Exploratory Research into the Maintenance of the Slijkgat

An Analysis of the morphology of the Haringvliet

Renske de Winter

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Report

August 2008

Preface

This thesis concludes the Master of Science program at the Faculty of Civil Engineering and Geosciences at the Delft University of Technology, The Netherlands. The specialisation within my master program was hydraulic engineering and more specifically on coastal engineering.

The research done the last months focused on the morphological developments of the Slijkgat in the Haringvliet. A very interesting area to research since lots of theoretical knowledge gained during my college years could be put into practice during this thesis and I ended up learning a lot more, something I really enjoyed.

During my thesis I had the opportunity to get to know two companies: the Port of Rotterdam and Deltares. At the Port of Rotterdam I was part of the Project Organisation Maasvlakte 2, I found it very special and inspiring to witness the process of a mega process as Maasvlakte 2. The cooperation with Deltares (former WL|Delft Hydraulics) made it possible to bring the study to a higher level.

I would like to thank Prof. Stive and Mr Vellinga by helping me to find topic for research and support during my thesis. Secondly I would like to thank Prof. Roelvink, Mr Wang, Mr Labeur and Mr Boer for their time, interest and great support they gave me by sharing their knowledge. Finally I would like to thank Arjen Luijendijk, my daily support at Deltares, for his continuous support, accessibility and interesting discussions.

Apart from my supervisors I would like to thank my Deltares graduation colleagues, for their comments, support and laughter: Claartje, Johan, Anton, Gao, Marten, John, Robert, Laura, Thomas, Carola, Thijs, Claire and Steven.
Special thanks go to my family and especially my parents, who gave me the opportunity to attend university. Moreover I would like to thank Daan for his interest, encouragement, support and patience.

Renske de Winter
August 2008

Summary

This thesis is an exploratory research into the maintenance of the Slijkgat, by analysing the morphological behaviour of the Slijkgat and the Haringvliet. The Slijkgat is the approach channel for the fishery harbour of Stellendam. The delta area west of the Haringvliet Dam started to accrete after the construction of the dam around 1970, therefore maintenance dredging became necessary. Recently it was decided to deepen the channel over a width of 100 m from -5.00 NAP to -5.50 NAP and to maintain this depth. Based on the Stakeholder Agreement for Maasvlakte 2 the municipality of Rotterdam will become responsible for this deepening and maintenance. The responsibility for the implementation is transferred to Project Organisation Maasvlakte 2 of the Port of Rotterdam.

This study investigates the possibilities for maintaining the Slijkgat; the possible maintenance scenarios are based on future morphological developments. These future developments are derived from a historical morphological analysis. This analysis is based on bed level measurements and Delft3D Flow calculations. Data sets of 1986, 1992, 1998 and 2003 were used and these data were compared. From this analysis it can be concluded that the sediment volume in the total study area is approximately stable, but that the sediment volume is shifted within the area. The Inner Area has become shallower, while the Outer Area has eroded. The Delft3D Flow calculations show that the amount of water that is discharged through the Slijkgat has increased in the period 1986 -2003.

In the future the Slijkgat will most likely remain open as a result of river discharges. The dimensions of the cross-sectional area of the Slijkgat depend on these high river discharges, since these move sediment from the channel. As a result the Slijkgat is in a dynamic equilibrium since these high river discharges only occur a few times per year. The rest of the year the Slijkgat is accreting. The past ten years ebb and flood channels have developed in the Slijkgat. As a result the bed level in the Slijkgat is varying. Although the dimensions of the cross-sections increase in general due to the increase of tidal volume, some locations will remain around -4.5 to -5 m NAP due to ebb and flood channels.

To utilise the system dynamics, the dependency of the cross-sections on river discharge is used as base for the scenarios. During high river discharge current velocities are high in the Slijkgat and sediment is transported, which makes that the channel dimensions increase. This principle is used for the formulation of different scenarios, which are all evaluated based on the increase of current velocities in the Slijkgat.

In general it can be concluded that velocities in the Slijkgat can increase by opening the sluices during a shorter period. For the shallow areas near the sluices these effects are significant. Where the Slijkgat meets the Outer Area velocities decrease and the effects of the change in discharge regime is less noticeable. A permanent change in closing policy can reduce the maintenance activities at the locations closest to the sluices.

A new closing policy that will be implemented is 'de Kier'; the sluices will opened during high water and salt water will enter the fresh water reservoir. If this new policy is implemented current velocities will increase in the Slijkgat, since the total amount of water will increase. Furthermore discharging through only the southern or the northern sluices does not make a difference for the current velocities.

This thesis is part of the Master Hydraulic Engineering at Delft University of Technology. The research study is carried out in collaboration with the Port of Rotterdam, Project Organisation Maasvlakte 2 and Deltares.

Samenvatting (Summary in Dutch)

Dit afstudeeronderzoek is een verkennende studie naar het onderhoud van het Slijkgat. Slijkgat is de aanvaargeul voor de vissershaven van Stellendam. Het onderzoek is uitgevoerd door het morfologische gedrag van het Slijkgat en de Haringvliet te onderzoeken. Het deltagebied west van de Haringvlietdam is gaan aanzanden na het afsluiten van de zeearm de Haringvliet. Een gevolg hiervan was dat het Slijkgat gebaggerd moest worden om voldoende diepgang te behouden. Onlangs is besloten om het Slijkgat te onderhouden op een diepte van -5 m over een breedte van 100 m, in de toekomst zal de geul verdiept worden naar -5,5 m eveneens over een breedte van 100 m. Naar aanleiding van het Stakeholdersakkoord voor Maasvlakte 2 zal de gemeente Rotterdam zorg dragen voor deze verdieping en de instandhouding daarvan. De verantwoordelijkheid voor de uitvoering hiervan is gelegd bij de Projectorganisatie Maasvlakte 2 van het Havenbedrijf Rotterdam N.V.

Dit onderzoek analyseert de mogelijkheden voor het onderhouden van het Slijkgat in lijn met de natuurlijke ontwikkelingen. De mogelijke onderhoudsscenario's zijn gebaseerd op toekomstige morfologische ontwikkelingen van het Slijkgat. Deze toekomstige ontwikkelingen zijn afgeleid van een morfologische analyse. Deze analyse is gebaseerd op bodemdata en berekening gemaakt met Delft3D Flow. Bodem data was beschikbaar van 1986, 1992, 1998 en 2003, deze jaren zijn ten opzichte van elkaar vergeleken. Uit deze vergelijking blijkt dat het sedimentvolume van het totale studiegebied ongeveer stabiel is, het wordt echter wel herverdeeld binnen het gebied. Het intergetijde gebied is aan het aanzanden, terwijl de buitendelta aan het eroderen is. Delft3D Flow-berekeningen laten zien dat het totale volume water dat wordt afgevoerd door het Slijkgat toeneemt in de periode 1986 – 2003.

Het Slijkgat zal in de toekomst open blijven ten gevolgen van rivierafvoeren. De afmetingen van het Slijkgat zijn afhankelijk van hoge rivierafvoeren, aangezien dan erosie optreedt in de geul. Het Slijkgat verkeert in een dynamisch evenwicht, aangezien hoge rivierafvoeren slechts een aantal keer per jaar optreden. Het overige deel van het jaar is het Slijkgat aan het aanzanden. De afgelopen tien jaar zijn er eb- en vloedscharen ontstaan in het Slijkgat. Dit resulteert in een variërende bodemligging. Ondanks dat de dimensies van het Slijkgat in zijn algemeenheid toenemen, blijven er ondieptes ontstaan door de aanwezigheid van eb- en vloedscharen.

Om de dynamica van het systeem te benutten, is de afhankelijkheid van rivierafvoer als onderzoeksuitgangspunt genomen. Tijdens deze hoge rivierafvoeren zijn de stroomsnelheden in het Slijkgat hoog en wordt sediment getransporteerd, waardoor de afmetingen van de geul toenemen. Dit principe is gebruikt voor de verschillende scenario's. Alle scenario's hebben als doel de stroomsnelheden in het Slijkgat te laten toenemen en zijn op basis hier van beoordeeld.

In zijn algemeenheid kan gesteld worden dat stroomsnelheden in het Slijkgat toenemen als de Haringvlietsluizen gedurende een kortere periode geopend worden. Op deze manier wordt dezelfde hoeveelheid water geloosd in een kortere periode, wat leidt tot een hoger debiet gedurende een kortere periode. Voor ondieptes dicht bij de sluis zijn de toenamen in stroomsnelheid significant. Daar waar het Slijkgat uitstroomt in zee zijn de effecten van een toename in stroomsnelheid kleiner. Een permanente verandering in sluisbeleid kan leiden tot minder onderhoudsbagger werk in het deel nabij de sluizen.

Een nieuw sluitingsbeleid dat binnenkort ingevoerd wordt is 'de Kier', de sluizen zullen dan tijdens hoog water openstaan zodat zout water het zoete Haringvlietmeer kan binnendringen. Als dit wordt geïmplementeerd zullen de stroomsnelheden in het Slijkgat toenemen, aangezien het totale volume water dat gedurende een getijperiode door het Slijkgat stroom toeneemt. Daarnaast is ook onderzocht of het spuien door de zuidelijke of de noordelijke sluizen verschil maakt. In de simulaties maakt het voor de stroomsnelheden en de volumes water in het Slijkgat niet uit welke sluizen er gebruikt worden.

Dit afstudeeronderzoek is een onderdeel van de Master Hydraulic Engineering van de Technische Universiteit Delft. Het onderzoek is uitgevoerd in samenwerking met het Rotterdamse Havenbedrijf, Project Organisatie Maasvlakte 2 en Deltares.

Contents

Appendices

List of Figures

1 Introduction

This thesis is part of the Master Hydraulic Engineering at Delft University of Technology. The research study is carried out in collaboration with the Port of Rotterdam, Project Organisation Maasvlakte 2 and Deltares. In this chapter the background and the objectives of the project are discussed.

1.1 Background of project

The Slijkgat is a channel located in the Haringvliet mouth, the first tidal inlet south of Rotterdam in the south-western part of the Netherlands. The Slijkgat is the approach main channel for the fishery harbour of Stellendam, near the Haringvliet Sluices. The Slijkgat is the life line for the fishing activities in Stellendam. However, it is also used as a hinterland connection. Figure 1 shows the mouth of the Haringvliet.

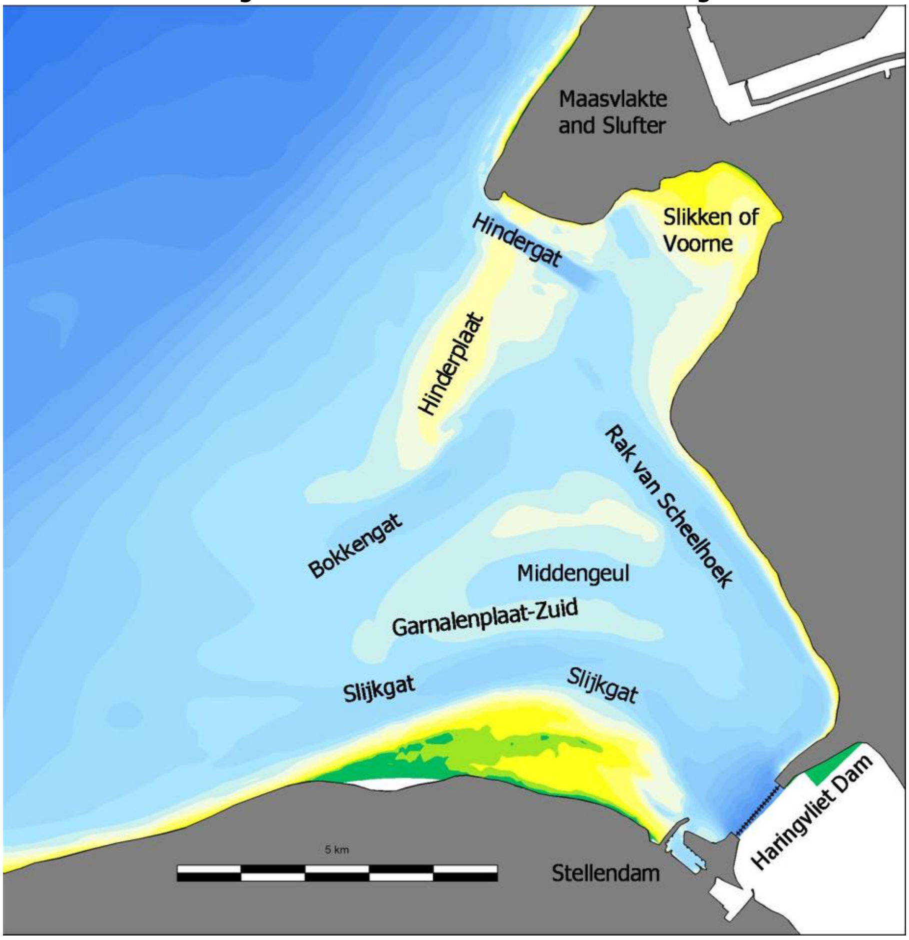

Figure 1 Mouth of the Haringvliet

The Haringvliet west of the dam started to accrete after the construction of the Haringvliet Dam. After the closure of the Haringvliet Estuary the Department of Waterways and Public Works (Rijkswaterstaat) became responsible for keeping sufficient navigation depth in the channel. Other channels in the mouth of the Haringvliet also became shallower due to the changing hydraulic conditions. It is expected that two future developments, the opening of the Haringvliet Sluices during high water and the construction of Maasvlakte 2 will influence the morphological development of the Haringvliet Mouth. The maintenance dredging of the Slijkgat can play a crucial part in the morphological development of the mouth of the Haringvliet. It has been decided to deepen the channel over a width of 100 m from -5.00 NAP to -5.50 NAP and to maintain this depth. Based on the Stakeholder agreement for Maasvlakte 2 the municipality of Rotterdam will become responsible for this deepening and maintenance. The responsibility for the implementation is transferred to Project Organisation Maasvlakte 2 of the Port of Rotterdam.

1.2 Objectives

The main objective of this thesis is to do an exploratory study into the maintenance of the Slijkgat after it is deepened.

The main objective is derived into two sub-objectives:

- Morphological analysis of the development of the Slijkgat with the aid of numerical modelling and historical data.
- Prediction of the future morphological behaviour of the mouth of the Haringvliet

1.3 Methodology

To reach the objective of the study, the first sub-objective was to analyse the morphological system of the Haringvliet. The Slijkgat is part of the mouth of the Haringvliet and therefore the complete morphological system of the Haringvliet has been analysed. This analysis was based on measured bed level data and numerical flow computations. Although the goal of this thesis was to provide morphological predictions, only flow calculations have been made, since it is complex to model a morphological situation on the scale of the Slijkgat. For the numerical flow computations an existing Delft3D model has been used.

This historical analysis will provide insight in the dynamics of the morphological system. Future developments of the Haringvliet Mouth can be derived from this historical analysis. Depending on the development of the system different maintenance scenarios will be formulated. The efficiency of these scenarios has been evaluated. In combination with the morphological analysis a morphological maintenance approach has been formulated. Figure 2 presents the flow chart of the study.

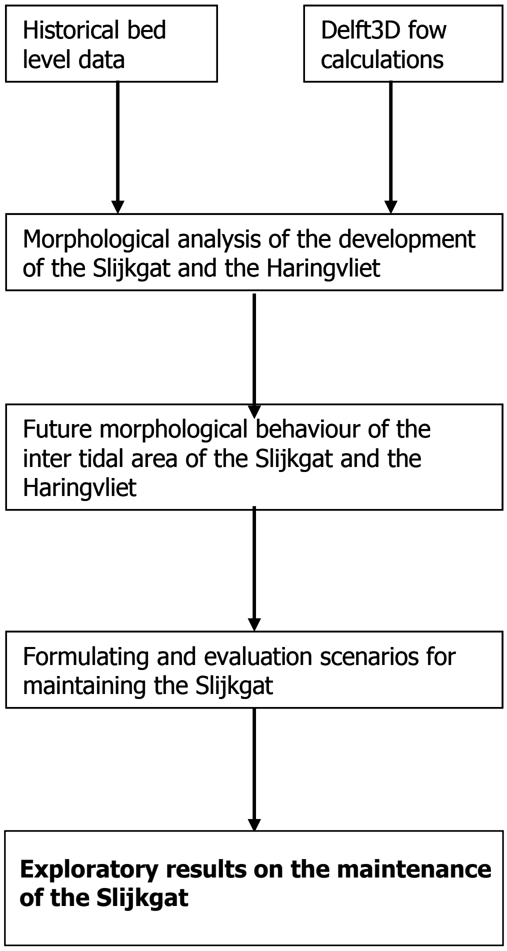

Figure 2 Flow chart of the project

1.4 Reader's guide

Chapter 2 gives a summary on the human interventions in the Haringvliet. This chapter also discusses the hydrodynamics and morphodynamics of the Haringvliet. The analysis of the morphological system is described in Chapter 3. This analysis is based on bed level data and numerical flow calculations. Chapter 4 presents the expected future morphological development of the Haringvliet and possible scenarios on the maintenance of the Slijkgat. The evaluation of these scenarios, which leads to the main objective of this thesis, is discussed in Chapter 4. The main conclusions and recommendations of this thesis are given in Chapter 5.

2 The Haringvliet Estuary, Interventions and Dynamics

2.1 Introduction

This chapter provides a literature review on the area of interest. The area of interest is the Haringvliet estuary, the area west of the Haringvliet Dam. This area has been studied since the developments in the Slijkgat depend on the developments in this area. This study looks into the developments in the Slijkgat. However, the area of interest is larger.

This chapter first discusses the interventions which have influenced the delta area in the last 60 years (Section 2.2). Subsequently the dynamics of the Haringvliet are discussed. Section 2.3 describes the hydrodynamics. Among other things the influence of tide and river discharge are discussed in this section. The morphodynamics in the Haringvliet have been changed drastically due to the (human) interventions, of which the siltation of the mouth stands out. This and other morphodynamic aspects will be discussed in Section 2.4.

2.2 Interventions

In the last 60 years the Haringvliet has been influenced by several human interventions, which all have influenced the morphological development of the Haringvliet. An overview of these interventions is presented in Figure 3. The Haringvliet area is presented in Figure 4.

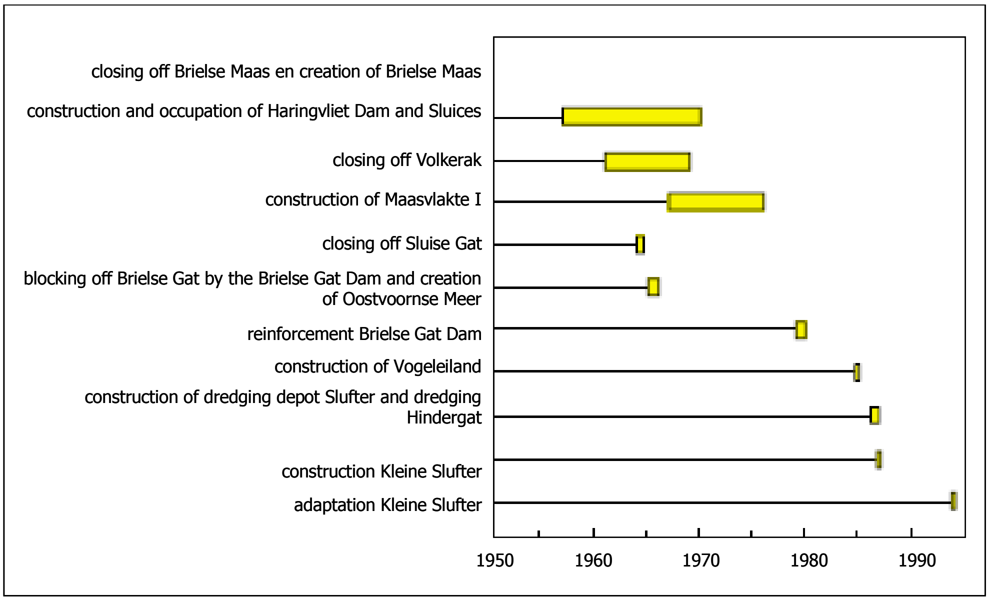

Figure 3 overview of engineering activities [based on: van Vessem 1998]

Figure 4 The Haringvliet Area

The series of interventions started by the closing of the Brielse Maas, in 1950. Three years later in 1953 the southern part of the Netherlands was flooded after a storm surge. As a reaction to this flooding a safety plan was formulated, named the Delta Plan. A part of this plan consisted of the closing of some of the tidal inlets in the southern part of the Netherlands. One of the inlets that was closed as a result of the Delta Plan is the Haringvliet. This inlet was closed by the Haringvliet Dam, in which sluices were constructed for the discharge of river water. In 1958 the construction activities started and the dam was finished in 1970.

Due to this closure of the estuary a large fresh water lake was created east of the Haringvliet Dam. Nowadays this fresh water lake is important to meet the demand for fresh water for drinking water purposes in the western part of the Netherlands. At the same time this dam creates a sharp transition in estuary characteristics and the corresponding ecotypes. The inner area has become shallower as a result of the closing of the estuary; this change of morphology is explained in Section 2.4 .

The reclamation of a new port area north to the Haringvliet started before the Haringvliet Dam was finished. Between 1967 and 1976 the Maasvlakte had been constructed for the expansion of the harbour activities in the Port of Rotterdam. The Maasvlakte was extended approximately ten years later, 1986-1987, with the Slufter. This latter area located to the south east of the Maasvlakte is used for the storage of contaminated dredging material. Due to the construction of the Maasvlakte and the Slufter a special type of flora and fauna has been able to develop in the northern part of the estuary, the Slikken of Voorne. The typical characteristics of this area are: shallow sea, salt marches, overgrown beaches, moreover beaches and dunes are present. This type of environment is not an indigenous phenomenon in the stretched Dutch coast, however it could develop due to the shelter of the Slufter and the Maasvlakte [Van Vessem, 1998].

The Maasvlakte will be extended again in the near future. A new port area will be reclaimed, called Maasvlakte 2. It is expected that Maasvlakte 2 will be completed in 2013. The construction of Maasvlakte 2 may influence the morphology of the Haringvliet Mouth. Some computational models have been developed to calculate the effect of Maasvlakte 2 on the morphology of the Haringvliet Mouth. Those models show that shoals will develop less rapidly, due to lower sediment supply from the north [Roelvink, 2005].

Parallel to the construction of Maasvlakte 2 a new closing policy for the Haringvliet Sluices will be implemented. In this new policy the Haringvliet Sluices are (partly) opened during flood, so salt water can enter the fresh water basin east of the dam during high water. The objective of this change is to reduce the difference between salt and fresh water as it is today. The new closing policy might lead to large volumes of water transported though the inner area west of the Haringvliet Dam.

2.3 Hydrodynamics

Several hydrodynamic processes are present in the Haringvliet Area. Since all these processes have different influences they are discussed separately. Four processes are discussed in this section: tide, wind, wave and fresh river water run off. The influence of processes can differ at different locations in the area.

2.3.1 Tide

Due to Coriolis forcing the tidal wave enters the North Sea from the North and moves counter clockwise around amphidromic points (Figure 5). As a result the tidal wave travels from south to north along the Dutch coast and high water occurs earlier in the south than the north. For the Haringvliet Delta this phenomenon is shown in Figure 46 in Appendix A. The black line represents the water level at the coast of Goeree during a tidal cycle, while the red line represents the water level at Hoek van Holland; a location more to the North. The phase lag between these two locations is approximately 20 min. Ergo the tidal wave enters the mouth of the Haringvliet from the south and residual circulation occurs in this area. The net current in the area is counter-clockwise. Especially around the Hinderplaat the phenomenon of a residual current is strongly present.

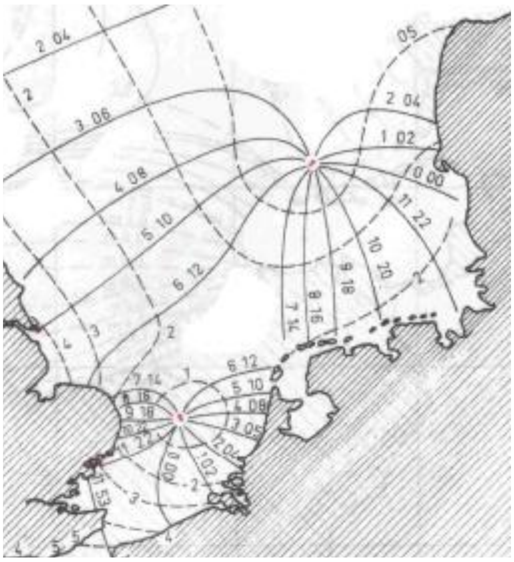

Figure 5 Amphidromic points in the southern North Sea [Wang 2007]

Along the Dutch coast the tide is semi-diurnal. Diurnal means that there are high and low waters, both twice a day. There is a daily inequality, which means that one high water is higher than the other. In front of the coast of Goeree, the average high water is 1.29 meter NAP and the average tidal difference is 2.11 m. At the Haringvliet Dam the average high water is 1.44 m NAP and the average tidal difference is 2.32 m. An overview on the tidal quantities is given in Appendix A.

Before the construction of the dam, the Haringvliet estuary was a long basin and the water level in the basin was out of phase with the water level at sea. After the construction the length which was subject to tidal movement decreased and the Haringvliet became a short basin. Hence the water level is currently in phase with the water level at sea. Since the current is the derivative of the water level change, the flow pattern changed as well after the closure of the Haringvliet Dam. The flow pattern for the situation after the closure is visualised in Figure 6. Below a description of the corresponding phases is given.

After the closure of the Haringvliet Estuary (Figure 6 [Tönis, 2000]).
Phase 1: at high tide, the water enters the estuary at the south side and leaves the estuary at the north side.
Phase 2: about 3 h after high tide, the current inside the entire estuary is in ebb direction.
Phase 3: at low tide, the water enters the estuary at north side and leaves from the south side.
Phase 4: the current at sea is in ebb direction and inside the estuary in flood direction.

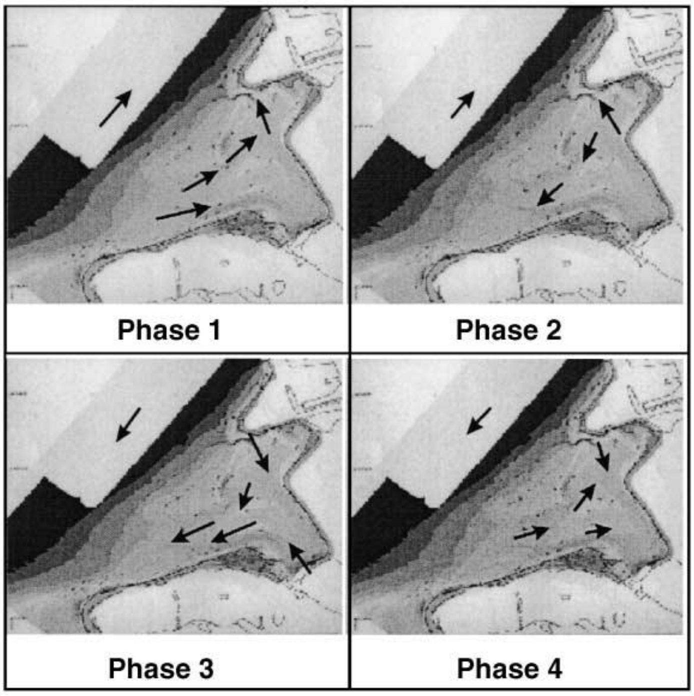

Figure 6 Current directions in the channels during a tidal cycle in the Haringvliet mouth. The tidal cycle had four phases [Tönis 2000]

Figure 7 shows the currents in the Slijkgat which are in correspondence with the flow pattern as described above. This figure shows that the current velocities at sea are approximately in phase with the velocities outside the estuary and approximately the same as in the Slijkgat being 0.75 m/s. The figure also shows that the water level difference near the sluices is approximately 2.5 m with a high water level of 1.7 m.

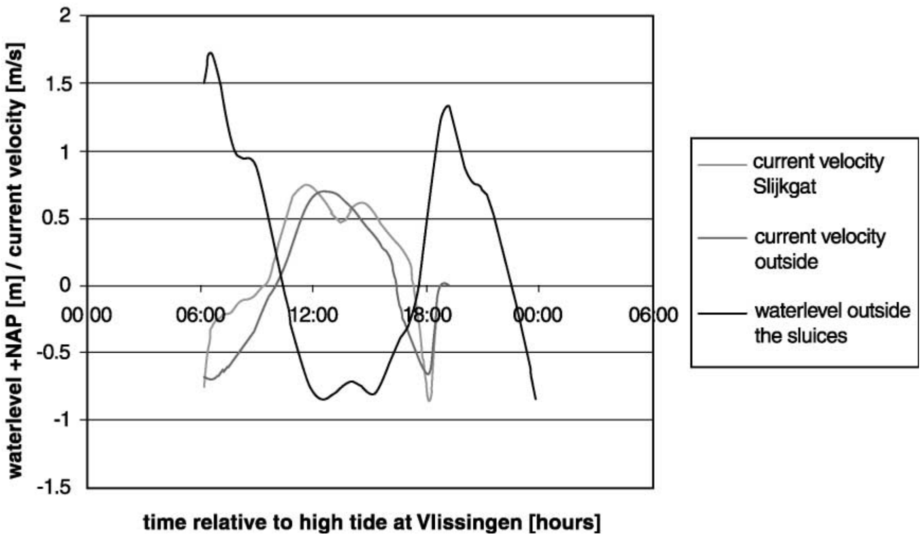

Figure 7 Current velocities in the Slijkgat and outside and water level near the Sluices after closure (ebb current is positive). Horizontal and vertical tide show a phase lag of 90°. The estuary has become a short basin.[Tönis 2000]

2.3.2 Wind

An aspect that is related to wind force is water level set-up. If stresses are directed in a certain direction for a longer period, the generated stress might cause water level set-up as visualised in Figure 8. The length of the fetch is important. The fetch is the length over which the wind stresses occur. A larger fetch means a larger water level set-up. For the Haringvliet area mainly wind form the North West causes set-up, since this direction has the largest fetch. The water level set-up in the Haringvliet can be up to 1.5 m.

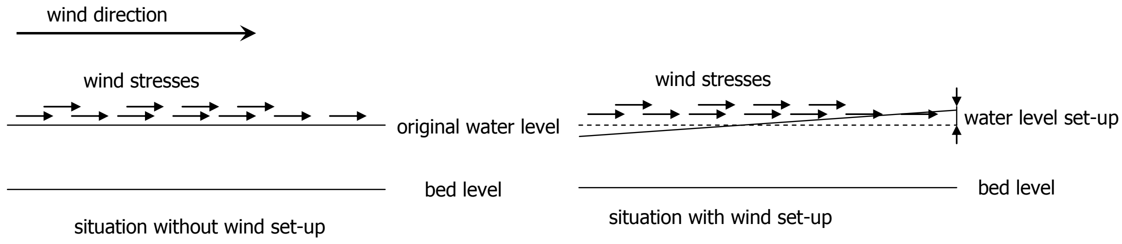

Figure 8 Wind set-up

Processes that also occur in the Haringvliet are wind induced waves and currents. Local wind waves are generated if the wind is blowing over the surface. In the interaction between wind and water the surface stress can generate a wind driven current. Both processes are not studied closer since they will not be subject of investigation in this study, since their influence in morphological behaviour is small.

2.3.3 Waves

A wave climate can be visualised with wave roses. Figure 9 shows wave roses for several areas in the Haringvliet Area. The wave rose shows the relative frequency of occurrences of wave heights for each direction. Different colours represent different wave height classes, the length of a bar represents the relative frequency of occurrences. The influence of wind set-up on the wave has been has been taken into account in Figure 9.

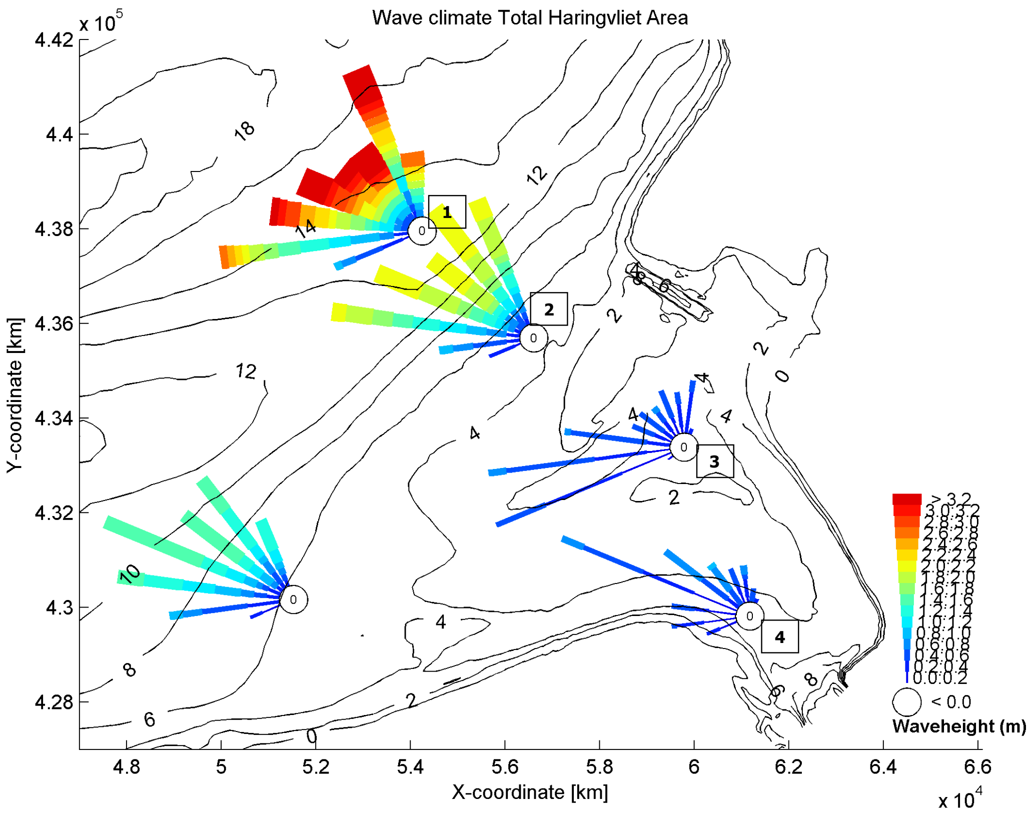

Figure 9 Wave climate in the Total Haringvliet Area (A large copy of this figure is displayed in Appendix A)

Waves are generated offshore before they propagate towards the coast. The wave characteristics change when the waves approach the coast, mainly due to shoaling, refraction and wave breaking. Therefore, first location 1 as shown in Figure 9 is studied since this location is situated relatively offshore (a water depth of -13 m NAP). Most waves at this location are originally from two directions, namely the North West and the South West. The figure shows that the directional sector is from other western directions. Furthermore from Figure 9 it can be derived that from the North West higher waves occur than from the South West and that from the North Western direction waves larger than 3 m occur.

When approaching the Haringvliet the bed level becomes shallower and waves start to change due to shoaling, refraction and wave breaking. This is very well visible at location 2 where the water depth is -4 m NAP. Due to refraction the waves approach the location from a smaller directional sector. Due to wave breaking wave heights have decreased significantly and the largest wave that occurs is 2 m. Wave breaking is visible on the picture below which is taken from the Kwade Hoek (Figure 10).

East of location 2 a sand bar (the Hinderplaat) is located perpendicular to the approach direction of the waves. Location 3 is at the east of the Hinderplaat positioned in the shelter of this sand bar. Although the bed level is higher than at location 2 (> -4 m NAP), smaller waves occur since most of the waves lose wave energy due to breaking. Most waves at location 3 have a south western direction. This side is more exposed to the sea because of the Bokkengat. The last location that is studied is 4, which is near the Haringvliet Sluices. Most waves approach this location from the North West, which means that they are travelling through the Slijkgat. At location 3 and 4 the mean wave height is about 0.4 m and the maximum wave height is about 0.6 m.

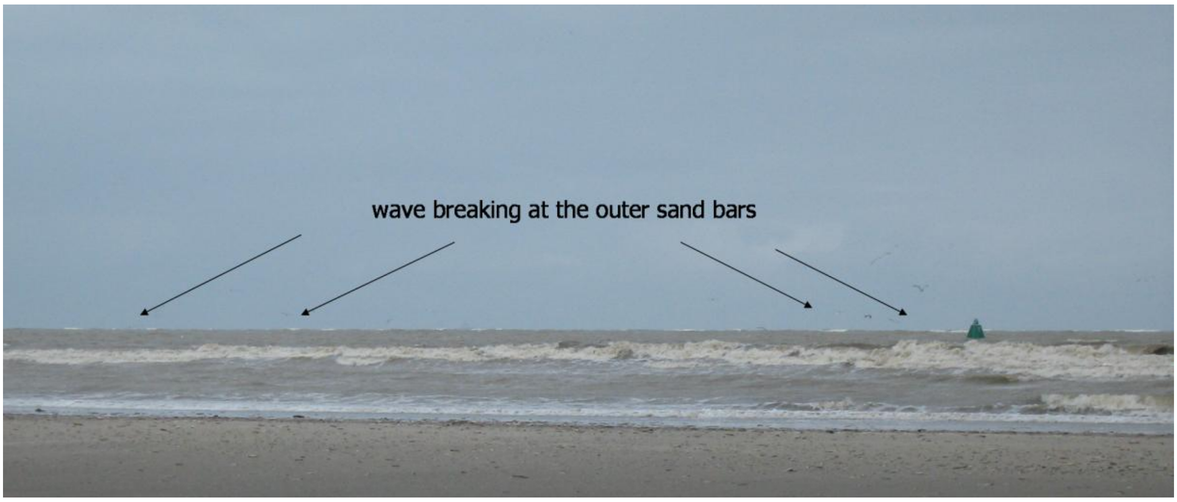

Figure 10 Wave breaking at the outer sand bars. Photo taken from the Kwade Hoek on 18 March 2008.

2.3.4 River Discharge

Before the construction of the Haringvliet Dam river water could discharge naturally. After the closure river water is only discharged through the Haringvliet Dam during low water. The fresh water run-off from the Haringvliet Lake influences the Haringvliet Mouth. Most of the river water is discharged to the sea through the Slijkgat [Van Vessem, 1998]. It may therefore be expected that the river water run-off has a large effect on the dynamics of the Slijkgat. The river discharge from 1992 to 2006 is shown in Figure 11.

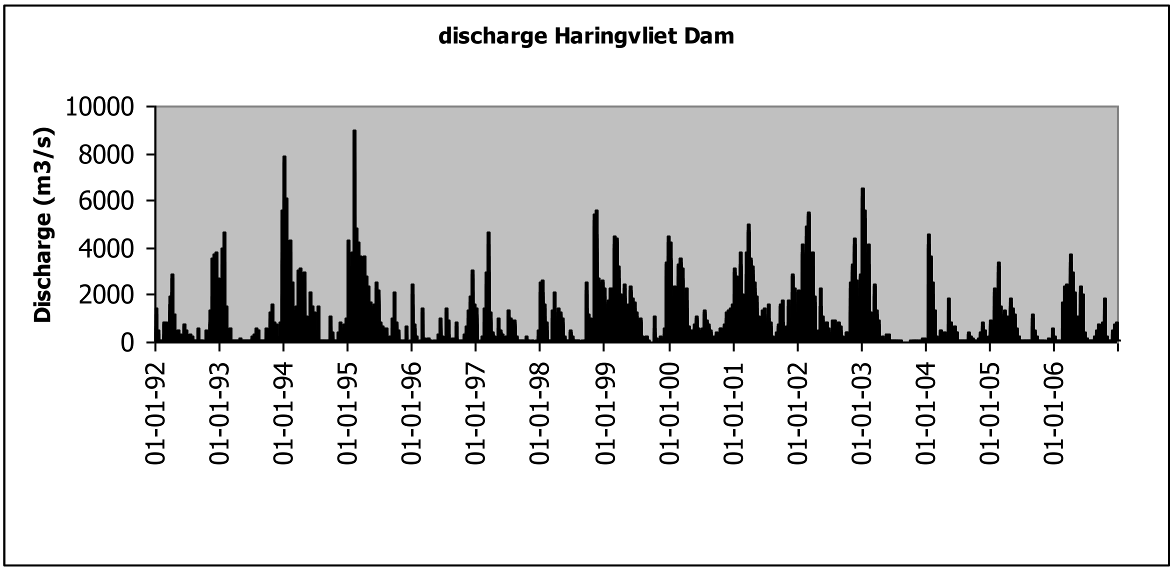

Figure 11 River discharge Haringvliet Dam The discharges are shown in m3/s, this is a daily average. The sluices are only opened during low water (A larger copy of this figure is displayed in Appendix A)

The discharges are shown in m3/s, which is a daily average. The sluices are only opened during low water, so the actual discharge is approximately two time as high. The graph shows that the discharge during summer is sometimes (almost) zero, while the average discharge in winter can be in a very extreme situation up to 9000 m3/s.

2.3.5 Hydrodynamic classification

The hydrodynamic processes do not influence the area in the same manner, since some processes are more dominant than others. To determine what kind of classification the delta has, Hayes (1980) distinguished five classes (Figure 12). Each class has a typical type of coastal development. The classification of Hayes is formulated for tidal inlets and provides prediction for the development of the coast. In this study the Hayes classification is used to give an impression which part of the Haringvliet area is influenced by which process.

In the Haringvliet Delta four locations are picked to determine in which classes they fit. The same locations are used as in Section 2.3.3 on the wave climate (Figure 9). Location 1 is the most western location, location 2 is west of the Hinderplaat, location 3 is north of the Garnalenplaat and location four is near the Haringvliet Dam. For each location the mean wave height is determined by SWAN calculations. It was established that location 3 and 4 have the same mean wave height, therefore these locations are plotted at the same point in the graph. The tidal range of the locations are based on the report of Steijn(2001) (Figure 46, Appendix A).

Figure 12 shows that the most western point (location 1) is classified as wave dominated, changing near the Hinderplaat to the transitional of tide and wave dominated. In the eastern part of the inner area the mean wave height is much smaller (locations 3 and 4) and can therefore be classified as tide-dominated.

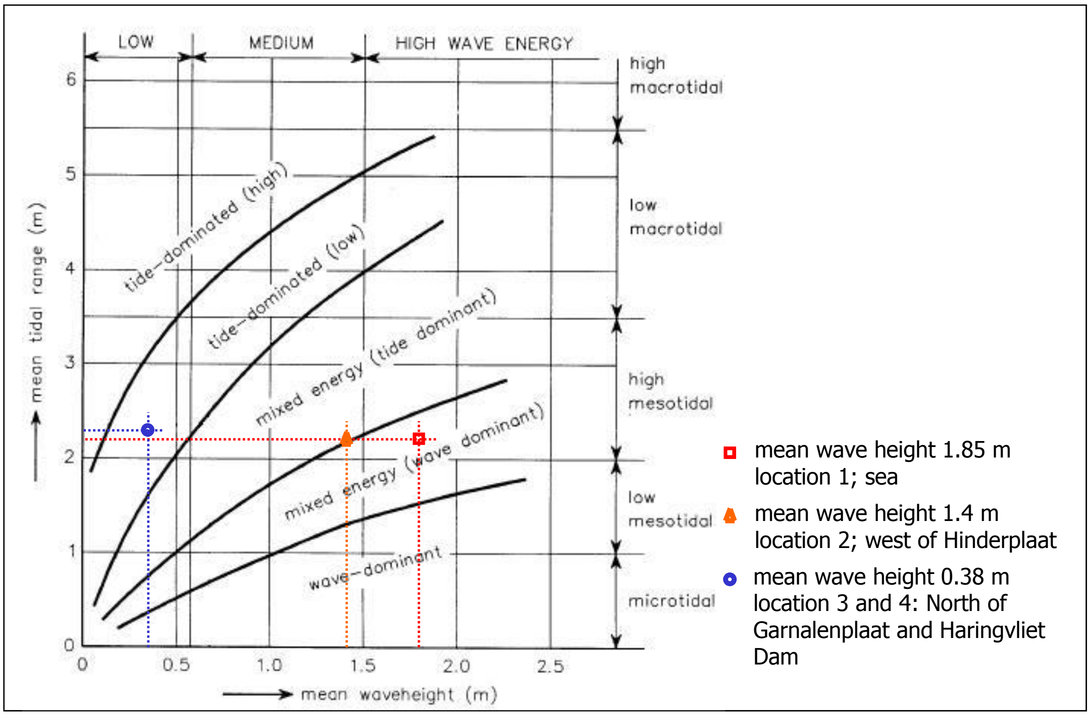

Figure 12 Hydrodynamic classification of tidal inlets, based on Hayes. Location numbers correspond with numbers in Figure 9

The classification of Hayes only takes the tidal range and the mean wave height in consideration. For the Haringvliet Delta the river run off discharged through the Haringvliet Sluices might also be of importance, which is not taken into account in this classification.

2.4 Morphodynamics

This chapter discusses the morphodynamics of the Haringvliet mouth. Section 2.4.2 elaborates on the sediment transport processes. Section 2.4.3 provides background information on the sediment characteristics in the Haringvliet. The dredging activities are discussed in section 2.4.3. The morphology of the Haringvliet has changed drastic after the construction of the Haringvliet Dam, the main changes are discussed in Section 2.4.4.

2.4.1 Transport processes

The hydrodynamic processes discussed in Section 2.3 include several processes by which sediment is transported. These are discussed in this section. Firstly the focus will be on the Haringvliet, followed by the sediment transport processes in the Slijkgat.

Van Vessem (1998) listed the following sediment transport processes for the Haringvliet:

- Tidal currents
- Waves; cross-shore sediment transport
- Waves; long shore sediment transport

- Transport over the Hinderplaat as a result of water level gradient between the west and east side of the sand bar
- Currents as a result of river discharge

Figure 13 gives an overview of the sediment transport processes in the Haringvliet. Along the coast of Goeree and the Slufter coast long shore sediment transport occurs due to wave breaking. Along the coast of Goeree this transport is directed to the North East, while the longshore current along the Slufter coast is directed to the North. The transport along Goeree in the Slijkgat is also tide driven. In the other tidal channels, the tidal currents cause sediment transport as well. In the Slijkgat currents as a result of river discharge also influence the sediment transport.

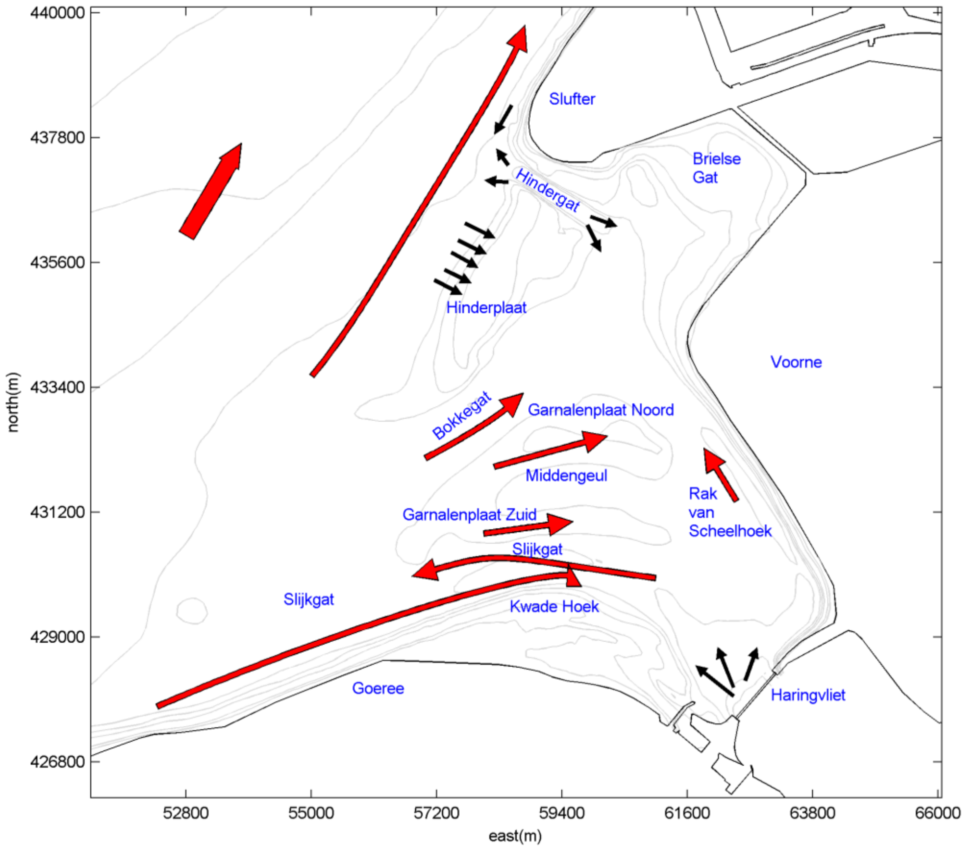

Figure 13 Overview of sediment transport vectors.

The report of Steijn (1998) focussed among other areas on the Slijkgat. In this report a detailed distinction is made between the different types of transport. An overview of the occurring sediment transport in the Slijkgat can be found in Figure 14.

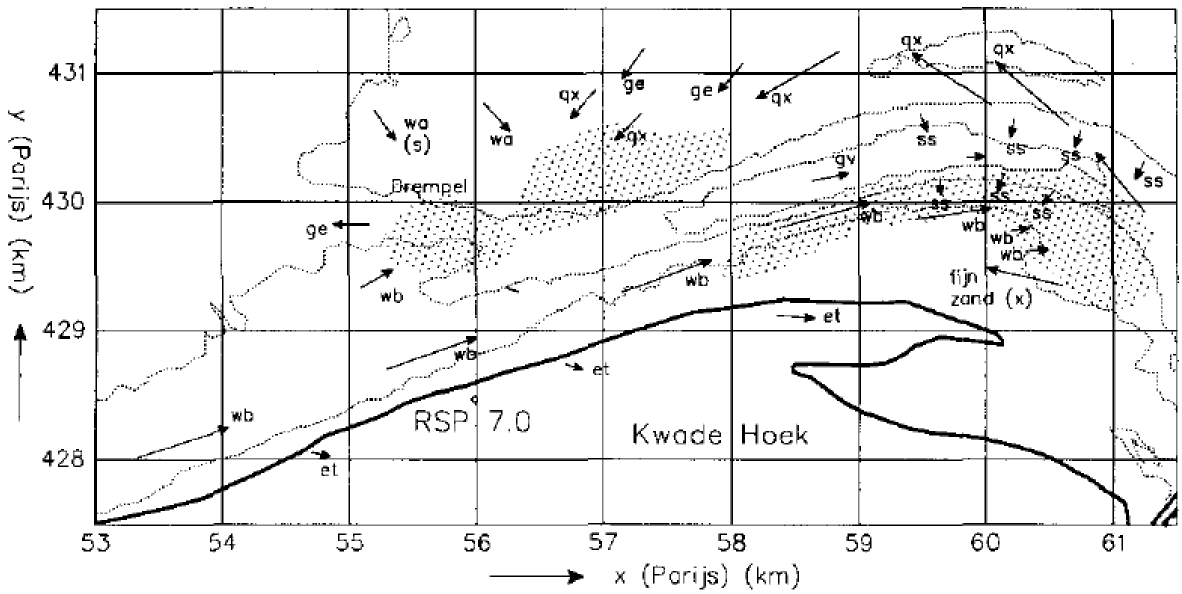

Figure 14 Governing sand transport in the Slijkgat [Steijn 1998]

The corresponding descriptions of the abbreviations are:
et: Aeolian transport(wind driven, above water)
ge: Tidal current, ebb dominated
gv: tidal current, flood dominated
ss: secondary current (circulatory flow/ transversal circulation; Dutch spiraalstroming in de bochten)
wa: waves, wave asymmetry transport (in wave direction)
wb: waves, surfzone transport
s: during storm or storm surges
qx: during extreme sluice discharge through the Haringvliet Dam

The dotted regions represent areas that are silting up. Areas with a tendency to erode. are not present near the Slijkgat.

Before the construction of the Haringvliet Dam, the longshore current along the coast of Goeree was in balanced with the tidal current. After the construction of the Haringvliet Dam, the tidal forcing became less dominant and the Kwade Hoek could extend as a result of the longshore sediment transport.

According to Van Vessem, the morphology of the Slijkgat changes during extreme river discharges. However, there is no change of total volume of sediment within the system. Erosion occurs in the eastern part of the channel, of which the sediment settles at the sill of the channel. The sill is located at the location where the current characteristics change from wave dominant to tidal dominant. The system is wave dominant west of the sill and tide dominant east of the sill [Van Vessem 1995].

2.4.2 Sediment characteristics

This section focuses on the sediment characteristics of the Haringvliet area, where after the characteristics in the Slijkgat are discussed.

At the sea side of the Haringvliet larger sediment can be found than in the eastern areas. Figure 15 gives an overview on the sediment characteristics in the mouth of the Haringvliet. At the Hinderplaat sand with a D50 above 125 μm can be found. Sediment north of the Garnalen Plaat and in the Rak van Scheelhoek have a D50 around 100 μm. In this area and at the Slikken of Voorne relatively large percentage of silt is measured in 1994[Van Vessum, 1998].

The sediment composition of the Slikken of Voorne is remarkable. Besides very fine material also relatively large D50 of 200-225 μm are found in this area. It is most likely that this sediment originates from the Slufter coast.

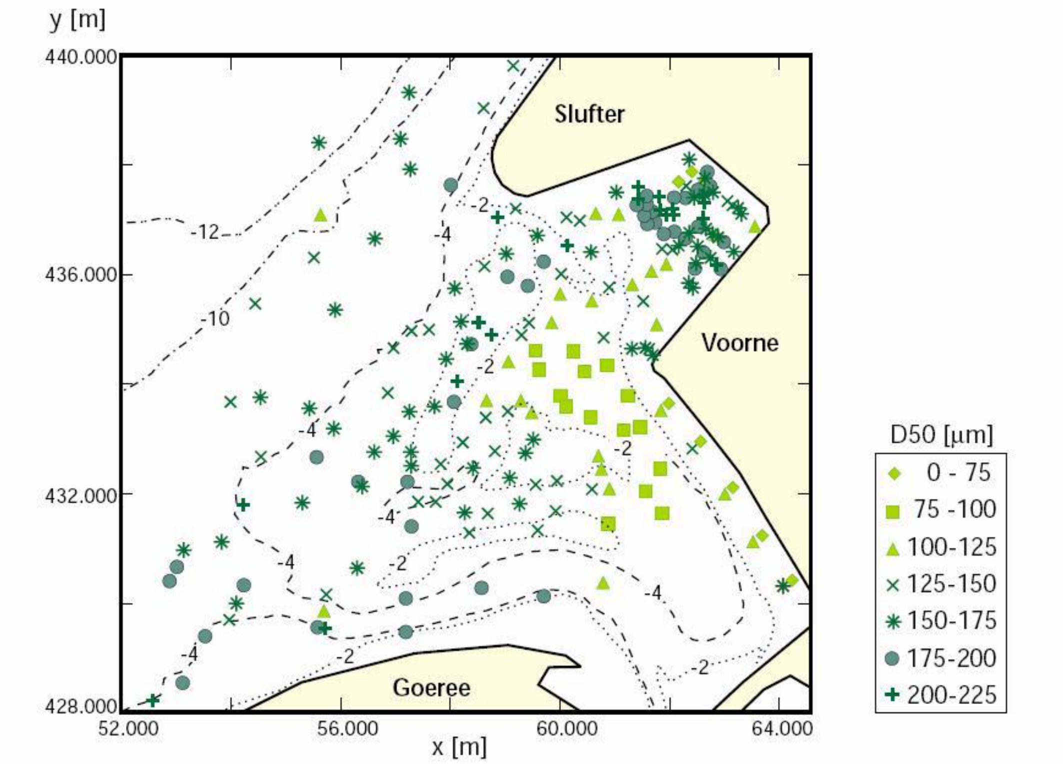

Figure 15 Spatial distribution of median grain size in mouth of the Haringvliet in 1994[after Van Vessum 1998] The contour lines are depth contours.

Recently measured sediment samples in the Slijkgat have been analysed. In the entire channel sand was found. On some locations, the sill among others, very fine sediment was found, although still sand. Dredgers from the Port of Rotterdam experienced very cohesive sand during dredging activities (personal communication). Mainly the northern part of the sill was very cohesive, cohesive sediment is transported at higher velocity. The northern part of the sill will not erode easily.

2.4.3 Dredging activities

Since the Slijkgat is accreting, maintenance dredging has to take place to maintain sufficient navigation depth. There are three information sources on the dredging activities. The first one is literature, which mainly describes the dredging activities before 2000. The second source is data from Rijkswaterstaat on maintenance dredging in 2002. The third and most recent source is personal communication with the Baggerdienst of the Port of Rotterdam, this mostly provided qualitative data.

In Van Vessem (1998) the dredging volumes between 1983 and 1997 are given (Figure 16). The average dredging volume is approximately 265.000 m^3 per year and the dredged material mainly consists of sand. Roughly 50% of the sand was used commercially and extracted from the system. The other 50% is used for nourishments or dumped at disposal areas. The maintenance dredging took place between buoy SG5/6 and SG9/10 (Figure 17).

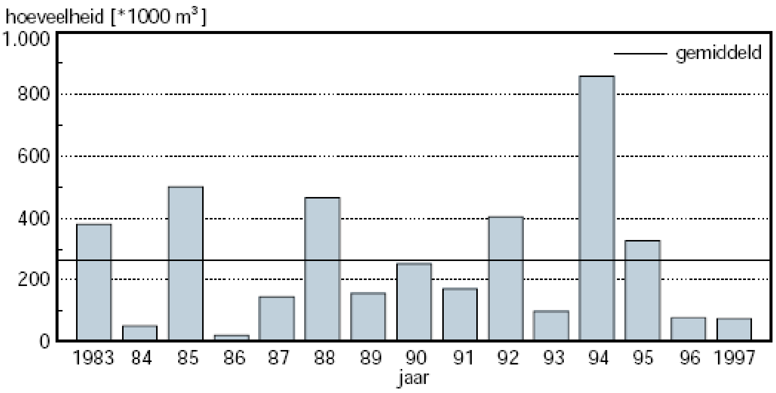

Figure 16 dredging volumes between 1983 and 1997 [van Vessem 1998]

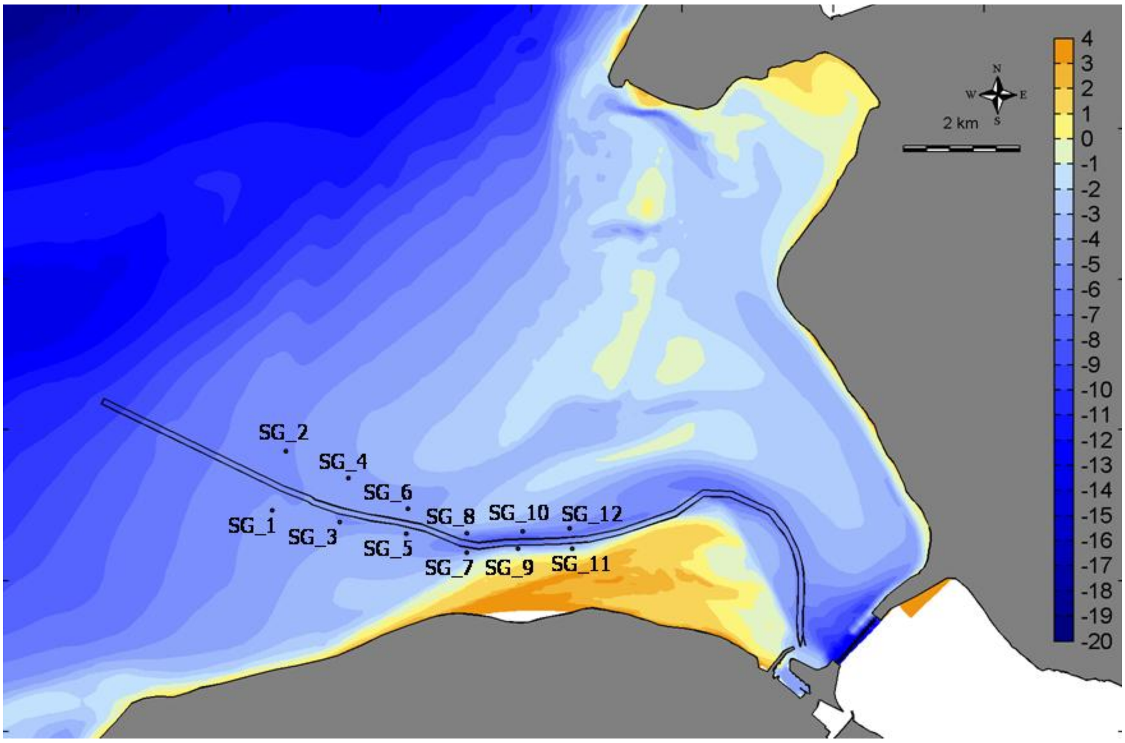

Figure 17 Location approach channel in 2008 (the plotted bed level dates from 2003)

As described in the introduction, after the closing of the Haringvliet estuary the Department of Waterways and Public Works (Rijkswaterstaat) was responsible for maintaining sufficient depth in the approach channel to Stellendam. In 2003 the maintenance responsibility was handed over to the Port of Rotterdam. In Van Vessem (1998) the dredging activities until 1998 are discussed. To complement the data between 1998 and 2003 the Baggerdienst of the direction Noordzee of Rijkswaterstaat provided data from dredging activities in 2002. In 2002 about 105.000 m^3 was dredged. In the experience of Dredging experts of the Port of Rotterdam accretion occurs mainly at the sill.

2.4.4 Changing morphology after the closing of the estuary

After the construction of the Haringvliet Dam the tidal volume in the Haringvliet decreased rapidly. The tidal volume is the total absolute amount of water that passes a cross-section during one tidal cycle. Due to the construction of the dam, no water could pass and this value declined. Before the construction of the dam the dimensions of the cross-sections were in equilibrium with the tidal volume that crossed these cross-sections. Since the closing of the estuary, the channel dimensions were so large that current velocities were relatively low. These low current velocities made it possible for sediment to settle. As a result of this mechanism the mouth of the Haringvliet stared to accrete.

Tönis (2000) has extensively investigated this accretion of the Haringvliet Mouth after the closure by the Haringvliet Dam. Tönis concluded that the sediment volume in the Haringvliet Mouth had increased since 1970. Figure 18 shows the increase in sand volume from 1970 to 2000. This graph shows that the equilibrium situation between the tidal volume and the channel dimensions is almost reached, as the sediment volume has hardly increased in the last years. The calculation on which Figure 18 is based does not include the northern part of the mouth, since the construction of the Slufter Dam has artificially added sediment to the system [Tönis, 2000]. Based on this data one might assume that the situation in the mouth of the Haringvliet is becoming more or less stable. Figure 48 to Figure 50 in Appendix A show the mouth of the Haringvliet in 1957, 1970 and 1995. These figures confirm the developments as indicated above. The two main channels, the Slijkgat and Rak van Scheelhoek, have become shallower since 1970.

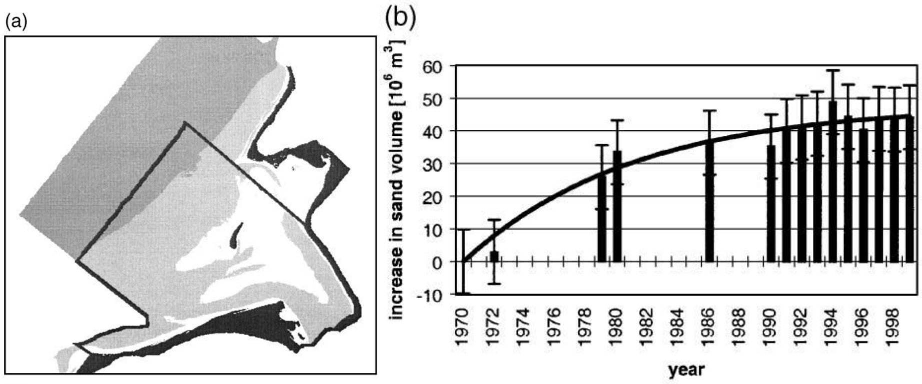

Figure 18(a) Calculation area excluding the area affected by the Slufter Dam. (b) Increase in sand volume in the area relative to 1970. [Tönis 2000]

3 Analysis morphology Haringvliet

In this chapter the morphology of the Haringvliet for the period between 1986 and 2003 is analysed. Based on an analyses of the morphological system during this period, qualitative predictions can be made about the morphological develop in the future. These predictions can help solving the main objective of this thesis: how to maintain efficiently the approach channel the Slijkgat.

In this chapter several areas within the Haringvliet area are investigated. The nomenclature of this area is explained below. The area incapsulated by the red line is the Total Haringvliet Area, the blue area is the Outer Area, while the green area is the Inner Area.

The analysis will firstly focus on each area, starting with the Total Haringvliet Area, the locations of the areas are displayed in Figure 19. The first section will discuss the method used for this analysis. The last section discus the conclusions on the morphologic analysis.

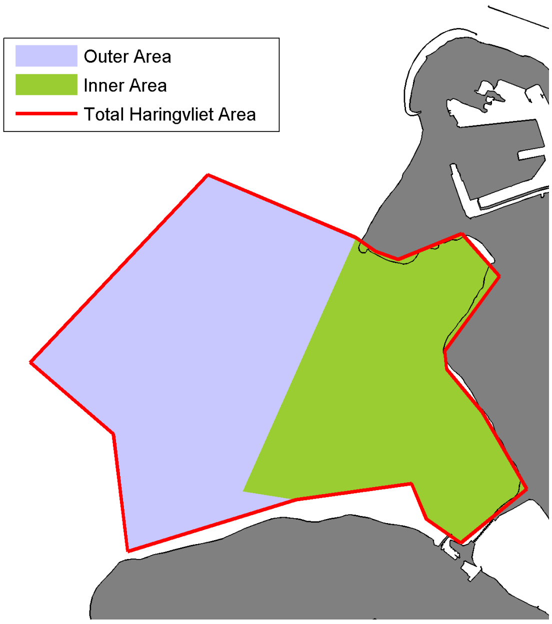

Figure 19 Nomenclature of the areas as studied in this chapter

3.1 Method

The morphological analysis is based on bed level measurements and numerical calculations. The bed level measurements that are used date from 1986, 1992, 1998 and 2003. This data is used to determine trends in bed level movement. This data is also the basis for the sand balance which is calculated for all the areas. The bed level of 1986 is used as a reference point.

With numerical calculations the tidal volumes for different bed levels and different scenarios has been determined. These calculations are also used to provide insight in the current velocities in the tidal channels.
Table 1 below gives an overview on the type of study and the corresponding basis of the analyses. It has to be noted that the Delft3D-FLOW calculation uses bed level of different years, which will be explained in more detail in Section 3.1.1.

Table 1 Overview on the basis of analysis

type of study	**basis of analysis**
Bed level movement	Bed level measurements
Sand balance and hypsometric curve	Bed level measurements
Tidal volumes through tidal channels	Delft3D-FLOW simulations and bed level measurements
Distribution of tidal volume	Delft3D-FLOW simulations
Current velocities in the tidal channels	Delft3D-FLOW simulations

3.1.1 Haring Relation

If a tidal system is in equilibrium, a relation between cross-sectional area and the volume of water flowing through this channel during ebb, flood or full tidal cycle can be established. This section will elaborate on this relationship and on the specific situation for the Haringvliet as formulated by Haring in 1967.

The average current during a tidal cycle is defined as the tidal volume divided by the channel cross-sectional area and the tidal period. Tidal volume is the sum of the absolute volumes passing a cross-section during ebb and during flood. There are also methods which use the ebb or flood volume or the tidal prism (P) In this study the tidal volume is used, since the river discharges can be a large part of the total volume and when using the tidal volume this river discharge is taken into account. The average tidal current v is therefore expressed as:

$$v = \frac{TV}{A_c \cdot T} \qquad (3.1)$$

where:

TV = tidal volume(which includes the river discharge) $\left[m^3\right]$,

A_c = cross-sectional area of inlet channel below MSL $\left[m^2\right]$,

T = time of tidal period $\left[s\right]$.

At low velocities sediment has the possibility to settle, while at high velocities sediment can be picked up and transported. Both depend on the sediment characteristics. Since the velocities depend on the tidal volume and the channel dimension a relationship can be found between the channel dimensions and the tidal volume. The basic form of this relation is given by:

$$A_e = \alpha \cdot TV \tag{3.2}$$

A_c = equilibrium dimension of cross-sectional area $\left[m^2\right]$,

α = empirical coefficientt $\left[m^{-1}\right]$.

The coefficient α depends on:

- average tide, neap tide or spring tide
- ebb or flood dominance of a channel
- salinity influence in the vertical
- wave impact
- size and shape of the storage area
- presence of men made structures
- relation between the width and the depth of a channel (or the hydraulische radius)
- bed roughness
- grain size in suspension and bed load
- magnitude of the sediment transport, mainly at shallow water

Haring (1967) was the first who formulated this relation for tidal channels along the Dutch coast. He found the following relation for the Haringvliet Area:

$$A_c = 3.785 \cdot 10^{-5} \cdot TV \tag{3.3}$$

After Haring's study, several other studies were carried out for the Haringvliet to refine this formula. Arends (1997) compared several studies and concluded that Harings formulation was the most accurate. Therefore Harings formula (2.3) is used in this chapter as the reference situation for the Haringvliet Inner Area.

3.1.2 Delft3D model

The simulations used in this study are based on an existing model [Roelvink 2005]. This chapter discusses briefly the settings of this model. Although the interest of this study is the morphological development, only hydrodynamic calculations are made since this gives an indication on the current velocities. Sediment transport will be initiated among others by current velocities. So based on the current velocities the effect on the morphological development can be estimated. Morphological modelling on the scale of the Slijkgat is difficult, since the main dynamics occur due the presence of ebb and flood channels (Section 3.4.1). These local effects are difficult to model and require much more resolution of the model.

The hydrodynamic calculations are not forced by waves, since the hydrodynamic classification of Hayes (Section 2.3.5) showed that the Inner Area is mainly tide dominated.

River discharge can influence the flow pattern in the Haringvliet mouth and is therefore applied at the system. River discharge is in all simulations enforced at the Nieuwe

Waterweg, north of the Haringvliet Area. The river discharge through the Haringvliet Sluices varies, from zero to extreme situations. Normally river water is discharged when the water level outside is below mean sea level.

In the simulations four bed levels are applied dated from 1986, 1992, 1998 and 2003. So that the flow calculation could be done for different years and the results of different year bed level could be studied. The variations in bed level are only applied in the Haringvliet mouth, since this study wants to determine the differences in tidal volumes for different year. The bed level data is obtained from the UCIT database. The study area is limited by the size of the smallest data set, which is the data set of 2003. For the area outside the area of interest, the bed level of the existing model is used, which dates from 1986.

For the tidal forcing a representative tidal condition is applied at the boundaries of the model; this is called morphological tide. An astronomic tidal condition consists of different components, which are the result of, amongst others, the force of the sun and the moon. These different element make that the tidal wave differs per day. The morphological tide is tidal cycle that represents the monthly average.

The hydrodynamic simulations are all 2DH. This means that the flow calculations are depth averaged. So vertically only one grid cell is defined while horizontally large numbers of grid cells are defined, Figure 20. The grid that is used during the simulations covers the area between the Brouwersdam in the south and Noordwijk in the north, see Figure 20. The grid used for this simulations is at least 50x50 m^2 an at most 600x600 m^2. The grid size is smaller at the Haringvliet Mouth compared to the grid size at sea.

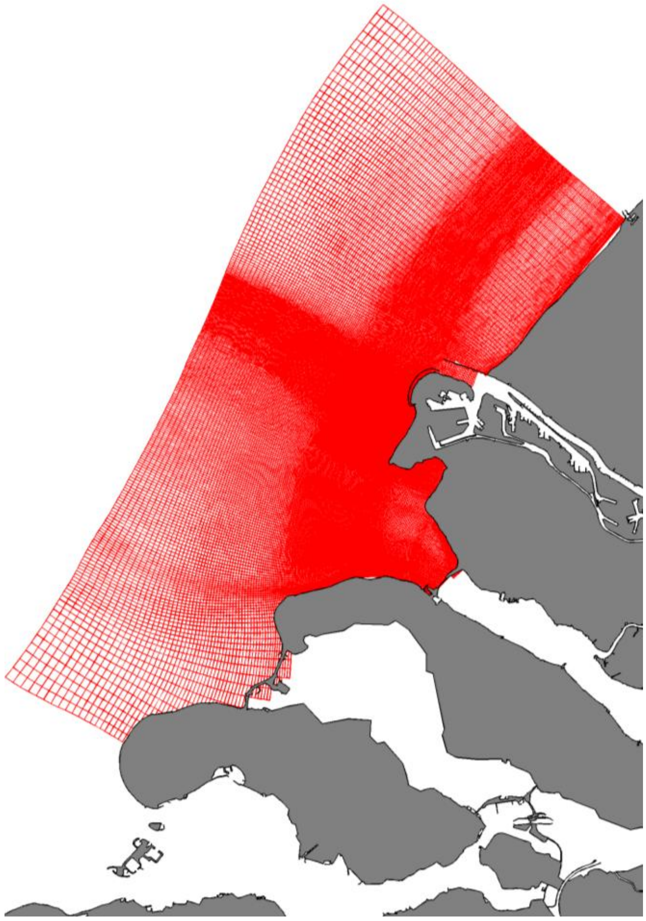

Figure 20 Computational grid used for the Delft3D Flow calculations

Table 2 Overview parameter settings

Parameter	**Value**	**Description**
Δt	60	flow time step [s]
ρ_w	1025	water density [kg/m^2]
ρ_a	1.25	air density[kg/m^2]
Vicouv	1	horizontal eddy viscosity [m^2/s]
Dicouv	1	horizontal eddy diffusivity [m^2/s]
k_s	0.05	Nikuradse coefficient [m]
Dryflc	0.1	threshold depth [m]
CSTbnd	TRUE	boundary condition [-]

Model assumption

- For the focus of this study it is assumed that density gradients are of minor importance. Simulations are therefore done in two-dimensional mode (2DH).
- No calibration and validation of the hydrodynamic model is carried out in this study, since the hydrodynamic calibration and validation in previous study [Steijn, 2001] already have shown that the hydrodynamic model results are reasonable.
- River discharge at the Haringvliet is kept constant over the discharge period, a 'block'-function is used. The difference in water level west and east of the sluices is not taken into account when applying the river discharge.

3.2 Total Haringvliet Area

The first area to be studied is the total Haringvliet Area, which consists of both the Outer Area and the Inner Area. This section will study the morphology based on a sand balance, bed levels and hypsometric curves. The combination of these elements makes it possible to analyse the morphology of the Total Haringvliet Area.

3.2.1 Sand balance of Total Haringvliet Area

The previous chapter discussed the closing of the Haringvliet estuary, which resulted in a reduction of the tidal volume and accretion in the Inner Area. Tönis (2000) investigated this accretion and stated that the accretion has reduced over the last few years. This analysis focuses on the sand balance of the Haringvliet Area during the last 17 years (from 1986 to 2003). To study the sand volumes for the Total Haringvliet Area the bed level data from 1986 is used as the reference year. Other bed level measurements date from 1992, 1998 and 2003. The amount of sedimentation and erosion between 1986 and that specific year has been calculated, by subtraction of the bed level of the reference year from these years' bed levels.

The results indicated that the Inner Area accreted between 1986 and 2003, while the Outer Area eroded (Figure 21). This figure shows which areas have eroded (blue) and which areas have accreted(yellow/ red). Figure 22 shows that the total volume of sand in the Total Haringvliet Area slightly decreased between 1986 and 2003. The sub-areas show a different development.

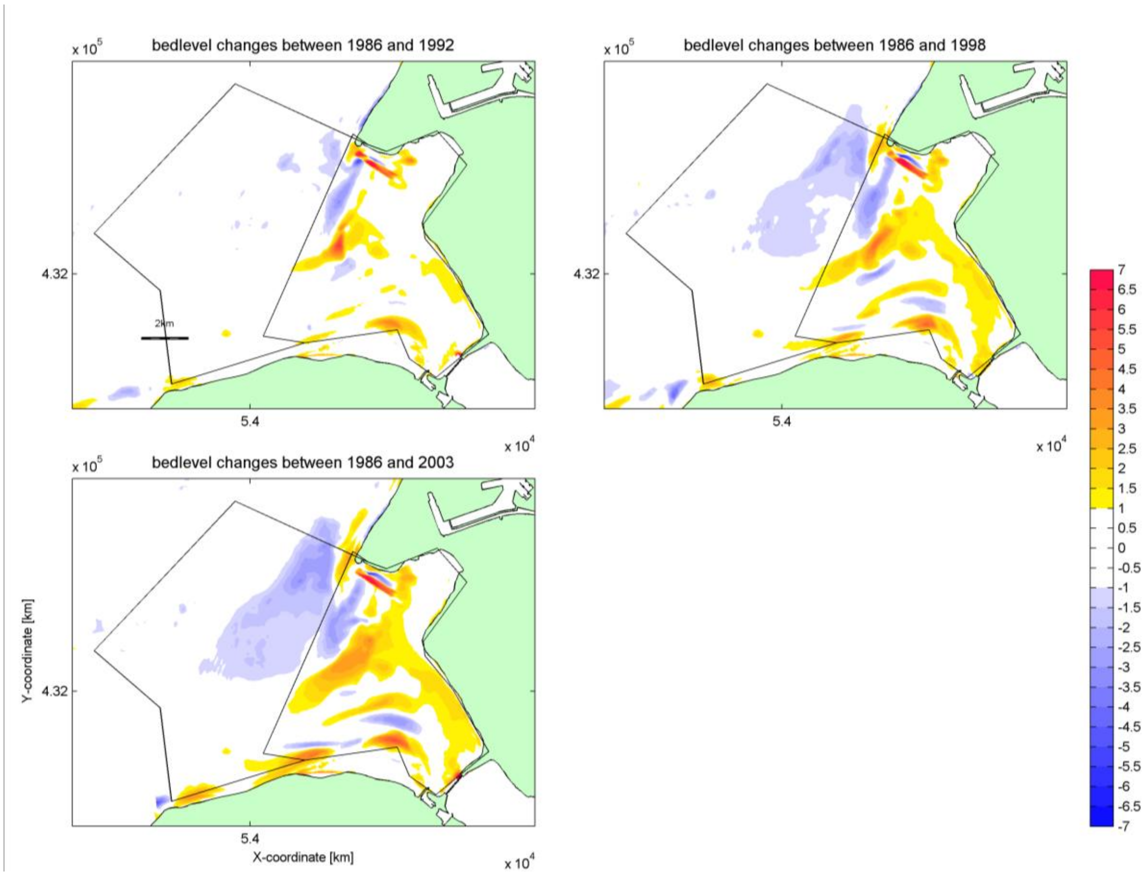

Figure 21 Sedimentation and erosion areas in the Haringvliet. 1986 is used as reference year. (A larger copy of this figure can be found in Appendix B Figure B1)

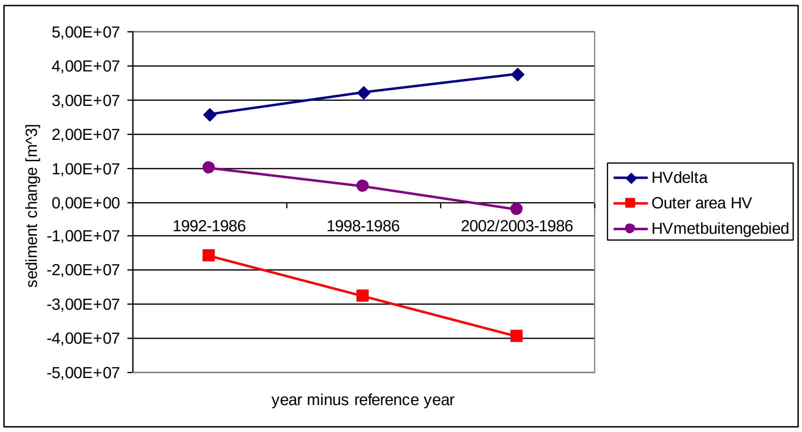

Figure 22 Sand balance of the Inner Area of the Haringvliet. The seaside eroded as shown previously in Figure 21, while the land side accreted.

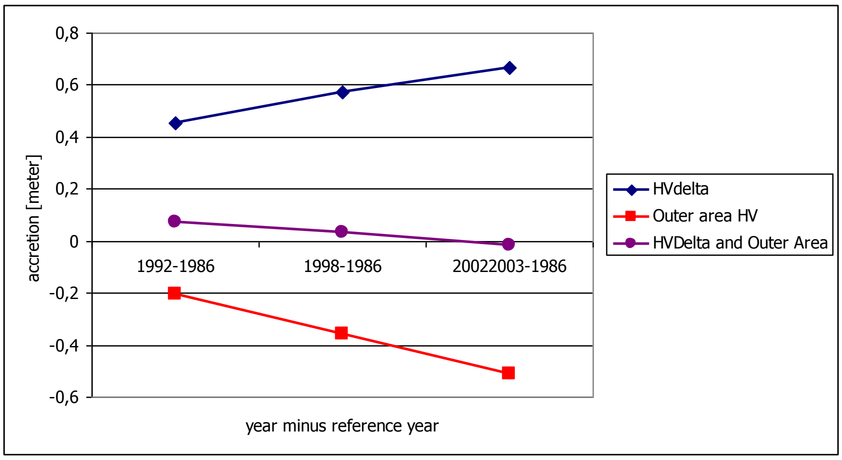

Figure 23 Accretion per meter of the total Haringvliet area, the sea part of the Haringvliet and the land side of the Haringvliet.

3.2.2 Hypsometric curve

The hypsometry of a certain area shows which part of an area in square meters has a bed level below a reference depth. A hypsometry can be visualised in a hypsometric curve. This curve is a graph which represents the area in square meters at and deeper than a certain depth. On the y-axes the depth is plotted, while on the x-axes the cumulative area is plotted. Plotting hypsometric curves of several years in one graph provides information of an increase or decrease of the area for certain depth classes. The hypsometry of the Total Haringvliet Area is presented in Figure 24. The area for which this hypsometry is calculated is shown in Figure 21 (the total area).

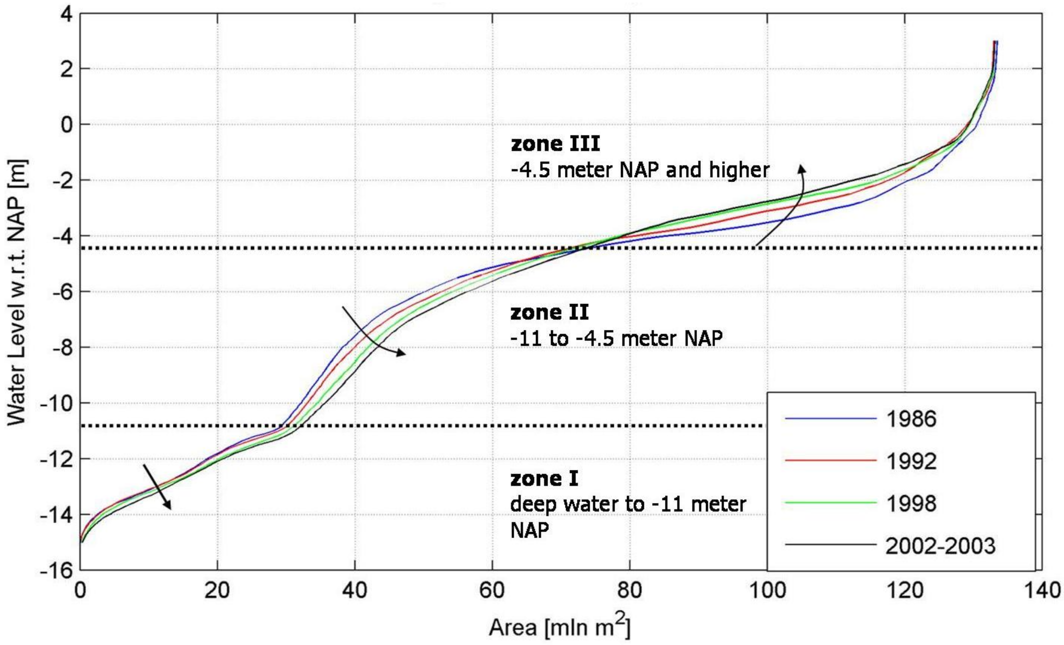

Figure 24 Hypsometric curve of the Total Haringvliet Area divided into three zones

Two transitions can be observed in the hypsometric curve. As a result three zones are formed; Zone I: from deep water to -11 m NAP, Zone II: from -11 m to -4.5 m NAP and Zone III: from -4.5 m and higher. The total surface area of each zone remains approximately the same; the depth contours within each zone are however migrating. Especially in Zone II and III major movements are visible. Zone II, the area between -11 m NAP and -4.5 m NAP, became deeper between 1986 and 2003, and has an eroding trend. Zone III, the area from -4.5 meter and higher, has become shallower since 1986 and shows and accreting trend. It may be concluded that the deep area becomes deeper, while the shallow area becomes shallower.

Based on the zones defined above, contour lines between 0 and -4.5 meter NAP and contour lines between -4.5 meter and -11 meter NAP are plotted to visualise where these zones are located in the Haringvliet Area. The plots of these contour lines are displayed at Figure B2 and B3 in Appendix B. These plots show that contours of zone III are mainly located in the Inner Area, where as the contour lines of zone II are located at the boundary of the Inner Area and the Outer Area.

Bed level data indicates that the Outer Area is eroding. In this area the bed levels are mainly below -4.5 meter. The contour lines appear not to change much in this area. One should take into account that when a depth contour shifts a few meter landwards over the entire width of the area, the total area will become deeper and the erosion volume is quite large. This shift is also visible in the hypsometric curve.
The Inner Area is accreting. In the hypsometry the surface area of the zone above -4.5 meter remains approximately the same, but the hypsometric curve shows that the area is becoming shallower. The plots of the contour lines show major shifts in the Inner Area.

The explanation of the development above is twofold. The first event that triggered these developments was the closing of the Haringvliet Dam. This closing reduced the tidal volume and tidal currents became lower. The wave forcing from offshore as discussed in Section 2.3.3, remained the same after the closing of the Haringvliet Estuary. The wave force however became more dominant at the boundary of the Inner Area and the Sea Ward area, since the tidal force reduced. This pushed the corresponding depth contour landwards and caused erosion in the Outer Area.

The reduction of tidal force also has a direct influence on the development of the Inner Area. The reduction of tidal volume caused the current in the delta to become lower, allowing sediment to settle more easly. As a reaction the delta is accreting, which is also visible in the sand balance. This development will continue until there is a balance between the current in the channels and the settling of sediment. Eventually this process will result in a balance between the tidal volume (which forces the tidal current) and the channel dimension. Channels will stop to silt up if the balance between current velocities and settling is reached. This relationship is discussed in more detail in Section 3.1.1.

3.2.3 Conclusion Total Haringvliet Area

This section focuses on morphological development of the Total Haringvliet Area. Based on this analysis the following conclusions can be drawn:

Firstly, bed level data indicated that the Outer Area is eroding. In this area bed levels are mainly below -4.5 meter. The contour lines appear not to change much in this area. But a small shift landwards of a depth contour over the entire width of the area, has caused large erosion volumes.

Secondly, the Inner Area is accreting. In the hypsometry the surface area of the zone above -4.5 meter remains approximately the same, but the hypsometric curve shows that the area is becoming shallower. The plots of the contour lines show major shifts in the Inner Area.

The sand balance shows that the Inner Area is accreting while the Outer Area is eroding. The amount of sand in the Total Haringvliet Area is however approximately stable and sediment mainly redistributed within the system. After the construction of the dam the tidal forcing diminished while the wave forcing remained the same. The wave forcing became more dominant at the boundary of the Inner Area and the Outer Area, since the tidal forcing reduced. This pushed the depth contour landwards and caused erosion in the Outer Area.

3.3 Inner Area of the Haringvliet

Given the analysis of the previous section it can be concluded that the Inner Area is accreting. This section deals with the morphological developments of the Inner Area in more detail. Firstly, the bed level development is discussed by contour plots and the hypsometric curve. Secondly, the movement of sand bars in the Inner Area will be analysed. Section 3.3.3 discusses the relationship between tidal volume and channel dimension. Section 3.3.5 deals with the current patterns in the Inner Area. The second last section deals with the wave climate and in the last section conclusions are drawn.

3.3.1 Bed levels in the Inner Area

The depth contours of the Inner Area for the years 1986, 1992, 1998 and 2003 are plotted in Figure B4 Appendix B. The plots show that between 1986 and 2003 the area between -3 meter and -1 meter NAP increased considerably. In 1986 the area between -1 and +1 meter NAP was concentrated at the western part of the Delta, while in 2003 this area had been divided in several smaller areas, (Figure 26). In 2003 the area between -1 and 1 meters NAP was spread through the Inner Area. These new areas are located east of the -1 – 1 NAP area in 1986. In the next section the movement of specific sandbars will be discussed.

The sand balance discussed in the previous section showed an accreting trend in the Inner Area. The hypsometric curve plotted in, Figure 25 confirms this trend.

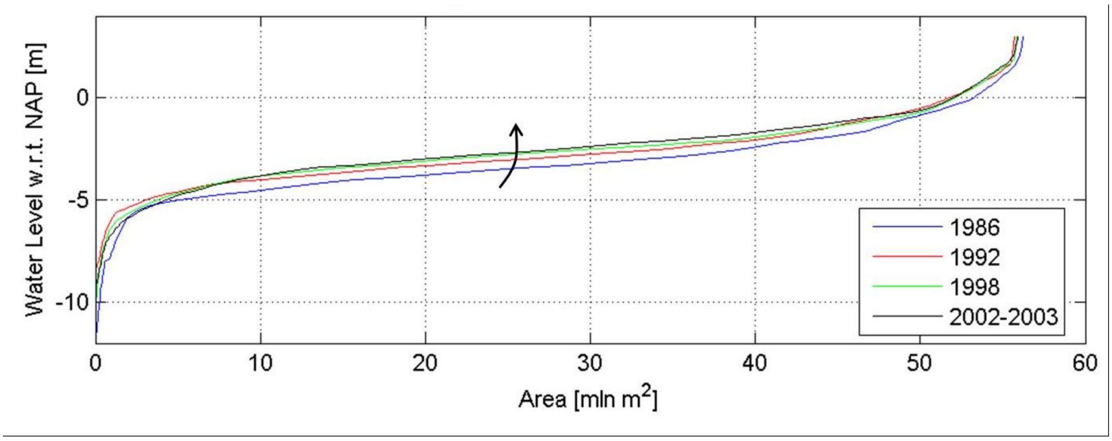

Figure 25 Hypsometric curve of Inner Area

3.3.2 Movement of sand bars

The contour line plots show a large movement of the depth contours. The movement of sand bars is studied on the basis of bed level data from 1986, 1992, 1998 and 2003. Figure B5 in Appendix B the bed levels of these four years are shown. The movement of various sand bars is discussed, to gain insight in these movements. This insight could help in predicting future developments.

The following sand bars are discussed: Hinderplaat, Garnalenplaat-Noord, Garnalenplaat-Zuid and Kwade Hoek. The location of the sand bars is shown in Figure 26.

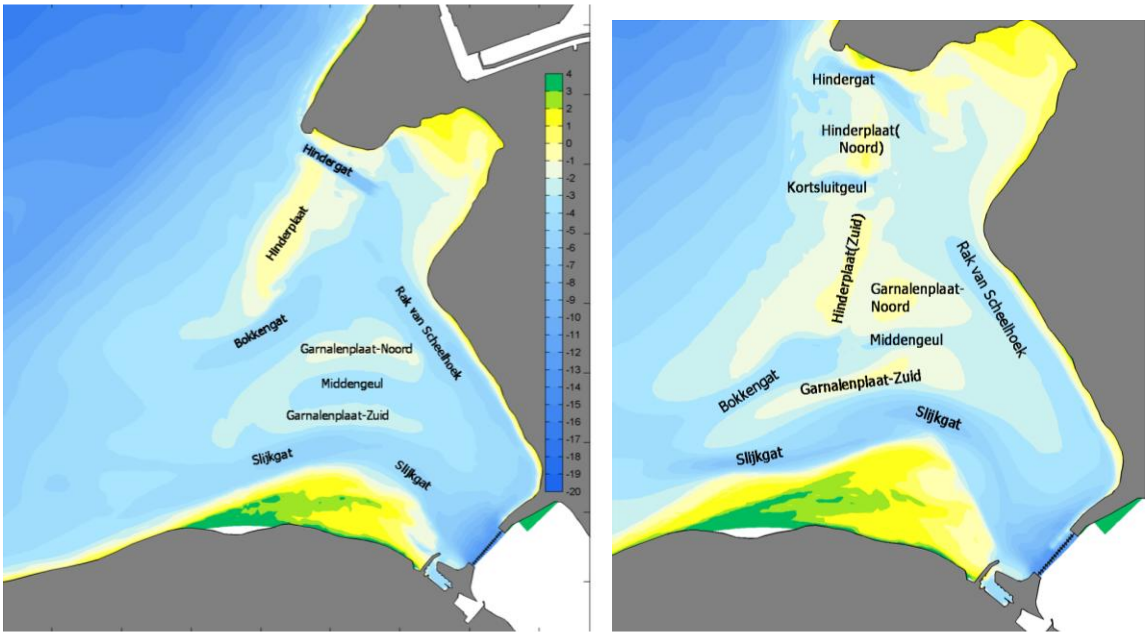

Figure 26 Location of sand bars and tidal channels in the Inner Area of the Haringvliet. The bed level of the left plot is from 1986, the bed level of the right plot is from 2003.

Hinderplaat:
The Hinderplaat is probably the most dynamic sandbar in the Haringvliet Delta. The entire sandbar is moving to the east. This is however not the only movement, the southern part of the sandbar is accreting, which results in an extension of the bar to the south-west. In 1986 the Hindergat (the channel north of the Hinderplaat) was created as a replacement of the Gat van Hawk in order to preserve the tidal movement in the area east of the Hindergat. The northern movement of the Hinderplaat narrowed the Hindergat, between 1986 and 2002. In this period a short-circuit channel (Kortsluitgeul) developed over the Hinderplaat. This channel splits the Hinderplaat in two parts. It is expected that the northern part of the Hinderplaat will move even more to the north and, finally, will merge with the Slufter coast. In this case the discharge function of the Hindergat will be taken over by the Kortsluitgeul.

Garnalenplaat-Noord:
The southern 'border' of the Northern Garnalenplaat has remained about the same during the last 17 years. The Garnalenplaat-Noord is however extending in northern direction. This accretion combined with the eastern movement of the Hinderplaat, will result in a merge of those two sandbars in one large sandbar. The Bokkengat has almost completely disappeared due to this merging process.

Garnalenplaat-Zuid:
The Garnalenplaat-Zuid has developed strongly in the last 17 years. Only a small area is located above -2 meter NAP in 1986. The bed level data of 2003 shows that this sandbar has extended much; the extension took place to the west. Garnalenplaat-Zuid developed parallel to the Slijkgat and with that it is 'guiding' the Slijkgat towards the North Sea.

Kwade Hoek:
The development of the Kwade Hoek is not as strong as the developments of the other sandbars. The Slijkgat is however channelled between the Garnalenplaat-Zuid at the north and the Kwade Hoek at the south. The development of the Kwade Hoek is interesting for this study, since it directly interferes with the development of the Slijkgat. After the construction of the Haringvliet Dam, the Kwade Hoek extended to the north, due to longshore sediment transport from the south and the abrupt absence of tidal current after the closure of the estuary [Steijn 1998].

3.3.3 Tidal volumes in the Inner Area

In Section 3.1.1 it is explained that there exist a relation between tidal volume and the channel dimensions. Calculations haven been done to determine the tidal volume through the channels during different years. For these calculations the Delft3D FLOW module is used, as explained in Section 3.1.2 For each year two scenarios are calculated: one with discharge at the Haringvliet Dam and one without river discharge. In both situations tidal movement is included.

During the summer the discharge is sometimes zero. This is close to the situation when only the tidal movement is the driving force. The opposite of this situation is the situation during winter. Therefore an average winter discharge is used as a second scenario in these calculations (period 1 December to 31 March, 1200 m^3/s).

The results of these calculations are plotted in the figures below. Figure 27 represents the simulation without river discharge and in Figure 28 the situation with river discharge is plotted. On the y-axes the cross-sectional area is plotted and on the x-axes the tidal volume. The tidal volume is the total (absolute) amount of water that crosses a cross-section during a tidal cycle. Each year has its own colour and symbol. The blue line represents the relation of Haring (formula 3.3) between tidal volume and channel dimension. This relationship is formulated for the situation in 1967 before the Haringvliet Dam was constructed and the estuary was closed.
The abbreviations of the cross-sections are:

BG: Bokkengat
HG: Hindergat
KSG: Kort-sluitgeul (circuitchannel)
MG: Middengeul
RvS: Rak van Scheelhoek
SGbinnen: Slijkgat inner polygon
SGbuiten: Slijkgat outer polygon

The locations of the cross-sections are visualised at Figure B7 in Appendix B. All the cross-sections are located at an inner or an outer transect, see Figure 29, in order to have consistency in the calculations. Cross-sections with the same name may however be located at different positions in different years, due to the movement of some sandbar and accompanying the movement of tidal channels. All the cross-sections have a bed level of -3 m NAP or lower.

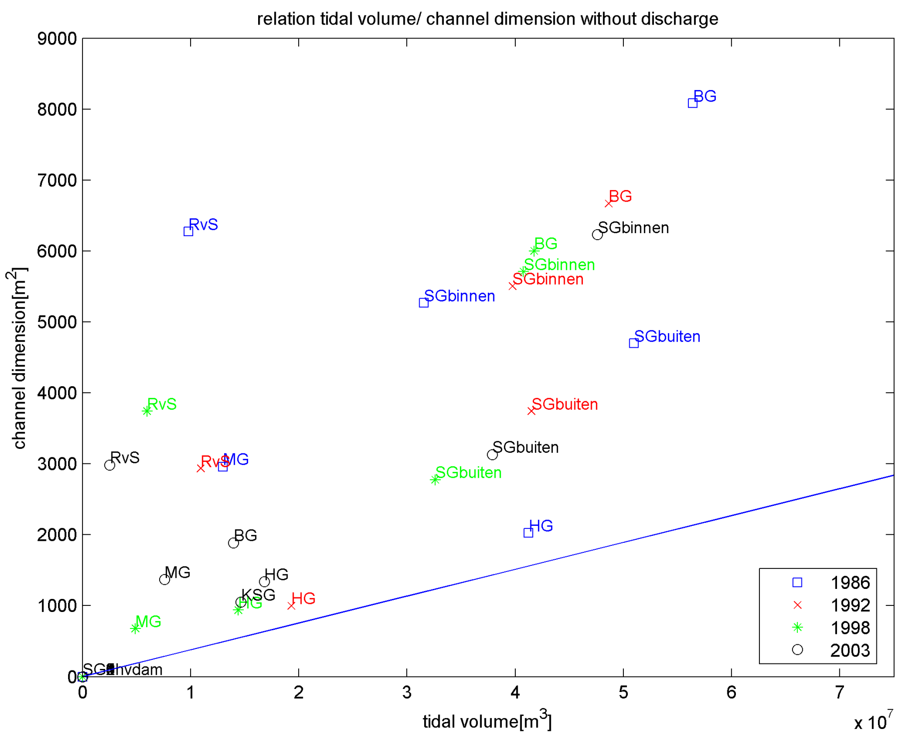

Figure 27 Tidal volume and channel dimension if the system is only forced by tide. The blue line represents the relation of Haring for the Haringvliet estuary [Haring, 1967]

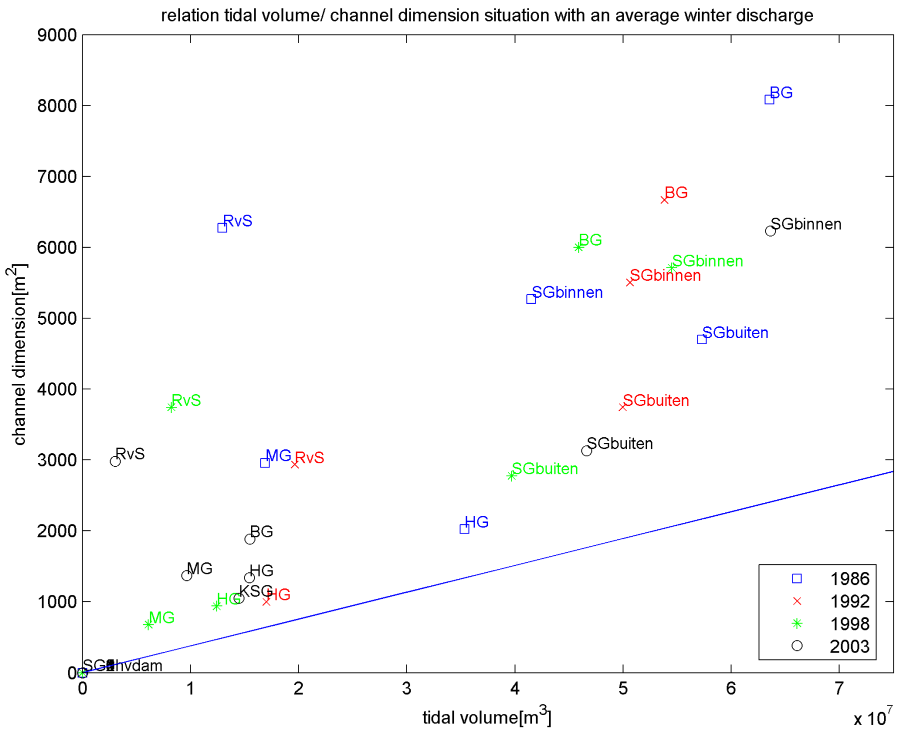

Figure 28 Tidal volume and channel dimension if the system is forced by tide and river discharge. The blue line represents the relation of Haring for the Haringvliet estuary [Haring, 1967]

The graphs above show that for both the situations with river discharge as without river discharge all the cross-sections are larger than expected based on the relation formulated by Haring. Notwithstanding this outcome some trends are visible in the graphs, the discussion below focuses on Figure 28.

It is remarkable that the cross-section of the Slijkgat (SGbinnen and SGbuiten) show an increase in tidal volume and channel dimensions, while other cross-sections for example the Hindergat (HG) show a declining trend in both tidal volume and channel dimensions. The Bokkengat (BG) shows a strong decline in channel dimension and tidal volume, for this cross-section it has been taken into account that the position of this cross-section has changed a lot (Section 3.3.2).

In general it can be stated that cross-sections located near the sea show in the graph a smaller gradient between tidal volume and channel dimensions than cross-sections located near the Sluices. This can have two explanations, firstly the cross-sections near the Haringvliet Dam are too large and will accrete in the future. Secondly the relation of Haring holds better for cross-sections near the sea.

The relation of Haring is based on the situation before the construction of the Dam. The environmental conditions for this situation are taken into account by the empirical coefficient alpha, as explained in Section 3.1.1. The environmental conditions of the Haringvliet have changed. It is therefore questionable if the relation of Haring is applicable for this new situation. The environmental conditions near the Haringvliet Dam have changed more drastically than the conditions near sea. This might be an explanation for the difference in gradient in the graph between those cross-sections.

Finally, the channels Hindergat (HG) and Kortsluitgeul (KSG) are discussed. In 1986 the Hindergat is dredged as a replacement of the Gat van Hawk. The Hindergat immediately started to accrete and the tidal volume that passes the Hindergat also declined. The bed level data of 2003 show that a new channel has been created which splits the Hinderplaat. For this new channel (the Kortsluitgeul) the relation between tidal volume and channel dimension is determined as well (Figure 28). In the simulated situation the relation between channel dimensions and tidal volume is approximately similar for the Hindergat as for the Kortsluitgeul. The conditions in the north can be considered free from human interventions. The Kortsluitgeul developed recently, therefore it is plausible that the dimensions of the Kortsluitgeul is an equilibrium profile.

3.3.4 Discharges distributions

The calculations discussed in the previous section are used to compare the tidal volumes between cross-sections and years. All the cross-sections are drawn along a transect. Two transects are used, one for the western 'boundary' of the Inner Area and a second one through the middle of the Inner Area.

Per transect the percentage of tidal volume is calculated that flows through each cross-section. This calculation is done for each year of which flow calculations in Delft3D are made, so 1986, 1992, 1998 and 2003. This makes it possible to see if relatively more water is discharged through a certain cross-section.

The results of this calculation are displayed at Figure B7 in Appendix B. The plots show that the tidal volume stays approximately the same between 1986 and 2003. For both the outer and the inner polygon. For the outer polygon the distribution of tidal volume does not change much. The distribution for the inner polygon does show a shift. The percentage of the tidal volume in Slijkgat East increased from 43.8 % to 65.7 % while the total tidal volume over the inner transect remained approximately the same in the period between 1986 and 2003. The other cross-sections at the inner polygon show a decreasing percentage of tidal volume. Therefore it can be concluded that a larger part of the tidal volume of the inner transect is discharge through the Slijkgat East cross-section.

(a) (b)

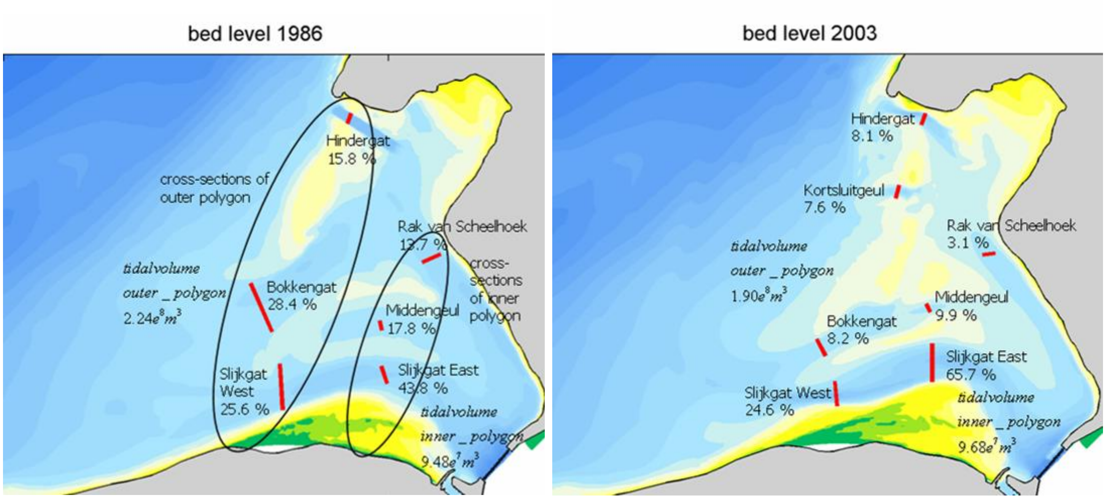

Figure 29 Percentages per cross-sections related to the inner of the outer transect.
a. water depth and percentages of tidal volume for 1986
b. water depth and percentages of tidal volume for 2003

The relation formulated by Haring between the dimensions of a tidal channel and the tidal volume is followed more precise for cross-sections of which the river discharge is a small portion of the tidal volume. These are the cross-section near the Outer Area, such as the Kortsluitgeul and the Hindergat. The relation of Haring is originally formulated for a situation where river discharge is a small portion of the total tidal volume. After the construction of the Dam, the tidal volume generated by tide diminished, while the river discharge stayed the same.

River water is mainly discharged through the Slijkgat. The tendency to transport more water through the Slijkgat has increased the last 17 years. If the tidal volume of the Slijkgat near the sluices is compared with the total tidal volume of all the cross-sections near the Haringvliet, the relative increase of tidal volume is 22%.

3.3.5 Current in the Inner Area

The simulation done in Delft3D gives, besides the possibility to calculate the tidal volumes, also the possibility to visualize the current patterns. The current patterns for the calculations with bed level data of 1986 and 2003 are displayed in Figure B9 to B12 in Appendix B. Both the situation with and without river discharge are presented.

The plots show that in 1986 the river discharges cause currents in the total Inner Area. In 2003 the bed level has changed in such a way that the river discharge mainly causes currents in the tidal channels.

Furthermore two plots are made which show the net current due to the river discharge. This is the difference between the current due to tidal forcing and river discharge and the current due to tidal forcing only. These plots show that the river discharge mainly causes currents during phase 2 and 3 of the tidal period, so only during low water when the sluices are open for river water discharge. In 1986 the river discharge causes currents in the whole Inner Area, while in 2003 the currents are mainly in the tidal channels. The Slijkgat discharges most of the river water.

The tidal wave approaches the Inner Area from the South through the Slijkgat and leaves the Inner Area from the North. The bed level data from 2003 show a new channel in the North of the Haringvliet, the Kortsluitgeul (section 3.3.2). This channel indicates that the system requires a channel in the northern part of the Haringvliet as a result of tidal phase difference.

3.3.6 Conclusions on the morphology of the Inner Area

The Inner Area accreted between 1986 and 2003 and the movement of sand bars is highly dynamic in the area. This increase in bed level is related to the construction of the Haringvliet Dam.

Based on numerical calculations it can be concluded that the channel dimensions are too large to be in equilibrium with the tidal volume if the system is forced with an average winter discharge. This can have two explanations: firstly, the tidal channels in Inner Area have not yet reached it equilibrium situation. Secondly, it is not the average winter situation that is governing, but an extreme discharge situation that determines the dimension of the tidal channels.

Water enters the Inner Area during flood via the Slijkgat. This water leaves the Inner Area via channels in the north, resulting in a result a residual circulation. The creation of the Kortsluitgeul shows that the morphological system requires a channel in the northern part.

3.4 Slijkgat Area

The last area which is studied is the Slijkgat Area. This area consist of the approach channel the Slijkgat and the surrounding sand bars. the Slijkgat Area is part of the Inner Area as is visualised in Figure 30. the Slijkgat Area is studied since the main goal of this thesis is to predict the morphological behaviour of the Slijkgat.

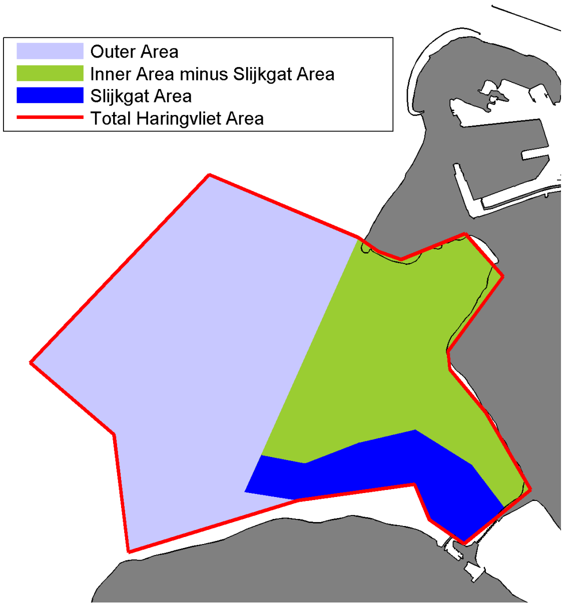

Figure 30 Location of the Slijkgat, the dark blue area is the Slijkgat Area

The morphological analysis consists of; firstly, a bed level data analysis, including sedimentation and erosion plots. Secondly the relation between tidal volumes and channel dimensions is discussed. Finally the current patterns in the Slijkgat Area are studied. In this section the same bed level data is used as in the previous section, so data from 1986, 1992, 1998 and 2003.

3.4.1 Morphological changes of the Slijkgat

Bottom level plots are made of the Slijkgat Area. These are displayed in Figure B13 Appendix B. In this Appendix also sedimentation and erosion plots can be found (Figure B14). Those plots are generated by subtracting the reference year 1986 from the years 1992, 1998 and 2003. The plots show the bed level change between a specific year and 1986.

The bed level plots show that the bed levels in the channel became lower between 1986 and 2003, while in the north of the Slijkgat the Garnalenplaat was accreting. The sedimentation and erosion plot confirm this. The plots show erosion (plotted in blue) in the channel while the areas around the channel are accreting (yellow/ orange).

For the Slijkgat Area also a hypsometric curve is made, see Figure 31. The hypsometric curve does not show a distinct trend as the other study areas did.
The hypsometric curve of the Slijkgat Area does not confirm this analysis, see Figure 31. It has however to be taken into account that the Slijkgat Area is larger than the Slijkgat-channel. The developments of the channel can therefore not be seen in the hypsometric curve of the Slijkgat Area.

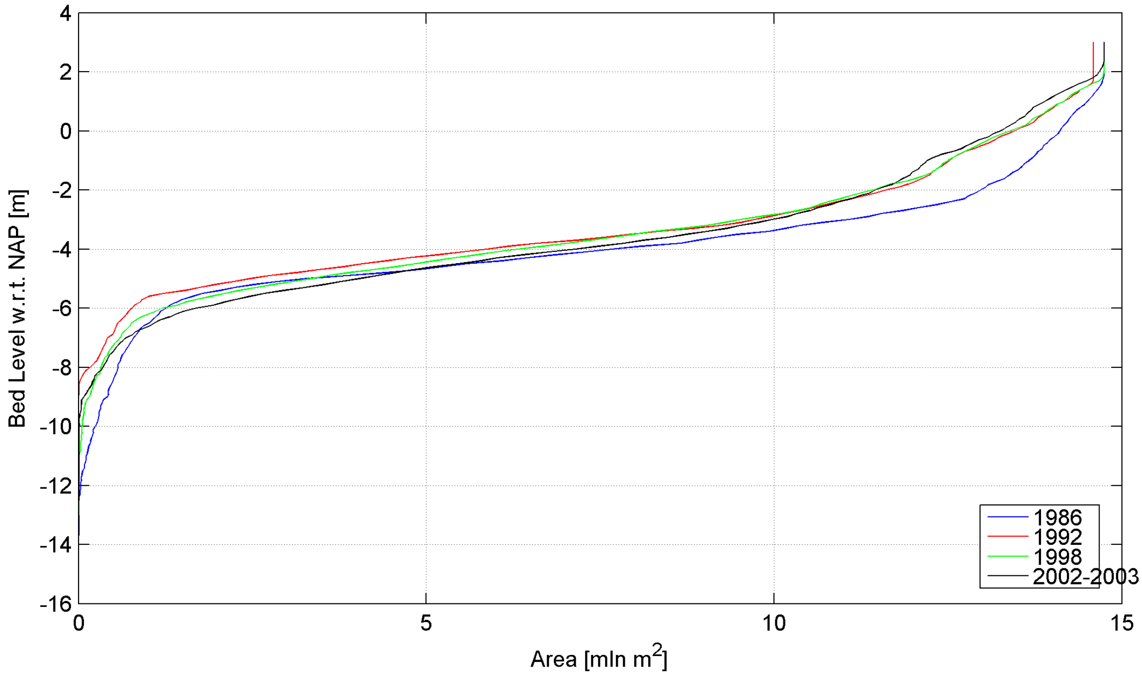

Figure 31 Hypsometric curve of the Slijkgat Area

3.4.2 Discharge through the Slijkgat and dimension Slijkgat

In Section 3.1.1 the relationship between tidal volume channel dimensions is displayed for the Inner Area. In this section the same analysis is done for the Slijkgat. The tidal volumes used in this section are based on Delft3D flow calculations. The channel dimensions are based on bed level measurements. The graph below (Figure 32) shows the tidal volumes calculated for a situation without river discharge but with tidal forcing. Figure 34 shows the tidal volumes if an average winter discharge is discharged during low water at the Haringvliet Sluices.

The cross-sections of one year are plotted in the same colour. The abbreviation SG stands for Slijkgat, while the numbering is from west to east. All the cross-sections lay below -3 meter NAP.

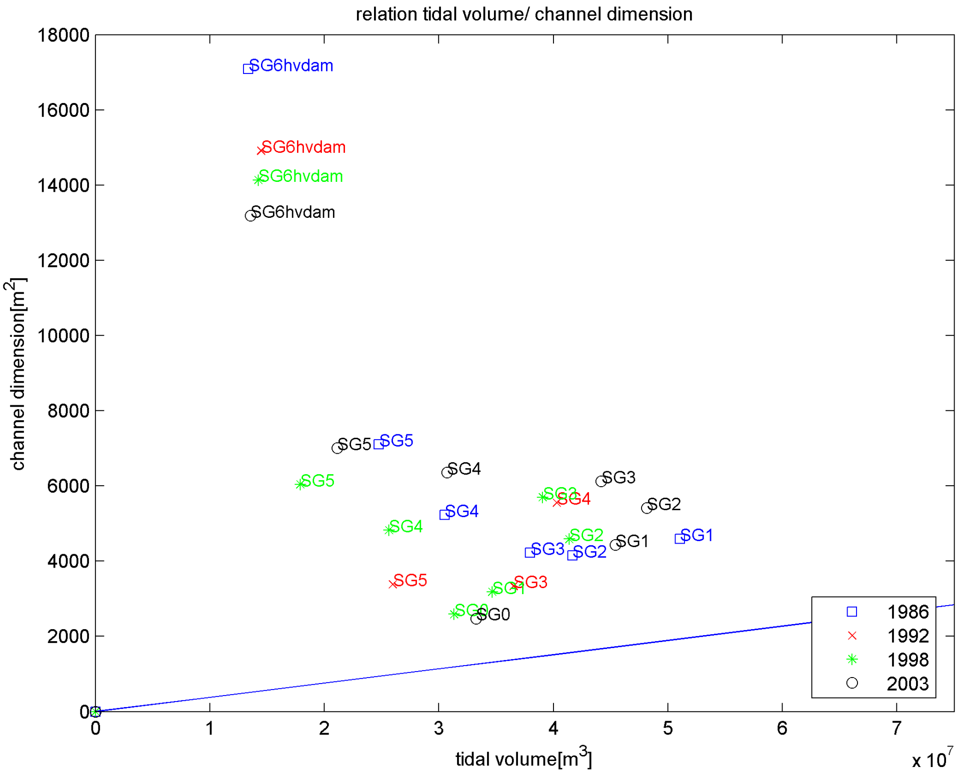

Figure 32 Tidal volume and channel dimension if the system is only forced by tide. The blue line represents the relation of Haring(1967) for the Haringvliet estuary

Figure 32 shows that the points which visualise the relation between tidal volume and channel dimension are not even close to the relation of Haring. The study of Arends (1997) gives an explanation of this. In this study the decline of cross-sectional area is calculated. In this study 1970 is the reference year; the cross-sections of other years are plotted as percentage of the original cross-section. The results, plotted in Figure 33, show that after the high river discharges of 1993 and 1995 the cross-sections became larger. From this study it is concluded that the Slijkgat is reaching its equilibrium state. Especially since high river discharge at the end of the eighties did not influence the dimensions of the Slijkgat. Secondly, it can be concluded that a situation with river discharge is governing.

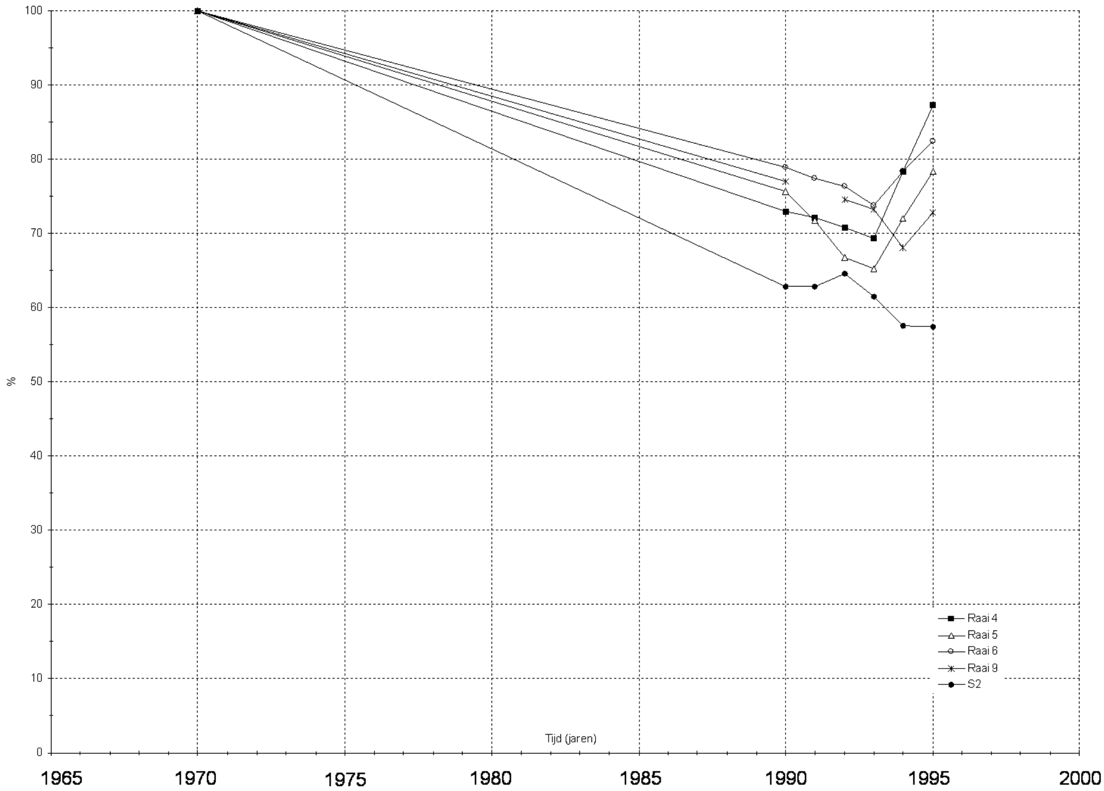

Figure 33 percentage compared to 1970 of the cross-section of the Slijkgat [Arends, 1997]

In the graph below, Figure 35, the results of the flow calculations with river discharge are displayed. The cross-sections at the same location are connected. The blue line represents the relation between tidal volume and channel dimension formulated by Haring for the Haringvliet Estuary.

A close-up of the graph is shown in Figure 35. This close –up shows that none of the cross-sections follow the relation of Haring most cross-sections are however migrating along a line. Cross-sections further from the sea (SG3 and SG4) follow a steeper line than those close to the sea (SG0, SG1). The migrating motion of the cross-section might have to do with movement of ebb and flood channels and with the difference in river discharge per year. Note, in this model the discharge is equal for all years. The bed level data is however measured data, the change of bed level might be related to the change in the river discharge.

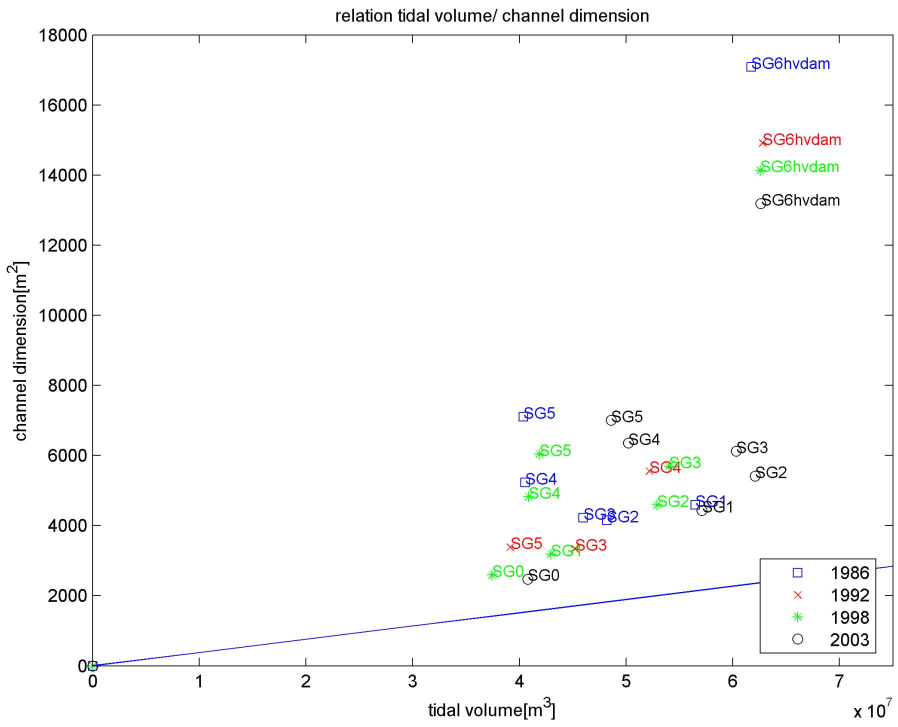

Figure 34 Tidal volume and channel dimension if the system is forced by tide and river discharge. The blue line represents the relation of Haring(1967) for the Haringvliet estuary

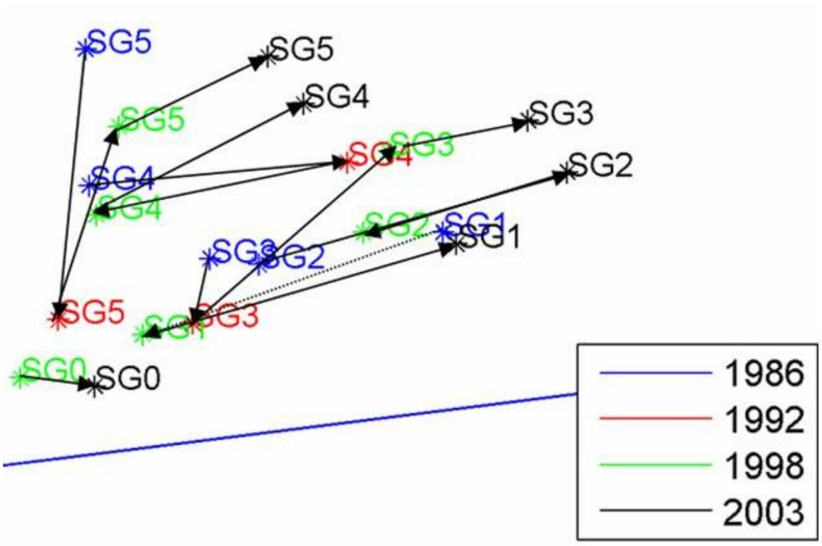

Figure 35 Tidal volume and channel dimension if the system is forced by tide and river discharge. The blue line represents the relation of Haring(1967) for the Haringvliet estuary

The tidal volumes in the previous charts are related to the situation with an average winter discharge. Since it is well possible that the dimensions do not depend on the average discharge, but on an extreme discharge, simulations have been made with the highest discharge prior (within three months) to the bed level measurement. Figure 36 shows the results for these simulations.

The figure shows that the result between the year are plotted more separate of each other. 2003 had the highest discharge and the largest tidal volumes, 1992 is in the middle, while 1998 had the lowest discharges. In general all the cross-sections are closer to the relation of Haring. The cross-section near the sea (eq. SG0) are closer to the relation of Haring then the cross-sections near the Haringvliet Dam (eq. SG5) .

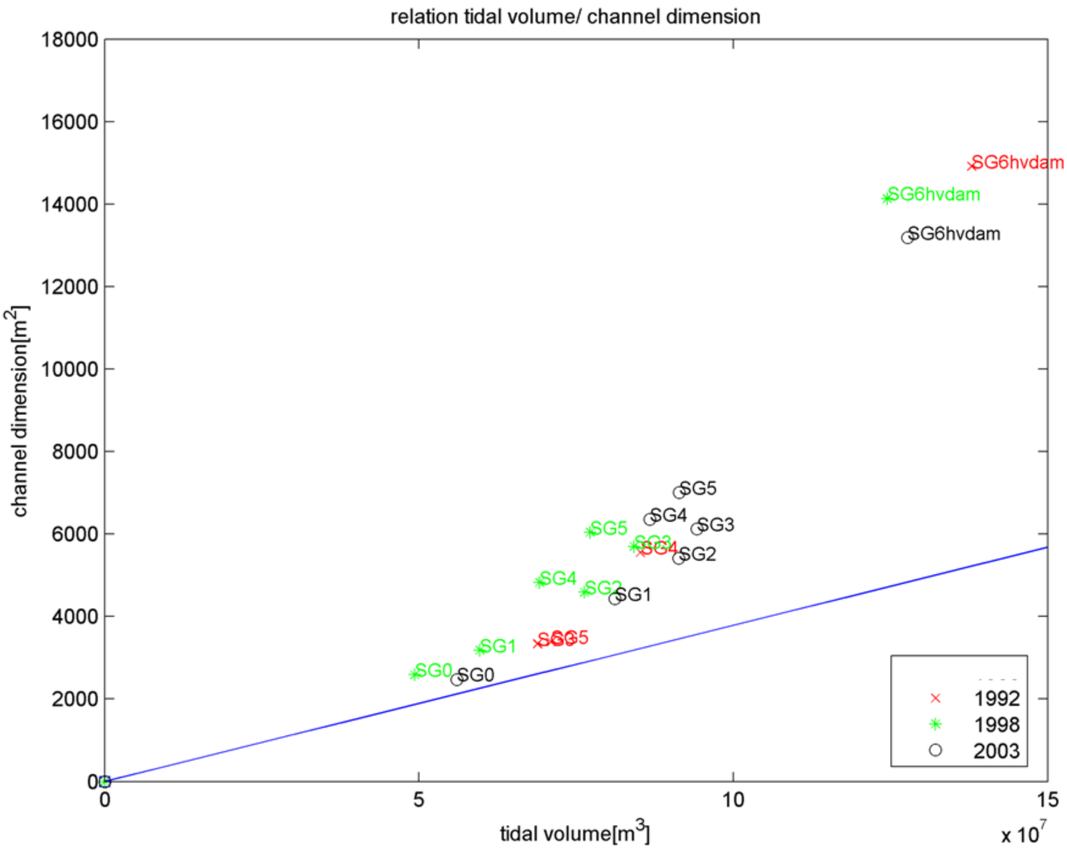

Figure 36 Tidal volume and channel dimension if the system is forced by tide and river discharge which occurred within 3 months before the bed level measurements. The blue line represents the relation of Haring(1967) for the Haringvliet estuary

Summarizing it can be concluded that the cross-sections in the Slijkgat have reached their equilibrium dimensions. Due to the changing morphology around the Slijkgat and changing river discharges (which result in different tidal volumes) the dimension of the Slijkgat are continuously adjusting to the new situation. Since the surrounding area is becoming shallower it can discharge less water. As a consequence of the accretion of the surrounding area it can in general be concluded that the tidal volume of the Slijkgat is increasing and the channel is becoming deeper. Moreover, the channel is developing ebb and flood channels. This also results in sills between the ebb and flood channels so the channel is locally becoming shallower. Recent sediment measurements in the Slijkgat showed only the presence of sand in the channel. A process of flocculation is therefore not governing for the accretion on the sill. If flocculation would be governing, silt should haven been found).

Although the cross-sections are reaching their equilibrium state, the relation between tidal channel and tidal volume does not follow the relation Haring formulated in 1967. Haring's relation was based on the situation before the Haringvliet Sluices were constructed. Cross-sections close to the sea, as at the western part of the Slijkgat, follow the relation of Haring closer than those at the eastern part. This can be influenced by the portion of river discharge in the tidal volume. Haring formulated the relation for a situation where river discharge was a fraction of the tidal volume. This discharge changed after the construction of the Haringvliet Dam. The empirical coefficient alpha in the formula 3.2 and 3.3 depends moreover an a number of environmental conditions (Section 3.1.1) that might have changed compared to the situation before the presence of the Dam.

3.4.3 Currents through the Slijkgat

The flow calculations are also used to provide current patterns in the Slijkgat Area.
The current patterns of the Slijkgat are displayed in Figure B15 to B18 Appendix B. Four different scenarios are shown. For each scenario four phases of the tidal period are plotted. The four scenarios are:

- bed level 1986 with tidal forcing
- bed level 1986 with tidal forcing and average winter discharge during low water
- bed level 2003 with tidal forcing
- bed level 2003 with tidal forcing and average winter discharge during low water

If the system is forced with the highest discharge just prior to the bed level measurements, the relation between channel dimensions and tidal volume approaches the relation of Haring. According to this relation, all the channel dimensions are still too large for the tidal volume that is transported through the specific cross-section. The current velocities in the Slijkgat are with these highest discharges directed seawards during ebb.

3.4.4 Conclusions of Slijkgat Area

The Slijkgat is part of the Inner Area. This area has become shallower over the last twenty years. This trend is also visible for the sand bars surrounding the Slijkgat, the Garnalenplaat-Zuid has expanded to the west and is directing the Slijkgat. The channel the Slijkgat however does not show an accreting trend. The dimensions of the channel have increased and since the channel is reaching its equilibrium profile ebb and flood channels start to develop.

Compared to the relation of Haring the tidal channels are always too large compared with the tidal volume. The derivation from the relation of Haring is smaller for cross-sections near the sea. Explanations why the relation of Haring is not followed can be, that the tidal volumes calculated as a result of the simulation do not represent the actual tidal volume present. Another explanation might be that the environmental conditions on which the empirical coefficient alpha is based have changed after the construction of the Haringvliet Dam.

3.5 Discussion

Above it is concluded that the morphology of the Slijkgat is dominated by river discharge. The classification of Hayes as presented in Chapter 2 depends on wave height and tidal range. Therefore for the purpose of this study the Hayes classification is used in conjunction with the river discharge classification specifically used for the Slijkgat Area (illustrated in Figure 37). There is some overlap between the different zones. For example it is expected that during the winter large waves occur and the zone of mixed energy shifts more landwards in front of the Slijkgat.

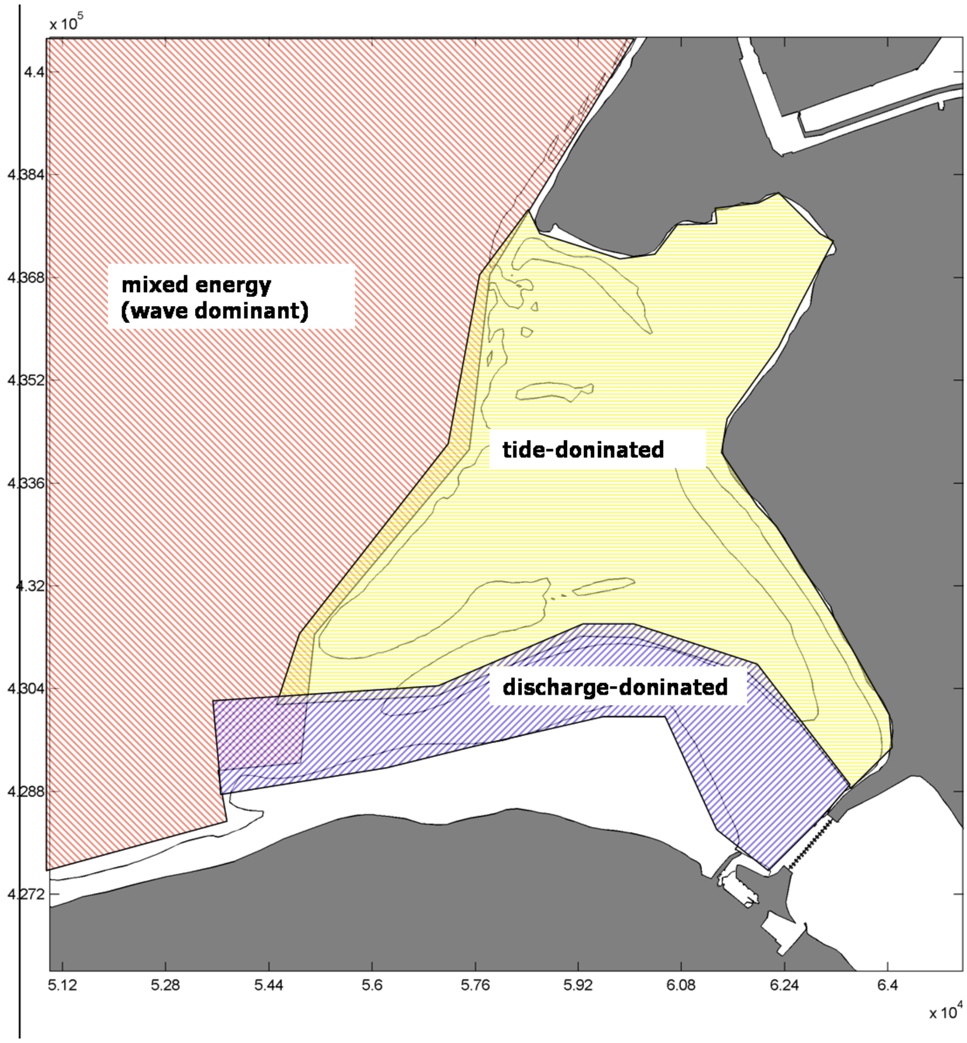

Figure 37 Dominating processes in the Total Haringvliet Area

The situation in the Haringvliet is highly dynamic. This is due to the variations in river discharge which causes the Slijkgat to adapt constantly to the situation of that moment. High river discharge changes the situation rapidly by increasing the cross-sectional area. In a period with little or no river discharge the system starts to accrete towards the equilibrium state as a result of the low discharge. This process goes inversely exponential proportional to the disturbance compared to the desired profile. This process is more fluent and takes more time than the erosion by high river discharges. qualitative impression of this is given in Figure 38, where it can be seen that the morphology of the Slijkgat can be considered as a pulsating system.

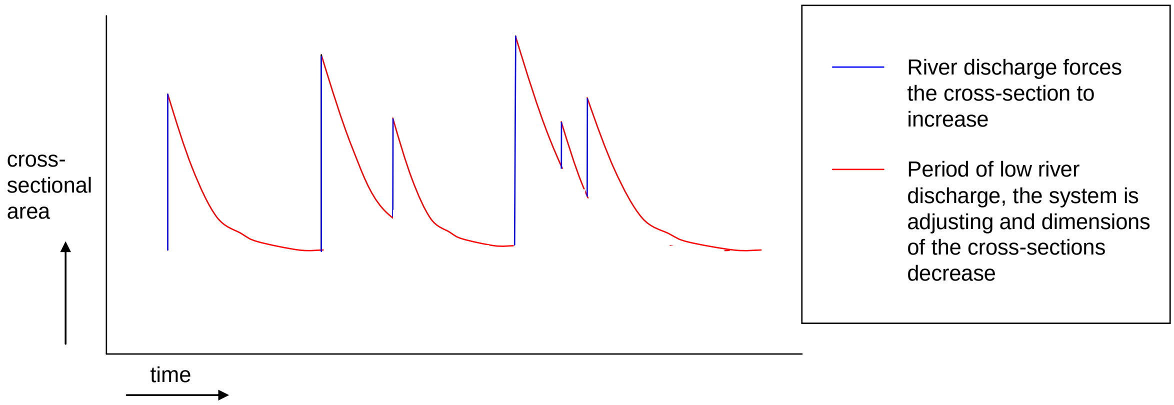

Figure 38 The morphology of the Slijkgat as an episodic behaving system due to differences in river discharge

As shown in Figure 37, the morphology of the south of the Haringvliet (the Slijkgat Area) is dominated by river discharge. For almost the entire year the dimensions of cross-sections of the Slijkgat are too large except for the situation during high river discharges. During the remaining period current velocities are relatively low, since the dimensions are large for the amount of water passing. These low velocities allow sediment to settle and the channel starts to accrete.

When studying the current patterns of two extreme situations(no and high river discharge) the following conclusions can be drawn (Figure 39):

- During extreme river discharge, normally in winter time, the dimensions of the Slijkgat increase. This is visualised by the blue line in Figure 39.
- During the summer when the river discharges are low or even zero, the relatively large cross-sections in the Slijkgat allow large volumes of water to enter the Inner Area during flood. Due to residual circulation the northern part of the Haringvliet remains open. This is demonstrated by the red line in Figure 39.

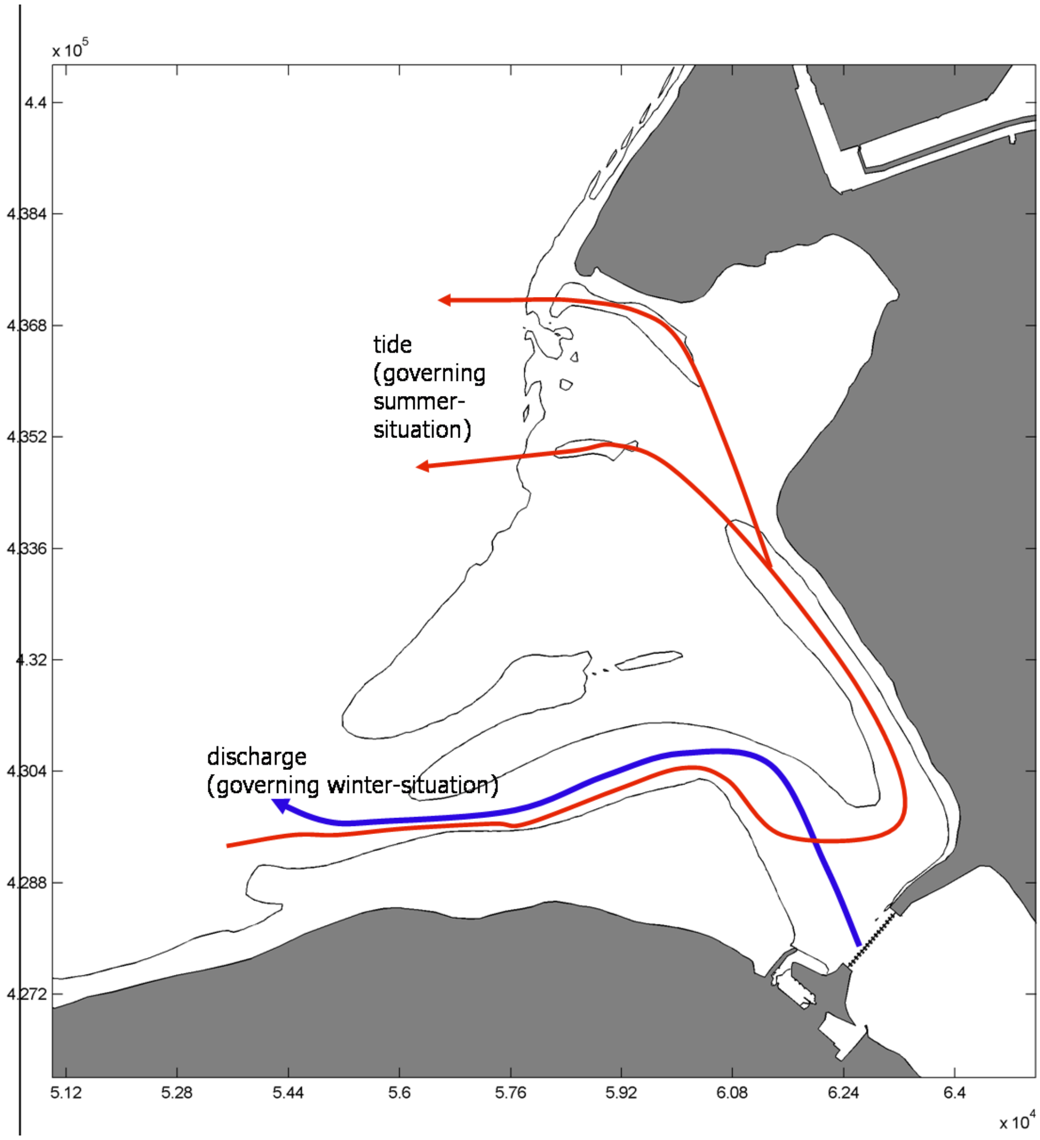

Figure 39 Dominating currents for a situation with high river discharge and a situation with no river discharge

3.6 Conclusions morphological analysis

The objective of the chapter is to give insight in the morphological development of the Slijkgat. The Slijkgat is part of the Inner Area which is part of the Total Haringvliet Area. To give predictions on the scale of the Slijkgat the total morphological system must be studied. Therefore first the Total Haringvliet Area has been studied, secondly the Inner Area has been studied which is one scale smaller and finally the Slijkgat Area has been studied.

The morphological analysis shows that the Inner Area is accreting while the Outer Area is eroding. The sand balance for the Total Haringvliet Area shows that the amount of sand in the Total Haringvliet Area is approximately stable and that it is only redistributed within the system. After the construction of the dam the tidal forcing diminished while the wave forcing remained the same. The wave forcing became more dominant at the boundary of the Inner Area and the Outer Area, since the tidal forcing reduced. This pushed the depth contour landwards and caused erosion in the Outer Area.

The channels are too large according to the relation between tidal volume and channel dimension formulated by Haring(1967). This can have three explanations. Firstly, the tidal channels in the Inner Area have not yet reached their equilibrium situation and will accrete future until the equilibrium profile is reached. Secondly, it is not the average winter situation that is governing, but an extreme discharge situation that determines the dimension of the tidal channels. Thirdly, the empirical coefficient α takes environmental conditions into account, that might have changed after the construction of the Haringvliet Dam. For example the portion of river water has increased as part of the tidal volume. The deviation with the relation of Haring is smaller for cross-sections located near the sea. Arends (1997) concluded that the extreme river discharge is governing, therefore the third explanation is probably true.

The current analysis shows that water enters the Inner Area during flood via the Slijkgat. This water leaves the Inner Area via channels in the north, resulting in a residual circulation. The creation of the Kortsluitgeul shows that the morphological system requires a channel in the northern part.

River water from the Haringvliet Sluices is mainly discharged through the Slijkgat. The tendency to transport more water through the Slijkgat has increased the last 17 years. This is determined by calculating the total amount of tidal volume that pass the western part of the Haringvliet, so the tidal volume over all the cross-sections and bars. This total tidal volume remain approximately the same, while the percentage of the total volume transported through the Slijkgat increased from 43.8 % to 65.7 %.

The cross-sections in the Slijkgat have reached their quasi-equilibrium dimensions. Due to the changing morphology around the Slijkgat and varying river discharges (which result in different tidal volumes) the dimensions of the Slijkgat are continuously adjusting to the new situation. In consequence of the accretion of the surrounding area, it can in general be concluded that the tidal volume is increasing and the channel is becoming deeper. The channel is moreover developing ebb and flood channels, which also results in sills between the ebb and flood channels; so the channel is locally becoming shallower.

The Slijkgat has to adjust continuously to the situation of that moment. High river discharge changes the situation rapidly by increasing the cross-sectional area. In a period with little or no river discharge the system starts to accrete and migrate towards a different equilibrium situation as a result of the low discharge. The morphology of the Slijkgat can be considered showing a episodic behaviour.

The morphology of the Inner Area balances on two elements. First, the river discharge which keeps the Slijkgat open. Second, these large cross-sectional area make tidal flooding and sedimentation of the Inner Area possible.

4 Scenarios maintenance policy for the Slijkgat

This chapter presents and evaluates scenarios that may optimise the maintenance activities of the Slijkgat. To optimise these maintenance activities it is advisable to utilise the system dynamics. First the expected morphological developments are presented (Section 4.1) . The future morphological development of the Haringvliet and the Slijkgat can be derived from the analysis of the previous chapter. In Section 4.2 first boundary conditions for the scenarios are presented, where after an overview on the scenarios are shown. In Section 4.3 the scenarios will be evaluated.

4.1 Future developments

The Slijkgat is part of the morphological system of the Haringvliet, therefore first the morphological predictions for the Total Haringvliet Area are given, subsequently the expected developments of the Slijkgat are discussed. The last paragraph discusses the dynamic equilibrium of the Haringvliet as a result of future developments.

The sand balance of the Total Haringvliet Area is approximately in equilibrium. Within the system sediment is however transferred from the Outer Area to the Inner Area (Section 3.2). The Inner Area is accreting. It is expected that the Inner Area will continue taking in sediment until a balance is reached between the tidal volume and the dimensions of the tidal channels. The process of the eroding Outer Area is also expected to continue. In the northern part of the Outer Area, the bathymetry will shift from ebb-tidal delta towards no-inlet bathymetry. While in the southern part, where the Slijkgat is discharging river water, an ebb-tidal delta will remain. Figure 40 shows the cross-sections for an ebb-tidal delta and a no-inlet bathymetry.

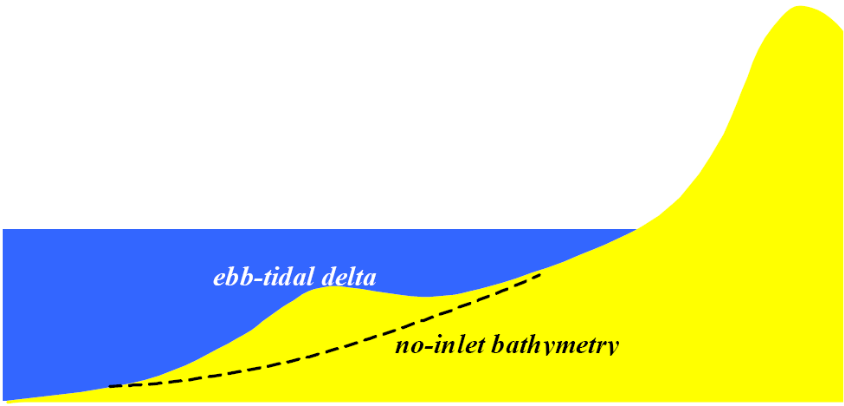

Figure 40 Cross-section of ebb-tidal delta, indicating the cross-shore boundary by no-inlet bathymetry [Goor 2003].

Contrary to the rest of the Inner Area, the Slijkgat is not expected to accrete. The dimensions of the Slijkgat are approaching their quasi-equilibrium state. As a result of high river discharge the Slijkgat will remain open. The last 17 years the volume of water discharged through the Slijkgat increased, Section 3.4. A result of the increase in volume is that the dimensions of the Slijkgat are increased. Although the Inner Area is accreting, the Slijkgat remains open. Due to the accretion of the Inner Area the tendency that more water is discharged through the Slijkgat will remain. The Slijkgat has reached its dynamic equilibrium state. The change of the Inner Area will influence the Slijkgat, since the Slijkgat is part of the Inner Area. This trend is also visible in the bed level data discussed in Section 3.4.1. The Slijkgat is developing a pattern of ebb and flood channels, since the cross-sectional dimensions are approaching their equilibrium state. With the development of ebb and flood channels sills between the channels may occur in the future.

In the future the Haringvliet will reach a dynamic equilibrium. The system will remain dynamic, since one of the main forces of the system, high river discharge, only occurs a few times per year. This dynamic system is based on two phenomena: river discharge and tidal phase difference. If the discharge through the Haringvliet Sluices was absent, the Inner Area would probably completely silt up. River water is however discharged through the Haringvliet Sluices and therefore the Slijkgat is not silting up. The circumstance that the Slijkgat remains open enables tidal movement to enter the Inner Area. As a result of tidal phase difference water that enters the Inner Area in the south leave this area in the north and the channels in the north stay open.

4.2 Model Scenarios

This section gives an overview of the scenarios for which simulations have been done. The boundary conditions for the scenarios are however presented first. The future developments of the area, discussed in the previous section, are taken into account for the formulation of the boundary conditions and the scenarios, since the main objective for the boundary condition and the scenarios is to take the system dynamics into account.

4.2.1 Boundaries conditions of the scenarios

As described in Section 1.2 the main objective of the thesis is to do an exploratory research into the maintenance of the Slijkgat, given a deepened of the channel to -5,5 m NAP. The scenarios are therefore focussed on the effects they have on the morphological development of the Slijkgat. Large disturbing effects on the Inner Area are however undesirable. Figure 41 shows the location of the approach channel; the green area was located above the -5.5 m NAP in 2008.

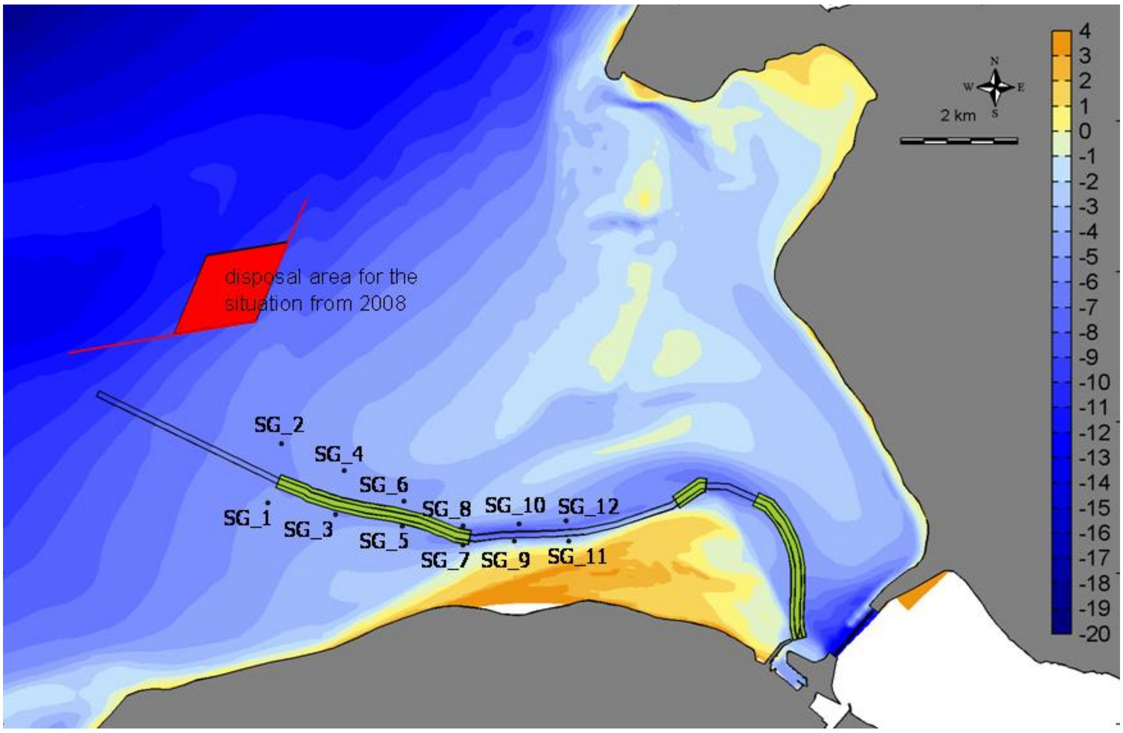

Figure 41 Location of the channel and disposal area from 2008. The green areas mark the locations where the bed level was above -5.5 m NAP in 2008. The red area marks the disposal area. The bed level dates from 2003.

In Chapter 3 it was concluded, based on the morphodynamic analysis, that the dimensions of the Slijkgat are dependent on river discharge. This river discharge can be controlled, since it is discharged through the Haringvliet Sluices. The total volume of water which has to pass the sluices is however determined by uncontrollable natural processes. All the scenarios have in common that the method of discharging the river water is to some extend controllable. The amount of river water that enters the Netherlands is distributed via several river and channel to the sea. This distribution is humanly controlled, with the aid that the salt water can not penetrated to far into the Nieuwe Waterweg.

The second common factor for all scenarios, is that either the tidal volume must increase or the current velocities in the channel must increase in order to minimise siltation. The tidal volume causes currents in the channel. The velocity of these currents depends on the dimension of the channel. Hence if velocities are so high that sediment is picked up and transported, the dimensions of the channel will increase. With low velocities sediment will settle and the channel depth will decrease. In a natural system the current velocity is proportional to the tidal volume. In the Haringvliet these current velocities can be artificially increased, since the river discharge through the Haringvliet Sluices is controllable. Therefore an increase in current velocities is possible, while the tidal volume remains the same.

The third common factor for all scenarios is that an extreme discharge is used, as reference. During high river discharge the dimensions of the Slijkgat increase rapidly. This in contrast to the period of accretion which happens during a longer period (Figure 38). Therefore the highest river discharge that occurred within three months before the bed level measurement is the basis value for the river discharge and used as reference, which is a daily average of 2685 m^3/s.

The bed level data used for this study date from 1986, 1992, 1998 and 2003. Since the data from 2003 is most recent, this set is used for evaluating the scenarios. By using the bed level data from 2003, it is possible to compare the different scenarios to the results from the morphological analysis of Chapter 3.

The boundary conditions for the scenarios as described above are in short:

- The focus of the scenarios is on the developments in the Slijkgat
- The river water discharge in controllable.
- Tidal volume or current velocities must increase, to maintain large profiles in the Slijkgat
- The bed level data from 2003 are the basis for the simulation in this chapter

4.2.2 Model scenarios

This section provides an overview of the scenarios that are simulated to investigate the possibilities for minimising the maintenance of the Slijkgat. In these simulations two elements can differ; the bed level and the operation of the Haringvliet Sluices.

The reference used for the bed level is the bed level of 2003. This makes it possible to compare the scenario simulation with the simulations as described in Chapter 3. Since extreme discharges are governing for the dimensions in the Slijkgat the reference used for the discharges is the highest discharge that occurred just prior to the bed level measurements in 2003, which is of 2685 m^3/s. This is a daily average, which means that the actual discharge enforces in the simulation is higher, since the sluices are normally closed above mean sea level. To generate higher velocities in the Slijkgat higher river discharges are not necessary needed. By controlling the sluices high velocities can be generated even with lower discharges. This would mean that the dimensions of the Slijkgat will be less depending on the natural high discharge, since the corresponding high velocities can be generated artificially by controlling the sluices. The scenarios that are investigated have as reference the simulation with high river discharge. It is expected that for other river discharges the effects on the system will be proportionally the same.

Below an overview of the variations in bed level scenarios and discharge is given.
Bed level scenarios:

B1 Bed level 2003, this data set is also in simulation in Chapter 3, reference bed level

B2 Reference bed level with the adjustment that the Slijkgat is over a width of 100 m deepened to -5.5 m on locations where it used to be shallower than -5.5 m.

B3 Reference bed level with the adjustment that the level of the Rak van Scheelhoek is raised to the same depth as surrounding sand bars.

B23 This is a combination of B2 and B3. Both the Slijgat is deepened so that in the whole channel the at least -5.5 m deep over a width of 100 m and the Rak van Scheelhoek has the same depth as surrounding sand bars.

Plot of the different bed level scenarios is given in Figure C1 Appendix C. The scenarios B3 and B23 are taken into account, since the Rak van Scheelhoek has the tendency to accrete rapidly (Section 3.3.2). Previous simulations showed that relatively more water is discharged through the Slijkgat. Changes in the bed level of the Rak van Scheelhoek might influence the amount of water transported through the Slijkgat and with that the current velocities.

The scenarios for the discharge are given below.

D1 reference discharge 4963 m^3/s discharged during low water (appr. 6 hours).

D2 8335 m^3/s discharged during 4 hours

D3 16669 m^3/s discharged during 2 hours

D4a Kier-scenario for an average winter situation: so a discharge of 1200 m^3/s as daily average. On top of this the Haringvliet Sluices are 150 m^2 opened during high water. A detailed explanation on the Kier-scenario can be found in the paragraph below Table 4

D4b Kier-scenario for the extreme discharge situation of 2003: so a daily average discharge of 2685 m^3/s. On top of this the Haringvliet Sluices are 400 m^2 opened during high water. A detailed explanation on the Kier-scenario can be found in the paragraph below Table 4

D5a The discharge is similar to the reference discharge (D1), only for this scenario water is only discharged through the northern sluices.

D5b The discharge is similar to the reference discharge (D1), only for this scenario water is only discharged through the southern sluices.

The total volume of river water passing the Haringvliet Sluices is the same for D1, D2, D3 and D5. The time of the opening of the sluices is however variable. For scenarios D4a and D4b the total tidal volume is different, this is explained below.

D4a and D4b, Kier-scenarios

In the near future a new closing policy will be implemented for the Haringvliet Sluices. In this new policy the sluices will be put ajar (*dutch: op een kier*) during high water. The size of the opening depends on the amount of fresh water run-off since the salt may not penetrate too much to the East considering the take-in of fresh drinking water(Table 3).

Table 3 Kier-policy. The size of the opening of the sluices during flood, depending on the river discharge [Projectorganisatie Realisatie de Kier 2004]

Daily average river discharge	**Opening**
Below 1000 m^3/s	The sluices are closed.
From 1000 to 1700 m^3/s	The opening is increasing linearly from 50 to 400 m^2
From 1700 to 2600 m^3/s	The opening is 400 m^2 both during ebb as during flood
Larger than 2600 m^3/s	The opening of the sluices is the same during ebb as during flood.

For the kier scenarios simulated in this study this means the following.

- If an average winter situation is simulated with a daily average discharge of 1200 m^3/s. The sluices are opened 150 m^2 during flood. The water level in front of the dam increases during flood and with that the water intake increases. For discharge scenario D4a the maximum discharge that is entering the fresh water lake is 267 m^3/s. All the water that enters the fresh water lake during flood is added to the discharge volume that is discharged during ebb.
- Discharge scenario D4b simulates a river water discharge which has a daily average of 2685 m^3/s. The maximum discharge that enters the fresh water lake during flood is 2133 m^3/s.

Table 4 shows the combinations of discharge and bed level scenarios.

Table 4 Overview on scenarios

	B1 (bed level 2003)	B2 (Slijkgat at least -5.5 m)	B3 (RvS same height as sandbar)	B23 (combination B2 and B3)
D1 (6 hours)	**x**	**x**	**x**	**x**
D2 (4 hours)	**x**			
D3 (2 hours)	**x**			
D4a (kier)	**x**			
D4b (kier)	**x**			
D5a (North)	**x**			
D5b (South)	**x**			

x = simulation

4.3 Evaluations of scenarios

The results of the scenarios are all compared to a reference simulation. The reference simulation is the simulation with the bed level of 2003 (B1) and a discharge during low water of 4963 m^3/s (D1). First the effect of a different bed levels is evaluated. Subsequently the effects of different discharge regimes are discussed.

The effect of variety in bed level is marginally for the bed level situation in 2003. Figure 42, shows the velocities in the Slijkgat for the bed level of 2003 and the bed level in 2003 of which the Slijkgat is at least -5.5 m deep over a width of 100m. The graph shows that current velocities for the reference situation and the situation in which the deepening is approximately the same.

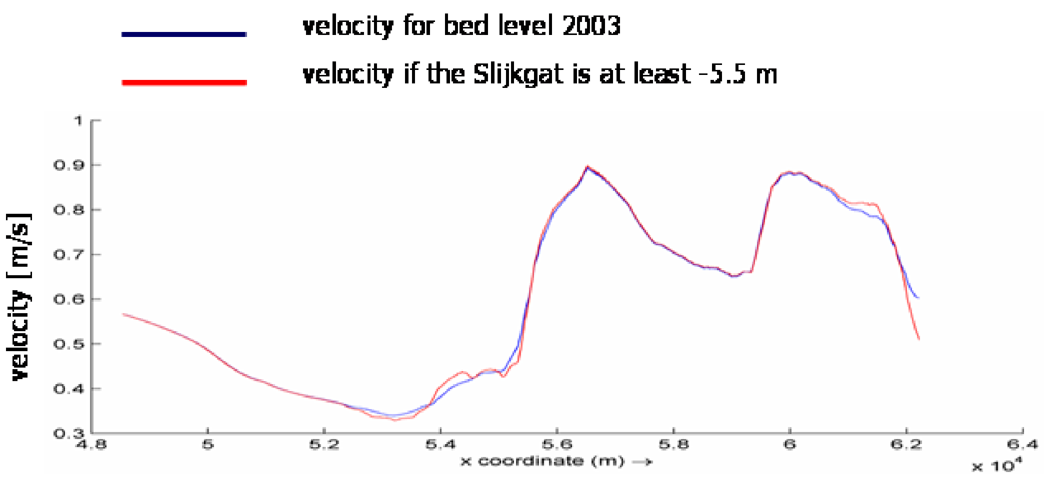

Figure 42 Current velocities in the Slijkgat for the reference situation in red (bed level 2003) and the situation for which the Slijkgat is at least -5.5 m deep in blue.

The other bed level scenarios, B2 (raised bed level of the Rak van Scheelhoek) and B23 (Slijkgat al least -5,5 and an elevation of the Rak van Scheelhoek) give comparable results. Since the current velocities is related to the amount of water that is discharged during a tidal period, below an overview is given of the relative discharge volumes through the Slijkgat and the Rak van Scheelhoek.

Table 5 Relative discharge through the Slijkgat for different discharge scenarios

scenario	relative discharge through the Slijkgat*
B1 D1	67 %
B2 D1	67 %
B3 D1	70 %
B23 D1	70 %
B1 D5a (north)	67 %
B1 D5b (south)	67 %

* the percentage is compared to the inner transect as formulated in Section 3.3.4. This transect compares the Tidal Volume that passes the Slijkgat near the sluices with the total tidal volume that passes the inner transect, Figure C2 and C3 Appendix C

Table 5 shows that an elevation of the Rak van Scheelhoek increases the total discharge through the Slijkgat with 1% for both scenarios B2 as B23. In simulation B2 and B23 the Rak van Scheelhoek is elevated to the level of the surrounding sand bars. The Inner Area is accreting so the Rak van Scheelhoek and the surrounding sand bars of the Rak van Scheelhoek may become shallower in the future. In this case more water may be discharged through the Slijkgat, a tendency that was also visible in Section 3.3.4.

The paragraphs above explained that the differences between bed level scenarios are small. The evaluation of other scenarios will therefore focus on different discharge scenarios, which are simulated with the reference bed level. First the scenarios in which the sluices are opened during a shorter period are evaluated (D2 and D3), secondly the 'Kier' scenarios (D4a and D4b) and finally the scenarios which focus on using only the southern or the northern sluices (D5a and D5b).

If the sluices are opened 4 hours during low water (D2), instead of 6 hours (D1), the instant discharge is approximately 1.5 times larger. (4963 m/s versus 8335 m/s). The currents in the Slijkgat are with these simulations also approximately 1.5 times larger, Figure 43. The effect of opening the sluices during a shorter period is mostly noticeable for the elevations near the dam. Near the sea the channel widens and current velocities are low for both simulations.

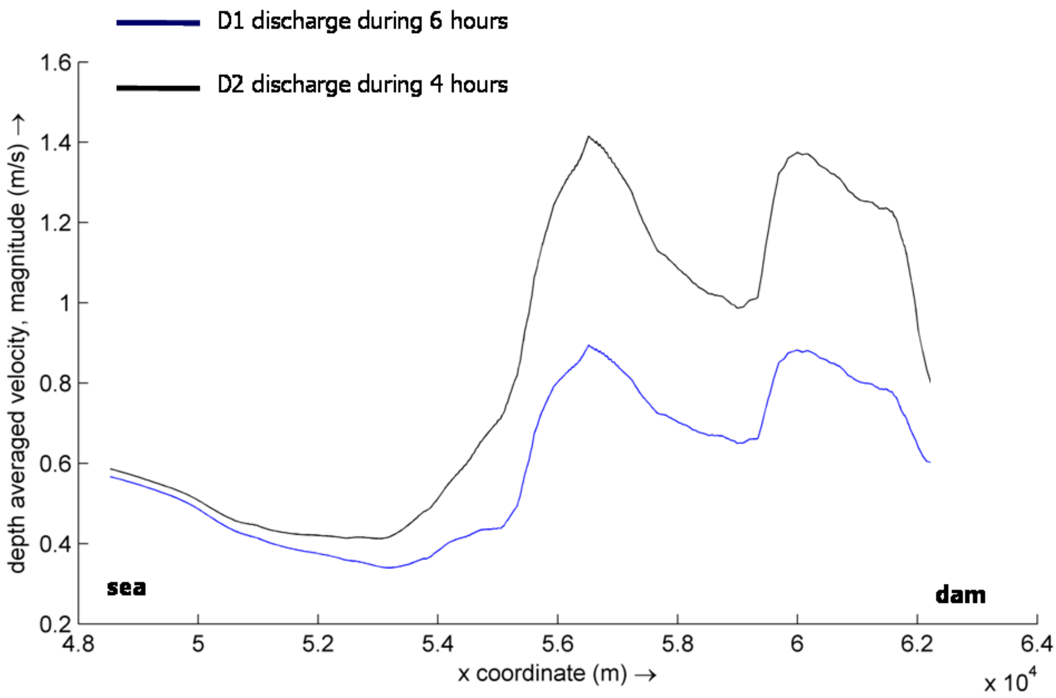

Figure 43 Current velocities in the Slijkgat, for D1(blue) and D2 (black)

Secondly the simulation in which the sluices are opened 2 hours during low water is discussed (Scenario D3). If the sluices are opened 2 hours during low water, the current velocities become extremely high. These high velocities do not only occur in the Slijkgat, but the velocities increase in the total area, as shown in Figure C4 and C5, Appendix C. Scenario D3 shows that velocities might become too large and unrealistic as a result of opening the sluices during a shorter period. These high velocities have a negative effect on the Inner Area. In Figure C6 Appendix C the current velocities in the Haringvliet are plotted, every 30 minutes from the opening of the sluices.

The simulations in this study show that it is possible to generate larger currents in the Slijkgat by adjusting the opening time. In these simulations the physical boundaries of the sluices are not taken into account. Further research in needed to determine to maximum instant discharge capacity of the sluices. The discharge scenarios discussed above show that if the time of discharging is decreased, current velocities in the Slijkgat can increase. It is advisable to do future research to find the optimum current velocities in the Slijkgat and the corresponding discharge in the Slijkgat. If the optimum discharge through the Slijkgat is known the corresponding time for the opening of the Haringvliet Sluices can be determined depending on the river discharge. In this chapter the reference discharge is a high discharge in 2003. For lower discharges the policy of opening the sluices during a shorter time span is also possible. If the optimum velocity in the Slijkgat is applied every day, sediment does not get the possibility to settle and less dredging activities may be needed.

If the sluices are opened during high water, kier-scenarios (D4a and D4b), water can enter the Haringvliet Lake. As a result more water must be discharged during low water. These higher amounts result in high currents in the Slijkgat. In Figure 44 D4b and D1 are plotted. Comparing this figure with Figure 43 shows the effect of scenario D2 reaches further to the sea compared to the Kier scenario.

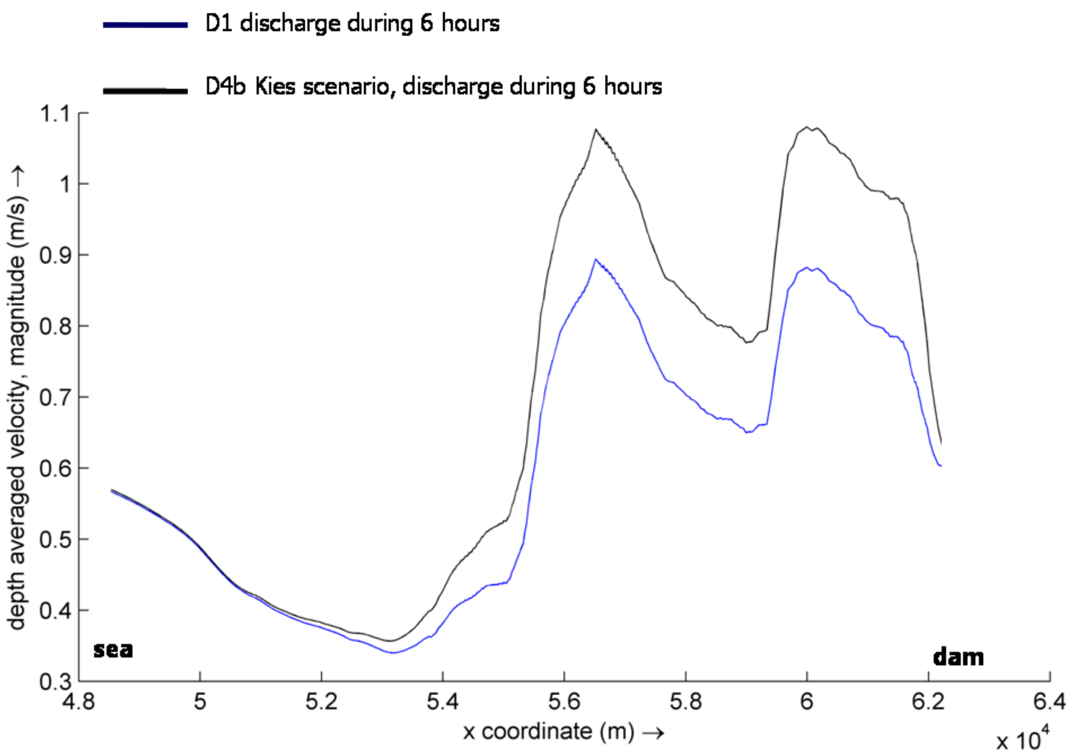

Figure 44 Current velocities in the Slijkgat, for D1(blue) and D4b (black)

The scenarios where the sluices are only opened in the north (D5a) or in the South (D5b) do not seem to make a difference. The water depth in front of the sluice is so deep that the water is equally distributed in front of the sluices, Figure 45. The tidal volumes transported through the Slijkgat are equal for scenario D5a and D5b.

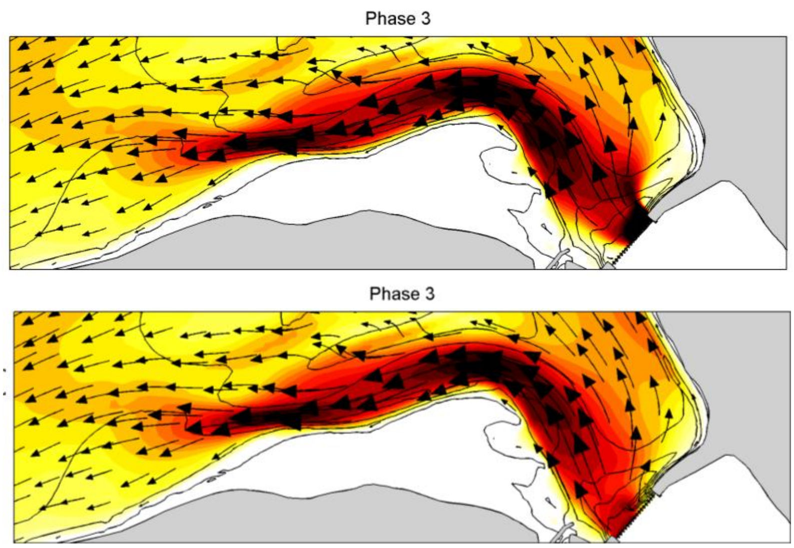

Figure 45 Current plots for simulations with bed level B1 (2003) and discharge scenarios D5a and D5b.

4.4 Conclusions scenarios

Table 6 gives on overview on the result of the different scenarios. Scenario D1_B1 is the reference scenario; the other scenarios are judged relative to this scenario.

Table 6 Evaluation of scenarios

	B1 (bed level 2003)	B2 (Slijkgat at least -5.5 m)	B3 (RvS same height as sandbar)	B23 (combination B2 and B3)
D1 (6 hours)	0	0	0	0
D2 (4 hours)	+			
D3 (2 hours)	- -			
D4a (kier)	-*			
D4b (kier)	+			
D5a (South)	0			
D5b (North)	0			

- - = the results are highly undesirable
- = the results of this scenario are worse than the reference scenario
0= the results are neutral compared with the reference scenario
+= the results of the scenario are better than the reference scenario
*For this scenario(D4a) a lower river discharge have been used, therefore it is logic that the result are not a good as the reference scenario with a higher river discharge.

5 Conclusions and Recommendations

This chapter provides an overview of the conclusion of this study, moreover recommendations are given. The objective of the thesis was to do an exploratory research into the maintenance of the Slijkgat. To answer this objective the research focused on the natural behaviour of the Slijkgat. Therefore two sub-objectives were formulated:

- Morphological analysis of the development of the Slijkgat with aid of numerical modelling and historical data.
- Predict the future morphological behaviour of the Inner Area of Haringvliet

These sub-objectives support the main objective:
An exploratory study into the maintenance of the Slijkgat after it is deepened.

5.1 Conclusions

The conclusions are split in two categories, first the conclusions on the sub objectives are given, the conclusions on the morphological analysis and the future morphological behaviour. Secondly the conclusions on the main objective are given.

Conclusions on morphological behaviour and future behaviour:

- The sediment balance of the area of interest is approximately zero.
- Sediment is however redistributed from the Outer Area to the Inner Area. The Outer Area is eroding, while the Inner Area is accreting.
- The sand bars in the Inner Area are highly dynamic.
- The Slijkgat is influenced by the development in the Inner Area, since it is part of this Inner Area.
- The cross-sectional dimensions of the Slijkgat have reached their equilibrium state.
- Due to ebb and flood channels the bed level of the Slijkgat will remain shallow at some locations.
- West of the Slijkgat an ebb tidal delta will remain, with a corresponding shallowness.
- The Slijkgat will likely remain open as a result of river discharge.
- If the Slijkgat remains open, sea water can enter the Inner Area via the Slijkgat. Due to tidal phase difference the northern part of the Inner Area may remain open.
- In the future the Haringvliet will reach a dynamic equilibrium, since one of the main forces of the system, high river discharge, only occurs a few times per year.

Conclusion on the exploratory research into the maintenance of the Slijkgat:

- High velocities during high river discharge determine the dimensions of the Slijkgat. These high velocities can during low river discharge artificially be generated by opening the sluices during a shorter period.
- If the optimum velocities for the Slijkgat are known, these velocities can be generated by opening the sluices for a period related to the river discharge. If these optimum velocities occur on a regular basis, less dredging activities may be needed.

- The effect of opening the sluices during a shorter period is mostly noticeable for the shallow areas near the dam. The effect is less significant for the sill near the sea. At this location the Slijkgat is widening and therefore current velocities decrease even if the sluices are opened during a shorter period.
- The 'Kier'policy, which means that the sluices will also be opened during high water, has a positive effect on the current velocities, since this closing policy will increase the tidal volume.
- Discharging though only the southern or the northern sluices does not make a difference for the tidal volume and the current velocities in the Slijkgat.

5.2 Recommendations

The recommendations are also divided in recommendations that correspond with the sub-objectives and recommendations that correspond to the objective. The recommendations of the sub-objective concentrate on measurements, since measurements can improve the morphological analysis and with that the future morphological behaviour of the Slijkgat.

Recommendations on the sub-objectives:

- Measurements I:
  The Slijkgat is part of the Inner Area. The behaviour of the Slijkgat depends on the developments in the Inner Area. Therefore it is advisable to measure regularly the Slijkgat and the surrounding area.
- Measurements II:
  It is advisable to register the amount of dredging material and the time and location of the dredging and disposal activities, since this can provide insight in the accretion rate.

Recommendations on the objective:

- Closing policy I:
  The optimum current velocity in the Slijkgat have to be determined. Depending on this optimum velocity the instant discharge can be calculated. The river discharge is a natural variable. The discharge through the Slijkgat can be controlled by the opening time op the sluices. For each river discharge an optimum opening time can be determined
- Closing policy II:
  It has to be determined which discharge is physical possible, given the discharge capacity of the sluices. In this study a schematisation is used and the physical boundaries of the sluices are not taken into account.
- Closing policy III:
  If the Haringvliet Sluices are opened during a shorter period, river water might be discharged through other channels, for instance the Nieuwe Waterweg. It has to be determined what the effect of a new closing policy are related to other channels in the south-western part of the Netherlands. Furthermore salt water may not penetrate the Nieuwe Waterweg to deep. Therefore, during periods of little river water, the salt water penetration in the Nieuwe Waterweg is governing for the distribution of river water in the south-western part of the Netherlands.

- At some locations the Slijkgat will have the tendency to accrete. A combination of maintenance dredging and a tidal prism might be a solution to reduce the frequency of dredging activities.
- It is advisable to adjust the dredging activities to the seasonal conditions.
- It is advisable to dispose the dredged material outside the morphological system. The disposal area presented in this report seems suitable.

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A Figures belonging to Chapter 2

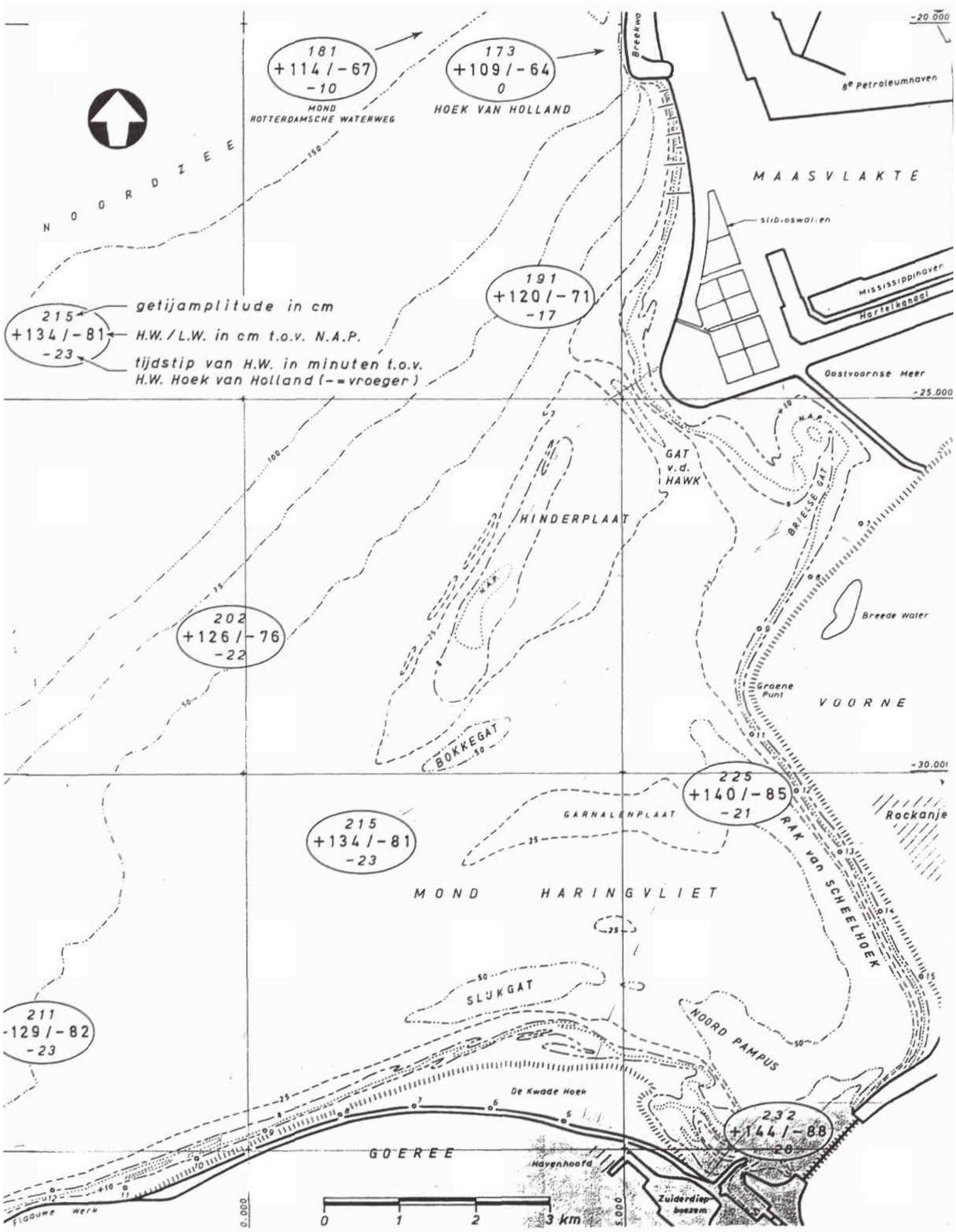


Figure 46 Average tidal quantities for the Haringvliet Mouth, period 1975-1982 [Steijn, 2001]

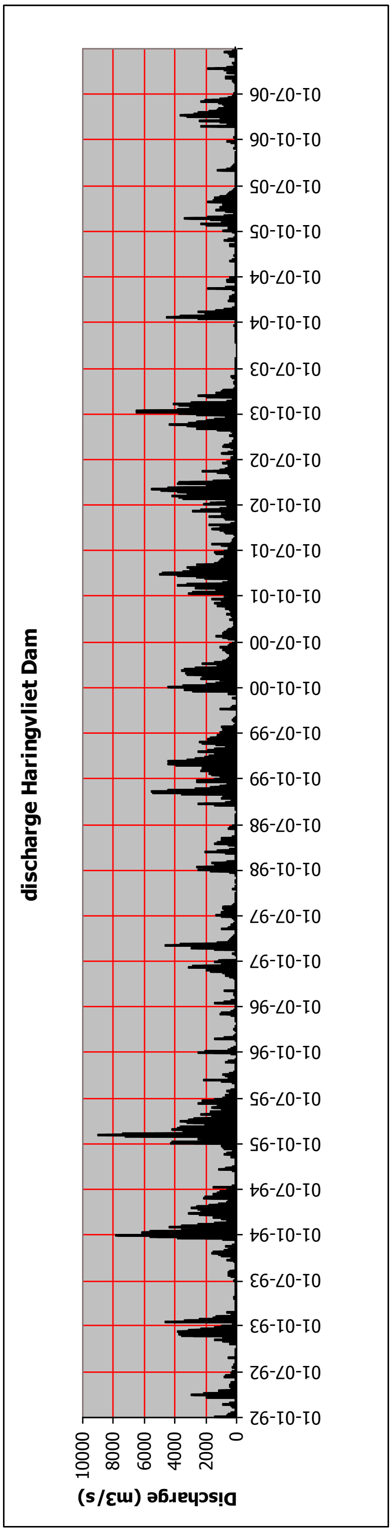


Figure 47 River discharge at the Haringvliet Sluices. Discharge is an daily average

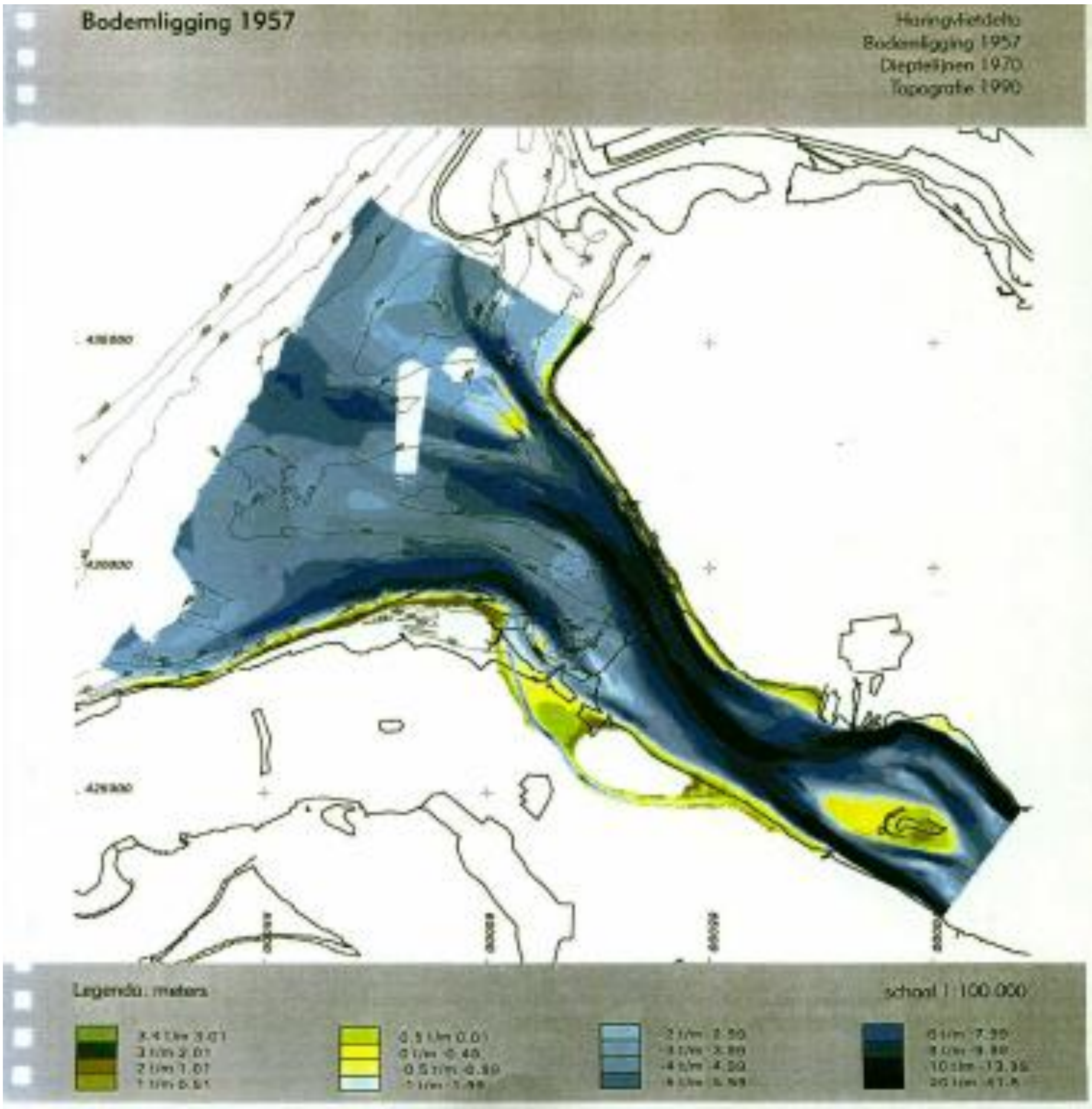


Figure 48 Mouth of the Haringvliet; bottom location 1957; depth contours 1970. A land boundary of 1986 is used. [Samenwerkingsverband Maasvlakte 2 varianten (1998)

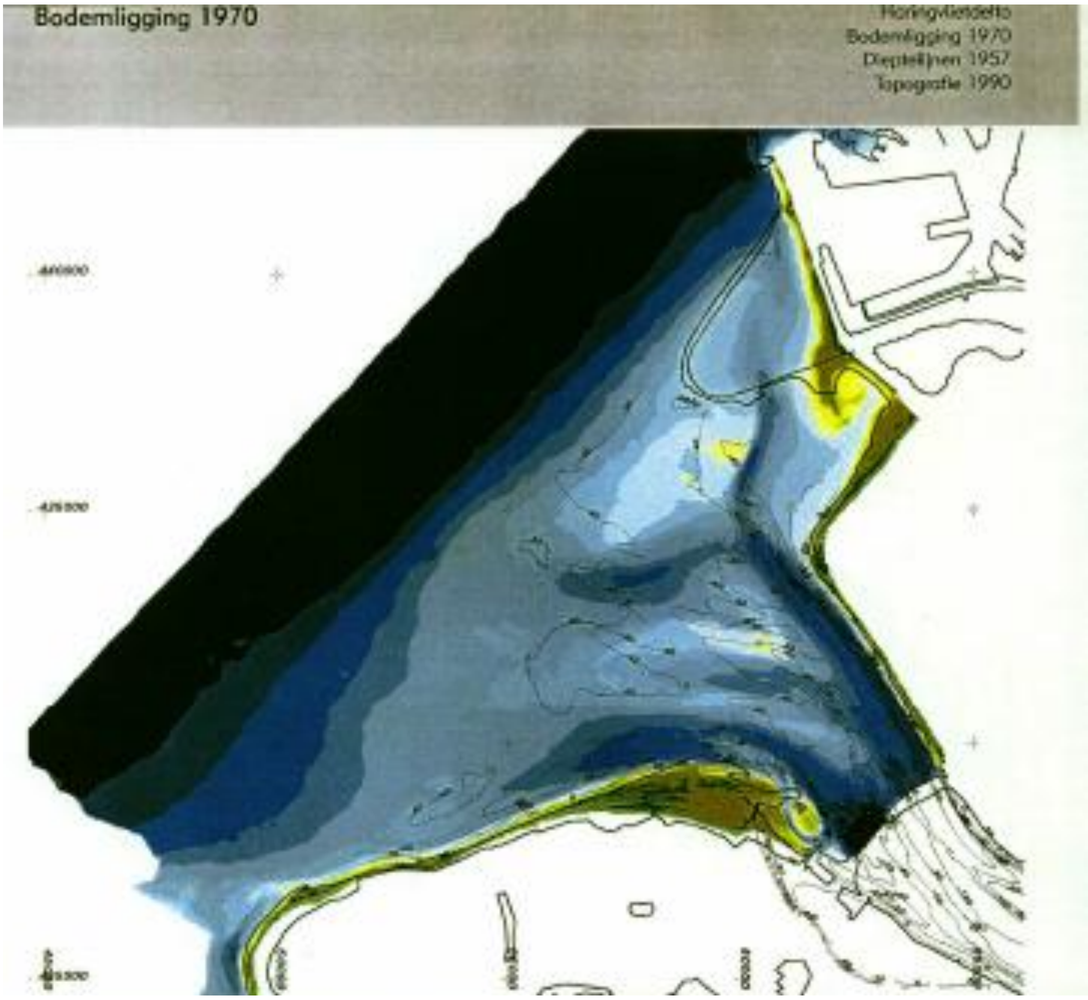


Figure 49 Mouth of the Haringvliet; bottom location 1970, depth contours 1957. A land boundary of 1986 is used. [Samenwerkingsverband Maasvlakte 2 varianten (1998)]

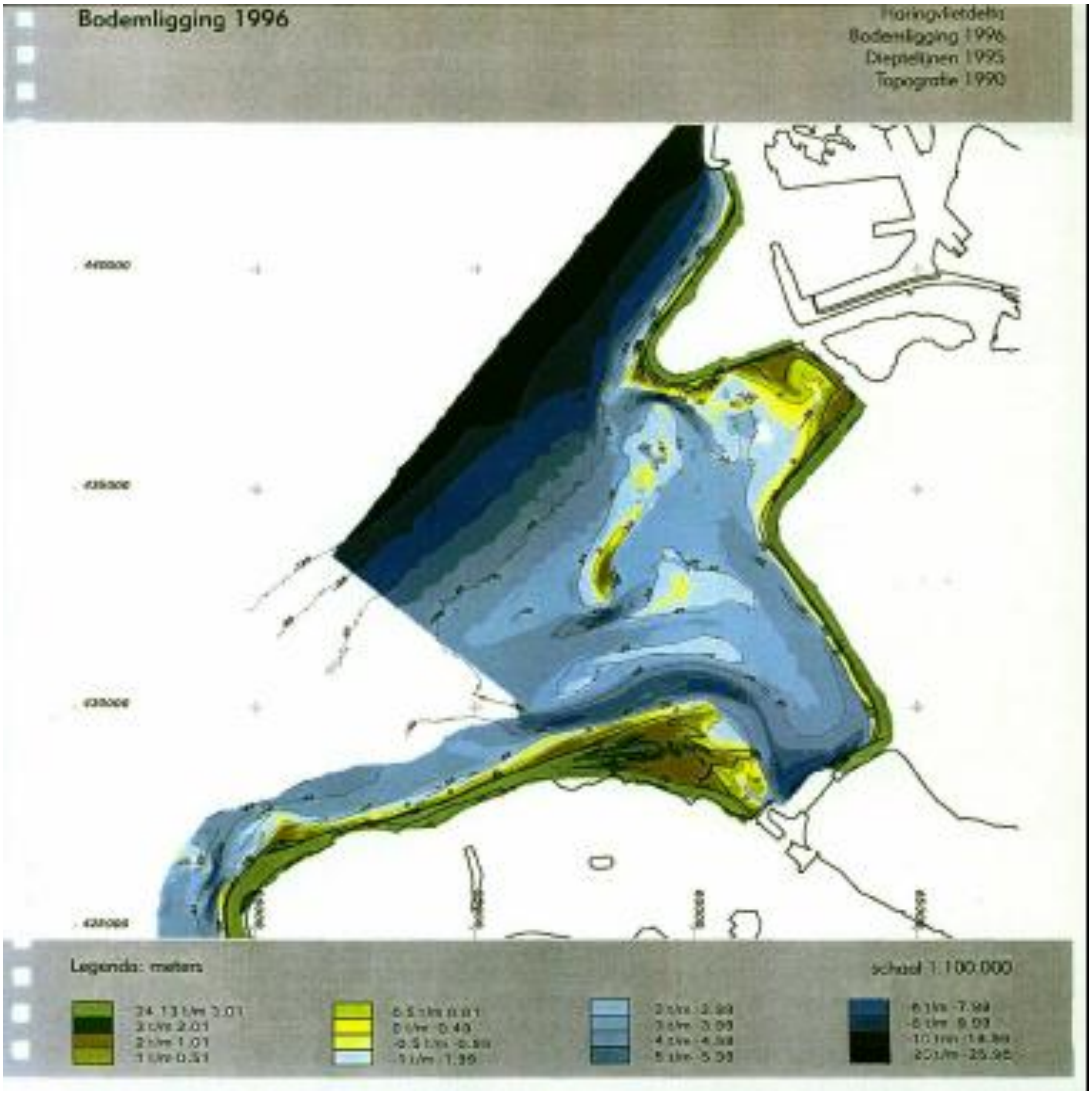
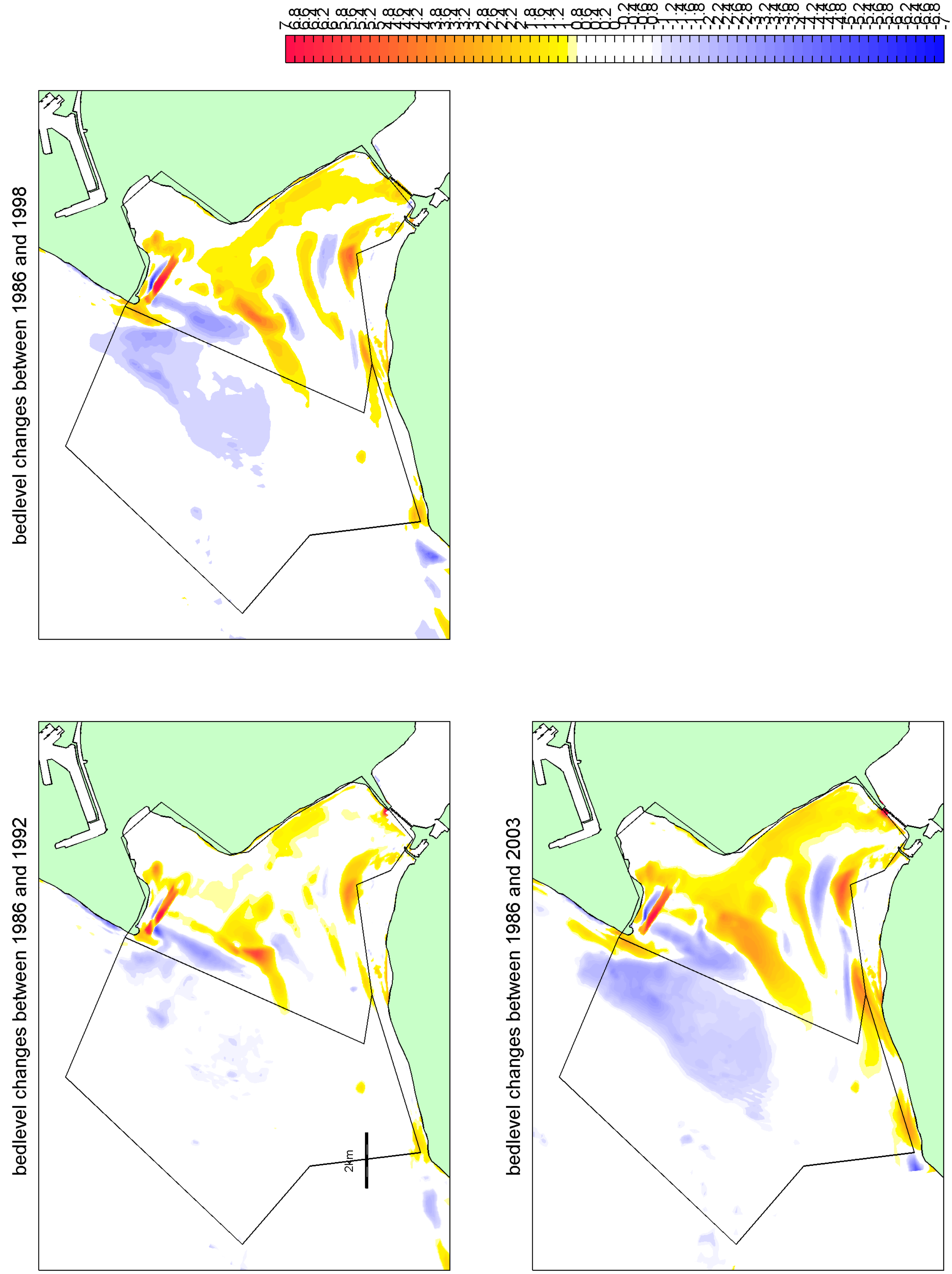
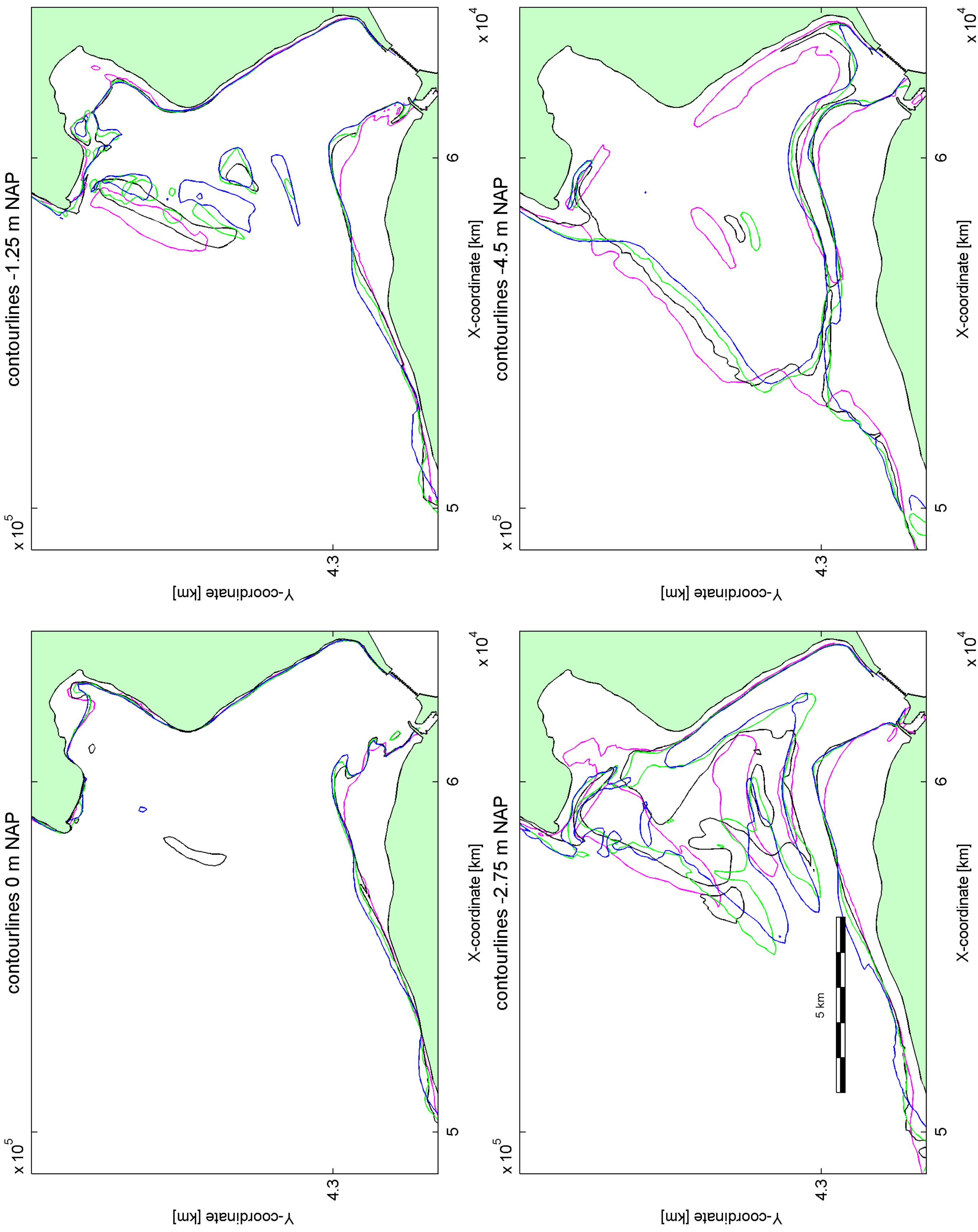


Figure 50 Mouth of the Haringvliet bottom location 1996, depth contours 1995. A land boundary of 1986 is used. [Samenwerkingsverband Maasvlakte 2 varianten (1998)]

B Figures belonging to Chapter 3



Sediment and erosion areas in the Haringvliet mouth 1986 is used as reference year		Aug 2008
	Maintenance of the Slijkgat	
Port of Rotterdam | Deltares | Delft UT		Fig B1



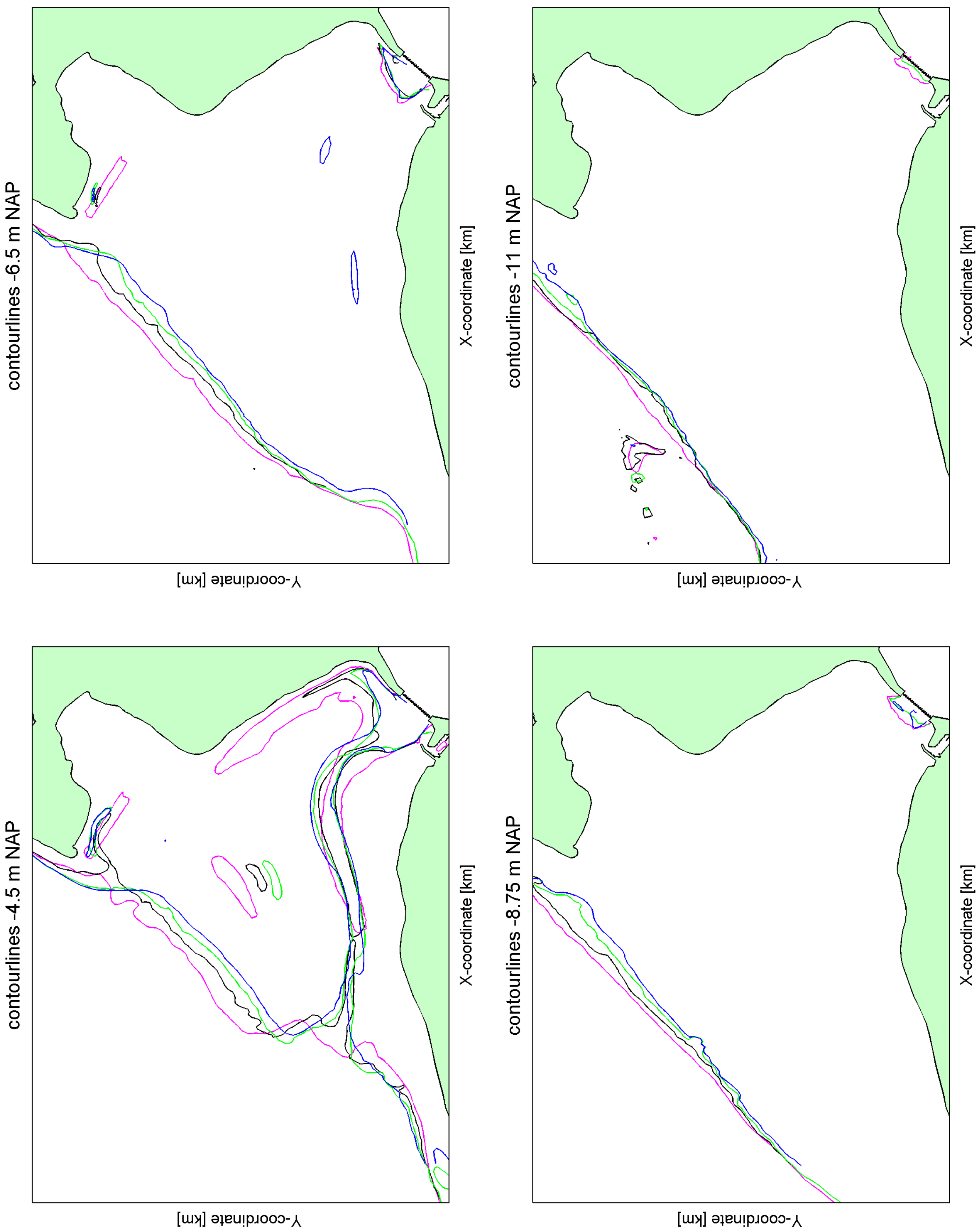
Contourlines between 0 and -4.5 meter NAP

Aug 2008

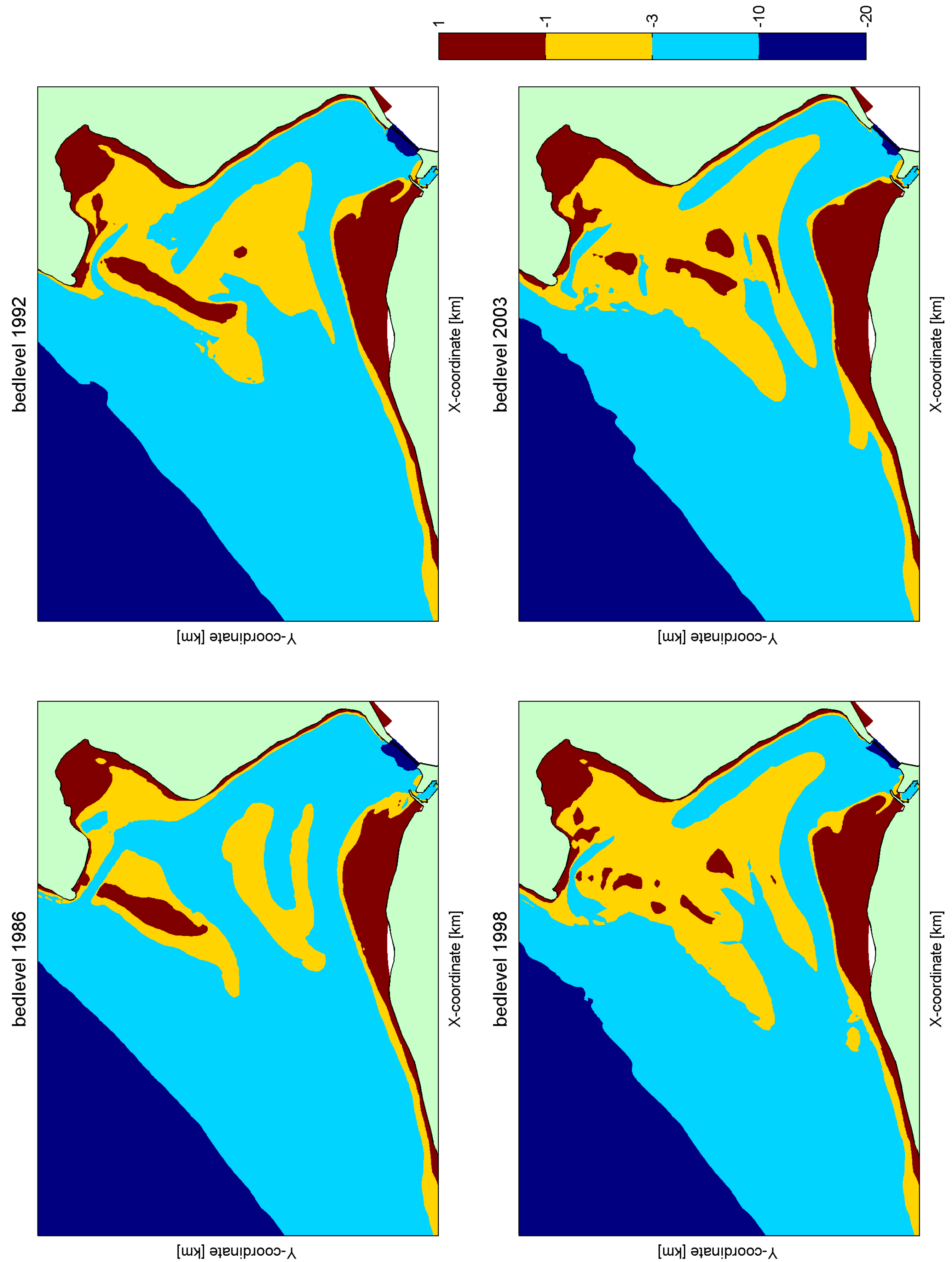
Maintenance of the Slijkgat

Port of Rotterdam | Deltares | Delft UT

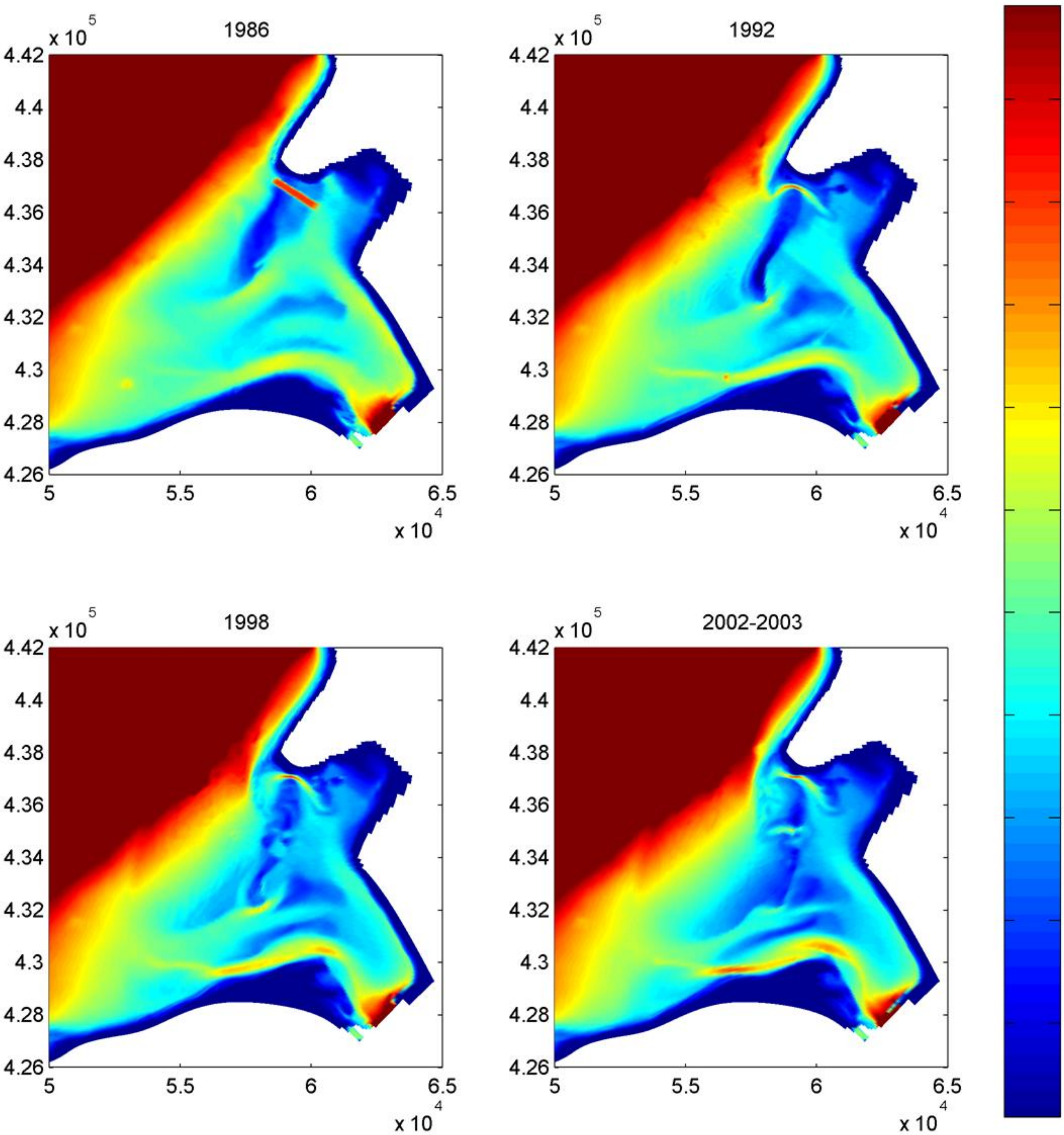
Fig B2



Contourlines between -4.5 meter and -11 m NAP		Aug 2008
	Maintenance of the Slijkgat	
Port of Rotterdam | Deltares | Delft UT		Fig B3



Morphological areas in the Outer Delta of the Haringvliet Bedlevels 1986, 1992, 1998 and 2003		Aug 2008
	Maintenance of the Slijkgat	
Port of Rotterdam | Deltares | Delft UT		Fig B4



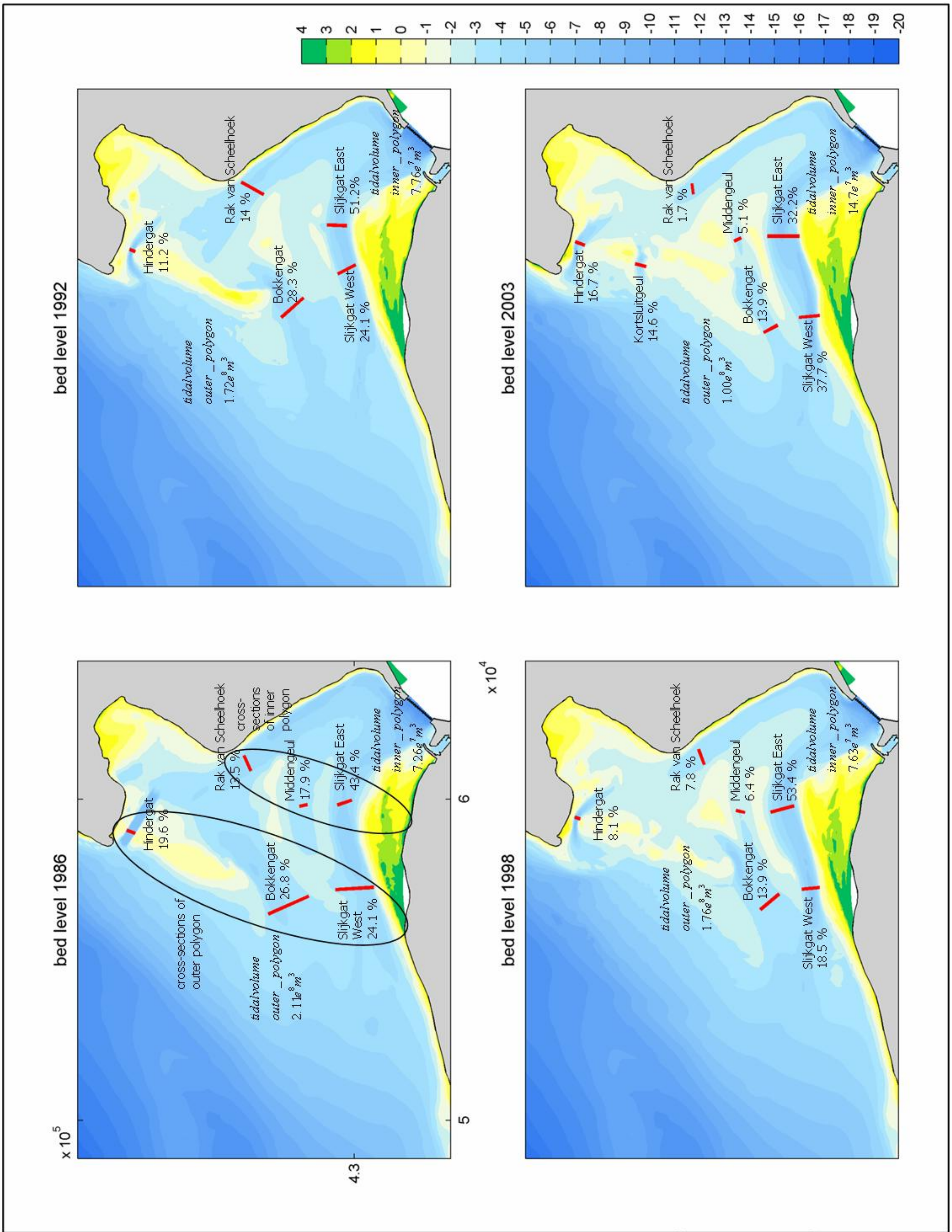
Bed level 1986, 1992, 1998, 2002-2003

Aug 2008

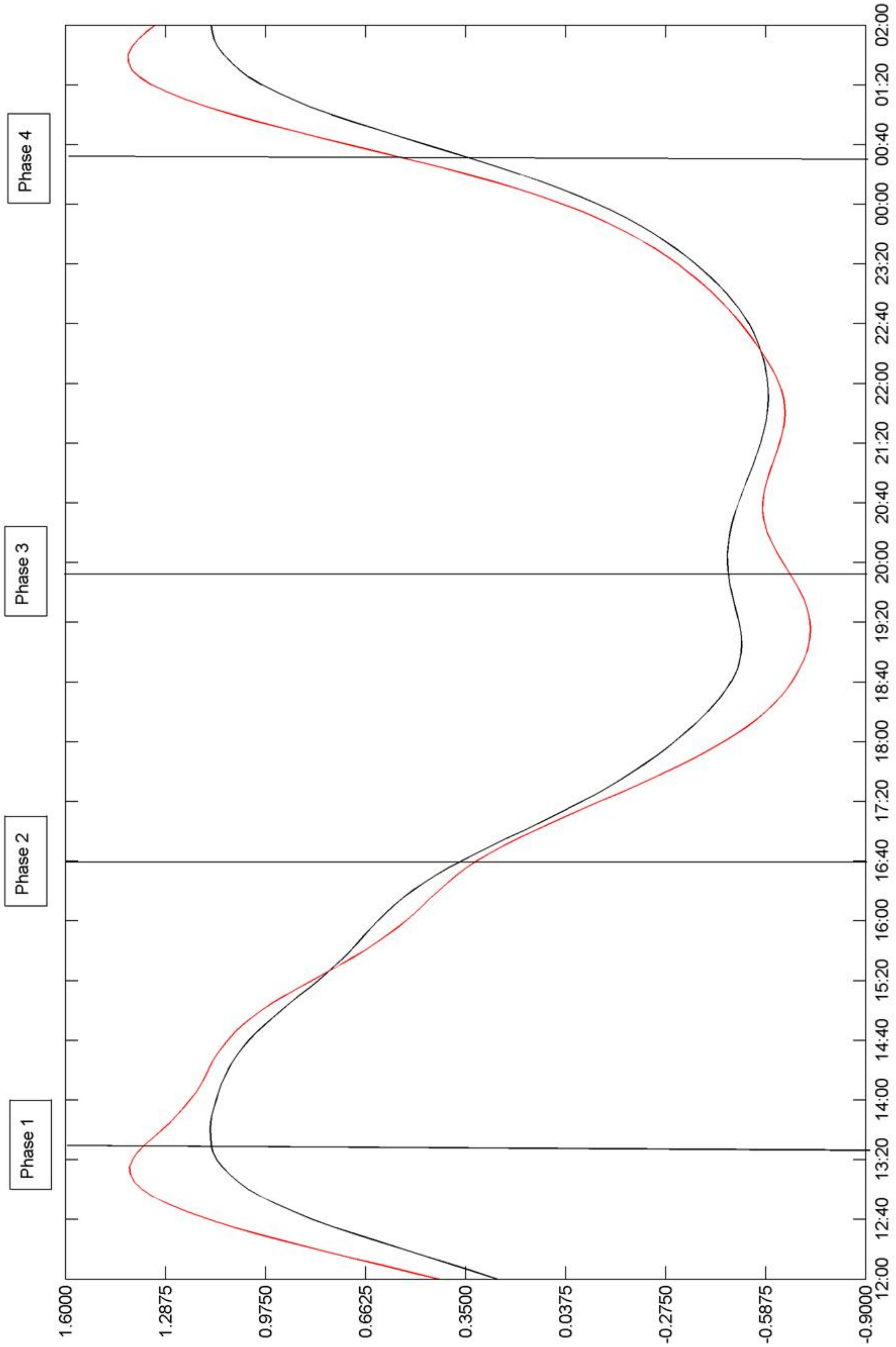
Maintenance of the Slijkgat

WL | DELFT HYDRAULICS

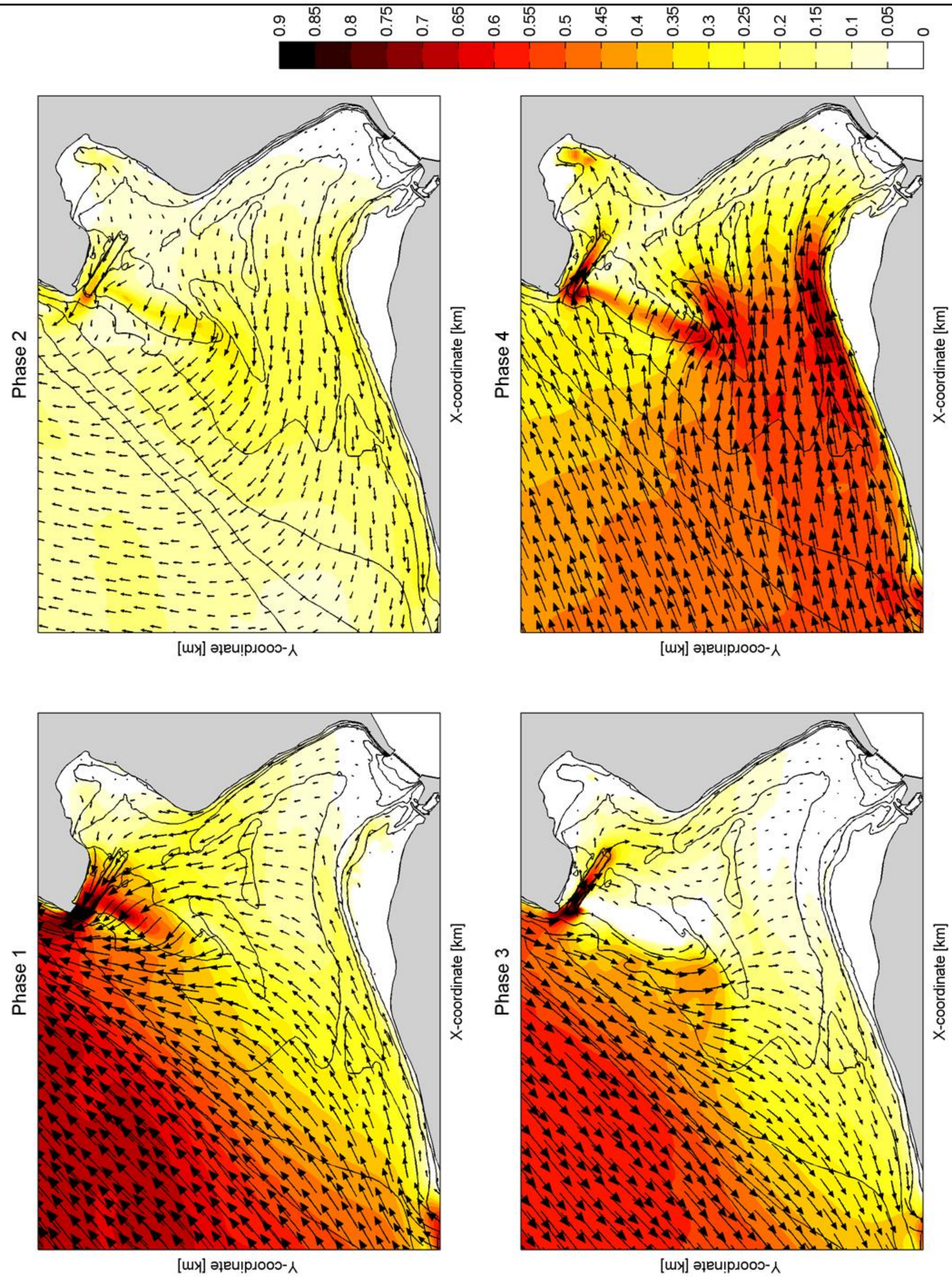
Fig B5



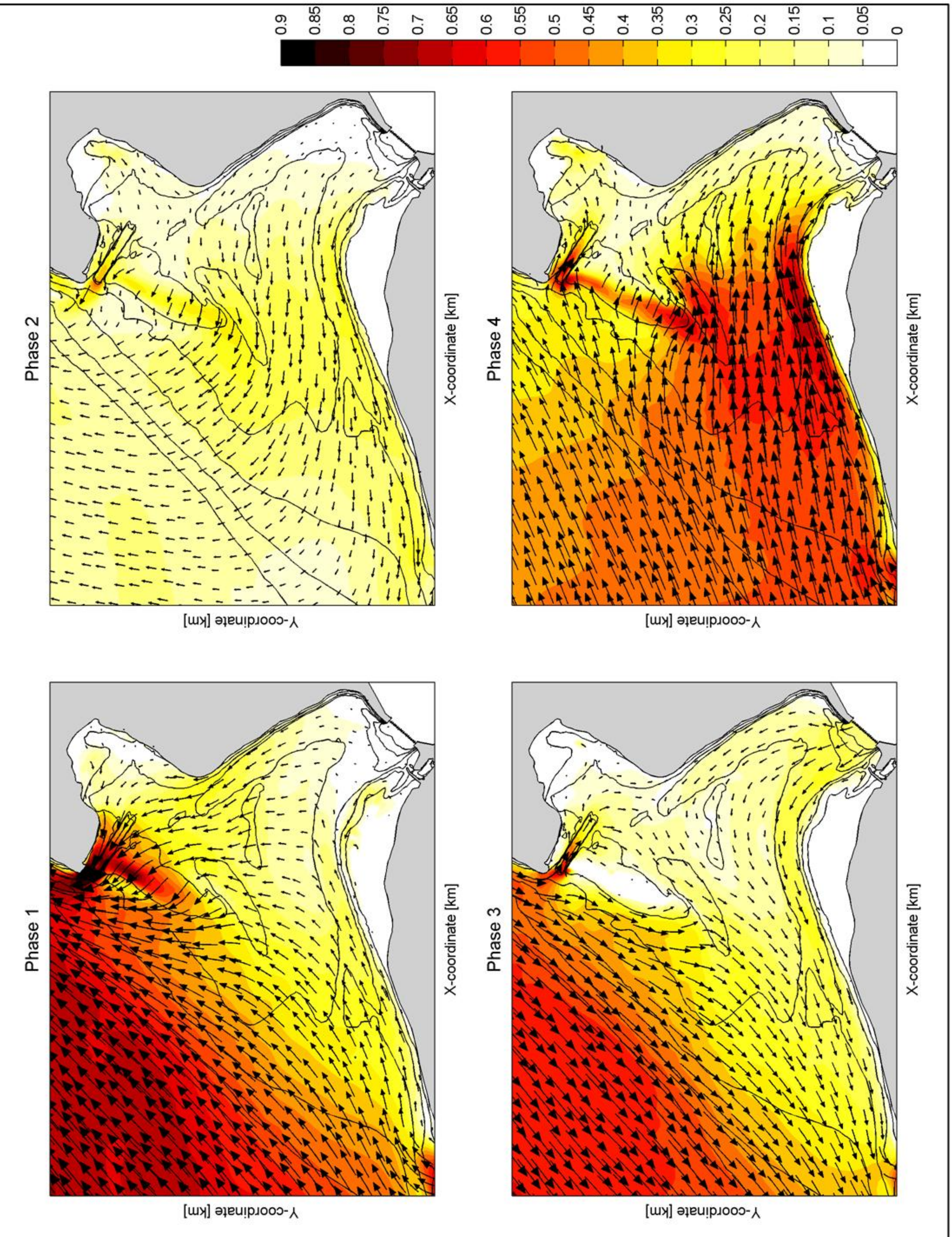
Percentage of tidal volume per cross-section for each polygon tidal volumes without river discharge bed levels of 1986, 1992, 1998 and 2003		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B6



Water level at Hoek van Holland and Hindergat Phases of which current plots are made		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B7



Current during a tidal period, plotted for four phases Bed level 1986 Tidal forcing (no river discharge)		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B8



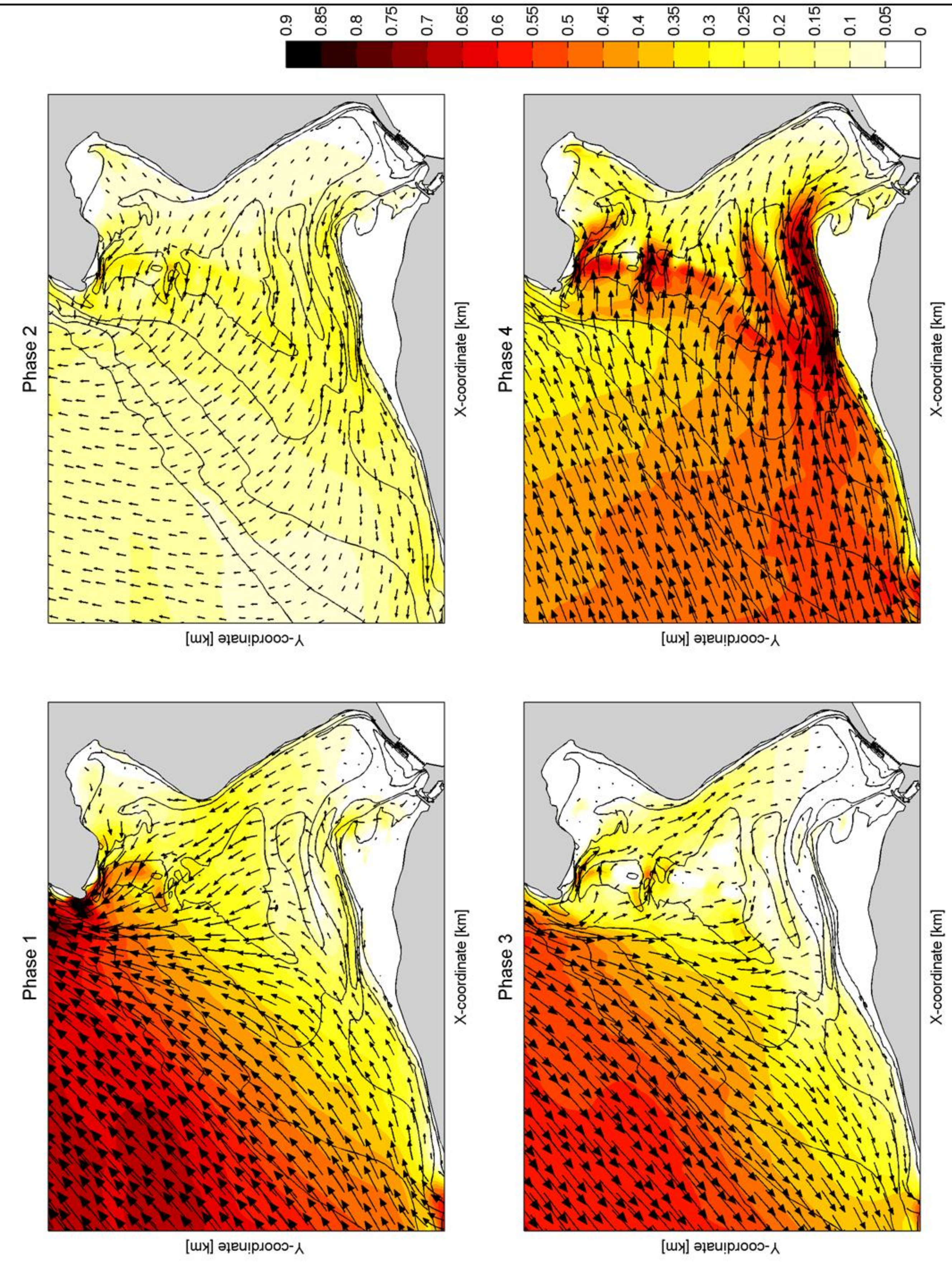
Current during a tidal period, plotted for four phases
Bed level 1986
Tidal forcing and average winter discharge during low water

Aug 2008

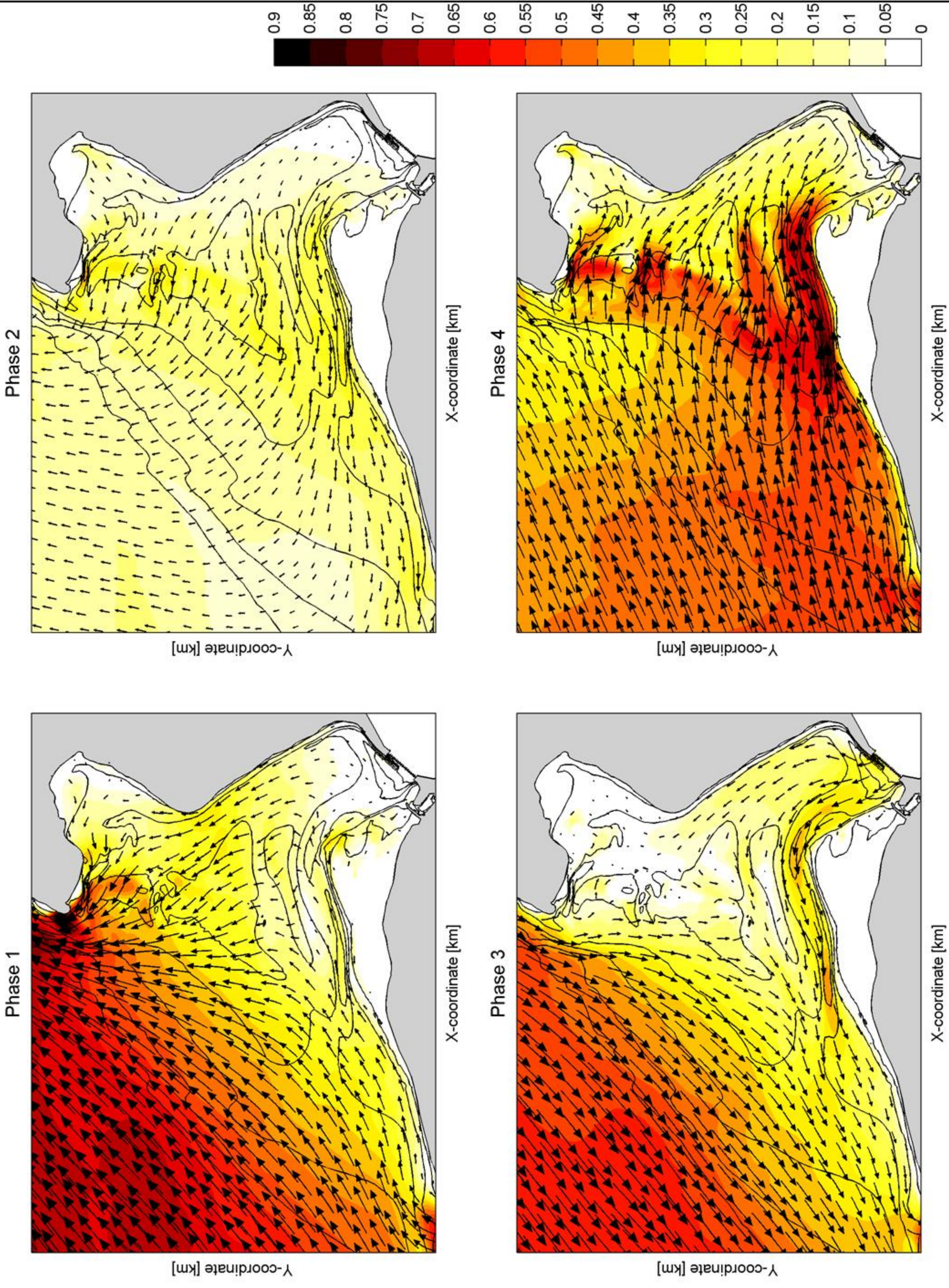
Maintenance of the Slijkgat

WL|Delft Hydraulics

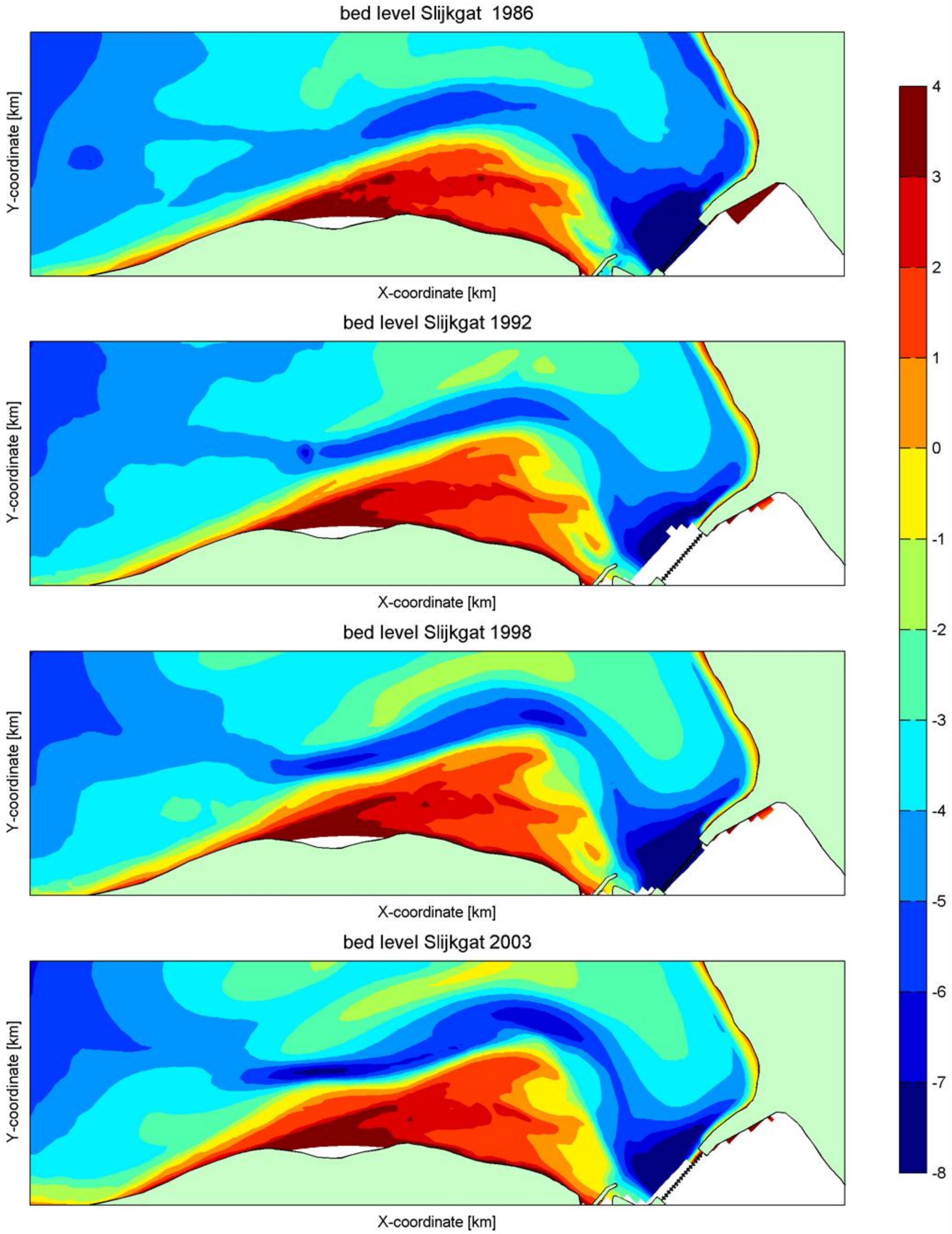
Fig B9



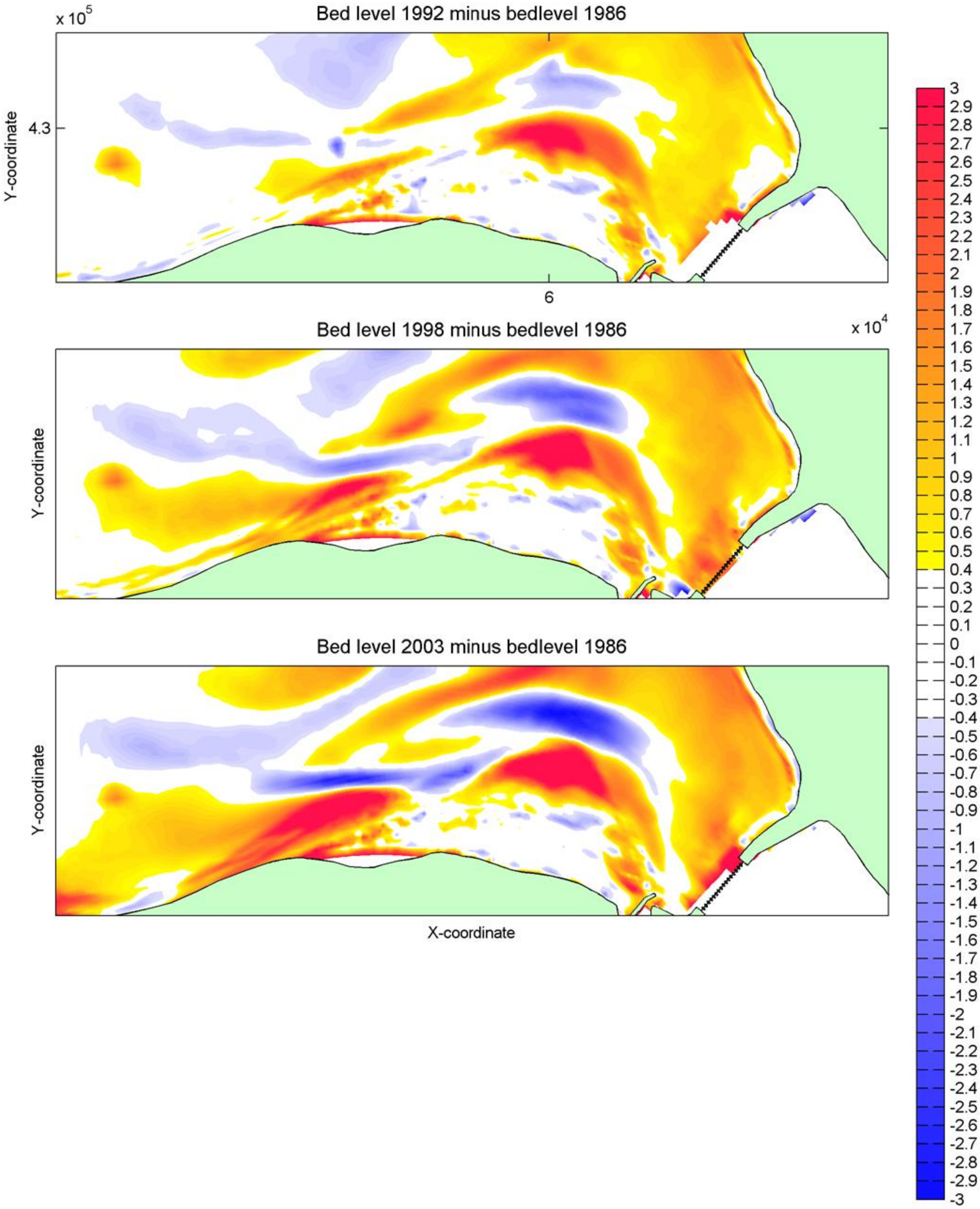
Current during a tidal period, plotted for four phases Bed level 2003 Tidal forcing (no river discharge)		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B10



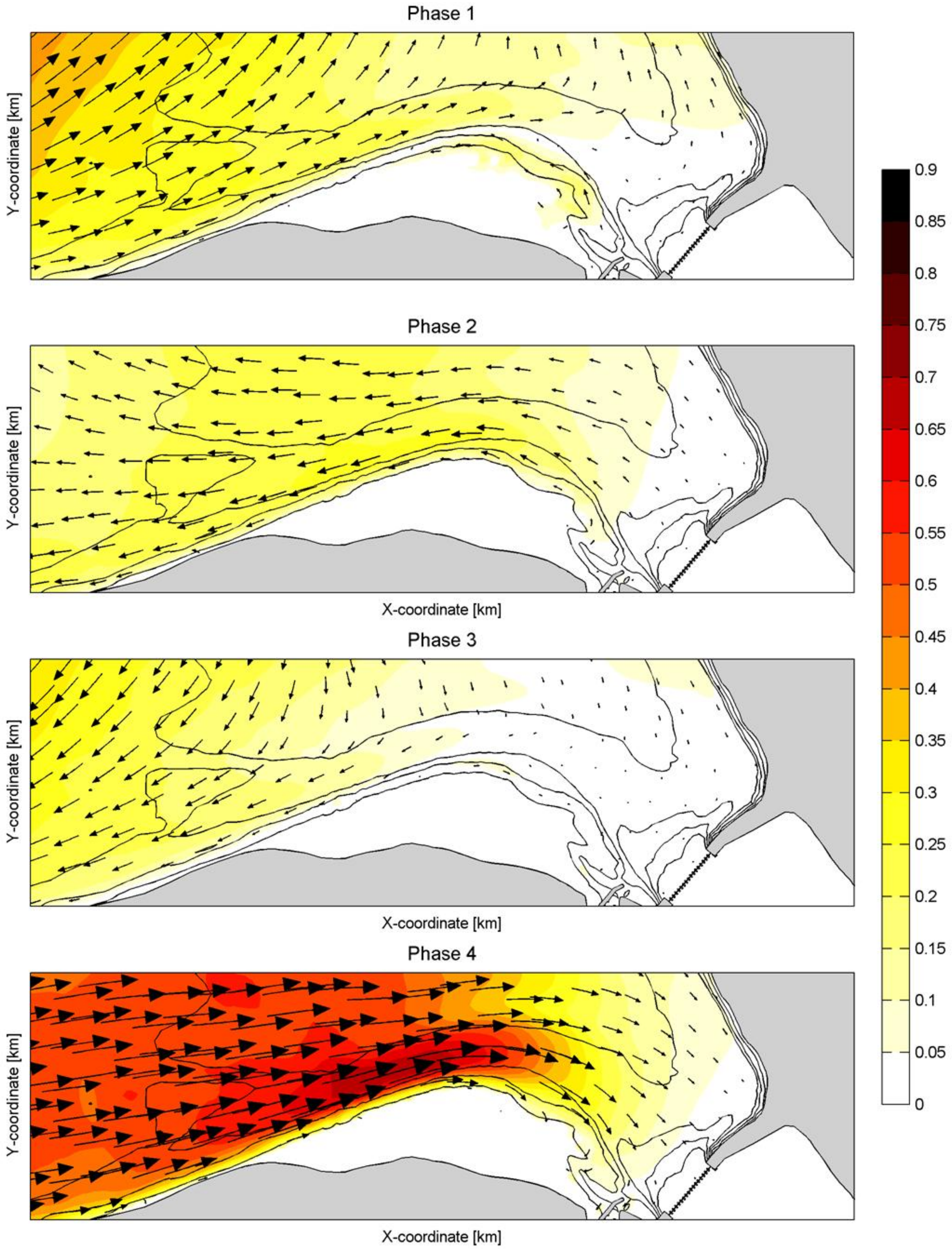
Current during a tidal period, plotted for four phases Bed level 2003 Tidal forcing and average winter discharge during low water		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B11



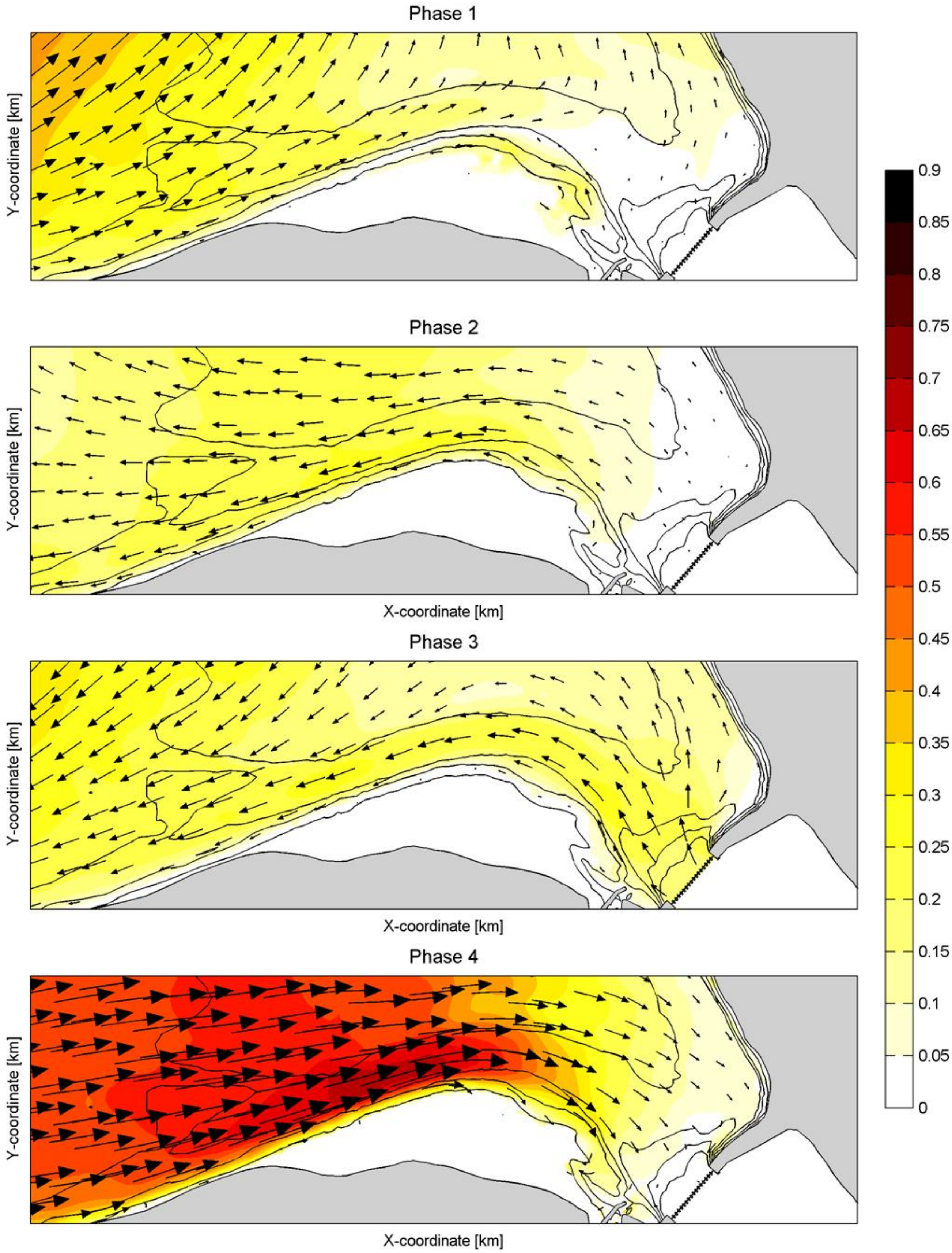
Bed levels of Het Slijkgat 1986, 1992, 1998 and 2003		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B12



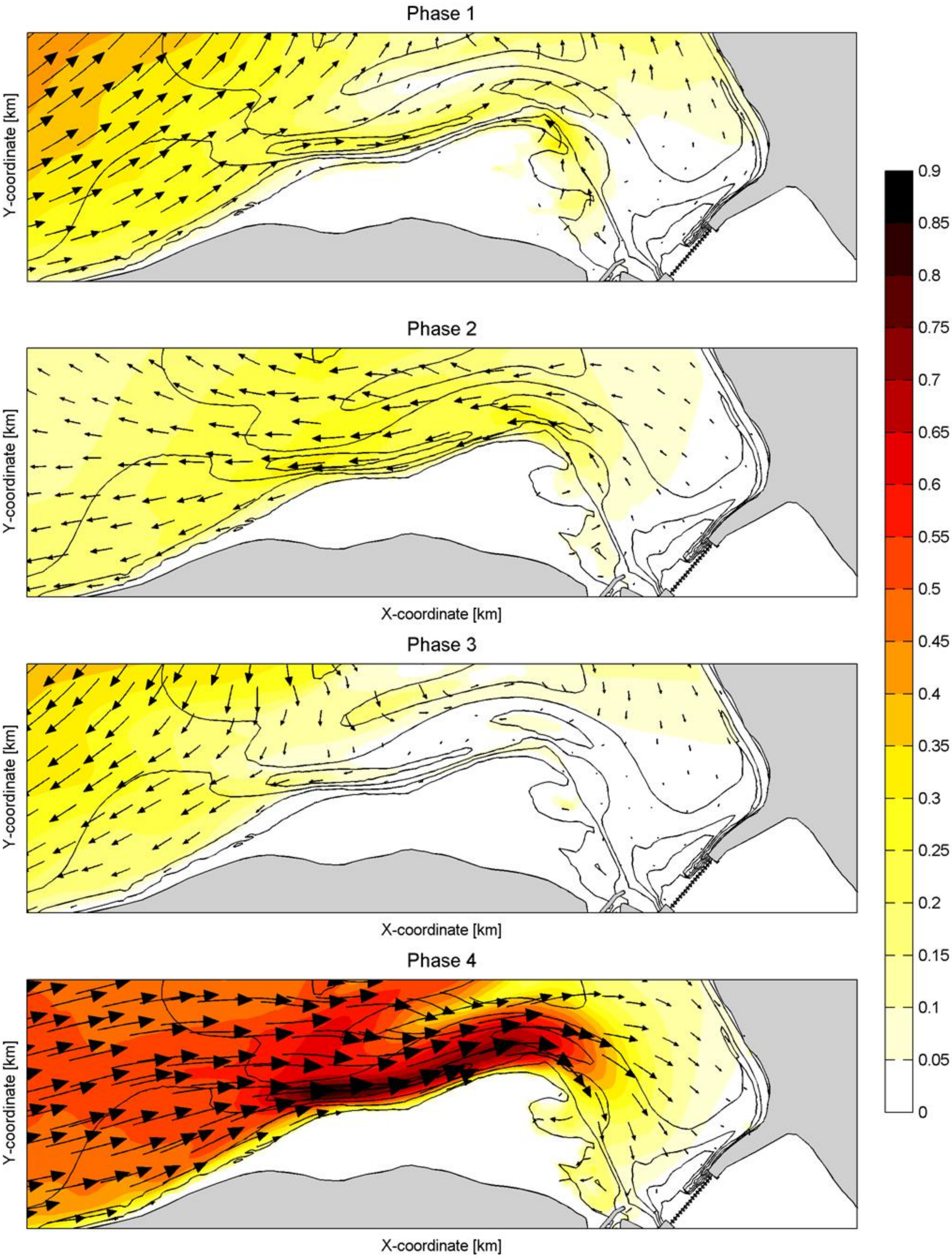
Erosion and sedimentation in Het Slijkgat Bed level 1992 minus 1986; Bed level 1998 minus 1986; Bed level 2003 minus 1986		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B13



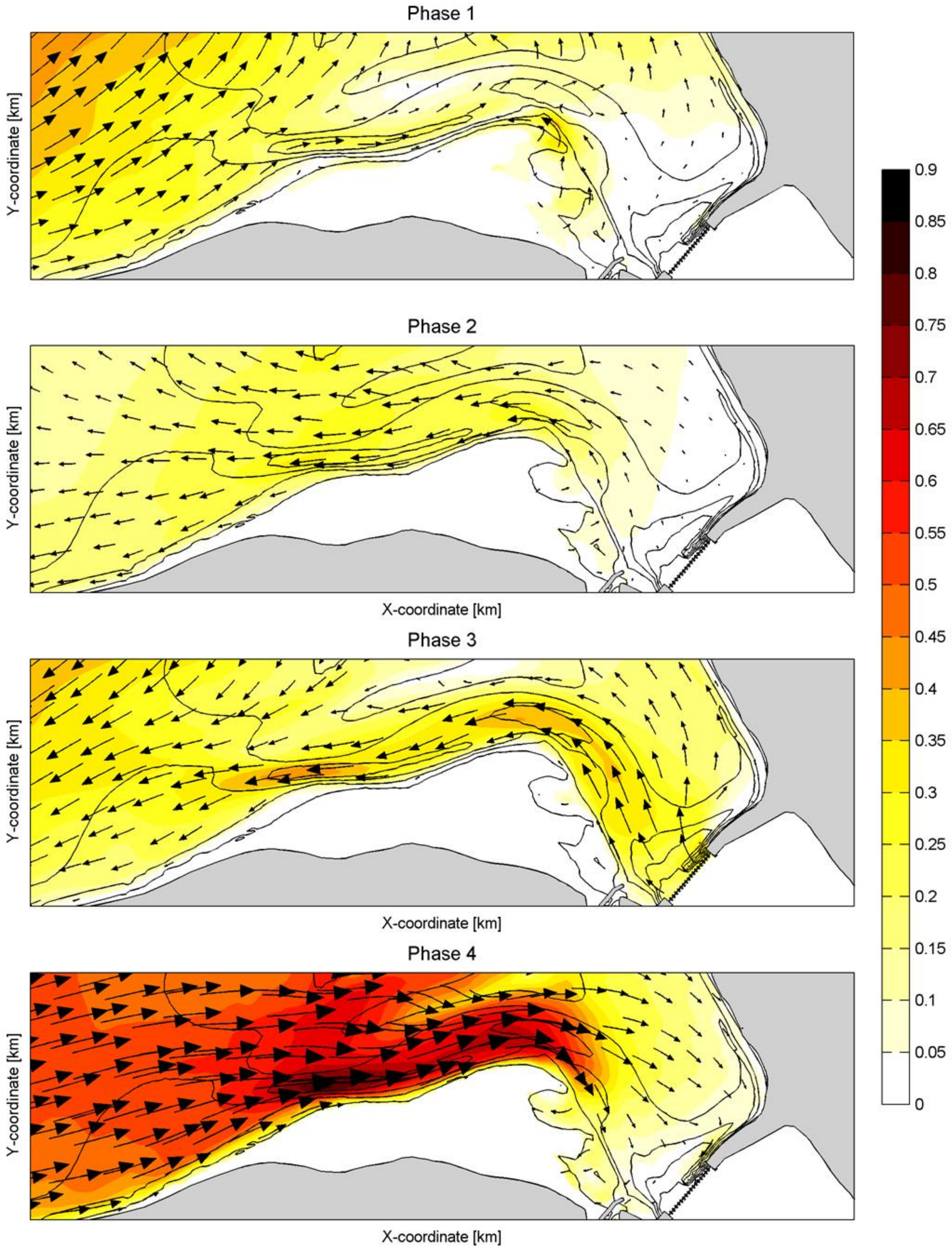
Current during a tidal period, plotted for four phases Bed level 1986 Tidal forcing (no river discharge)		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B14



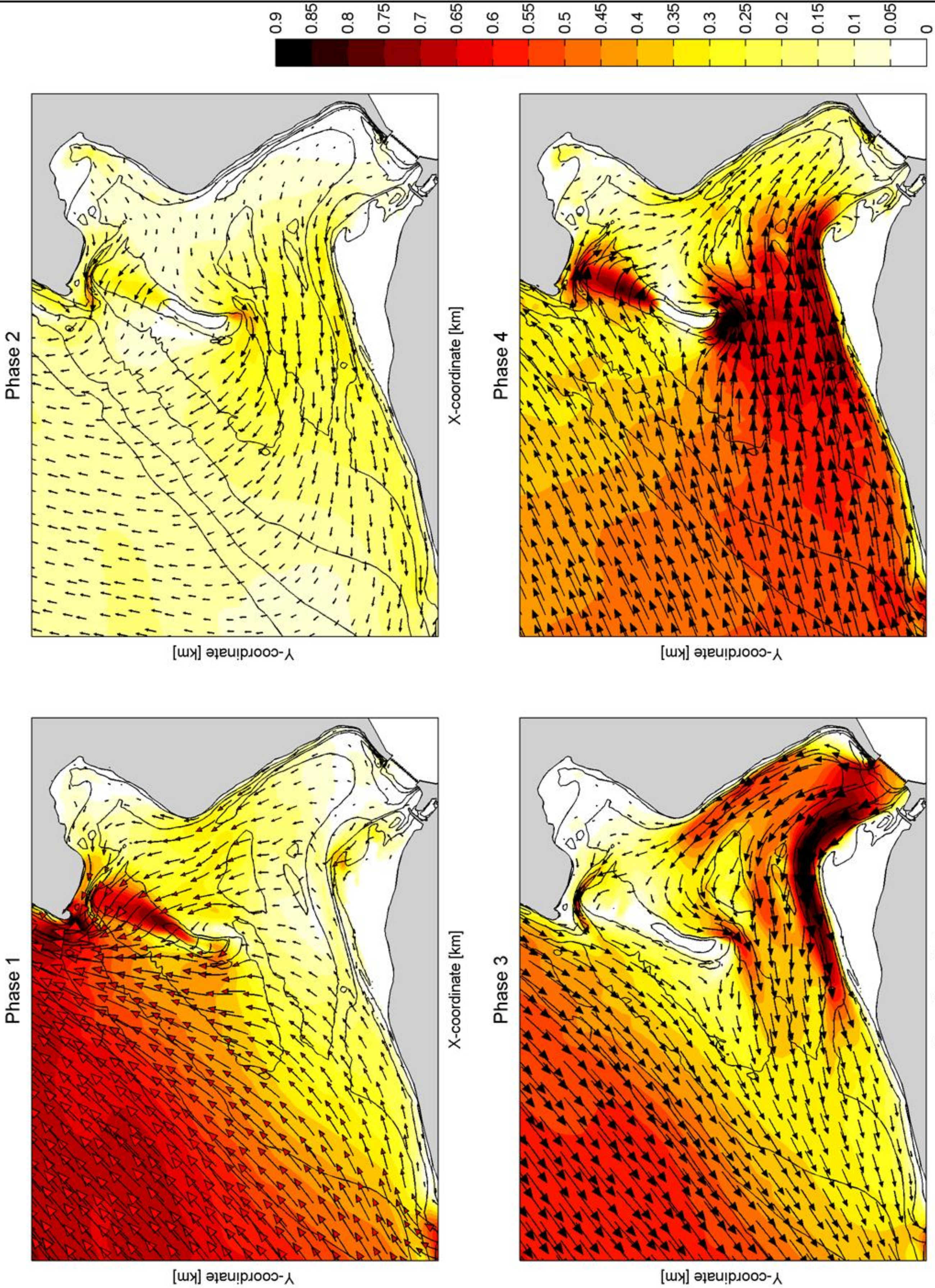
Current during a tidal period, plotted for four phases Bed level 1986 Tidal forcing and average winter discharge during low water		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B15



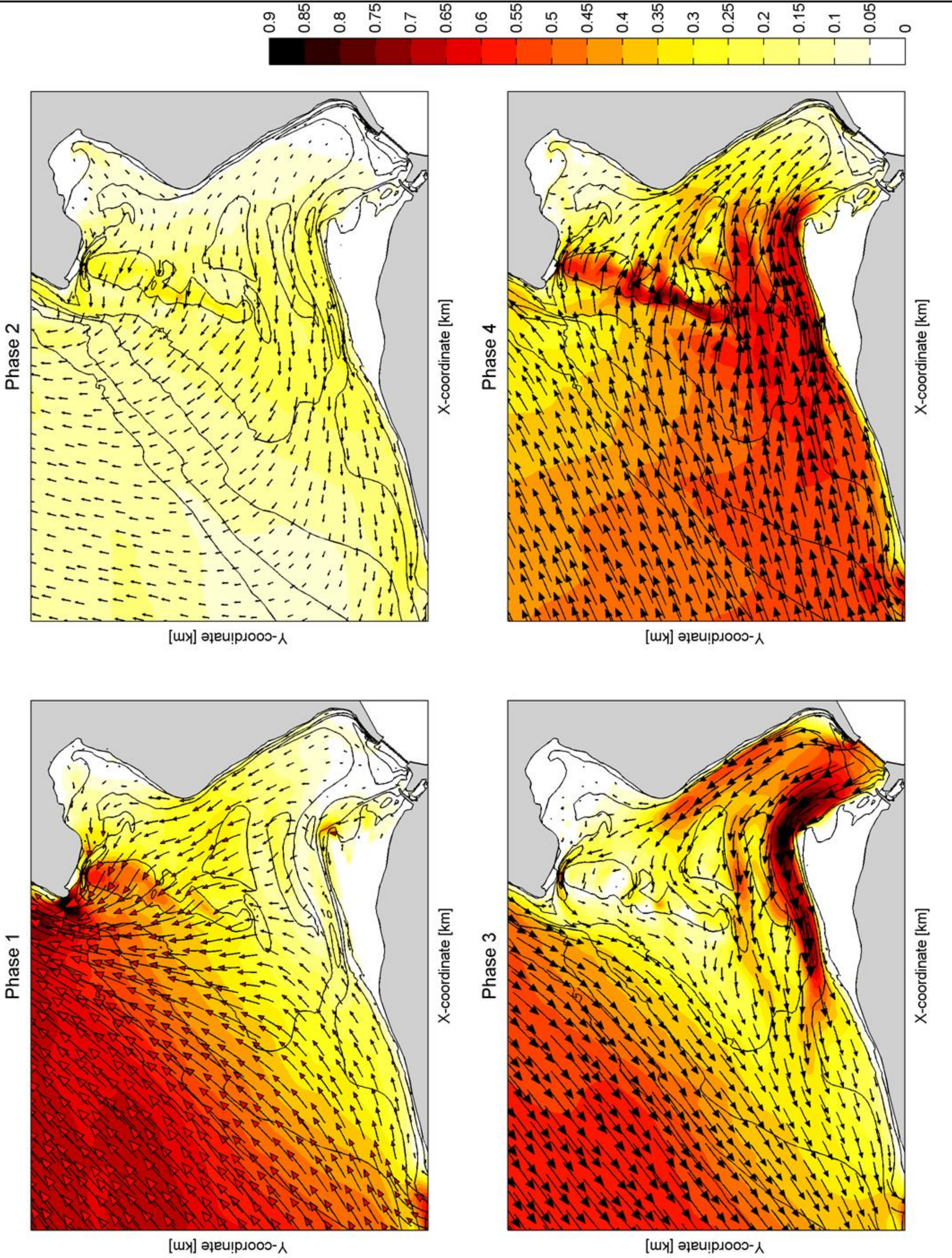
Current during a tidal period, plotted for four phases Bed level 1986 Tidal forcing (no river discharge)		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B16



Current during a tidal period, plotted for four phases Bed level 2003 Tidal forcing and average winter discharge during low water		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B17

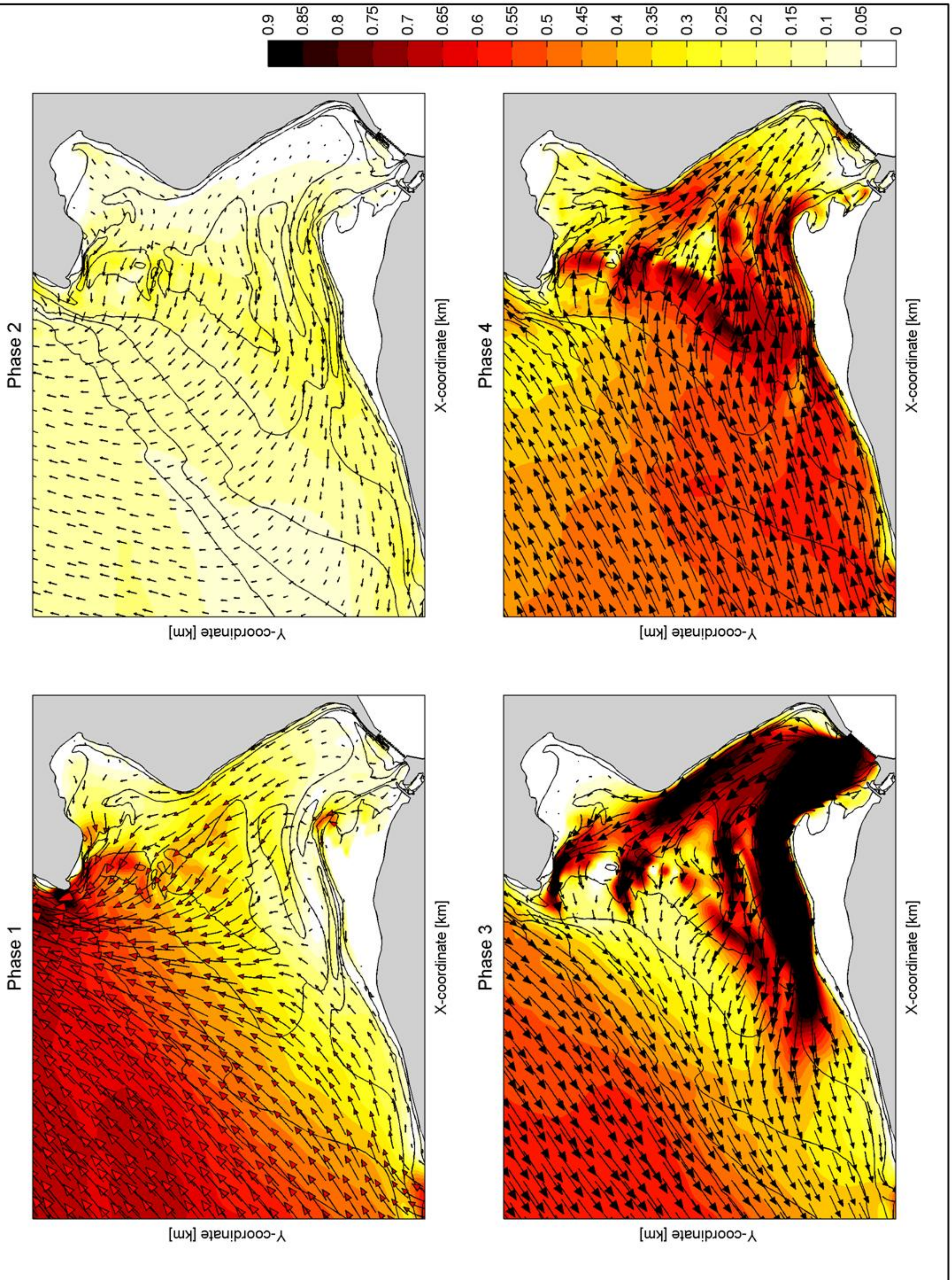


Current during a tidal period, plotted for four phases Bed level 1992 Tidal forcing and 2920m3/s/dag discharge during low water		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B18

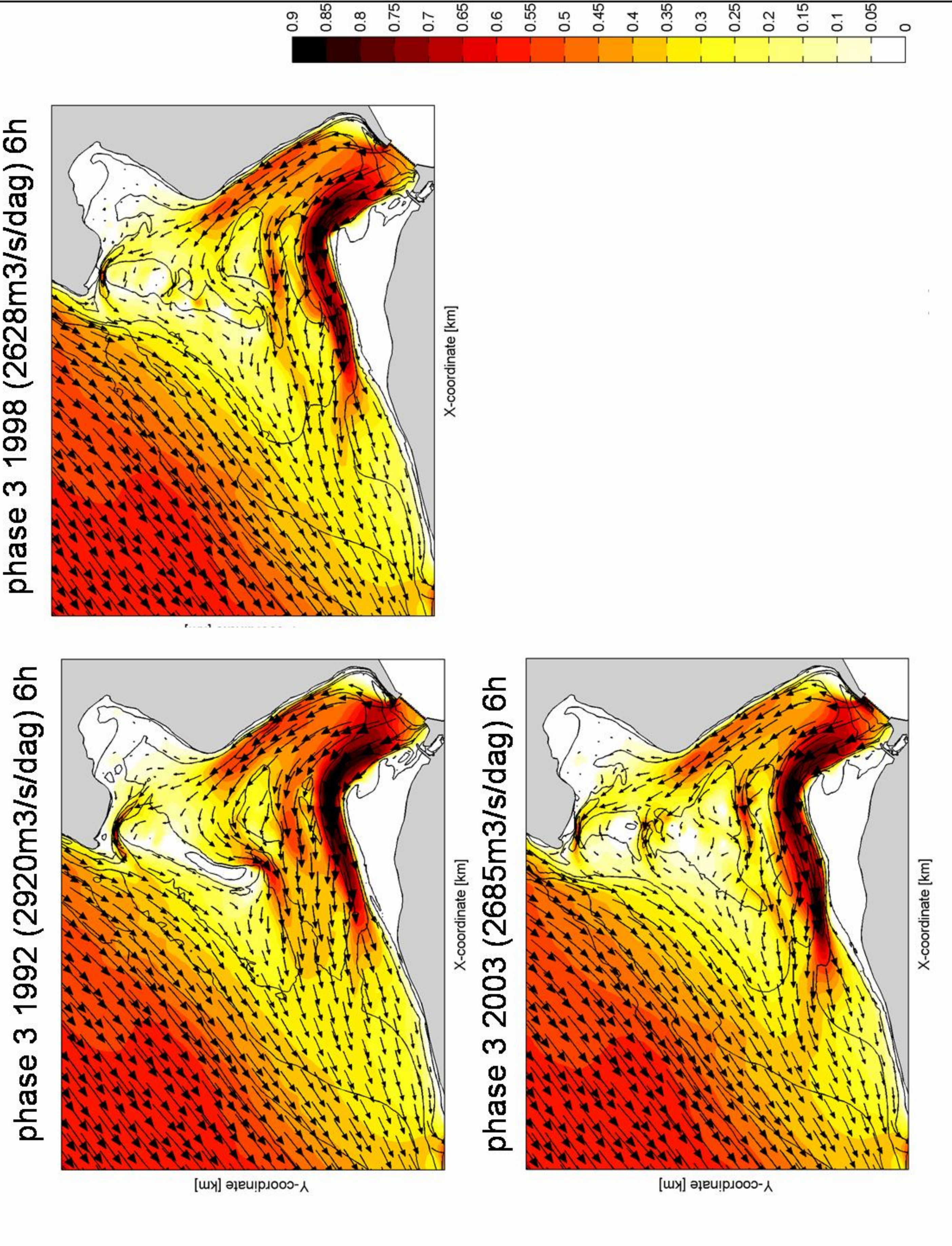


Current during a tidal period, plotted for four phases
Bed level 1998
Tidal forcing and 2628m3/s/dag discharge during low water

	Aug 2008
Maintenance of the Slijkgat	
WL|Delft Hydraulics	Fig B19

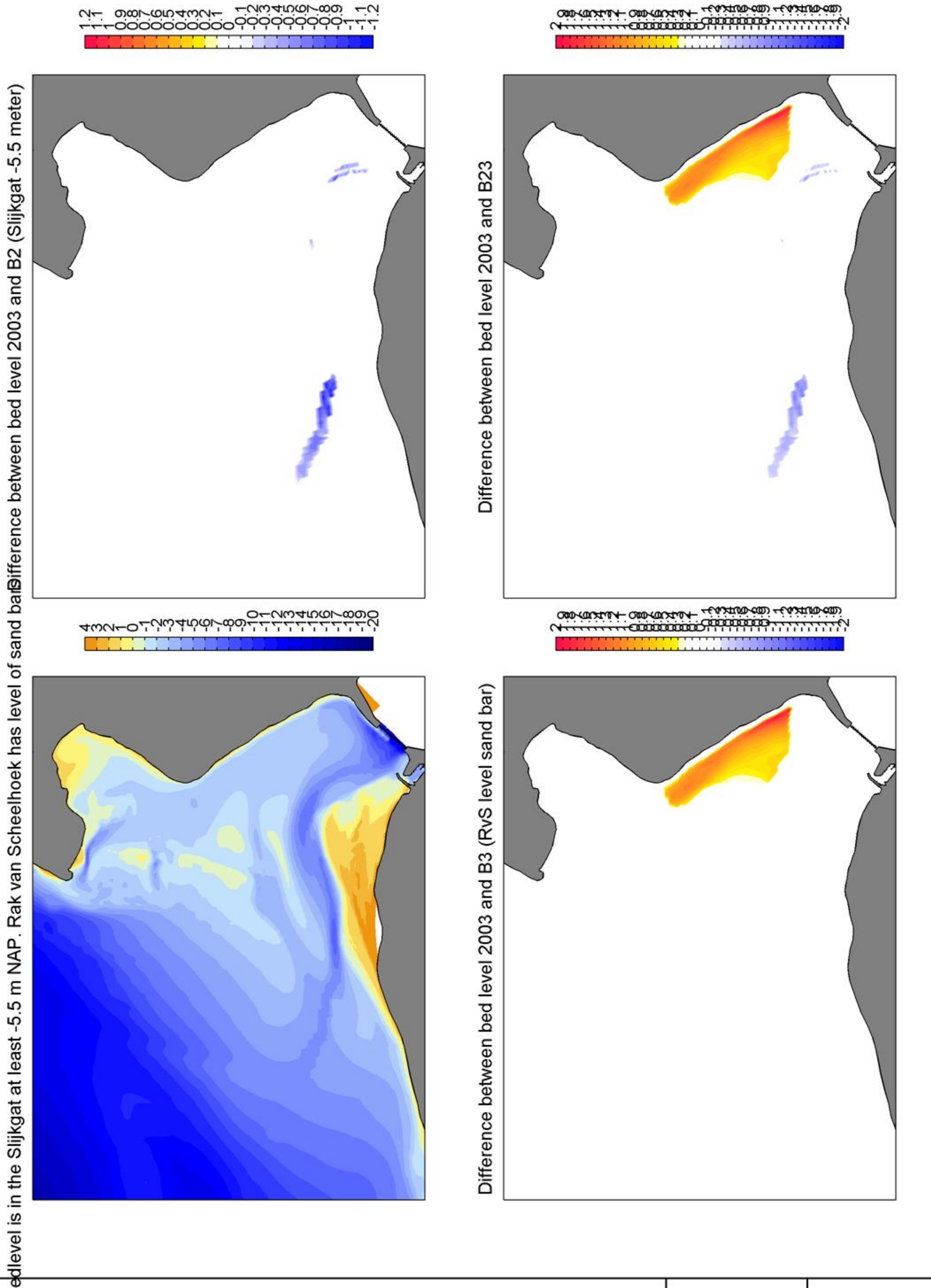


Current during a tidal period, plotted for four phases Bed level 2003 Tidal forcing and 5176 winter discharge during 6 hours low water		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig B20



currents during "phase 3", for 3 years, 1992, 1998, 2003 Tidal forcing and the highest river discharge that occurred 3 months before the bed level data measurements	Aug 2008 Maintenance of the Slijkgat
WL|Delft Hydraulics	Fig B21

C Figures belonging to Chapter 4



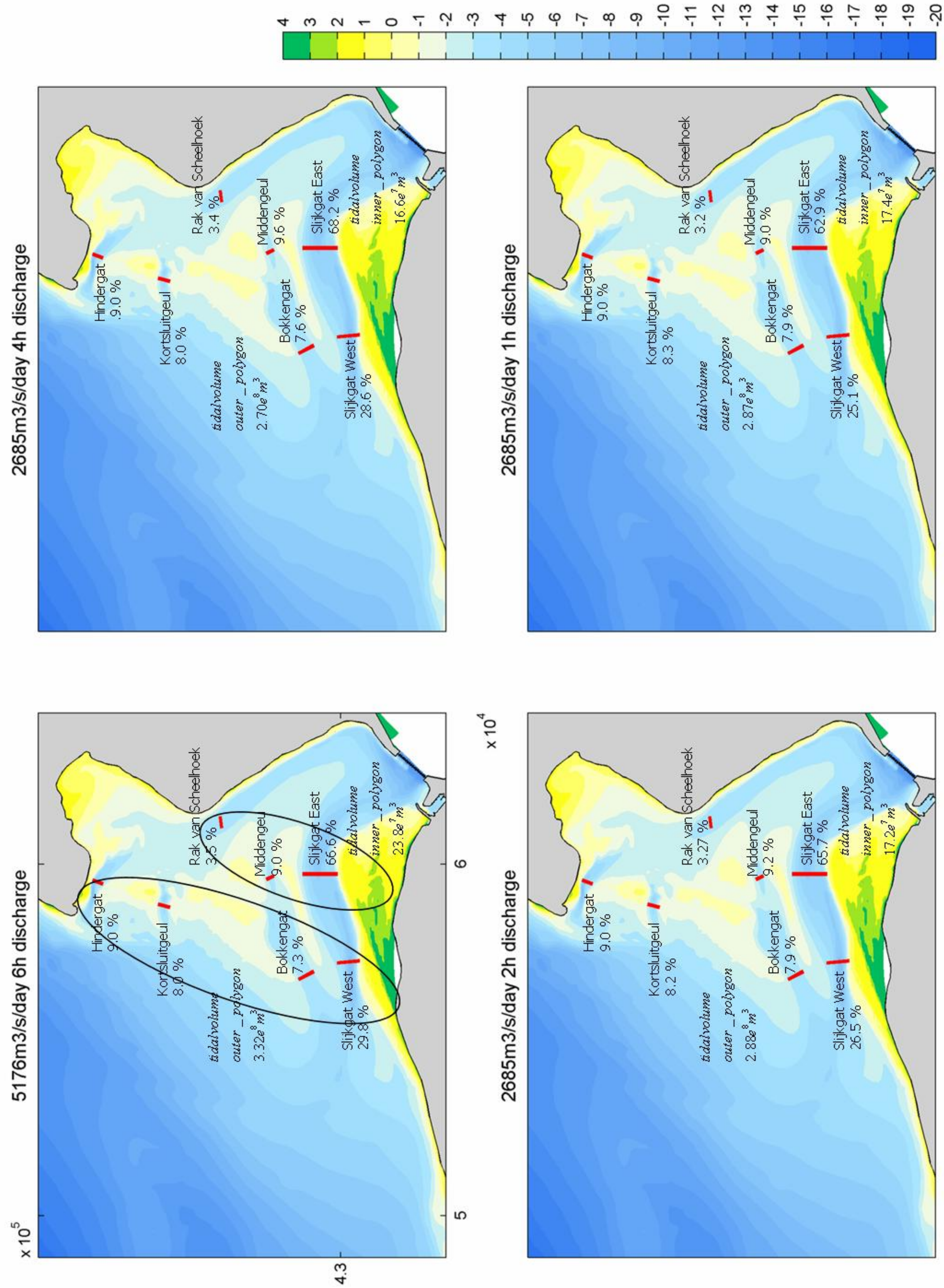
Bedlevel of the scenario with the most adjustments, B23.
The difference between the scenario and the bed level of 2003 is visualised

Aug 2008

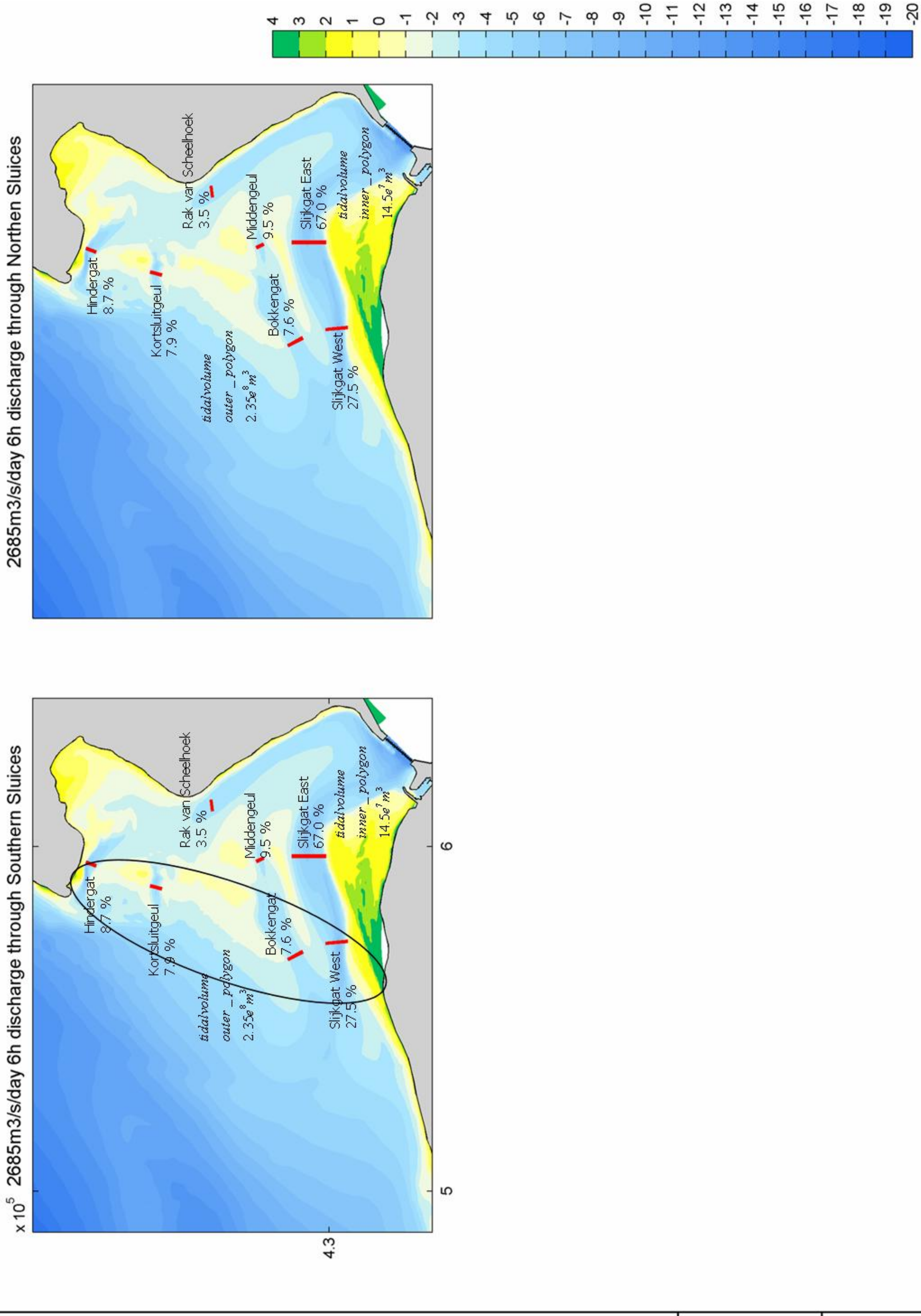
Maintenance of the Slijkgat

WL|Delft Hydraulics

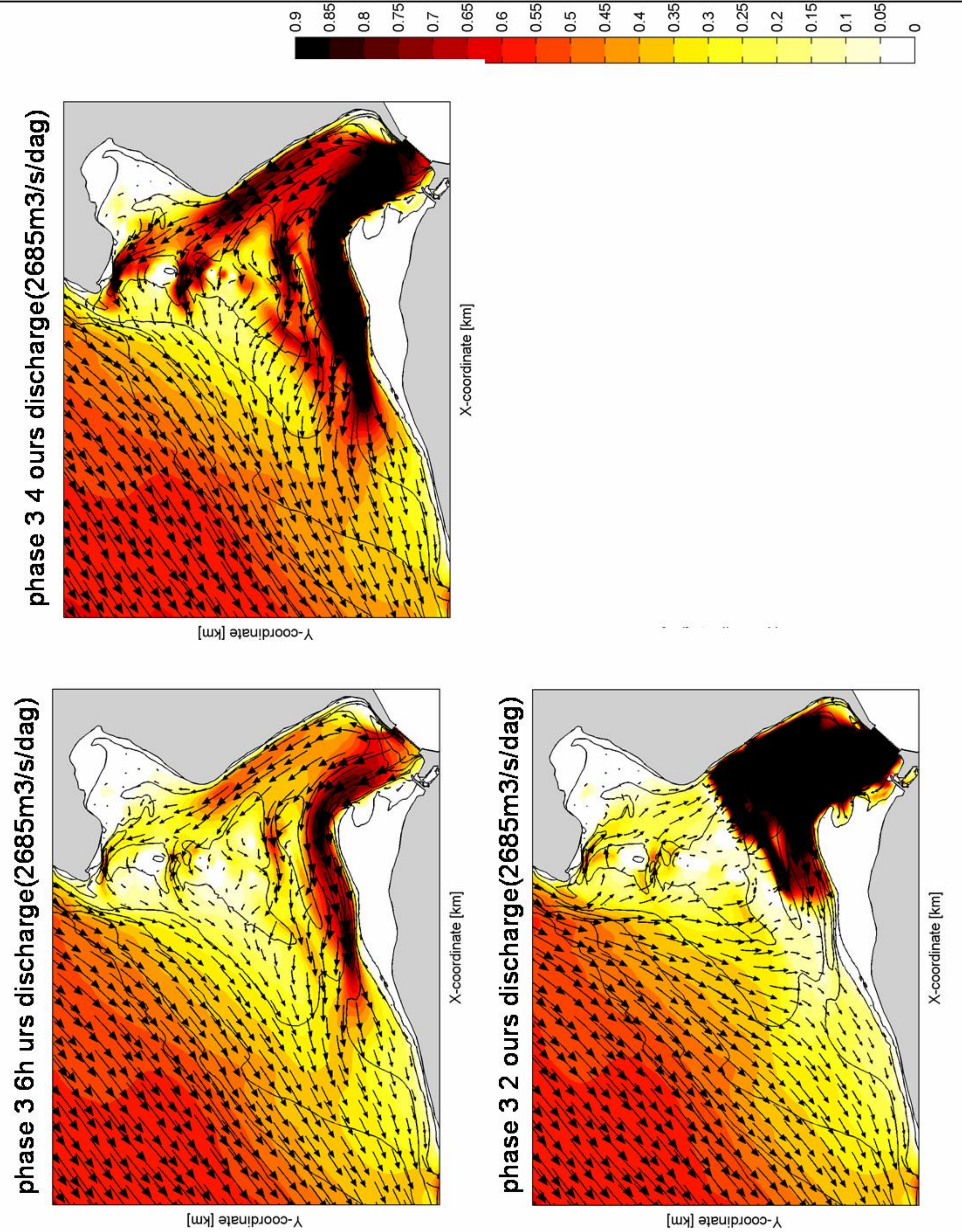
Fig C1



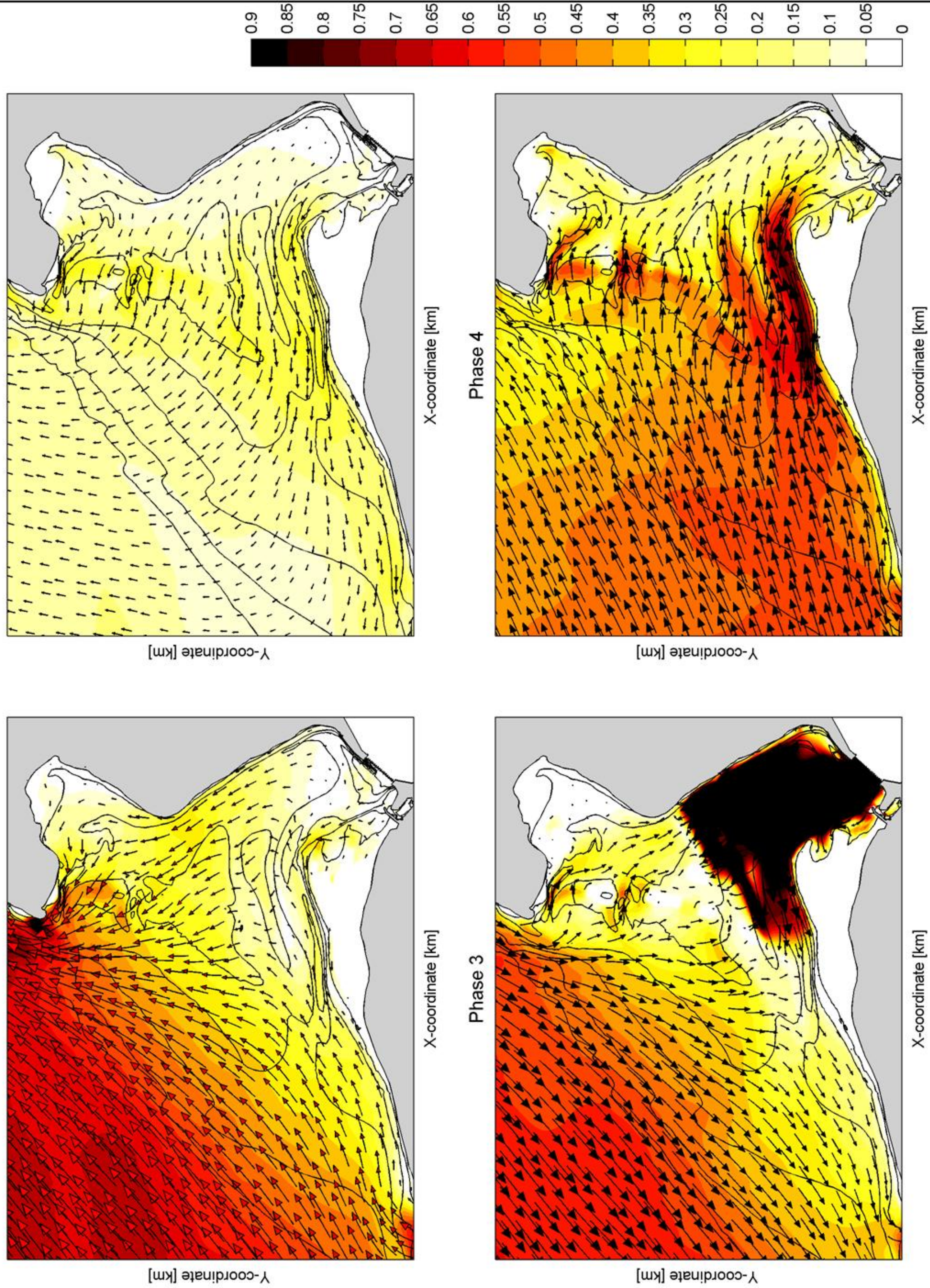
Percentage of tidal volume per cross-section for each polygon tidal volumes with different river discharge time sluices open differs bed levels of 2003		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig C2



Percentage of tidal volume per cross-section for each polygon tidal volumes with different river discharge time sluices open differs bed levels of 2003		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig C3

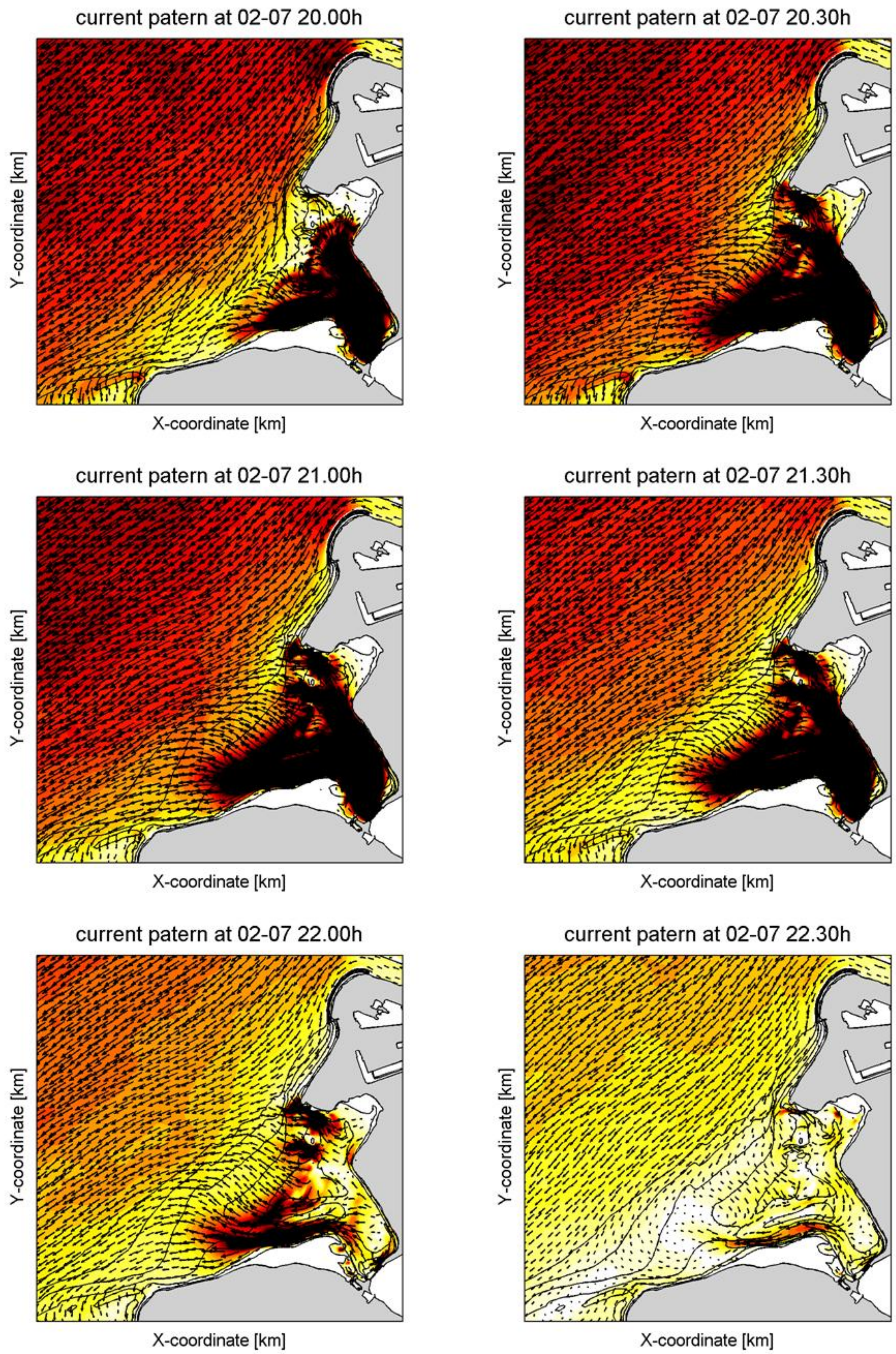


currents during "phase 3", for 3 discharge hypothesis 6, 4, 2 hours reference discharge is 2685m3/s/d bed level 2003		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig C04



Current during a tidal period, plotted for four phases
Bed level 2003
Tidal forcing and 2685 winter discharge during 2 hour low water

	Aug 2008
Maintenance of the Slijkgat	
WL|Delft Hydraulics	Fig C5



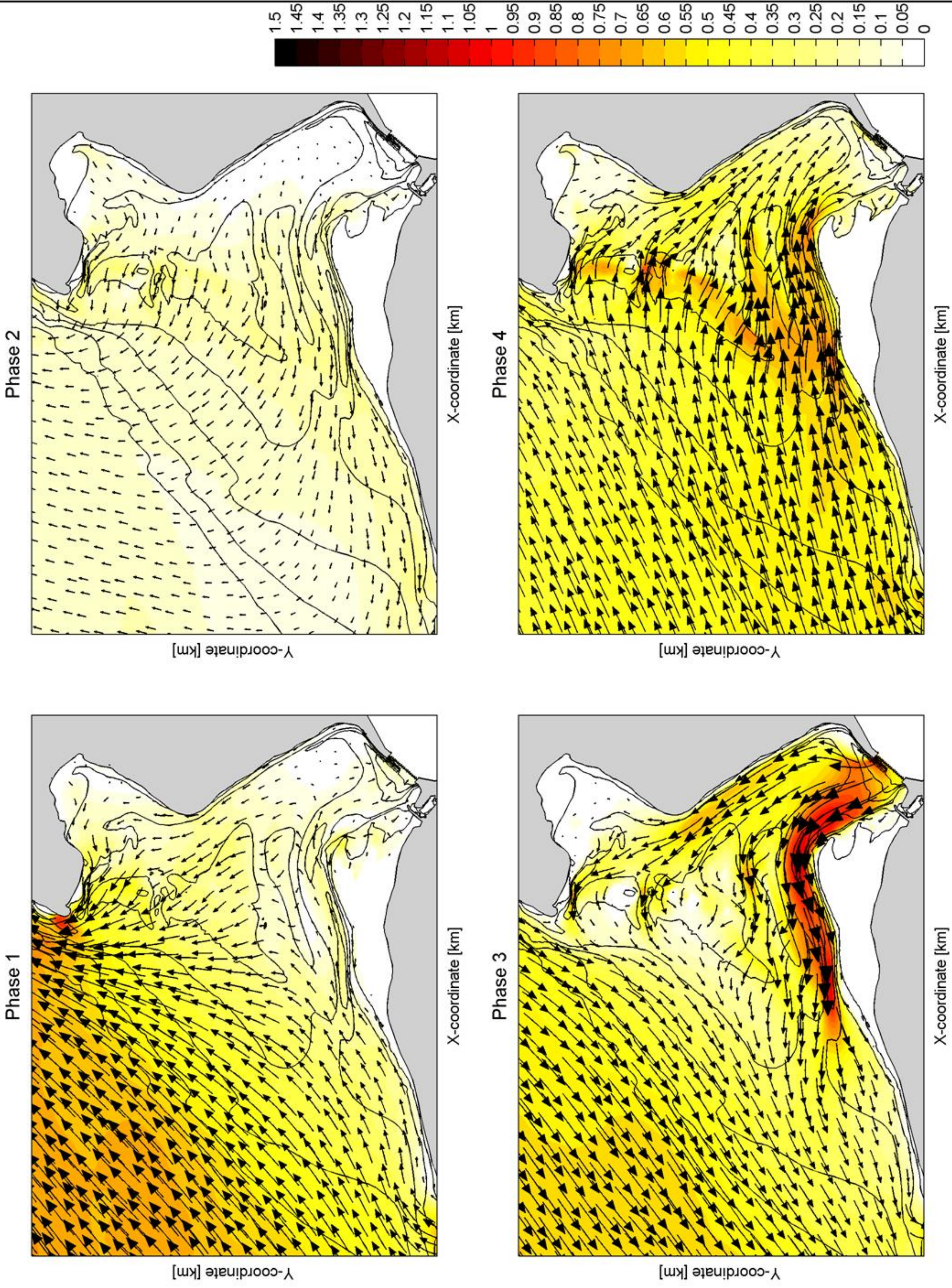
Bedlevel 2003
Tidal forcing and 2685m3/s/dag during 2hours
6 moments after the discharge started

Aug 2008

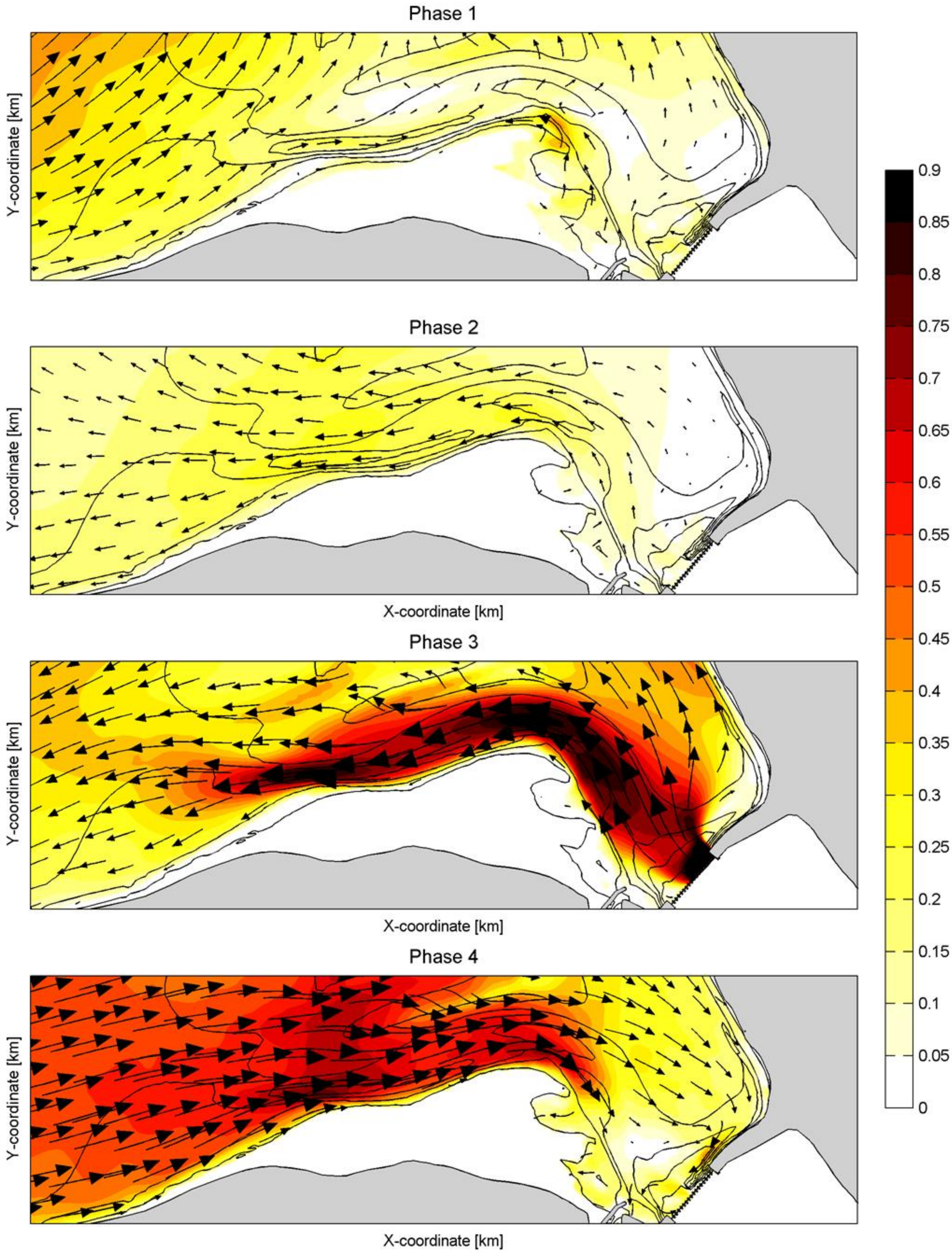
Maintenance of the Slijkgat

WL|Delft Hydraulics

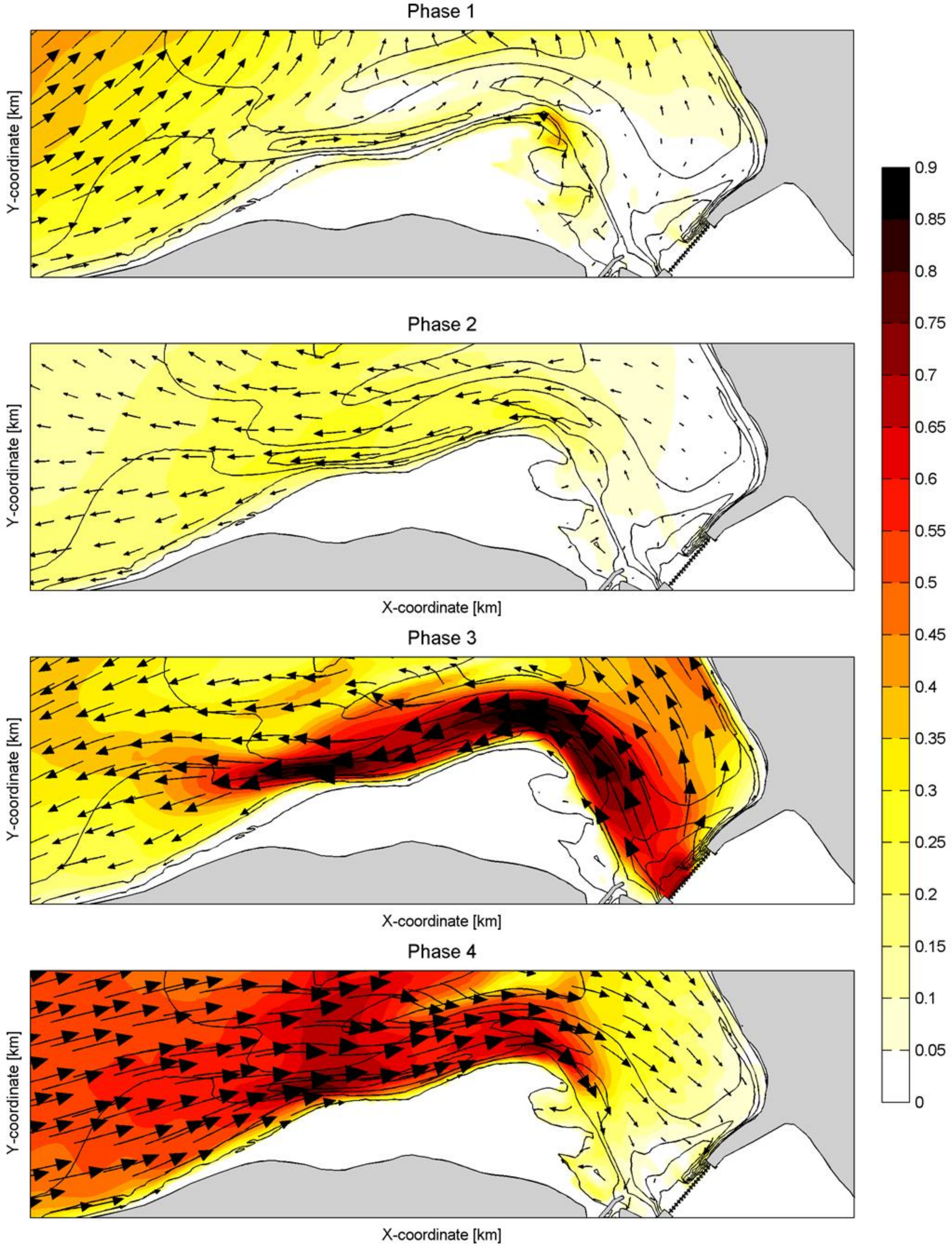
Fig C6



Current during a tidal period, plotted for four phases Scenario B1 D4B 6H Bed level: HV MOND2003		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig C7



Current during a tidal period, plotted for four phases Bed level 2003; tidal forcing and 2685 discharge during hour low water from northern Sluices		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig C8



Current during a tidal period, plotted for four phases Bed level 2003; tidal forcing and 2685 discharge during hour low water from southen Sluices		Aug 2008
	Maintenance of the Slijkgat	
WL|Delft Hydraulics		Fig C9