Long-term morphological response of tidal inlet systems to changes in basin area

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El viento

Por eso tengo que volver
a tantos sitios venideros
para encontrarme conmigo
y examinarme sin cesar,
sin más testigo que la luna
y luego silbar de alegría
pisando piedras y terrones,
sin más tarea que existir..

(Plabo Neruda, Fin de Mundo)

Preface

This report completes my education in Environmental Engineering, started at Politecnico di Milano and supported by two different experiences abroad as exchange student that enlarged my knowledge and played a significant role in my personal growth.

This M. Sc. thesis has been carried out at the Technical University of Delft (TU Delft), where all my knowledge on tidal inlet systems and scientific research methods was formed. I'd like to thank my supervisors, prof.dr.ir M.J.F Stive, and especially T.J. Zitman, not simply for assisting me in this study but especially for teaching me how to tackle challenges and tough moments.

I'd like to thank prof. G. Passoni, associate supervisor in Italy, for giving me the chance of experiencing these six months in which I could consider many aspect of my life.

Finally I want to give thanks to all the persons that always stand by my side. My mother, for her daily support, for being so present and understanding, for her courage and her strength. My father, that holds my hand, any time. My family, especially my beloved grandmas, for trusting in me and for being an example of unity. My friends, the ones that made pleasant these years at university, the ones that have been sharing the important moments, all the ones that were able to cover the distances, the travelling companions. Last but not least Roger, indispensable partner and friend, that in these last years gave me love, joy, energy, support, unforgettable instants, much more than I could ever expect.

I'm grateful to all of them for being part of my life.

Summary

Along the majority of the world's shoreline, tidal inlet systems represent a common morphological feature. Like in the Wadden Sea, which forms one of the major intertidal areas on the Earth, they are found along barrier islands coasts and they play a significant role in the sediment budget of the coastal zone.

The present study investigates the long-term morphological response of tidal inlet systems to changes in basin area, aiming to derive insight into the influence of the basin area on the system morphology and on its evolution time-scale.

Tidal inlets are highly dynamic systems that evolve under a constant interaction of forcing and morphological adjustment. In order to model and predict their long-term morphological evolution, the analysis is carried out at high level of aggregation. In this aggregated scale perspective, three morphological elements can be distinguished within a tidal inlet system, namely the ebb-tidal delta, the channel and the flat. Field observations reveal that a relationship exists between the elements state (viz. wet/dry volume) and the hydrodynamic conditions (tidal prism).

ASMITA (Aggregated Scale Morphological interaction between a Tidal inlet and the Adjacent coast) concept is built on the existence of an equilibrium state. This behaviour oriented model, describes the evolution of tidal inlet systems towards the equilibrium in terms of exchange of sediment, which depends on the need and the availability of sediment. In the present study, ASMITA is used to simulate the long-term morphological evolution of tidal systems in response to changes in basin area.

The size and the shape of the basin area plays an important role in the morphological development of tidal inlet systems as it determines largely the propagation of the tidal wave and, hence, it influences the tide-residual sediment transport. In the original formulation of ASMITA the basin area is considered time-invariant and therefore acting as a fixed morphometric condition on the morphological development of tidal inlet system. To evaluate the influence of a temporal change in basin area, the model implementation has been extended with the area varying as function of time. Three different scenarios are chosen in this report in order to assess the morphological evolution of tidal inlet systems:

- asymptotic increase/decrease of basin area
- periodic area change
- abrupt change

The scenarios considered aim to describe a possible modification of the size of the basin due to natural phenomena (viz. variations in weather climate, migration of barrier islands, accretion of new land) and human interventions such as re-opening or damming part of the area.

Since the basin area is the sum of the channel and the flat area, the change in the area can be ascribed to a combination of relative change in the flat area and in the channel area. Only two possible combinations are considered in the present study: an immediate response of the channel area (Ac/Af=const.), and no response of the channel area (Ac=const.).

When a change in basin area is imposed on a tidal inlet system, the tidal prism experiences a consequent variation. As a result, the system will deviates from its state of equilibrium and will start to import or export sediment, depending on the imposed change, until a new balance is reached between the dimension of the elements and the hydrodynamic conditions.

The analysis of the long-term morphological response to changes in basin areas is carried out on two adjacent basins of the Dutch Wadden Sea, viz. Vlie and Borndiep. The two basins respond to the required characteristics for this study, as they have wide different initial size of the basin area, and as their intertidal area has a rather different extension. This provides to draw insight into the dependence of the morphological behaviour on the size of the basin and on the influence of the channel area.
The morphological evolution of Vlie and Borndiep is then simulated in response to the defined scenarios. The tidal system are seen to follow the imposed disturbance even in the case of a sudden increase of the basin area with 50%

A sensitivity analysis on the system time scale is carried out on the basis of the analysis of the morphological behaviour of the systems under abrupt changes of the area. From this analysis, the time-scale appears to be influenced mainly by the size of the basin (the bigger being the slower), and by the imposed disturbance. The channel area was observed to play a significant role only on the response of Vlie, whereas Borndiep was observed to be flat dominated.

Contents

1 Introduction

1.1 Problem definition

Along the majority of the world's shoreline, tidal inlet systems represent a common morphological feature. Like in the Wadden Sea, which forms one of the major intertidal areas on the Earth, they are found along barrier island coasts and they consist of a coastal inlet and a tidal basin. As they constitute an interruption of the shoreline processes, they play a significant role in the sediment budget of the coastal zone and, thus, in its long-term evolution.

Due to the relevance of tidal inlets as delicate ecosystems and to the wide number of human activities that take place there, many studies and extensive interdisciplinary research works were brought out on the Wadden Sea, aiming to understand and, therefore, to estimate the dynamics and evolution processes it undergoes.

A recent study *(van Goor, 2001)* pointed out a clear dependence of the tidal inlets response to perturbation of their topographic extension and geometry. The above case study analysed the long-term morphological response to sea-level rising of two different basins of the Dutch Wadden Sea (Amelander Zeegat and Eierlandse Gat), characterised by different basin area. It was shown that, under an imposed rate of sea level rising, they react differently, the smaller being the faster to reach the new equilibrium configuration. Consequently, the time-scale, equal to the characteristic time for adaptation after the initial perturbation, was shown to be dependent both on the magnitude of disturbance and on the extension of the basin area.

On the basis of these results, this report aims to evaluate how sensitive the time scale is on the size of the basin area of each single tidal inlet system, in order to evaluate whether an interaction of the two basins might influence the overall equilibrium. Aiming to asses the influence of changes in basin area on the long-term morphological response of tidal inlet systems, a gradual change in time of the area is then imposed to the system. Indeed, by varying the basin area of each system, and by comparing the time-scale of the long-term morphological response of both tidal inlets, we aim to point out insights on the their possible interaction across the tidal divide. The analysis focuses on a possible shift of the tidal divide toward one of the two inlets as a consequence of the mutual morphological development.

The morphodynamic development of tidal inlet systems results from a complex, multi-scale dynamic interaction of waves, currents and bed topography and involves stochastic variations of the forcing acting on the system. When analysing the long-term morphological response of the system to changes in basin area, we deal with macro-scale processes (time-scale of decades to centuries and space-scale covering the whole tidal inlet system).

Predicting and modelling the large-scale behaviour of tidal inlet systems means dealing with intrinsic or practical limits of predictability.

Indeed, the large-scale behaviour seems to be hardly derived as integration of small-scale knowledge. Process-based models are actually based on physical processes that are characterised by smaller time-scales. The integration to a higher scale can thus cause uncertainties and errors, as long-term variations in the processes would not be considered.
The limited predictability is coped with a different approach. Based on the extrapolation of observed morphological behaviour, and on the knowledge of physical processes, behaviour-oriented models describe large-scale behaviour of tidal inlet systems at an aggregated level. In this aggregated scale perspective the system is subdivided in morphological elements, each of them being characterised by a single state variable.

In the present report, the long-term morphological response of tidal inlet systems under gradual change in basin area is therefore examined by an aggregated scale model (ASMITA).

1.2 Area of interest

The area of interest of this report is the Dutch Wadden Sea. The Dutch Wadden Sea extends over the first 200 km (west to east) of the Wadden Sea coast and it can be subdivided into ten tidal basins. According to *Dean (1988)* the different tidal basins can be distinguished as morphodynamic independent entities, forming a more or less separate sand-sharing system. These entities include their adjacent barrier islands, which separate the tidal basin from the open sea, the outer or ebb-tidal delta, the inlet throat, the flat area, and the tidal divide. However, as it will be analysed in the present report, two different adjacent basins may influence each other across the tidal divide.

In the present report two tidal inlets of the Dutch Wadden Sea, Vlie and Ameland are considered (see Figure 1.1), as they present the required characteristic for our purpose, having basin areas different in size, and as field data are available.

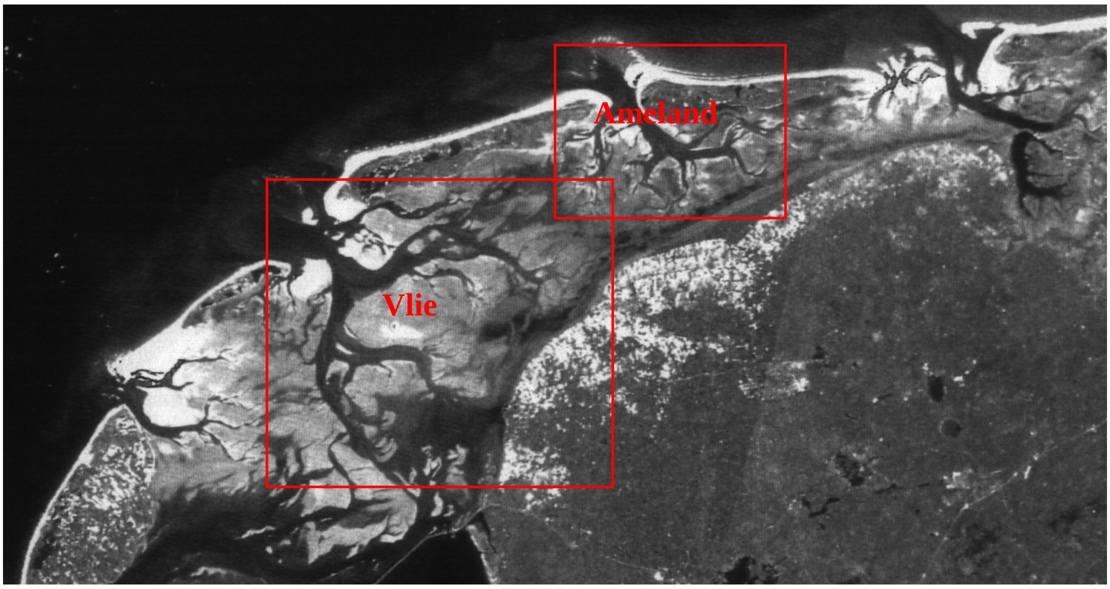


Figure 1-1. Satellite view of the Dutch coast

1.3 Objective

Field observations and theoretical considerations on the evolution and interaction of two tidal inlet systems, are assessed to better understand the overall development of the Wadden Sea.

A sensitivity analysis on changes in the basin area will be carried out, providing insight into the effective feasibility and need to analyse two coupled basins, as a whole system.

The changes in basin area are assumed gradually varying with time, simulating the effect of an external perturbation (e.g. a variation in the wind climate or in tidal currents, gradual shift of barrier islands) or of a mankind interventions (e.g. closure works, or reopening of enclosed areas).

The analysis is built around the concept of the existing model ASMITA (Aggregated Scale Morphological Interaction between a Tidal inlet and the Adjacent coast, *Stive et al., 1998*), which simulates the morphological behaviour of tidal inlet system. Running the model for different morphometric (basin area) conditions yields a set of inlet characteristic time-scales, from which the influence of this variable on the morphological evolution can be pointed out.

On the basis of the achieved insight, it will be concluded whether it is feasible to couple two different basins, while aiming to predict their morphological evolution.

2. The Dutch Wadden Sea: morphodynamics and evolution

2.1 Introduction

The Wadden Sea fringes the Dutch, German and Danish coasts over a distance of nearly 500 km with a maximum width of approximately 35 km. Towards the North Sea, the Wadden Sea is bordered by some 20 large and many small barrier islands, peninsulas and sandy shoals. Behind these islands lies the tidal flat area. This area constitutes one of the major intertidal areas on the Earth and counts 33 adjacent tidal inlet systems, different in size, features and morphology.

The morphodynamic evolution of the Dutch Wadden Sea is determined by numerous different factors and mechanism, resulting from the interaction between the forcing and the morphological adjustments. Tidal inlets are highly dynamic systems formed by different morphological elements. As a dynamic response to natural and human forcing, they change their topography within long-term processes, by exchanging water and sediment, within the system and with the outside world. Due to the net transport of sediment the elements, and thus the whole system, exhibit a morphological evolution.

The purpose of this chapter is to provide an overview of the morho-dynamics of the Dutch Wadden Sea, in order to gain a better understanding of the interrelation between the hydrodynamics and the morphology of the area in the long-term development.

Hereafter, a description of the elements used to schematise tidal inlet system is firstly given, likewise they are considered in our aggregated scale perspective (see Chapter 3), aiming to characterise each element and its accompanying morphological behaviour. In a tidal inlet system two main areas can be recognised: the coastal inlet and the tidal basin. The coastal inlet consists of the outer delta and the adjacent barrier islands, whereas the tidal basin consists of a channel network and a flat area.

Subsequently, the significant factors and forcing that play an important role in the large-scale evolution of tidal inlet systems are illustrated, in order to distinguish how and where they affect the system.

Finally, a brief overview of the specific geological and historical evolution of the Dutch Wadden Sea is gathered, in order to provide a picture of the systems ability toadapt itself to changing boundary conditions. The scale of interest is there enlarged to a mega-scale, as the evolution of the whole coastal stretch is analysed over the millennia.

2.2 Tidal Inlets System

The Dutch Wadden Sea is characterised by a series of adjacent tidal inlet systems. Each inlet comprises a coastal inlet and a tidal basin area. The coastal inlet consists of an ebb-tidal delta with the inlet itself, and the connecting parts of the barrier islands. The back-barrier area, namely the tidal basin, is formed by two morphological elements: the channel and the flat area.

The morphological elements (see figure 2.1) of the Wadden Sea are presented herein.

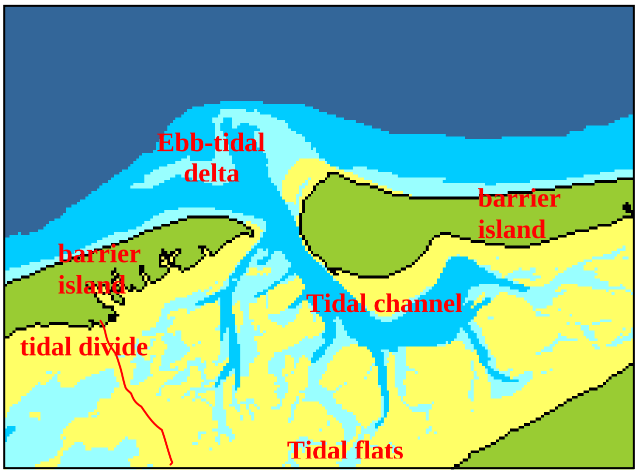


Figure 2-1. Morphological units of tidal inlets

2.2.1 Coastal Inlet

An interruption in a barrier beach is commonly referred to as a tidal inlet, if it is maintained by tidal flow. The tidal inlet, being the morphologically most dynamic area of system, includes an inlet throat and an ebb-tidal delta. The coastal inlet normally interacts with barrier islands, whence, due to the influence of waves, tides, and wind-driven currents, sediment can be transported in and out of the inlet. The overall stability of this system is assumed to be dependent on a balance between tidal prism, representing the tidal energy, which maintains the opening and the wave energy that tends to close it *(Bruun, 1978)*.

Ebb-tidal delta

Situated on the seaward side of the inlet throat between neighbouring barrier islands, the ebb-tidal delta is the result of sedimentation by the tidal currents flowing through the inlets, and the subsequent action of waves, longshore currents and the tidal wave along the coast. They are morphologically and dynamically connected to the inlets, forming important morphological elements along the barrier islands.

As shown in Figure 2.2, the ebb-tidal delta normally consists of a main ebb channel, channel margin linear bars, a terminal lobe, i.e. a rather steep seaward-sloping body of sand, swash platform and bars, and marginal flood channels. The latter usually occur between the barrier islands coast and the swash platforms.

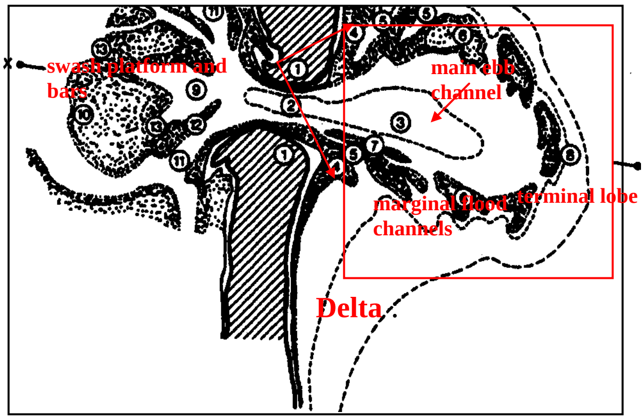


Figure 2-2.Ebb-tidal delta

Accordin to *Adams* and *Walton (1976)*, the ebb-tidal delta is defined as the volume of sand stored above a reference coastline that should be present without the inlet. The so defined volume, which is also used in the Asmita model, is shown below.

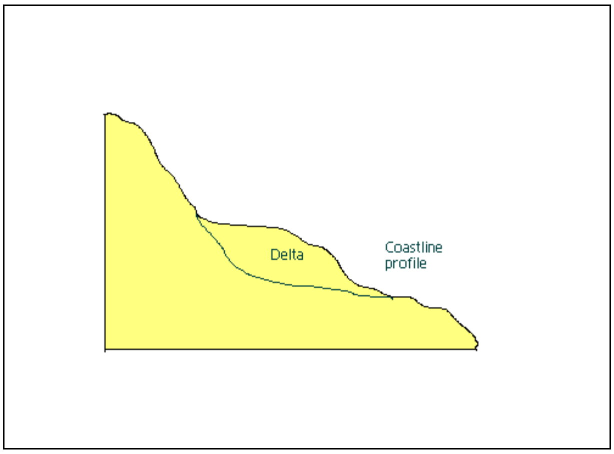


Figure 2-3. Cross-section profile of delta relative to the coast

When the whole system is out of equilibrium, a net sediment exchange occurs between the system and the outside world.

The ebb-tidal delta is the closest source of sediment to the system, as it represents the interfacing element. Hereafter, a description of the development and of the sediment transport processes is given.

Many studies suggest that the geomorphology of an ebb-tidal deltas responds to hydrodynamic processes *(Sha, 1989)*. Studies brought out by Sha on Texel inlet revealed that the tidal prism affects the orientation of the main ebb-channel. More in detail, the larger ebb-tidal deltas along the Dutch Wadden Sea, characterised by larger tidal prisms, show an updrift asymmetry (directed westward), whereas downdrift (eastward) oriented deltas are crossed by considerably smaller tidal prisms. This is due to the relative more important wave influence that forces the deltas downdrift.

In Figure 2.4 a) and b), the morphology of the deltas along the West and the East, respectively, Frisian Islands is shown.

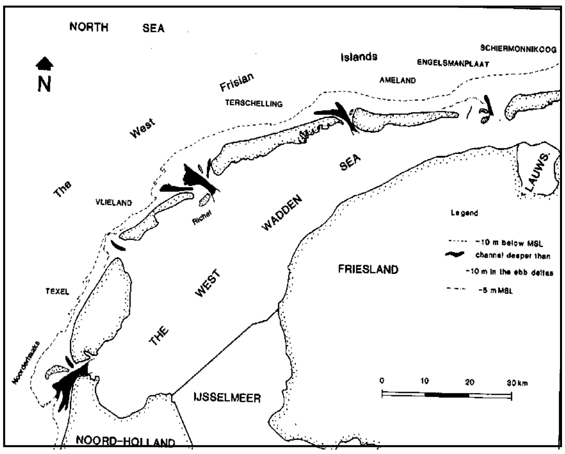


Figure 2-4a). Location and orientation of the ebb-tidal deltas along the West Frisian Islands

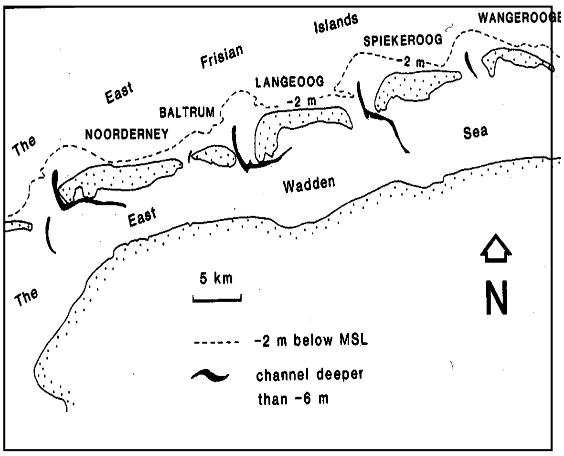


Figure 2-4b). Location and orientation of ebb-tidal deltas along the East Frisian Islands

On the one hand, the asymmetrical orientation of smaller ebb-tidal deltas is ascribed to the fact that wind-driven waves dominantly attack from the west. Hence they produce an easterly longshore drift which forces a downdrift asymmetry on the deltas. On the other hand, the updrift orientation of the larger ebb-tidal deltas is due to the influence of tidal currents that pass through the inlet.

It can be concluded that the morphodynamic character and orientation of ebb-tidal deltas is the result of the combined interaction of tidal currents (parallel to the coast and through the inlets) and wave action *(Sha, 1989)*.

The sediment transport at the outer delta can be seen as an intermittent process *(de Vriend & Bakker)*, in which the sediment is transported, deposited and picked up, depending on the prevailing conditions.

The longshore drift, generated by the obliquely incidenting waves, is interrupted by the outer delta. Inhere the sediment may enter via the channel or may be transported from the updrift island to the downdrift island either around or across the delta. The by-passing of the inlets, i.e. the process which allows material to become part of the littoral drift downstream of the interruption, may occur via off-shore bars or by tidal flow action. The first occurs only with considerable wave action, whereas the latter is due to predominant tidal flow.

According to *Bruun (1978)*, the tidal flow by-passing is dominant for the inlets along the Dutch coast.

Barrier Islands

Barrier islands lie on the seaward side of the Wadden Sea. They are formed and sustained by the combined action of wind, waves and tides, that govern sedimentation and erosion processes. Moreover, according to *Hayes (1975)*, their length exhibits a relation with the mean tidal range (refer to section 2.3). In general, a barrier island consists of sedimentary subenvironments, such as lower and upper shoreface, intertidal beach, dunes and tidal marshes. On the intertidal beaches, sedimentation and erosion processes are mainly due to wave-action, coast-parallel, residual currents and wind-driven phenomena.

The barrier islands provide a considerable shelter from wave energy to the basin. The wave energy that penetrates through the gorge, it decays rapidly, as the waves break on the shoals of the ebb-tidal delta. Behind the gorge the waves start to radiate into the basin and the wave height exhibits a continuous decay.

2.2.2 Tidal Basin

Tidal basins are defined as semienclosed embayements, connected to the open sea by a narrow entrance and subject to daily tidal action. The basin area is characterised by a meandering, braided and/or branched channel system, ebb-and flood chutes, intertidal sand and mud flats, and marshes.

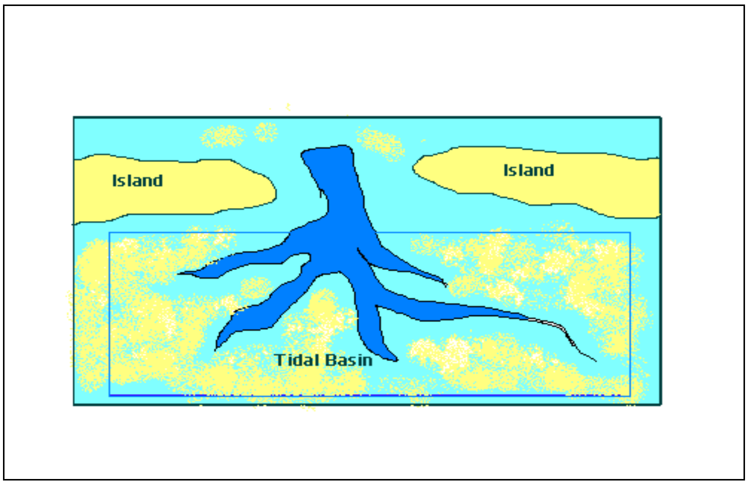


Figure 2-5. Top view of the tidal basin

The influence of waves entering from the North Sea into the back barrier area, mainly around high tides, decreases rapidly due to refraction and strong decrease of water depth towards the back barrier area. Here the wave energy is strongly reduced right after the passage of the inlet throat *(Nyemeyer, 1986).*

Two main different elements can be identified in this area: the channel and the flat. Inhere sediment is transported through a system of channels to and from the flat, showing a persistent interaction between these elements of the basin.

Channel

In the Wadden Sea the inlet channel splits up into an extensive network, which constitutes the main pathway for water and sediment transfer within the basin. Through the channel the tidal waters flow to and from the intertidal shoals.

The cross-sectional area of the channel appears to be related to the tidal prism. This relation is likely to apply to the Dutch Wadden Sea, as has been shown by several studies carried out on the area *(Renger & Partenscky, 1974, 1980; Renger, 1976; Eysink, 1979, 1990, 1991; Dieckman, 1985; Dieckman & Partenscky, 1986).*

Therefore, from the mentioned relation, it can be gathered that also the channel volume will be affected by the tidal prism.

Tidal Flat

According to general classification of the coastal features *(Eysink, 1993)*, the presence of tidal flats depends on the tidal range, on the size and shape of the basin area, and on its orientation relative to the dominating wind direction and to the wave directions at sea.

The tidal flat area of the Wadden Sea, is the area that normally inundates and dries twice a day, being the tide semi-diurnal. The tidal flat area is defined as the area between MLW and MHW (see Figure 2.6).

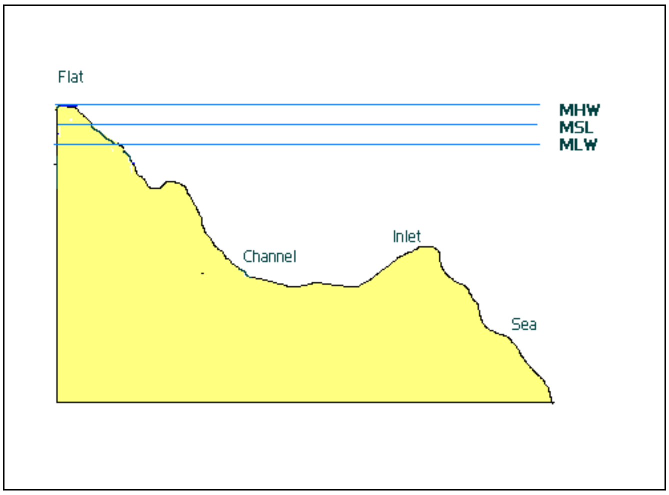


Figure 2-6. Cross-section of a tidal inlet system

The tidal flats can be subdivided in a zone between low water spring and mean high water, namely shoals and gullies; and in a zone above the mean high water, i.e. high shoals and salt marshes. Shoals are fully exposed during low water spring and flooded during mean high water. For the Dutch Wadden Sea, a typical value of their maximum elevation is 0.3 m below mean high water, while the average flat levels stands 1.3 m below mean high water. On the other hand, higher intertidal shoals are flooded only during spring tide and/or storms.

Tidal divide

Another important morphological element of the back barrier area is the tidal divide, separating the tidal basins of adjacent inlet systems. Morphologically the tidal divide forms a slightly elevated ridge connecting the mainland with the barrier islands. In the Wadden Sea a morphological watershed is formed where the tidal waves entering through a westerly inlet meets the waves entering through the next. Because the tidal wave approaches from the west, the tidal wave enters each consecutive inlet with a time lag. As a result the tidal divide occur asymmetrically displaced towards the east in the rear of the island and the mainland.

2.3 Tidal inlet morphodynamics

2.3.1 Introduction

In the foregoing section (2.2), the morphological elements of a tidal inlet system have been defined and analysed. The aim of this section is now to illustrate which are the factors that play a significant role in the macro-scale system's development. The morphological response of tidal inlet system to the factors presented hereafter it is likely to cover a time-scale of decades up to century

Depending on the predominant action of waves or tides, which are the main forcing on the system, tidal inlet systems show different morphological features (section 2.3.2). *Hayes (1975)*, indicated a tidal inlet classification that correlates the characteristic wave and tide to the morphological plight. This classification is presented hereafter (see Section 2.3.3)

2.3.2 Significant factors and forcing on tidal inlet system

Tidal inlets are highly dynamic systems undergoing morphological development. As a dynamic response to natural and human forcing, they change their topography within long-term processes. Depending on the considered area of the tidal inlet system, i.e. coastal inlet or tidal basin, we may identify different factors that mainly affect the morphological development. The coastal inlet is mostly affected by the tidal prism and the incoming waves, whereas the tidal basin is influenced by the tidal range and the geometry of the basin area.

In general, previous studies *(Eysink, 1993)* have shown that morphology evolution of the system on a large-scale is governed by hydrodynamic and morphometric conditions, such as:

- Tidal range and flow;
- Seasonal variations in waves and winds conditions;
- Geometry of the basin;
- Relative sea level rise;
- Sediment transport mechanisms.

The combination of the above mentioned factors is likely to affect the large-scale development of tidal inlets, over a time span of decades to centuries. Hereafter the mentioned factors are outlined.

Tidal range and flow

The tidal range, viz. the difference between low and high water level, is a very important hydrodynamical factor for the morphological development and shape of tidal inlet. Mostly, it depends on the ocean tides (defined as the alternating rise and fall in sea level with respect to the land, produced by the gravitational attraction of the moon and the sun) and their interaction with the continental shelf. The configuration of the coastline local depth and the ocean-floor topography may play an important role in altering the range. A balance of different phenomena (reflection and resonance of the tidal wave into the basin, frictional dissipation of energy in shallow water) actually yields the actual tidal range.

In the North Sea, the tidal wave moves from the S(W)to the N(E), propagating anticlockwise along the Dutch coast, and enters the Wadden Sea through the inlets. Due to the distortion of the tide by friction and other non-linear interactions (see above), the flood period may become longer than the ebb period and vice versa. This effect is known as tidal asymmetry and it induces that maximum tidal velocities during the shortest period are larger than maximum tidal velocities during the longest period.
Moreover, the volume of water crossing the inlets during a tidal cycle, known as **tidal volume**, produces different flow velocities into the basin. High current velocities are observed at the throat, where deep channels are formed due to their scour-capacity. On leaving the throat, tidal flow velocity decreases towards the tidal divide, where the sediment can settle giving rise to ridges formation.
Since the sediment transport is proportional to the flow velocity, this observed discrepancy will influence the sediment pattern.

According to *Hayes (1979)*, the tidal range can be characterised by its order of magnitude as follows:

Table 2-1. Tidal range classification *(Hayes, 1979)*

Classes	Tidal Range (m)
Microtidal	< 1.0 m
Low Mesotidal	1.0 - 2.0 m
High Mesotidal	2.0 - 3.5 m
Low Macrotidal	3.5 - 5.5 m
High Macrotidal	> 5.5 m

Based on this classification, *Hayes* stated that the mean tidal range determines the length of barrier islands: the larger the tidal range the smaller the island length. Moreover it affects the ebb-tidal delta orientation, and the formation of flat area.

Regarding our area of interest, the range of the semi-diurnal tide varies from 1.3 m near Den Helder to 2.8 m in Delfzijl. The tidal range is thus found to be mesotidal, likely to preserve the maintenance of barrier islands, large inlets and ebb-tidal delta, and to enhance the formation of flat area and salt marshes.

Seasonal variations in waves and winds conditions

Seasonal waves and winds influence the morphological evolution of tidal inlet systems, as they affect the sediment transport processes into the basin and at its boundaries.

Nearshore wave climate is of high importance for morphological processes in tidal inlets. Longshore, the predominant wave direction determines the flux component as driving force for the littoral drift, whereas onshore wave conditions restrict the area where the ebb-tidal delta can spread. On the other hand, the wave front pattern in tidal inlet system is significantly affected by tidal currents and rapid changes in bottom topography.

As explained in the foregoing section (see 2.3.2), the combination of tidal range and wave climate provides the tidal inlet classification, enclosed therein. The wave climate is generally characterised by the mean wave height H_s on a yearly average basis as follows:

Table 2-2. Wave energy climate *(Hayes, 1979)*

Wave energy	H_s (m)
Low wave energy	$H_s < 0.6$ m
Medium wave energy	0.6 m$<H_s<$1.5 m
High wave energy	$H_s>$1.5 m

Nevertheless, the wave breaking on the shoals in the ebb-tidal delta area induce strong energy dissipation, restraining wave influence into the basin. The backbarrier area, hence, will be affected by local wind-generated waves.

Wind-generated waves are produced by the local prevailing wind. They travel in the direction of the prevailing wind. The height of wind waves varies depending on the strength of the wind, the time the wind has been blowing and the fetch. The higher the wind speed, and the longer the duration and fetch, the higher the wave and the larger the period. The effect of wind-generated waves is primarily an increase of the intensity of vertical mixing.

Furthermore, wind stress exerted on the surface produce a net transport of water, in the direction of the wind. As a mass balance, the lower part of the water column will be directed in the opposite direction.

Geometry of basin

Changes in the geometry of the basin constitute one of the most important factors in the long-term morphological evolution of tidal inlet systems. The size of the basin can change in response to, for instance, a gradual sea level rising (see next section) and bottom subsidence, or to sudden changes due to mankind interventions, like embankments and dikes constructions.

The accompanied change in tidal volume will influence dimensions and orientation of every single element of the system. The previous equilibrium configuration will, therefore, be affected involving a perturbation of the dynamic equilibrium between hydraulics and morphology. As a reaction more sediment will be trapped or eroded in order to restore the dynamic equilibrium situation.

Relative sea level rise

About 18,000 years ago, during the maximum of the last glacial period, global sea level stood somewhere between 120 m and 175 m lower than the present (Jelgersma &Tooley, 1993). With increasing temperatures, the water that was bound on land in icecaps started to melt, inducing a sea level rise of 21 mm/yr over the time period 8,600 to 7,100 BP *(Streif, 1989)*, partly due to subsidence of he North Sea basin.
After about 6,000 BP bottom subsidence (at a rate of 1 to 1.5 mm/yr) began to dominate, eustatic sea level (the change in sea level without considering changes in bottom level) rising at a rate of only 0 to 1 mm/yr. The sea level rise has been rising continuously along the years.

Data registered in the Wadden Sea, along the last century manifested an average increase of about 18 cm per century. *(Dutch National Reaserch Programme on global air pollution and climate change, Modelling the impact of climate change on the Wadden Sea ecosystem, 2001).*

The mean trends in yearly mean high water (MHW), yearly mean sea level (MSL) and yearly mean low water (MLW) are gathered below. The data are registered in one of the gauges along the Wadden Sea in Germarny.

It can be observed, in Figure 2.7 below, that the mean high water levels increased somewhat faster than the mean sea level. According to *Bouwmeester (1993)*, this discrepancy would imply that the local amplitude is expected to increase, resulting, hence, in an increasing tidal volume.

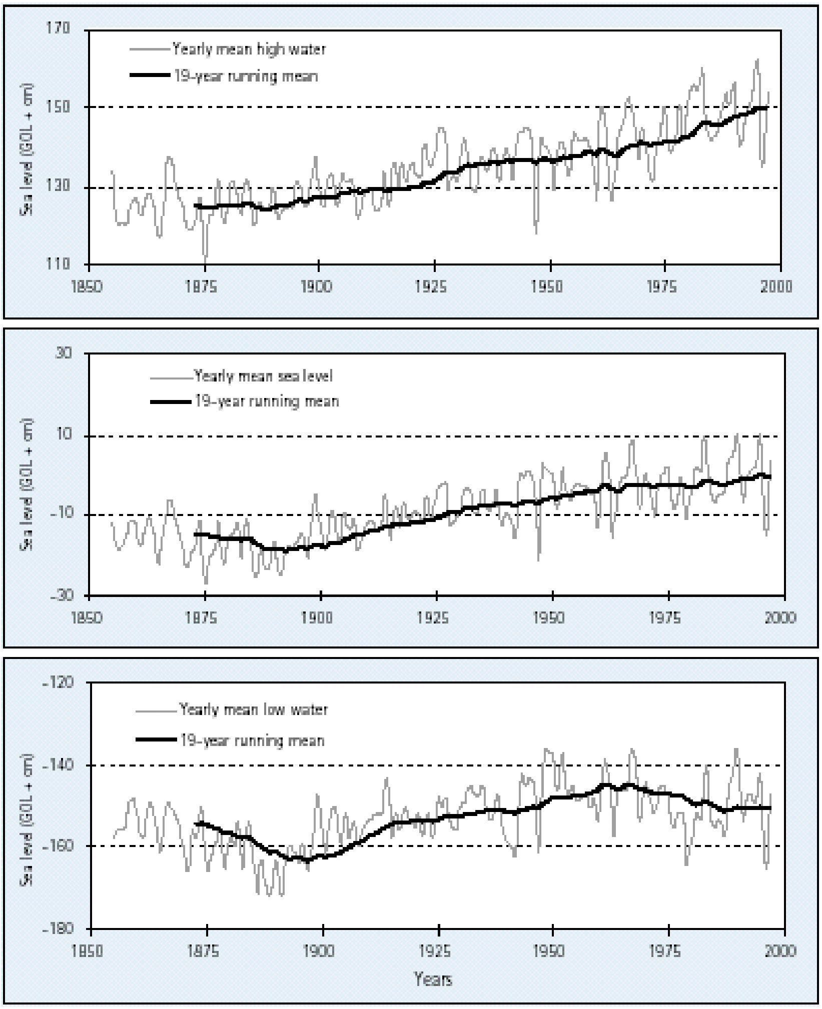


Figure 2-7. Mean MHW, MSL, MLW at gauge Cuxhaven (Germany)

Nowadays, the Earth is experiencing a general climate change, resulting from the combination of natural (volcanoes, changes in solar activity, and changes in the Earth's orbit) and human forces (emission of greenhouse gases). Due to the observed global warming trend, a general rise in mean sea level is likely to occur in the future.
As forecasted by several studies, the mean sea level will rise from 36 cm up to 100 cm by 2001, as the worst case scenario. This rise will result mainly from the melting of glaciers and thermal expansion of the upper layers of the ocean.

Global mean surface temperature increases and rising sea level from thermal expansion of the ocean are projected to continue for hundreds of years, owing to the long time-scales on which the deep ocean adjusts to climate change.

Also ice sheets will continue to react to climate warming and contribute to sea level rise for thousands of years after climate has stabilised. The consequences of the forecasted scenarios of sea level rise are multiple, embracing aspects related to the Wadden Sea (i.e. morphological changes, biological and socioeconomic consequences).

Sediment transport mechanisms

Sediment transport is a rather complicated process in any kind of tidal inlet. Depending on the actual hydrodynamic conditions, the sediment transport follows typical circulation pattern in tidal inlets and affects their morphology. According to *Ehlers (1988)*, the majority of the sediment movements occur in the ebb delta. The transport in and out of the tidal inlet plays a subordinate role, whereas sediment transport across the tidal flats is accordingly low.

Fitzgerald, Nummedal & Penland (1984) pointed out a scheme that well describes the Frisian tidal inlets. The longshore component of predominant wave energy flux and unidirectionally acting residual tidal currents induce littoral drift, which is superimposed by mainly wave induced cross-shore transport. In the vicinity of the inlet the interaction of hydrodynamics and morphological structures creates a more differentiated sediment transport pattern.

The interruption of littoral drift leads to an accumulation of sand at the updrift side of the inlet. In the updrift part of the inlet, flood currents and wave bump produce a net lagoon-ward sediment transport, which is additionally fed by the washover of breaking waves on the shoals. This sediment gets partially into the basin and partially into the main ebb channel. From there it is transported back to the ebb delta shoals. This process performs the mentioned by-passing mechanism.

Sediment transport generally manifests itself in two main forms: bed load and suspended load transport. Bed load transport occurs in a thin sheet of sediment moving above the bottom, while suspended load transport is ascribed to advection/diffusion phenomena.

2.3.3 Tidal inlet classification

From a macro-scale prospective *Hayes (1979)* classified tidal inlet based on two parameters that mostly characterise their morphology, the tidal range and the wave energy. A combination of these two parameters results in a distinct classification of tidal inlets, providing a tool to predict their morphological features.

The classification of tidal inlets leads to a distinction into wave- or tide-dominated, or transitional morphological types.

According to *Hayes (1979)*, the following types of tidal inlets with respect to tide/wave dominance can be distinguished:

1. Wave dominate;
2. Mixed energy (wave dominant);
3. Mixed energy (tide dominant);
4. Tide dominated (low);
5. Tide dominated (high).

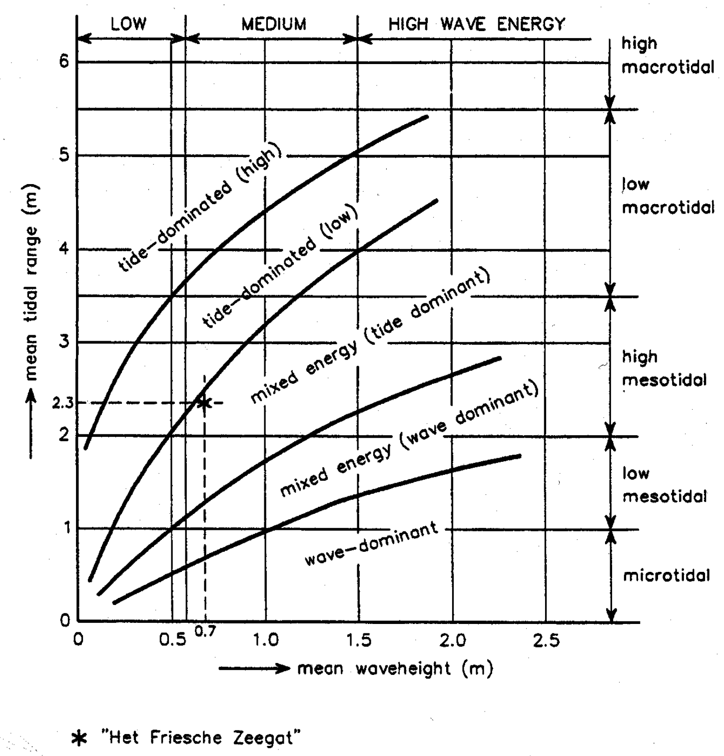


Figure 2-8. Tidal inlets classification

Hayes pointed out a correlation between the hydrodynamic characteristics, viz. tidal range and wave climate, and the morphological features of the coastline, in accordance with this classification.

Wave dominated types have long continuous barriers, with abundant washover and few inlets. Mixed energy present a larger number of inlets with larger ebb-tidal deltas, when wave dominated, and usually drumstick barriers if tide dominated. Tide dominated (low) occasionally show wave built bars, whereas high tide dominated exhibit tidal current ridges, extensive salt marshes and tidal flats, deep inlet gorges and large ebb-tidal deltas.

Likewise the Friesche Zeegat, considered as a sample in the chart above, the Dutch coastline is found to be mixed energy (tide dominated). Accordingly, its morphology manifests the characteristic morphological features (large number of inlets with large ebb-tidal deltas, and drumstick barriers).

2.4 History of the Dutch Wadden Sea

2.4.1 Introduction

In the previous sections the morphological units of tidal inlet systems (2.2) and their characteristic evolution processes on macro-scale (2.3) were presented. The aim of this section is to apply the general considerations on the study-case of the Dutch Wadden Sea, showing how the morphodynamic development of every single inlet contributes to the global evolution process on a time span of centuries to millennia (mega-scale).

Hence, a reconstruction of the morphodynamic behaviour of the Dutch Wadden Sea is presented herein, in order to achieve a better understanding of the long-term morphological evolution of tidal inlets and their relative basins. The history of its dynamic evolution will thus provide a picture of the systems ability to adapt itself to external forcing.

The reconstruction reported is based on historical and geological data and maps. On the other hand, the configuration of the channels and the intertidal areas was achieved with support of nautical chart and archives, as the maps were roughly accurate.

2.4.2 Geological and historical evolution

The geographic area now known as the Wadden Sea can be considered a geologically young formation. Although, by looking at its historical evolution over the millennia, it can be observed that it experienced strong morphological changes.
Both relative sea-level change and sediment losses and gains have determined the morphological evolution of the Dutch Wadden Sea, as will be illustrated hereafter.

The Pleistocene topography of the western and northern Dutch coast, shown in Figure 2.9, had determined for an important part of the Holocene evolution of the Dutch Wadden Sea. The landscape exhibits an irregular surface of glacial till and fluvial sediments dating from the Riss glacial stage. Low-lying areas, which can be observed in the figure below, were submerged during the Eemian (Riss-Wurm, approximately 75,000 years BP) whereas shallow marine and tidal flat sediments with a characteristic fauna were deposited in the embayments. During the last glacial stage (about 10,000 years BP) the icecaps didn't reach the Dutch region and the sea level was found to be about 100 m lower than the actual level *(van der Spek, 1994).*

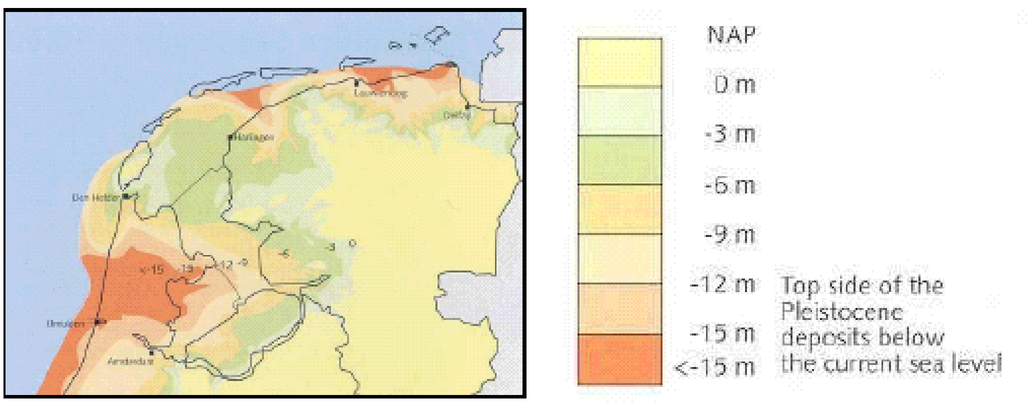


Figure 2-9. Pleistocene landscape

Studies on the relative sea level in the coastal plain of the Netherlands *(Jelgersma, 1961, 1979;* and *Van de Plassche, 1982)* led to a reconstruction of trend curves for the Holocene relative sea level rise. The curves show a rapidly sea level until about 7,000 BP, mainly resulting from the melting of Scandinavian and Laurentide icecaps, but partly also by subsidence of the North Sea basin.
During the first half of the Holocene the accelerated sea level rise (80 cm per century and more) has led to a transgressive and retrograding coastal system, in which the Pleistocene river valleys were submerged. The coastal areas became marshy and a peat layer was formed on the Pleistocene subsurface.

At the end of the fast Holocene transgression about 5,800 BP, the sea had invaded the Pleistocene river-valleys in the western and northern parts of the Netherlands. In the western part this had resulted in a lagoon-type coast, while the eastern part of the Dutch Wadden Sea area was developing into an estuarine coast.
The rate of sea-level rise reduced from 80 to 40 cm/century, between 7000 and 5000 years ago. Due to the decreasing sea level rise, a diversion in coastal evolution started to occur between the western and the northern part of the Dutch coast: the western part became a prograding coast and the northern part remained transgressive.

Figure 2-10. Approximately 5800 BC

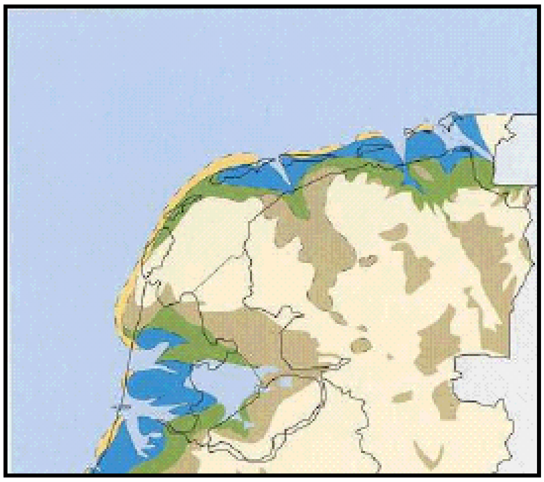


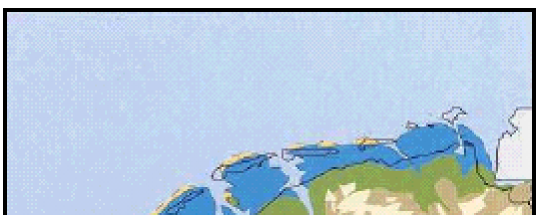
Figure 2-11. Approximately 4000 BC

In the **Western area**, corresponding to **South and North Holland**, the transgression continued until approx. 5000 BP. Subsequently, the sediment supply by various large rivers, erosion of headlands, old ebb-tidal deltas and the North Sea, defeated the effect of the sea level rise, causing the coast to prograde. The change from a transgressive to a regressive barrier was direct consequence of the lower rate of sea level rise. This corresponded to infilling of the basin: the intertidal areas behind the coastal zone became shallower and tidal channel systems were eventually silted up (5500 -3300 BP). By that time the coastline had been closed and large surfaces behind it were covered with fresh water. Further north, in the area corresponding to the **Western Dutch Wadden Sea** (Texel-Terschelling), the Pleistocene surface was at relative high elevation, thus strongly reducing the influence of the sea. The area followed the evolution process of the remaining western area, until 3700 BP. After 3700 BP part of the area east of the Vlie channel or east of the line central Texel-Bolsward gradually changed into a Wadden area.

In the **Eastern Dutch Wadden Sea,** the Pleistocene surface was lower, with a number of small rivers incised. Between 6000 and 5000, probably originated the barrier islands *(Sha, 1992).* In this area, low sediment supply, enhanced by continuos sea level rise, forced the islands to shift landward. As sediment was demanded to balance the sea level rise in order to replace the eroded deposits , the island coasts acted as buffer, resulting in a shift coastward.
Unlike the western Dutch Wadden Sea, were peat formation was more extensive as flats were more sheltered behind long coastal barriers, here the stronger marine inluence led to clay deposits.

The rate of sea level rise continued to decline and reached the value of 20-40 cm/century after another 2000 years (Jelgersma, 1979, van de Plassche, 1982, Roep & Beets,1988). As the rate reached 0.15 m per century, the sediment supply was sufficient to extend the flat areas, fill the interchannel areas. Then, salt marshes became a widespread feature, approximately 3,000 ago.

The northern tidal basin starts to enlarge again between 800 and 1000 A.D. The continuing sea level rise, coupled with local peat extraction and other human interventions, such as the digging of ditches and channels to drain the marshes are likely to have caused the internal erosion. The upper peat layers, mostly present in the western area, were swept away by the sea. The resulting enlargement of the basin facilitated the creation of the Zuider Sea. The basin silted up again, due to the adaptability of the new area for sediment settling. Few centuries later, land reclamation began.



Since the early Middle Ages, a new type of external forcing acts in evolution process of the Dutch coastline intervened a new external forcing: human interventions. Since then, the basin of the Wadden Sea, has been shaped by the intensive and continuos human activities. Digging of ditches and small canals to drain the lowlands, peat digging for fuel and salt extraction, dikes constructions to enclose sheltered areas and to reclaim lost land, became common activities in the Wadden Sea.

With the aim of flood protection and land reclamation, the Wadden Sea progressively reduced its extension, reducing the tidal prism as well. As a result, inlets and channels got shallower, and the volume of the ebb-tidal deltas decreased.

The most impacting human interventions, however, are found in the 20th century, the closure of the Zuider Sea, with the construction of the Afsluitdijk (1932), and of the Lauwers Sea (1969) being the major ones. As yet, the effects of the latter interventions are still uncertain as they influence the long-term morphological development of the wadden Sea. Nonetheless, it is remarkable that, due to a decrease of tidal prisms and due to wave-induced longshore bypassing processes around the tidal inlets, migrations of the inlet throats towards the East seems to occur.

2.5 Summary

This chapter dealt with the morphological elements and processes that interest the Wadden Sea on a macro-scale. As a final conclusion, it can be stated that the morphology of the Wadden Sea depends on the hydrodynamic and morphometric conditions. Based on this, in the following chapter, the morphological equilibrium equations and the ASMITA approach will be pointed out.

In the last section of the chapter, the history of the dynamic evolution of the Dutch Wadden Sea had provided a picture of the system ability at adapting itself to acting forcing, as well as a brief overview of its evolution on a mega-scale.

3 Morphological modelling of tidal inlet systems

3.1 Introduction

The morphology of tidal inlet systems is the result of a complex, multi-scale dynamical interaction of hydrodynamic and morphometric conditions, as it was illustrated in the foregoing chapter. Both stochastic (wave climate) and deterministic (tides) forcing are involved in their large-scale development.

According to *De Vriend (1998)*, the limited predictability can be tackled through the concept of **cascade of scales**:

- **Micro scale** (process scale): primarily it concerns the constituent processes (waves, currents and sediment transport), that take place on a smaller scale than the corresponding morphodynamic behaviour (ripple and dune formation). The principal forcing are diurnal tide and daily weather conditions, such as waves and winds climate.
- **Meso scale** (dynamic scale): it concerns the "primary" morphodynamic behaviour due to the interaction of the constituent processes and bed topography, involving morphological features like channels and shoals. The principal forcing are seasonal and interannual variations in tide and weather conditions, and human interventions.
- **Macro scale** (trend scale): it concerns slow trends at scales larger than the "primary" morphodynamic behaviour, which are due to secular effects in the system's inherent behaviour, or to gradual changes in the external forcing, or system parameters. The principal forcing are long-term cycles in tide, variations in wave climate within decades, and human activities.
- **Mega scale**: it concerns the interaction of the principal elements over a space-span of kilometres and a time-span of centuries. The principal forcing are the mean sea level rise, climate changes, long term tidal variations, soil subsidence, etc.

Since a wide range of space and time scales are involved in the dynamic evolution of the system, one single model is likely to be an insufficient tool to derive insights on the morphology of tidal inlet system.

Intrinsic and practical limits of predictability can be overcome by aggregation of scales. On the basis of the known behaviour at scales below and above the limit found, another model is formulated on higher scale level, not deepening on details characteristic of the lower level. A cascade of models at different levels of aggregation turns out to be a possible solution *(De Vriend, 1998).*

The purpose of the present chapter is to introduce the ASMITA model as an available approach to predict and describe the long-term morphological evolution of the tidal inlet systems in response to changes in basin area. Hence, in the following sections ASMITA concepts and assumptions are illustrated.

In Section 3.3 the equilibrium relation used in ASMITA are presented. Subsequently in sections 3.4 and 3.5, the governing equations and the required parameters are set out in detail.

3.2 ASMITA: Aggregated Scale Morphological Interaction between Tidal inlets and the Adjacent coast

3.2.1 Introduction

When dealing with changes in basin area, the morphological response of tidal inlet systems involves large length-scales processes. Practically, the morphological evolution of the system takes place over a time span of decades to centuries, and covers space areas of tens of kilometres. According to *De Vriend (1998)* (see previous section), the scale of interest is therefore a macro-scale. Based on the concept of cascade of scales, aiming to predict long-term evolution of tidal inlets on a macro-scale, an aggregated modelling approach is chosen.

ASMITA was formulated from the studies on the response of the Mediterranean deltaic plains of Ebro, Po and Rhone rivers to climate and other human-induced changes *(Jimenez et al., 1996; Capobianco et al. 1996).* It can be considered as an aggregation on the one hand and as an extension of the model formulation for tidal basins, namely ESTMORF model on the other hand (*Wang et al., 1996; Fokkink et al. 1996).* The aggregation concerns the fact that system elements are characterised by one state variable (total wet/dry volume). The extension refers to the incorporation of the ebb-tidal delta and directly adjacent coast.
This aggregated scale model focuses on the residual interaction occurring on a long-term scale within the geophysical elements of the coastal fringe.

In the following sections, the model schematisation and formulation will be illustrated.

3.2.2 Model schematisation

In ASMITA, the degree of schematisation is determined by the elements of the system, which delivers the lower boundary to the relevant spatial scale.

This concerns typically the ebb-tidal delta, for which there is presently no other option than to consider its volume as an integral state variable.

Hence the ebb-tidal delta is modelled as a single element, which makes it not very sensible to model the tidal basin and the adjacent coast in more detail *(Stive et al., 1998).* The same level of schematisation is hence adopted for all the elements in the system.
From the perspective of our aggregated scale model ASMITA, a tidal inlet system is seen as consisting of three major morphological elements (the adjacent coast could also be included as additional element, but it won't be considered in the present report):

- **tidal flats**
- **channel**
- **ebb-tidal delta**

Additionally, an outside world, characterised by an overall permanent equilibrium state, can be defined. The outside world corresponds to the coastal zone surrounding the outer delta and it is assumed to be able to provide sediment to the system unconditionally. Furthermore, it should be kept in mind that the outside world is assumed not to influence the dynamics of the tidal inlet system and is thus assumed to act as a boundary condition

The elements that constitute the system are shown in Figure 3.1.

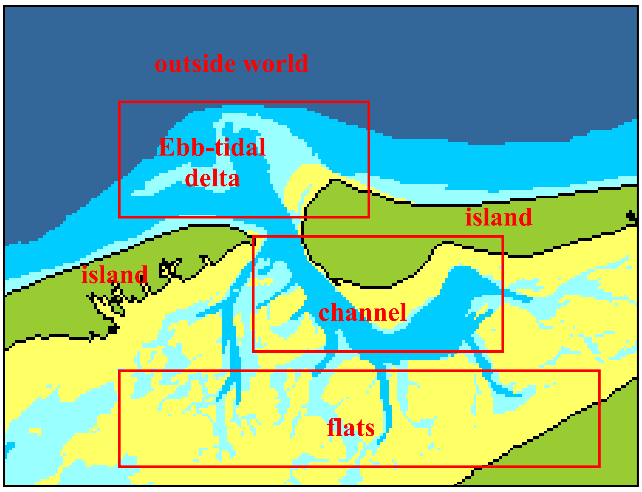


Figure 3-1. Schematisation of tidal inlet systems

As mentioned in the previous section, each of these elements is described by one morphological variable, viz. a total wet/dry volume. In Table 3.1 a volume definition for each element is given:

Table 3-1. Volume defintion for morphological elements in ASMITA

Element	Volume definition (m^3)
Ebb-tidal delta	Volume of the delta V_d above a fictitious sea bottom, which would be there if there was no inlet (**sand volume**)
Channel	Total channel volume V_c under MLW (**water volume**)
Tidal Flat	Total volume of the flat V_f between MLW and MHW (**sand volume**)

3.2.3 Model concept

The most important hypothesis used in the model concept is that a morphological equilibrium can be defined for each element depending on the hydrodynamic and morphometric conditions.

Empirical relations between state variables and parameters of the governing hydrodynamic conditions are thus required for defining the equilibrium state. These relations are derived from literature (*Eysink, 1990)* and are based on various field investigations. As it will be presented in section 3.3, the volume of an element in a state of morpho-dynamic equilibrium is correlated to the tidal range, tidal prism and the basin area (A_b).

The equilibrium concentration represents a key element in the modelling concept. In order to define the equilibrium concentration of each element, it is necessary to introduce the notion of **overall equilibrium concentration c_E**:

> when all elements are in equilibrium a constant sediment concentration is present, the so called **overall equilibrium concentration**. The overall equilibrium concentration equals the outside world concentration, and represents a time-invariant boundary condition for the system.

For each element of the system a local **equilibrium concentration c_e** is defined based on the above notion. The element is in morphological equilibrium if c_e it is equal to c_E, tends to erode if it is larger than c_E and sedimentation occurs if it is smaller than c_E. The local equilibrium concentration depends on the actual volume V, and gives insight into the deviation of the actual volume from the equilibrium one V_e. To represent this behaviour a simple power relation is used:

$$c_e = c_E \left(\frac{V}{V_e} \right)^n \tag{3.1}$$

where the power n is larger than one, most commonly taken as 2 in compliance with a third power for the sediment transport as a non-linear function of the mean flow velocity. The sign of the power is positive if the volume represents a dry (sand) volume and negative if it is a wet (water) volume (see previous section).

When the volume of each element deviates from its state of equilibrium, a need or surplus of sediment is created. This leads to sediment exchange between the elements. According to *De Vriend (1996)*, the interaction between the different elements through sediment exchange plays an important role for the morphological development of the whole system. As shown in Figure 3.2, it is assumed that long-term residual sediment transport only occurs between tidal flat and the channel, the channel and the delta, the delta and the outside world. This is realised by the in-and out-going tidal prism within the system and by the combined action of waves and tidal prism at the boundary. The sediment exchange with the surrounding zones is assumed to have no influence on the evolution of the system and it is taken into account in ASMITA by the overall equilibrium concentration.

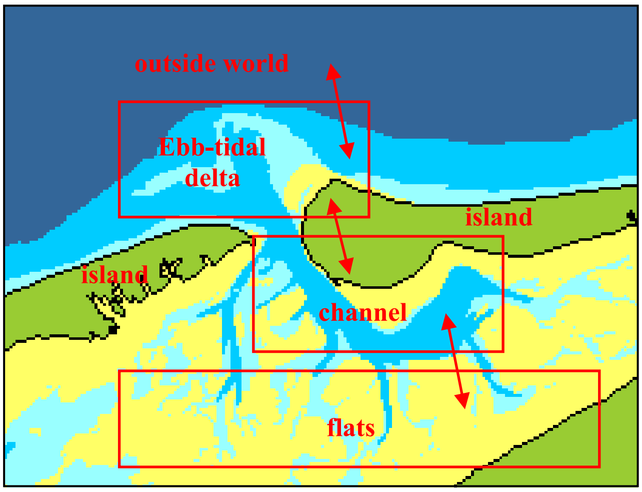


Figure 3-2. Schematisation of sediment exchange

The model concepts can be summarised as follows *(Stive et al., 1998)*:

- under constant (in a long term average sense) external (hydrodynamic) conditions, the equilibrium situation for the morphological state variables is known as a function of those conditions or it is assumed to be known under the given scenario;
- in the equilibrium situation an overall long-term averaged equal sediment concentration in each system elements exists;
- in case of external forcing of the elements' state variables new local equilibrium concentrations are defined. This leads to net sediment exchanges between the elements, which are described by a diffusion-type transport, where the diffusion is assumed to take into account, all the possible transport processes.

3.2.4 Model formulation

The equilibrium state is defined in the model depending on the hydrodynamic conditions. In the following section the empirical relations for each element are pointed out. In general, as mentioned previously, the equilibrium state is given as function of the tidal prism, the tidal range and the basin area (A_b):

$$V_e = V_e(P) \text{ or } V_e = V_e(H, A_b) \tag{3.2}$$

According to the model concept, morphological changes occur when the local sediment concentration deviates from the local equilibrium sediment concentration. The evolution of element volumes can be described in terms of availability of sediment which is assumed proportional to the difference between local equilibrium concentration c_e and the actual sediment concentration c. The morphological change for an arbitrary element holds:

$$\frac{dV}{dt} = w_s \cdot A \cdot (c - c_e) \tag{3.3}$$

where: w_s = vertical exchange coefficient (m/s)
A = horizontal area of the element (m^2)
t = time

The morphological change results in erosion when the actual concentration is smaller than its local equilibrium value and in sedimentation when it is larger than its local equilibrium value.

The availability of sediment, and thus the morphological change of each element, depends on the mass balance of the element. The sediment balance of an arbitrary element reads:

$$\sum_j^n \delta_{ij}(c_i - c_j) = w_{s_i} \cdot A_i \cdot (c_i - c_e) \tag{3.4}$$

herein $\sum_j^n \delta_{ij}(c_i - c_j)$ = the residual horizontal exchange between adjacent elements

δ_{ij} = horizontal exchange coefficient between adjacent elemnts
(c_i-c_j) = difference in actual sediment concetration
n = number of adjacent elements

The diffusive exchange, summed over all the adjacent elements, represents the long-term residual transport related to the difference between the actual concentrations of the elements.

In Appendix A, equation given for an arbitrary element are specified for every single element of the system (outer delta, channel, tidal flats).

3.3 Morphological equilibrium: empirical relations for tidal inlet system

As stated in the previous section, one of the most important hypothesis in the ASMITA model is that a morphological equilibrium can be defined for each element of the system, on the basis of the actual hydrodynamic conditions and morphometric characteristics it is liable to. Empirical relations between state variables, viz. the wet/dry volume of each morphological element of the system, and parameters of the governing hydrodynamic conditions, have been derived by *Eysink (1992)*, based on several field observations.

For each element, the morpho-dynamic equilibrium volume is observed to be correlated to the tidal range, tidal prism and the basin area A_b:

$$V_e = V_e(P) \text{ or } V_e = V_e(H, A_b) \tag{3.5}$$

Eysink and *Biegel (ISOS*2 Project, Phase 2, 1992)*, provide a wide depiction of the empirical relations for tidal inlet systems, comparing the equation describing Dutch and foreign inlets found after different authors *(O' Brien, 1931; Jarret, 1976; Shigemura, 1976, 1980*; *Gerristen* and *De Jong 1983, 1984; Dieckmann, 1988; et al.)*.

In the following sections, first a correct definition of tidal prism (tidal range was defined in the previous chapter) is given, as it represents an important hydraulic parameter in the equilibrium relations. Subsequently, the empirical relations valid for Dutch tidal inlets and adopted by the ASMITA approach will be gathered.

3.3.1 Tidal prism

The mean tidal prism is defined as the water volume between mean low water (MLW) and mean high water (MHW) in the basin. The mean amount of water that is exchanged per tide twice a day, viz. the mean tidal prism, depends on the size and shape of the basin and the tidal range.

According to *Eysink* and *Biegel (1992)*, in hydrodynamic equilibrium conditions, the tidal prism can be expressed as follows:

$$P = (1 - \alpha_f \frac{A_f}{A_b}) A_b \overline{\Delta h} \tag{3.6}$$

For short basins (i.e. the length of the basin is small compared to the wave length), whence the tidal motion is like a standing wave, the spatial variation of the surface elevation can be neglected. Therefore the tidal prism can be calculated as follows:

$$P = H \cdot A_b - V_f \tag{3.7}$$

where H is the tidal range (m), A_b is the basin area (m^2) and V_f is the volume of the flats between mean low water level (MLW) and mean high water level (MHW) (m^3).

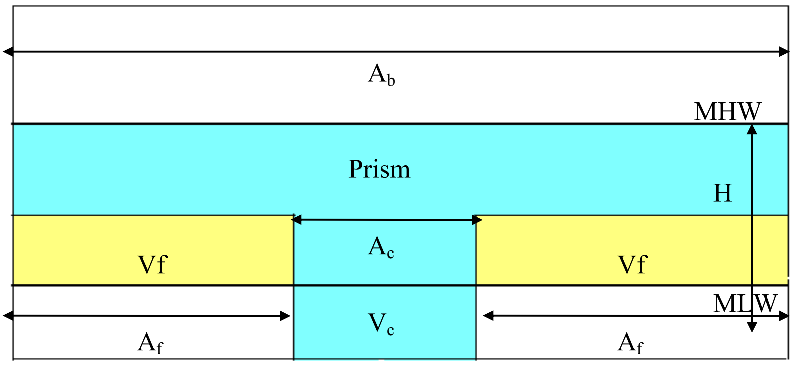


Figure 3-3.Tidal prism schematisation

where: A_f = Flat area between MHW and MLW (m^2)
A_b = Basin area at MHW (m^2)
A_c = Channel cross-sectional area (m^2)
V_f = Flat volume, between MHW and MLW (m^3)
V_c = Channel volume, below MLW (m^3)
H = Tidal range (m)
P = Tidal prism (m^3)
α_f = Empirical coefficient (-)
Δh = Mean tidal range (m)

3.3.2 Morphological equilibrium relations used in ASMITA

The morphological relations, holding for the inlets of the Dutch Wadden Sea, are presented herein. They provide a relationship between the equilibrium state of each element and the hydrodynamic and morphometric conditions.

Channel

For basin of the Wadden Sea a rather firm relation between the volume of the channel and the tidal prism has been proven to exist. Considering that wave action into the basin is negligible, the correlation between the channel volume and the tidal prism appears realistic. The following relation is used:

$$V_{channel} = \alpha_c P^{1.55} \tag{3.8}$$

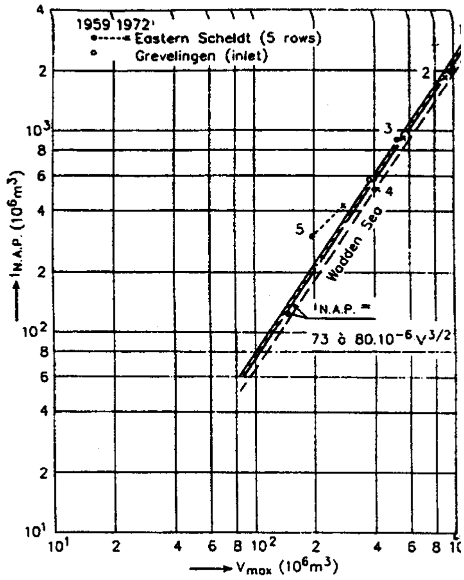


Figure 3-4.Channel volume- mean tidal volume

where: $V_{channel}$ = Equilibrium channel volume, below MLW (m^3)
α_c = Empirical equilibrium coefficient ($m^{-1.65}$)
P = Mean tidal prism (m^3)

Ebb-tidal delta

According to *Walton and Adams (1976),* the volume of the ebb-tidal delta is defined as the sand volume stored above the bottom level that would be there if the coast was uninterrupted. Based on the bathymetric reconstruction of the coastal profile without the outer delta, the volume of the ebb-tidal delta reflects., therefore, the storage of sand exceeding the reference coastline.

The outer deltas of the Dutch Wadden Sea appear to agree with the relation stated by *Walton and Adams (1976)*, found for American outer deltas. Generally the best match is observed with the relation for highly exposed deltas.

The relation holds as:

$$V_{delta} = \alpha_d P^{1.23} \tag{3.9}$$

where: V_{delta} = Equilibrium sand volume of the outer delta (m^3)
P = Mean tidal prism (m^3)
α_d = Empirical equilibrium coefficient ($m^{-0.69}$) depending on wave conditions

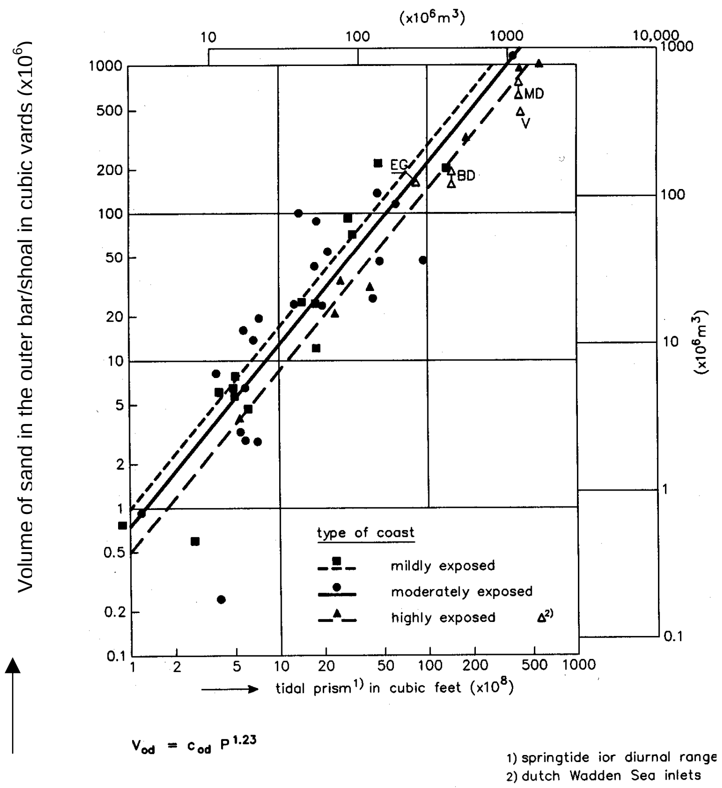


Figure 3-5. Sand volume outer deltas in USA in relation to the mean tidal volume of the inlet, according to Walton and Adams

Tidal flats

According to *Davis (1964)* and *Hayes (1979)*, the existence of tidal flats depends on the tidal range. Nevertheless, for the Dutch Wadden Sea with a meso-tidal range, the relative tidal flat area A_f/A_b can not be only directly correlated with the tidal range. *Eysink (1990)* stated that the relative flat area is related to the area of the basin itself. The following relation for the German Bight was found by *Renger* and *Paternscky (1974)*:

$$A_f / A_b = 1 - 2.5 \cdot 10^{-2} A_b^{0.5} \tag{3.10}$$

Moreover, the height of the tidal flats is related to the tidal range. The dimensionless coefficient α_f represents the height of the flats relative to MLW. According to *Eysink,* a relation exists between the area of the basin and the coefficient α_f:

$$\alpha_f = 0.41 - 0.24 \cdot 10^{-9} A_b \tag{3.11}$$

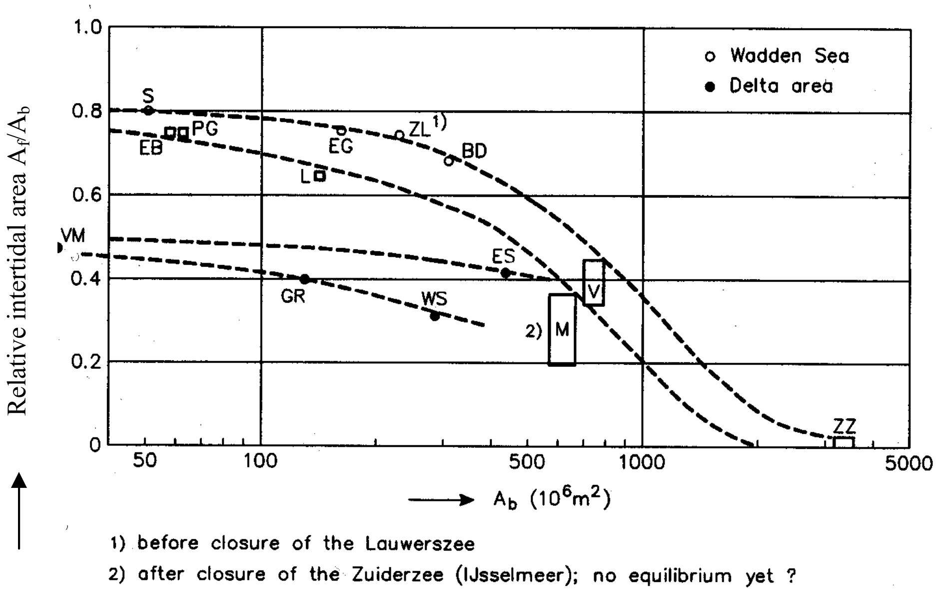


Figure 3-6. Relative area of the intertidal zones in the Dutch Wadden Sea and delta area *(Eysink and Biegel, 1993)*

The volume of the tidal flat is defined as the product of the area of the flats and the their height above MLW. Hence it can be expressed as follows:

$$V_f = \alpha_{fe} \cdot \left(\frac{A_f}{A_b} \right) \cdot A_b \cdot H \tag{3.12}$$

herein: A_f = Area of tidal flats, measured at MLW (m^2)
A_b = Area of the basin, measured at MSL (m^2)
V_f = Volume of tidal flats, measured at MLW (m^3)
H = Mean tidal range (m)
α_{fe} = Empirical coefficient for the averaged flats height (-)

3.4 Model parameters

In this section are summarised all the parameters found in the present chapter that have to provided when making computations with ASMITA model.

Table 3-1. Model paremeters

Tidal Range (H)	The tidal range is given as a representative hydrodynamic condition. The tidal prism and, therefore, the equilibrium volumes of the elements are derived from this input.
Equilibrium equations	Empirical relations for the definition of the morphological equilibrium state are required. These equations, discussed in the previous section, are generally applicable for the Dutch Wadden Inlets.
Overall equilibrium concentration (c_E)	The overall equilibrium concentration is required in order to estimate the local equilibrium concentration and thus the actual state of each element. It is assumed equal to the concentration determined by the longshore transport. For the Dutch coast, it has been estimated by *Van Goor (2001)*, in a range from 1.2e-4 to 2.4e-4. In the present study 2e-4 is used
n-power	When defining the local equilibrium concentration, this input is needed. Based on a sediment transport formula, it is taken equal to 2 *(Van Goor, 2001)*. We must remind that it is taken positive for dry volumes (i.e. delta, flats) and negative for wet volumes (i.e. channel).
Geometric parameters (A,V)	Initial volumes and horizontal areas of each element are required parameters for running the ASMITA model.
Vertical exchange coefficient (w_s)	This input defines the long-term residual erosion or sedimentation. It represents the net vertical exchange per unit area, per second. Values ranging from 1e-5 to 1e-4 m/s are normally used.
Diffusion coefficient (δ)	The diffusion coefficient gives insight on the sediment exchange capacity between adjacent elements. Values ranging from 500 to 1500 m^3/s are used for the Dutch Wadden inlets.

4 Implementation of ASMITA model imposing the basin area as time-variant

4.1 Introduction

In Chapter 2, the forcing and factors that mainly affect the morphological behaviour of tidal inlet system were presented. As mentioned in there the morphodynamic evolution of the system is carried out as a constant interaction of forcing and morphological changes.

The basin area turns out to be a significant boundary condition in the morphological development of tidal inlet systems, as it influences not simply the geometry of the basin but affect the hydrodynamic conditions (see Chapter 3).

The purpose of this report is to analyse the sensitivity of tidal inlet systems to changes in basin area, in order to evaluate whether it is necessary to couple two adjacent tidal inlet systems when predicting their equilibrium configuration. In this chapter the imposed changes in basin area are illustrated. It should be kept in mind that the fictitious time-variant changes of the area were derived arbitrarily, based on theoretical considerations and on the available field observations.

The aim of the analysis is to draw insights on the time scale of the morphological response of the tidal inlet systems, depending on the initial geometric conditions (viz. the size of the basin) and on the changes imposed (viz. the time scale and the rate of the change).

The long-term morphological response (100 years) is simulated by the ASMITA model, as explained in the following chapter.

4.2 Changes in basin area and ASMITA

As illustrated in Chapter 3 (section 3.4), ASMITA model requires as input parameter, among the others mentioned in there, the areas of the elements constituent the system. In the ASMITA original formulation the area of each element was considered time invariant and therefore acting as fixed boundary condition in the morphological development of tidal inlet systems.

According to ASMITA approach, the morphodynamic evolution of the system is schematised as follows in the flow chart:

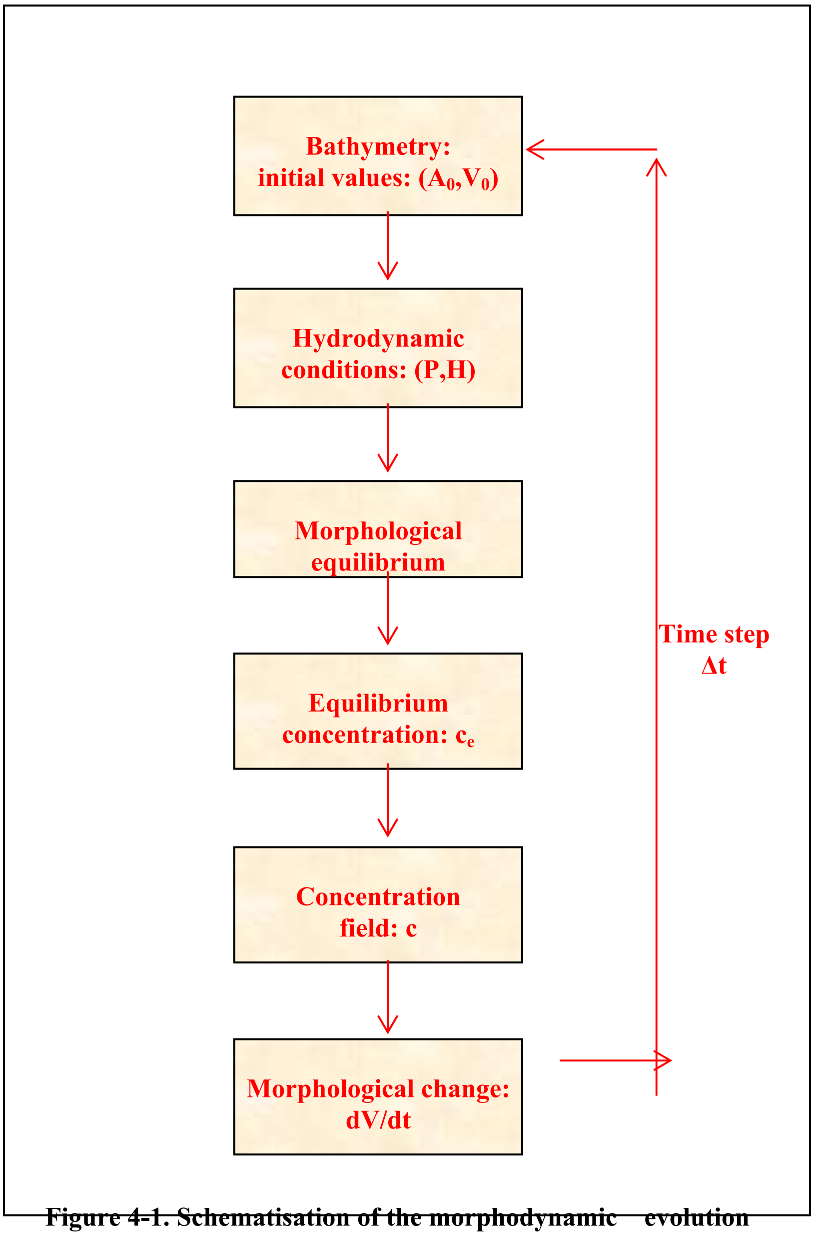


Figure 4-1. Schematisation of the morphodynamic evolution in ASMITA

As show above, in ASMITA approach, the morphological change of the system is supposed to occur as a variation of the initial volume of the elements and no change in the area is taken into account.

$$A_b = A_f + A_c = \text{const.} \tag{4.1}$$

On the other hand, as explained in the foregoing sections, the area of the basin play an important role in the hydrodynamic conditions, as it rules the water volume that can enter through the inlet.

In order to assess the influence of the basin area on the morphological evolution of tidal inlet systems, changes in basin area are imposed to the system and taken as time-variant:

$$A_b = A_f + A_c = A_b(t) \rightarrow \frac{dA_b}{dt} \neq 0 \tag{4.2}$$

where: A_f = Flat area between MHW and MLW (m^2)
A_b = Total area of the basin at MHW (m^2)
A_c = Channel area (m^2)
t = Time (s)

Since the basin area is calculated in ASMITA as the sum of the flat area and the channel area, the change in the area can be ascribed to a combination of relative change in the flat area and in the channel area. For sake of simplicity, only two possible combination were considered:

- $A_c / A_f = \text{const.} \rightarrow$ The change of basin area results from the same increase/decrease in flat area and channel area;
- $A_c = \text{const.} \rightarrow$ The change of basin area results from increase/decrease of the flat area.

In addition, possible insights on the influence of the channel area on the morphological evolution of tidal inlet system can be drawn, if significant changes in the time-scale of the system response are observed.

Thus, when looking at the flow chart, it has to be considered that, besides the simulated morphological change of the volume of the element (i.e. the state variable describing the morphodynamic evolution of the system in the aggregated scale perspective), also the imposed change in basin area will contribute to modify the initial conditions at every time-step.

Aiming to evaluate how sensitive is the system to such a phenomenon, three different scenarios, that can describe natural processes as well as mankind interventions, are chosen.

4.3 Different scenarios

4.3.1 Introduction

In the present section the selected scenarios, differentiated by distinct possible trends in time of the basin area, are presented. The area development towards a new final value is described by a mathematical formulation, in which the required parameters are related to the **time-scale** (viz. the characteristic time for adaptation), and the **initial** (A_0) and final values (A_f).

Aiming to describe possible modification of the size of the basin due to natural phenomena an **exponential** (section 4.3.2) and **oscillating** (section 4.3.3) trend are chosen, whereas a **third grade polynomial** (section 4.3.4) function is chosen to dissimulate the abrupt change due to mankind interventions.

4.3.2 First scenario: Exponential change

Mathematical formulation

As a first possible scenario, an exponential function is taken, aiming to describe natural processes leading to changes in basin area. The required parameters in the function are the morphological time-scale of the process and the initial and final values of basin area. The expression for a gradual increase holds as follows:

$$A_b(t) = A_{b0} + (A_{bf} - A_{b0}) \cdot (1 - e^{-\lambda \cdot (t - t_0)}) \tag{4.3}$$

herein: $A_b(t)$ = Total area of the basin at MHW, as function of time (m^2)
A_{b0} = Initial value of the basin area (t=0) (m^2)
A_{bf} = Final value of the basin area ($t=\infty$) (m^2)
t = Time (s)
t_0 = Start time, set equal to zero (s)
λ =$1/\tau$ being τ, the characteristic time-scale of the process (s^{-1})

$$\tau = \frac{A_{bf} - A_{b0}}{\Delta A_{b0}}, \text{ in which } \Delta A_{b0} = \text{initial adaptation rate.}$$

The above illustrated function is shown graphically in Figure 4.2:

Insert exp. function

As the aim of this report is to investigate the mutual interaction of two adjacent tidal inlets, for a gradual decrease applies the same morphological development.

$$A_b(t) = A_{bf} + (A_{b0} - A_{bf}) \cdot e^{-\lambda(t-t_0)} \tag{4.4}$$

This expression is shown graphically in Figure 4.3.

Insert chart

Physical explanation

In nature the changes in basin area can be ascribed to different processes, characterised by slow and gradual alterations of the actual conditions. When considering a natural increasing/decreasing of the basin area it is reasonable to relate the phenomenon to the following processes:

- variations of weather climate
- gradual migration of barrier islands
- accretion of new land

How the mentioned processes can affect the area of the basin is outlined in the following sections.

Variations of weather climate

In broad lines the sediment transport pattern is determined by the local tidal prism that moves sediment in and out of the basin and the sediment content of the water. Within the Wadden Sea, the sediment content varies from the inlet towards the mainland coast and the tidal divide, exhibiting a gradient in the fine-grained content of the water. The closer to the mainland coast and the tidal divide the higher the fine-grained sand and silt content. The spatial gradient in sediment composition within the tidal basin is explained by the difference in flow velocities, and therefore the different sand transport capacity within the basin. High flow velocity in correspondence of the basin throat can move coarser sediment, whereas the reduced velocity on the flats area moves back and forth fine-grained and silt.

According to *Postma (1961)*, changes in weather climate (viz. wave and wind climate) can play a significant role in sediment contents on the tidal flats. As illustrated in Chapter 2, wind generates shear stress at the water surface, causing drift currents and wind waves. The effect of wind on the flow pattern is very complicated, as it depends on the local water depth and on the wind direction and velocity.

In general, it can be consider that, depending on the actual weather climate, the above mentioned gradients in sediment content can change position, due to the changing flow velocity and pattern.

With increasing wind speed also the flow turbulence level in the water will increase due to wind drift currents and spilling and breaking waves. As shown by many investigators, the sediment content in the Wadden Sea increases as well. *Reineck (1978)* observed that the silt content can range from 100 mg/l during calm water to 300 mg/l during storm surges. *Kamps (1962)* investigated the influence on wind direction (Figure 4.1) and velocity (Figure 4.2) on the sediment content of the water near landreclamtion work at Julianapolder and Westpolder. Thus, as shown in figures below the sediment content on tidal flats and shallow areas is likely to be modified by wind climate.

Insert pictures from ISOS* 2, phase 4

According to *Eysink (1993),* the sediment transport mechanism will then be affected by the "settling lag" and "scour lag". Practically settling of fine sediments occurs at lower flow velocities than erosion. This result in different location, within a water body, for particular sediment grains to erode or settle (scour lag). Besides, suspended sediment needs time to reach the bed, after the flow velocity drops below a critical flow velocity for sedimentation (settling lag). If the flow velocity and the water depth decrease in landward direction, a net landward sediment movement occurs.

The combination of the processes described above could lead to gradual and progressive enlargement or reduction of the basin area along landward boundaries and low energy areas (low flow velocities and low wave action) likewise the tidal divide.

Gradual migration of barrier islands

The barrier islands are strongly interrelated with the morphological development of the Wadden Sea, as they represent the closest source of sediment for tidal inlet system, when extra sedimentation is needed to balance disturbance on the previous equilibrium configuration (i.e. to compensate the sea level rising)

When considering the morphological evolution of the barrier islands it can be observed that erosion occurred at the seaside coast, causing, in general, a slowly progressive migration of the island landward and eastward. As shown in Figure 4.3, the retreat of the coastline does not occur at a constant rate, but is likely to undergo to large long-term and short-term fluctuations, related to the dynamics of the channels and shoals of the backbarrier area (viz. the tidal basin).

Insert figure of Vlie

The erosion of the coastline is nowadays controlled by human intervention, such as groynes, bed protection and beach nourishment.

Yet, the unprotected coastline can still shift as a result of a complex interaction between tides and waves, which deposit and remove sediment along the coast and via the tidal inlets. In Figure 4.4, the dynamic shit at the inlet of Ameland is shown.

Insert figure of Amelander

The retreat of the barrier islands, and their associated migration, could lead to a transient change in the basin area.

Accretion of new land

Along the mainland coast, the sheltered and hydrodynamically calm environment can provide the conditions for siltation (i.e. deposition of fine sand and sand), if an adequate supply of sediment is available. According to Eysink (1993), the deposition can be explained by a number of processes that enhance the phenomenon, such as:

- flocculation of clay minerals;
- coagulation of silt and clay by shellfish
- fixation of silt to bed by slime and diatoms
- reduction of flow and wave action by vegetation or landreclamation works.

Since these processes either increase the fall velocity of silt or reduce the energy level, they result in better conditions for deposition of sand and clay particles.

The natural accretion of new land can be considered as one of the cause for natural reduction of the basin area.

4.3.2 Second scenario: Oscillating change

When considering

5 Analysis of the long-term morphological response of tidal inlet systems

5.1 Introduction

In the previous chapter, different scenarios of changes in basin area were defined. As illustrated in there, three possible trends of the area change are considered in order to investigate the effects of a time-variant basin area on the long-term morphological development of tidal inlet systems.

In the present chapter the long-term morphological response of tidal inlet systems under changes in basin area is examined using the behaviour oriented model ASMITA, implemented as specified in the foregoing chapter. The model is run for different morphometric conditions of two different tidal inlet systems, aiming to draw insights on the time-scale of the morphological response depending on the initial geometric conditions (viz. the size of the basin) and on the changes imposed (viz. magnitude and the rate of the change).

On the basis of the results gained by *Van Goor (2001)* on the relevance of the initial topographic extension of the tidal basins on their morphological time-scale, the analysis is carried out on two tidal inlet systems of the Dutch Wadden Sea characterised by basin areas different in size. It should be noted that both systems are characterised by basin length small compared to the tidal wave length. That is a basic requirement for application of the mentioned model. The selected tidal systems are pictured hereafter.

In chapters 2 and 3, the tidal prism was pointed out to be one of the key forcing behind the morphological evolution of tidal inlet systems. When changing the basin area, the tidal prism changes consequently. Therefore, in order to better understand the volumetric changes of the system's elements considered in our analysis (delta, channel, and flat area), the evolution of the tidal prism simulated by ASMITA is also presented. It has to be considered that, according to the chosen approach, the tidal prism is assumed to change with the basin area, whereas the tidal range is considered time invariant.

5.2 Tidal inlet systems of the Dutch Wadden Sea: selection of the study-cases

The Dutch Wadden Sea is formed by ten tidal basins, characterised by different size, tidal prism, and mean tidal range. Data available on the Dutch tidal basins are gathered in table 5.1 below *(Eysink, 1993)*:

Table 5.1. Characteristic data of the Dutch Wadden basins *(Eysink, 1993)*

Basin	Basin data			Mean tidal data	
	Ab (km^2)	Af/Ab (%)	L(km)	P (10^6 m^3)	Δh (m)
Marsdiep	656	19.5	65	1015	1.65
Eijerlandse Gat	161	61.5	16	205	1.65
Vlie	719	45	26	1190	2
Borndiep	269	63	30	475	2.15
Pinkegat	52	75	7.5	80	2.15
Zoutkamperlaag	123	74	21	195	2.25
Eilanderbalg	35	75	10	48	2.4
Lauwers	128	67	20	210	2.45
Schild	31	72	10	42	2.45
Westerems	467	43	45	1095	2.7

According to the purpose of the present study, Vlie and Borndiep are chosen to carry out the analysis on the influence of basin area on the morphological evolution of tidal inlet systems. Indeed, the two basins agree to the peculiarities required for the present study:

- the initial size of the basin area is different being one rather larger than the other. It is thus possible to gain insight into the dependence of the time-scale on the size of the basin;
- the two basins lie adjacently to one other. It is possible to relate the morphological evolution of one system to the other;
- the intertidal areas of the basins have different extension, being smaller for the basin with larger tidal prism (Vlie). Larger basins have a greater drainage capacity, and the channel area is then larger than the flat area. This leads to analysing the influence of the channel area on the time-scale, for two different situations(i.e. a channel area relatively small and a channel area comparable with the flat area);
- the basin length of both basins is small compared to the wave length. ASMITA model is thus applicable to the two cases.

Besides the tidal range specified for each basin in the table above (5.1), the required parameters for the model, as mentioned in chapter 3 (see section 3.4), are the initial geometric conditions (V_0, initial volume, and A_0, initial area) of each element, the vertical exchange (w_s) and the diffusion exchange coefficients (δ), and the global equilibrium concentration (c_E). In this study case the parameters for both inlets were derived from *Biegel and Eysink (1992)*, *Kragtwijk (2001)*, and *Van Goor (2001).*

Vlie

Vlie inlet lies between the barrier islands of Vlie and Terschelling. The characteristic morphology of this tidal system can be observed from the digitised map (Figure 5.1).

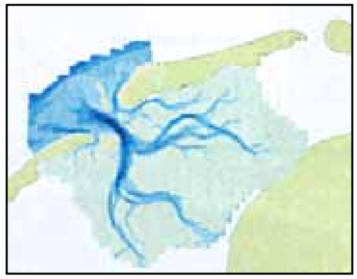


Figure 5-1.Digitised map of Vlie, 1982 (*Rijskinstituut voor Kunst en Zee/RIKZ, 2001*).

As inital values for ASMITA computations, we refer to the values used by *Kragtwijk (2001)* in the model calibration, which were derived from the available bathymetric data of *Biegel and Eysink (1992).* The parameters set in the model are presented in Table 5.2, below.

Table 5.2. Input parameters for Vlie *(Kragtwijk, 2001)*

Element	A_0 (10^8 m^2)	V_0 (10^8 m^3)	w_s (10^{-4} m/s)	δ (m^3/s)	c_E (-)
Ebb-tidal delta	1.70	3.6	1	δ_{do}=1770	2e-4
Channel	4.80	13.5	1	δ_{dc} =2560	
Flat	2.80	1.31	1	δ_{fc} =1300	

It should be noted that the diffusion exchange coefficients were derived from *Kragtwijk,* by scaling the values of the coefficients found by *Van Goor* from the field data on the Zoutkamperlaag. The diffusion coefficients originate from the mass-balance equation and represent the tide-averaged residual sediment transport between two adjacent elements, which takes place through a certain cross section and over a certain length. It can be expressed as follows:

$$\delta = \frac{DA_c}{L} \tag{5.1}$$

where: δ = Diffusion coefficient [m^3/s]
D = Dispersion coefficient [m^2/s]
A_c = Cross-section where the sediment exchange takes place [m^2]
L = Length over which the sediment transport takes place [m]

Assuming that the dispersion coefficient doesn't vary substantially in the Wadden Sea, the coefficients were scaled with Ac/L. As a representative length-scale, *Kragtwijk* used the square root of the basin area for the exchange between the delta and the channel, whereas for the exchange between the delta and the outside world the delta area was used. For the exchange between the channel and the flats, the scale factor is related to the wet volume measured between the average level of the flats and mean high water.

Borndiep

The inlet of Bordiep lies between the barrier islands of Terschelling and Amelander. In Figure 5.2 it can be found the characteristic morphological features of this tidal system, adjacent to Vlie.

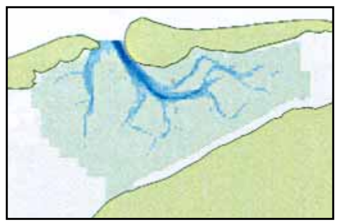


Figure 5-2.Digitised map of Borndiep, 1984 (*Rijskinstituut voor Kunst en Zee/RIKZ, 2001).*

The input data for Borndiep are the ones used by *Van Goor (2001)*, and are illustrated below in Table 5.3

Table 5.3. Input parameters for Borndiep *(Van Goor, 2001)*

Element	A_0 (10^7 m^2)	V_0 (10^8 m^3)	w_s (10^{-4} m/s)	δ (m^3/s)	c_E (-)
Ebb-tidal delta	7.47	1.31	0.1	δ_{do}=1500	2e-4
Channel	9.87	3.02	0.5	δ_{dc}=1500	
Flat	17.80	1.2	1	δ_{fc}=1000	

During the last century, the selected basins were affected by human activities that changed the Wadden Sea morphology drastically (viz. the closure of the Zuider Sea and of the Lauwers Sea). Therefore, it is not likely that the two inlet systems are at present in a state of equilibrium. Yet, equilibrium should be the starting point of our model simulations, as we want to isolate the influence of changing the basin area. In view of that, we have used ASMITA to estimate the equilibrium that the tidal inlet systems evolve towards if the present forcing remains unchanged. The morphological evolution towards the equilibrium is shown in Figure 5.3

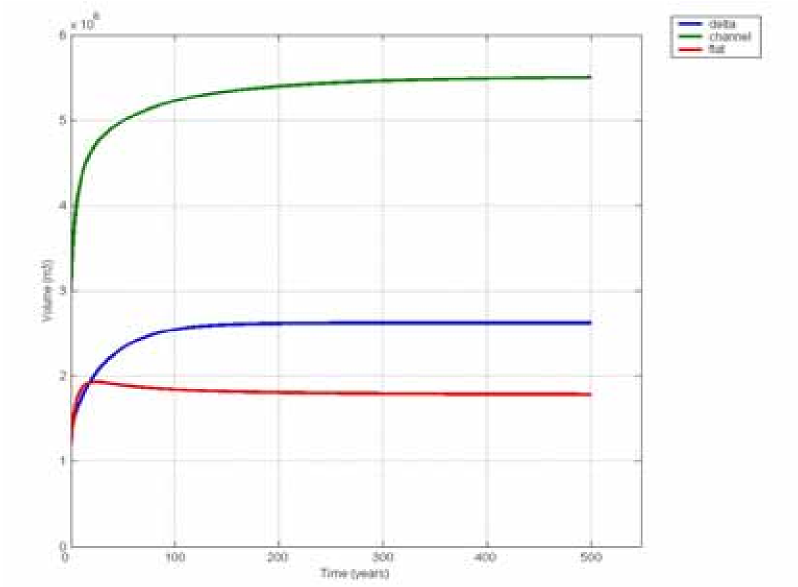


Figure 5-3a). Morphological evolution of Borndiep

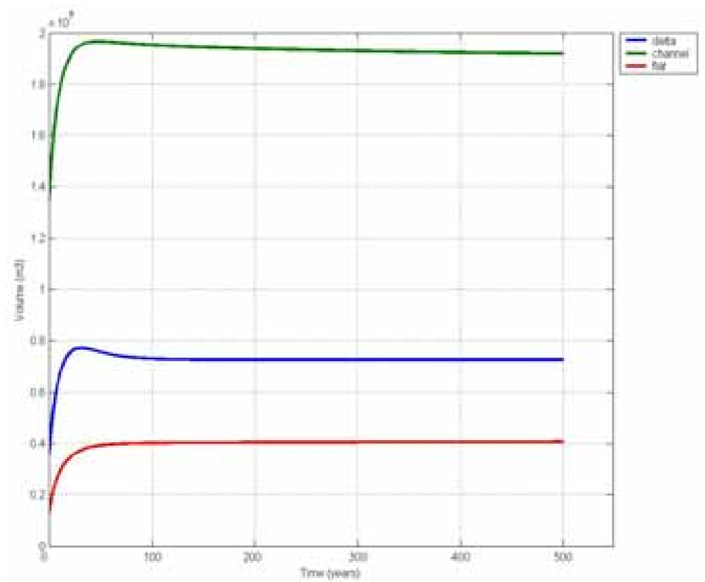


Figure 5-3b). Morphological evolution of Vlie

In Appendix C, the simulated volumetric values of the elements used for the present analysis are presented.

5.3 Changes in tidal prism

According to the literature referred to in observed in the foregoing chapters, the tidal prism is one of the key forcing behind the morphological development of tidal inlet systems. When changing the basin area with time, a consequent change is experienced by the tidal prism. Therefore the equilibrium between the hydrodynamic conditions and the morphology of the system is disrupted. The system is out of balance and evolves toward a 'new' equilibrium configuration by importing (exporting) sediment from the outside world and by redistributing sediment within the system.

Referring to the empirical equilibrium equations reported in chapter 3, it can be observed that the equilibrium volumes of the channel and the delta are directly related to the tidal prism, whereas the flat volume is related to the basin area and the tidal range. For short basins, considered in the present study, the tidal prism can be expressed by the equation illustrated in chapter 3 (equation 3.7)

In Appendix E, the tidal prism development simulated by ASMITA for the different scenarios considered is gathered. When looking at the simulated trend it can be observed that the tidal prism follows the basin area evolution when it is gradually increasing (decreasing) likewise the exponential function, as well as when the size of the area is oscillating.

On the other hand, when the area exhibits an abrupt change, like in the third scenario considered, the tidal prism firstly follows the sudden change in basin area, but then it keeps on evolving towards the equilibrium value, though the area size is constant. Since the tidal range was considered time-invariant, the continuos adjustment of the flat volume (see equation 3.7) can explain the development of the tidal prism, when the basin area is changed abruptly.

In the following section, the long-term morphological response of Vlie and Borndiep for the different scenarios is simulated and analysed, on the basis of the considerations above.

5.4 ASMITA runs

5.4.1 Introduction

The long-term morphological response of Vlie and Borndiep when undergoing to changes in basin area is analysed hereafter for the scenarios illustrated in chapter 4.

As mentioned there, the aim of the study is to predict and evaluate how the changes in basin area can affect the long-term morphological evolution, in order to determine whether it is feasible to investigate the interaction of two different basins.

The analysis focuses on the time-scale of the response of both systems for the three scenarios pointed out. Indeed, when finding rather different time-scales, it can be argued that the evolution of the faster system will take place at the expenses of the other. As a result of this joint evolution the tidal divede can shift towards either one or the other basin.

It has to be reminded that the analysis is carried out on a macro-scale, as it predicts the long-term morphological evolution. The volumes of the elements considered (i.e. outer delta, channel, and flat area) are simulated and no definite description of the effective local sediment transport pattern is gained.

5.4.2 First scenario: Asymptotic change

The first scenario simulates a natural change of the basin area that takes place gradually and slowly, following an exponential trend. Based on field observations available (see Appendix F), the imposed change in channel and flat areas (i.e. basin area) was ranged from 1% to 5% of the initial values. Two different combination of change in basin area were considered, viz. Ac/Af=constant and Ac=constant. The observed differences for the two situation considered are furthe explained in section 5.6.3.
As a characteristic time scale of the processes, values of 10 and 20 years were taken.

In Figure 5.4, the morphological evolution for a gradual increase of the area up to 5% of the initial value is shown, for Borndiep (5.4a) and Vlie (5.4b). The characteristic time-scale of the imposed change is set to 20 years.

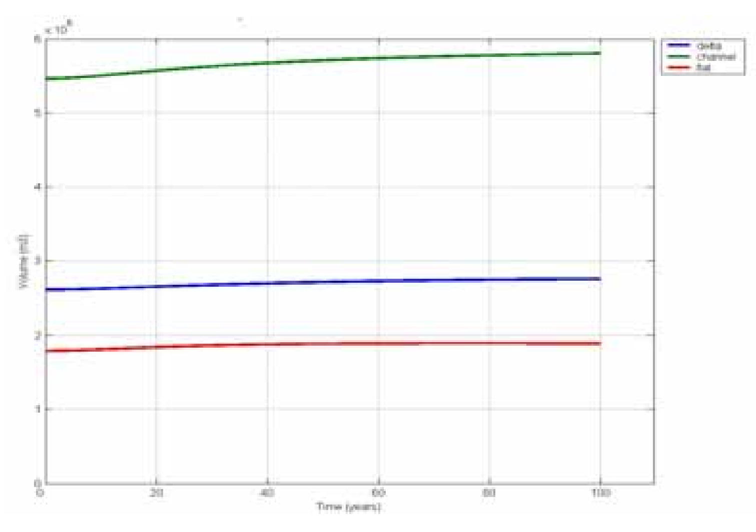


Figure 5-4a). Morphological evolution of the elements (Borndiep)

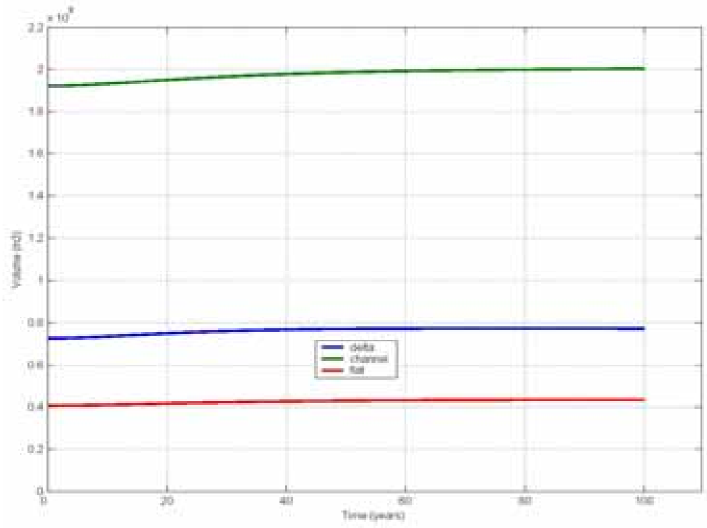


Figure 5-4b). Morphological evolution of the elements

As it can be observed from the simulated morphological evolution, the elements scarcely change, despite their gradual increase (decrease) in size. The elements follow the change in basin area, likewise the tidal prism.

This can be explained considering that the morphological evolution of the elements in ASMITA takes place asymptotically, having an exponential character:

$$(V\text{-}V_e) = (V_0\text{-}V_e) \cdot e^{\left(-\frac{t}{\tau}\right)} \tag{5.1}$$

in which: V = volume as function of time
V_0 = initial volume
V_e = equilibrium volume
t = time
τ = morphological time-scale, expressed as

$$\tau = \left| \frac{V_0\text{-}V_e}{\Delta V_0} \right|$$, being the ΔV_0 initial adaptation rate.

In ASMITA, the morphological time-scale τ for a system consisting of three elements is not explicitly expressed. Nevertheless, it can be derived for a single element system, in order to gain insight into the order of magnitude. For a single element system (i.e. the channel connected with a boundary with a constant sediment concentration c_E) it can be derived as follows.

The mass-balance equation reads:

$$w_s \cdot A_c \cdot (c_{ce} - c_c) = \delta_{co} \cdot (c_c - c_E) \tag{5.2}$$

The actual concentration can be then expressed:

$$c_c = \frac{\delta_{co} \cdot c_e + w_s \cdot A_c \cdot c_e}{\delta_{co} + w_s \cdot A_c} \tag{5.3}$$

Substituting the actual concentration and the equilibrium concentration (equation 3.1) in the equation for the morphological change

$$\frac{dV_c}{dt} = w_s \cdot A_c \cdot (c_{ce} - c_c) \tag{5.4}$$

yields to the following expression:

$$\frac{dVc}{dt} = \frac{\delta_{co} \cdot w_s \cdot A_c \cdot c_E}{\delta_{co} + w_s A_c} \left[\left(\frac{V_{ce}}{V_c} \right)^n - 1 \right] \tag{5.5}$$

Linearising the non-linear equation around the equilibrium value by a Taylor series expansion and neglecting terms of higher order, it yields to:

$$\frac{dV'}{dt} = \frac{\delta_{co} \cdot w_s \cdot A_c \cdot c_E}{\delta_{co} + w_s A_c \cdot V_{ce}} \cdot V' \tag{5.6}$$

where $V' = V_c - V_{ce}$ is the disturbance from the equilibrium value.

The solution of the equation is:

$$V' = V_0' \cdot e^{\left(-\frac{t}{\tau}\right)} \tag{5.7}$$

herein $V'_0 = V_{c0} - V_{ce}$ is the disturbance for t=0,

$$\tau = \frac{1}{c_E n} \cdot \left(\frac{V_{ce}}{w_s \cdot A_c} + \frac{V_{ce}}{\delta_{co}} \right) \tag{5.8}$$

is the time-scale.

The equilibrium volumes of Vlie and Borndiep can be calculated by deriving the equilibrium tidal prism from ASMITA equation (3.7), taking the equilibrium volume of the flat as given from the equation 3.12. Consequently the equilibrium volume is calculated on the basis of the empirical equation that relates the volume of the channel to the tidal prism (equation 3.8). For a fixed area and for the exchange coefficients illustrated above, it turns out that the characteristic time-scales are respectively 63 years and 38 years.

The values found are broadly representative for the time-scale of the three elements system. Nonetheless, they bring out insights on the relevance of the initial size and on the order of magnitude (decades). The adaptive behaviour of the elements and the time-scale comparable with the time-scale of the process affecting the area, can be an explanation of the limited influence of a gradual change on the morphology of the systems. Furthermore, the character of the disturbance, taken as a temporal change that approches asympotically a maximum, can also be an explanation.

5.4.3 Second scenario: Periodic change

The second scenario considers an oscillating change of the basin area due to fluctuations of the weather climate. The imposed change in channel and flat areas (i.e.basin area) was again ranging from 1% to 5% of the initial values. A characteristic period of 50 years for the in basin area was taken, whereas the phase lag was set to 20 years.

In Figure 5.5, the morphological evolution for an oscillation of the area up to 5% of the initial value is shown, for Borndiep (5.5a) and Vlie (5.5b). The characteristic period is set to 50 years.

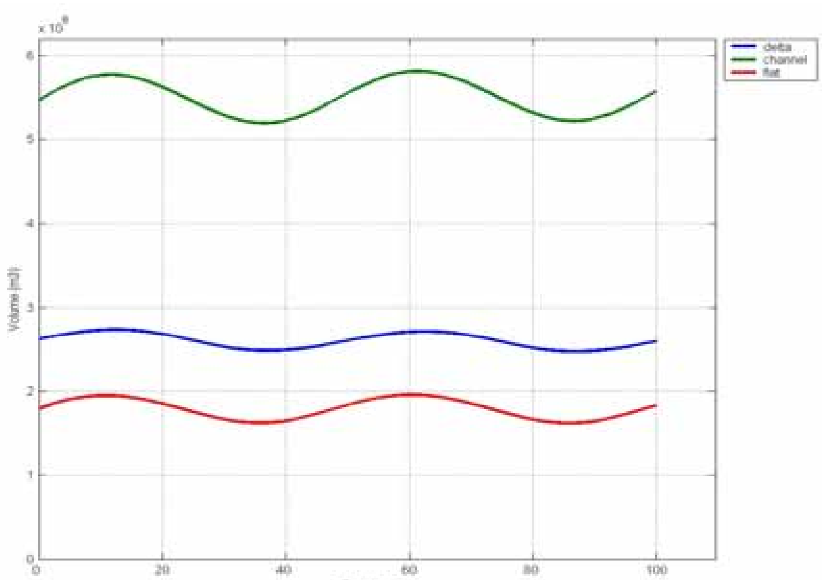


Figure 5-5a). Morphological evolution of the elements (Borndiep)

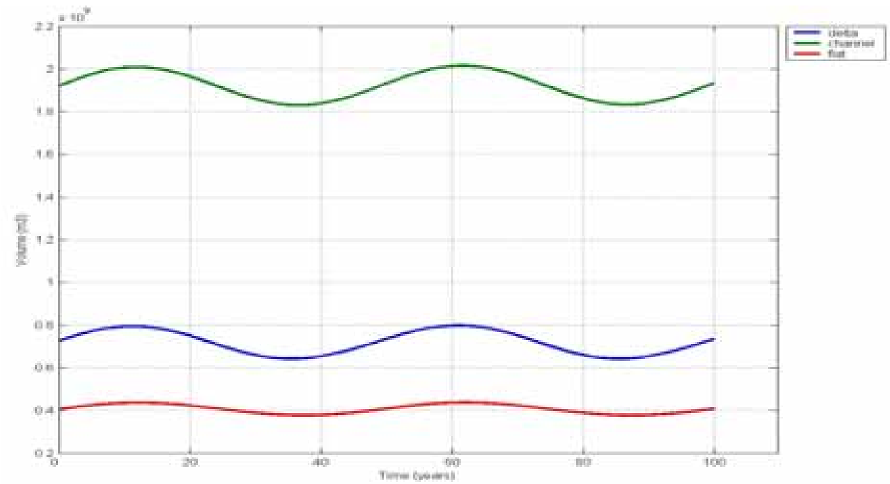


Figure 5-5b). Morphological evolution of the elements (Vlie)

The elements, likewise the tidal prism, evolve following the oscillating character of the basin area. The long-term response is thus scarcely affected by a gradual change due to fluctuations in weather climate, as the system is able to adapt itself to the imposed variations. This is also confirmed considering the time-lag between the imposed change and the response of the system, the phase-lag of the morphological response is observed to deviates for few years (approximately 5) from the phase-lag of the imposed change.

5.4.4 Third scenario: Abrupt change

When considering an abrupt change of the basin area, we now refer to a mankind intervention. The basin area is increased (decreased) in a range from 10% to 50% of the initial value. In order to monitor the influence of the channel area, the change in basin area is taken as resulting from the same increase (decrease) of the channel and the flat area (A_c/A_f constant), or as resulting from the variation of the flat area (A_c constant).
As a characteristic time-scale of the process, the time in which the abrupt change takes place (t_1-t_2) was considered. Since the enlargement (reduction) of the basin is though as resulting from human activities, it seemed reasonable to chose values of 2-5 years.

The morphological evolution of the elements when experiencing an abrupt increase of 50% of the initial basin area within five years is shown in Figure 5.6.

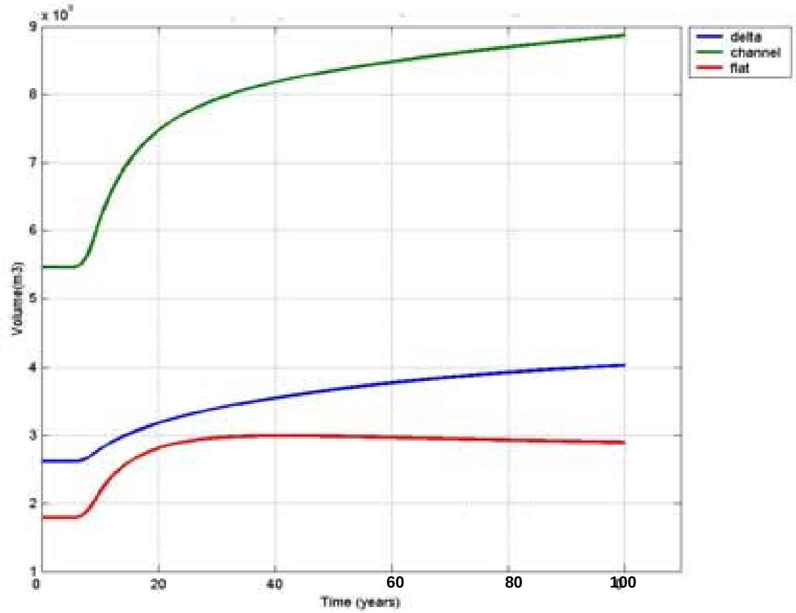


Figure 5-6a). Morphological evolution of the elements (Borndiep)

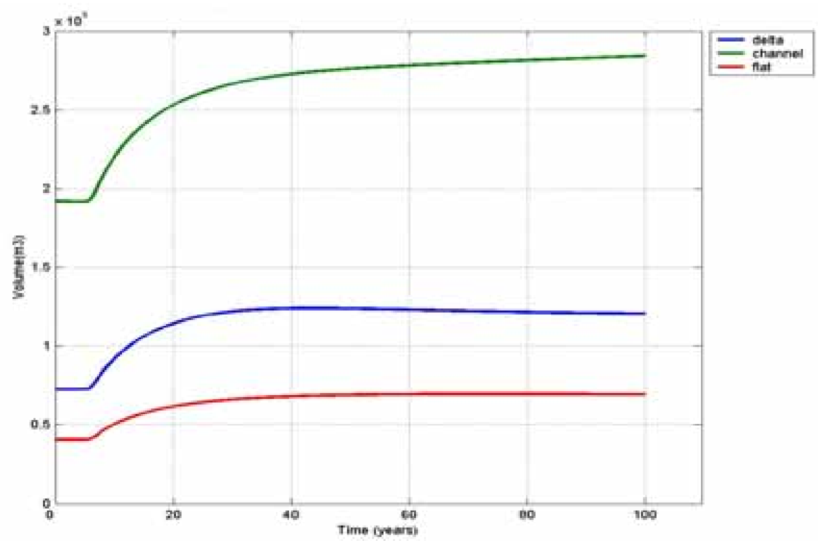


Figure 5-6b). Morphological evolution of the elements (Vlie)

Sudden change of the basin area (e.g. due to re-opening or damming part of the basin) induces, as can be observed in Figure 5.6, significant volumetric changes of the elements of both systems. The disturbance of the system seems to affect its morphological development, even many years after the re-opening of the enclosure work is completed.

This can be explained, considering the consequent abrupt and considerable change induced in the tidal prism (see section 5.3).

Indeed, the dynamic equilibrium holding between the hydrodynamic conditions and the dimensions of the system is drastically disrupted.

To cope with a new amount of water that is now able to enter the basin, the flat needs to increase considerably as its actual volume deviates from the equilibrium one. Due to the intervention the delta and the channel want to grow as well as their volume is relatively to small compared with the new hydrodynamic conditions (see equations 3.7 and 3.8, empirical relation between, respectively, the delta and the tidal prism and the channel and the tidal prism). From the computational results, it follows that the delat grows towards a new equilibrium, but not at the expenses of the two elements. Comparing the initial volume with the equilibrium volume of the channel (calculated as illustrated in section 5.4.2), it can be observed that it increased by 62% in Borndiep and by 83% in Vlie. As the area of the channel was, in both cases, increased by 50%, it can be concluded that the channel erodes. The sediment available may will be used to satisfy part of the need for sediment in the delta and flat. Import of sediment from the outside world via delta and channel, may provide what the flat needs more than can be provided by the eroding channel.

In the case of Borndiep, the erosion process in the channel is so noticeable that the flat exhibits an overshoot that reaches a maximum some 35 to 40 years after the start of the basin enlargment.

As illustrated above, the tidal systems endeavour to restore their morphodynamic equilibrium by a complex interaction of the elements that exchange sediment with the outside world and between themselves. The process continues until the size of the elements and the tidal prism are again in equilibrium.

5.4.5 Conclusions on the analysis of the long-term morphological evolution in response to changes in basin area

In the previous sections, the long-term morphological response of Vlie and Borndiep to imposed changes in basin area was analysed. In order to better understand the morphological response of the systems, it should be kept in mind that for the different scenarios considered, the imposed changes were relatively different. When dealing with natural variations (scenarios 1 and 2), the imposed change was ranging from 1% to 5% , whereas a considerable change in the size of the basin area was considered in the third scenario (i.e. up to 50%). The morphological response will then depend on the imposed forcing and on its evolution time-scale.

Based on this, it can be observed that a small disturbance (likewise in scenario 1 and 2) that is gradually and slowly (time-scale of 20 years) occurring on the system involves a relatively small morphological variation of the elements. Besides, the time-scale of the morphological response of the system appears to be comparable with the time-scale of the imposed change.

On the other hand, the effect of an abrupt and considerable change in basin area on the system is twofold. Firstly the elements exhibit an important variation in volume, and then the morphological time-scale of the evolution process is not comparable with the time in which the change in basin area takes place (few years). A sudden change of the topographic extension of the basin is likely to involve a strong interaction of the systems.

In the following section, we'll try to derive insights on the time-scales of Vlie and Borndiep, aiming to evaluate whether it is worth to model the systems coupled as a single system.

5.5 Morphological time-scale

5.5.1 Introduction

As mentioned in the foregoing sections, time-scale of the morphological evolution toward the equilibrium is an important parameter in the morphological behaviour of tidal inlet system, when aiming to analyse the interaction of two adjacent basins.

5.5.2 Definition of the time-scales

The time-scales of the processes considered in the analysis (viz. the change in basin area and the morphological response of the system) are simply defined as follows.

The characteristic time-scale of a sudden change of the basin area (third scenario) evolution is taken as the time in which the change is completed: λ= t1-t2 (see Chapter 4). The time-scale is illustrated in Figure 5.7.

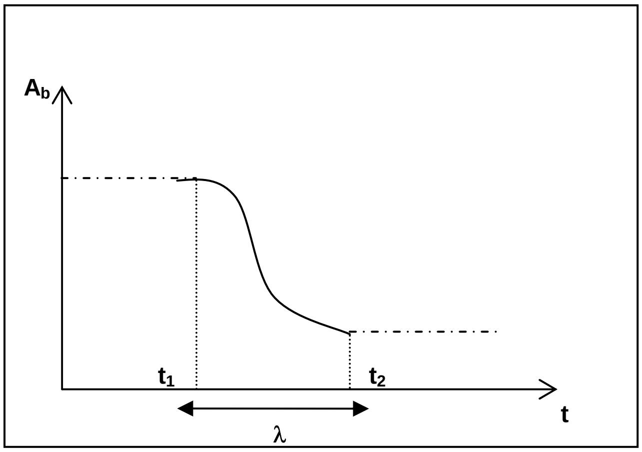


Figure 5-7. Time-scale of the area evolution

In order to define a time-scale of the system response, it is necessary to zoom in the evolution of the individual elements after the perturbation. Assuming that the time-scale of the whole system is determined by the slowest element, it is important to analyse the trend of the elements in order to point out which shows the slowest response.

When considering the evolution of the elements when the basin area is reduced by 50% within 5 years, it is observed that the delta exhibits a rather stable character within approximately 30 years. On the other hand, the flat manifests a non-monotonous behaviour. According to *Kragtwijk (2001)*, the element that overshoots its equilibrium is likely to have the smallest time-scale and, therefore, to be the faster. *Kragtwijk (2001)* investigated the morphological behaviour of two elements (delta and channel) and explained the deviation of one element from its equilibrium value in terms of demand and supply of sediment. In this case, both the channel and the delta want to grow. The delta need sediment to grow whereas the channel produces sediment. The two elements can thus benefit from each others evolution. As soon as one of the element reaches its equilibrium state, this benefit vanishes. From that moment on, the slower of the the two elements will continue its evolution and that may force the other element to overshoot its equilibrium. For instance, if the delta reaches its equilibrium first, it will still need to act a transfer of sediment produced by the channel. This transfer function can be fulfilled only if the delta volume exceeds the equilibrium, otherwise there is no incentive to export sediment to the outside world. Simultaneously, the overshoot hampers diffusive transport of sediment from the channel to the delta. Hence, the overtrat limits its own growth. When the channel is sufficiently close to its equilibrium, the overshoot will fade and the two elements will jointly tend towards their respective equilibrium.

It is the slowest element that dominates the time-scale of the system.

The time-scale is then defined by considering the simulated equilibrium volume of the channel. The equilibrium volume is calculated, again, from the empirical relation used in ASMITA:

$$V_c = \alpha_c \cdot P^{1.55}$$

where the tidal prism P is derived from equation 3.7, being $V_f = V_{fe}$ (A_{bf}, h) calculated from the empirical equation 3.12 in which A_{bf} is the final value of the basin area and h is the tidal range.

The time-scale μ is then taken as the time in which (see Figure 5.8)

$$\left|\frac{V(t)-V_e}{V_0-V_e}\right| = 1/e \tag{5.9}$$

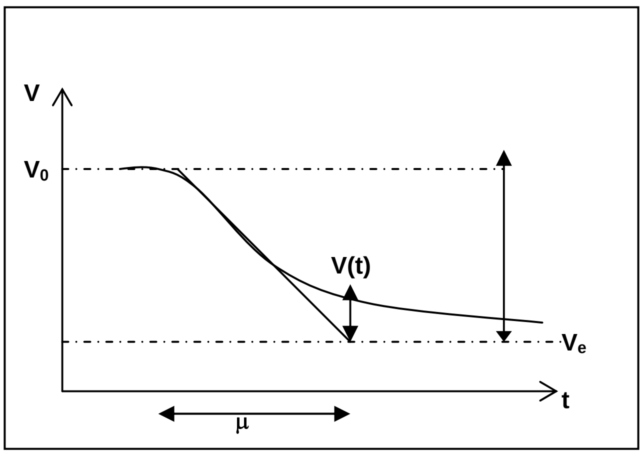


Figure 5-8. Morphological time-scale of the system response

5.6 Sensitivity analysis on system time-scale

The sensitivity analysis on the system time-scale is carried out for Vlie and Borndiep by varying the magnitude and time-scale of the imposed change of the basin area.

If the time-scale of the imposed change in basin area (third scenario) is infinitly small, the response time-scale is determined only by the magnitude of the imposed change. On the other hand, if we introduce the imposed change graduall, we allow the system to start responding before the change is complete. Compared to the immediate change, the actual perturbation will be smaller and hence, the response time-scale will be larger. In other words, increasing the time-scaleof the imposed change will result in an increasing response time-scale. In the extreme case of a very slowly imposed change, the system will follow at negligible distance. In that case, the two time-scales will be almost equal.

It is the aim of the analysis dealt within the present section, to assess exactly this behaviour quantitatively and to evaluate the effect in this respect of the initial size of the basin.

First we will look at the overall behaviour of the system when imposing a basin area of 50% of the original value (see section 5.6.1) and after that we will assess smaller changes as well (see section 5.6.2). Subsequently we will look into the affect of assigning the imposed change to both falt and channel of to flat alone (see section 5.6.3)

5.6.1 Time-scale of the abrupt change in basin area

The results of the sensitivity analysis can be observed in Figure 5.9, for an imposed increase of 50% (see also Appendix H).

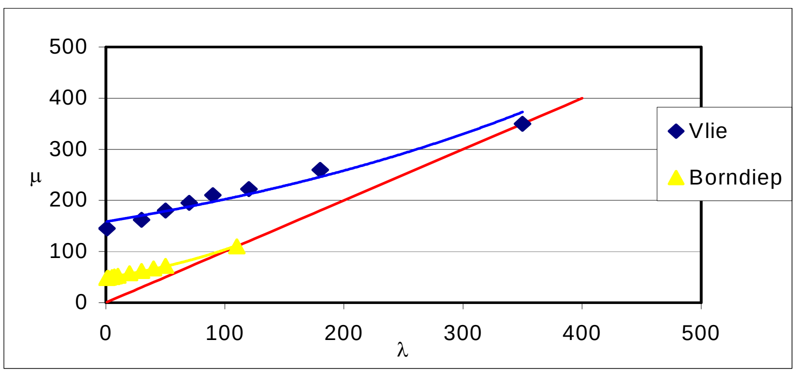
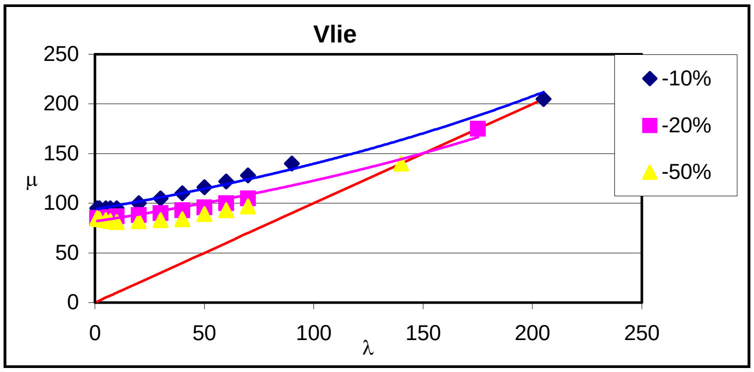


Figure 5.9 Correlation of the morphological time-scale of the system with the time-scale of the area evolution

As expected, the response time-scale increases with increasing the time-scale of imposed change. They tend towards each other asymptotically. The obtained computational results suggest that this asymptotic behaviour scales with the size of the inlet system. The Borndiep is able to keep pace with the imposed change at a far smaller time-scale than Vlie (approximately 110 and 350 years, respectively).

5.6.2 Disturbance on the system

The disturbance imposed on the system is ranged with 10% to 50% of the initial value, considered as enlargement of the area as well as reduction. The time-scale of the system is hereafter related with the magnitude of the perturbation, aiming to assess its influence on the long-term morphological response.
For the basins considered in this report, the total disturbance appears to affect the time-scale differently (see also appendix H).



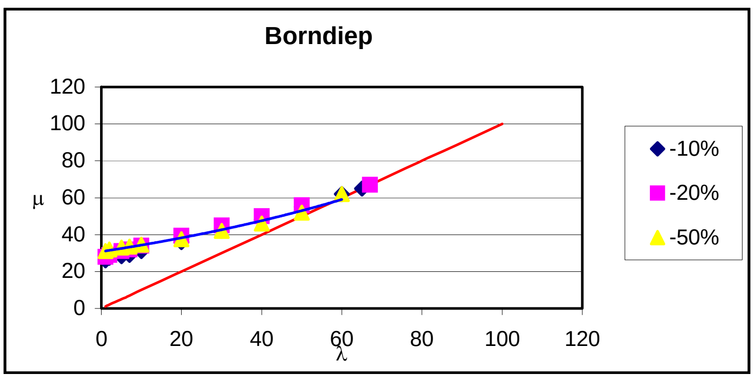


Figure 5.10. Time-scale variation in response of different disturbances

When considering Borndiep, it can be observed that decreasing the basin area from -10% to -50%, hardly affects the response time-scales (the time-scales differ for few years, and are equally affected by an increasing time-scale of the change imposed on the basin area). More significant variations are observed when varying the magnitude of a possible enlargement of the area up to 50%. This behaviour can be interpreted, considering that, when increasing the basin area, the basin turns into a relatively bigger system. The adaptation-time is therefore greater, as it has been observed so far. On the other hand, the slight variations when decreasing the basin area could find a justification on the characteristic time-scales of the Wadden Sea. The values gained with the sensitivity analysis, ranged, for λ=1, from 26 to 30 years. Those values are possibly the characteristic time-scales of macro-scale processes of the Wadden Sea. Analysing the time-scale response of a smaller basin could provide insight into this finding.

Vlie, on the contrary, exhibited a substantial dependence on the magnitude of the disturbance both when increasing the area and when reducing it. The time-scale drops down to 30 years when changing from -10% to -50%, as the system becomes relatively smaller. Likewise, the time-scale varies considerably when increasing the perturbation on the system, as it needs more time to react and adapt itself.

Comparing the results for the systems, the same considerations of the previous section still apply (see section 5.6.1). Besides, depending on the disturbance imposed, it can be observed that the difference in time-scales can result amplified or reduced. Decreasing the size of Vlie leads to curtail the time difference, whereas the opposite trend is observed when increasing its size. Again, this is due to the dimension of the systems.

5.6.3 Influence of the channel area

The influence of the channel area is investigated for Vlie and Borndiep, by keeping it constant, and thus imposing the change in basin area as deriving from a variation of the flat area, or keeping constant the ratio Ac/Af, and thus ascribing the variation of the basin area as derived from a combined perturbation on channel and flat.

The morphological time-scales appear to be differently influenced in the two basins analysed (see Figure 5.11)

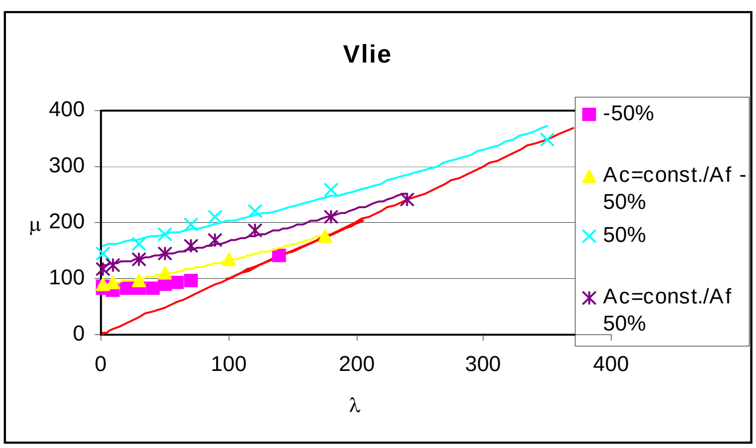


Figure 5-11. Influence of the channel area on the morphological time-scale

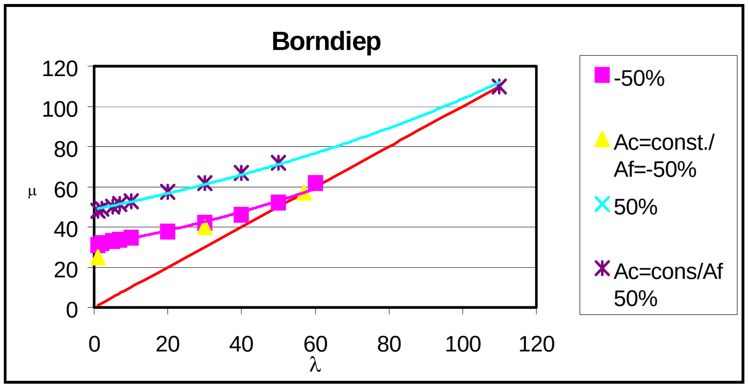


Figure 5.12. Influence of the channel area on the morphological time-scale

Borndiep time-scale seems hardly affected by the area of the channel, either when the basin area (i.e. the flat area) reduces or when it increases, being also independent of the disturbance imposed (see also appendix F). Conversely, when considering Vlie, it can be perceived that the channel area is an important parameter in the morphological response of the system. This is due to the relevant percentage of channel area on the total basin area. The intertidal area (Af/Ab) is 45% and 63% of the basin area, for Vlie and Borndiep respectively. Indeed the initial size of the area plays a substantial role on the reflected disturbance on the tidal prism. The bigger the area of the channel, the bigger its influence on the tidal prism. As a consequence, the influence of the channel area on the morphological time-scale is noticeable for Vlie, whereas it appears negligible for Borndiep.

5.7 Conclusions on the sensitivity analysis

In the foregoing section, a sensitivity analysis on the system time-scale was carried out for two actual basins of the Dutch Wadden Sea. The systems, being different in size, and characterised by different intertidal area, appeared to respond to an abrupt change in basin area with peculiar behaviour.

Apparently, the magnitude of the disturbance had a significant influence on the time-scale of Vlie, both when reflecting an increase or a decrease of the area. Borndiep exhibited a rather constant time-scale when the area decreased, whereas the time-scale was affected when increasing the area. The finding confirmed the relevance of the initial size of the basin and suggested that the analysis should be carried out on a smaller basin, in order to evaluate the comperatively small influence of a decreasing basin area on the morphological response of Borndiep.

The influence of the channel area appeared to be dependent on its relative extension on the total basin area, being greater for bigger areas.

6 Conclusions and Recommendations

6.1 Conclusions

The present research work on the influence of the basin area on the long-term morphological response of tidal inlet systems, led to the following conclusions:

- The long-term morphological response of tidal inlet systems to changes in basin area is modelled with the aggregated scale model ASMITA. As the basin area is taken as time-invariant in the original model formulation, ASMITA was implemented imposing a function that describes the variations of the basin area with time.

- Three different scenarios of possible changes in basin area were considered, aiming to simulate a natural change as well as a human intervention. The selected scenarios are:

1. Exponential change
2. Oscillating change
3. Abrupt change

The basin area is given as the sum of the channel area and the flat area. The imposed change in basin area can thus result from a combination of disturbance on both the elements. In order to investigate the influence of the channel area, two possible situations are assessed:

1. The same variation occurs on the area of the channel and on the area of the flat (A_c / A_f = constant)
2. The variation on the basin area is ascribed to a change of the flat area (A_c=constant)

- When changing the basin area, the main consequence is a similar change of the tidal prism. The latter turned out to be a key forcing behind the morphological evolution of tidal inlet systems. By varying the tidal prism, the equilibrium between the hydrodynamic conditions and the dimensions of the elements is disrupted. The response of the tidal system is then investigated, focusing on the characteristic time-scale of the morphological response.

- The analysis of the morphological response was carried out for two basins of the Dutch Wadden Sea (Vlie and Borndiep), in order to evaluate how the initial size of the basin can affect its time-scale. From the analysis of the response for the mentioned scenarios, it was observed that the system is able to follow the imposed disturbance.

Even in the case of imposing a sudden increase of the basin area with 50%, the considered systems appeared able to find a new equilibrium state.

- The time-scale of the system is not directly expressed in ASMITA. Nevertheless, it is an important parameter of the morphological behaviour of tidal inlet systems under a sudden change of the basin area. In the present study, the time-scale of the channel is taken as the characteristic time-scale of the whole system, as the channel turned out to be the slowest responding element.

- From the sensitivity analysis on the morphological time-scale, it was pointed out that a strong dependence exists on the dimension of the tidal system: the smaller imposed the faster. Moreover, factors like the time-scale of the area evolution, the disturbance on the systems and the initial extension of the area of the channel were observed to play an important role on the morphological time-scale.

6.2 Recommendations

- In the present report, it was assumed that the wave motion of the tidal wave within the basin is not affected by a change in basin area. Nevertheless a considerable increase of the size of the basin could affect the wave propagation and the assumption, behind the expression of the tidal prism, of standing wave could drop drown. It seems reasonable to investigate the tidal wave pattern, in order to verify the validity of the assumption.

- The diffusion coefficients were found to be dependent on the area on which the sediment exchange takes place *(Kragtwijk, 2001)*. In the present report they are assumed to be constant. Yet, they are an important parameter for the morphological behaviour, as they rule the exchange sediment rate with the outside world, and within the system. Further investigations on the variability of the diffusion coefficients are suggested.

- In the present report the coastal stretch is considered independent of the morphological evolution of the tidal inlet systems. It appears realistic, that response of the tidal system to changes in basin area can involve the adjacent coast. In order to better understand the morphological development of tidal inlet system, the interaction with the adjacent coast (barrier islands) should be considered, defining the coast as an element interacting with the other elements of the system.

- The theoretical analysis carried out in the present study should be tested on a real case, in order to calibrate the implemented model. More bathymetrical and tidal data are required for this purpose.

- Finally, the finding on the considerably different time-scales for the basins analysed suggested that, in the case of abrupt change of the basin area, they could mutually interact. Presumably, the faster system could evolve toward the equilibrium at the expense of the other, and thus modify its morphology. The main recommendation for further studies is to extend the morphological modelling to two coupled systems.

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Vriend, H.J. de, Dronkers, J., Stive, M.J.F., Dongeren, A. van., Wang, J.H., 1998, *Coastal inlets and tidal basins*, CTwa5303, Faculty of Civil Engineering and Geosciences, Delft

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Appendices

A ASMITA equations

Appendix A: ASMITA equations

The equations used in the ASMITA model are gathered herein. They hold for each element as follows:

Ebb-tidal delta

Equilibrium volume [m^3]:

$$V_{de} = V_{de}(P) \tag{A1}$$

The morphological change [m^3/year]:

$$\frac{dV_d}{dt} = w_s A_d (c_d - c_{de}) \tag{A2}$$

The local equilibrium concentration [-]:

$$c_{de} = c_E \left(\frac{V_d}{V_{de}} \right)^n \tag{A3}$$

The sediment mass balance, i.e. the morphological change (left hand) equals the residual exchange with the adjacent elements (right hand):

$$w_s A_d (c_{de} - c_d) = \delta_{od}(c_d - c_E) + \delta_{dc}(c_d - c_c) \tag{A4}$$

Channel

Equilibrium volume [m^3]:

$$V_{ce} = V_{ce}(P) \tag{A5}$$

The morphological change [m^3/year]:

$$\frac{dV_c}{dt} = w_s A_c (c_{ce} - c_c) \tag{A6}$$

The local equilibrium concentration [-]

$$c_{ce} = c_E \left(\frac{V_{ce}}{V_c} \right)^n \tag{A7}$$

The sediment mass balance, i.e. the morphological change (left hand) equals the residual exchange with the adjacent elements (right hand):

$$w_s A_c (c_{ce} - c_c) = \delta_{dc} (c_c - c_d) + \delta_{fc} (c_c - c_f) \tag{A8}$$

Flat

Equilibrium volume [m^3]:

$$V_{fe} = V_{fe} (A_b, H) \tag{A9}$$

The morphological change [m3/year]:

$$\frac{dV_f}{dt} = w_s A_f (c_f - c_{fe}) \tag{A10}$$

The local equilibrium concentration [-]

$$c_{fe} = c_E \left(\frac{V_f}{V_{fe}} \right)^n \tag{A11}$$

The sediment mass balance, i.e. the morphological change (left hand) equals the residual exchange with the adjacent elements (right hand):

$$w_s A_f (c_{fe} - c_f) = \delta_{fc} (c_f - c_c) \tag{A12}$$

B Empirical coefficients in the equilibrium equations

Appendix B: Empirical coefficients in the equilibrium equations

The empirical equations for the morphological equilibrium used in the ASMITA model are herein summarised.

Empirical equilibrium equations

- Ebb-tidal delta:

$$V_{de} = \alpha_d \cdot P^{1.23} \tag{B1}$$

where: V_{de} = equilibrium sand volume of the outer delta [m^3]
P = tidal prism [m^3]

- Channel:

$$V_{ce} = \alpha_c \cdot P^{1.55} \tag{B2}$$

where: V_{ce} = equilibrium water volume of the channel [m^3]
P = tidal prism [m^3]

- Flat:

$$V_{fe} = \alpha_{fe} \left(\frac{A_f}{A_b} \right) A_b \cdot H \tag{B3}$$

$$\alpha_{fe} = \alpha_f - 0.24 \cdot 10^{-9} A_b \tag{B4}$$

where: V_{fe} = equilibrium sand volume of the tidal flats [m^3]
H = tidal range [m]
A_b = basin area at MHW [m^2]
A_f = flat area at MLW [m^2]
α_f = empirical coefficient for the average tidal flat level [-]

Empirical coefficients for the Wadden Sea

The empirical coefficients derived for the Wadden Sea from the literature *(Eysink and Biegel, 1992-1993)* are enclosed in table B1:

Table B-1 . Empirical coefficients used in ASMITA

System's elements	Empirical coefficients	
Ebb-tidal delta	α_d	$6.57 \cdot 10^{-3}$
Channel	α_c	$65 \cdot 10^{-6}$
Flat	α_f	0.41

C Input parameters in ASMITA simulations

Appendix C: Input parameters in ASMITA simulations

The data used in ASMITA computations for the present study are derived from *Biegel (1993).* The volumetric data refer to the actual boundaries

Appendix D Evolution of the basin area

Appendix D 1A Asymptotic increase (Borndiep)

Appendix D 1B Asymptotic decrease (Borndiep)

Appendix D 2A Asymptotic increase (Vlie)

Appendix D 2B Asymptotic decrease (Vlie)

Appendix D 3A Periodic change (Borndiep)

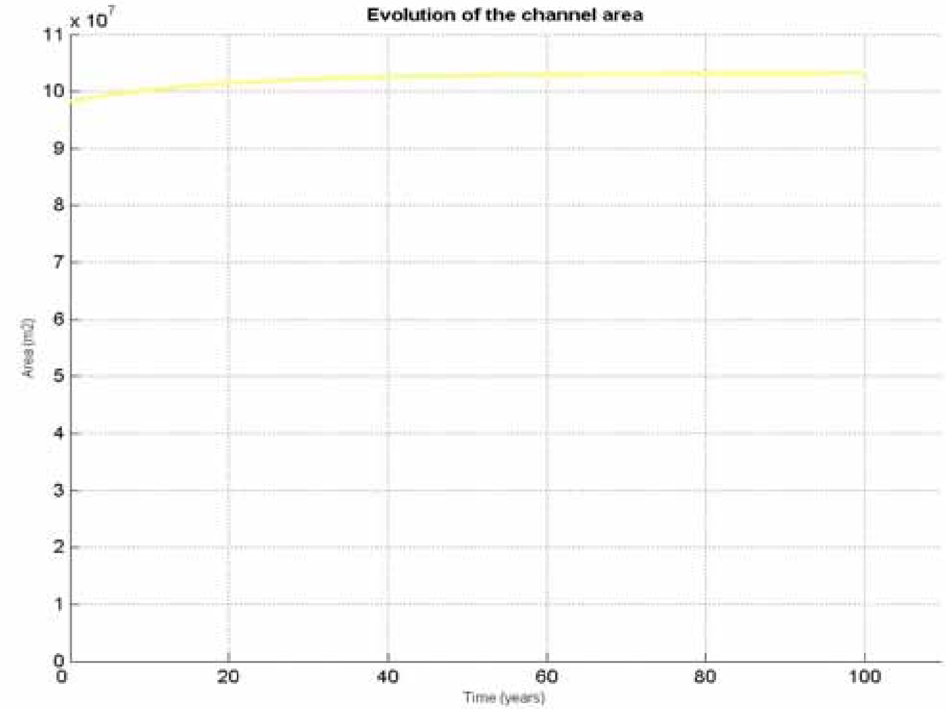
Appendix D 3B Periodic change (Vlie)

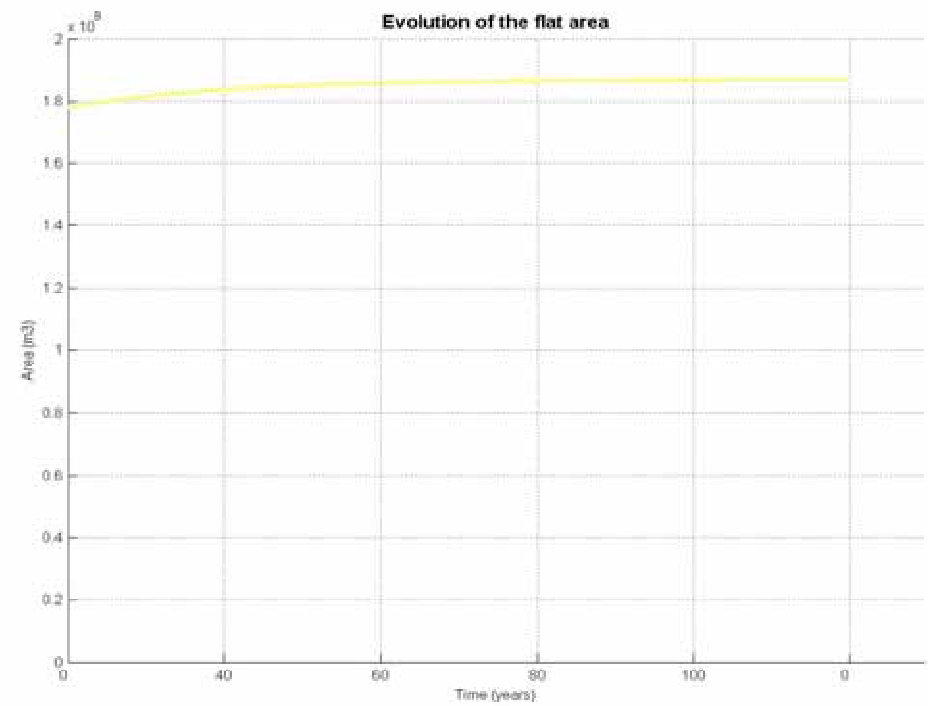
Appendix D 4A Abrupt increase (Borndiep)

Appendix D 4B Abrupt decrease (Borndiep)

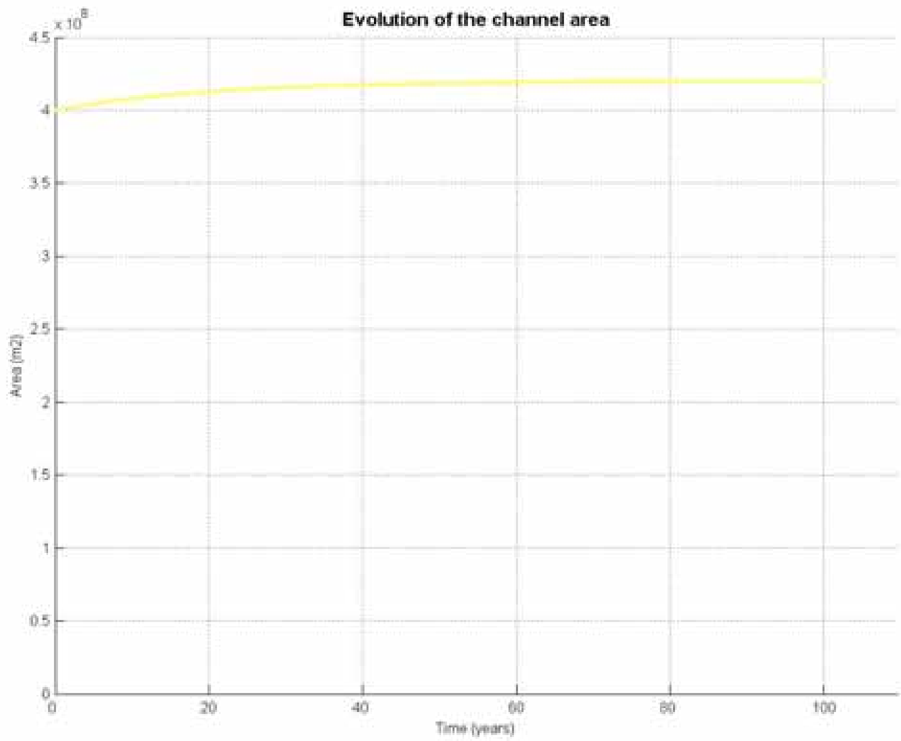
Appendix D 5A Abrupt increase (Vlie)

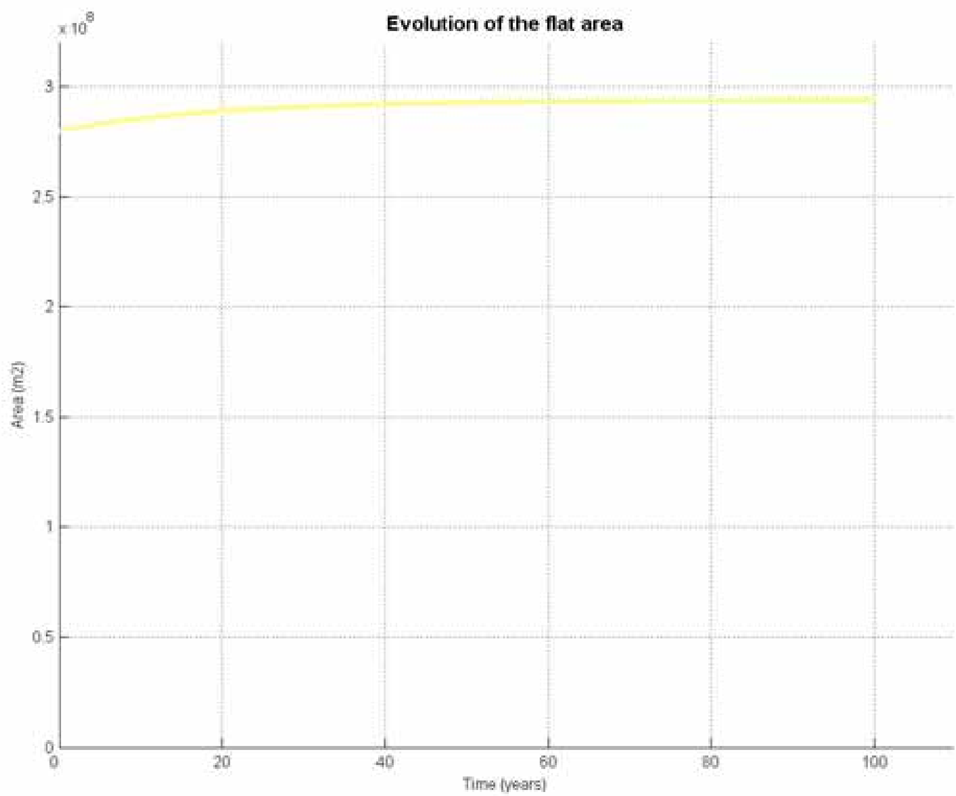
Appendix D 5B Abrupt decrease (Vlie)



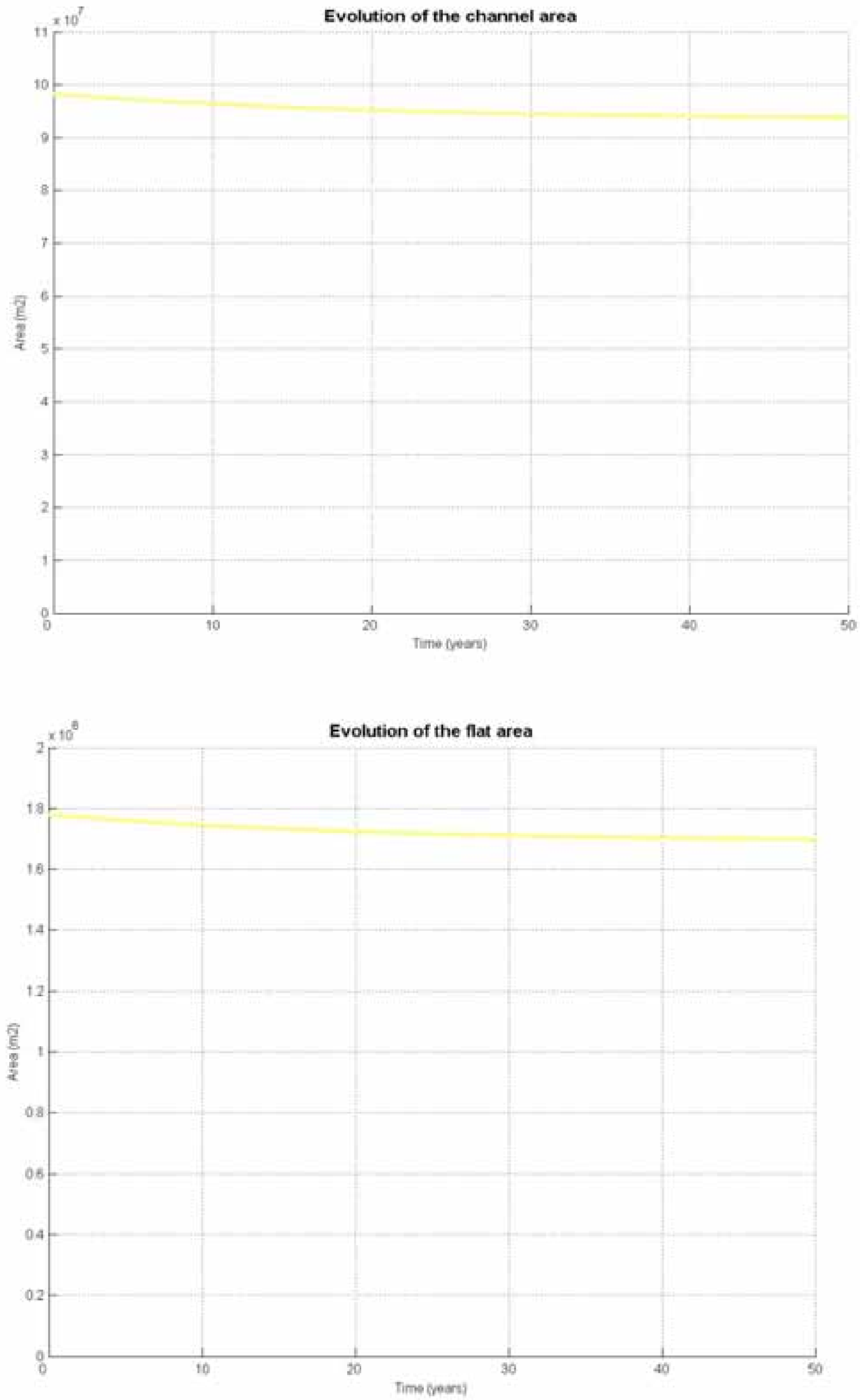


Evolution of the basin area (channel and flat) imposing an asymptotic increase of 5%, with a time-scale of 20 years

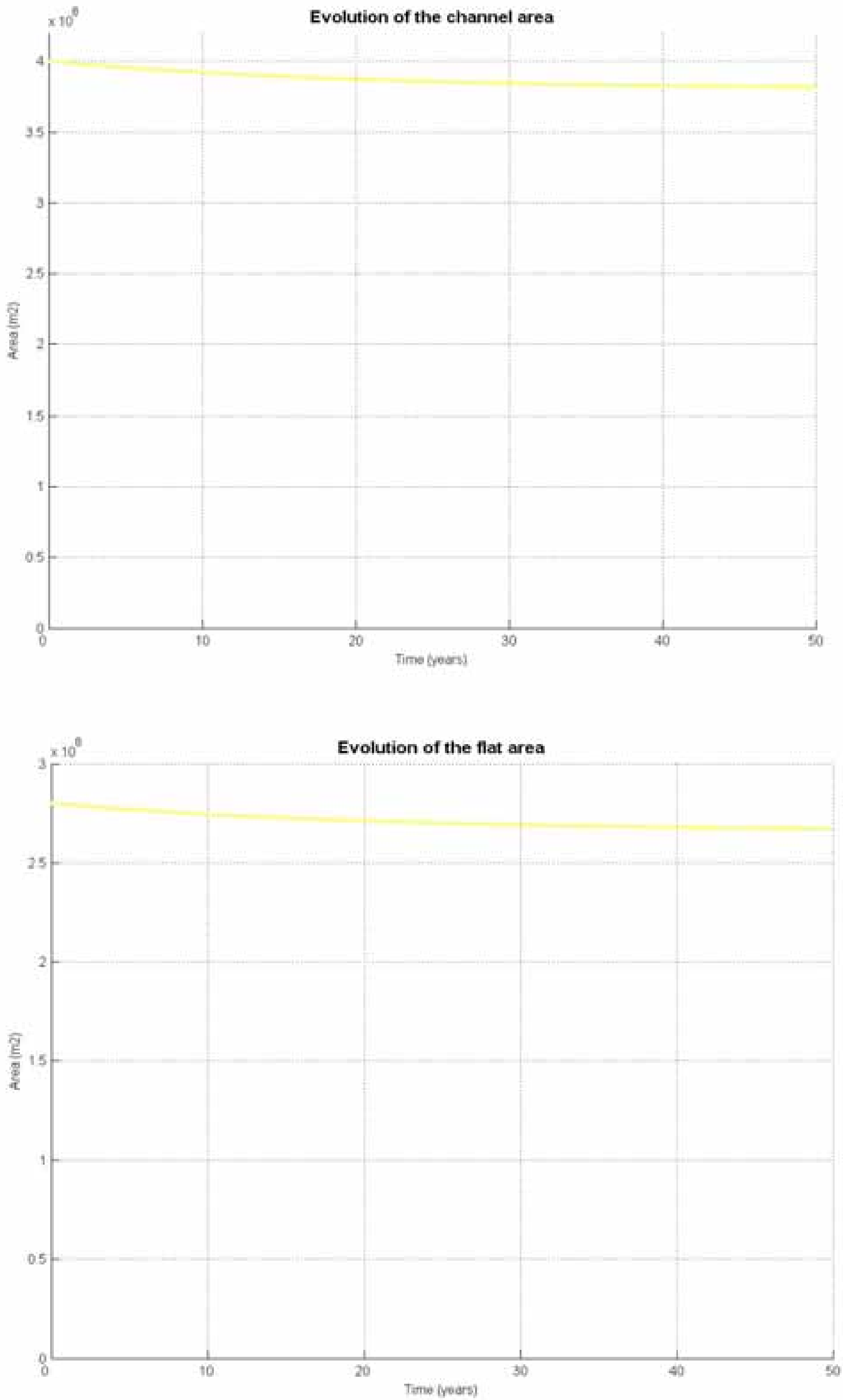




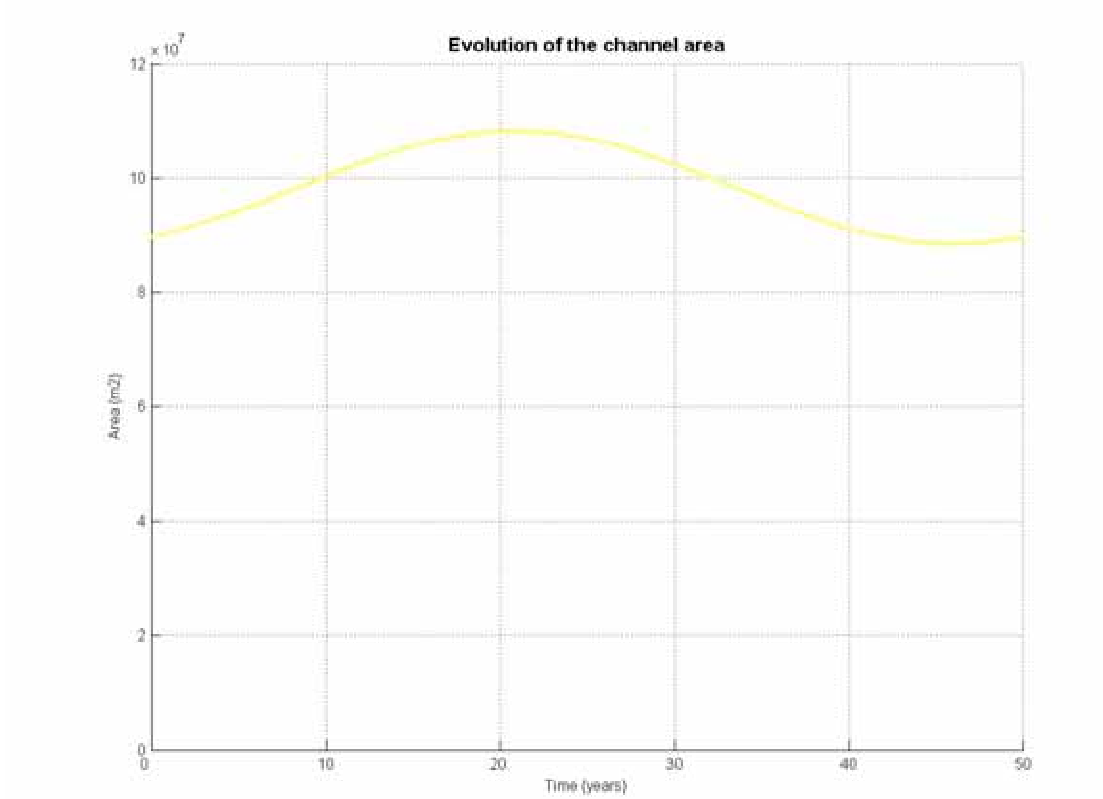
Evolution of the basin area (channel and flat) imposing an asymptotic increase of 5%, with a time-scale of 20 years

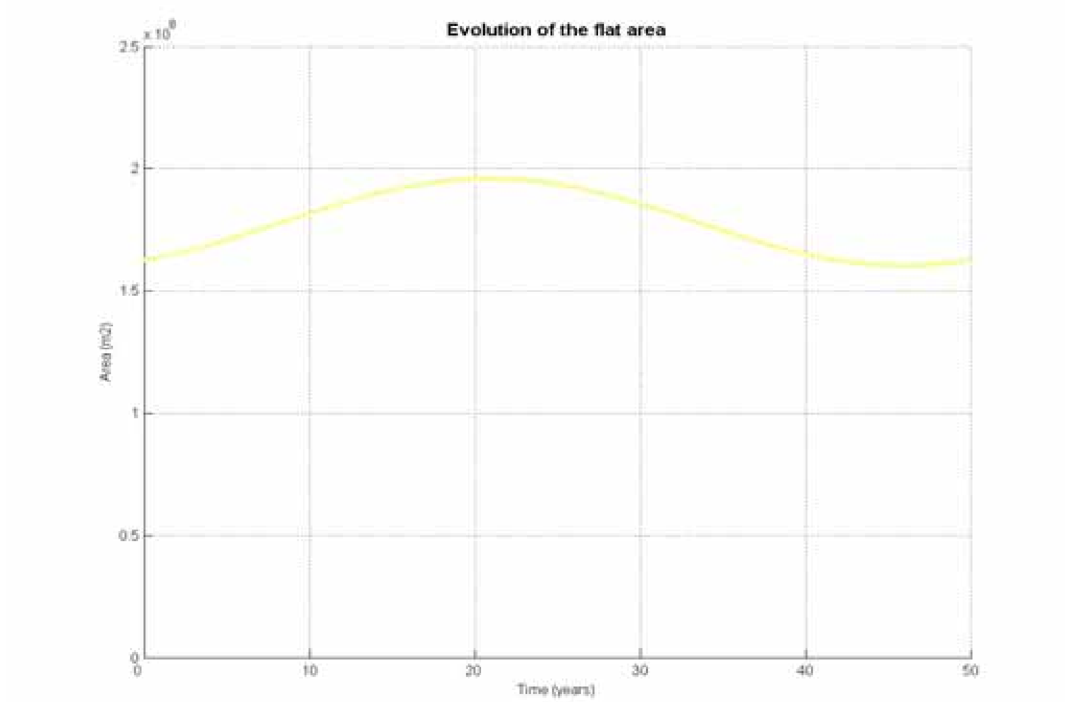


Evolution of the basin area (channel and flat) imposing an asymptotic decrease of 5%, with a time-scale of 20 years

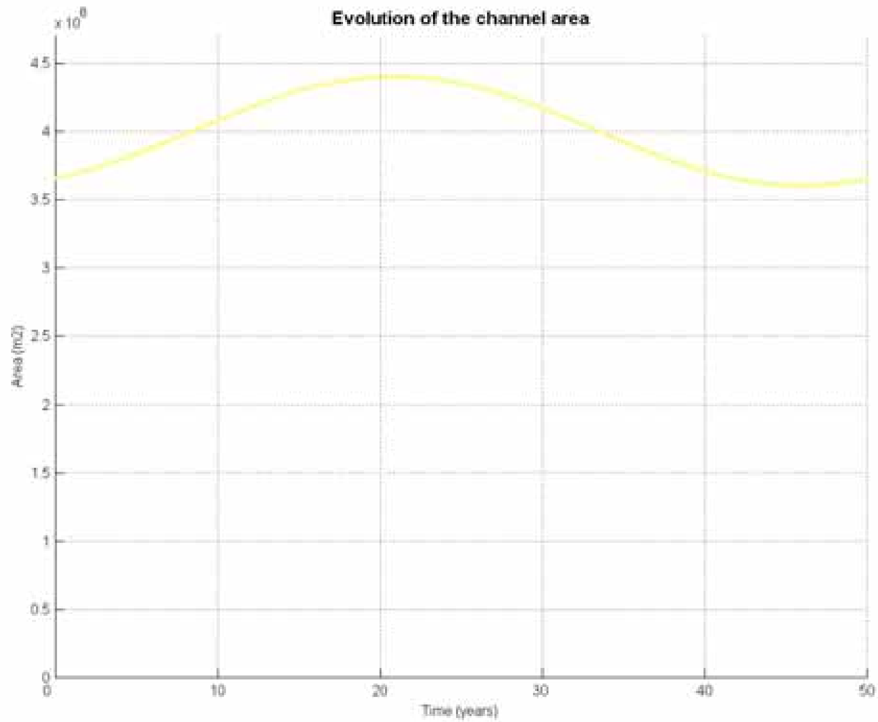


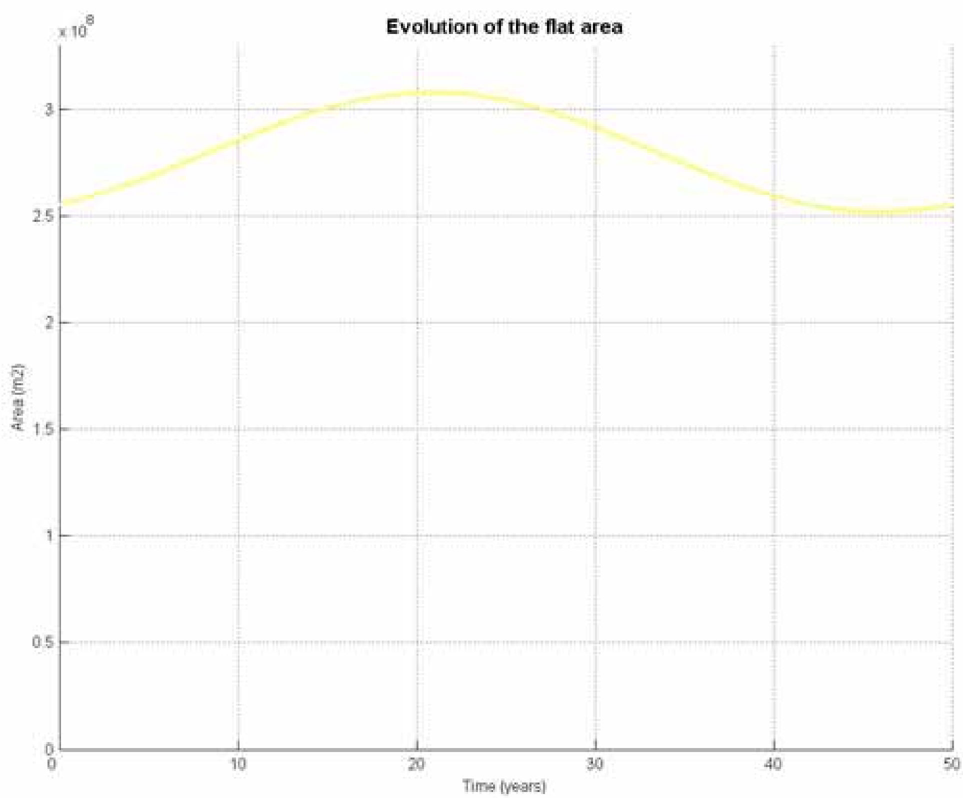
Evolution of the basin area (channel and flat) imposing an asymptotic decrease of 5%, with a time-scale of 20 years



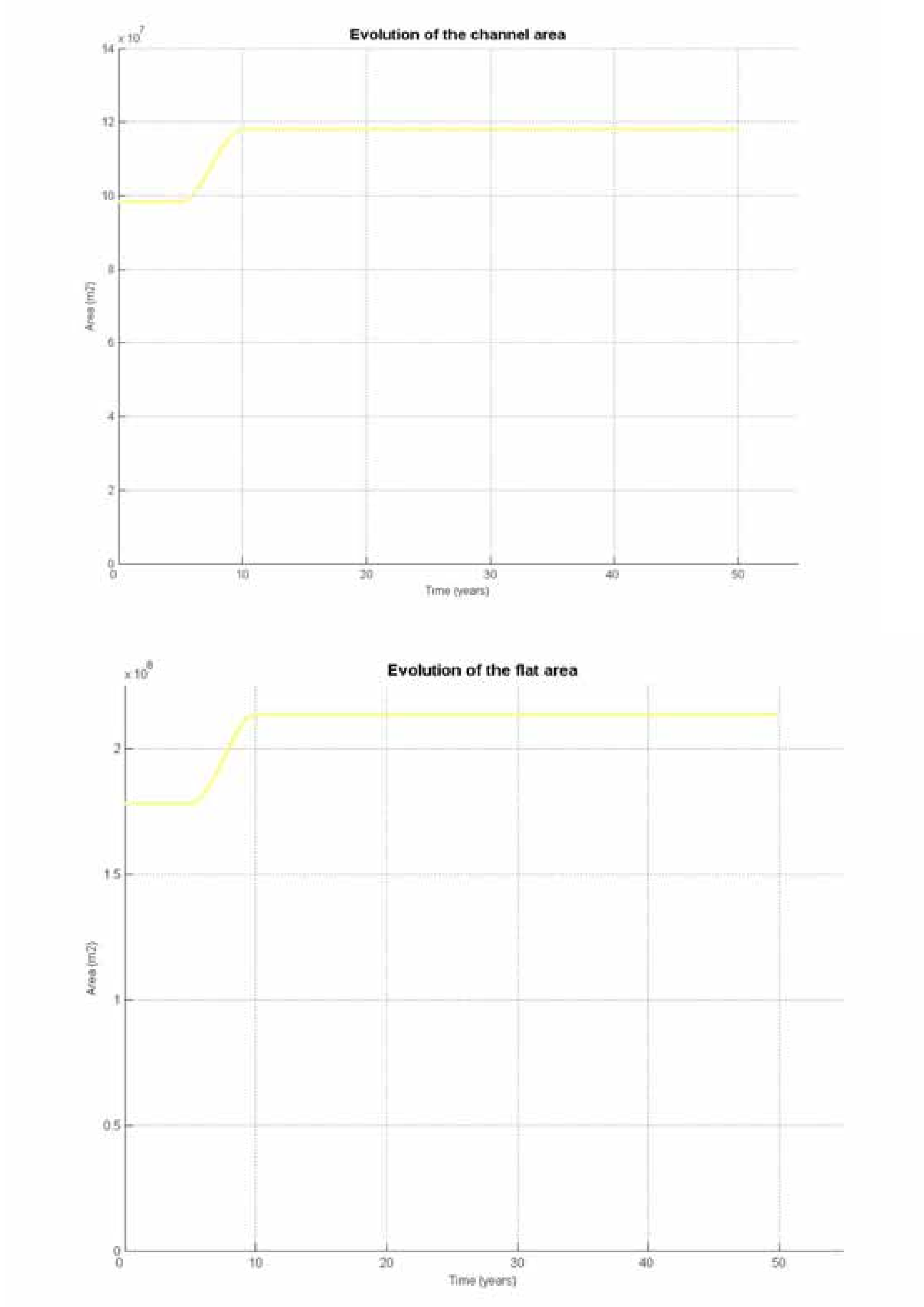


Evolution of the basin area (channel and flat) imposing a periodic variation of 5%, with a period of 50 years

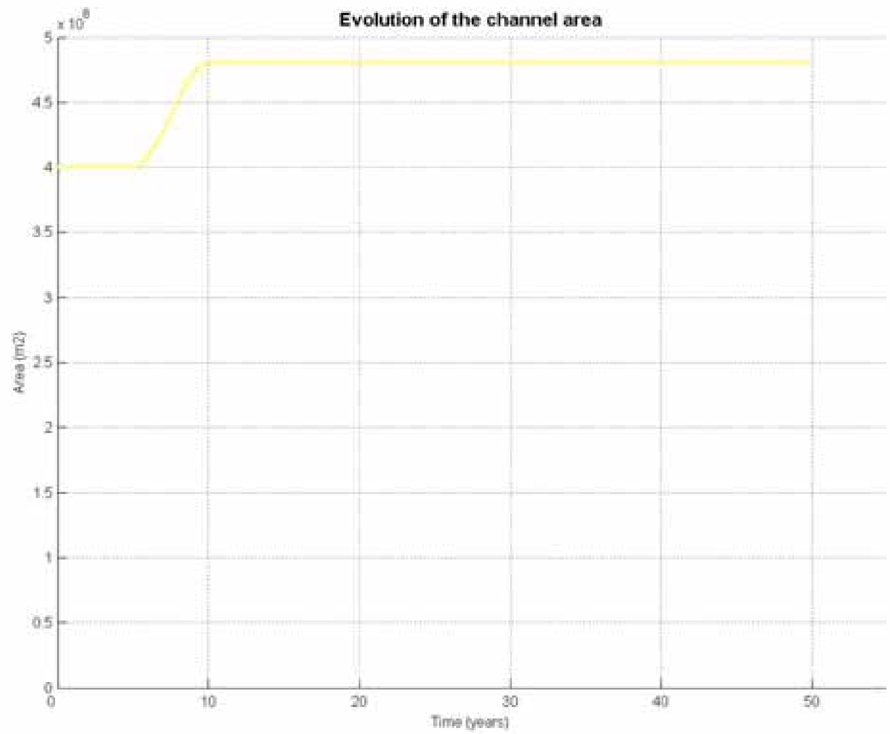


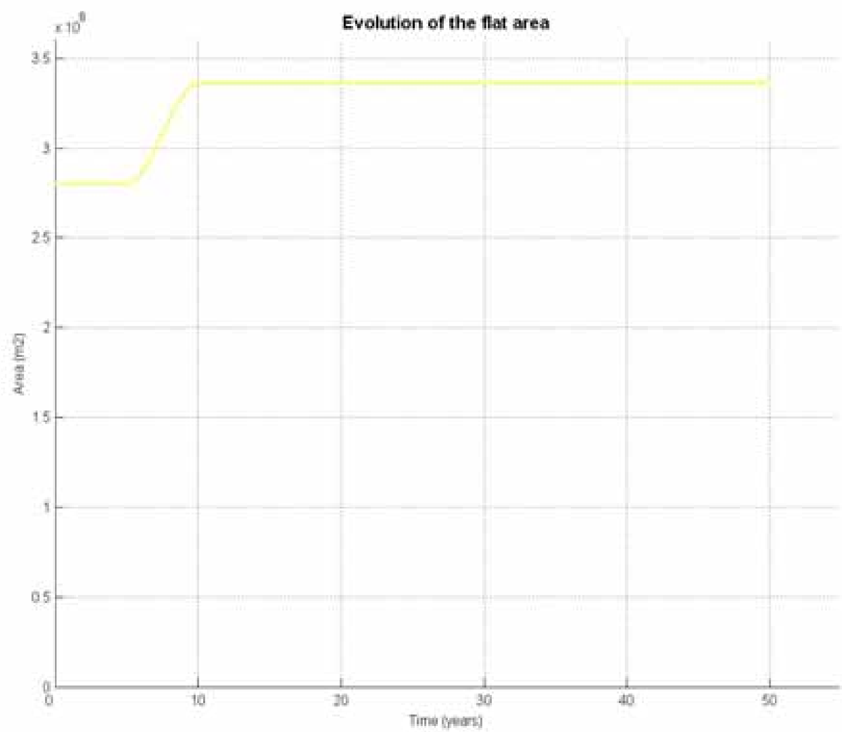


Evolution of the basin area (channel and flat) imposing a periodic variation of 5%, with a period of 50 years

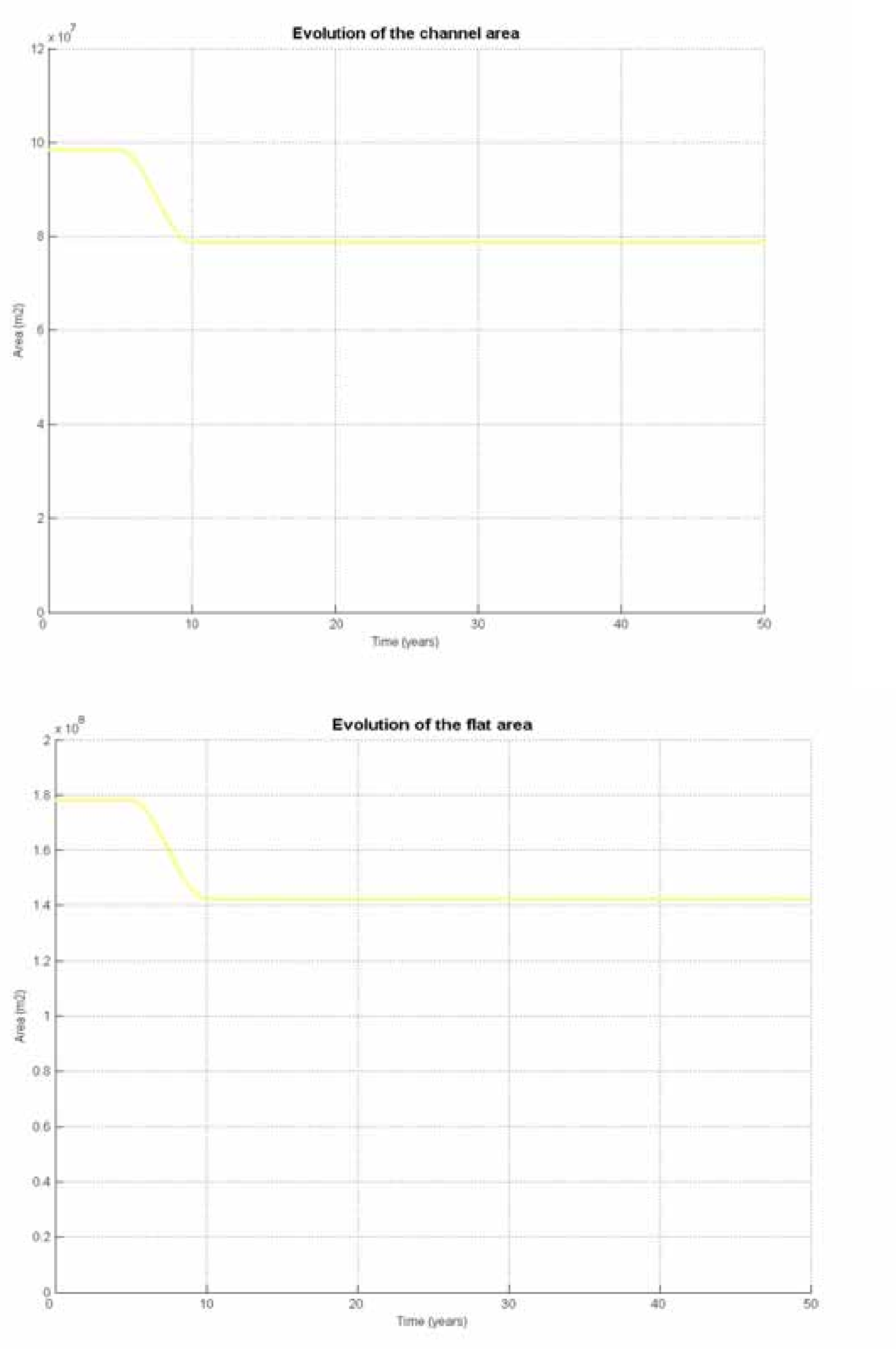


Evolution of the basin area (channel and flat) imposing an abrupt increase of 20%, within 5 years

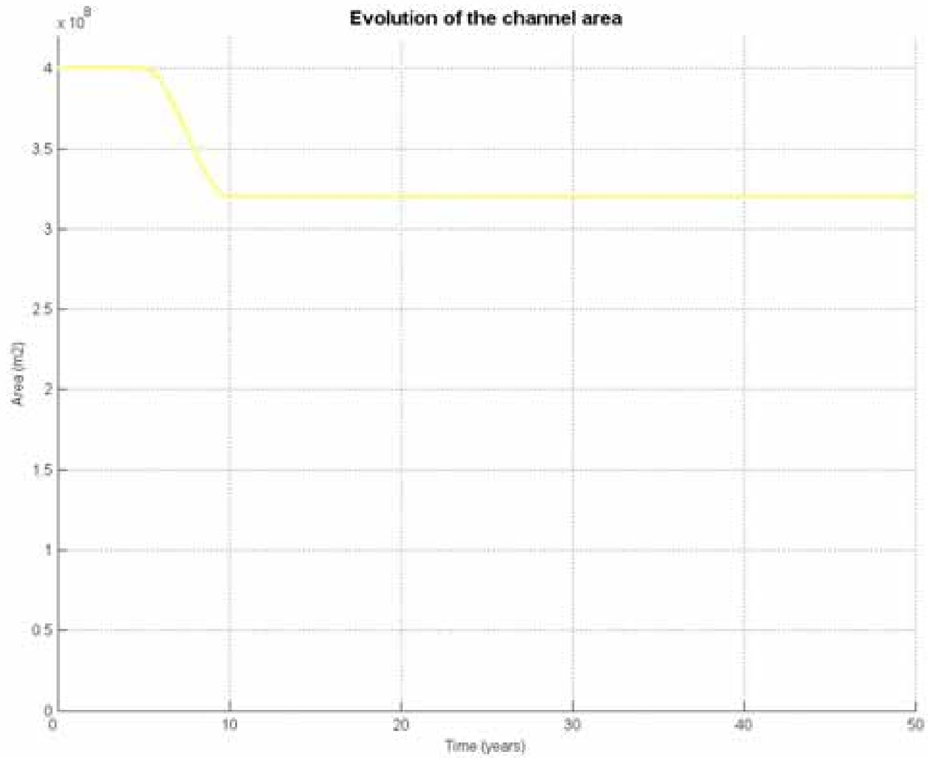


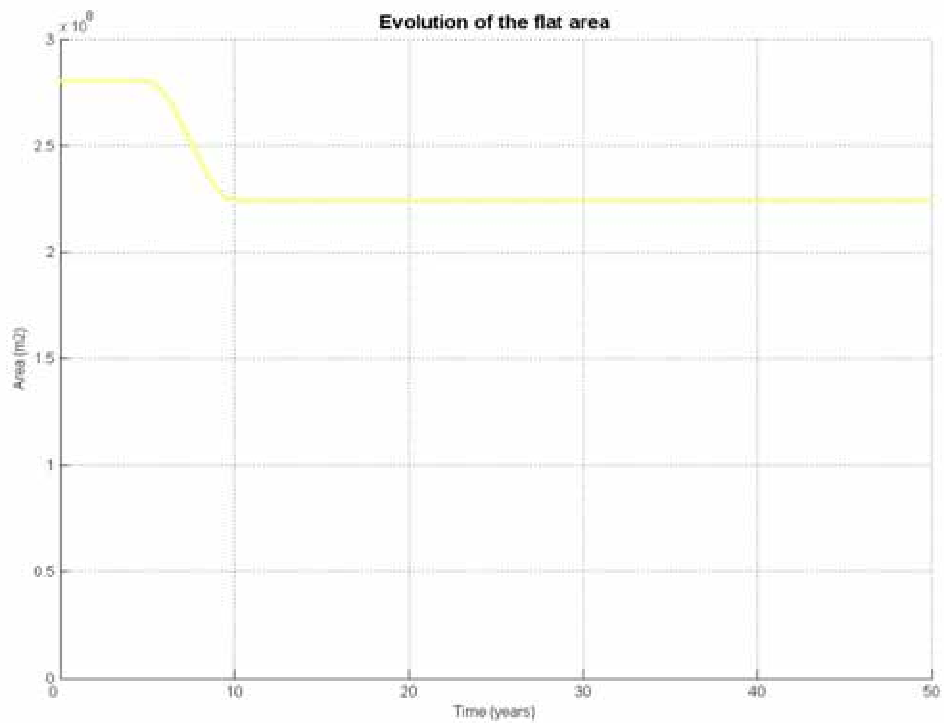


Evolution of the basin area (channel and flat) imposing an abrupt increase of 20%, within 5 years



Evolution of the basin area (channel and flat) imposing an abrupt decrease of 20%, within 5 years





Evolution of the basin area (channel and flat) imposing an abrupt decrease of 20%, within 5 years

Appendix E Evolution of the tidal prism

Appendix E 1A Asyptotic increase

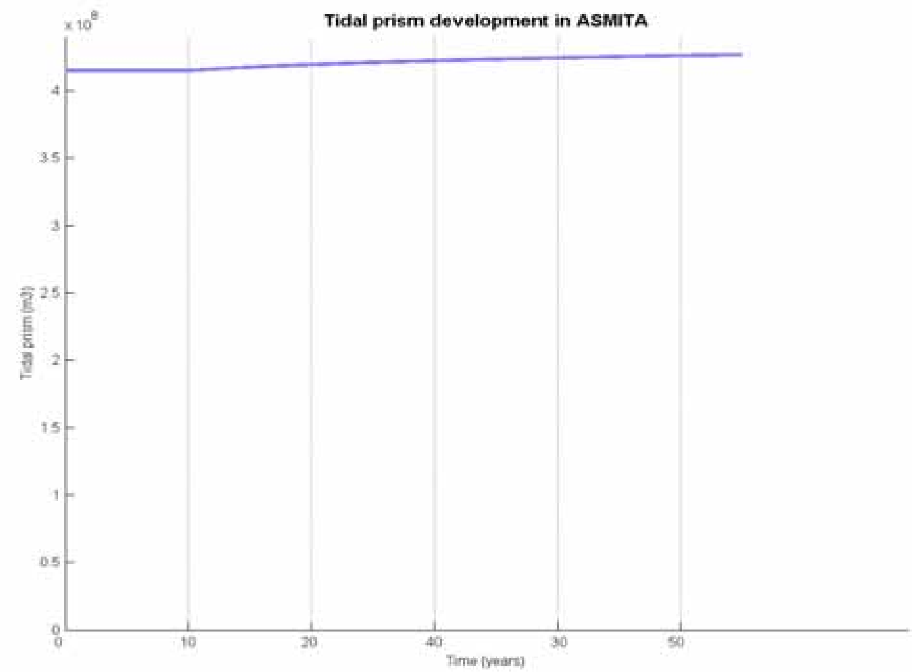
Appendix E 1B Asymptotic decrease

Appendix E 2 Periodic change

Appendix E 3A Abrupt increase

Appendix E 3B Abrupt decrease

a)



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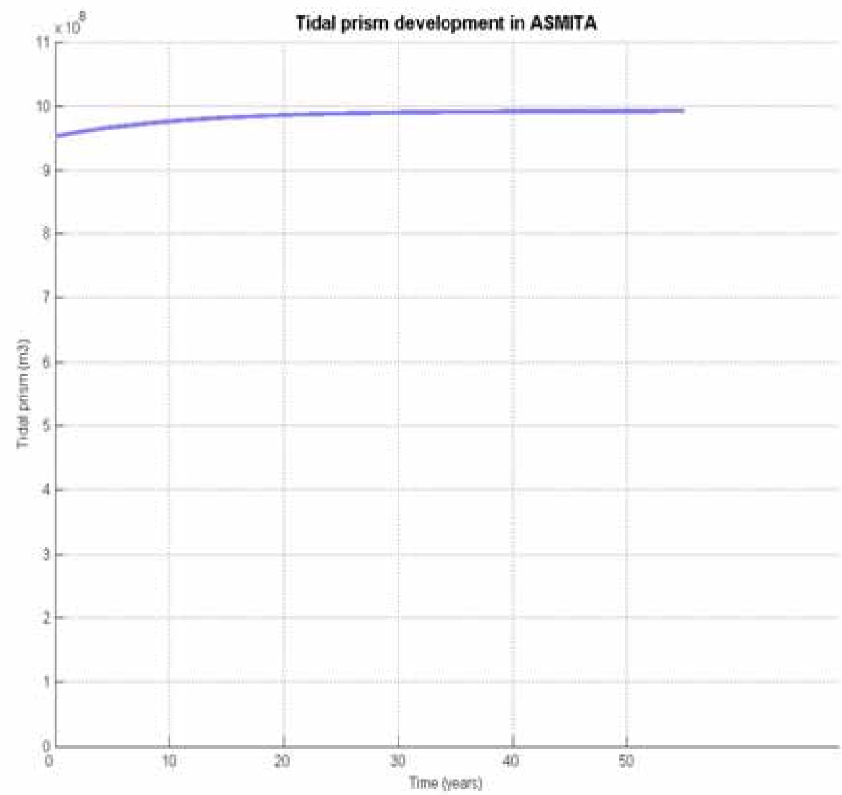
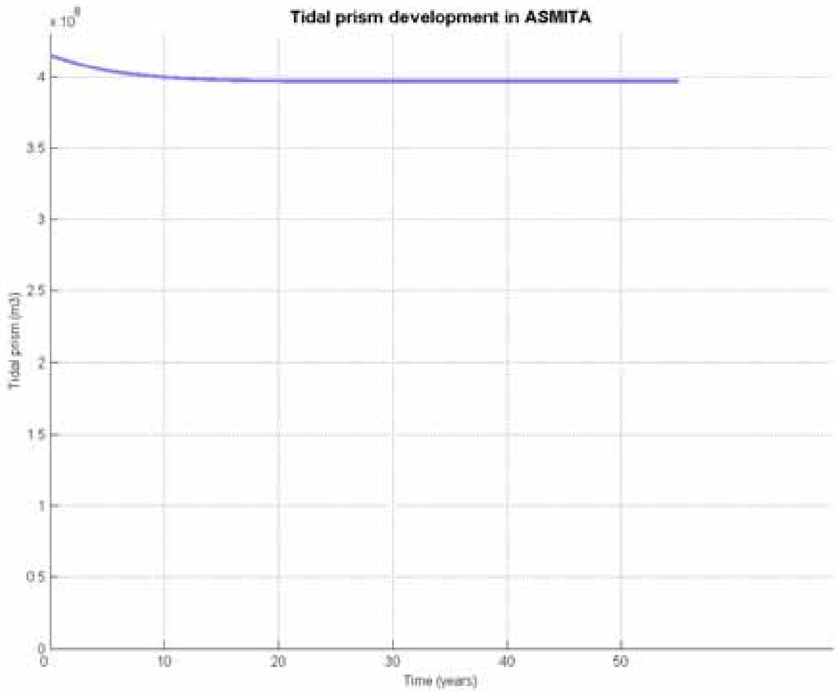
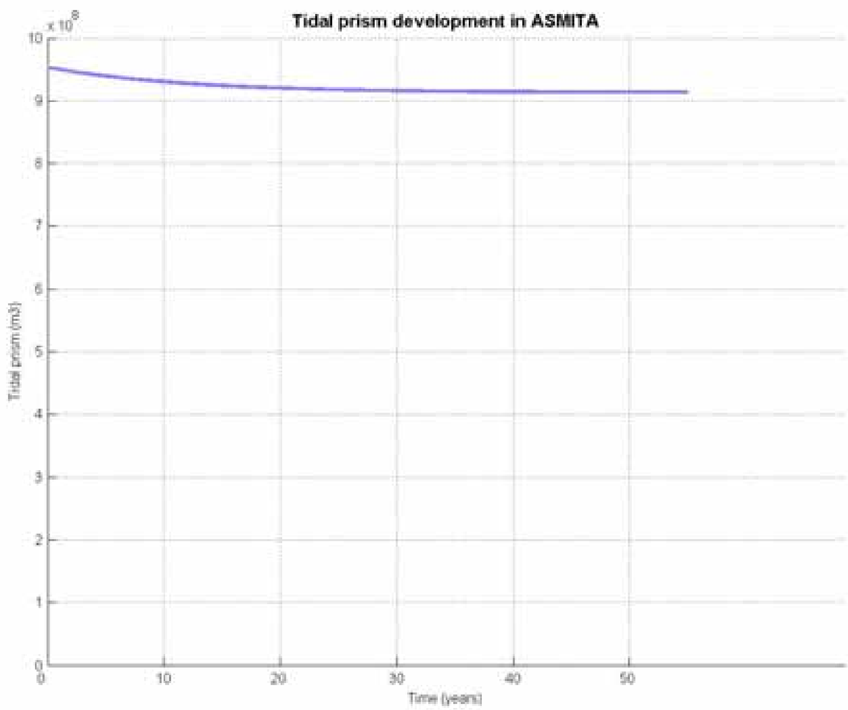


Evolution of tidal prism imposing an asymptotic increase of basin area (5%, time-scale 20 years) in Borndiep a) and Vlie b)

a)

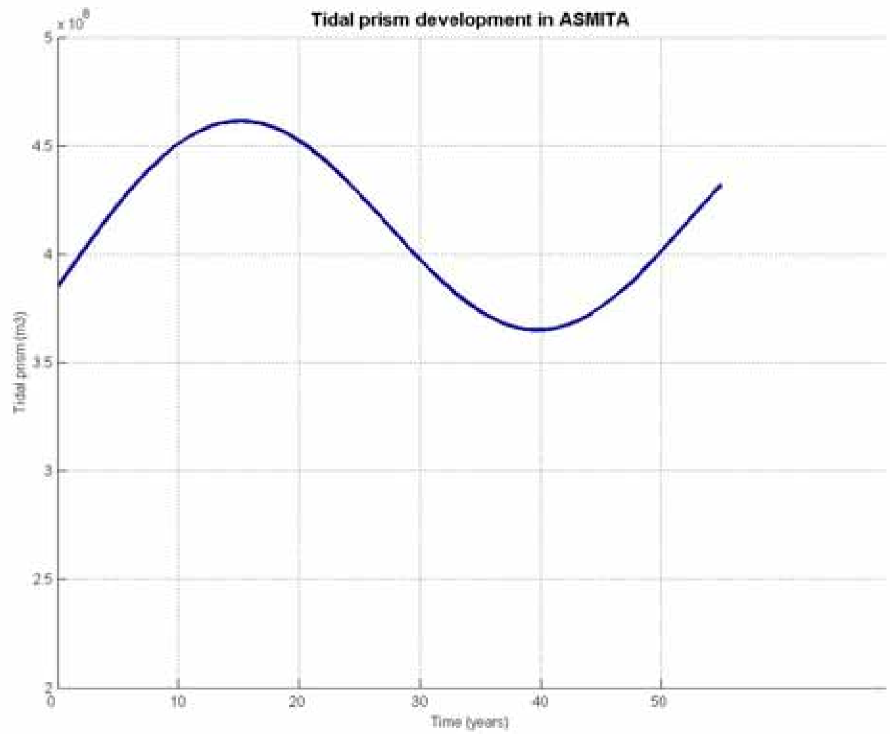


b)

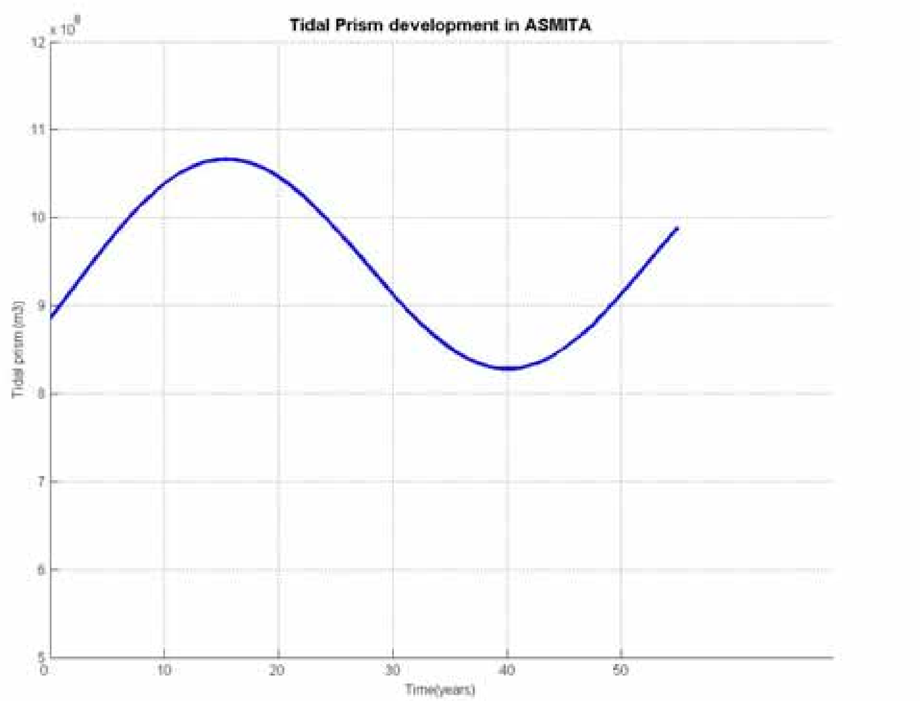


Evolution of tidal prism imposing an asymptotic decrease of basin area (5%, time-scale 20 years) in Borndiep a) and Vlie b)

a)

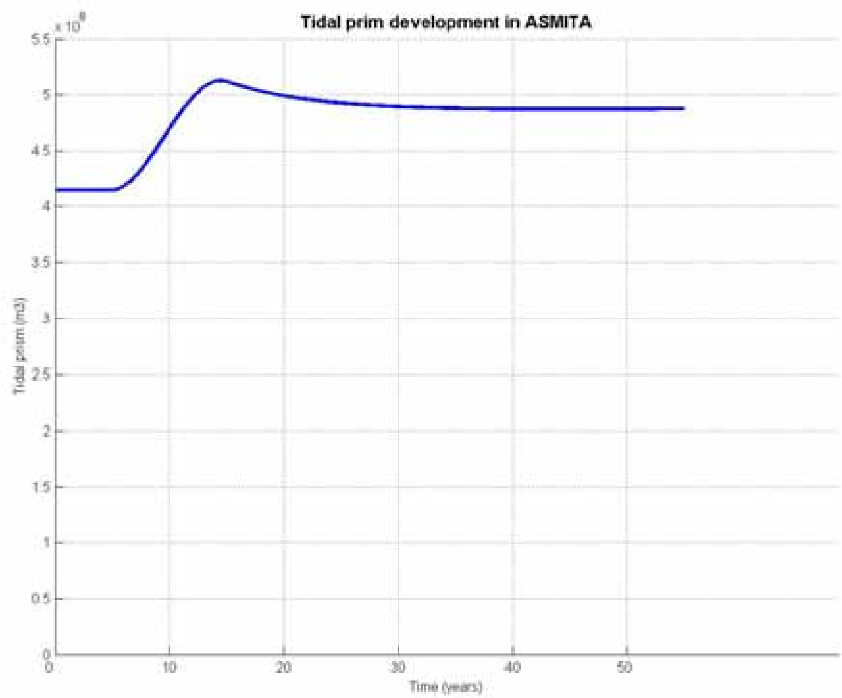


b)

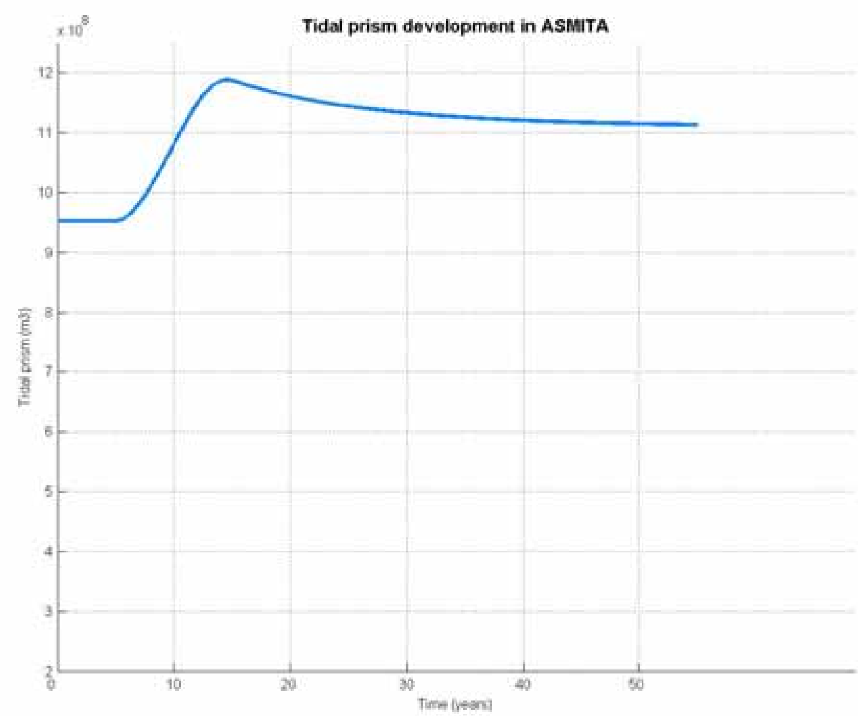


Evolution of tidal prism imposing an periodic change of basin area (5%, period 50 years) in Borndiep a) and Vlie b)

a)

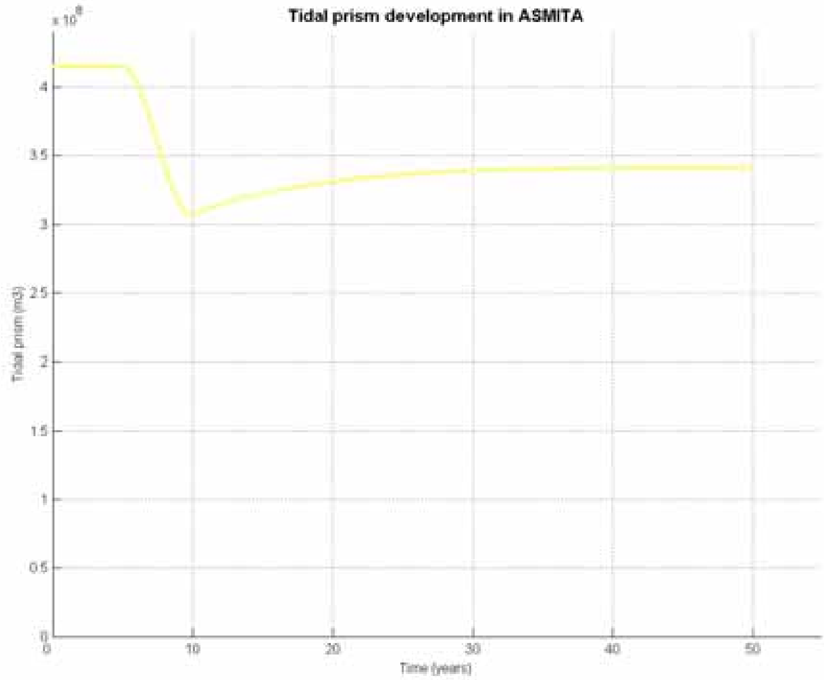


b)

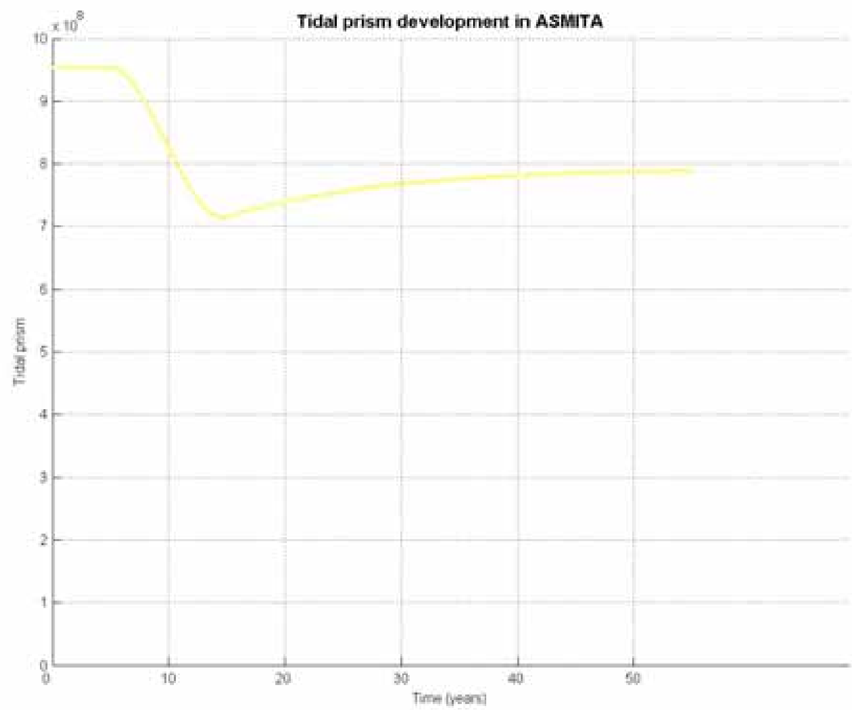


Evolution of tidal prism imposing an abrupt increase of basin area (20%, within 5 years) in Borndiep a) and Vlie b)

a)



b)



Evolution of tidal prism imposing an abrupt decrease of basin area (20%, within 5 years) in Borndiep a) and Vlie b)

Appendix F Basin data available for Borndiep and Vlie

Appendix F Basin data available for Borndiep and Vlie

Data derived from Biegel (1993).

Table F.1.1. Vlie data, actual boundaries

Year	MHW (m)	MLW (m)	VMHW ($10^9 m^3$)	Tidal prism (10^8 m^3)	VMLW (10^9 m^3)	AMHW (10^8 m^2)	Af (10^8 m^3)	Ac (10^8 m^2)
1933	0.84	-1.06	2.62	1.28	1.35	7.4	2.87	4.53
1951	0.84	-1.06	2.51	1.24	1.27	7.32	2.87	4.45
1972	0.84	-1.06	2.47	1.23	1.24	7.34	3.40	3.95
1977	0.84.	-1.06	2.45	1.22	1.23	7.37	3.53	3.84
1983	0.84	-1.06	2.49	1.23	1.26	7.36	3.53	4.01

Table F.2.2. Borndiep data, actual boundaries

Year	MHW (m)	MLW (m)	VMHW ($10^8 m^3$)	Tidal prism (10^8 m^3)	VMLW (10^9 m^3)	AMHW (10^8 m^2)	Af (10^8 m^3)	Ac (10^7 m^2)
1926	0.91	-1.24	7.56	4.66	2.9	2.7	1.72	9.8
1950	0.91	-1.24	7.64	4.53	3.11	2.71	1.69	10.2
1973	0.91	-1.24	7.61	4.56	3.05	2.71	1.78	9.34
1978	0.91	-1.24	7.55	4.58	2.97	2.71	1.77	9.44
1984	0.91	-1.24	7.64	4.70	2.94	2.72	1.73	9.92

Appendix G ASMITA runs

Appendix G 1A Morphological evolution of Borndiep (First scenario)

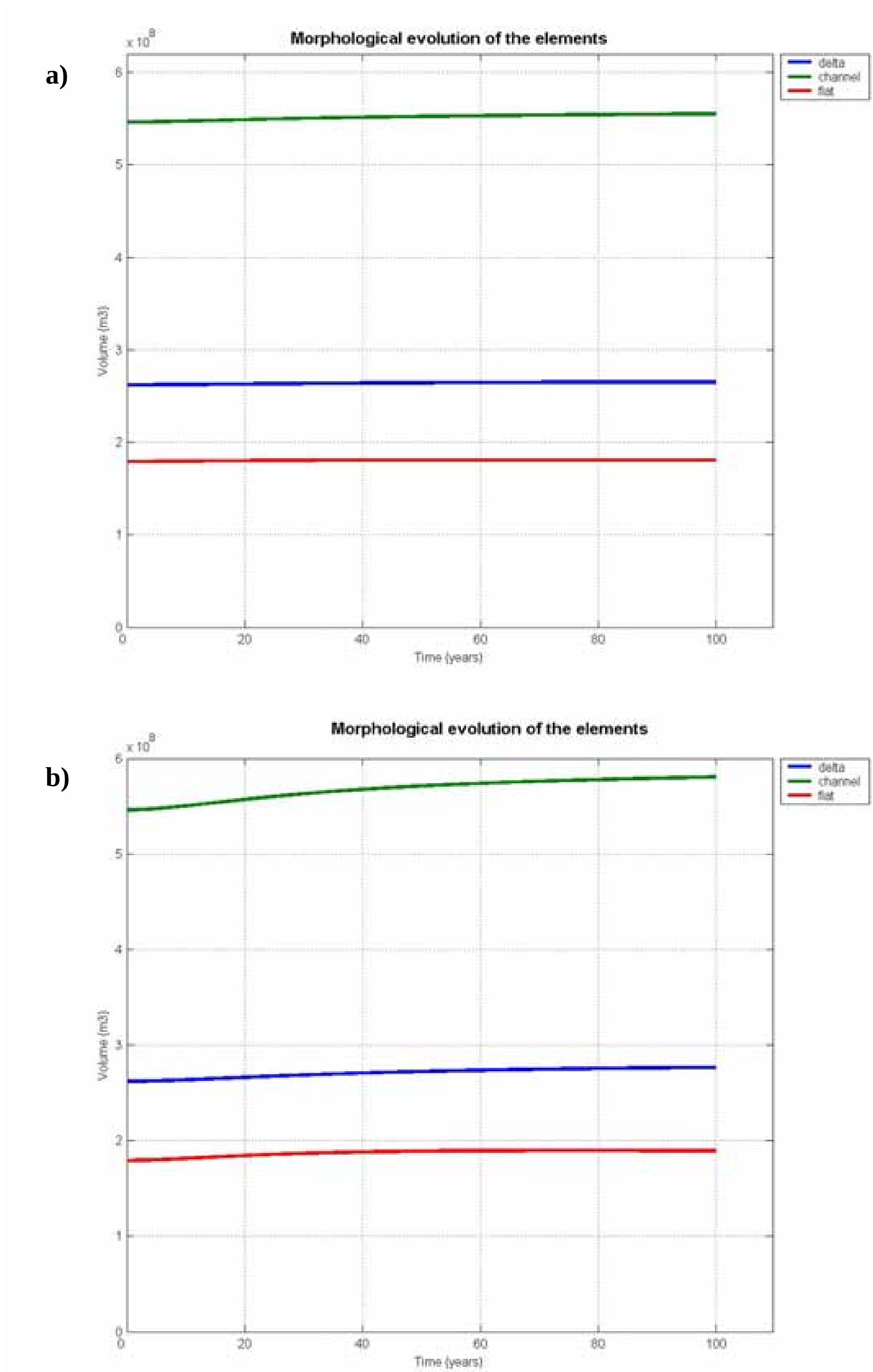
Appendix G 1B Morphological evolution of Vlie (First scenario)

Appendix G 2A Morphological evolution of Borndiep (Second scenario)

Appendix G 2B Morphological evolution of Vlie (Second scenario)

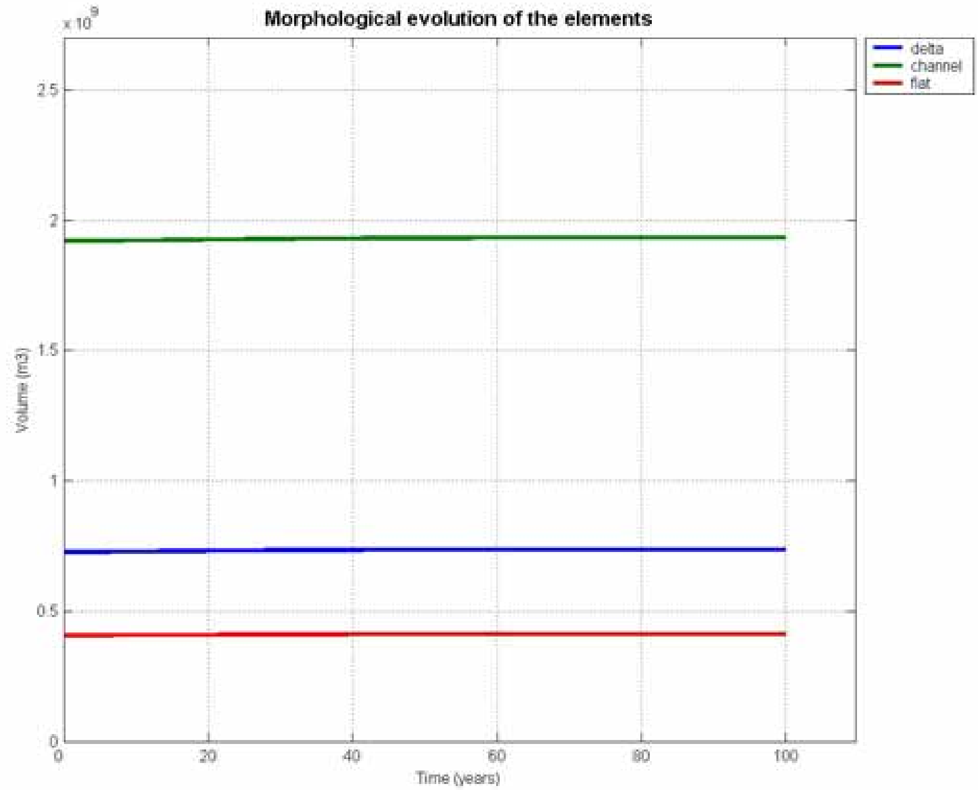
Appendix G 3A Morphological evolution of Borndiep (Third scenario)

Appendix G 3B Morphological evolution of Vlie (Third scenario)

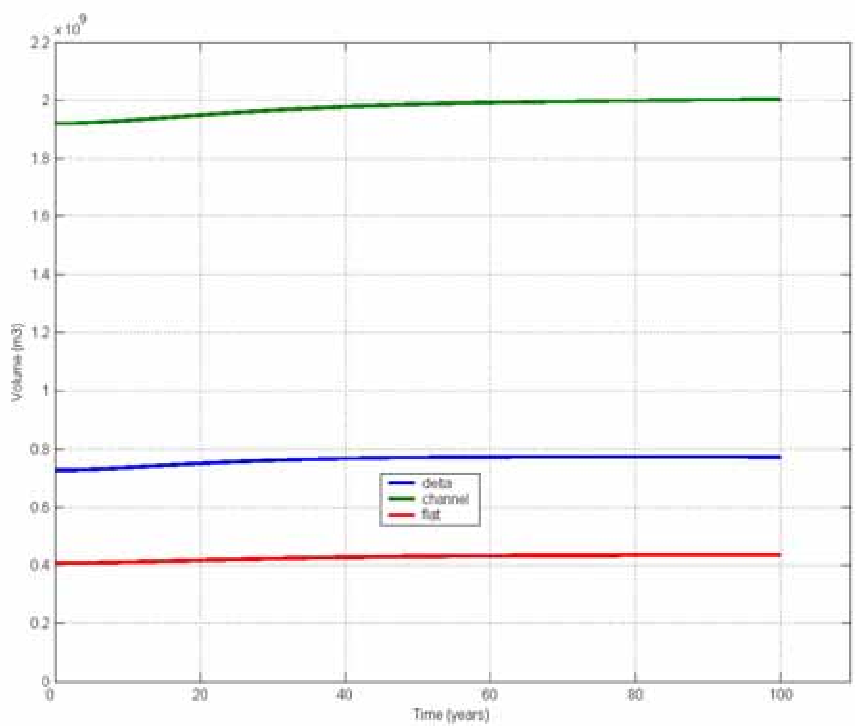


Morphological evolution of Borndiep imposing an asymptotic increase of basin area [1% a); 5% b)], with a time-scale of 20 years

a)

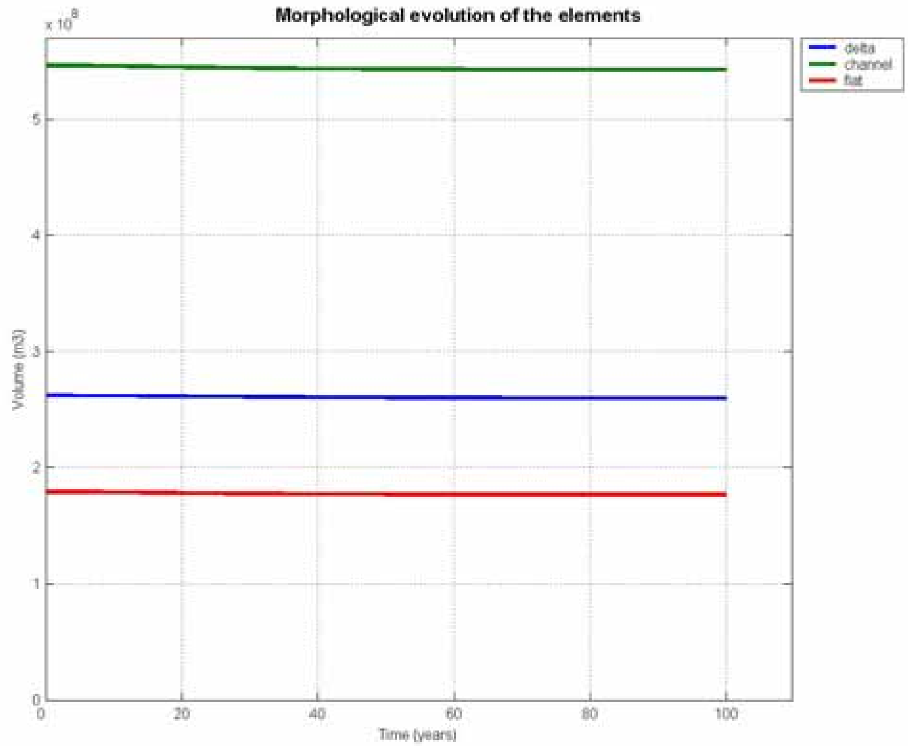


b)

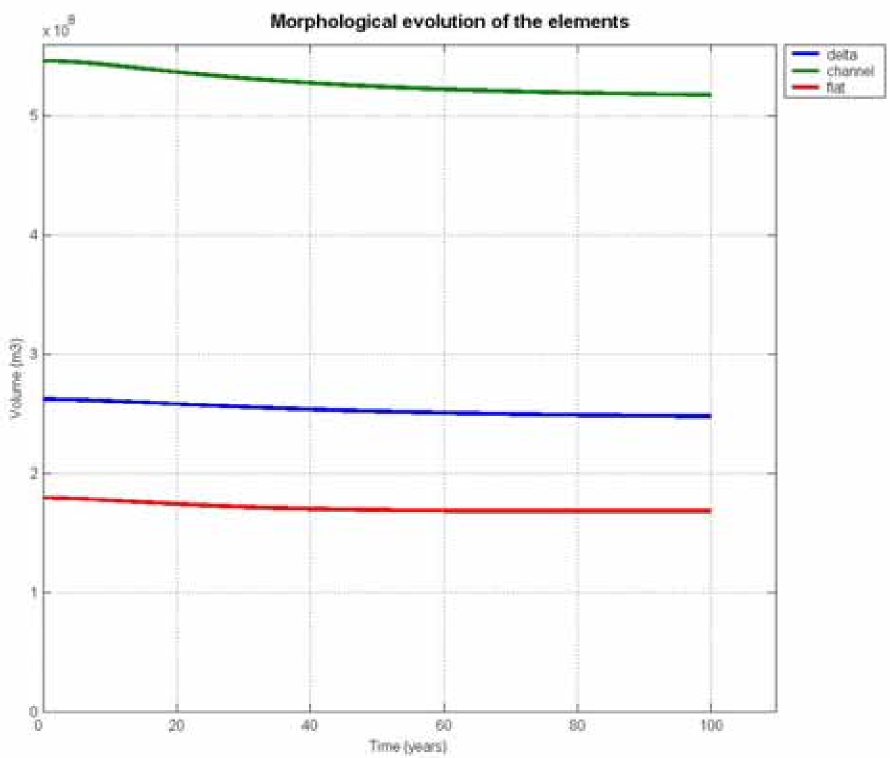


Morphological evolution of Vlie imposing an aymptotic increase of basin area [1% a); 5% b)], with a time-scale of 20 years

a)



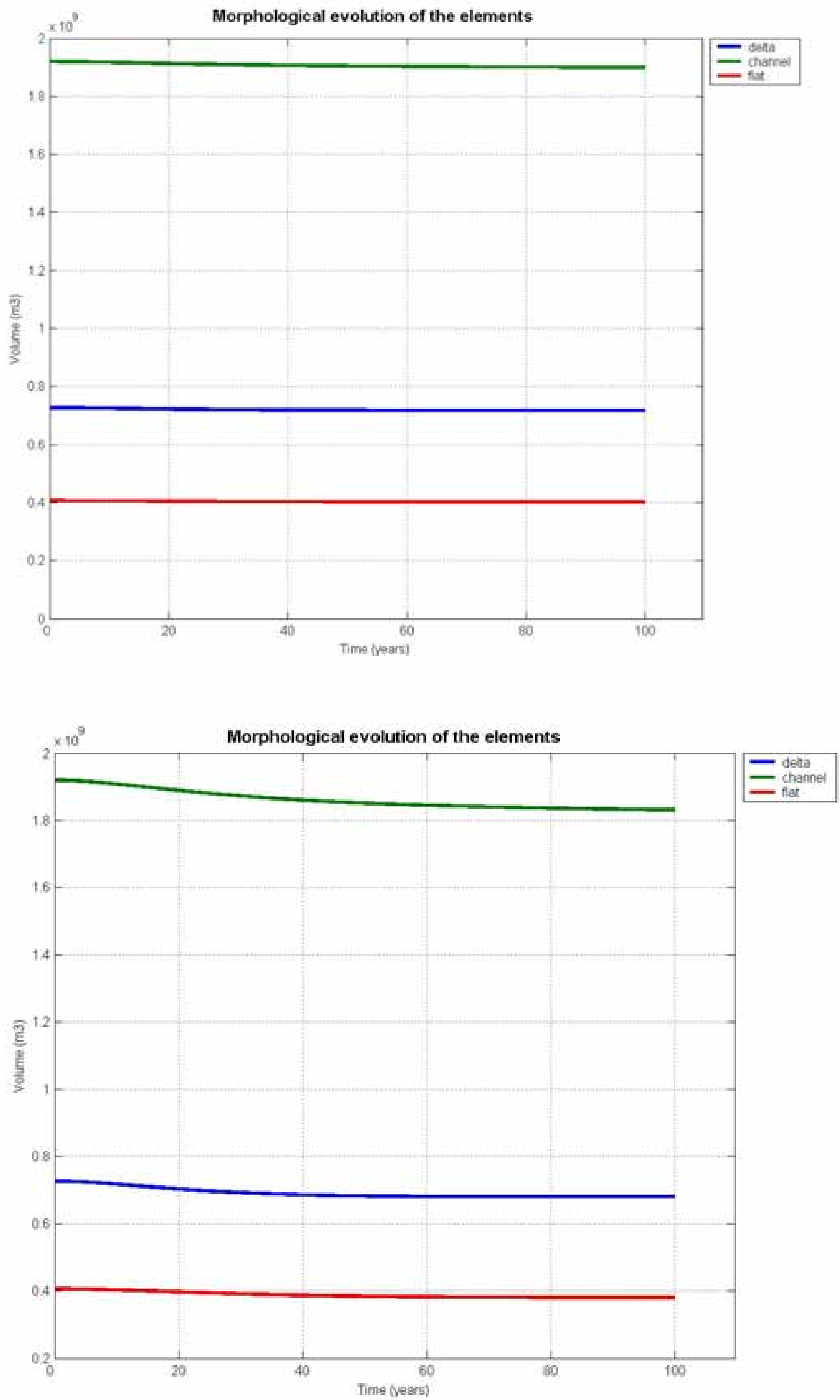
b)



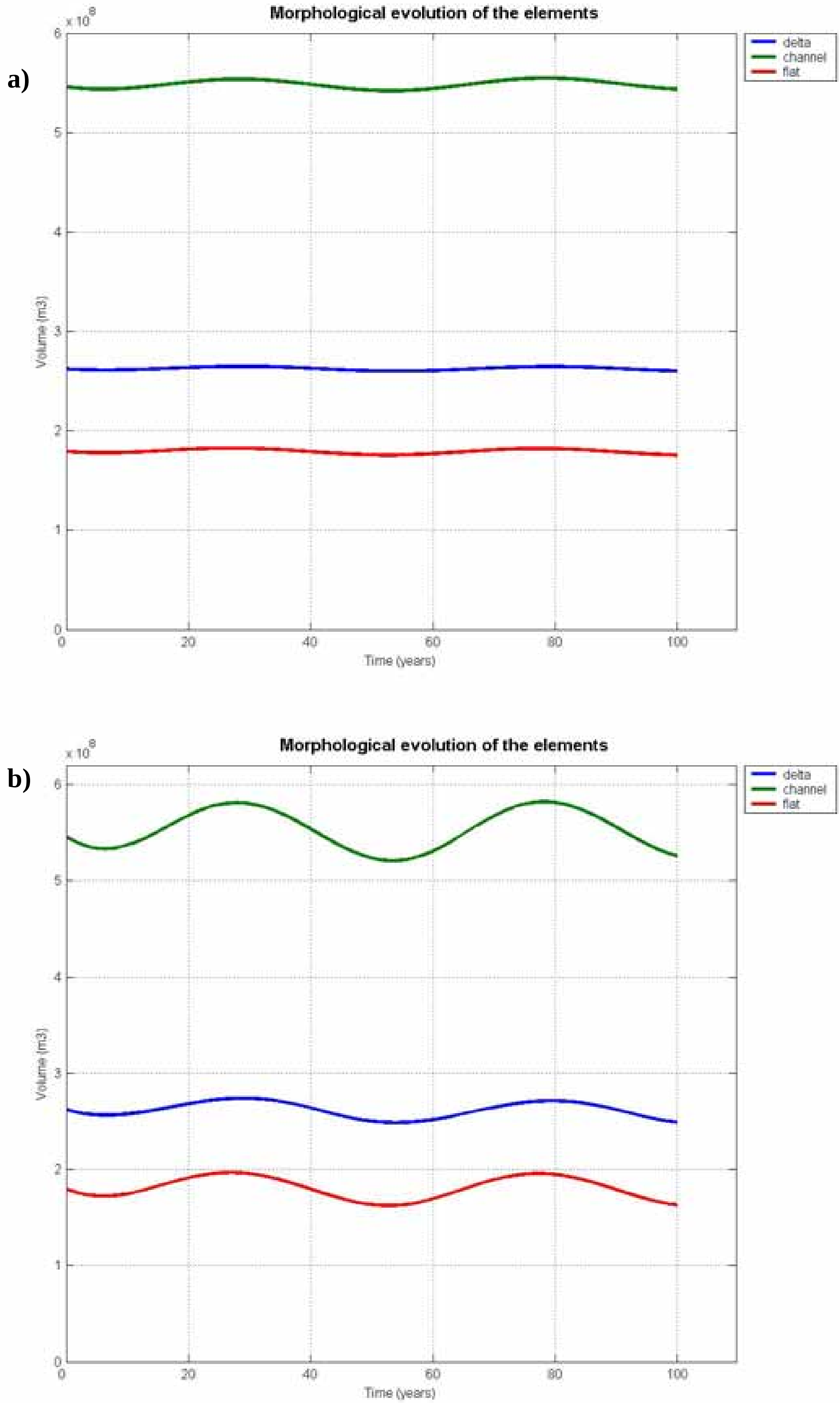
Morphological evolution of Borndiep imposing an asymptotic decrease of basin area [1% a); 5% b)], with a time-scale of 20 years

a)

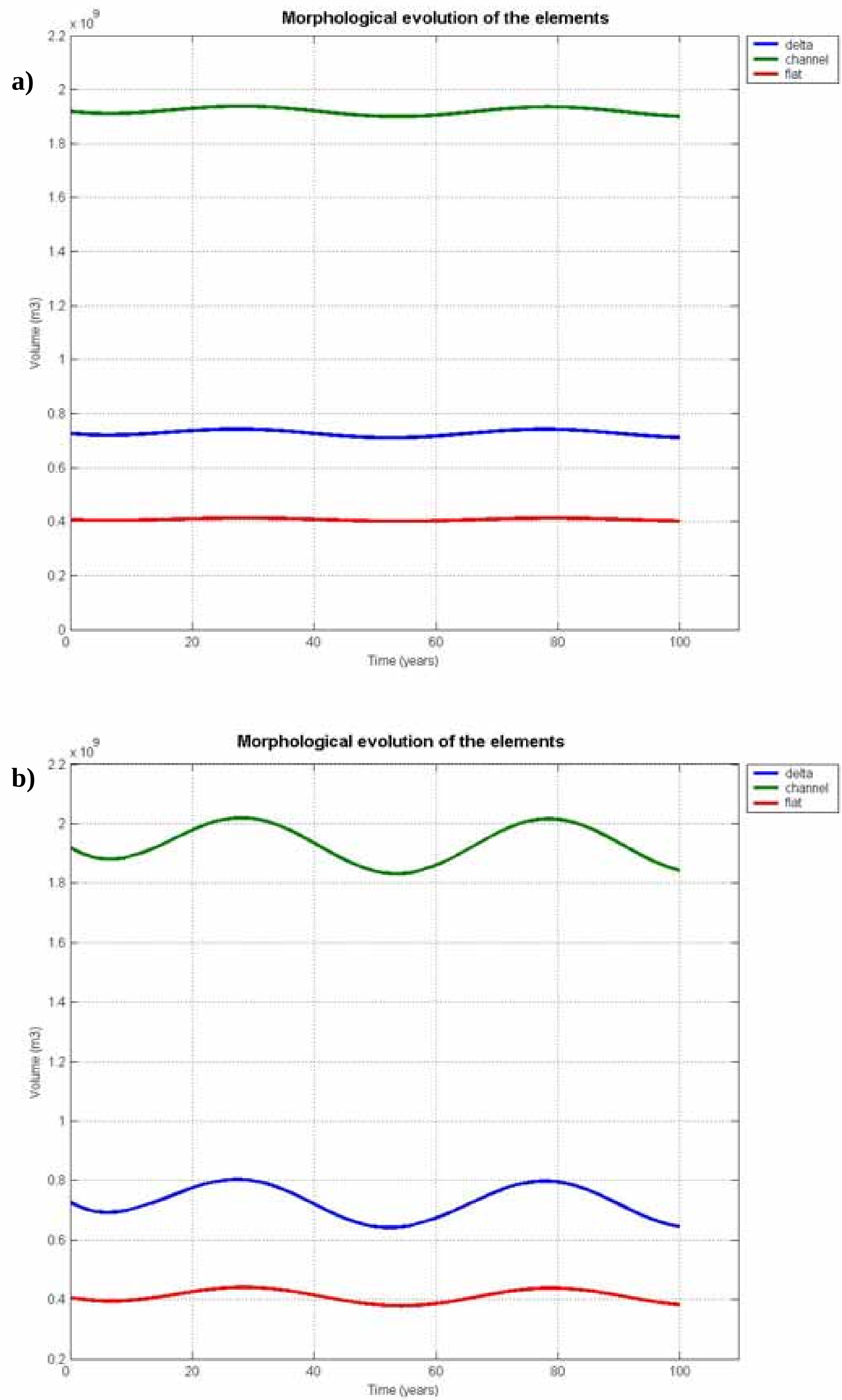
b)



Morphological evolution of Vlie imposing an asymptotic decrease of basin area [1% a); 5% b)], with a time-scale of 20 years

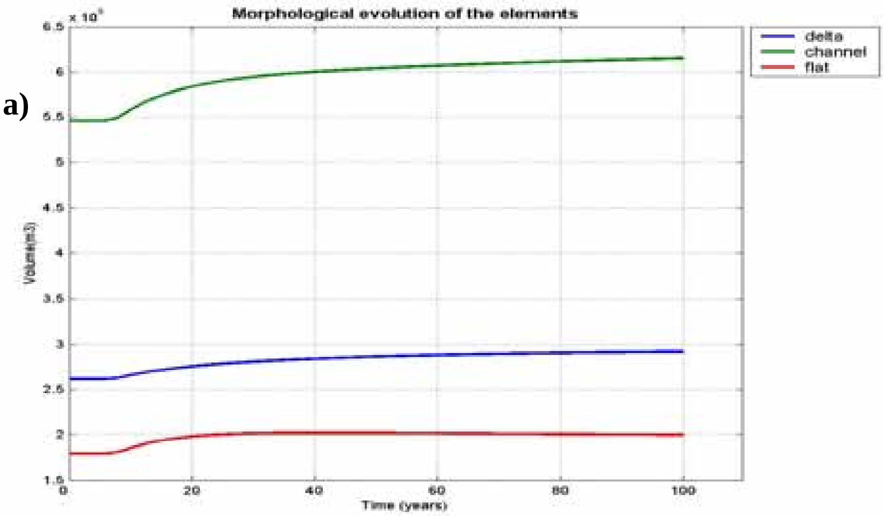


Morphological evolution of Borndiep imposing an periodic change of basin area [1% a); 5% b)], with a period of 50 years

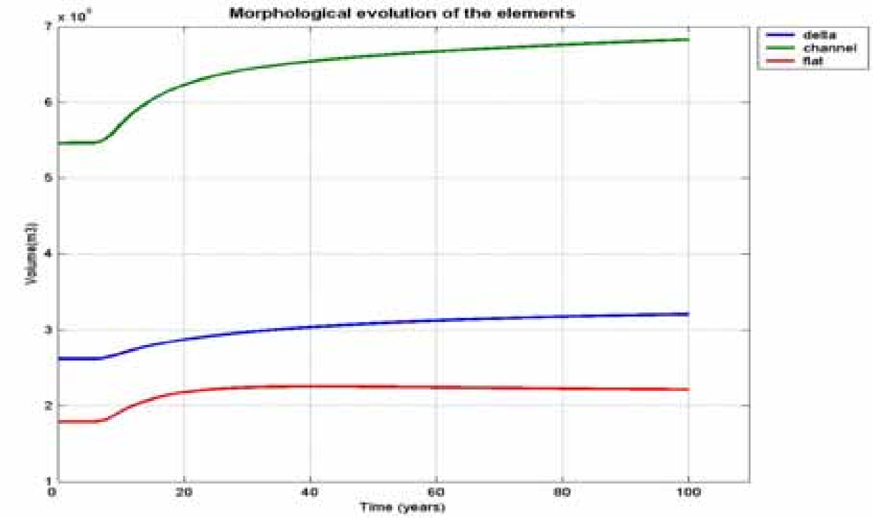


Morphological evolution of Vlie imposing an periodic change of basin area [1% a); 5% b)], with a period of 50 years

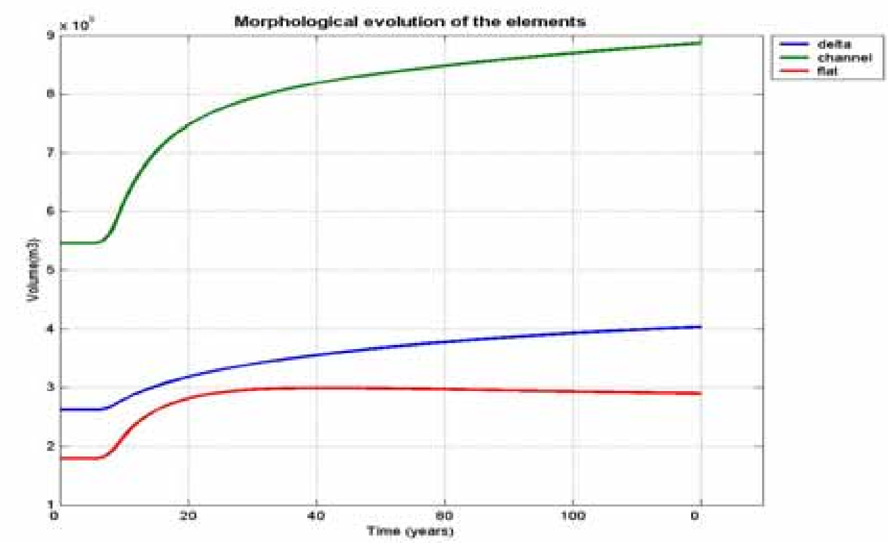
a)



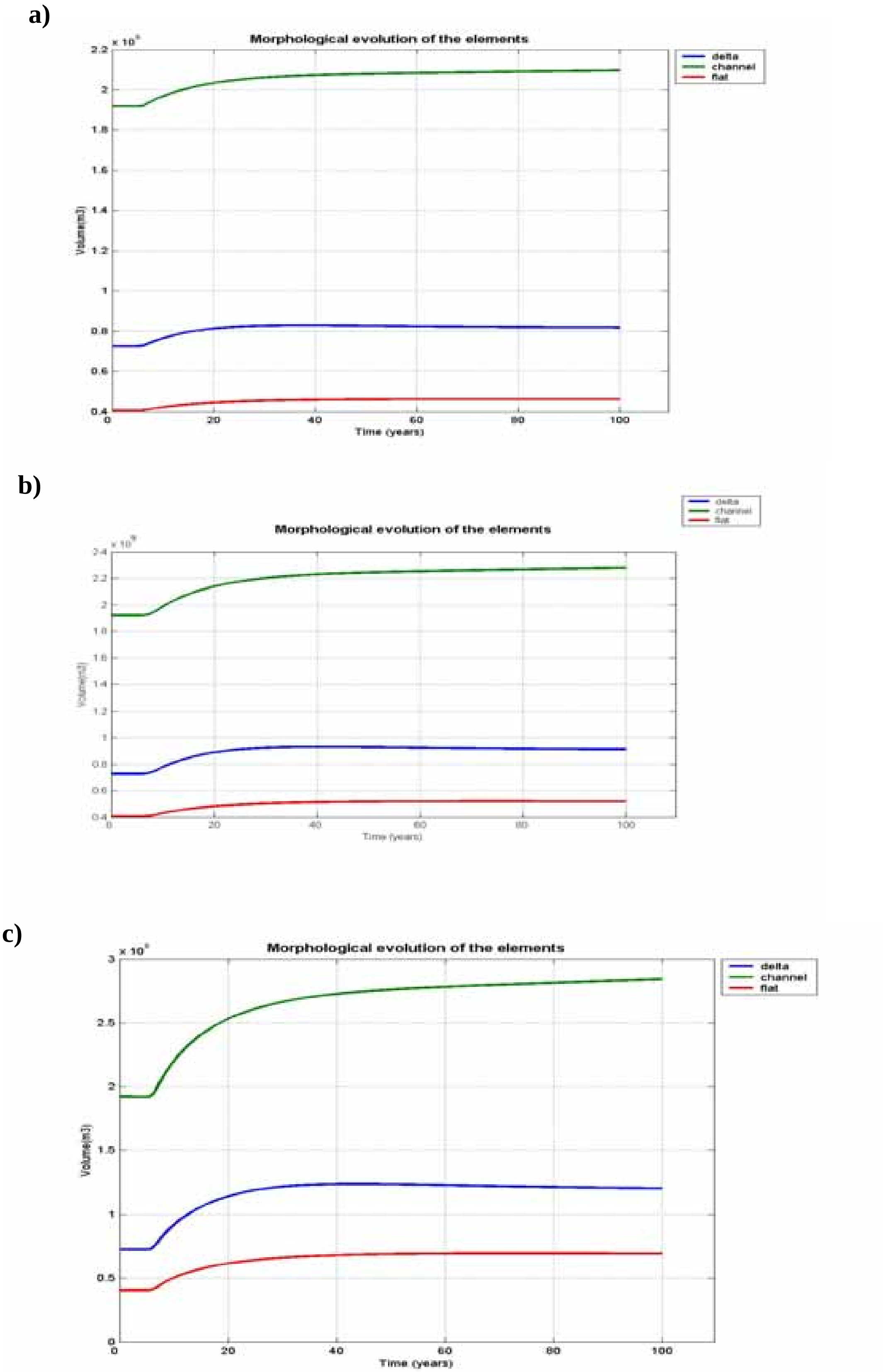
b)



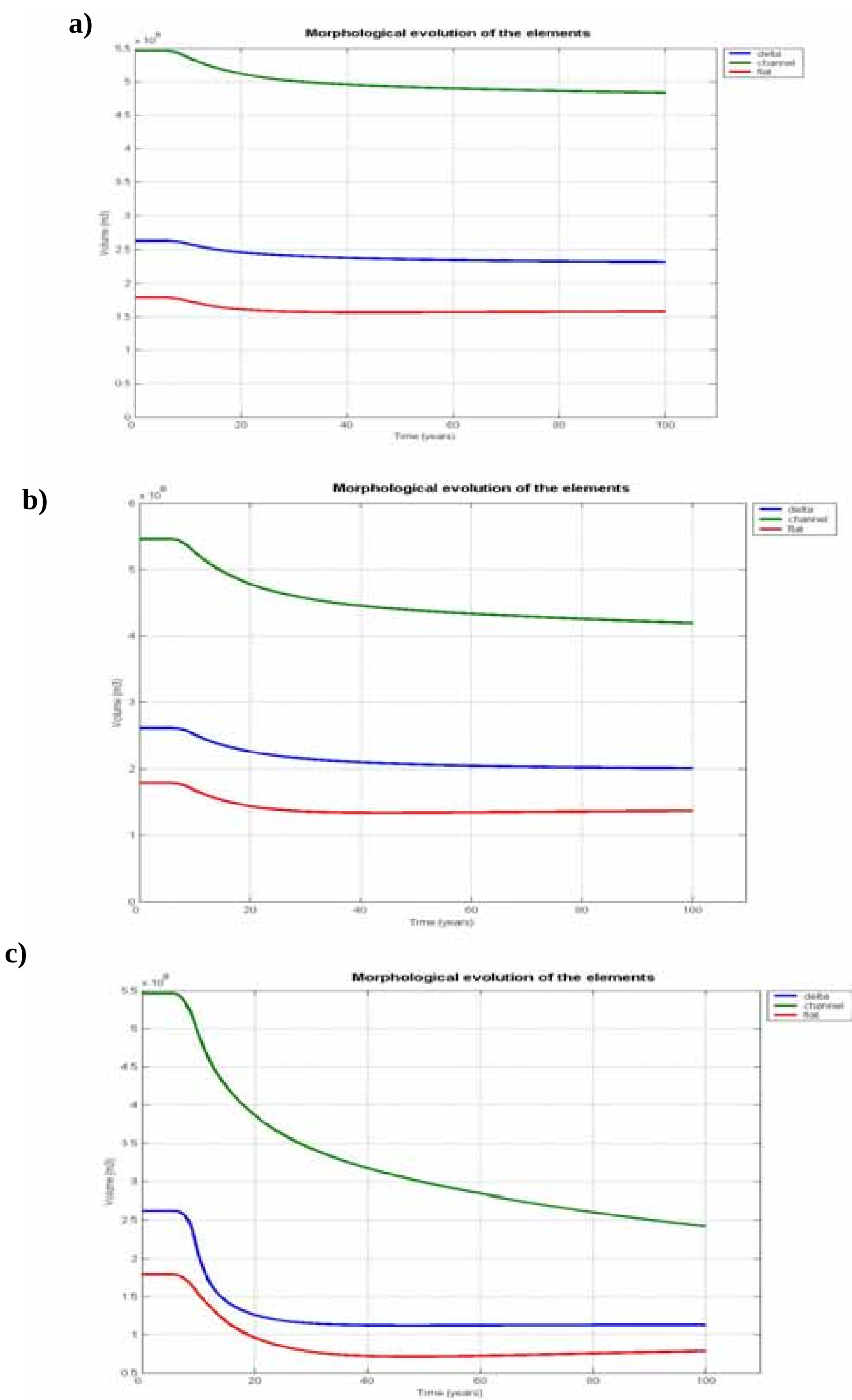
c)



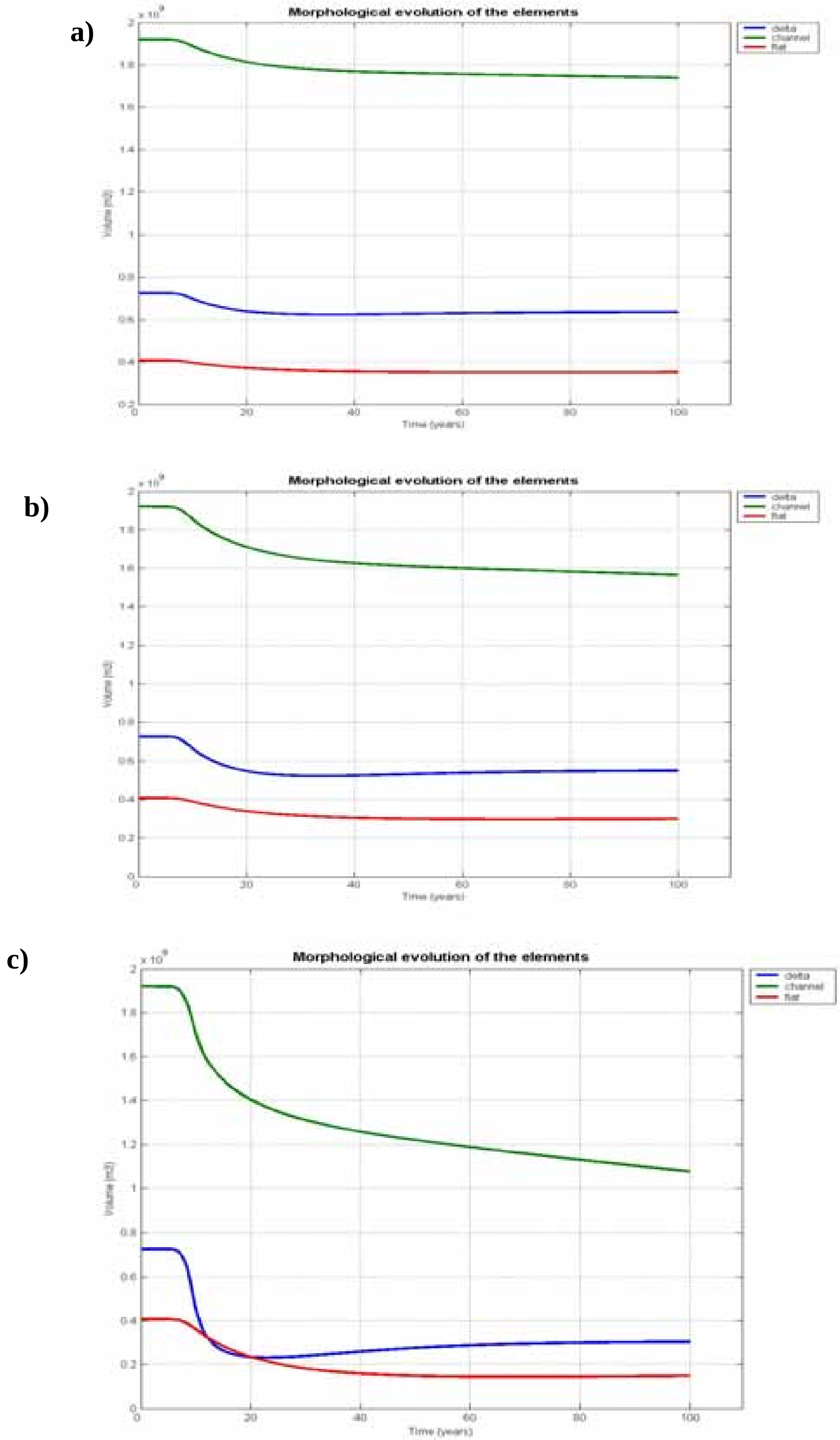
Morphological evolution of Borndiep imposing an abrupt increase of basin area [10% a); 20% b); 50% c)], within 5 years



Morphological evolution of Vlie imposing an abrupt increase of basin area [10% a); 20% b); 50% c)], within 5 years



Morphological evolution of Borndiep imposing an abrupt decrease of basin area [10% a); 20% b); 50% c)], within 5 years



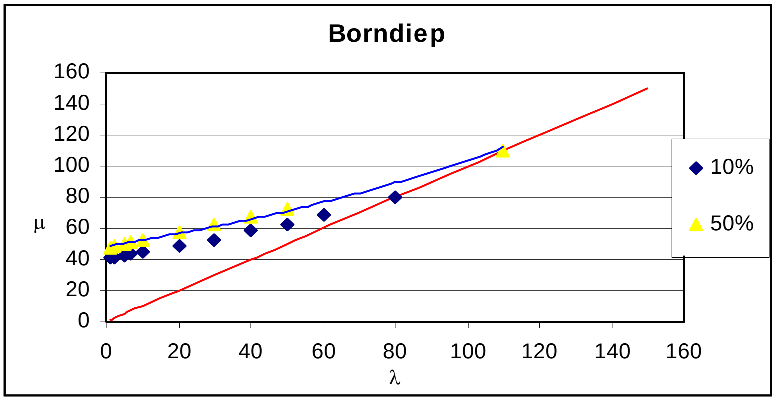
Morphological evolution of Vlie imposing an abrupt decrease of basin area [10% a); 20% b); 50% c)], within 5 years

Appendix H Sensitivity analysis on system time-scale

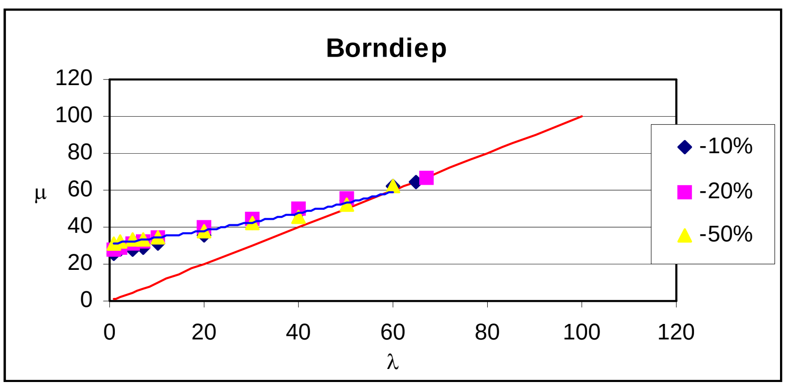
Appendix H Sensitivity analysis on system time-scale

H1A Disturbance on the system (Borndiep)

a)



b)

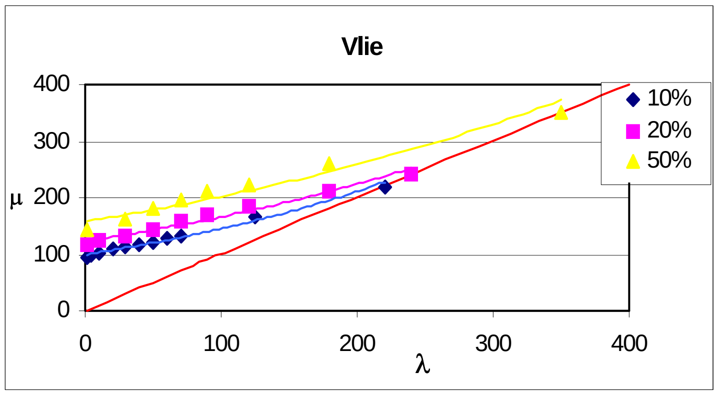


Effect of different disturbances on the system time-scale a)increase of the basin area;b)decrease of the basin area (Borndiep)

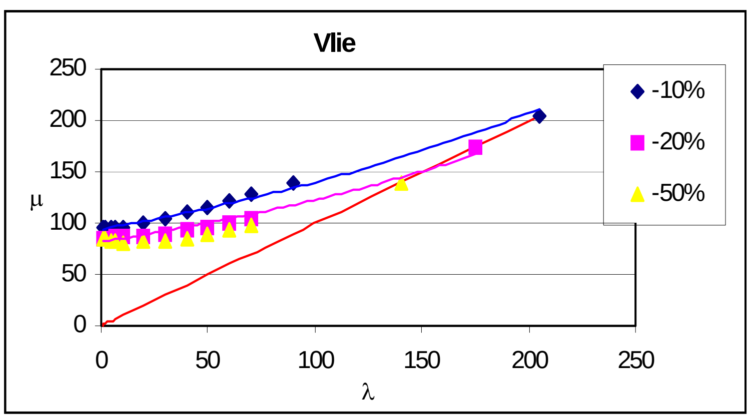
H1 B **Disturbance on the system (Vlie)**

H1B **Disturbance on the system (Vlie)**

a)



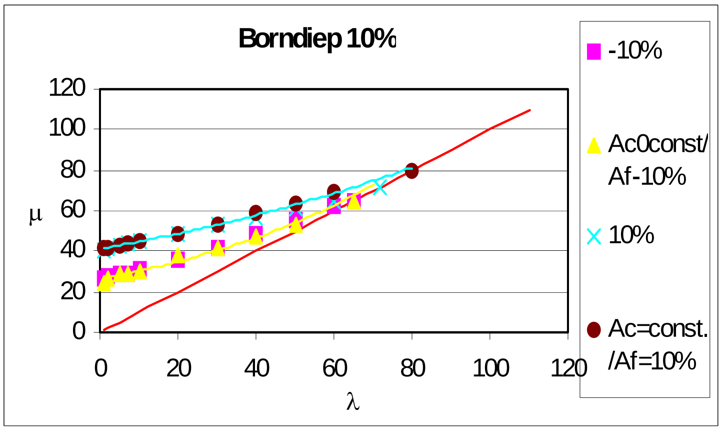
b)



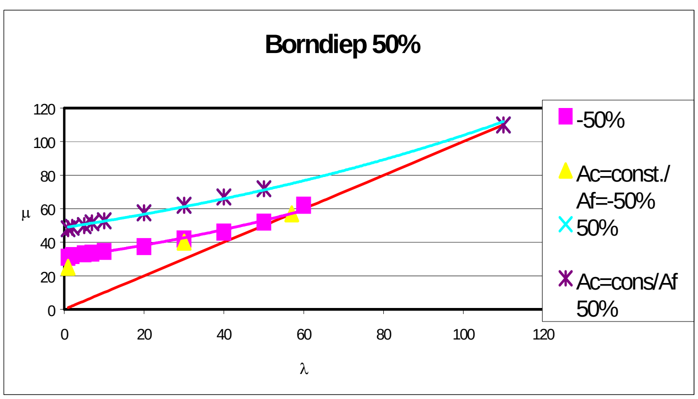
Effect of different disturbances on the system time-scale a)increase of the basin area;b)decrease of the basin area (Vlie)

H2A **Influence of the channel area (Borndiep)**

a)



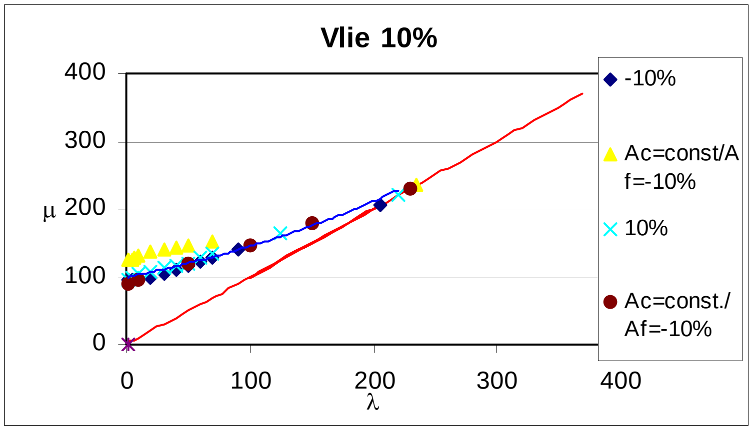
b)



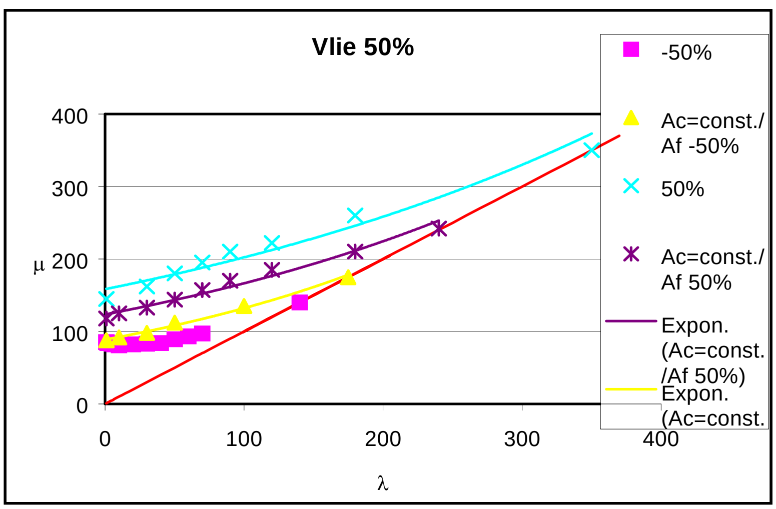
Influence of the channel area, for different disturbances, on the system time-scale
a) 10%;b) 50%
(Borndiep)

H2B **Influence of the channel area (Vlie)**

a)



b)



Influence of the channel area, for different disturbances, on the system time-scale
a) 10%;b) 50%
(Vlie)