increase of the seaside concentration the effect of the higher boundary concentration works longer through the estuary and also the upstream boundaries get higher sedimentation rates. But still the highest rates are in the area where the diffusion conditions were increased.

Conclusion

From the following case can be concluded that it is possible to locally increase the sedimentation rates. Two methods were discussed in this case and each has its own advantages and disadvantages. The advantage of the boundary concentration is that this sorts a very local effect with the branches adjacent of the boundary and stays closest to the real physics. The branches closest to the boundary are thus largely affected, while for example in the Cochin case the Gorge, which is next to the boundary, has no need for higher sedimentation rates. Also if the stratification would get deeper inside the estuary this method is difficult to use.
The diffusion coefficient on the other hand has as disadvantage that it works more throughout the estuary instead of only locally. The advantage on the other hand is that it is easier to determine the zone where the morphological activity has to be raised than with the boundary concentration, because the diffusion coefficient can be determined for every branch.
In the Cochin case with the short intrusion length for the salt wedge the increase of the boundary concentration seems the most promising approach. Also because this increase can maybe be determined by measuring the concentration in this salt wedge.

5.4 Port Expansion

The Cochin Port Trust has as its objective to stay the second largest harbour along the west coast of India. To keep this position the harbour needs to expand. Because India is one of the fastest growing economies in the world, especially a lot of oil-products need to be imported, since India has not sufficient oil fields to be self-providing. With a growth of cargo last year of 16 % the harbour of Cochin is in need of expansion. At present most docks are general cargo docks, could these be changed in specialised docks efficiency would be gained. The plans for expansion that are in progress of getting through the line of approval now are the container terminal at Vallarpadom Island and the construction of an offshore oil terminal. The Port Trust has got the approval of the national government to start with the Vallarpadom project, the offshore terminal is still waiting for approval until all alternatives are revised. The building of a harbour on Vypeen Island is one of the other possibilities, deepening the harbour channels another.
For this project the construction of a container terminal on Vallarpadom island is not an interesting case that can be examined any further, this case requires more accuracy in this area than there is available in the model.
The overall deepening of the harbour channels is something that can be put into the model, the disadvantage of this deepening is that more and more dredging will be needed and the dredging capacity has its maximum and so does the depth in the harbour, this depth is 19 meters (Menon, 2002). This has as an effect that the larger ships that are foreseen, when the Suez channel is dredged till a depth of 21,6 meters, in the future still cannot enter. For these ships a different solution has to be found.
In the run where both harbour channels are evenly deepened we take a depth of 18 meters. As a reminder the depth of the inner channels is now 12 meters for the Ernakulam channel and 10 meters for the Mattanchery channel. The results of interest are the volume of dredged material

that is necessary to get to this depth and the development of the upstream areas as a reaction on this increasing depth in the harbour area. In advance it can be noticed that because of the flood-dominance in the Mattanchery channel the deepening of this channel will probably cause more dredging volume than the Ernakulam channel. Also most the mayor docks are now placed in the Ernakulam channel, which includes the oil dock. So also a run will be performed where the Mattanchery channel keeps its own depth and the Ernakulam channel is deepened. This run is also done to see if this deepening of only one channel decreases the total effect on the estuary significantly.
Another run that is going to be preformed is if a harbour is constructed outside of the estuary at Vypeen Island, only smaller ships then have to enter the harbour, this can result in smaller dredged volumes inside the harbour. In this runs the depth is decreased a few meter to a depth of 9 meters everywhere. The results of interest for these runs are the time it takes for the system to come to the preferred new depth and the volume of dredging then necessary to keep the right depth. Because the part outside the estuary is not included in the model, no quantitative remarks can be made about the volume that needs to be dredged neither in capital dredging nor in maintenance dredging in the new harbour. When doing the runs with increasing depth in the harbour area, it is important to remember that an approach channel is present and with deepening the harbour area, this approach channel also needs additional dredging.

Run 1: Inner channels both 18 m deep

In the following runs the depths will be evenly distributed. This means that the average depth of both channels will be increased till the navigational channel has reached the same depth. For this purpose a depth of 18 meters is chosen for the channels, since this is presently the depth of the Suez channel.[11]
If the navigational channels reach a depth of 18 meters the average depth for the Mattanchery channel is approximately 9 meter and for the Ernakulam channel approximately 13 meter for the first part and 13 meter for the second part. The second part of the Ernakulam channel is now shallower than the first part but in this run they will be dredged till the same depth. First the capital dredging for these depths has to be calculated, for the Mattanchery channel this is a volume of approximately the extra depth times the area, if the siltation rates don't increase dramatically, for the Ernakulam channel the same goes. The Values are in Table 5-1.

Channel	Capital dredging	Previous Maintenance dredging	New Maintenance dredging[12]
Ernakulam channel 1	$5,4*10^6$ m^3	$120*10^3$ m^3/month	$161*10^3$ m^3/month
Ernakulam channel 2	$10,8*10^6$ m^3	$120*10^3$ m^3/month	$200*10^3$ m^3/month
Mattanchery channel	$8,4*10^6$ m^3	$180*10^3$ m^3/month	$227*10^3$ m^3/month

Table 5-1 Dredging figures with Ernakulam and Mattanchery channel 18 metres deep

The figures of the new maintenance dredging show that especially in the Ernakulam channel 2 the dredging volume has to be increased much. The difficulty in this comparison is that the figures now maybe corrupted because more dredging takes place in the Ernakulam channel 1 now, but the ratio between the two parts of the Ernakulam channel is not known. So more significance should be given to the sum of the dredging volumes in the Ernakulam channel, where an increase can be seen in dredging volume of 50 % and in the Mattanchery channel an increase of 26 % can be expected. The cross-sectional areas grew respectively 57% and 111%. It follows from these figures that Mattanchery channel is already more than the Ernakulam channel an ideal sand catch,

[11] Bruun (1989), www.schuttevaer.nl
[12] Average of wet season and dry season

this means an area where all floating sediment siltates. This takes away the fear of high dredging volumes with the deepening of the Mattanchery channel.
One has to reckon with the fact that a lot of additional dredging has to occur in the approach channel to keep it to this depth. This additional dredging in the approach channel is probably not the sediment from the estuary that already almost completely siltates in the approach channel, but additional sediment from the sea that is drawn into the approach channel by the two jetties on both sides of the inlet.
First the two models are tried separately to see what effect the dredging has on both seasons. In the wet season the depths in the harbour area are quite constant. From the plot in appendix 5.2 one can see that the depths in the harbour area are constant for a long time till the depths in the Ernakulam channel go down fast. The reason the depths increase after a while is the increase of the tidal prism, because of the increasing depths further upstream the estuary. The growing depths in the harbour channels can be stopped in reality by stopping the dredging or at least less dredging. In comparison with only the dry season model, also plotted in appendix 5.2, the depths in the southern area increase much more in the wet season model. This larger growth of depths in the southern branches can be deducted from the A-P curves for both seasons as plotted in appendix 4.4. It can be seen that the curves in the wet season have a much more curved shape which allows more growth of the tidal prism than a vertical curve. Namely with an increasing prism the curve moves to the right, with a curved line the new equilibrium lays a lot higher than with a vertical line.
The dry season model on the other hand increases the depths in the harbour area much more than in the wet season model. From this graphs a expected long term dredging pattern can be determined. First the initial dredging volumes are higher during dry season than during wet season, but the fast increasing depths in the dry season indicates a faster decreasing of dredging volume in this season.
From the shape as it is plotted now it can be concluded that the wet season is the stabilising factor for the harbour area and the dry season is the more stabilising factor for the southern branch. This does not mean less dredging is necessary during wet season than during dry season. As stated before the initial dredging is in the wet season lower than during dry season. This could be expected since the morphological activity inside the estuary during dry season is higher than during wet season. With the extreme increase of depth of the gorge also the seaside has to be taken into account. This means the outside has to be dredged to an increased depth also and additional sand could be drawn to this Gorge from the seaside. The dredging activity inside the estuary also has an effect on the whole coastal system.
The deepening of the estuary needs a larger outer delta and draws a large volume of sand out of the coastal system, which can cause more erosion on the coasts of Kerala. This erosion could be increased since the outer delta is probably located around the approach channel and this sediment is also dredged and dumped out of the system. So one should be careful when applying such big dredging operations.
After the two separate runs has to be viewed what the outcome is of the combined model. Here the model will be switched every 96 morphological time steps. Also per switch will be looked how much the dredging activity can be brought down to still maintain a depth of 18 meters. Finally a long-term dredging cycle shall be drawn up.
What we see in this run, which is plotted in appendix 5.1 is that during wet season the harbour area stabilises but the southern area gets deeper. This affects the tidal prism in the dry season, which becomes bigger and thus the harbour area becomes deeper during the dry season. This increase of tidal prism is mainly attributed to the increase of the cross-sectional area in the branch south_1. The increase of the tidal prism influences the dredging figures which decrease fast during dry season in the Ernakulam channel and are more constant in the Ernakulam channel during wet season. The Mattanchery channel has constant dredging volumes since the siltated material comes almost directly from the sea, because Mattanchery channel is a flood channel. The

reason the southern areas become deeper during the wet season is bipartite. First of all the increase of the tidal prism requires the cross-sectional area to grow. Secondly the sand from these parts is than used to fill the dredged channels transported by the river discharge. The dredging figures throughout the years can be seen in Figure 5.1.

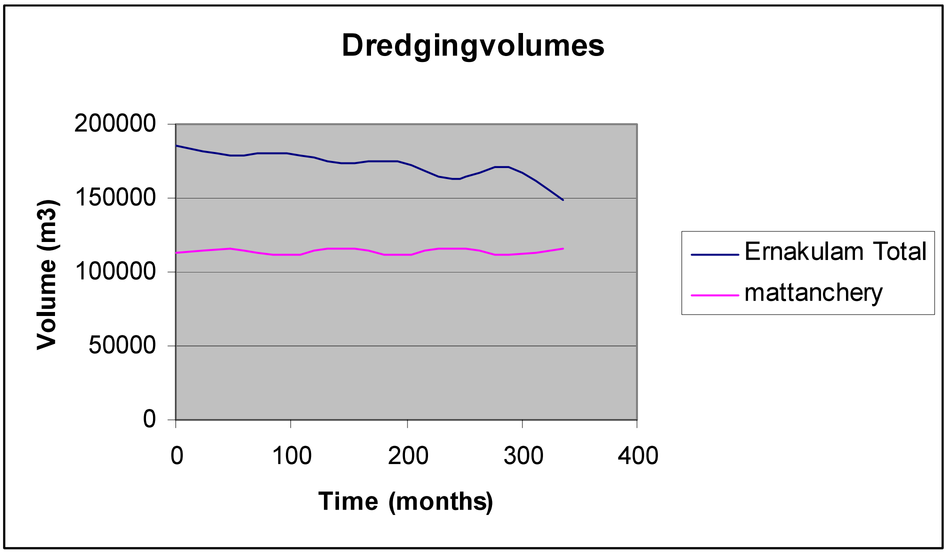


Figure 5.1 Dredging volumes for Channel depth is 18 meters

In the underneath tables one can see a quite constant dredging volume in the wet season and a quite decreasing volume in the dry season, because of the reasons stated above. That the dredging volumes would decrease was expected since the deepening of a channel is a self-dimming cycle. The dredging causes the prism to grow what reduces the dredging. This goes on until a new equilibrium is found.

Time	Ernakulam channel	Mattanchery channel
4	178500	115500
12	174000	115500
20	163500	115500
28	149000	115500

Table 5-2 Dredging volumes during dry season

Time	Ernakulam channel	Mattanchery channel
0	185100	112800
8	180000	111700
16	174500	111700
24	171000	111700

Table 5-3 Dredging volumes during wet season

Now the results have to be revised with the assumptions and limitations made in the previous chapter. One assumption was that the system is now in equilibrium. If the changes that this dredging operation bring along and especially the time scale for the changes to be completed, it is reasonable to say that the great dredging operations in the early 80's probably have the same scale of effect on the estuary. In this run the biggest consequences even become apparent after the twenty years that have past since these dredging operations took place. If those dredging operations had the same effect the estuary and the tidal prism should be increasing. This left out of course the reclamations that took place before and after 1983 and that cause a decreasing tidal

prism. What can be stated qualitatively is that deepening the harbour area increases the dredging volume but also increases the tidal prism, which decreases the dredging volume in the long term until a new equilibrium is reached.
A marginal note with the large changes after 20 years is that as stated before the stability of most of the southern branches with a large area and a small or even no discharge is not very good. In chapter 4 was stated that the storage area_2 has an unstable character and this was switched off. Also the south_1 branch has just a more stable character but large changes can also give this branch an unstable character. The cross-sectional area of this southern branch place on the A-P curve is so that it causes the prism to grow fast when the cross-sectional area grows, where could be seen in chapter 4 that the other southern branches are on a place in the A-P curve at which the prism hardly changes when the cross-sectional area increases.
The storage area could be switch out with the remark that this is not an important branch in the flow pattern in the estuary, switching of the south_1 branch gives great limitations about the applicability of the model. So the effects in the long run in the dry model should be observed with a little reservation and more the pattern should be observed than the actual quantitative results.
What can be concluded out of this run is that dredging operations can have large long-term effects on the morphology of an estuary. The tidal prism and the channel depths should get bigger because of these dredging operations, this is in contradiction with the morphological change after the last dredging operations as reported in literature. This can be attributed to the fact that seemingly the reclamation effect exceeds the effect of the dredging operations. Since reclamations are forbidden since the Coastal Zone Regulations are in act this reclamation effect will vanish in the long term. A dredging operation has than thus a deepening effect on the estuary. Quantitatively it is more difficult to say something about the change in the estuary since the current morphological development is not known. What can be said is that the harbour area will increase in depth with a few meters because of the dredging and the adjacent branches because they supply the sediment. The southern branches will increase in depth in the order of a meter. The order of alterations of depth are in accordance with the changes over the last few decades as reported in chapter 4.

Run 2: Ernakulam channel 18 meters deep, Mattanchery channel = 10 meters deep

In this run only one of the channels is dredged to 18 meters, the other channel shall only be accessible for smaller ships. Since the Ernakulam channel is already the longest, deepest and has the most docks, this channel shall be dredged till the depth of 18 meters. Purpose of this run is to see if large changes in the pattern of morphological development occur when only one of the channels is dredged. These changes could maybe occur because of a change in the water movement when the ratio of the two harbour channels is changed. Another purpose of this run is to see if the dredging of only one channel will positively change the dredging volume. Of course the volume will be less but maybe because the dredging in the Mattanchery channel can be decreased is even not much higher than the current maintenance dredging volumes. This can then have positive consequences for the sediment balance entire coastal system in comparison with the last run.
This run will only be done in the combined model, which can be compared with run 1 see if the dredging of only 1 channel has less drastic consequences on the estuary.
As could be expected the pattern of changes in the estuary are similar to the run where both channels are changed except the speed in which the changes occur is less. The run is plotted in appendix 5.2. The same limitations that were applicable for the first run are also valid for this run. In the underneath tables the dredging figures during wet and dry season are given.

Time	Ernakulam channel	Mattanchery channel
4	182500	87000
12	176500	85000
20	170300	83000
28	161500	78000

Table 5-4 Dredging volumes during dry season

Time	Ernakulam channel	Mattanchery channel
0	184800	88800
8	179000	88200
16	177000	87600
24	173000	86600

Table 5-5 Dredging volumes during wet season

The big difference with the run where both channels were deepened is that now the dredging volumes in the wet season are consequently higher than during dry season. This pattern is especially visible in the Mattanchery channel. It can be contributed to the fact that the Mattanchery channel because of the changed ratio becomes an ebb channel in dry season, see Figure 5.2

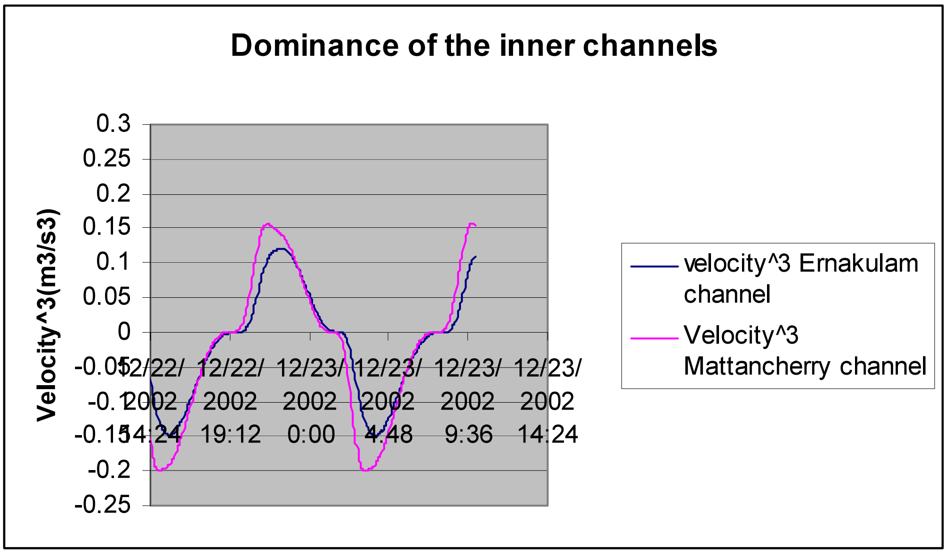


Figure 5.2 Dominance check of the inner channels (positive is flood dominance negative is ebb-dominance)

From this figure can be seen that both channels are ebb-dominant concerning the sediment transport. This can be explained by the already in chapter 4 referred phase of the water level and the discharge. Since they are in phase a higher velocity is needed to get the same volume of water out of the estuary than in. The Mattanchery channel though lets still more volume of water in than out.
It is also observed that the dredging in the Mattanchery channel can be reduced when the Ernakulam channel is dredged deeper. In the end after 28 years the total volume of dredging is only 14 % higher than the dredging volumes now, while this was 26 % in the case where both channels were deepened.

This adjustment in the harbour layout thus seems a good alternative to allow the larger ships into the harbour without increasing the maintenance dredging volume too much. This of course depends on the capacity that is needed for the larger ships, but in the beginning just one channel for the larger ships seems enough.
A point that has to be taken into account when these runs are done is that these runs are done assuming the boundary conditions don't really change. One should think here of changes in the economic or natural climate. Maybe the demand for terminals in the Cochin harbour grows so heavily that before the morphological changes have been completed another adjustment in the estuary layout is made. These changes can't just be put on each other but additional changes can be expected.

Run 3: Ernakulam channel and Mattanchery channel = 9 meter deep

In this run there will be the construction of an additional harbour on Vypeen Island, since this harbour cannot be represented in this model, only the effects it has on the inner harbour can be observed. Since larger ships don't have to enter the inner harbour dredging activity can be decreased. It is to be seen if decreasing the channel depths to their depths before 1983 causes the dredging volumes to go down even to the dredging volumes before 1983. For this runs all channels are brought back to their original depth before 1983 of 9 meters, for the average depth this means the Ernakulam channel_1 becomes 8 meters deep, the Ernakulam_2 6 meters and the Mattanchery channel 3,5 meters.
For the combined run first a timescale has to be determined for the switch between the wet season model and dry season model, this because if in one of the models the dredging should begin again and not in the other before the switch this could corrupt the results. In both models the dredging is stopped and the development of the estuary is then observed.
It is seen that the siltation process in both models is practically the same and in both models the Mattanchery channel siltates much faster than the Ernakulam channel. The runs can be seen in appendix 5.2. Since the model in the dry season looks extremely unstable also branch south_1 is turned of for this run to see if this gives very different results and if the model than appears to go to a new equilibrium better. The wet season model already seems to go to a new equilibrium. This can be seen from the logarithmic shape of the depth graphs.
When the south_1 branch is fixed this doesn't really change the results of the run. This means that it is not fixed in the combined run.
Now the time in which the dredging has to start again have o be determined. The results are in Table 5-6.

Channel	Wet season reaching of new depth (months)	Dry season reaching of new depth (months)
Ernakulam 1	36	35
Ernakulam 2	18	18
Mattanchery	5	5

Table 5-6 Timescale of changes in the separate models after the stopping of the dredging

From the changes it is seen that the new dredging depth is reached even faster in the Mattanchery channel than one real season. Because the changes are so fast a time step of 48 morphological time steps or 2 years is chosen and a running period of 20 years.
From the dredging results given in the tables below it becomes clear that especially in the Mattanchery channel the decrease in depth has hardly a positive consequence on the dredging volumes. The dredging is almost constant after the initial period in which the stopping of the dredging is taken along. In the Ernakulam channel on the other hand the dredging volumes decrease quite significantly but then increase when time progresses. This increase comes because of the decrease of the tidal prism, when the branches throughout the estuary get shallower. This

decreasing of depth is going very slow. As we saw in the previous runs the Ernakulam channels sedimentation pattern is much more dependent on the overall changes in the estuary than the pattern in the Mattanchery channel. This is probably because the tidal prism of the Ernakulam channel is much more dependant on the changes inside the estuary than the prism of the Mattanchery channel.

Time (months)	Season model used	Ernakulam Channel new dredging volume (m^3)	Mattanchery channel new dredging volume (m^3)
0	Wet	11500	70500
24	Dry	55500	86000
48	Wet	77100	85500
72	Dry	77500	86000
96	Wet	79100	86500
120	Dry	79500	86000
144	Wet	82600	87500
168	Dry	83500	86000
192	Wet	82600	87500
216	Dry	86500	87000

Table 5-7 Dredging figures for shallower harbour channels

Also interesting to see is that if these dredging figures are compared with the dredging figures before 1983 and than especially the ratio between the to channels, that they are completely different. Where dredging before 1983 was hardly necessary in the Ernakulam channel, nowadays still large maintenance dredging volumes have to be dredged. This indicates a shrunken tidal prism since then. A plot of this run is in appendix 5.2.

5.5 Construction sand exploitation

This last case will discuss the reason and effects of sand mining in the Cochin region. Since many people in the Cochin area are not in possession of well constructed houses and the demand for new buildings is high in the Keralan area, because of the growing economy, construction sand is one of the raw materials with a high demand and there are not a lot of places where the mining of good construction sand in Kerala can take place. The riverbed is almost exhaustedly used for this purpose and accidents do happen at the banks of the rivers with illegal mining and collapsing houses. If this mining would stop it would not only mean loss of sand but also loss of many jobs. Currently there is won 50000 ton of sand a day in the Periyar river (Krishnakumar, 2003) and 832 truckloads of sand from the southern rivers (Local government, 2003), this is approximately 25000 ton a day.
Because of the coastal legislation it's forbidden to do any mining in the coastal regions because of environmental and legislative issues. This legislation is recorded in the Coastal Zone Management Plan of the Keralan government and forbids mining for minerals, which are available outside the coastal regulation zone (Ramachandran, 2002). This act means that the mining of sand, which is available but hard to get outside the estuary is forbidden. This is also proclaimed in the Coastal Zone Management plan (Madhusoodanan, 1997). Nowadays there are several techniques to environmentally friendlier win the sand from the bottom of the lake, like dredging for the coarser particles and dumping the not necessary particles on places where unwanted erosion occurs. The problem with the dumping inside the estuary is the turbidity that is caused by this dumping. This causes an anaerobe environment, which is bad for the hydrobiology of the area. So maybe suppletion before the eroding Keralan coast is an option.

The sand is mostly available at the mouth of the rivers that are flowing into the estuary. Another aspect is that it is not preferable to change the shape of the rest of the estuary dramatically by the mining of the sand. The runs by the Estmorf model will check the depths and give insight in how the area will react on large changes in the depths through the area. Since the Estmorf model is not capable to adjust the widths from the branches, one should keep in mind that very deep channels probably also get different geometry. To see what is the optimal place where the sand can be mined, it has to be seen where the locations are with a high percentage of sand particles.
There is a high percentage of sand particles in the south_2 and south_3 branches at the mouth of the Muvatthapuzha(Veerayya, 1974). These measurements are fairly old and some changes in the textural composition have been reported, but it is still expected that the coarsest fractions are in these branches.
From the sensitivity analysis of the hydrodynamic model can be deducted that changes in the cross-sectional area of the south_3 branch bring along the largest changes in the tidal prism. So it is intended to mainly use the south_2 branch as provider for the sand mining. The definition of sand is particles bigger than 0.063 mm are used (Phi < 4). Phi is a different notation for the particle size. For construction sand the coarser fractions are more important with Phi is smaller than 2 and preferably well sorted. In branch south _2 there are some sides with 100 % sand with moderate sorting and mean particle sizes of Phi<2. In Josanto, 1971 six measurements are taken to determine the particle size. 90 % of the particles can be defined as sand with an average Phi of 1.8. It is attempted to get the same volumes of sand that are now won from all rivers, also a run is performed where only the volume of sand for the southern rivers are replaced by this mining.
The volume of sand that has to be won from the bottom is 47200 m^3/day if all the same volume is won as all rivers together and 15700 m^3/day if the southern rivers would be replaced. This is 700000 m^3 respectively 240000 m^3 sand per half a month (morphological time-step), which is 780000 m^3 or 270000 m^3 soil per half a month. This is with a porosity of 0.4, which is a usual value for the porosity of sand. First a short term run is done in both models separately to see in which model the effects are least. This can than be taken along in the decision in which season the dredging can take place best.
The problem with modelling this mining of sand in the dry season model is that one of the adjacent branches was fixed, this presumably corrupts the results because the expected subsidence of the bottom will not be represented in the model. For this reason the mining will be done in the wet season model. Also a combined run will be tried but then the mining also only takes place in the wet season. From the short turn runs it was already seen that the wet season model also reacts less on the dredging than the dry season model. The disadvantage of dredging in the wet season in reality is that the weather circumstances can delay the dredging activities, but since the dredging in the open sea only stops for one month it is not expected to give too much problems.
First a run with continuously dredging of 27000 m^3 in the southern channel is applied continues, this dredging causes approximately 2,4 centimetre of bottom subsidence per month, when the dredging is applied in the wet season model only, the entire estuary just increases in depth Figure 5.3.

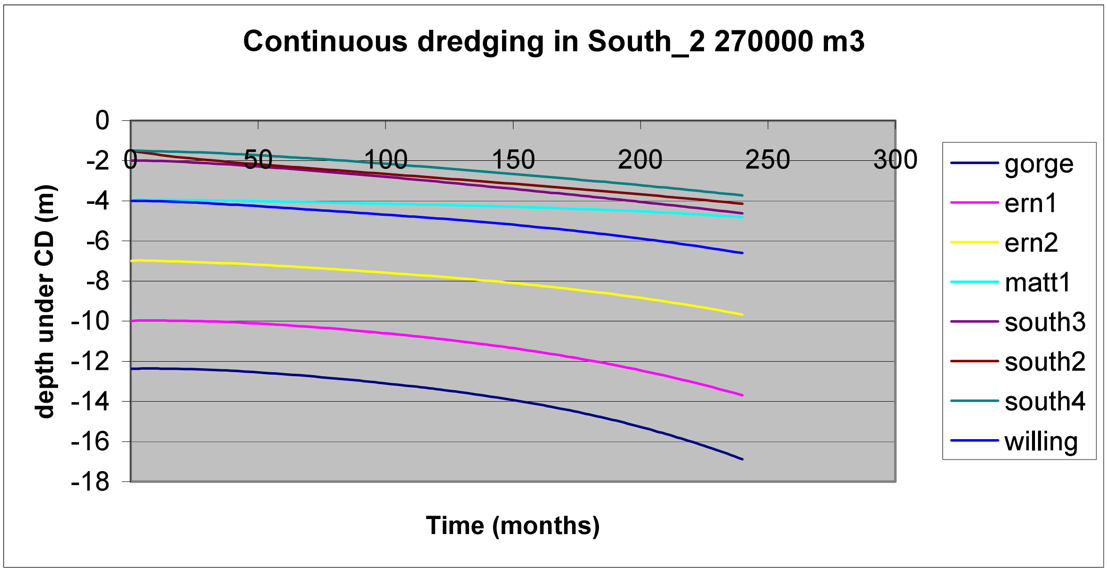


Figure 5.3 continuous dredging in branch south 2

This is what was expected since the tidal prism is continually growing because of the mining. This kind of mining brings thus too great effects in the estuary and cannot be applied.
Now two different scenarios will be tried to see if these effects can be dimmed. The mining will be done in periods of four years with the other four years for restoring. This four-year cycle is chosen because the changes in the estuary seem than small enough to restore in the last run. The dredging stops in the dry season, which gives the system a chance to restore itself. In the case of the expansion of the harbour we saw already that the dry season was the stabilising factor for the southern branches.
After seen the effects when only the sand mining volume of the southern rivers is replaced it is not useful to look at the effects when all the sand mining is replaced. Because the effects will only be bigger and bring along unacceptable changes to the estuary.
In the next run the dredging will be stopped every four years for four years and than continued. The morphological development of twenty years will be observed to see if the changes in the estuary are not too drastic.

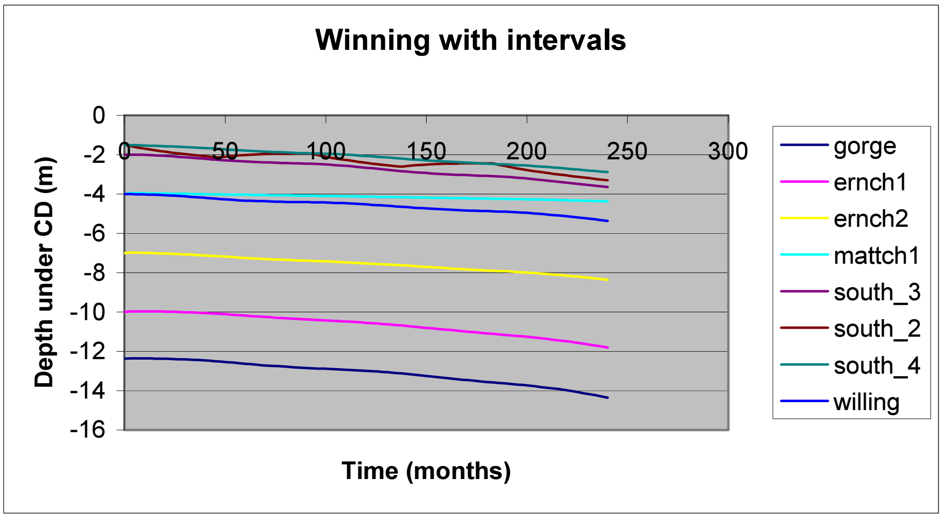


Figure 5.4 Mining with 4 year intervals

The changes have the same shape as in the run when no stoppage periods are implemented, the difference is of course that the changes are less. When these runs are done one should keep in mind that the harbour channels won't increase in depth as plotted in the above figure because the dredging activity will be decreased then. This is a positive result of the sand mining in the southern branches.
This run means that the restoration time probably has to be longer and that mining this quantity out of the estuary seems unacceptable, since one of the reasons the Coastal Zone Management plans were drawn up was to prevent to great alterations of the coastal zone to happen. The changes that have started with the dredging even though a four-year interval is taken cannot be stopped also if the mining stops the estuary gets deeper.
In the final run the dry season is used as restoration time for the estuary, since one of the adjacent changes of south_2 is the fixed storage area the shifting period has to be as short as possible and even then the results have to be watched with care since this branch cannot restore itself during the dry season and thus causes a larger prism because of its larger cross-sectional area. The shifting time will be set on one season or six months.

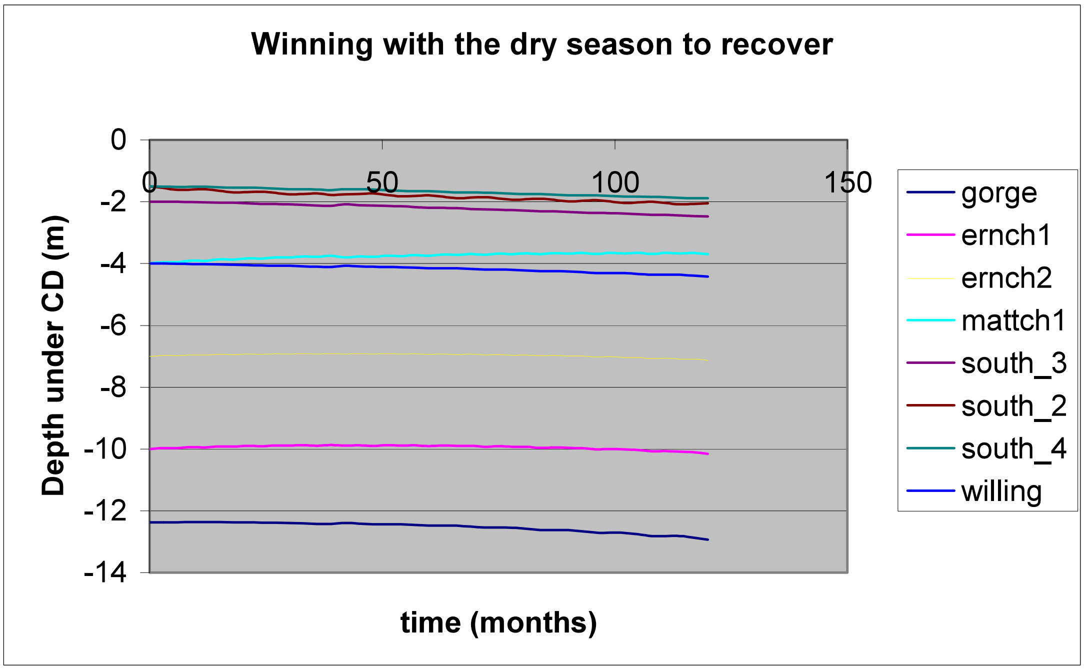


Figure 5.5 Sand mining with the dry season as recover time

The results look quite promising since the changes are now not very big after ten years. On the other hand it seems reasonable to stop with the mining now since an erosion trend has set in. the dry season doesn't completely restore the south_2 branch but it restores it partly and it is expected that if the mining is stopped after ten years that the estuary will almost completely restore. This is checked by running the wet season model and the dry season model for five more years to see what happens if the sand mining stops. From these runs it is seen that the system doesn't really recover although south_2 gets shallower again but also hardly additional changes will occur. This means the restore capacity of the estuary is not very big and sand mining has to be done with great care.

5.6 Conclusion coastal zone management

In this section some conclusions are be drawn concerning coastal zone management, which plays an important part in this report. First the harbour expansion and sand mining cases will be discussed and subsequently some characteristics of the general morphological behaviour of the system are assessed that may be relevant for coastal zone management with respect to both policy formulation and infrastructural development.

Harbour expansion

After presenting the results of the runs concerning an expansion of the harbour the consequences of the changes inside the estuary are discussed. First some general issues will be discussed; afterwards for each alternative the pros and the cons are discussed. Then a superficial choice can be made what alternative has the best effects on the estuary.
In the case it is seen that deepening the harbour also causes an overall deepening of the estuary, including the southern branches. The deepening of the southern branches may have severe consequences, some of which are treated here.
Since most of the branches have quay walls it is important to consider whether the quay walls are not undermined and then collapse because of the increased depth. Because this increase in cross-sectional area can only be done by bottom subsidence since they are regulated by quay walls. The increase in depth may also have large effects on the bank vegetation. Since in the area south of the Thanneermukkon bund a nature reserve is present, containing mangroves around a bird sanctuary, such operations may have large effects on the wildlife.
In Menon (2002) another problem is brought to attention. An increase in depth increases the tidal propagation and thus velocity of the salt-water intrusion. This may have great effects on the paddy fields in the southern end of the estuary. If this propagation becomes too fast, the Thanneermukkon bund has to be closed earlier during the year and the closing of this bund has large effects on the environment. As stated before a lot of polluted silt piles up behind the bund and a longer closing of this bund would even longer prevent the silt from being moved out of the estuary. As a quick comparison the average depth change can be checked. First the average depth was 3.6 metres, right after the dredging operation this changes to 4.1 metres and after twenty years the average depth is 4.9 metres. This is an increase in the velocity of the tidal wave from 6 m/s before the dredging to 6.4 m/s right after the dredging to 7 m/s after twenty years. This means the tidal wave arrives 20 minutes earlier after 20 years, which has as a consequence that the tidal effect has increased compared to the river discharge and the closing regime of the Thanneermukkon bund has to be adjusted.
On the other hand a decrease in depth of the southern branches, as in the third run with the additional harbour, has also some unwanted consequences. The disadvantage of bringing down the dredging volumes is the continuing shrinkage of the backwater system. This shrinkage has an impact on the biosphere of the area but also on the refreshing time of the estuary. If the tidal prism becomes smaller it will take even longer to dispose of all the polluted sediment. In the general evaluation of the coastal system we go into this in more detail.
The different alternatives for expanding the harbour are now discussed with respect to their advantages and disadvantages. In alternative 1 where both channels are dredged to a depth of 18 meters the deeper dredged channels cause increase in harbour capacity since larger ships can also enter. Therefore, this is also beneficial for the economic growth of the area. This growth will also increase employment, which is very important for this region where many people are unemployed. From a negative point of view the drastic changes of the estuary can be mentioned, which has the before mentioned disadvantages of undermining of current structures and higher propagation velocity of the tidal wave which causes the Thanneermukkon bund to close sooner. Also the effect on the coastal zone is not entirely obvious. Because of the larger prism a large

volume of sediment will be exported downstream, but it is certain that it will not all reach the shorelines. Dredging takes place in the harbour area, mainly dredging marine sediment and in the approach channel where most of the sediment of the estuary is dredged. It thus seems that the coastal erosion will only increase because of this large scale dredging operation. This scenario is of course not certain since a lot of sediment is transported outside, because of the growth of depths inside the estuary.
Since alternative 2, where only the Ernakulam channel is deepened, is the weakened version of alternative 1 all the consequences will primarily be the same except they are less drastic. This is both true for the disadvantages as for the advantages.
The third alternative with an additional harbour causes a great economic growth since the harbour capacity becomes much bigger and is, if constructed well, less dependent on sedimentation and the development of the whole of the estuary. Also the employment will rise with constructing this additional harbour and also in operating it. Contrary to the specialised dredging, the construction of a harbour causes employment for a wider range of people.
The biggest disadvantage is of course the cost of such an additional harbour. At the moment the Keralan government cannot afford to build such a big project and has to look for funds from the national government. It is not certain whether this project is high on the priority list of the Indian government since the government already funded the building of an additional container terminal on the Vallarpadom Island.
Other disadvantages are the further shrinking of the backwaters. It is questionable whether this is really a disadvantage since this shrinkage is a natural process. But this shrinking causes some problems with the transport of polluted silt. To what extent the peak discharges play a role in this disposal is not known. So it is not certain whether this negative effect occurs. The farmers will be pleased since additional land is probably naturally reclaimed and the propagation of salt water is delayed.
If the shrinkage of the backwater has very unfavourable consequences, it can always be decided to keep the harbour channels at their current depth. The coastal erosion is expected to decrease because in this alternative the shrinkage of the estuary will mainly be caused by the decrease in dredging volumes from the harbour, although it is not known what the additional harbour will do for the coastal erosion.
The additional harbour also has an impact on the environment since Vypeen Island is one of the few places in the Cochin area, which has fewer inhabitants. The other two alternatives use the already existing industrial area.
In the underneath table the consequences of the different alternatives are compared with the current situation as reference. The criteria in the table are deducted from the above analysis and some additional general criteria were formulated like environment and costs.
This table may be used for analysing the interferences in the estuary. The first two alternatives assume a deeper estuary; the last alternative makes the estuary shallower. For other interferences that cause these changes except for the first three criteria the same consequences can be expected.

	Deepening both channels	Deepening Ernakulam Channel	Building of additional harbour
Economic profit	+	+	++
Employment	+	+	++
Costs	-	-	--
Morphological effects	Large-scale erosion	Erosion	Sedimentation
Refreshing time scale	0	0	-
Tidal propagation	--	-	+
Coastal erosion	-	-	0
Environment	0	0	-

Table 5-8Comparison of different alternatives with socio-economic aspects

From this table, of course, no definite choice can be made for this exact case; it is just to show the positive and the negative aspects of the different alternatives. The different criteria should be worked out more quantitatively if a definite choice was to be made.

Sand mining

From the results of runs concerning the sand mining a few remarks can be made. The Cochin estuary is not the great new source for sand mining if not to large alterations are acceptable inside the estuary. The self-restoration capacity of the estuary is not very good. When due to the mining of sand a small disturbance is applied, the estuary is able to restore to its old form. The changes if applied not too fast will not cause a continuing change in the estuary, as is seen in the case where the dry model was the recover time. In the case where a four year interval was taken the system was brought out of is equilibrium in such a way that a totally new equilibrium had to be found and the system gets large deviations.
The advantage of the mining of sand is that the economic demand for sand is satisfied and employment is gained. Also the dredging volumes inside the harbour area can be brought down. The disadvantage is the drastic consequences it has on the morphology of the estuary. When we look at the Coastal Zone Management Plans as they are in their present form the mining of sand will not be allowed, but if the mining is carefully done it could be allowed when small adjustments in the estuarine geometry are accepted.
As can be seen from this case there is a vulnerable balance between economy and environmental issues. As mentioned in the first chapter there is a multiple demand for the resources the estuary can offer and for every choice to interfere in the system a balance has to be made to determine which aspects get priority. The difficulty is that in economic weaker times the environment and the long-term development is most of the time the underlying party and interferences are done that have a long-term morphological and environmental impact on the estuary.

System review

With the insight into the behaviour of the system gained in the various model exercises discussed before, some remarks can be made on the overall character of the morphological development in the estuary against the background of Coastal Zone Management.
The last two cases indicate that we are dealing with a very fragile system, where the smallest disturbance may cause huge alterations. This is, as found during the modelling phase, a consequence of the magnitude of the cross-sectional area in the southern branch near Panavally, see appendix 2.1. The tidal motion that governs the morphological evolution of this branch during the dry season, appears insufficient to maintain the cross section
Before jumping to conclusions about the possible physical instability of the estuary some marginal notes have to be made, of which some are formulated before. Not much field data are available on the branches that cause the instability in the model of the estuary. It is therefore not clear beforehand whether the observed instability is a model artefact or a natural phenomenon. Clarification of this issue requires further investigation, substantiated with a purposive field campaign. As this is beyond the scope of the present study, we abstain from any other conclusion than that there is an indication of instability of the system.
Another note concerning the morphology of the system is that it is not certain what the sediment balances of the estuary and that of the coastal area around its mouth are mutually related. This depends on a lot of conditions such as long-shore current, wave climate and transport mechanisms within the estuary. When the system is mostly bar passing, the coastal erosion may not be very dependent on the changes in the estuary system. With an r=20 (Bruun, 1978), as explained in the second chapter, this is not improbable. So it is difficult to make a direct connection between the changes in the estuary and erosion of the adjacent coastal area.

What does speak in favour for the theory of dependence though is that the change of dumping place of the dredged material, keeping it inside the system, caused the erosion to stop. In chapter 2 it was explained that dumping the material in the inlet, which was washed out during the ebb-currents, made the erosion stop. Also the fact that the material that is dredged from the harbour channels originates mainly from the sea indicates sediment exchange between the shore and the estuary.

The before mentioned model instability encountered for the dry season, does not occur in the model simulations regarding the wet season. This may indicate that the estuary maintains some dynamic equilibrium, characterised by a gradual, tide-induced siltation in the dry season and counteracting erosion caused by heavy river discharge during the monsoon. Under the present conditions, the system probably stays in its current shape but it cannot be excluded beforehand that even a comparatively small interference (either natural or man made) may cause a drastic change in shape. The present inlet of the Cochin estuary, formed in the 14e century, may very well be the result of some seemingly minor event.

But maybe even the coastal erosion can be seen as an indication of an instable system. As discussed in chapter 2, using the sand from the adjacent shorelines can fulfil a sand shortage in the estuary. Another important indication that the estuary is morphologically unstable is the apparent reduction of its horizontal area. Part of this reduction can be explained from human interferences, but a natural tendency to shrink seems to be present as well. No doubt, this process is intensified by the much interference carried out in the last century.. Especially in the southern areas the reclamations for the paddy fields have been countless. Also the Thanneermukkon bund constructed 25 years ago significantly changed the area of the estuary. Although this bund is operational during the dry season only, its effect may be substantial. As mentioned before, the instability occurs when the morphological evolution of the estuary is determined mainly by the tide and that happens to be in the dry season.

The mentioned dynamic equilibrium and possible instability of the system should be considered seriously in planning and designing further interventions in the estuary. From the model simulations it was seen that during wet season the southern branches show a tendency to deepen and during dry season to become shallower. The harbour area behaves oppositely. This means that adjustments, which cause deepening of the southern areas, are preferably done in the wet season so the system gets a chance to restore itself. For the harbour area this is not really a consideration, since the depths are maintained here by dredging.

Also from the model computations it seems that stopping with dredging means that the estuary will change dramatically, which means a complete silting up of the estuary. This means that the present dredging activities play a crucial role in maintaining the before mentioned dynamic equilibrium. Dredging is not only beneficial for the harbour area itself but also for keeping the entire estuary in its present condition. Without it, the estuary would show a tendency of sedimentation.

Also some remarks have to be made on the environmental issues in the estuary. Primarily upstream dumping of various kinds of waste by farmers and factories causes the Cochin estuary to be one of the most polluted estuaries in India. Two processes increase the damage caused by the pollution. Because of the shrinkage of the estuary the refreshing time for the water and the sediment is increasing, keeping the pollutants for a longer time in the estuary. Also the Thanneermukkon bund acts as a trap for polluted silt, especially during dry season of course. The problem is as we saw in the cases that these two problems arise, when opposite morphological development occurs. A shrinkage of the estuary causes the refreshing time to become even higher. A deepening of the estuary causes the Thanneermukkon bund to close faster and thus a larger pile of polluted silt upstream of the bund. It is thus difficult to say what is better for the environment a deepening of the estuary or shrinkage.

The indications of a morphological instability encountered in the present study, necessitate that plans for interventions in the estuary are accompanied by a thorough investigation on the attended morphological impact, as that may be substantial and adverse. Especially when the intervention is likely to have a large effect on the southern branches of the estuary, one should be aware that the impact might be severe, also in other parts of the estuary.

Chapter 6: Conclusions and recommendations

In this chapter the conclusions, which may be drawn from this thesis report are presented. Also some recommendations are presented for follow-up research. Finally, an evaluation of the project is presented. The purpose of this chapter is to summarize the study in terms of conclusions and recommendations.

6.1 Conclusions

The conclusions for the morphological development of the Cochin area, which may be drawn, are:

- Modelling of the Cochin estuary indicates that this system is quite unstable and that if human interferences are applied, first solid research has to be done. This instability is the consequence of much interference that has been done in the system up to now
- The cross-sectional areas as seen in the Pannavally area cause the system to be instable, because this cross-sectional area can be seen as the unstable point of the Escoffier graph.
- The system is kept open by the wet season, because the tidal prism of the dry season is not able to keep the large cross-sectional areas in southern branches open.
- The dredging process causes a positive feedback; if more dredging is applied the estuary will increase its tidal prism, which causes the dredging volumes to be less. The same is true, but than the other way around, when the dredging volumes are decreased.
- The Mattanchery channel is already close to an ideal sand catch and increasing or decreasing the depth has hardly any effect on the dredging volumes that are taken out of this channel.
- The building of an additional harbour would be very beneficial for the economy of Kerala but the harbour expansions also cause great problems like coastal erosion and environmental pollution.
- Sand mining can be allowed but only if enough restore intervals are built in and the mining has to be temporary.

Conclusions about the modelling of the area are:

- From this project it becomes clear that morphological modelling is hard to do with the data collection that was done for this project and during the project. The data collection for the Cochin estuary can be much approved. Nevertheless this lack of sufficient data had the advantage to make clear what kind of data is essential for constructing a semi-empirical model, because no overkill of information was available. It seems for the hydraulic part the boundary conditions (tide, river discharge) and the geometry of the non-storage areas are the most important parameters. In this project especially more detailed river discharge data and more accurate bathymetric data are lacking. Considering the results of the morphological model, it seems that especially the morphological history is important.
- This model should be seen as a set-up to determine the morphological development in the long term of the Cochin estuary. From this basis the processes that determine the morphological development of the estuary are defined and can be further investigated.
- The A-P relation (the cross-sectional area and the tidal prism) in the Sobek model procures stability in the Estmorf model. Since the Estmorf model only determines a point to be in equilibrium because it is appointed by the user without looking at the water

movement, it can be the case as in the Cochin model that this A-P relation in Sobek causes such an interaction that instability occurs.

- It is difficult to implement an estuary in the Estmorf model, when the boundary conditions vary a lot through the year as in the Cochin estuary model with seasonally closed dams.

6.2 Recommendations

The recommendations concerning the follow-up research are:

- More research has to be done to determine the connection between the long-term coastal erosion and changes in the estuary. Some theories about this connection have been described in this report and in literature, but no proof has been given yet.
- If a harbour is built on Vypeen Island, first the changes it would bring about in currents and sedimentation pattern inside and outside the estuary should be researched to find the ideal location for this external harbour.
- The influence of the extreme peak discharges should be investigated because they may change the entire bathymetry of the estuary and they might determine the stability of the estuary in its current situation.

Some other recommendations concerning the modelling and the used software are:

- If this model will be used for quantitative results in the future, more data has to be collected. Especially the lack of sufficient bathymetric data and morphological history has impeded the execution of this project.
- Large variations in boundary conditions can only be implemented in the Estmorf model by making separate models. It would be easier if it would be possible to make some of the input parameters variable (e.g. the diffusion coefficient for the opening and closing of dams). This however, would also make the Estmorf model more complicated.

Literature

Ajith Joseph K.,1996. Strait dynamics of tropical tidal inlets, 1996, Department of physical oceanography, Cochin University of Science And Technology.

Battjes, J.A., 2000. Vloeistofmechanica, March 2000, Faculty of Civil Engineering and Geosciences, TU Delft.

Battjes, J.A., 2001. Stroming in waterlopen, January 2001, Faculty of Civil Engineering and Geosciences, TU Delft.

Bruun, P, 1989, Port engineering. Vol. 1. Harbor planning, breakwaters, and marine terminals, Gulf, Houston

Bruun, P., 1978. Stability of Tidal inlets, 1978, Elsevier Scientific Publisher, Amsterdam

Chandramohan, P.V., 2002. Research scheme on Siltation in Estuarine Ports, April 2002, Cochin Port Trust.

Frederic R. Harris B.V., 1989. Vallarpadam container Transshipment Terminal, Cochin Port India. Morphological aspects/ Hydro morphological model study. Feasibility study, October 1989/september 1990, Delft Hydraulics.

Gopalan,U.K., D.T. Vengayil, P. Udayavarma and M. Krishnankuttty, 1983. The shrinking backwaters of Kerala, 1983, Journal of mayor biological assessment India.

Helvert, M. van, 2003. User manual ESTMORF 3.2, versie 2 Concept, Delft hydraulics.

Josanto, V., 1971. On the grain size of the Cochin Backwater sediments, Bull. Dept. Mar. Biol. Oceanogr. 1971, vol 5, 109-122.

Joseph, J, P.G.Kurup,1989. Volume transport and estuarine features at Cochin Inlet, Mahasagar. Volume 22 No. 4, 1989, pp165-172.

Karssen B., 1994. A dynamic/empirical model for the long-term development of estuaries, Development of the model, phase 1, Delft hydraulics.

Karssen B., 1994. A dynamic/empirical model for the long-term development of estuaries, Development of the model, phase 2, Delft hydraulics.

Krishnakumar, R., 2003. Rivers for Sale, Frontline, vol.20, issue - 2, January 2003, The Hindu

Madhusoodanan, M.S. & Balchand, A.N., 1997. Coastal Zone Management Plans for central parts of the state of Kerala, Second Indian National Conference on Harbour and Ocean Engineering, Thiruvananthapuram, December 7-10, 1997

Mathew, T.K and P.V. Chandramohan, 1993. Low cost dredging techniques at the port of Cochin, India, September 1993, terra et aqua no. 52.

Menon, N.N., A.N. Balchand & N.R. Menon, 2000.Hydrobiology of the Cochin Backwater system- a review, 2000, hydrobiologia 430: 149-183, 2000 Kluwer academic publishers.

Ramachandran, A., A.N. Balchand, B.Enserink, 2002. Assesing the impact of public participation in coastal zone management -An evolution of the peoples' Participatory Programmes in Coastal Villages in Kerala, India. Proceedings IAIA conference 15-21 June 2002. VVM The Hague.

Rasheed, K., 1997. Studies on dredging impact assessment (DIA) at Cochin, a tropical estuarine harbour, July 1997, faculty of marine sciences, department of physical oceanography.

Sassi Kumar, P.K., 1997. The mud banks of south-west coast of India and its effects on the coastline, Second Indian National Conference on Harbour and Ocean Engineering, December 7-10 1997.

Srinivas, K. & Dinesh Kumar, P.K., 2002. Tidal and non-tidal sea level variations at two adjacent ports on the southwest coast of India, Indian Journal of Marine Sciences, Vol. 31(4), December 2002, pp. 271-282

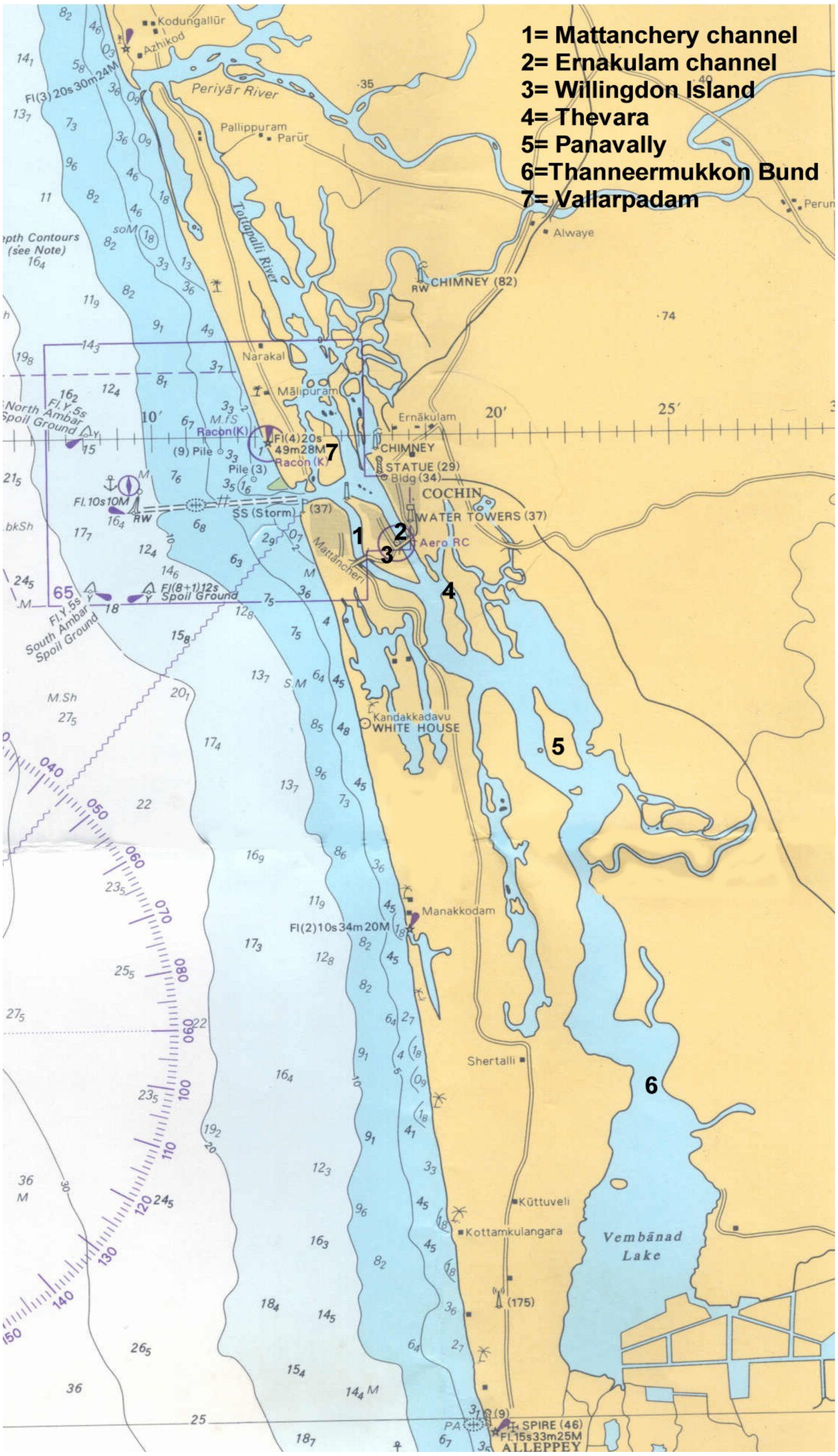
Veerayya, M. & Murty, P.S.N., 1973. Studies on the sediments of Vemband Lake, Kerala State: Part III - Distribution & Interpretation of Bottom Sediments, Indian Journal of Marine Sciences, vol. 3, June 1974, pp 16-27

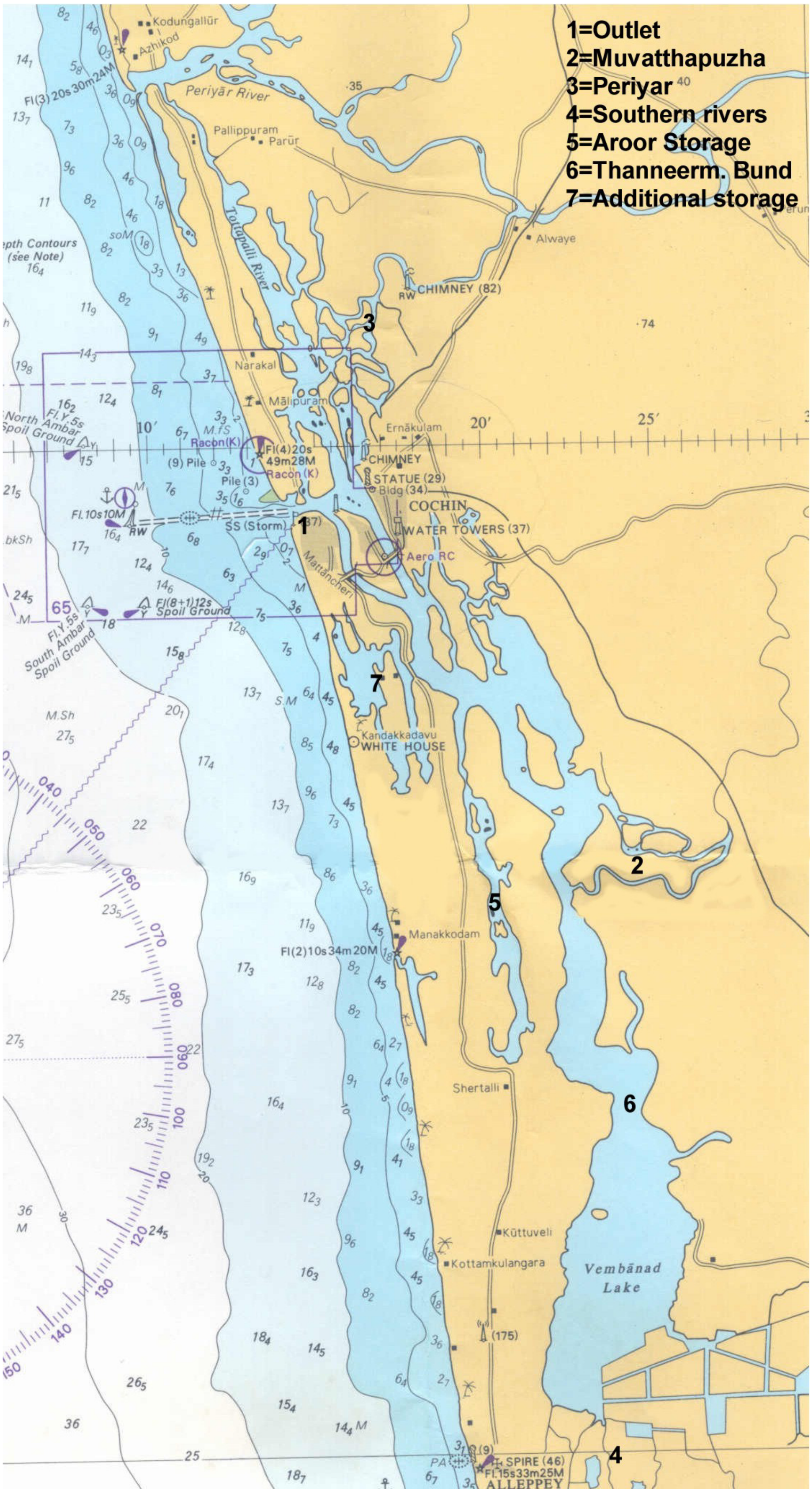
Vriend, H.J. de, J Dronkers, M.J.F. Stive, A. van Dongeren, Z.B. Wang, 2002. Coastal inlets and Tidal basins, January 2002, Faculty of Civil Engineering and Geosciences, TU Delft.

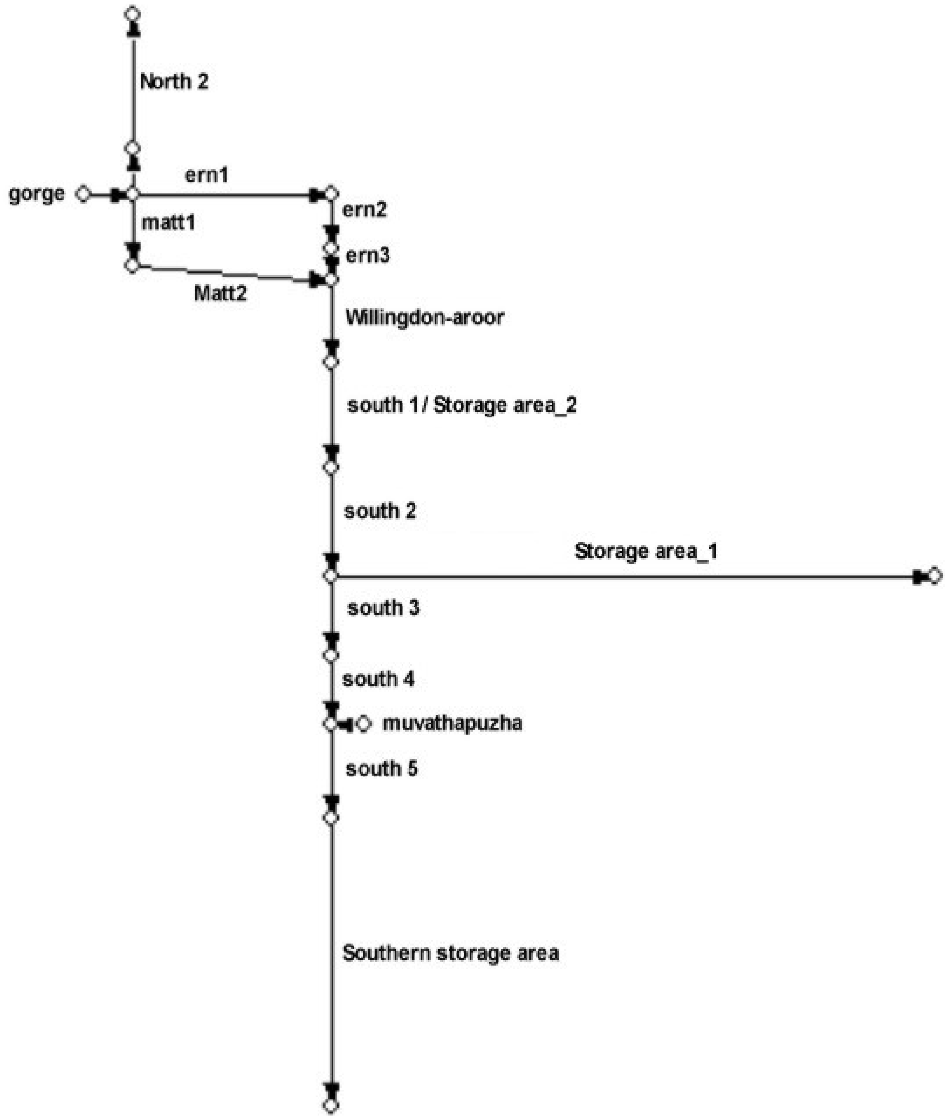
Wang, Z.B., Karssen B., 1991. Morphological modelling in estuaries and tidal inlets, a literature survey, Delft hydraulics.

Wang, Z.B., 2003. Personal communication.

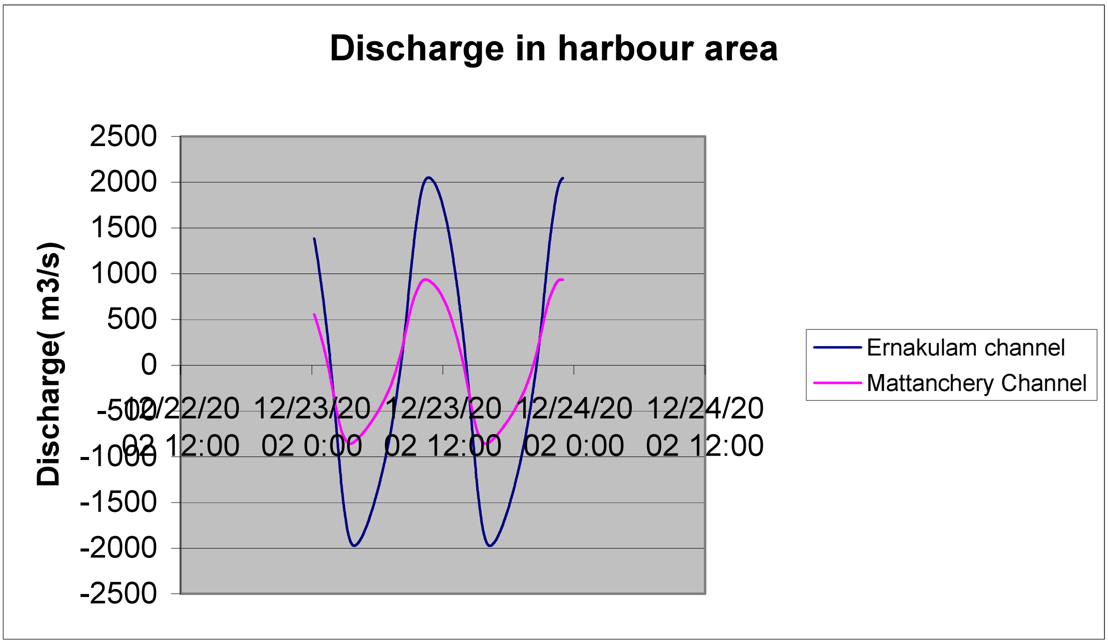
Appendix 2.1
Maps of the Cochin Area


1= Mattanchery channel
2= Ernakulam channel
3= Willingdon Island
4= Thevara
5= Panavally
6=Thanneermukkon Bund
7= Vallarpadam
Kodungallūr
Azhikod
Periyār River
Pallippuram
Parūr
Alwaye
CHIMNEY (82)
Narakal
Mālipuram
Ernākulam
CHIMNEY
STATUE (29)
Bldg (34)
COCHIN
WATER TOWERS (37)
Aero RC
Racon (K)
Fl(4)20s 49m28M
SS (Storm)
Mattancheri
North Ambar Spoil Ground
South Ambar Spoil Ground
Spoil Ground
Kandakkadavu
WHITE HOUSE
Manakkodam
Fl(2)10s34m20M
Shertalli
Kūttuveli
Kottamkulangara
Vembānad Lake
SPIRE (46)
Fl.15s33m25M
ALLEPPEY

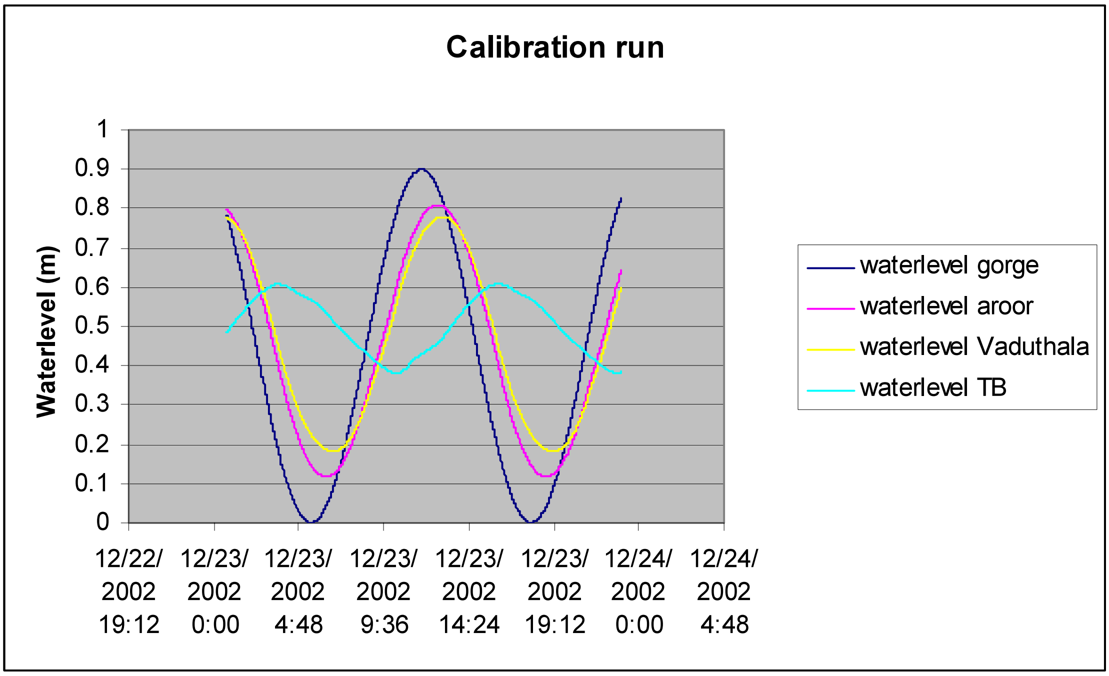

1=Outlet
2=Muvatthapuzha
3=Periyar
4=Southern rivers
5=Aroor Storage
6=Thanneerm. Bund
7=Additional storage
Kodungallūr
Azhikod
Periyār River
Pallippuram
Parūr
Alwaye
CHIMNEY (82)
Narakal
Mālipuram
Ernākulam
COCHIN
WATER TOWERS (37)
STATUE (29)
Aero RC
Racon (K)
SS (Storm)
Mattāncheri
Kandakkadavu
WHITE HOUSE
Manakkodam
Shertalli
Kūttuveli
Kottamkulangara
Vembānad
Lake
SPIRE (46)
ALLEPPEY
North Ambar Spoil Ground
South Ambar Spoil Ground
Spoil Ground


North 2
gorge
ern1
matt1
ern2
ern3
Matt2
Willingdon-aroor
south 1 / Storage area_2
south 2
Storage area_1
south 3
south 4
muvathapuzha
south 5
Southern storage area

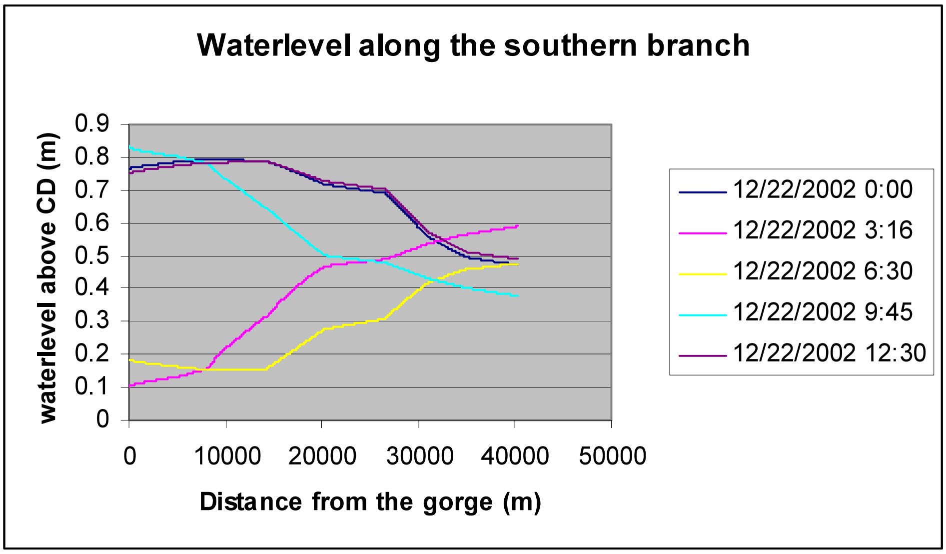
Appendix 4.1
Calibration Run



Discharge in harbour area
Discharge(m3/s)
2500
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2500
12/22/2002 12:00
12/23/2002 0:00
12/23/2002 12:00
12/24/2002 0:00
12/24/2002 12:00
Ernakulam channel
Mattanchery Channel

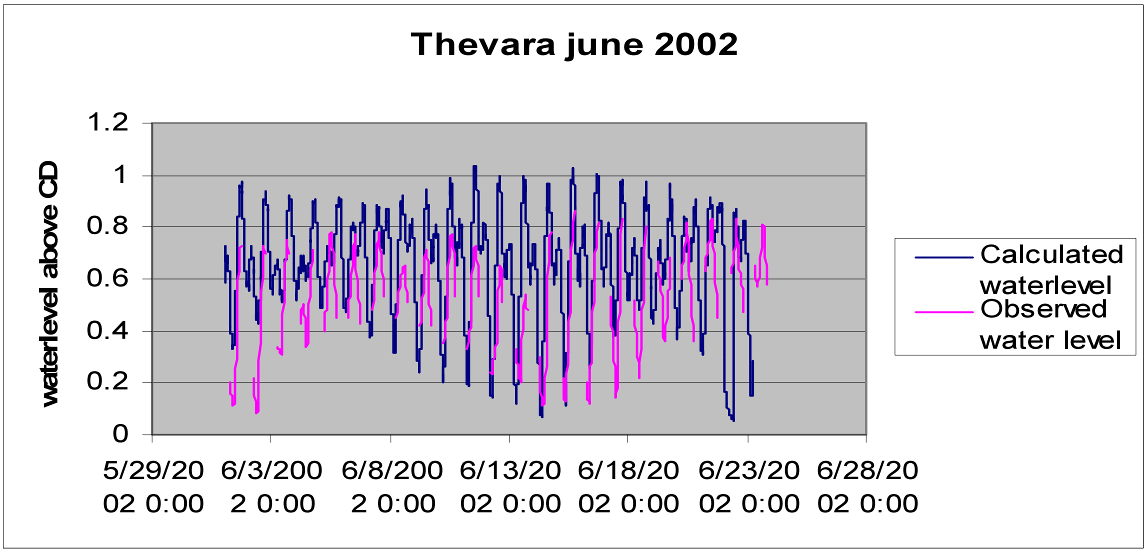


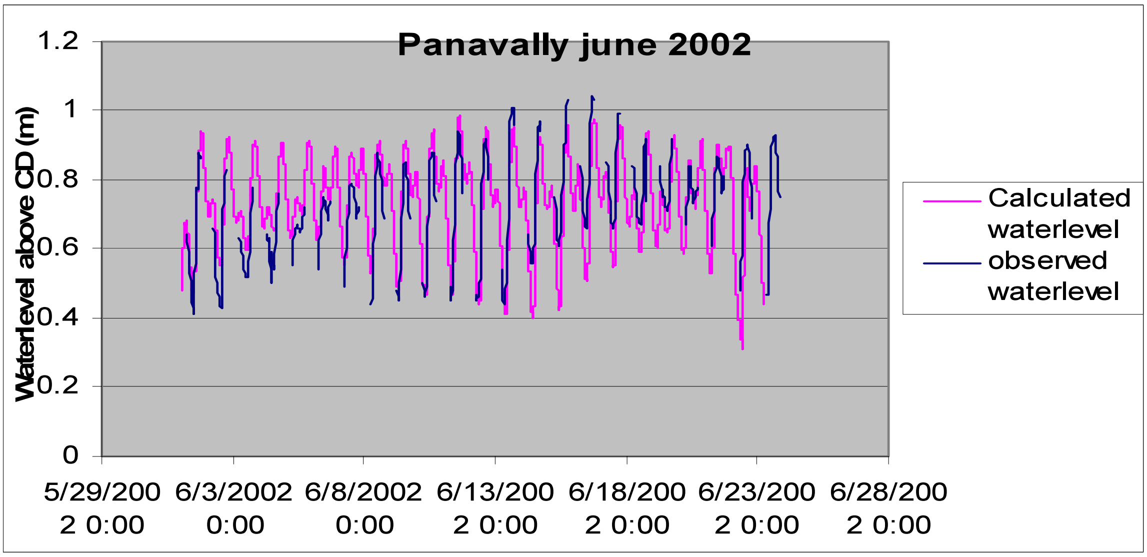
Calibration run
Waterlevel (m)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
12/22/2002 19:12
12/23/2002 0:00
12/23/2002 4:48
12/23/2002 9:36
12/23/2002 14:24
12/23/2002 19:12
12/24/2002 0:00
12/24/2002 4:48
waterlevel gorge
waterlevel aroor
waterlevel Vaduthala
waterlevel TB

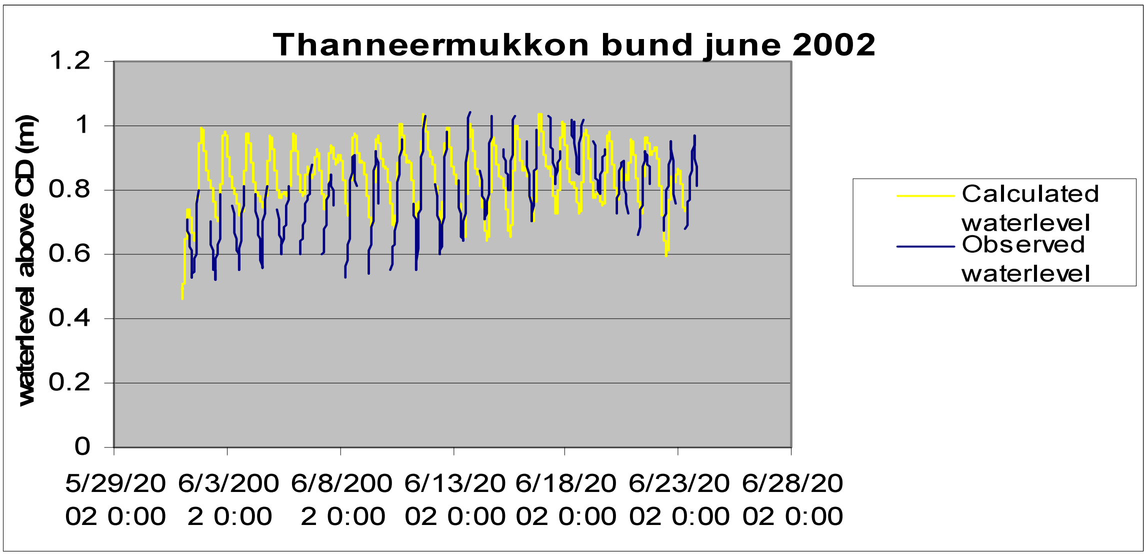


Waterlevel along the southern branch
waterlevel above CD (m)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
10000
20000
30000
40000
50000
Distance from the gorge (m)
12/22/2002 0:00
12/22/2002 3:16
12/22/2002 6:30
12/22/2002 9:45
12/22/2002 12:30

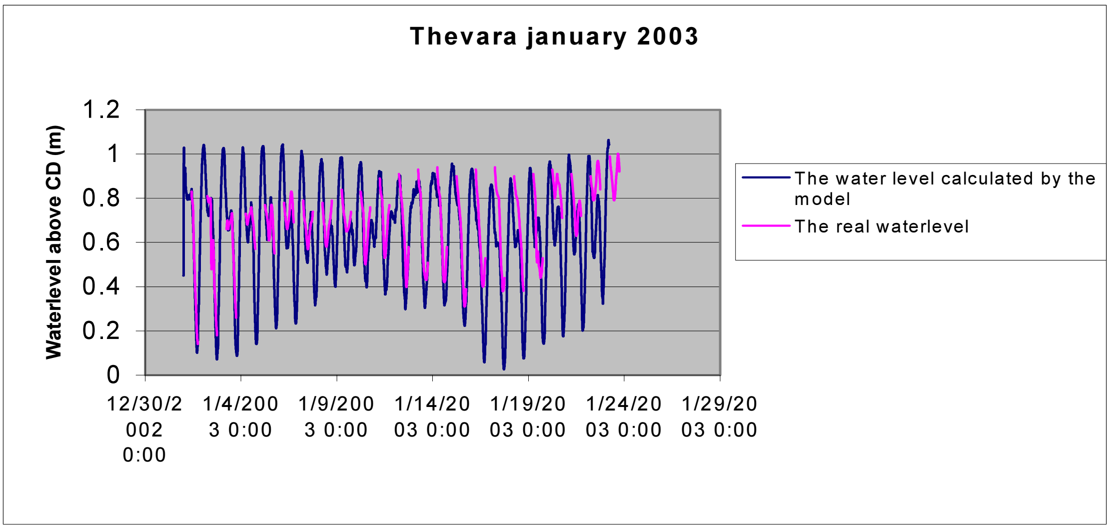
Appendix 4.2
Validation Run 1

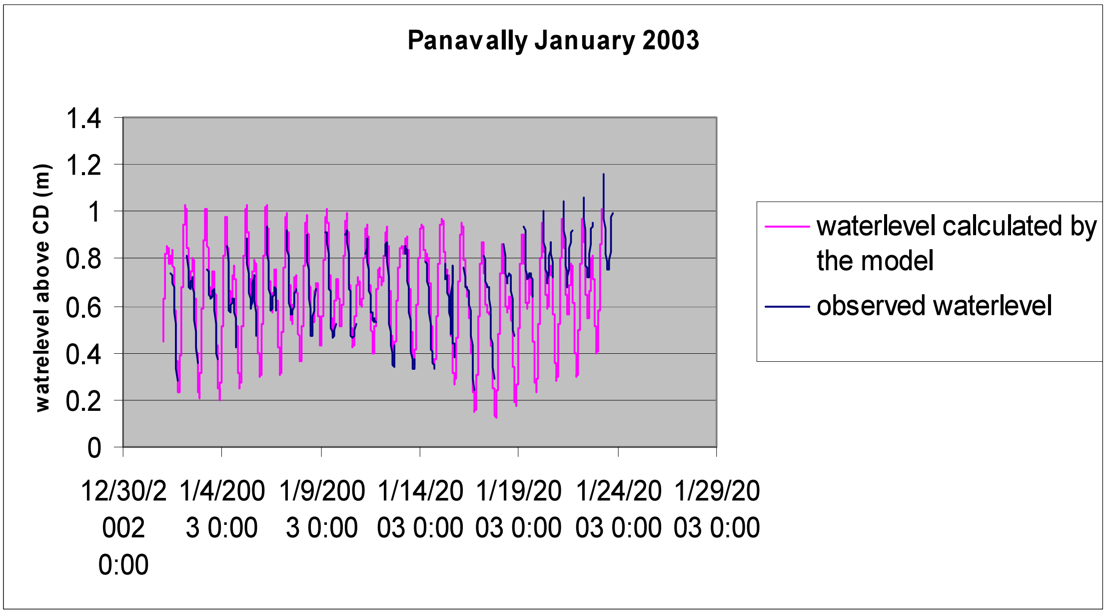

Thevara june 2002
waterlevel above CD
1.2
1
0.8
0.6
0.4
0.2
0
5/29/20 02 0:00
6/3/200 2 0:00
6/8/200 2 0:00
6/13/20 02 0:00
6/18/20 02 0:00
6/23/20 02 0:00
6/28/20 02 0:00
Calculated waterlevel
Observed water level

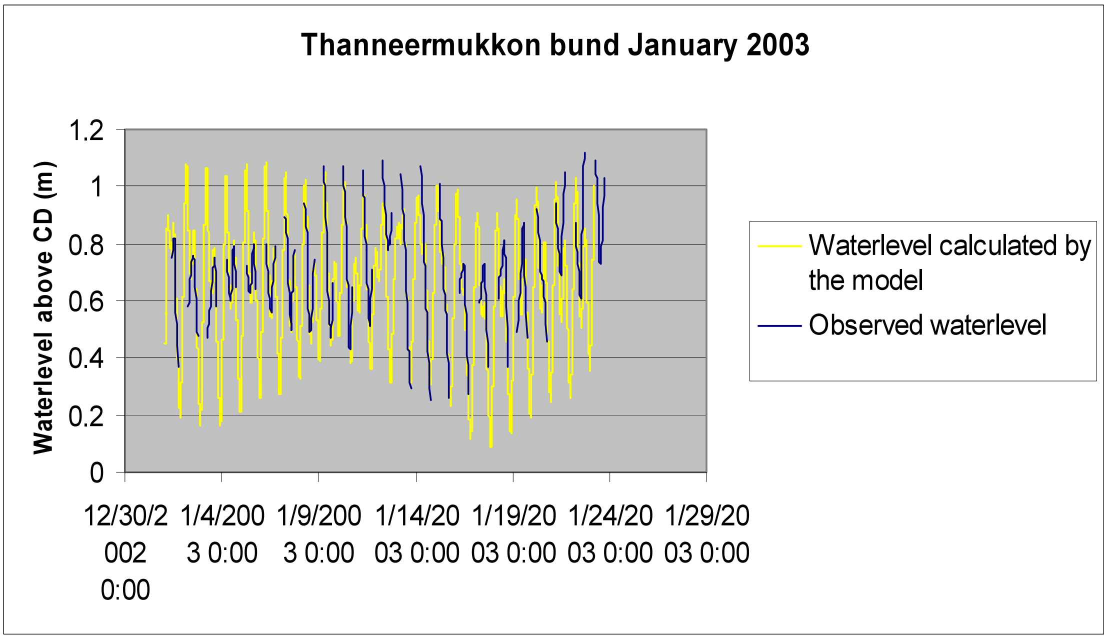

Panavally june 2002
Waterlevel above CD (m)
1.2
1
0.8
0.6
0.4
0.2
0
5/29/200 2 0:00
6/3/2002 0:00
6/8/2002 0:00
6/13/200 2 0:00
6/18/200 2 0:00
6/23/200 2 0:00
6/28/200 2 0:00
Calculated waterlevel
observed waterlevel


Thanneermukkon bund june 2002
waterlevel above CD (m)
1.2
1
0.8
0.6
0.4
0.2
0
5/29/20 02 0:00
6/3/200 2 0:00
6/8/200 2 0:00
6/13/20 02 0:00
6/18/20 02 0:00
6/23/20 02 0:00
6/28/20 02 0:00
Calculated waterlevel
Observed waterlevel

Appendix 4.3
Validation run 3

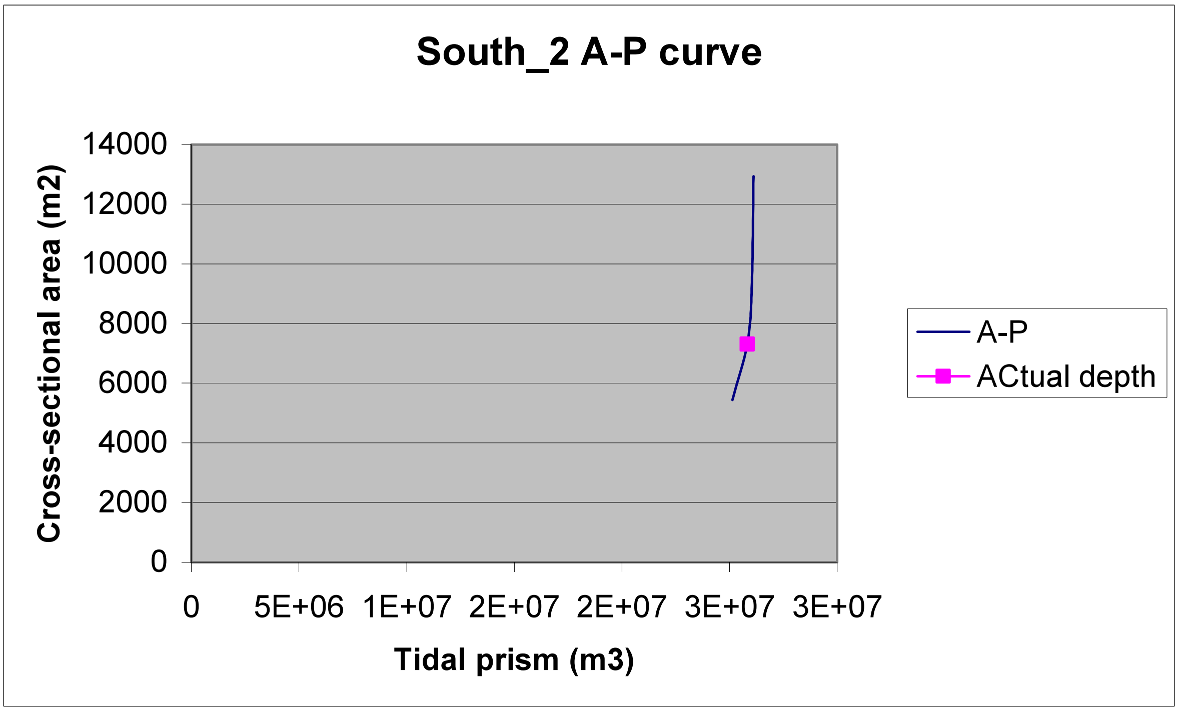

Thevara january 2003
Waterlevel above CD (m)
1.2
1
0.8
0.6
0.4
0.2
0
12/30/2002 0:00
1/4/2003 0:00
1/9/2003 0:00
1/14/2003 0:00
1/19/2003 0:00
1/24/2003 0:00
1/29/2003 0:00
The water level calculated by the model
The real waterlevel

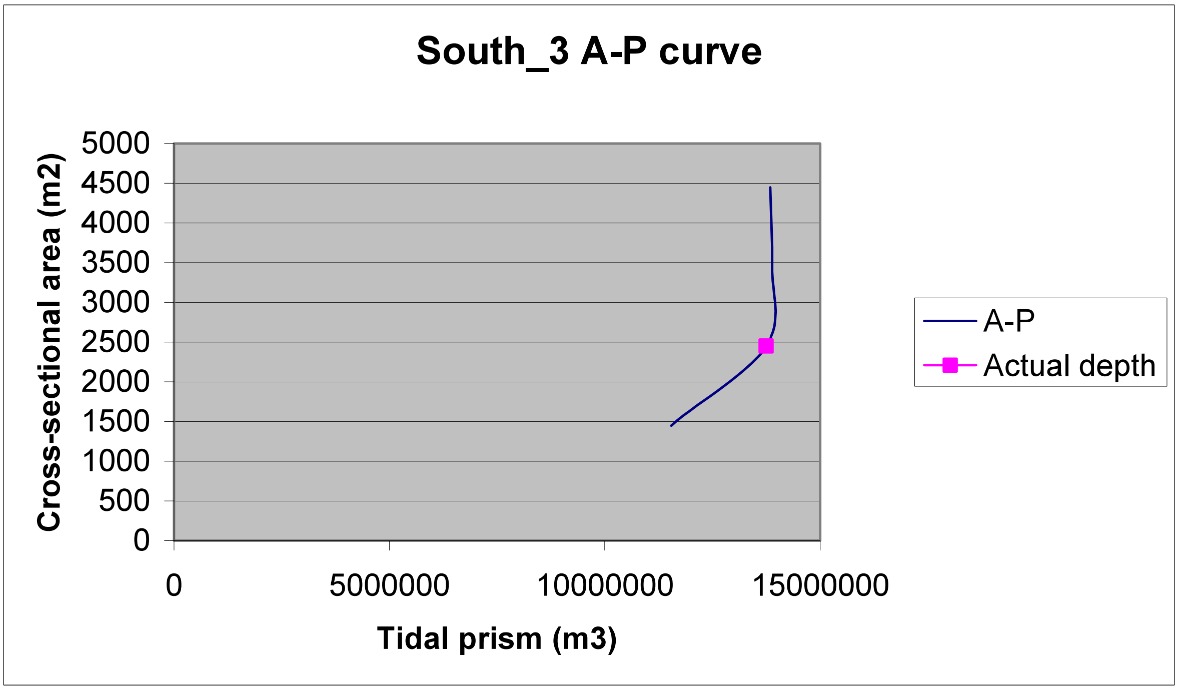

Panavally January 2003
watrelevel above CD (m)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
12/30/2002 0:00
1/4/2003 0:00
1/9/2003 0:00
1/14/2003 0:00
1/19/2003 0:00
1/24/2003 0:00
1/29/2003 0:00
waterlevel calculated by the model
observed waterlevel

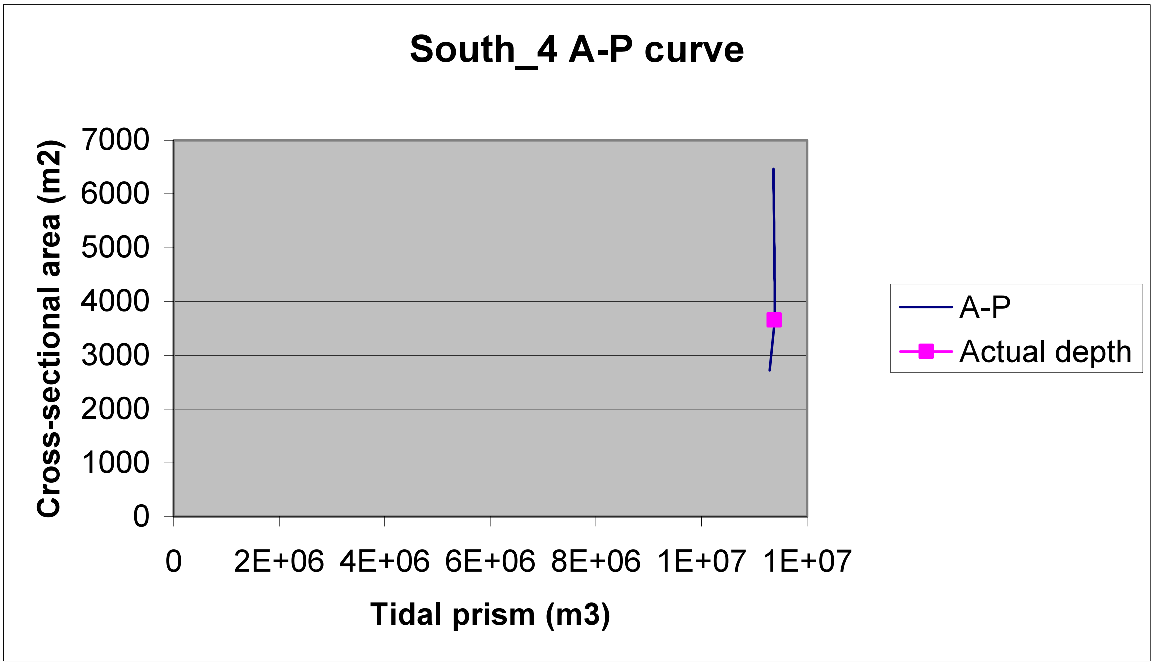

Thanneermukkon bund January 2003
Waterlevel above CD (m)
1.2
1
0.8
0.6
0.4
0.2
0
12/30/2002 0:00
1/4/2003 0:00
1/9/2003 0:00
1/14/2003 0:00
1/19/2003 0:00
1/24/2003 0:00
1/29/2003 0:00
Waterlevel calculated by the model
Observed waterlevel

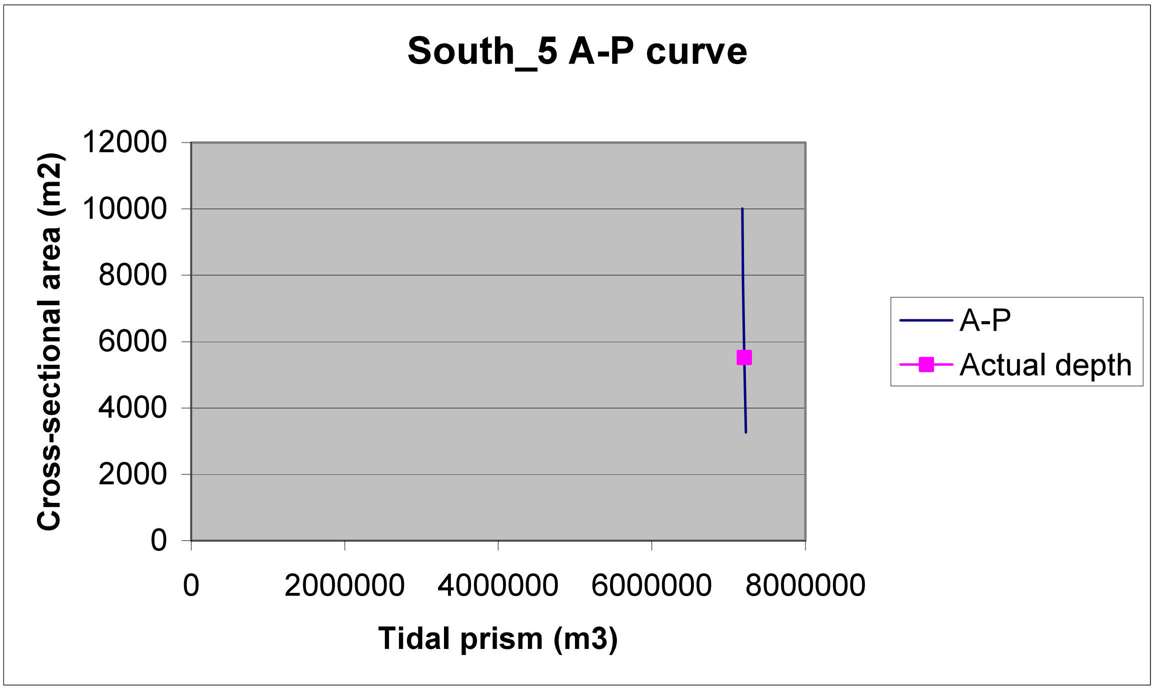
Appendix 4.4
Sensitivity Analysis

Dry season

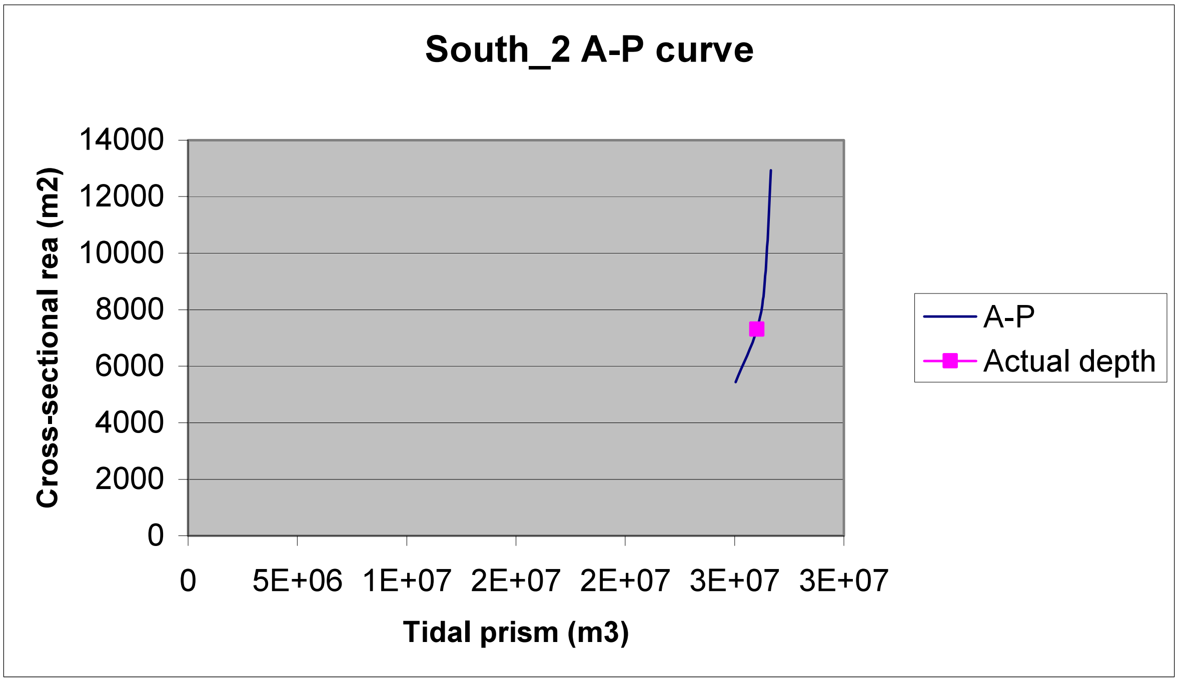

South_2 A-P curve
Cross-sectional area (m2)
14000
12000
10000
8000
6000
4000
2000
0
0
5E+06
1E+07
2E+07
2E+07
3E+07
3E+07
Tidal prism (m3)
A-P
ACtual depth

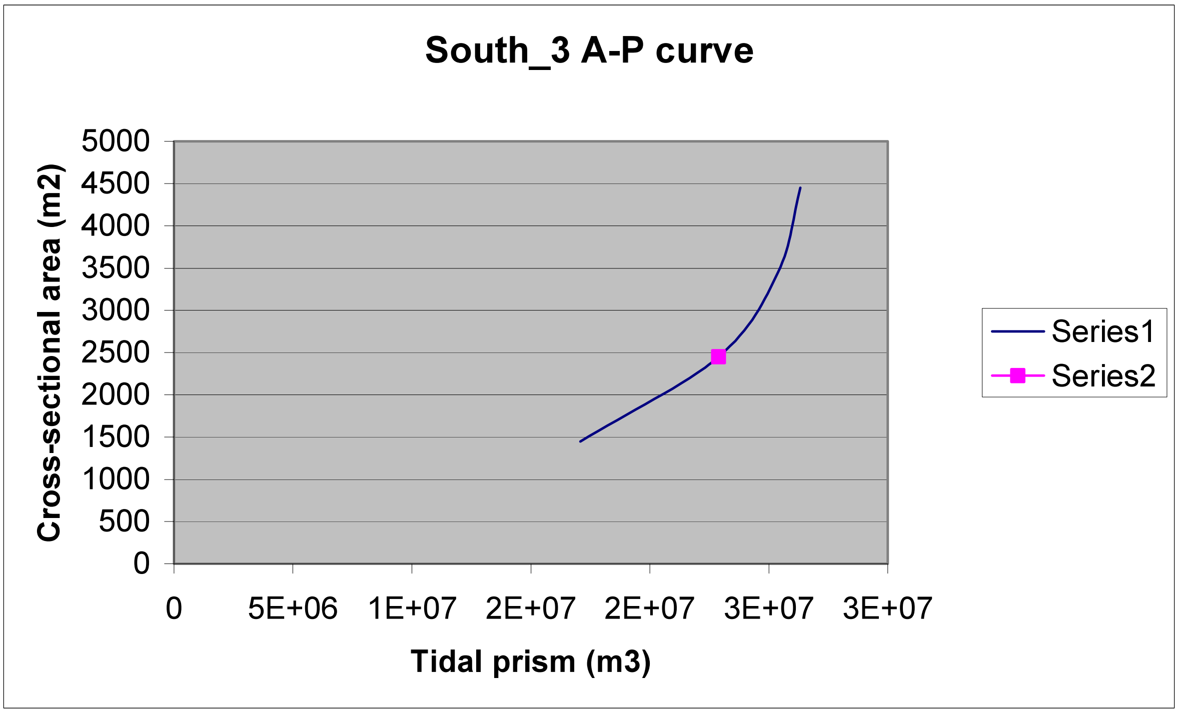

South_3 A-P curve
Cross-sectional area (m2)
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
0
5000000
10000000
15000000
Tidal prism (m3)
A-P
Actual depth

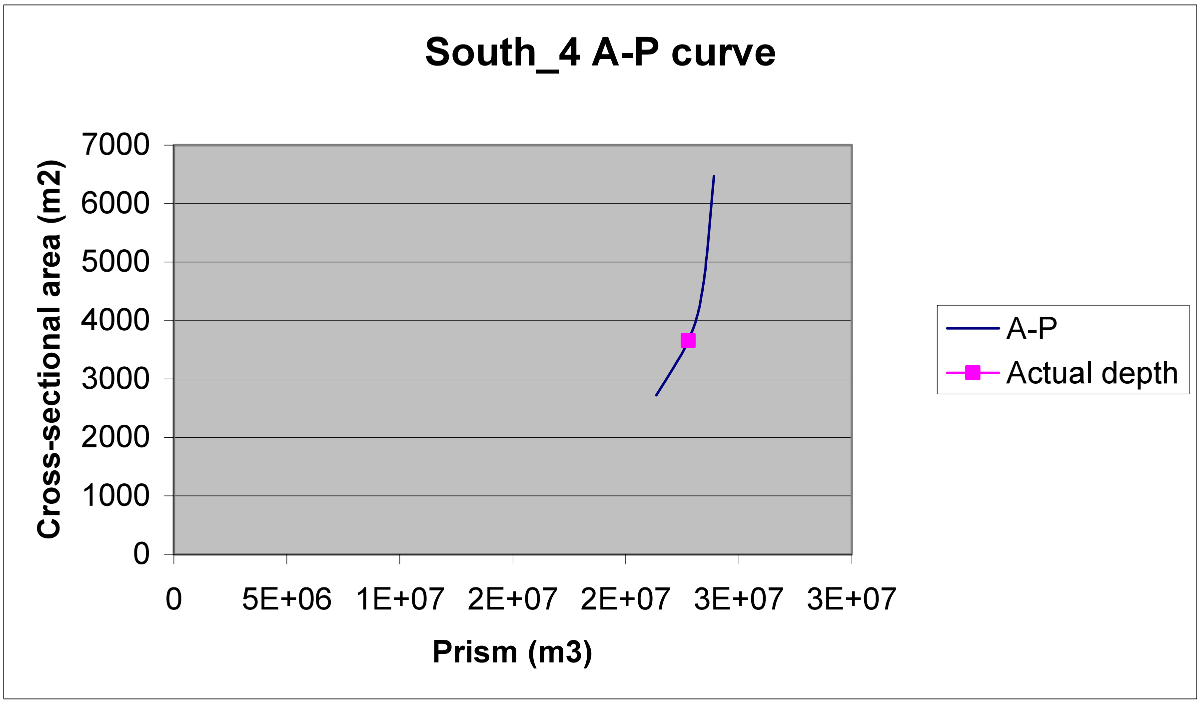

South_4 A-P curve
Cross-sectional area (m2)
7000
6000
5000
4000
3000
2000
1000
0
0
2E+06
4E+06
6E+06
8E+06
1E+07
1E+07
Tidal prism (m3)
A-P
Actual depth

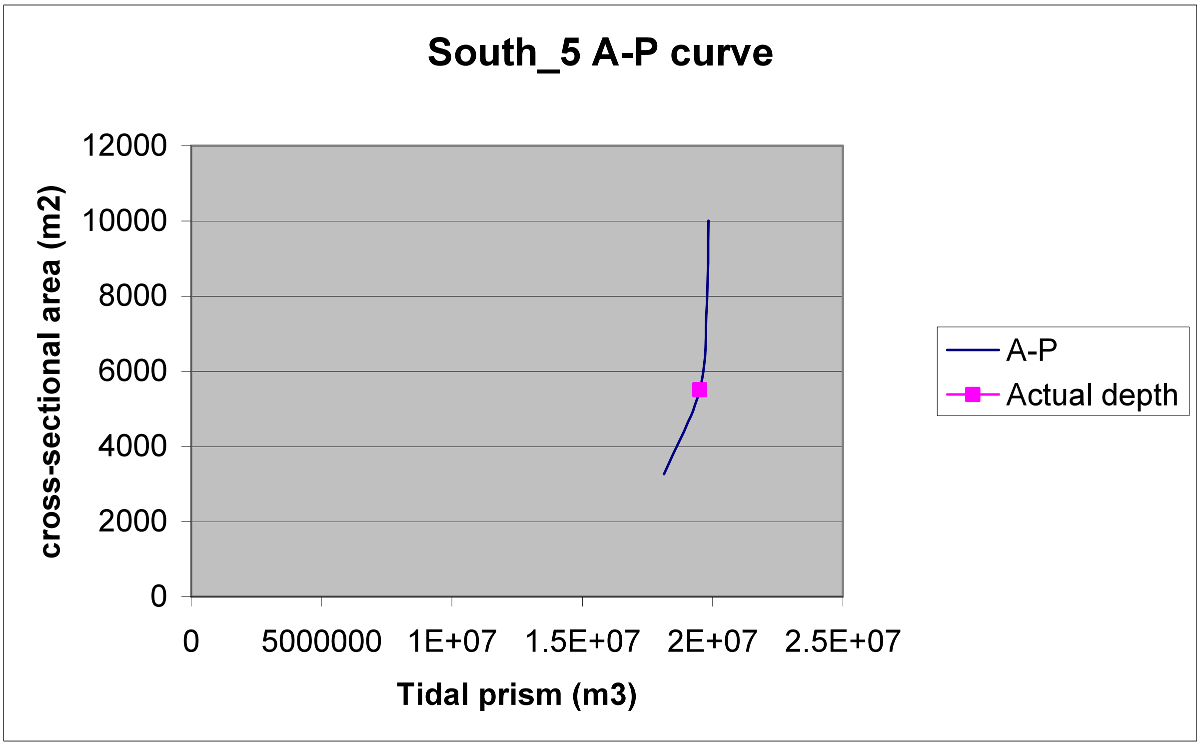

South_5 A-P curve
Cross-sectional area (m2)
12000
10000
8000
6000
4000
2000
0
0
2000000
4000000
6000000
8000000
Tidal prism (m3)
A-P
Actual depth

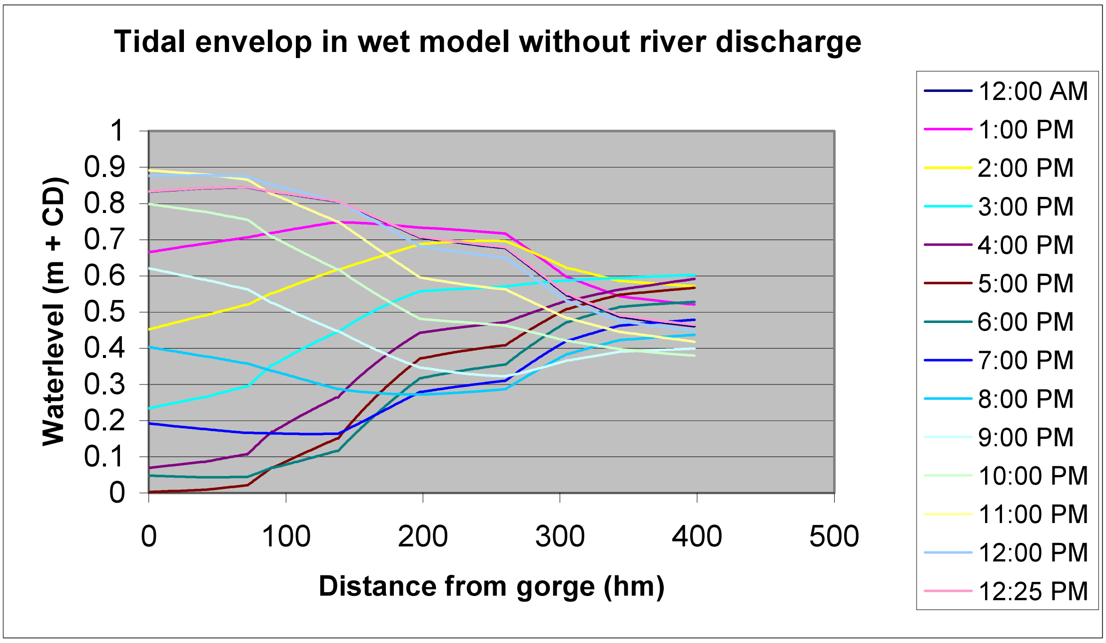
Wet season


South_2 A-P curve
14000
12000
10000
8000
6000
4000
2000
0
Cross-sectional rea (m2)
0
5E+06
1E+07
2E+07
2E+07
3E+07
3E+07
Tidal prism (m3)
A-P
Actual depth

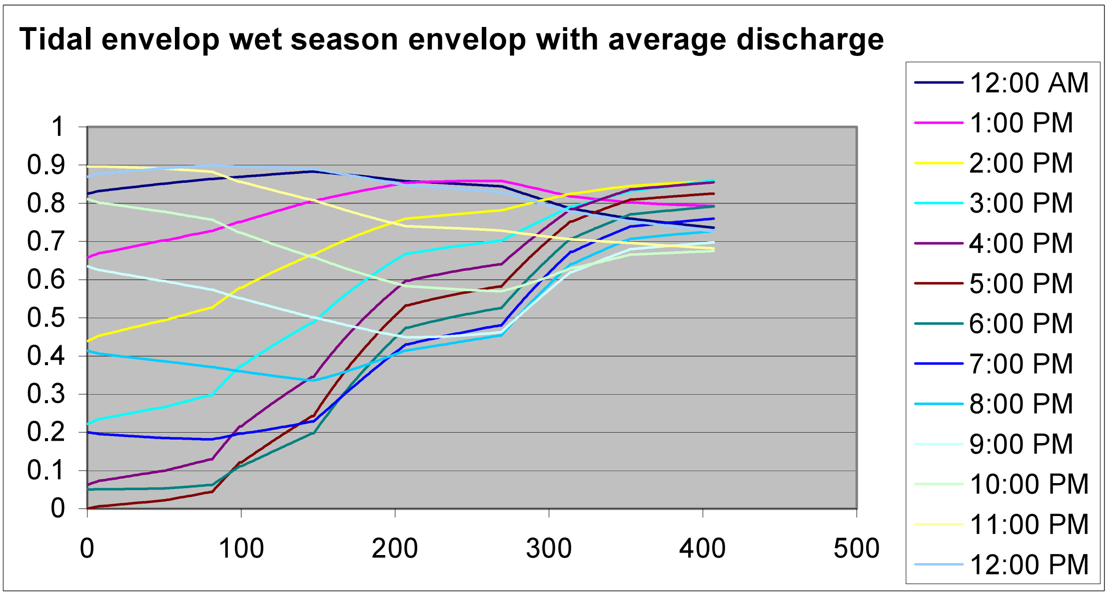

South_3 A-P curve
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
Cross-sectional area (m2)
0
5E+06
1E+07
2E+07
2E+07
3E+07
3E+07
Tidal prism (m3)
Series1
Series2


South_4 A-P curve
7000
6000
5000
4000
3000
2000
1000
0
0
5E+06
1E+07
2E+07
2E+07
3E+07
3E+07
Cross-sectional area (m2)
Prism (m3)
A-P
Actual depth

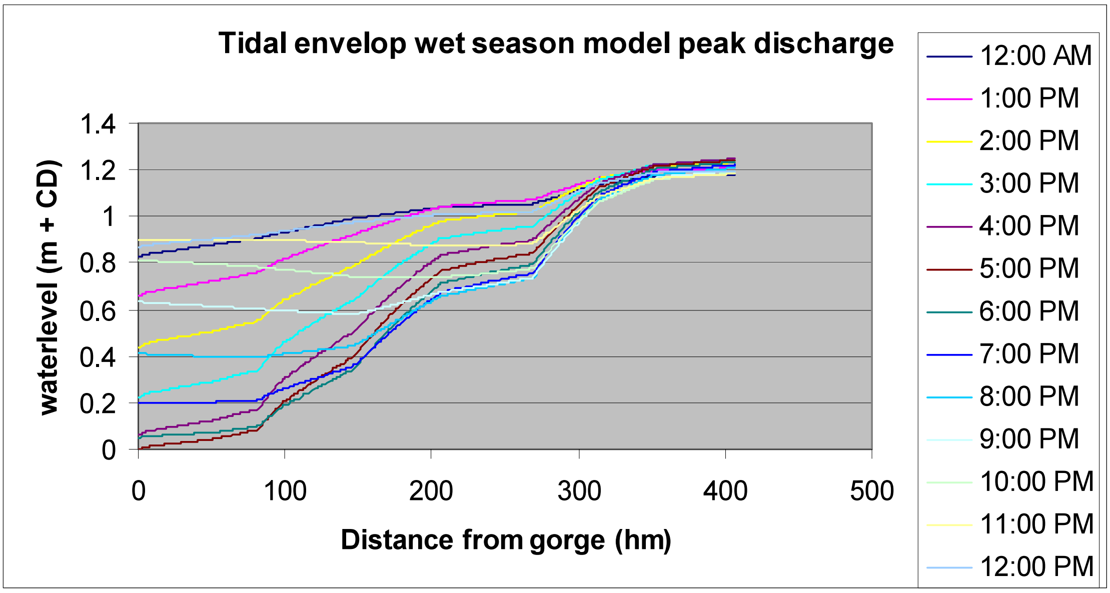

South_5 A-P curve
12000
10000
8000
6000
4000
2000
0
0
5000000
1E+07
1.5E+07
2E+07
2.5E+07
cross-sectional area (m2)
Tidal prism (m3)
A-P
Actual depth

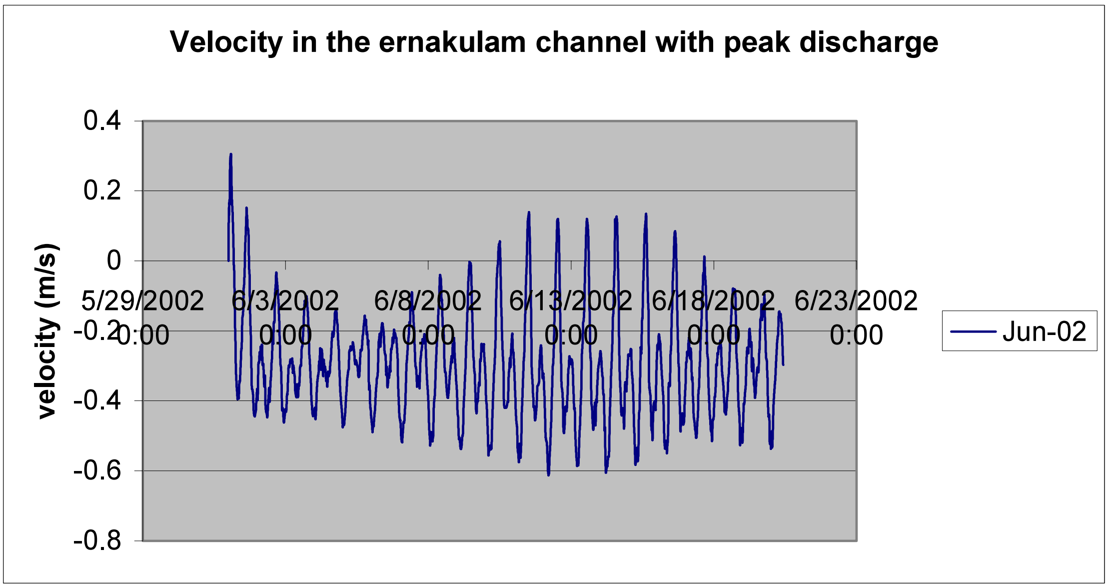


Tidal envelop in wet model without river discharge
Waterlevel (m + CD)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
Distance from gorge (hm)
12:00 AM
1:00 PM
2:00 PM
3:00 PM
4:00 PM
5:00 PM
6:00 PM
7:00 PM
8:00 PM
9:00 PM
10:00 PM
11:00 PM
12:00 PM
12:25 PM



Tidal envelop wet season envelop with average discharge
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
100
200
300
400
500
12:00 AM
1:00 PM
2:00 PM
3:00 PM
4:00 PM
5:00 PM
6:00 PM
7:00 PM
8:00 PM
9:00 PM
10:00 PM
11:00 PM
12:00 PM


Tidal envelop wet season model peak discharge
waterlevel (m + CD)
1.4
1.2
1
0.8
0.6
0.4
0.2
0
0
100
200
300
400
500
Distance from gorge (hm)
12:00 AM
1:00 PM
2:00 PM
3:00 PM
4:00 PM
5:00 PM
6:00 PM
7:00 PM
8:00 PM
9:00 PM
10:00 PM
11:00 PM
12:00 PM

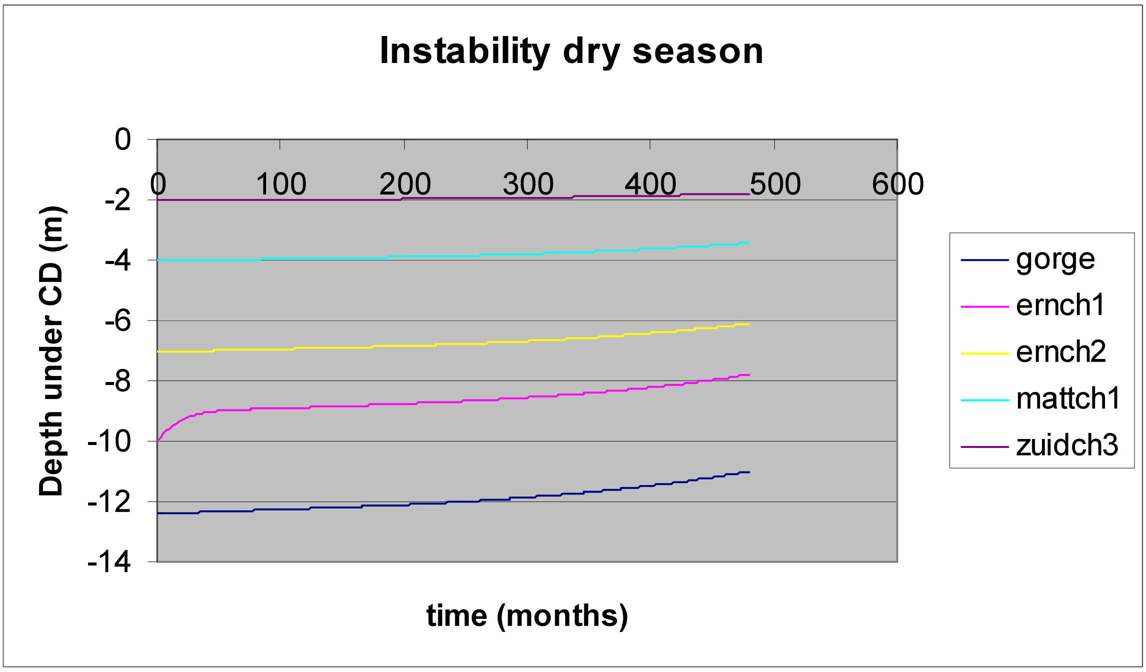

Velocity in the ernakulam channel with peak discharge
velocity (m/s)
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
5/29/2002 0:00
6/3/2002 0:00
6/8/2002 0:00
6/13/2002 0:00
6/18/2002 0:00
6/23/2002 0:00
Jun-02

Appendix 4.5
Calibration Estmorf model

The Estmorf.inp file

INPUT USER test		
1385700	= Het aantal seconden in 1 morfologische tijdstap	1E6-1E7
240	= Het aantal morfologische tijdstappen in de run	100-1000
12	= Het aantal stappen dat wordt genomen voor een nieuweimplic berekening	1-10
0	= Dummy staat standaard op nul	0
20	= Iteraties in de concentratiemodule	10-50
44700	= Aantal seconden in 1 getijperiode	44700 of 89400
3	= Afstemmingsslagen voor Implic-Estmorf bathymetrie	3-30
FILE data3.inp		
FILE		
FILE		
0.00	= zeespiegelstijging (m) als constante	
FILE		
1.0	= factor over de getijamplitude als constante	
FILE		
0.0	= bodemdaling (m) als constante	
1.0	= reststroom factor, waarmee de advectie eventueel kan worden uitgezet (factor 0)	
FILE		
0	= macht voor de splitsingspuntrelatie; 0=splitsingspuntrelatie staat uit	
FILE dispersc.inp		
500	= Dispersie in de geulen (als constante)(m2/s)	
50	= Dispersie geul-lage plaat (als constante) (m2/s)	
50	= Dispersie lage plaat - hoge plaat (als constante)(m2/s)	
0.0003	= Valsnelheid (m/s) =0.0003	
FILE		
0.00034	= beginconcentratie in de geul (als constante)	(-) = volume percentage
0.00034	= beginconcentratie op de lage plaat	
0.00034	= beginconcentratie op de hoge plaat	
0.00034	= Evenwichtsconcentratie	(-)
2.	= Macht van de transportformule in de geul	
2.	= Macht van de transportformule op de lage plaat	
2.	= Macht van de transportformule op de hoge plaat	
1.	= Dummy coefficient, op 1 laten staan	
1.	= Dummy coefficient, op 1 laten staan	
10.	= Minimaal toegelaten volume van een geul, default 100 m3	
START =		
1	= Dummy coefficient, op 1 laten staan	
FILE equiwlvl.inp		
0.73	= Evenwichtscoefficient voor de hoge plaat als constante	0.5-1
0.31	= Evenwichtscoefficient voor de lage plaat als constante	0-0.5
0	= Referentie vak (0 = lokaal)	
FILE equiarea.inp		
0.0002000	= Evenwichtscoefficient 1 voor de geul (als reststroom > breekpunt)	
0.0	= Dummy coefficient, default op 0 laten staan	
1.0	= Dummy coefficient, default op 1 laten staan	
1000000	= breekpunt voor het netto volume van transport, default 0 ! (onderscheid tussen eb/vloedgeul)	
0.0002000	= Evenwichtscoefficient 2 voor de geul (als reststroom < breekpunt)	
0.0	= Dummy, default 0	
1.0	= Dummy, default 1	
0.5	= numerieke parameters, niet veranderen	
10.		
10.		
10.		
0.		
1.0	= verhouding zand op de geulwand / geulbodem (qua dikte)	
OUTPUT HISTORY		
0 0 0	= uitvoer in history, begin, interval, eind; liever niet gebruiken	
OUTPUT MAP		
0 6 0 0 0	= uitvoer in mapvelden (Estmorf.map) ; begin - interval - eind (als nul dan eind van de run)	

The dry model



6.2.1 Final Calibration coefficients

		Wet season coefficients	dry season coefficients
7	Gorge	9.0550E-05	8.6100E-05
8	Ern_1	7.5400E-05	7.1200E-05
9	Ern_2	7.0751E-05	6.4200E-05
10	Matt_1	1.7200E-05	1.7500E-05
20	Matt_2	4.2512E-05	3.8100E-05
21	Ern_3	6.1360E-05	5.4600E-05
14	Vallarpadom	4.5000E-05	4.2000E-05
38	North 1	8.5000E-05	8.4000E-05
34	Willingdon Aroor	1.0920E-04	9.4300E-05
140	South_2	3.2405E-04	3.4700E-04
143	South_3	1.1594E-04	1.8900E-04
145	South_5	3.3169E-04	1.5300E-03
144	South_4	1.8649E-04	3.8700E-04
299	storage area 1	5.0946E-04	3.8200E-04
139	South_1	8.4082E-05	7.4300E-05
381	storage area 2	8.7096E-05	7.9300E-05
219	North 1	3.5970E-04	4.6000E-04
501	Muvatthapuzha	1.7976E-04	2.9900E-02
602	Southern storage area	4.9387E-04	

Appendix 4.6
Stability in Estmorf

In this appendix we treat the stability of the Estmorf model with the help of an simplified case. In this simplified case we have two branches of each approximately 25000 km long and 250 m wide. The depths of the branches are at first 4 and 2 metres this gives a very unstable situation in the Estmorf model, see figure 1.

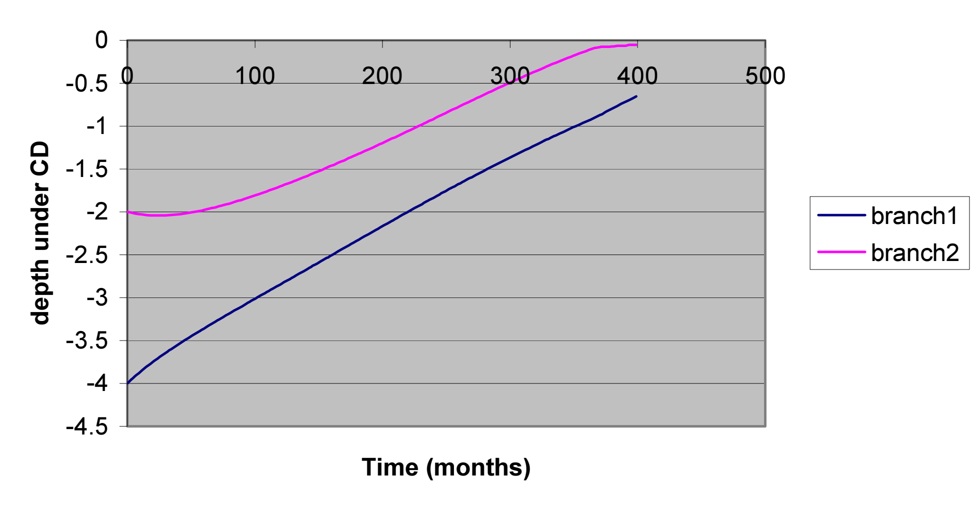


Figure 6 Instability of the Estmorf model with depths (branch1=4m; branch2=2m)

To check why this system is unstable, the A-P curve of both branches in the sobek model are checked. These are visible in figure 2, in figure 2 also the plot of the A-P curves for the Estmorf model are made. In this case these curves are all calculated for the beginning of the branch in contrary to Estmorf where the middle is taken, for the principle though this makes no difference.

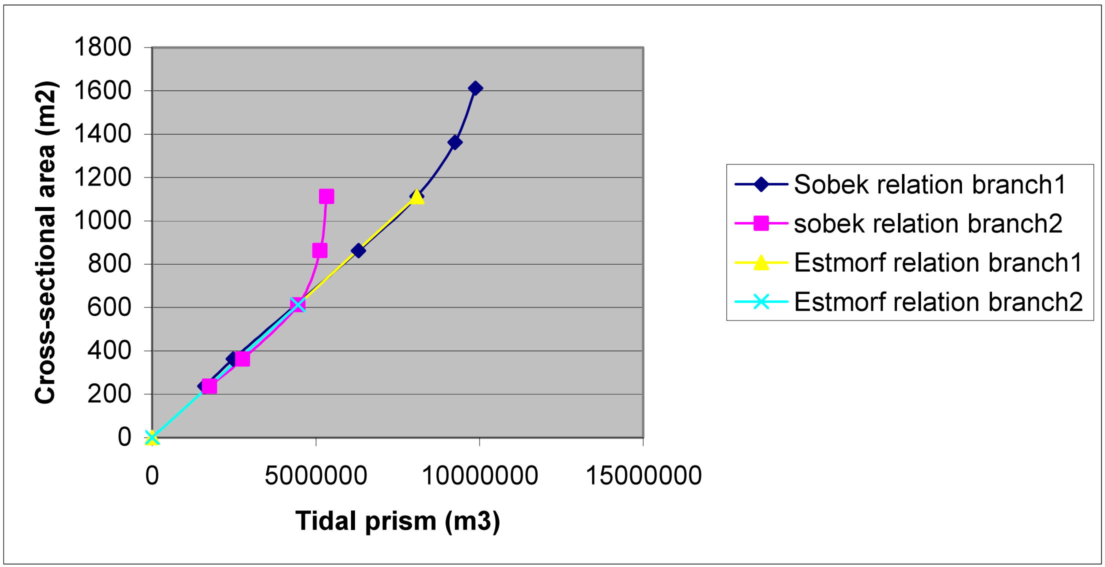


Figure 7 A-P relations in Sobek and Estmorf

From the Escoffier theory we expect to clear points when the Estmorf relation and the Sobek relation intersect, after all the theory of Escoffier also considers a constant coefficient. What we actually see is that in the smaller cross-sectional areas the Sobek curve almost is the same straight line as is the Estmorf curve. One can figure that a small disturbance in either the Estmorf line or the Sobek line in the area where they stick together will give a large difference in the final results since the intersection of both lines is far away of the current intersection. This shape of the Sobek curve cause a little instability not to come back to its equilibrium point but either to close or to deepen extremely. If we check if the highest points in figure 2 do give stability we deepen branch 1 to 6 meters and branch 2 to 4 meters. This should give stability, as it does, as can be seen in figure 3.

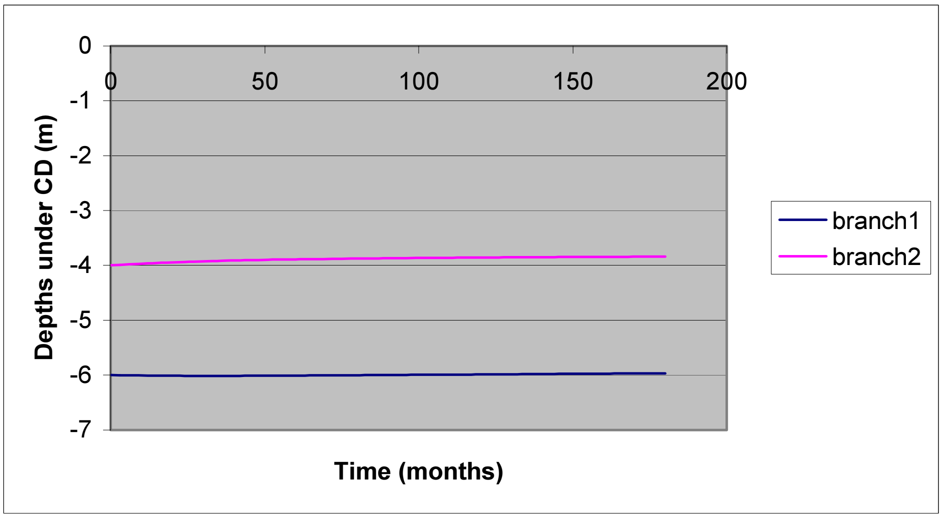
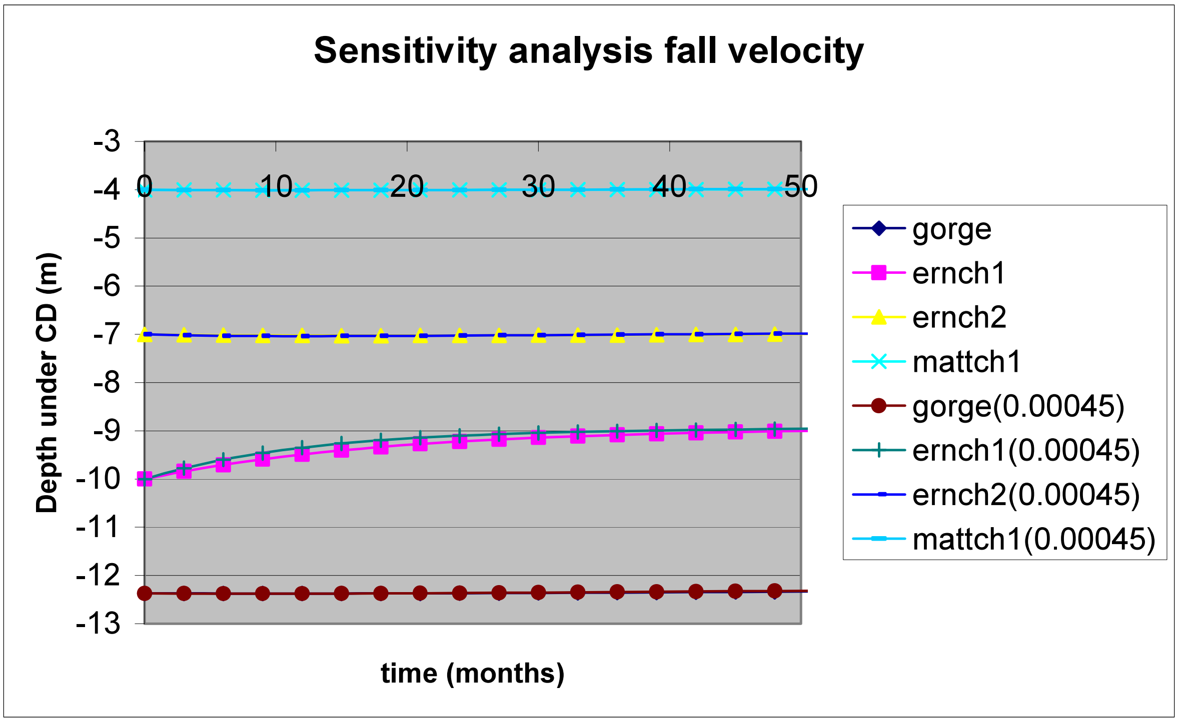
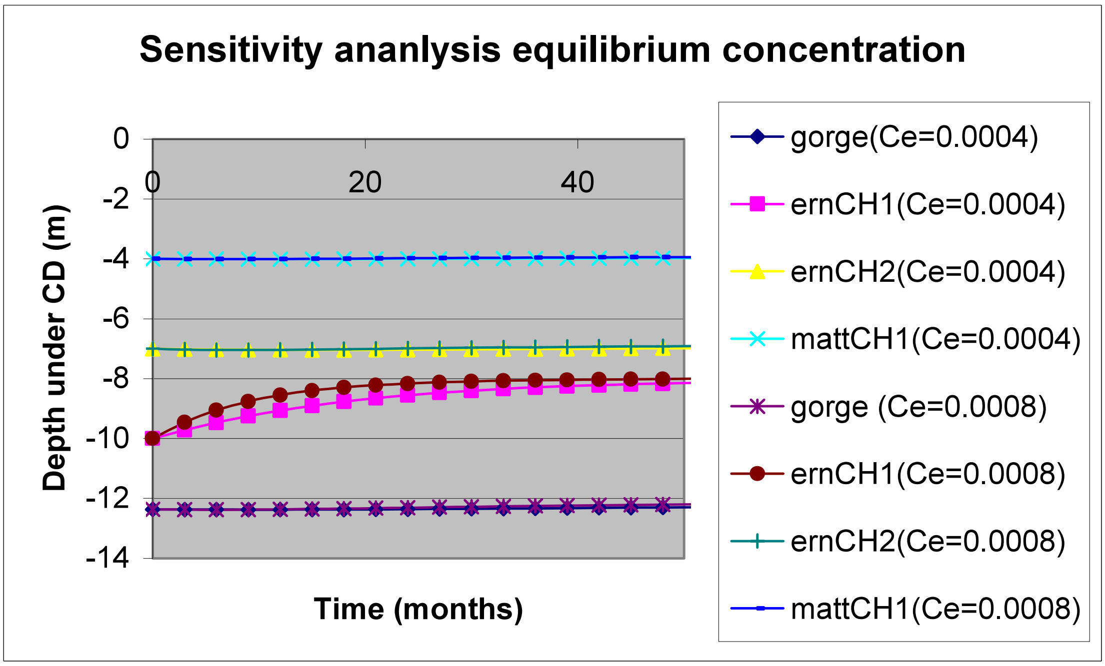
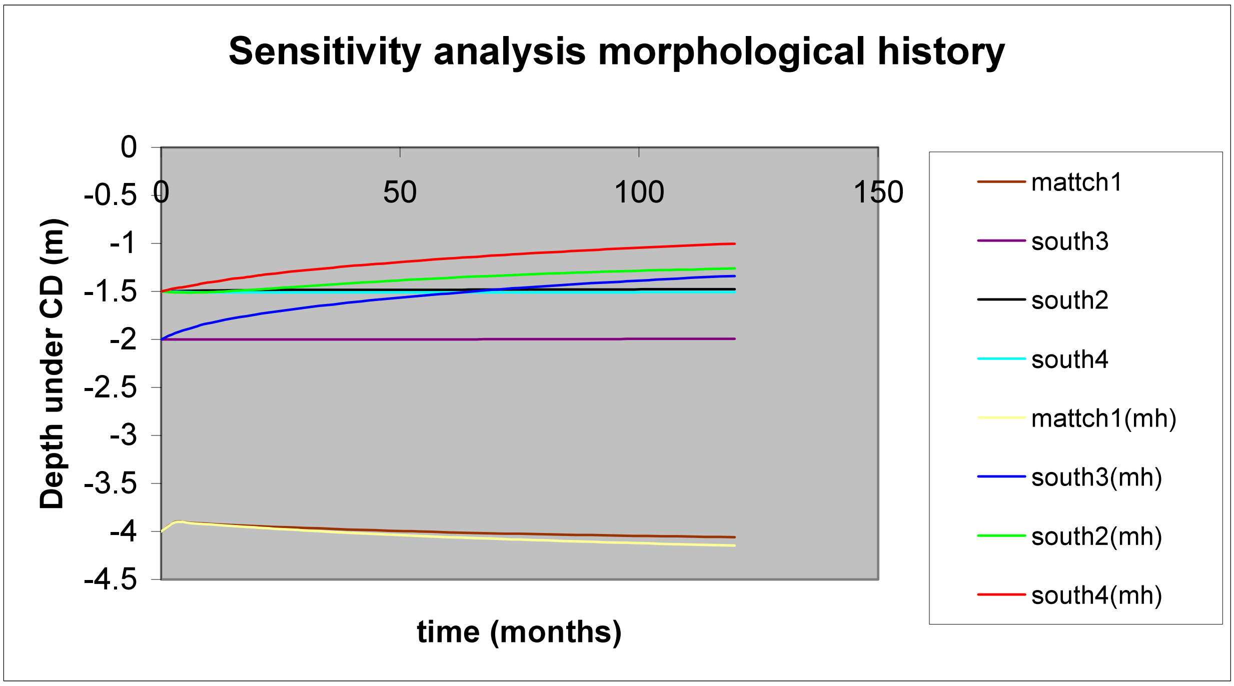


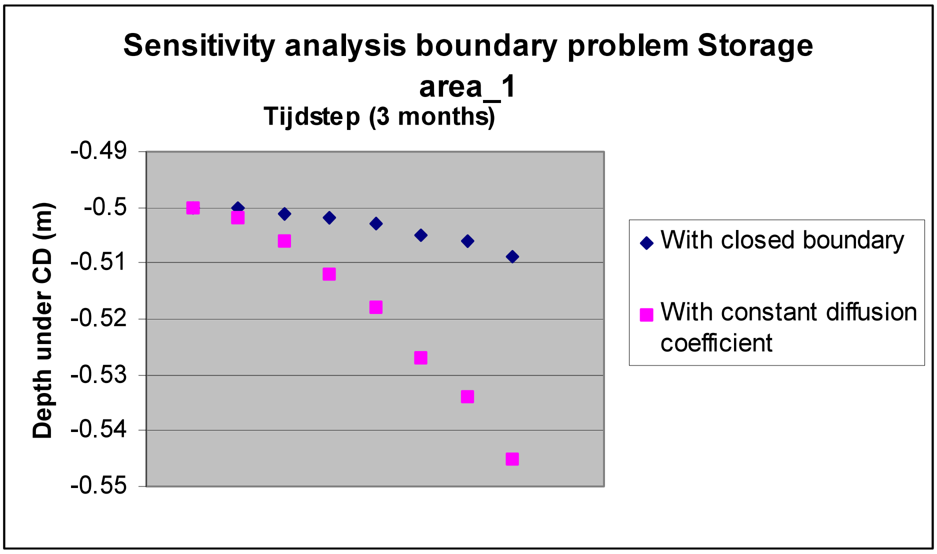
Figure 8 Stable Estmorf model with branch1=6 m and branch2=4 m

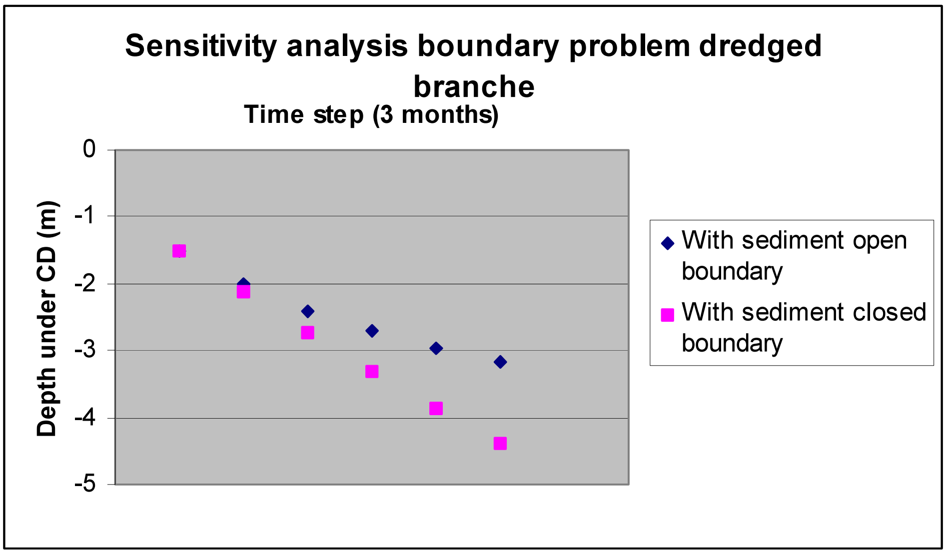
Appendix 4.7
Sensitivity analysis of the morphological model


Sensitivity analysis fall velocity
-3
-4
-5
-6
-7
-8
-9
-10
-11
-12
-13
0
10
20
30
40
50
Depth under CD (m)
time (months)
gorge
ernch1
ernch2
mattch1
gorge(0.00045)
ernch1(0.00045)
ernch2(0.00045)
mattch1(0.00045)

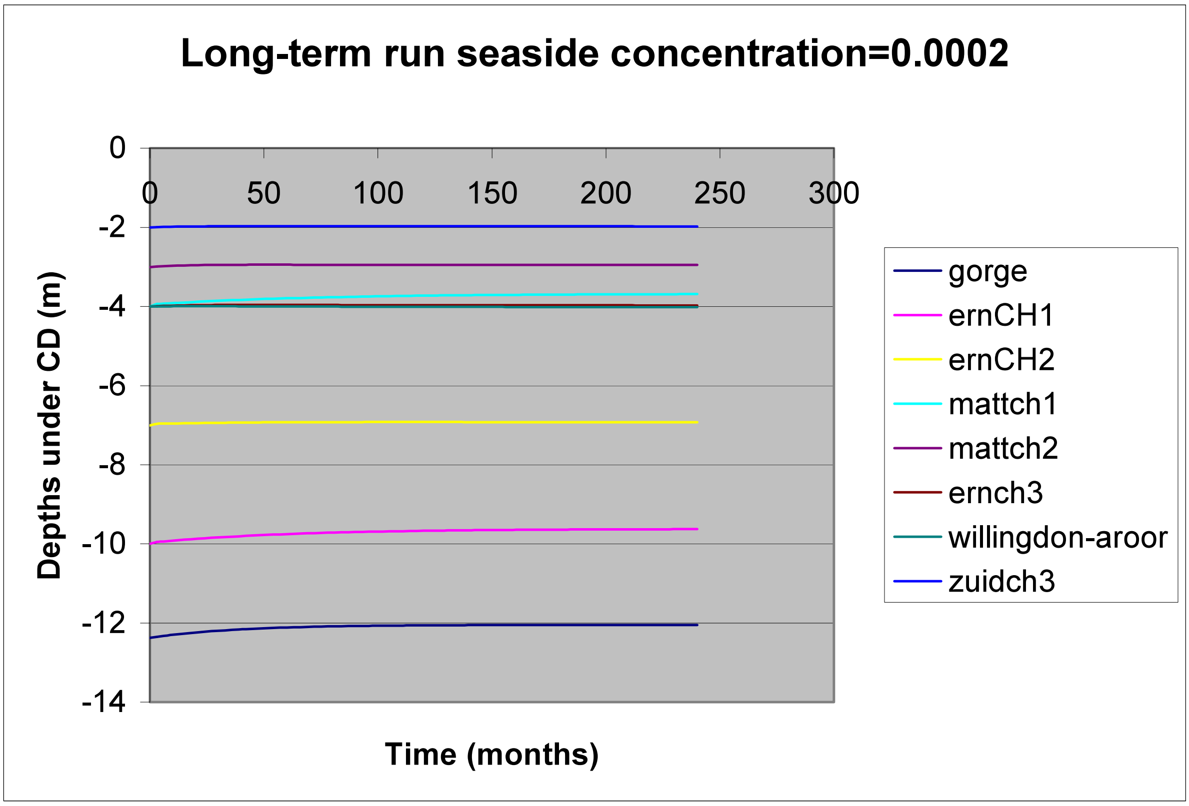

Sensitivity ananlysis equilibrium concentration
0
-2
-4
-6
-8
-10
-12
-14
0
20
40
Depth under CD (m)
Time (months)
gorge(Ce=0.0004)
ernCH1(Ce=0.0004)
ernCH2(Ce=0.0004)
mattCH1(Ce=0.0004)
gorge (Ce=0.0008)
ernCH1(Ce=0.0008)
ernCH2(Ce=0.0008)
mattCH1(Ce=0.0008)

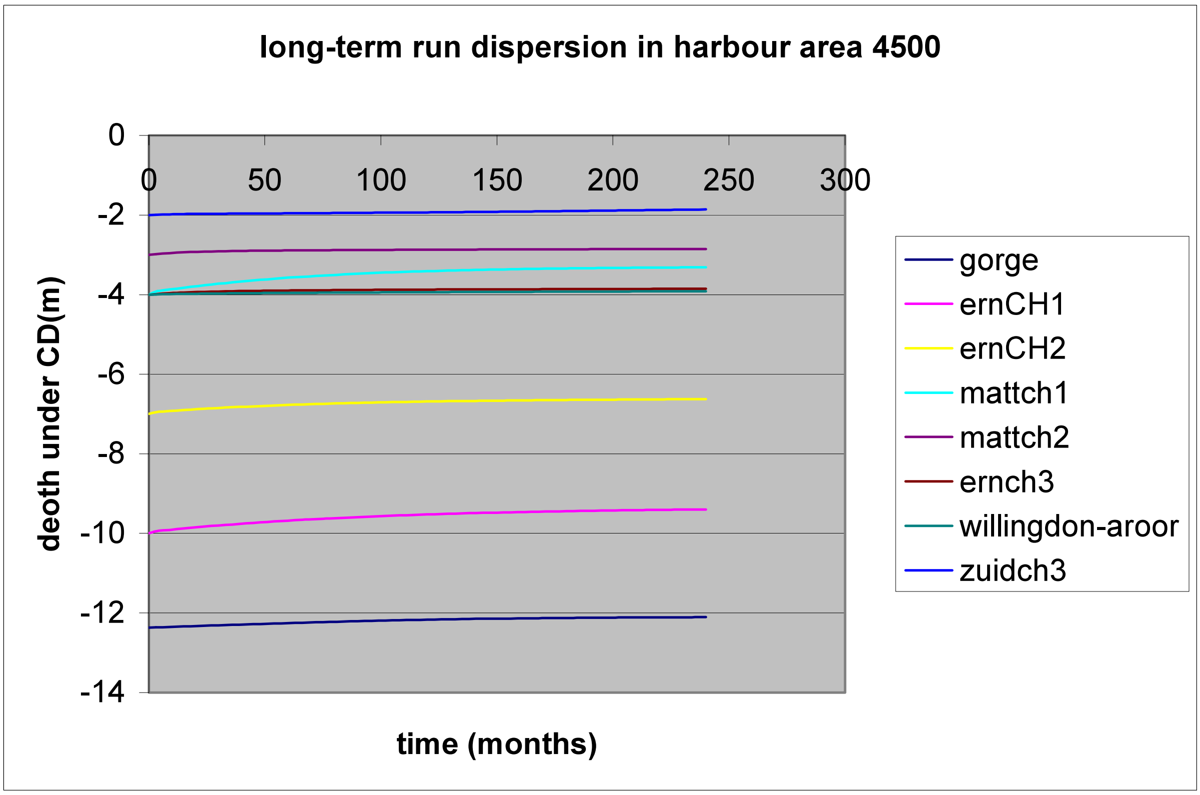

Sensitivity analysis morphological history
Depth under CD (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
0
50
100
150
time (months)
mattch1
south3
south2
south4
mattch1(mh)
south3(mh)
south2(mh)
south4(mh)


Sensitivity analysis boundary problem Storage area_1
Tijdstep (3 months)
Depth under CD (m)
-0.49
-0.5
-0.51
-0.52
-0.53
-0.54
-0.55
With closed boundary
With constant diffusion coefficient

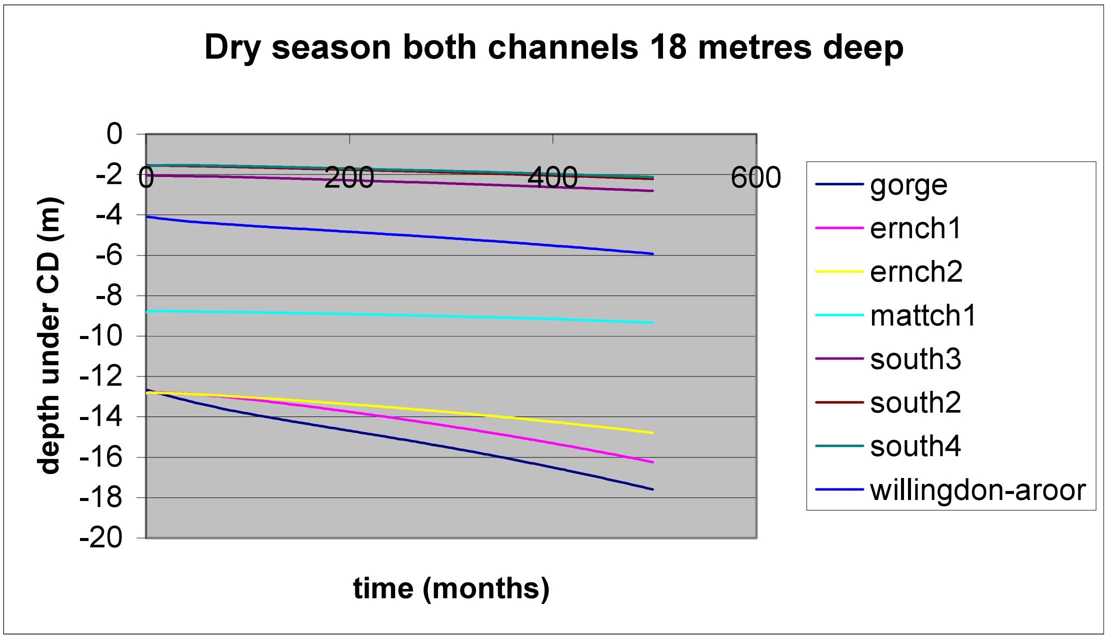

Sensitivity analysis boundary problem dredged branche
Time step (3 months)
Depth under CD (m)
0
-1
-2
-3
-4
-5
With sediment open boundary
With sediment closed boundary

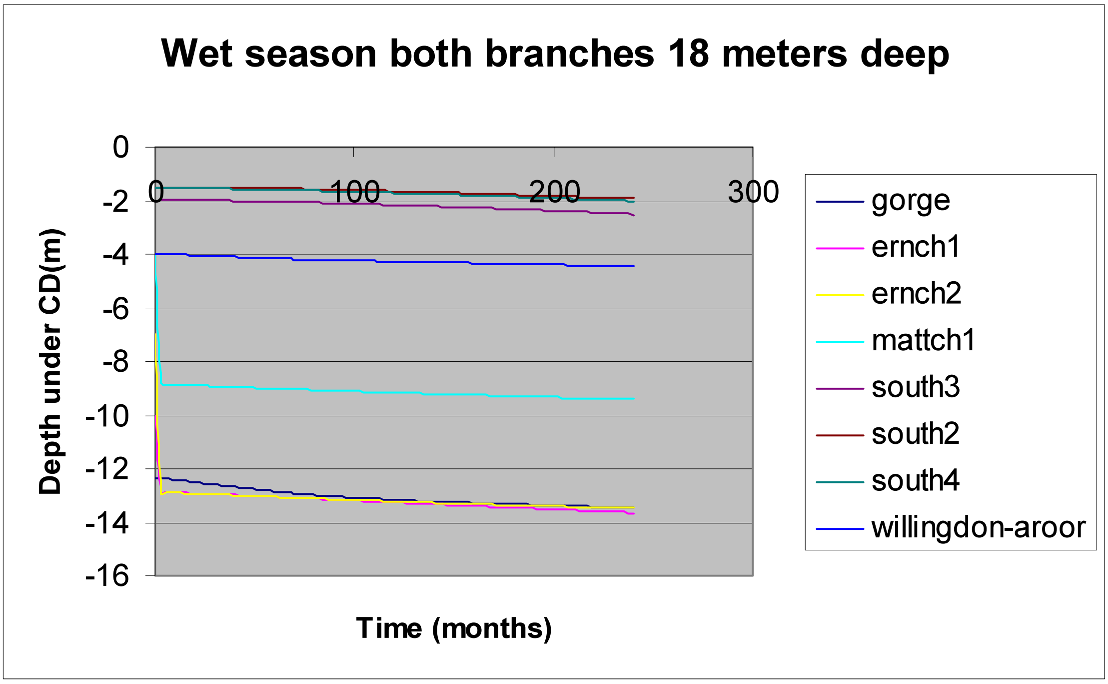
Appendix 5.1
Case study
Stratification

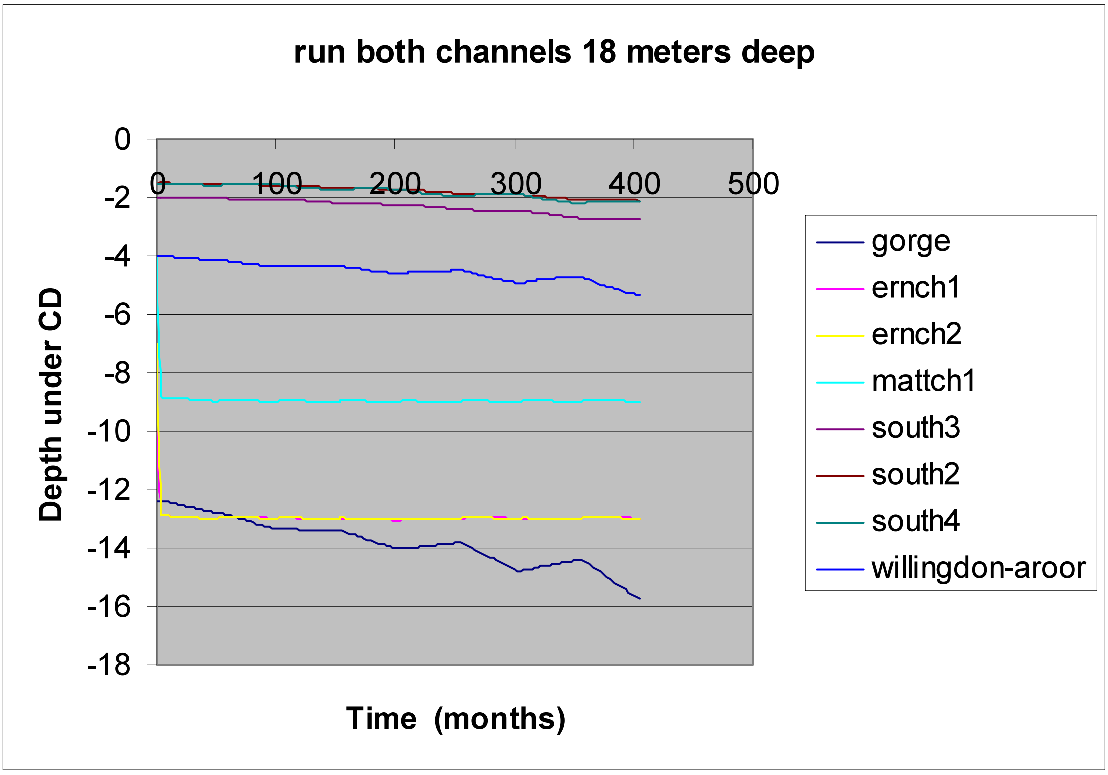

Long-term run seaside concentration=0.0002
Depths under CD (m)
0
-2
-4
-6
-8
-10
-12
-14
0
50
100
150
200
250
300
Time (months)
gorge
ernCH1
ernCH2
mattch1
mattch2
ernch3
willingdon-aroor
zuidch3

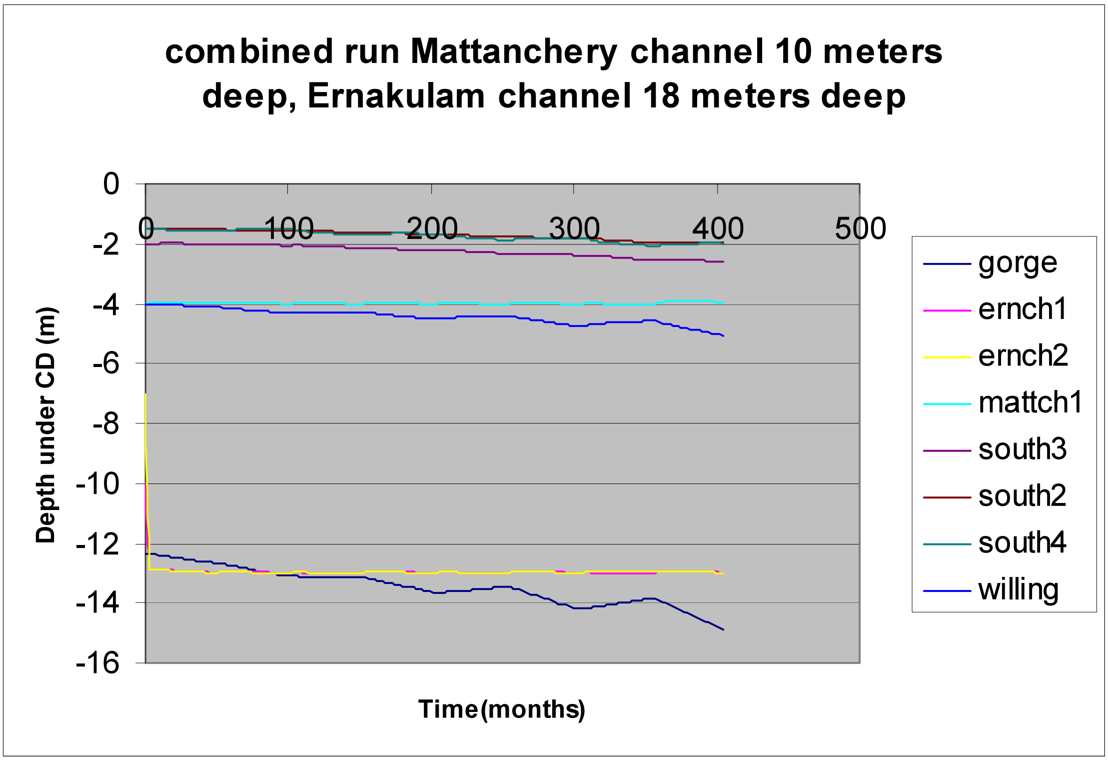

long-term run dispersion in harbour area 4500
deoth under CD(m)
0
-2
-4
-6
-8
-10
-12
-14
0
50
100
150
200
250
300
time (months)
gorge
ernCH1
ernCH2
mattch1
mattch2
ernch3
willingdon-aroor
zuidch3

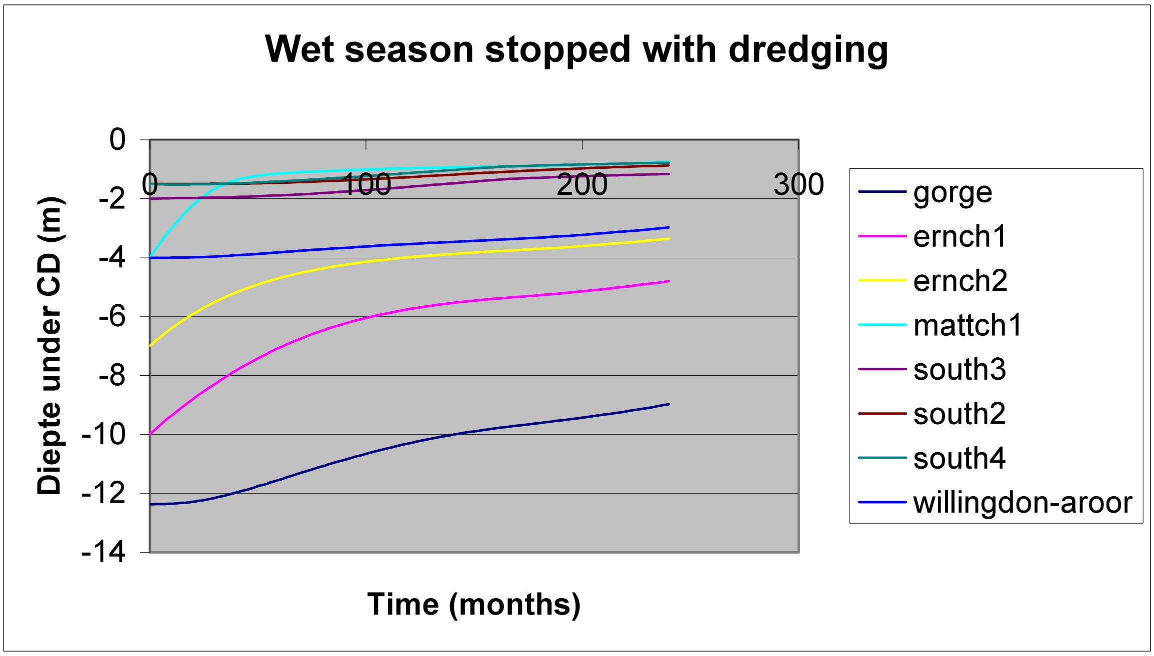
Appendix 5.2
Case study
Harbour expansion

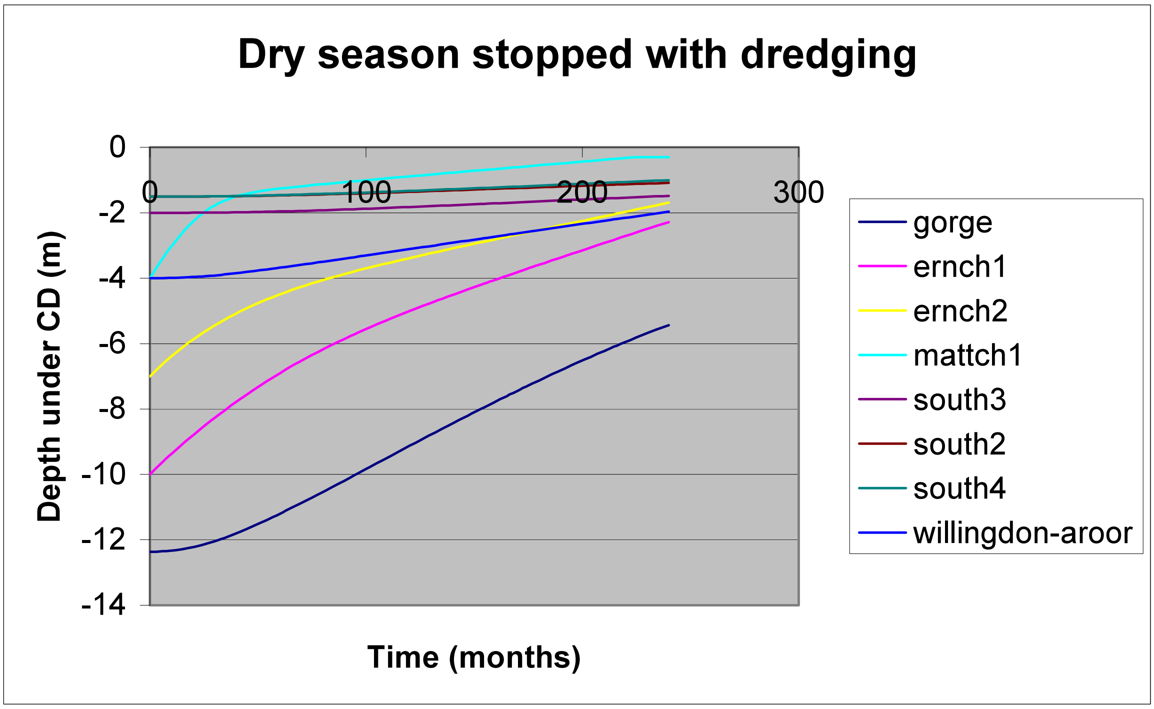

Dry season both channels 18 metres deep
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
-20
0
200
400
600
depth under CD (m)
time (months)
gorge
ernch1
ernch2
mattch1
south3
south2
south4
willingdon-aroor

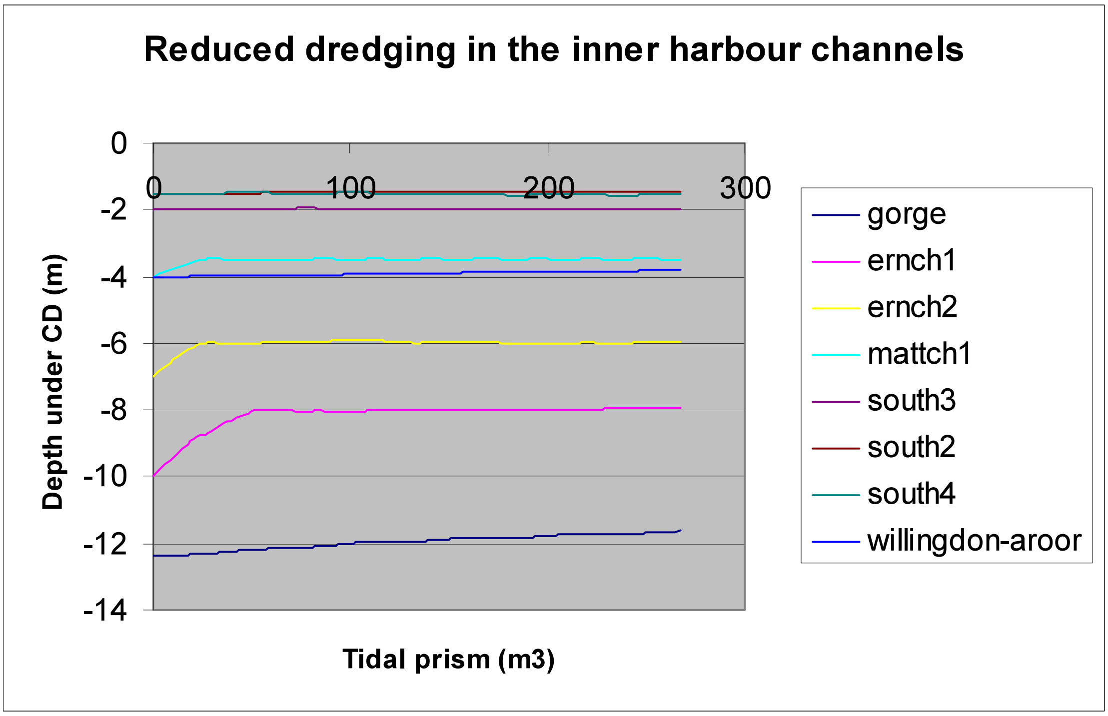

Wet season both branches 18 meters deep
0
-2
-4
-6
-8
-10
-12
-14
-16
0
100
200
300
Depth under CD(m)
Time (months)
gorge
ernch1
ernch2
mattch1
south3
south2
south4
willingdon-aroor

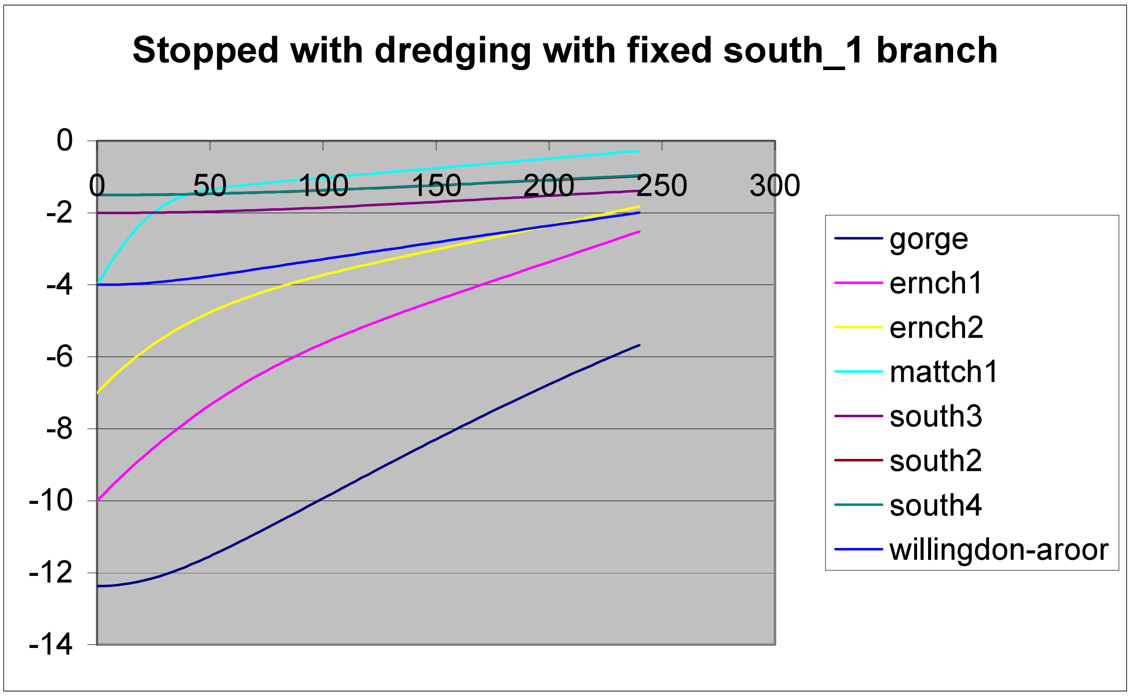

run both channels 18 meters deep
Depth under CD
Time (months)
0
-2
-4
-6
-8
-10
-12
-14
-16
-18
0
100
200
300
400
500
gorge
ernch1
ernch2
mattch1
south3
south2
south4
willingdon-aroor


combined run Mattanchery channel 10 meters deep, Ernakulam channel 18 meters deep
Depth under CD (m)
Time(months)
0
-2
-4
-6
-8
-10
-12
-14
-16
0
100
200
300
400
500
gorge
ernch1
ernch2
mattch1
south3
south2
south4
willing


Wet season stopped with dredging
Diepte under CD (m)
0
-2
-4
-6
-8
-10
-12
-14
0
100
200
300
Time (months)
gorge
ernch1
ernch2
mattch1
south3
south2
south4
willingdon-aroor


Dry season stopped with dredging
Depth under CD (m)
0
-2
-4
-6
-8
-10
-12
-14
0
100
200
300
Time (months)
gorge
ernch1
ernch2
mattch1
south3
south2
south4
willingdon-aroor


Reduced dredging in the inner harbour channels
0
-2
-4
-6
-8
-10
-12
-14
Depth under CD (m)
0
100
200
300
Tidal prism (m3)
gorge
ernch1
ernch2
mattch1
south3
south2
south4
willingdon-aroor


Stopped with dredging with fixed south_1 branch
0
-2
-4
-6
-8
-10
-12
-14
0
50
100
150
200
250
300
gorge
ernch1
ernch2
mattch1
south3
south2
south4
willingdon-aroor