Tidal River Development

Joint study on mitigation measures in the estuary mouth (Scheldt & Elbe)

by HPA and MOW Jun. 2013

Project part-financed by the European Union (European Regional Development Fund)

The Interreg IVB North Sea Region Programme

Table of Contents

Project part-financed by the European Union (European Regional Development Fund)

1 Introduction

The hydromorphological evolution of the European estuaries has been affected and changed by natural and human factors over a period of several decades. Flow cross-sections have been enlarged and tidally influenced adjacent areas have been lost.

At the **Elbe estuary** this development has resulted in an increase in the tidal range since the mid-fifties. At the same time, the "tidal pumping" effect (upstream directed transport) has been enhanced. This is leading, besides other unfavourable effects to a significant rise in the amount of dredged material in the Port of Hamburg.
On its way through the estuary, the tidal wave is exposed to a whole series of influences that alter its shape and intensity, such as wave propagation velocity, advection and dissipation [Parker, 1991]. These processes ultimately result in an asymmetrical tidal curve with a more steeply ascending flood tide and a more gently falling ebb tide. As demonstrated by Boehlich [2003], the curve for the Elbe estuary becomes more and more asymmetrical as it advances upstream from the North Sea. Due to the reflection of the tidal wave at the river topography and the Geesthacht weir the tidal range increases in spite of the continuous dissipation and energy losses in the upstream direction. In addition to the influence on the tidal range, the above-mentioned processes also affect advective transport processes of salt and sediments, for instance, as well as the current velocity. Baroclinic processes, for example, have a significant influence on the current and sediment transport in an estuary [Lang, 2001].
Baroclinic processes and the tidal pumping effect (see above), subsequently are enhanced. Finer sediment fractions, which used to settle in the shallow water areas, are now transported more upstream and finally reach the port of Hamburg. This leads to increased sedimentation of shallow water areas as well as more effort for maintenance dredging.

The tidal range in the **Scheldt estuary** has increased over the past decades. Since such an increase is not desirable, it is investigated which role the estuary mouth can potentially play in case of mitigating measures. Therefore, several exploratory scenarios have been investigated by means of the numerical flow model FINEL2D, in which the influence of the several units of the estuary mouth is considered. These morphological units are: the Wielingen channel, the Vlakte van de Raan and the Oostgat channel. The scenarios are merely simulated to get insight in how the mouth is contributing to the tidal propagation in the Scheldt estuary.

Climate change is likely to further aggravate this trend leading to numerous disadvantages. Similar situations involving similar challenges have likewise been observed at various North Sea region estuaries, in which a comparable process has occurred.

It has to be assumed that today's problems will be exacerbated in the future. Based on the present state of climate research, we can expect to see a substantial sea level rise. Studies conducted by the BAW in the framework of the projects KLIWAS and KLIMZUG North [HTG, 2011] confirms that a sea level rise would be accompanied by an even higher mean tidal range at the city of Hamburg. In addition there will be a deformation of the tidal curve and a time shift in the occurrence of high and low water. Furthermore the flood / ebb ratio (flood current velocity / ebb current velocity) will increase, the tidal pumping effect will be intensified and both the turbidity zone and the brackish water zone will be located further upstream.

Project part-financed by the European Union (European Regional Development Fund)

It is assumed that hydraulic engineering structures and soft sediment solutions in the mouth of the estuary are able to counteract the developments above described in a sustainable way, taking future challenges into account. Hydraulic engineering structures, in general, can either be designed as linear or expansive structures such as sandbanks.

For both the Elbe and the Scheldt estuary the objectives are to reduce the tidal range, decrease the ratio of flood current to ebb current, reduce the upstream transport of sediments and prevent the further upstream relocation of the brackish water zone. Aiming at dissipating the tidal energy entering the estuary the implementation of measures in the mouth of estuaries was examined.

2 Studies

2.1 Elbe estuary

Two fundamentally different options are considered in the study of mitigation measures in the Elbe estuary mouth (English summary: see Annex 1), that was taken out in the framework of the TIDE Project. The task was to investigate the effect of these measures on hydrodynamics and sediment transport.
The first measure concerns a fixed, linear structure (training wall, in red Fig.1) that can be neither flooded nor permeated. The second one relates to soft, expansive hydraulic engineering structures formed by raising existing sandbanks (blue). It is designed to be floodable in case of high water. The two structures also differ with regard to their location in the mouth of the estuary The linear structure is situated at the relatively narrow end of the mouth of the estuary, while the expansive structure is built in the wider, outer Elbe estuary (see Fig.1).

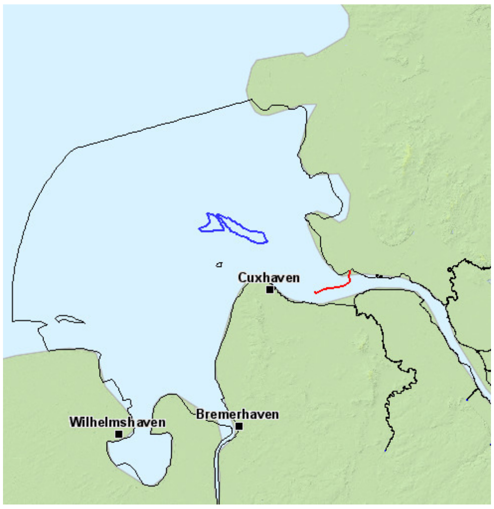

Fig.1: Overview of the Elbe estuary showing the modelled area (black line) with sketches of the expansive (blue) and linear (red) structures.

For the Elbe estuary the objectives was to reduce the tidal range, decrease the ratio of flood current to ebb current, reduce the upstream transport of sediments and prevent the further upstream relocation of the brackish water zone. The resulting target values of measures related changes of selected parameters are shown in Tab.1.

Project part-financed by the European Union (European Regional Development Fund)

The Interreg IVB North Sea Region Programme

The results of the studies showed that the structures in the Elbe estuary used for the model exercise are suitable to counteract the negative trends observed in the Elbe estuary over the last several decades described above.
Some of the above described targets could not be reached completely; therefore further investigations have to be carried out before a detailed planning process can start.

Tab.1: Overview of target achievement for selected tidal characteristic numbers

Tidal characteristic numbers	requested change	target achievment	relevant region
mean high water	decrease	✓	Hamburg
mean low water	increase	✓	
mean tidal range	decrease	✓	
max. flood current velocity	neutral	-	between the turbidity zone and Hamburg
max. ebb current velocity	neutral	-	
max. flood curr. : max. ebb curr.	decrease	✓	
max. suspended load	decrease	✓	
adv. transport of suspended load	rather decrease	✓	
adv. residual transport of sus. load	decrease	✓	
max. salinity	no increase	-	brackish water zone

2.2 Scheldt estuary

In order to investigate the effect of the morphological units in the mouth of the Scheldt estuary on the tidal range, several scenarios are hydrodynamically simulated (see Annex 2). An existing FINEL2D Western Scheldt model is used for the simulations. The model boundary is located significantly far from the Scheldt estuary mouth, by which the boundary conditions are not influenced by the interventions.

A total of 21 scenarios are simulated, see Tab.2. In the first scenario, scenario T0, the present day situation is calculated by which the recent observed bathymetry is applied. This scenario serves as reference for the results of the remaining scenarios. For each of the scenarios, five spring-neap cycles are simulated.

In a first set of nine scenarios (T1a-c, T2a-c, T3a-c), adjustments are made to the model bathymetry in the Oostgat, the Vlakte van de Raan or the Wielingen, see Fig. 2. The Wielingen is the main navigational channel. The Oostgat channel is a channel close to the coastline, while the Vlakte van de Raan is a shallow area between these two channels.

Project part-financed by the European Union (European Regional Development Fund)

The Interreg IVB North Sea Region Programme

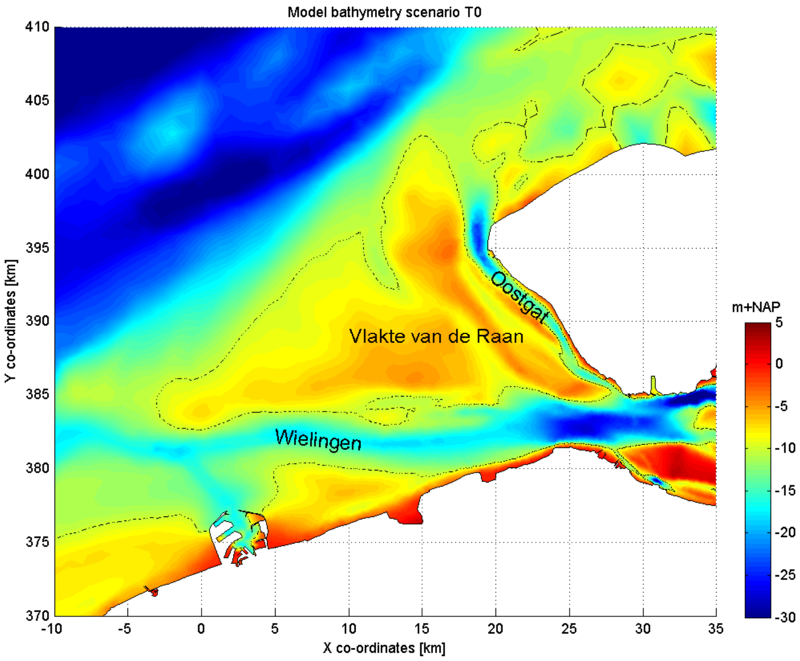

Fig.2: Model bathymetry of the estuary mouth of the Western Scheldt in 2011. The NAP -10 m contour line is indicated in the figure.

In the next scenario (T4) the bed level of the Oostgat is defined at NAP (Dutch Ordnance Level, which is approximately Mean Sea Level) and in another scenario the depth of the deep part of the Wielingen is decreased to NAP -17 m (T5), which equals the depth in the navigational channel. Beside these large scale scenarios, there are two scenarios defined in which the Wielingen channel is locally blocked by a shoal. The height of the shoal is NAP -10 m (T6a) and NAP -5 m (T6b) respectively.

In the last set of scenarios (T7a-b, T8a-e) the interventions are applied to all three units, using only two depths: NAP -18 m and NAP -2 m. In scenario T7a all three units are uniformly defined at NAP -18 m, while in scenario T7b both the Vlakte van de Raan and the Oostgat are defined at NAP -18 m, but the Wielingen is defined at NAP -2 m.

In the last five scenarios (T8a-e) the entire estuary mouth is defined at NAP -2 m, except for a navigational channel of 500 m wide, located at respectively the Oostgat (T8a), the Vlakte van de Raan (T8b) and the Wielingen (T8c) or for two navigational channels, located at the Oostgat and the Wielingen (T8d), and finally a scenario with a navigational channel of 2000 m wide, located at the Vlakte van de Raan (T8e).

The adjustments with respect to the basic model bathymetry are indicated in Tab.2 for each of the scenarios. The bathymetry of the scenarios is shown in the next sections, where the outcomes of the specific scenarios are discussed.

Project part-financed by the European Union (European Regional Development Fund)

The Interreg IVB North Sea Region Programme

Tab.2: Scenario definition: Bed level adjustments with respect to the basic model bathymetry for the different scenarios. 'Small' indicates a channel of 500 m wide. 'Wide' indicates a channel of 2000 m wide.

Scenario	Unit	Bed level adjustment	Volume
T0	N.a.	N.a.	0 Mm^3
T1a	Oostgat	-1 m	-48 Mm^3
T1b	Oostgat	-3 m	-145 Mm^3
T1c	Oostgat	-10 m	-484 Mm^3
T2a	Vlakte van de Raan	+1 m	277 Mm^3
T2b	Vlakte van de Raan	+3 m	833 Mm^3
T2c	Vlakte van de Raan	+10 m	2775 Mm^3
T3a	Wielingen	-1 m	-79 Mm^3
T3b	Wielingen	-3 m	-239 Mm^3
T3c	Wielingen	-10 m	-802 Mm^3
T4	Oostgat	Filled to NAP	648 Mm^3
T5	Wielingen	Filled to NAP -17m	51 Mm^3
T6a	Wielingen	Blocked to NAP -10m	31 Mm^3
T6b	Wielingen	Blocked to NAP -5m	116 Mm^3
T7a	Entire estuary mouth	Deepened to NAP -18m	-4881 Mm^3
T7b	Entire estuary mouth	Estuary mouth NAP -18m, Wielingen NAP -2m	-1932 Mm^3
T8a	Oostgat	Estuary mouth NAP -2m, Oostgat 'small' NAP -18m	1924 Mm^3
T8b	Vlakte van de Raan	Estuary mouth NAP -2m, Vlakte van de Raan 'small' NAP -18m	1884 Mm^3
T8c	Wielingen	Estuary mouth NAP -2m, Wielingen 'small' NAP -18m	1862 Mm^3
T8d	Oostgat and Wielingen	Estuary mouth NAP -2m, Wielingen and Oostgat 'small' NAP -18m	1666 Mm^3
T8e	Vlakte van de Raan	Monding NAP -2m, Vlakte van de Raan 'wide' NAP -18m	1361 Mm^3

Project part-financed by the European Union (European Regional Development Fund)

The Interreg IVB North Sea Region Programme

3 Conclusions

Measures conducted at the mouth of the estuary have a particularly strong impact on the development of hydrodynamics and are suitable to affect transport processes all over the estuary.

The amount of energy that carries the tidal wave into the estuary depends on the width of the mouth of the estuary. The wider the mouth, the more tidal energy will enter the river. River engineering measures to reduce the cross-section profile at the mouth can reduce the tidal energy entering the estuarine system, which affects various processes.

From the simulations for the Scheldt estuary it follows that the interventions in the estuary mouth have to be considerably large in order to obtain a significant effect on the tidal range.

Filling the full estuary mouth to a bed level of NAP -2 m, except for a navigational channel of 500 m wide at approximately the depth of the current main navigational channel (NAP -18 m), results in a large reduction (over 50%) of the tidal range. The cross-sectional area of the estuary mouth is reduced in such a way, that the discharge decreases significantly. By doubling the cross sectional area, the reduction of the tidal range becomes significantly smaller, with only a limited effect on the tidal range compared to the scenarios with a navigation channel of 500 m wide.

Deepening the Oostgat and applying a 'shoal' in the Wielingen in the mouth of the Scheldt estuary also result in a reduction of the tidal range, however to a limited extend compared to the amount of sediment involved in such a measure. Deepening the Wielingen and heightening the Vlakte van de Raan on the other hand, result in an increase of the tidal range. Lowering the Vlakte van de Raan could lead to a reduction of the tidal range, however the intervention needs to be considerable in order to obtain any significant effect. Besides, this intervention can potentially enhance the export of sand from the Western Scheldt.

4 References

Boehlich, 2003 Tidedynamik der Elbe; Marcus J. Boehlich; Mitteilungsblatt der Bundesanstalt für Wasserbau No. 86; 2003

HTG, 2011 Auswertungen klimabedingter Änderungen auf das Strömungs- und Transportverhalten deutscher Nordseeästuare – ein Vergleich von Ems, Jade-Weser und Elbe; I. Holzwarth, A. Schulte-Rentrop, F. Hesser; Proceedings of the HTG Conference 2011 Würzburg, pp. 275-282; 2011

Lang, 2001 Zur 3D-Modellierung der Tidedynamik im Ems-Ästuar –Einfluss barokliner Prozesse auf das Strömungsprofil-, Dr. Günter Lang, BAW-AK Colloquium presentation; May 2001

Lang, 2003 Analyse von HN-Modell-Ergebnissen im Tidegebiet, Dr. Günter Lang,

Parker, 1991 Tidal Hydrodynamics, National Oceanic and Atomspheric Administration, US Department of Commercial, Rockville Maryland, John Wiley & Sons, Inc., Bruce B. Parker (Ed.), USA 1991

Project part-financed by the European Union (European Regional Development Fund)

The Interreg IVB North Sea Region Programme

5 Annexes

Annex 1: Dissipating tidal energy in the mouth of the Elbe Estuary (English summery), BAW 2012
Annex 2: Influence of the morphology of the Scheldt estuary mouth on the tidal propagation (English report), Svasek Hydraulics 2013.

Project part-financed by the European Union (European Regional Development Fund)

The Interreg IVB North Sea Region Programme

Dissipating tidal energy in the mouth of the Elbe Estuary

Federal Waterway Engineering and Research Institute (BAW)

Bundesanstalt für Wasserbau
Federal Waterways Engineering and Research Institute

Project part-financed by the European Union (European Regional Development Fund)

The Interreg IVB North Sea Region Programme

IMPRINT

Federal Waterway Engineering and Research Institute (BAW)
Department of Hydraulic Engineering in Coastal Areas, Estuary Systems I
Dipl.-Ing. Morten Klöpper
January 2013

Disclaimer

The authors are solely responsible for the content of this report. Material included herein does not represent the opinion of the European Community, and the European Community is not responsible for any use that might be made of it.

Bundesanstalt für Wasserbau
Federal Waterways Engineering and Research Institute

Project part-financed by the European Union (European Regional Development Fund)

The Interreg IVB North Sea Region Programme

Table of Contents

Project part-financed by the European Union (European Regional Development Fund)

The Interreg IVB North Sea Region Programme

1 Introduction

The hydromorphological evolution of the Elbe estuary has been affected and changed by natural and human factors over a period of several decades. Flow cross-sections have been enlarged and tidally influenced adjacent areas have been lost. This development has resulted in an increase in the tidal range since the mid-fifties. At the same time, the "tidal pumping" effect (upstream directed transport) has been enhanced, leading to a significant rise in the amount of dredged material in the port of Hamburg as well as sedimentation of side channels and tributaries of the Elbe. Climate change is likely to further aggravate this trend leading to numerous disadvantages. Similar situations involving similar challenges have likewise been observed at various North Sea region estuaries, in which a comparable process has occurred. In the framework of the Interreg IVb TIDE project (Tidal River Development), national and international partners have been developing strategies and designing instruments to perform an integrated management of the estuaries of the North Sea region.
One of these instruments is the implementation of measures in the mouth of estuaries aiming at dissipating the tidal energy entering the estuary. Two fundamentally different options are considered here, using the Elbe estuary as an example. The task assigned to the Federal Waterways and Engineering and Research Institute (BAW) was to investigate the effect of these measures on hydrodynamics and sediment transport.

The “Concept for a sustainable development of the Elbe Estuary as an artery of the metropolitan area of Hamburg” (German: "Konzept für eine nachhaltige Entwicklung der Tideelbe als Lebensader der Metropolregion Hamburg") [HPA, 2006] already mentioned the *dissipation of the incoming tidal energy by hydraulic engineering constructions especially within the mouth of the estuary* as one of three cornerstones in a future action plan to develop the Elbe estuary in a sustainable way. Measures conducted at the mouth of the estuary have a particularly strong impact on the development of hydrodynamics and are suitable to affect transport processes all over the estuary. The amount of energy that carries the tidal wave into the estuary depends on the width of the mouth of the estuary. The wider the mouth, the more tidal energy will enter the river. River engineering measures to reduce the cross-section profile at the mouth can reduce the tidal energy entering the estuarine system, which affects various processes. On its way through the estuary, the tidal wave is exposed to a whole series of influences that alter its shape and intensity, such as wave propagation velocity, advection and dissipation [Parker, 1991]. These processes ultimately result in an asymmetrical tidal curve with a more steeply ascending flood tide and a more gently falling ebb tide. As demonstrated by Boehlich [2003], the curve for the Elbe estuary becomes more and more asymmetrical as it advances upstream from the North Sea. Due to the reflection of the tidal wave at the river topography and the Geesthacht weir the tidal range increases in spite of the continuous dissipation and energy losses in the upstream direction. In addition to the influence on the tidal range, the above-mentioned processes also affect advective transport processes of salt and sediments, for instance, as well as the current velocity. Baroclinic processes, for example, have a significant influence on the current and sediment transport in an estuary [Lang, 2001].

In the past, the reflection characteristics and energy dissipation have been changed by various influences. As a result more and more tidal energy reaches upstream areas as far as the Elbe's bifurcation area near the port of Hamburg. The tidal range in this area has increased dramatically over the past few decades [Boehlich, 2003]. The deformation of the tidal curve has simultaneously become more pronounced – a trend that is documented by a shift in the strength of the flood current compared to the ebb current, leading to the detriment of the ebb current velocity. In addition, the growing dominance of the flood current velocity increases upstream transport processes. Baroclinic processes and the tidal pumping effect (see above), subsequently are enhanced. Finer sediment fractions, which used to settle in the shallow water areas, are now transported more upstream and finally reach the port of Hamburg. This leads to increased sedimentation of shallow water areas as well as more effort for maintenance dredging.
It has to be assumed that today's problems will be exacerbated in the future. Based on the present state of climate research, we can expect to see a substantial sea level rise. Studies conducted by the BAW in the framework of the projects KLIWAS and KLIMZUG North [HTG, 2011] confirms that a sea level rise would be accompanied by an even higher mean tidal range in the area of the city of Hamburg. In addition there will be a deformation of the tidal curve and a time shift in the occurrence of high and low water. Furthermore the flood / ebb ratio (flood current velocity / ebb current velocity) will increase, the tidal pumping effect will be intensified and both the turbidity zone and the brackish water zone will be located further upstream.
It is assumed that hydraulic engineering structures in the mouth of the estuary are able to counteract the developments above described in a sustainable way, taking future challenges into account. In general, these can either be designed as linear or expansive structures such as sandbanks. For the Elbe estuary the objectives are to reduce the tidal range, decrease the ratio of flood current to ebb current, reduce the upstream transport of sediments and prevent the further upstream relocation of the brackish water zone. The resulting target values of measures related changes of selected parameters are shown in Table 1.1.

Table 1.1 Overview of target values for selected tidal characteristic numbers

Tidal characteristic numbers	requested change	relevant region
mean high water	decrease	Hamburg
mean low water	increase	
mean tidal range	decrease	
max. flood current velocity	neutral	between the turbidity zone and Hamburg
max. ebb current velocity	neutral	
max. flood curr. : max. ebb curr.	decrease	
max. suspended load	decrease	
adv. transport of suspended load	rather decrease	
adv. residual transport of sus. load	decrease	
max. salinity	no increase	brackish water zone

2 Analysis

The effects of river engineering measures in the mouth of estuaries are analysed taking the Elbe estuary as an example. This system study is conducted with the help of the BAW's Elbe simulation model, which is based on UNTRIM-3D, the three-dimensional hydrodynamic numerical modelling system. UNTRIM-3D is a finite volume method for unstructured grids that simulates steady-state and transient flow and transport processes in waters with a free surface. For a detailed description of both the method and the model see the German study report [BAW, 2012].

Two fundamentally different types of measures are considered in this study. They differ with regard to their location in the mouth of the estuary (see Figure 1). One is situated at the relatively narrow end of the mouth of the estuary (red line), while the other on is located in the wider, outer Elbe estuary (blue line). The first measure concerns a fixed, linear structure (training wall) that can be neither flooded nor permeated. The second one relates to soft, expansive hydraulic engineering structures formed by raising existing sandbanks. It is designed to be floodable in case of high water.

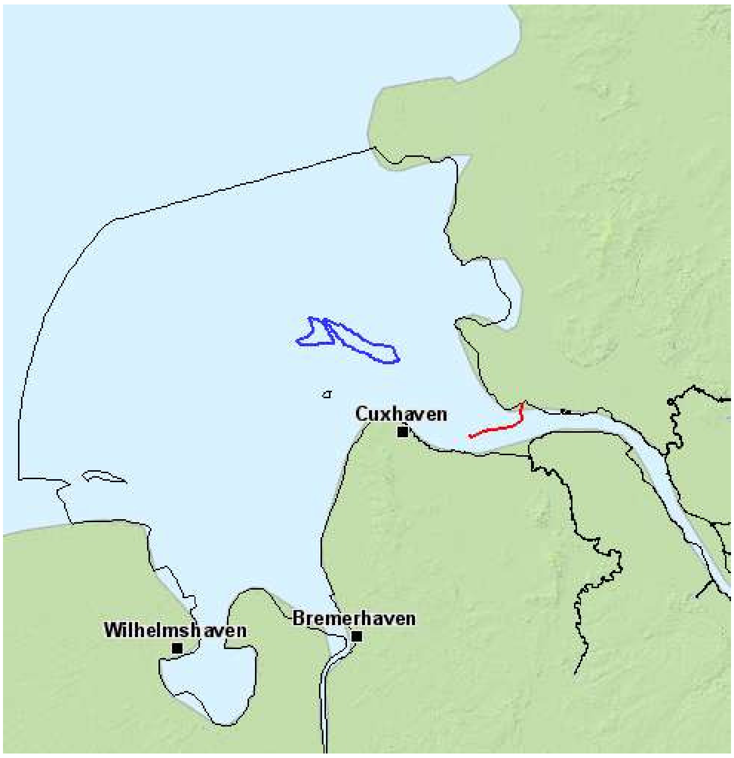

Figure 1 Overview of the Elbe estuary showing the modelled area (black line) with sketches of the expansive (blue) and linear (red) structures.

The linear structure is modelled as a dam structure with a crown height (+10 m above sea level) which ensures that the structure cannot be flooded. The dam follows existing morphological structures and runs from the harbour in Neufeld (see Figure 3) along the harbour fairway approximately up to the edge of the

Wadden Sea, then turns south-west and continues parallel to the *Neufelder Sand* embankment. It crosses the tidal channels *Neufelder Rinne* and *Medemrinne*, a secondary channel, roughly at the point where the Schleswig-Holstein Wadden Sea National Park begins and ends at the *Medemgrund* sandbank. This measure extends from Elbe km 703 (TIDE km 117) to km 715 (TIDE km 129). It is referred to in the following as development state AZ01 or the "linear structure up to *Medemgrund*" (see Figure 2).

To assess the impact of the linear structure more accurately two other alternatives are considered. The first is an extension of the dam up to the western end of the *Grosser Vogelsand* sandbank. It is referred to as development status AZ05 or the "linear structure up to *Grosser Vogelsand*". The second alternative is a shorter dam up to the channel *Medemrinne*. It is referred to as development status AZ03 or the "linear structure up to *Medemrinne*".

The expansive structure is situated approximately between Elbe km 735 (TIDE km 149) and km 750 (TIDE km 164). The *Grosser Vogelsand* and *Gelbsand* sandbanks are raised to +1 m above sea level. The Lüchterloch passage between these two banks remains opened. The elevation of the banks corresponds to a change in volume of approximately 240 million cubic meters. The mean high water in the region is approximately 1.6 m above sea level while the mean low water is approximately 1.6 m below sea level (during the investigation period). That implies that the areas concerned to be flooded at mean high water but remain dry for the majority of the tidal phase. The structures consequently blend in the natural structure of the surrounding Wadden Sea. This measure refers to the development status AZ02 or the "expansive structure with two sandbanks".

To evaluate the influence of the *Lüchterloch* on the tidal currents more precisely, another alternative is considered. A large sandbank is created by filling the *Lüchterloch* up to +1 m above sea level. This alternative refers to development status AZ04 or the "expansive structure with one sandbank". Figure 2 shows details of the model topography for all five development stages.

The five measures in the Elbe estuary were examined separately. The effects of the respective measures were described as differences between the modelling results and a model-reference condition (without any measures, designed current status or PIZ). The model simulations take place under mean boundary conditions (for details see the German report) [BAW, 2012].

The calculation results of the UNTRIM simulations comprise very large synoptic data records which are not directly suitable for a sufficient visualisation of the tidal characteristics. Therefore the dataset was reduced and the parameters which characterize the system's behaviour were determined. This procedure allows a comparison of the reference and the development state. Further details are given in Lang [2003]. The results are presented on profiles. For more information about the analysis and presentation of the results see German study report [BAW, 2012].

Changes in the tidal characteristic numbers caused by the examined river development measures are only taken into account if they exceed a significant, measurable threshold. The following threshold values are applied:

- Δ water level 1.0 [cm]
- Δ current velocity 2.5 [cm/s]
- Δ salinity 0.1 [-]

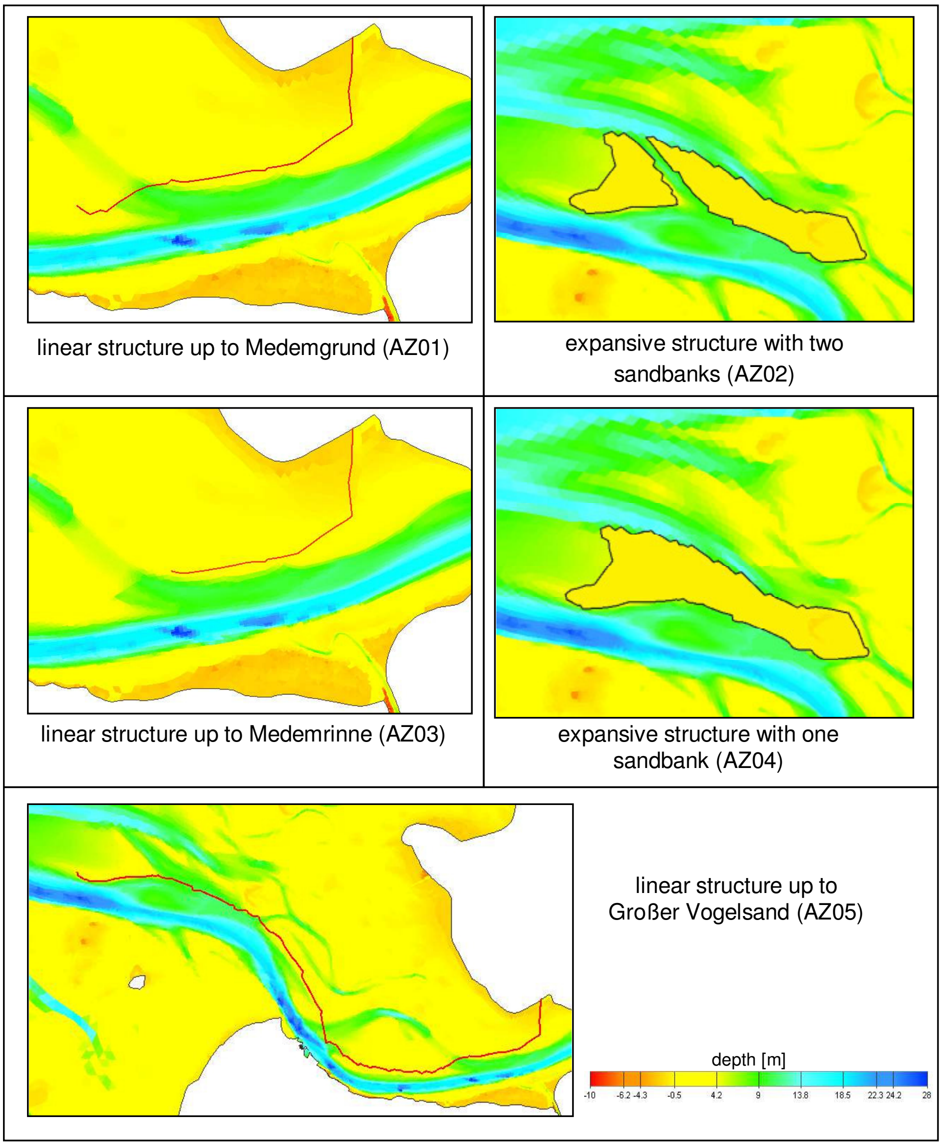

Figure 2 Details of the model topography for all five development stages.

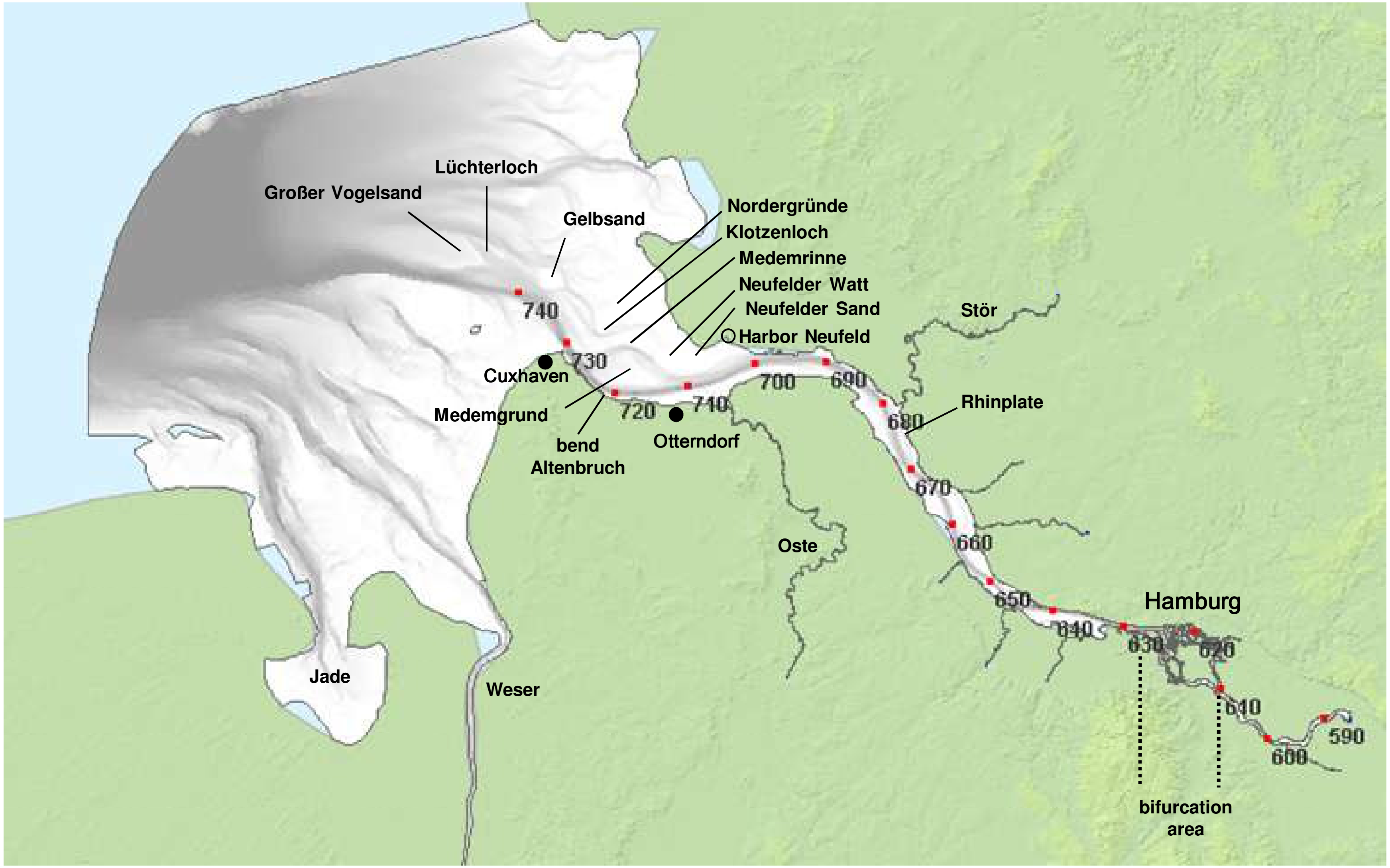

Figure 3 Overview of places and kilometre distances along the Elbe estuary.

3 Results

Water level

Both linear and expansive structures are suitable to reduce the effective cross-section at the Elbe river mouth. As a result, less tidal energy can enter the estuary leading to a reduction of tidal amplitude along the estuary. The effects of the structures are noticeable even beyond the city of Hamburg.

The dam of the linear structure up to *Medemgrund* (AZ01) separates the *Neufelder Sand* and *Medemrinne* tidal flats from the main channel which results in interrupting the interaction between these two parts. The amplitude of the tidal wave decreases upstream, as well as in the south of the structure. The mean low water rises (black curve in Figure 4) while the mean high water decreases (black curve in Figure 5). It can be observed that the tidal flats in the north of the linear structure were dammed up during flood tide. Furthermore, the tidal wave is reflected by the structure. As a result, the mean high water level rises north-west of the structure and the mean low water in the channel *Medemrinne* decreases. Due to this cut off of the *Medemrinne*, the ebb current has no supporting impact on the mean low water level anymore.

In development status AZ02, the enlarged sandbanks in the outer Elbe estuary form an expansive barrier against the tidal wave entering the estuary. Due to this expansive structure (AZ02) as well as the linear structure (AZ01), less tidal energy can enter the estuary because the effective cross-section at the mouth of the estuary is reduced. The sandbanks are flooded as soon as the water level gets higher than +1 m above sea level. The total available cross-section (for the inflow) increases with the rising water level. This explains why the structure has a greater impact on the mean low water level than it has on the mean high water level (red curve in Figure 4 and Figure 5). The smaller amplitude of the tidal curve upstream of the measure is therefore almost exclusively attributable to the fact that the mean low water level increases. North of the sandbanks the mean low water decreases because the elevated sandbanks cause a change in the flow direction of the ebb current.

The effect on the water level of the linear structure up to *Medemgrund* (black curve in Figure 4) is twice as big as the effect on the water level in the development status with the expansive structure with two sandbanks (red curve), because it constricts the cross-section to a greater extent. The impact of the expansive structure on the mean low water is slightly enhanced by additional shoring (filling the *Lüchterloch* with extra material, blue curve). However, since the degree of shoring is only minor compared to the available flow cross-section at high water, the expansive structures do not result in any significant reduction in the mean high water (red and blue curves in Figure 5). The change in the water levels is mainly the outcome of the separation of the *Medemrinne*. This can be shown by the comparison of the impact of the linear structure up to *Medemrinne* (green curve in Figure 4 and Figure 5) and the linear structure up to *Medemgrund* (black curve). The linear structure up to the *Grosser Vogelsand* sandbank has the biggest impact on both the mean high water and the mean low water (magenta curve). This development state reduces the effective cross section to the greatest extent.

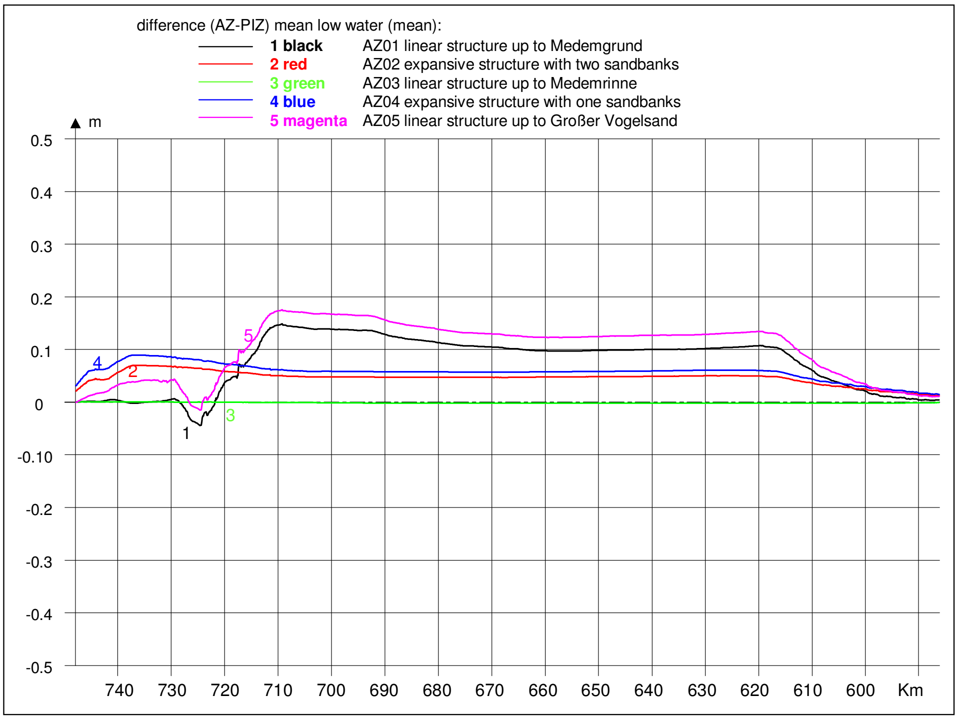

Figure 4 Difference (development status, AZ - designed current status, PIZ) in the mean low water on the longitudinal profile of the Elbe estuary for all five development states, in each case referred to the analysis period from June 11 to 25, 2006.

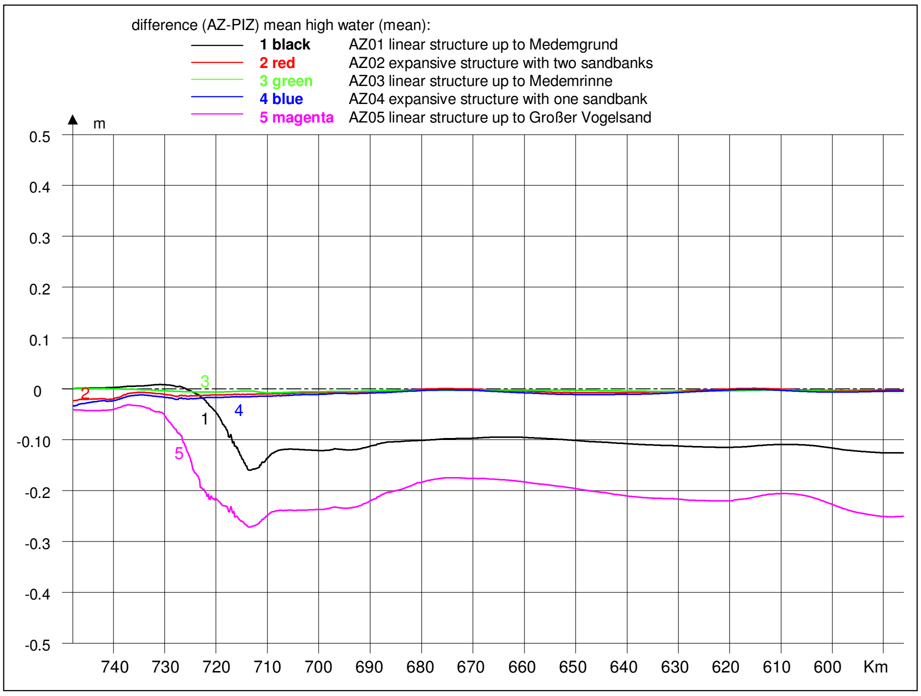

Figure 5 Difference (AZ - PIZ) in the mean high water on the longitudinal profile of the Elbe estuary for all five development states, in each case referred to the analysis period from June 11 to 25, 2006.

Current velocity

The reduction of the effective cross-section due to the simulated structures in the Elbe estuary reduces the tidal volume. As a result the current velocity decreases over a large area. This contrasts with the reduction in the cross-section in the area of the measures, where local increases in the current velocity can be observed.

The linear structure leading up to *Medemgrund* (AZ01) blocks off the channel *Medemrinne* and therefore the current velocity in this channel is considerably reduced. The flood and ebb currents that formerly passed the *Medemrinne* now flow through the main channel of the Elbe estuary. As a result the current velocity in the stretch between the cities of Cuxhaven and Otterndorf increases. Due to the expansive structures (AZ02) the occurrence of the currents also changes in the area that is affected by the measure. The water masses move around the sandbanks. Consequently the maximum current velocities can be observed in the south of the sandbanks, in the *Lüchterloch* and north-east of the *Gelbsand* sandbank.

Both, the linear and the expansive structure cause a reduction of the current velocities over a large area. Upstream of the expansive structure, the reduction in the maximum ebb current velocity is greater than the reduction in the maximum flood current velocity. Therefore the flood / ebb ratio is lower almost everywhere along the Elbe estuary. This ratio hardly changed in the flood-dominant stretch between the turbidity zone and the city of Hamburg due to the linear structure up to *Medemgrund*.

The differences between the maximum flood and ebb current velocities are shown in Figure 6 and Figure 7 for both, the expansive structure including two sandbanks as well as the linear structure up to *Medemgrund* and *Grosser Vogelsand*. The reduction in the current velocity upstream of the measures is greater in the case the linear structures are applied compared to the implementation of the expansive structures. However, in the area of the *Altenbrucher Bogen*, where the currents are forced out of the *Medemrinne* channel, there is a significant increase in the maximum current velocity of approximately 40 cm/s. The area of the *Altenbrucher Bogen* puts heavy demands on bank protection already today, since the current velocity is high in this area.

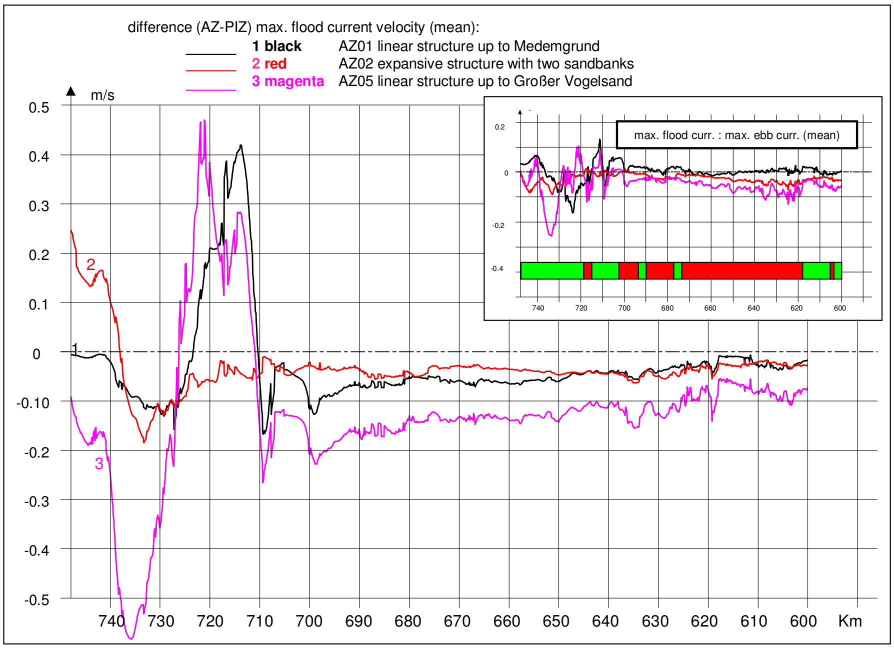

Figure 6 Difference (AZ - PIZ) in the maximum flood current velocity (mean) on the longitudinal profile of the Elbe estuary for the AZ01, AZ02, and AZ05 structures, in each case referred to the analysis period from June 11 to 25, 2006. The inset shows the difference in the ratio of the maximum flood current velocity (mean) to the maximum ebb current velocity (mean) during the same period. The coloured beam shows the dominance (flood= red; ebb= green) of the current velocity.

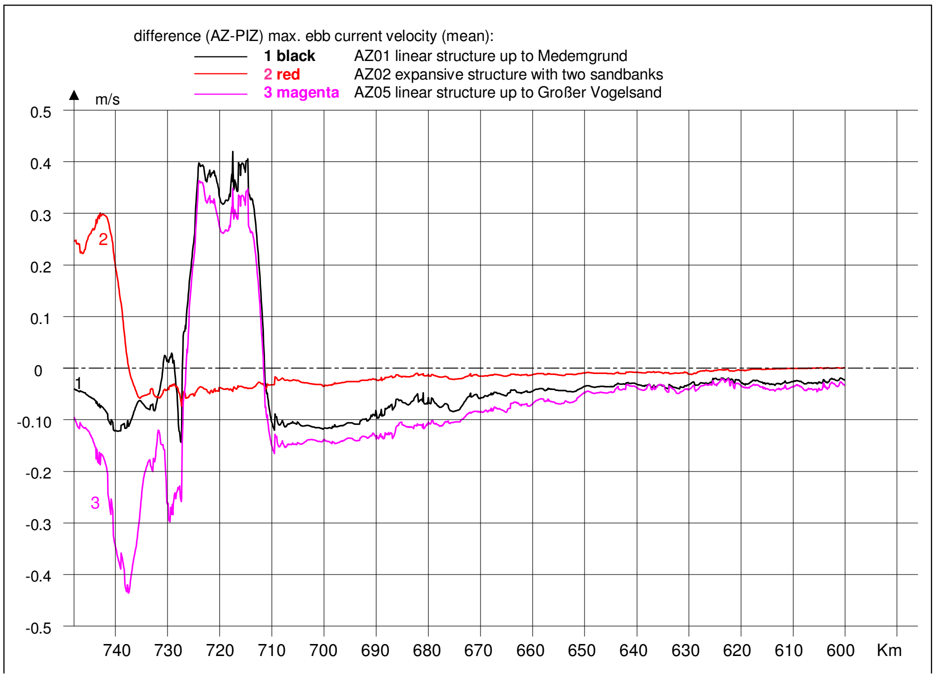

Figure 7 Difference (AZ - PIZ) in the maximum ebb current velocity (mean) on the longitudinal profile of the Elbe estuary for the AZ01, AZ02, and AZ05 structures, in each case referred to the analysis period from June 11 to 25, 2006.

Salinity

For different reasons both, the expansive structure and the linear structure up to *Medemgrund* result in an increase in the maximum salinity (Figure 8) of the Elbe estuary.

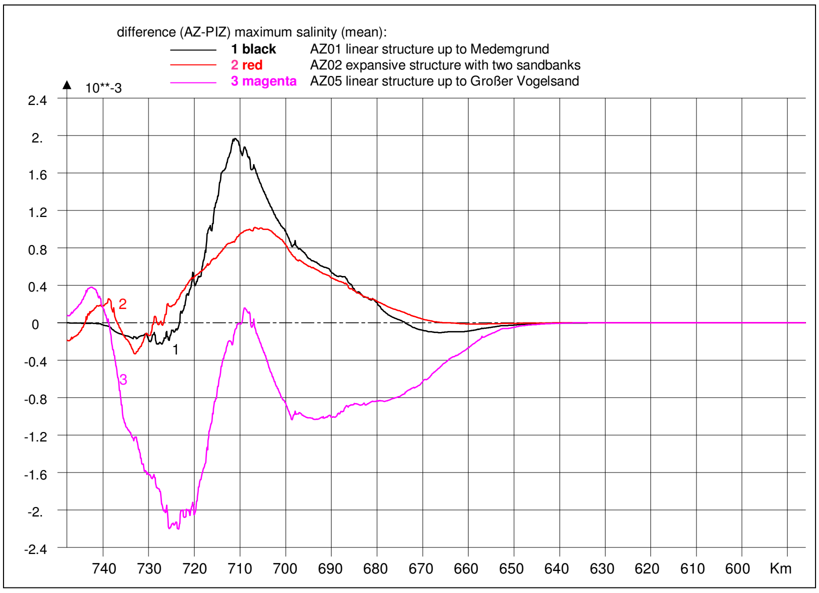

Figure 8 Difference (AZ - PIZ) in the maximum salinity in the longitudinal profile of the Elbe estuary for the AZ01, AZ02, and AZ05 structures, in each case referred to the analysis period from June 11 to 25, 2006.

The expansive structures interrupt the recirculation of less saline Elbe water coming from upstream over the areas north of the sandbanks. Instead, North Sea water with a higher salt content enters the Elbe estuary via the tidal flats. The interruption of the recirculation is shown in Figure 9 (left).

The linear structure up to Medemgrund leads to a reduction in the maximum salinity in the north of the structure. Less saline water from Medemrinne is pushed by the flood current into the Neufelder Watt and Neufelder Sand areas, preventing the water with high salinity content from flowing through the Klotzenloch channel and over the Nordergründe area (see Figure 9, right). Upstream of the structure the maximum salinity rises. The higher current velocity south of Medemgrund entrains the salt further upstream during flood tide. In the case of the linear structure up to Grosser Vogelsand, the same effect causes only a small, local increase in the maximum salinity (magenta curve in Figure 8). Since the current velocity decreases almost everywhere south of the dam, the salt – which only enters via the very narrow mouth of the estuary– is not entrained as far up into the estuary. Saline North Sea water is completely prevented from flowing over the tidal flats in the Elbe estuary. That leads to a rise in the maximum salinity north of the structure.

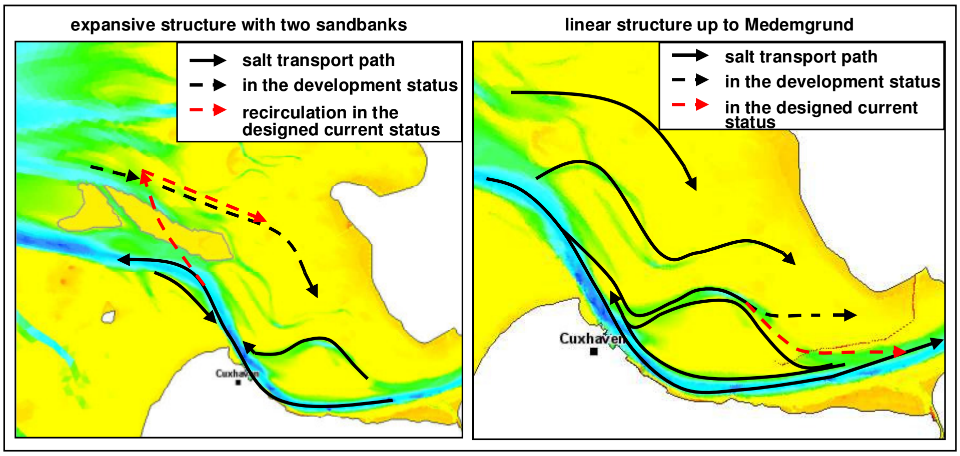

Figure 9 Schematic diagram of salt transport paths during one tide for the expansive structure with two sandbanks (left) and the linear structure up to *Medemgrund* (right).

Suspended matter

The reduction of the current velocity upstream of the structures induces a decrease in the suspended matter (Figure 10). In addition, the linear structures block the transport of suspended matter via the tidal flats into the estuary.

Both structures cause an overall decrease in the dynamics of suspended matter. The lower amount of suspended material means at the same time less advective transport of suspended matter (Figure 11). Since the reduction in the advective flood current transport is larger than in the ebb current, there is also less residual advective transport of suspended matter. As a result the upstream transport of suspended material between the turbidity zone (around Elbe km 690) and Hamburg decreases.

The impact of the linear structure up to *Medemgrund* (black curve) is roughly identical compared to the impact of the expansive structure including the two sandbanks (red curve). The linear structure up to *Grosser Vogelsand* (magenta curve) has the largest effect on the transport of suspended matter.

No values of suspended matter can be shown for the area along the linear structures in Figure 10 and Figure 11 because these are not directly connected; and cross- sectional integrated values would consequently not make any sense.

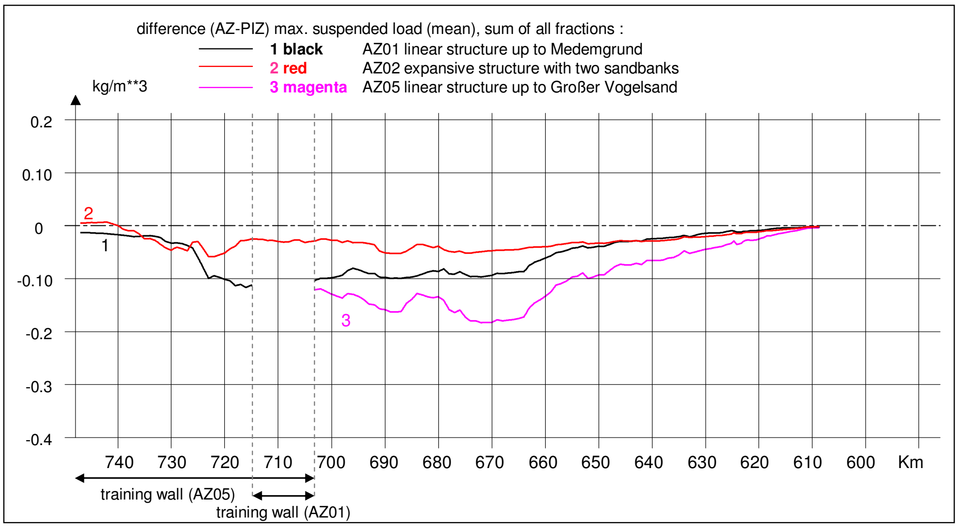

Figure 10 Difference (AZ - PIZ) in the cross-sectional integrated maximum suspended load (sum of all fractions) on the longitudinal profile of the Elbe estuary for the AZ01, AZ02, and AZ05 structures, in each case referred to the analysis period from June 11 to 25, 2006.

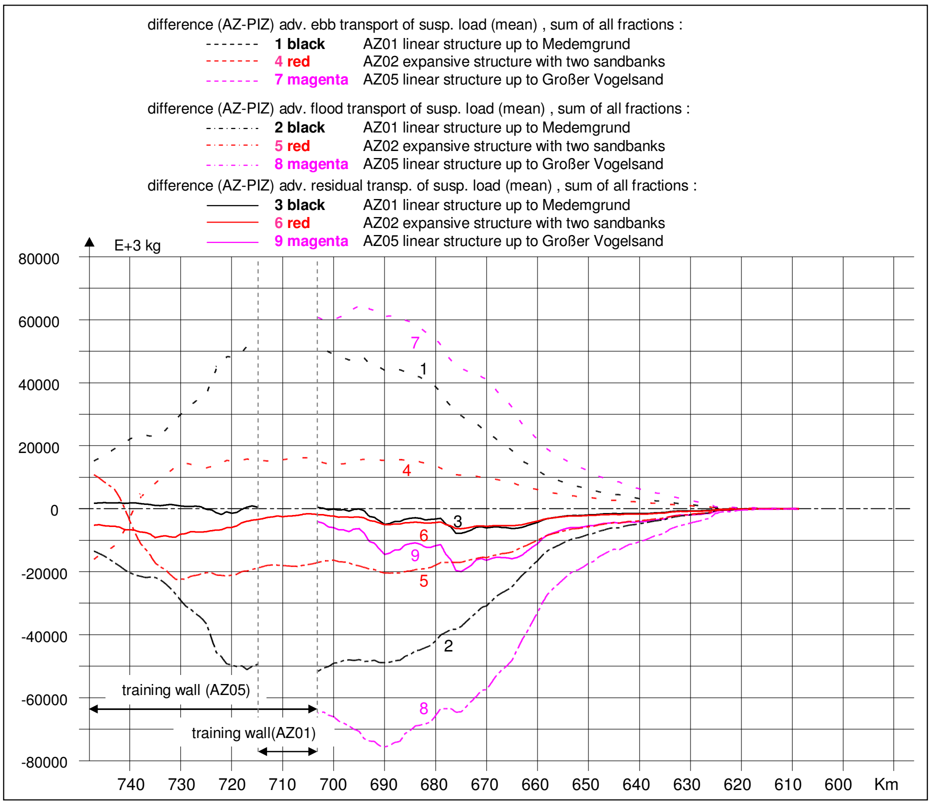

Figure 11 Difference (AZ - PIZ) in the cross-sectional integrated advective transport of suspended load by means of the ebb and flood currents (sum of all fractions) and in the cross-sectional integrated residual advective transport of suspended load (sum of all fractions) on the longitudinal profile of the Elbe estuary for the AZ01, AZ02 and AZ05 structures, in each case referred to the analysis period from June 11 to 25, 2006.

4 Conclusion

Both measures, those at the relatively narrow end of the mouth of the estuary (linear structures) and those in the wider, outer Elbe estuary (expansive structures) are suitable to improve the hydrological and morphological conditions in the whole Elbe estuary. In the model exercise less tidal energy enters the Elbe estuary due to the reduction of the effective cross-section in the mouth of the estuary. Consequently the tidal range is reduced. At the same time, local increases of current velocity can be observed in the area directly affected by the structures. Potential structures in the Elbe estuary should therefore be arranged in a way that the increase in current velocity occurs in less sensitive areas. The dominance of the flood current between the turbidity zone and the city of Hamburg can partially be mitigated. This effect can be demonstrated by the lower flood / ebb ratio caused by the measures. All structures have the effect of reducing the transport of suspended material, particularly in this stretch between the turbidity zone and the city of Hamburg. In addition to a reduction in the advective flood and ebb transport of suspended matter, there is also less advective residual transport of suspended material. The measures thus counteract the upstream transport of sediments in the Elbe estuary. The changed flow conditions due to the structures influence the transport of salt in different ways. The maximum salinity of the Elbe rises or declines depending on the specific implementation of the measures. Whereas the linear structures cause more intense effects on the residual advective sediment transport than the expansive ones, they have also a higher impact on critical current velocities in the area of the *Altenbrucher Bogen*.

The study shows that the structures in the Elbe estuary used for the model exercise are suitable to counteract the negative trends observed in the Elbe estuary over the last several decades. However, it must be noticed that all statements of this report are only applicable to the given state of the system (at average conditions). In particular, the study cannot provide any information on the impact of the structures if the sea level rise occurs.

The investigation was designed as a system study that does not take into account feasibility issues such as long term stability of the structures or other local aspects. These aspects have to be examined prior to the implementation of respective measures in the estuary mouth.

5 List of literature

BAW, 2012 — Untersuchungen des Strombaus und des Sedimentmanagements im Rahmen des Projektes TIDE, Maßnahmen zur Dämpfung der Tideenergie im Mündungsbereich der Elbe, M. Klöpper, BAW-Report, September 2012

Boehlich, 2003 — Tidedynamik der Elbe; Marcus J. Boehlich; Mitteilungsblatt der Bundesanstalt für Wasserbau No. 86; 2003

Lang, 2001 — Zur 3D-Modellierung der Tidedynamik im Ems-Ästuar – Einfluss barokliner Prozesse auf das Strömungsprofil-, Dr. Günter Lang, BAW-AK Colloquium presentation; May 2001

Lang, 2003 — Analyse von HN-Modell-Ergebnissen im Tidegebiet, Dr. Günter Lang, Mitteilungsblatt der Bundesanstalt für Wasserbau No. 86, 2003

HPA, 2006 — Konzept für eine nachhaltige Entwicklung der Tideelbe als Lebensader der Metropolregion Hamburg; H.P. Dücker, H.-H. Witte, H. Glindemann und K. Thode; HPA 2006

HTG, 2011 — Auswertungen klimabedingter Änderungen auf das Strömungs- und Transportverhalten deutscher Nordseeästuare – ein Vergleich von Ems, Jade-Weser und Elbe; I. Holzwarth, A. Schulte-Rentrop, F. Hesser; Proceedings of the HTG Conference 2011 Würzburg, pp. 275-282; 2011

Parker, 1991 — Tidal Hydrodynamics, National Oceanic and Atomspheric Administration, US Department of Commercial, Rockville Maryland, John Wiley & Sons, Inc., Bruce B. Parker (Ed.), USA 1991

Influence of the morphology of the Scheldt estuary mouth on the tidal propagation

Long Term Vision Western Scheldt Estuary, Safety and Accessibility

Final

1630/U13179/A/SPo 19 June 2013

SVASEK HYDRAULICS

Schiehaven 13G
3024 EC Rotterdam
Nederland
T +31 - 10 - 467 13 61
F +31 - 10 - 467 45 59
E info@svasek.com
I www.svasek.com

Document title	Influence of the morphology of the Scheldt estuary mouth on the tidal propagation Long Term Vision Western Scheldt Estuary, Safety and Accessibility
Short document title	Scenarios Scheldt estuary mouth
Status	Final
Date	19 June 2013
Project name	Long Term Vision Western Scheldt Estuary, Safety and Accessibility
Project number	1630
Client	Dutch ministry of Public Works (Rijkswaterstaat) Flemish department of Mobility and Public Works
Reference	1630/U13179/A/SPo

Author Sanne Poortman

Checked by Gerard Dam

SUMMARY

The tidal range in the Western Scheldt has increased over the past decades. Since such an increase is not desirable for functions related to accessibility, safety and ecology, it is investigated which role the estuary mouth can potentially have in case of mitigating measures. Therefore, several exploratory scenarios have been investigated by means of the numerical flow model FINEL2D, in which the influences of several morphological units of the ebb tidal delta are considered. These morphological units are: the Wielingen channel, the Vlakte van de Raan and the Oostgat channel.

The functioning of the tide in the estuary mouth can be described as follows: the channel the Wielingen, which is used as navigational channel, is mainly important for the inflow of the tide. Deepening of this channel will lead to a higher tidal range in the Scheldt estuary, whereas a shallower channel will lead to a lower tidal range. The Oostgat channel functions the other way around, and is mainly important for the outflow of the tidal wave. Deepening of this channel leads to a lower tidal range. The Vlakte van de Raan functions similar to the Oostgat channel: a deepening results in a lower tidal range.

The model computations have shown that the interventions in the mouth of the Scheldt estuary have to be considerably large in order to achieve a significant effect on the tidal range. The influence on the tide is limited for all applied interventions with respect to the amount of sediment to be removed/deposited.

TABLE OF CONTENTS

1 INTRODUCTION

The tidal range in the Scheldt estuary has increased over the past decades. Since such an increase is not desirable, it is investigated which role the estuary mouth can potentially play in case of mitigating measures. Therefore, several exploratory scenarios have been investigated by means of the numerical flow model FINEL2D, in which the influence of the several units of the estuary mouth is considered. These morphological units are: the Wielingen channel, the Vlakte van de Raan and the Oostgat channel.

This report discusses the set up and the results of the model computations. The morphological development itself is not taken into account.

Note that the scenarios that are simulated in this report are merely simulated to get insight in how the mouth is contributing to the tidal propagation in the Scheldt estuary.

2 MODEL SETTINGS AND SCENARIOS

In order to investigate the effect of the morphological units in the mouth of the Scheldt estuary on the tidal range, several scenarios are hydrodynamically simulated. The existing FINEL2D Western Scheldt model (Consortium Deltares-IMDC-Svasek-Arcadis, 2013) is used for the simulations. The model domain and model bathymetry are shown in Figure 2.1. The model boundary is located significantly far from the Scheldt estuary mouth, by which the boundary conditions are not influenced by the interventions. Figure 2.2 shows the main tidal stations that are used in this study.

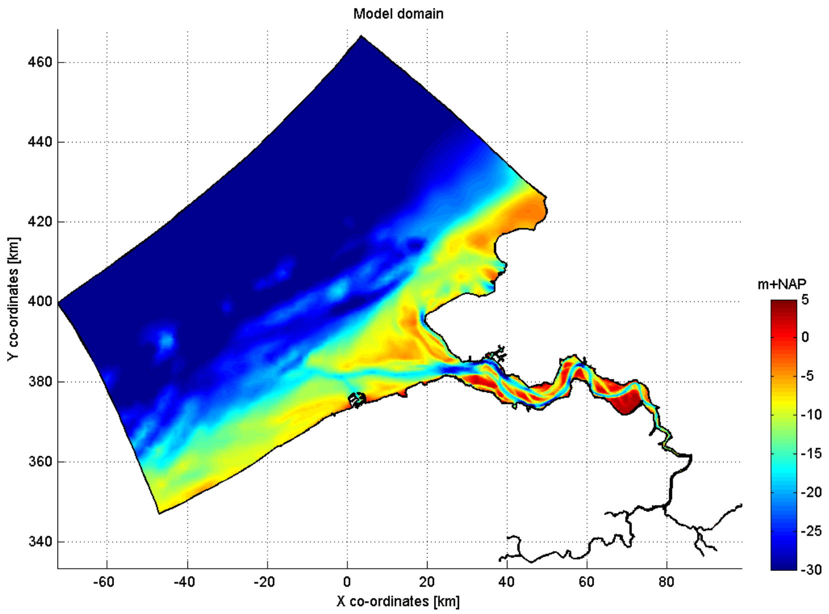

Figure 2.1: Model bathymetry and model domain of the FINEL2D Western Scheldt model.

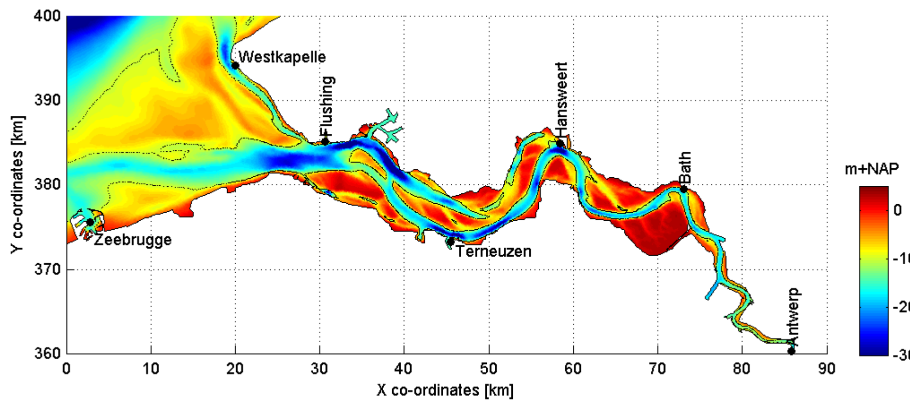

Figure 2.2: Main tide gauge stations in the Western Scheldt.

The basic bathymetry applied in this research consists mainly of a 20x20 m^2 GIS bathymetry of the Western Scheldt, dating from 2011 (Rijkswaterstaat Zeeland), complemented with a bathymetry of the Sea Scheldt, dating from 2010. The model bathymetry in the estuary mouth is shown in Figure 2.3. The NAP -10 m contour line is included in the figure.

A total of 21 scenarios are simulated, see Table 2.1. In the first scenario, scenario T0, the present day situation is calculated by which the recent observed bathymetry is applied. This scenario serves as reference for the results of the remaining scenarios. For each of the scenarios, five spring-neap cycles are simulated, starting at January 1st 2011.

In a first set of nine scenarios (T1a-c, T2a-c, T3a-c), adjustments are made to the model bathymetry in the Oostgat, the Vlakte van de Raan or the Wielingen, see Figure 2.3. The Wielingen is the main navigational channel. The Oostgat channel is a channel close to the coastline, while the Vlakte van de Raan is a shallow area between these two channels. For each of these morphological units separately, the depth is decreased by 1 m (Scenario T2a), 3 m (T2b) and 10 m (T2c) at the Vlakte van de Raan or increased by 1 m, 3 m and 10 m (Oostgat (T1a..T1c) and Wielingen (T3a..T3c)).

In the next scenario (T4) the bed level of the Oostgat is defined at NAP (Dutch Ordnance Level, which is approximately Mean Sea Level) and in another scenario the depth of the deep part of the Wielingen is decreased to NAP -17 m (T5), which equals the depth in the navigational channel. Beside these large scale scenarios, there are two scenarios defined in which the Wielingen channel is locally blocked by a shoal. The height of the shoal is NAP -10 m (T6a) and NAP -5 m (T6b) respectively.

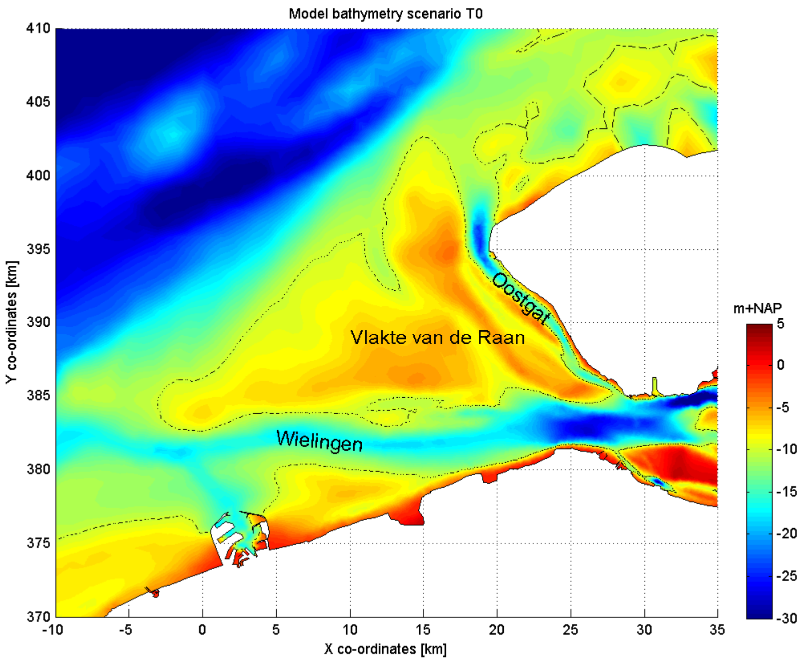

Figure 2.3: Model bathymetry of the estuary mouth of the Western Scheldt in 2011. The NAP -10 m contour line is indicated in the figure.

In the last seven scenarios (T7a-b, T8a-e) the interventions are applied to all three units. Only two depths are applied: NAP -18 m and NAP -2 m. In the first scenario (T7a) all three units are defined at NAP -18 m. In the next scenario (T7b), both the Vlakte van de Raan and the Oostgat are defined at NAP -18 m, while the Wielingen is defined at NAP -2 m.

In the three following scenarios the entire estuary mouth is defined at NAP -2 m, except for a navigational channel of 500 m wide, located at respectively the Oostgat (T8a), the Vlakte van de Raan (T8b) and the Wielingen (T8c). Besides these scenarios, there is a scenario with two navigational channels, located at the Oostgat and the Wielingen (T8d), and a scenario with a navigational channel of 2000 m wide, located at the Vlakte van de Raan (T8e).

The adjustments with respect to the basic model bathymetry are indicated in Table 2.1 for each of the scenarios. The bathymetry of the scenarios is shown in the next sections, where the outcomes of the specific scenarios are discussed.

Table 2.1: Scenario definition: Bed level adjustments with respect to the basic model bathymetry for the different scenarios. 'Small' indicates a channel of 500 m wide. 'Wide' indicates a channel of 2000 m wide.

Scenario	Unit	Bed level adjustment	Volume
T0	N.a.	N.a.	0 Mm^3
T1a	Oostgat	-1 m	-48 Mm^3
T1b	Oostgat	-3 m	-145 Mm^3
T1c	Oostgat	-10 m	-484 Mm^3
T2a	Vlakte van de Raan	+1 m	277 Mm^3
T2b	Vlakte van de Raan	+3 m	833 Mm^3
T2c	Vlakte van de Raan	+10 m	2775 Mm^3
T3a	Wielingen	-1 m	-79 Mm^3
T3b	Wielingen	-3 m	-239 Mm^3
T3c	Wielingen	-10 m	-802 Mm^3
T4	Oostgat	Filled to NAP	648 Mm^3
T5	Wielingen	Filled to NAP -17m	51 Mm^3
T6a	Wielingen	Blocked to NAP -10m	31 Mm^3
T6b	Wielingen	Blocked to NAP -5m	116 Mm^3
T7a	Entire estuary mouth	Deepened to NAP -18m	-4881 Mm^3
T7b	Entire estuary mouth	Estuary mouth NAP -18m, Wielingen NAP -2m	-1932 Mm^3
T8a	Oostgat	Estuary mouth NAP -2m, Oostgat 'small' NAP -18m	1924 Mm^3
T8b	Vlakte van de Raan	Estuary mouth NAP -2m, Vlakte van de Raan 'small' NAP -18m	1884 Mm^3
T8c	Wielingen	Estuary mouth NAP -2m, Wielingen 'small' NAP -18m	1862 Mm^3
T8d	Oostgat and Wielingen	Estuary mouth NAP -2m, Wielingen and Oostgat 'small' NAP -18m	1666 Mm^3
T8e	Vlakte van de Raan	Monding NAP -2m, Vlakte van de Raan 'wide' NAP -18m	1361 Mm^3

3 RESULTS SCENARIO T1

In scenario T1 the Oostgat is deepened. In scenario T1a the depth increases with 1 m (Figure 3.2), in scenario T1b with 3 m (Figure 3.3) and in scenario T1c with 10 m (Figure 3.4). An overview of the scenarios is given in Table 3.1.

Table 3.1: Adjustments with respect to the basic model bathymetry for the different scenarios.

Scenario	Unit	Bed level adjustment	Volume
T0	N.a.	N.a.	0 Mm^3
T1a	Oostgat	-1 m	-48 Mm^3
T1b	Oostgat	-3 m	-145 Mm^3
T1c	Oostgat	-10 m	-484 Mm^3

The mean tidal range is defined as the average difference between the high and low waters over the simulated period of five spring-neap cycles. The mean tidal range at the locations of the main tidal stations in the Western Scheldt is indicated in Figure 3.5. The locations of the tidal stations are indicated in Figure 2.2. The difference in tidal range with respect to scenario T0 is shown as well. The differences between scenario T1a, T1b, and T1c and scenario T0 are small, however for all three the scenarios a reduction of the tidal range in visible in the entire estuary. The largest reduction is visible in scenario T1c, where the intervention in the morphology of the estuary mouth is largest. The reduction is largest at Westkapelle, which is located in the Oostgat. The depth of the water level station coincides with the intervention and therefore the water levels are highly influenced. The smallest reduction can be found at Zeebrugge, which is located near the Wielingen. From Flushing and further east the difference in tidal range is approximately equal, and amounts approximately 0.5 cm for scenario T1a, 1 cm for scenario T1b and 3.5 cm for scenario T1c.

The mean phase difference in the propagation of the tide in minutes with respect to scenario T0 at Flushing is presented in Figure 3.6, as well as the difference with respect to scenario T0. In all three the scenarios, the deepening of the Oostgat results in an acceleration of the propagation of the tide. This acceleration is induced in the estuary mouth of the Western Scheldt. In the Western Scheldt itself, the difference with respect to scenario T0 is equal along the different tidal stations. The phase differences are small however, and are less than a minute for scenario T1a, approximately a minute for scenario T1b, and about three minutes for scenario T1c.

Figure 3.7 and Figure 3.8 shows the discharge through several sections in the estuary mouth. The figures show that the discharge though the Oostgat increases for all three the scenarios, at the expense of the discharge through the Wielingen and the Vlakte van de Raan. The larger the intervention in the Oostgat, the more the discharge increases in the Oostgat. The function of the Oostgat becomes more important with respect to the function of the two other morphological units when the Oostgat is deepened. The total discharge in the estuary mouth of the estuary is slightly decreased.

The redistribution of the discharge in the estuary mouth of the Western Scheldt has consequences for the flow velocities in the area. The difference in flow velocity of scenario T1a, T1b and T1c with respect to scenario T0 is presented in Figure 3.9, Figure 3.10 and Figure 3.11. It should be noted that the velocity is compared at the same moment in time, by which the comparison is not exact if phase differences occur. The phase difference is however only a few minutes, by which the influence of the difference in phase is very limited.

Figure 3.9 hardly shows any difference in flow velocity between scenario T1a and scenario T0. Scenario T1b and scenario T1c show larger differences, see Figure 3.10 and Figure 3.11. The flow velocity in the Oostgat has increased, where both the cross-sectional area and the discharge have increased. At Westkapelle, time series of the flow velocity are available, which shows the increases in velocity as well (not shown here). At the Wielingen channel and the Vlakte van de Raan, the flow velocity decreases, which corresponds with the decrease of the discharge. The effects of the intervention on the flow velocity increase as the intervention is larger.

Since the tidal range is decreased when the Oostgat is deepened, and the discharge of the Western Scheldt estuary mouth is somewhat decreased, it can be concluded that the Oostgat is mainly important for the outflow of the tide. The Wielingen on the other hand is important for the inflow of the tide (See Chapter 5). The propagation of the tide in the Western Scheldt can therefore be schematised as shown in Figure 3.1.

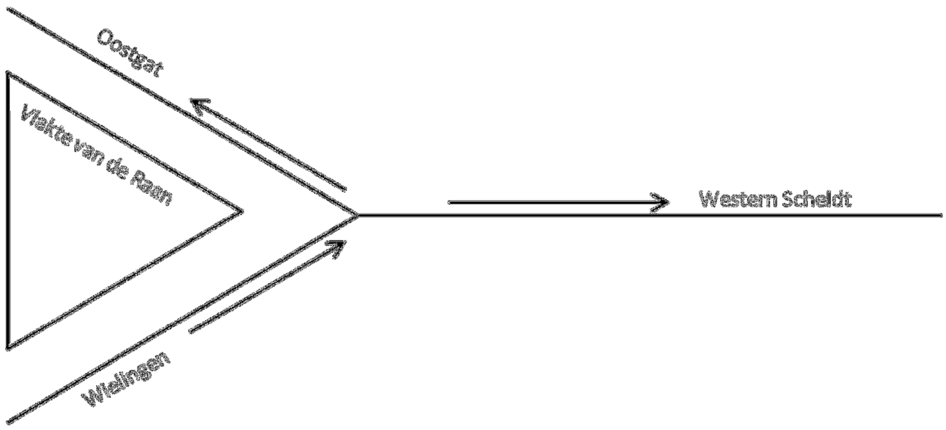

Figure 3.1: Schematisation of the propagation of the tide in the Western Scheldt.

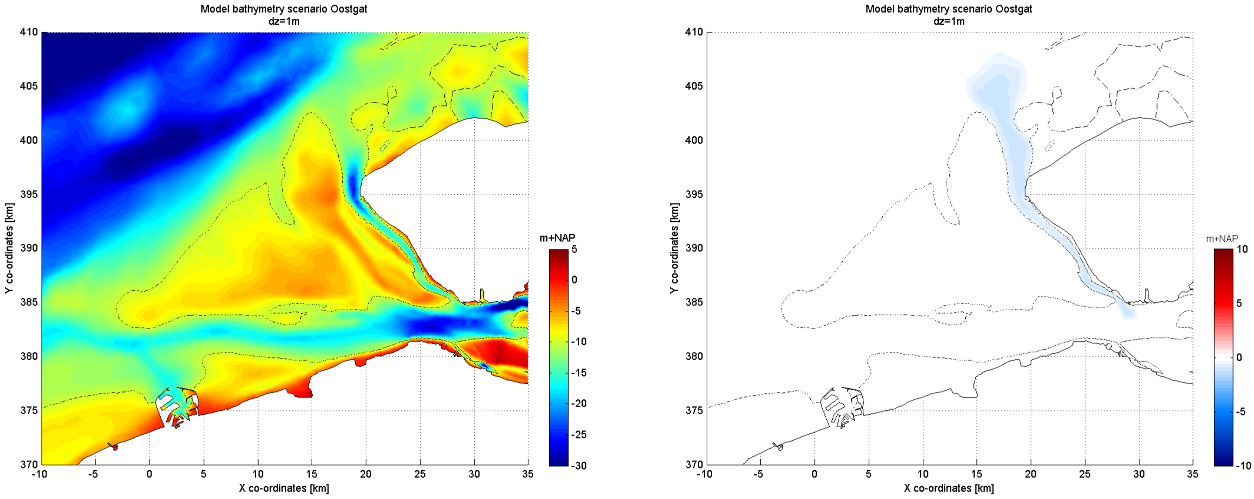

Figure 3.2: Model bathymetry for scenario T1a, and the difference with respect to scenario T0.

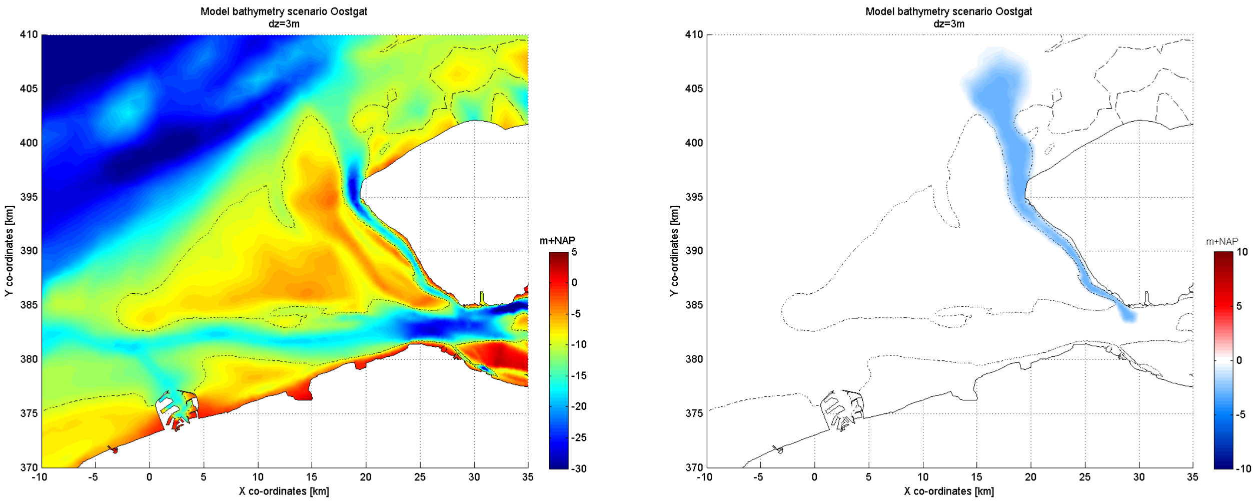

Figure 3.3: Model bathymetry for scenario T1b, and the difference with respect to scenario T0.

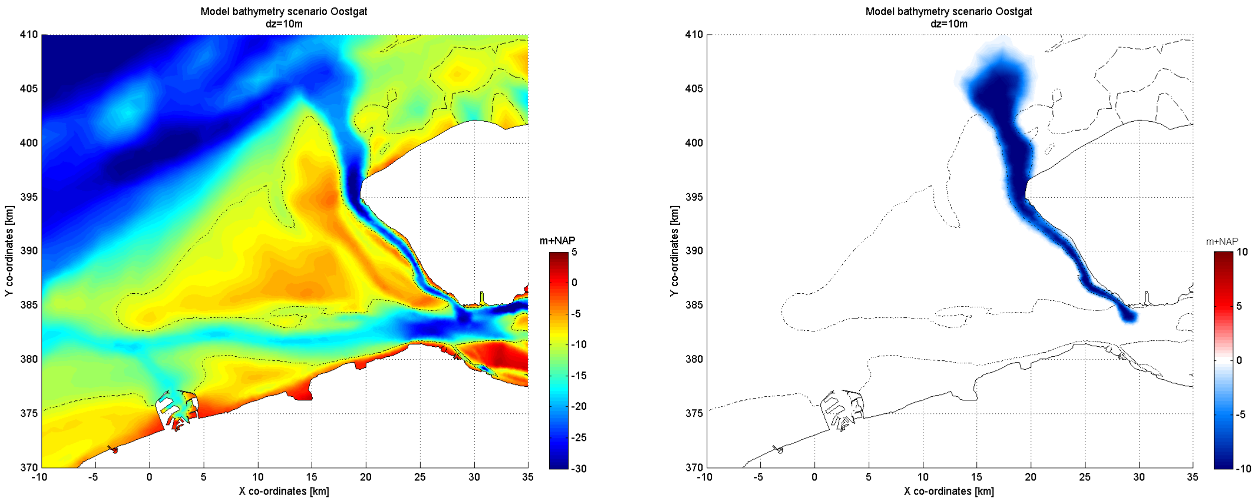

Figure 3.4: Model bathymetry for scenario T1c, and the difference with respect to scenario T0.

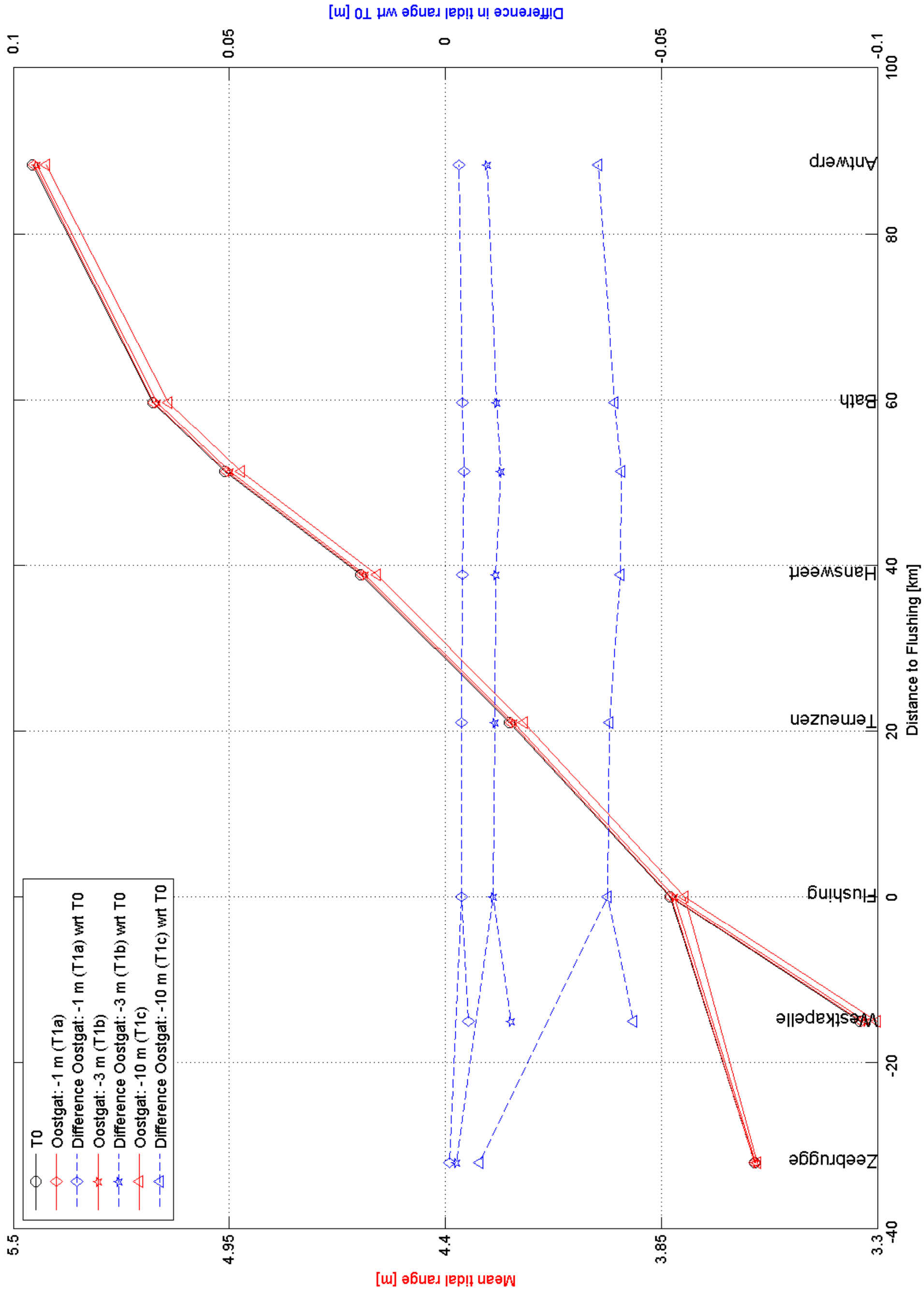

Figure 3.5: Tidal range for scenario T1 along the main tide stations in the Western Scheldt. Scenario T0 and the difference of scenario T1 with respect to scenario T0 are included in the figure as well.

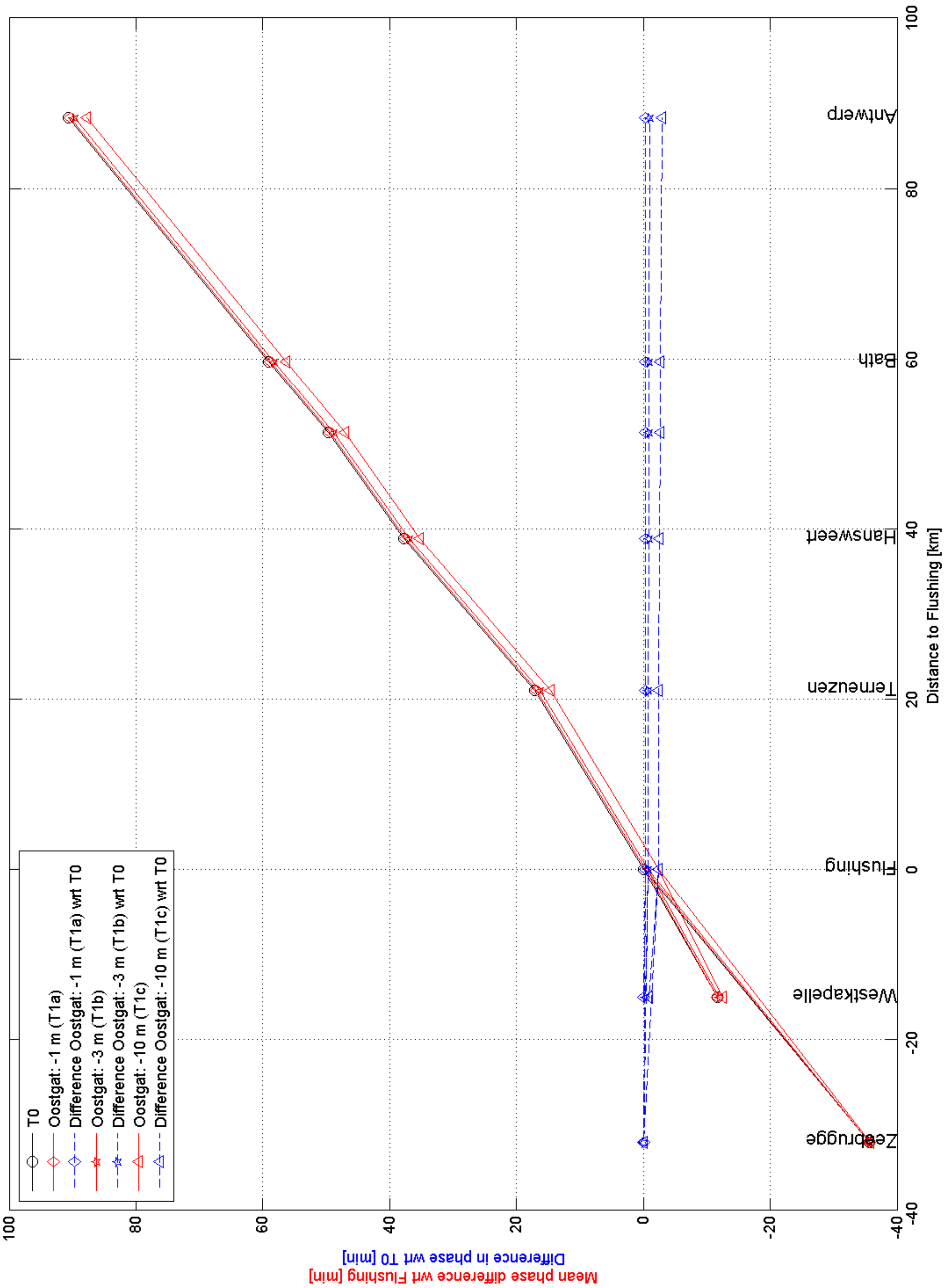

Figure 3.6: Phase difference with respect to T0 at Flushing for scenario T1 along the main tide stations in the Western Scheldt in minutes. Scenario T0 and the difference of scenario T1 with respect to scenario T0 are included in the figure as well.

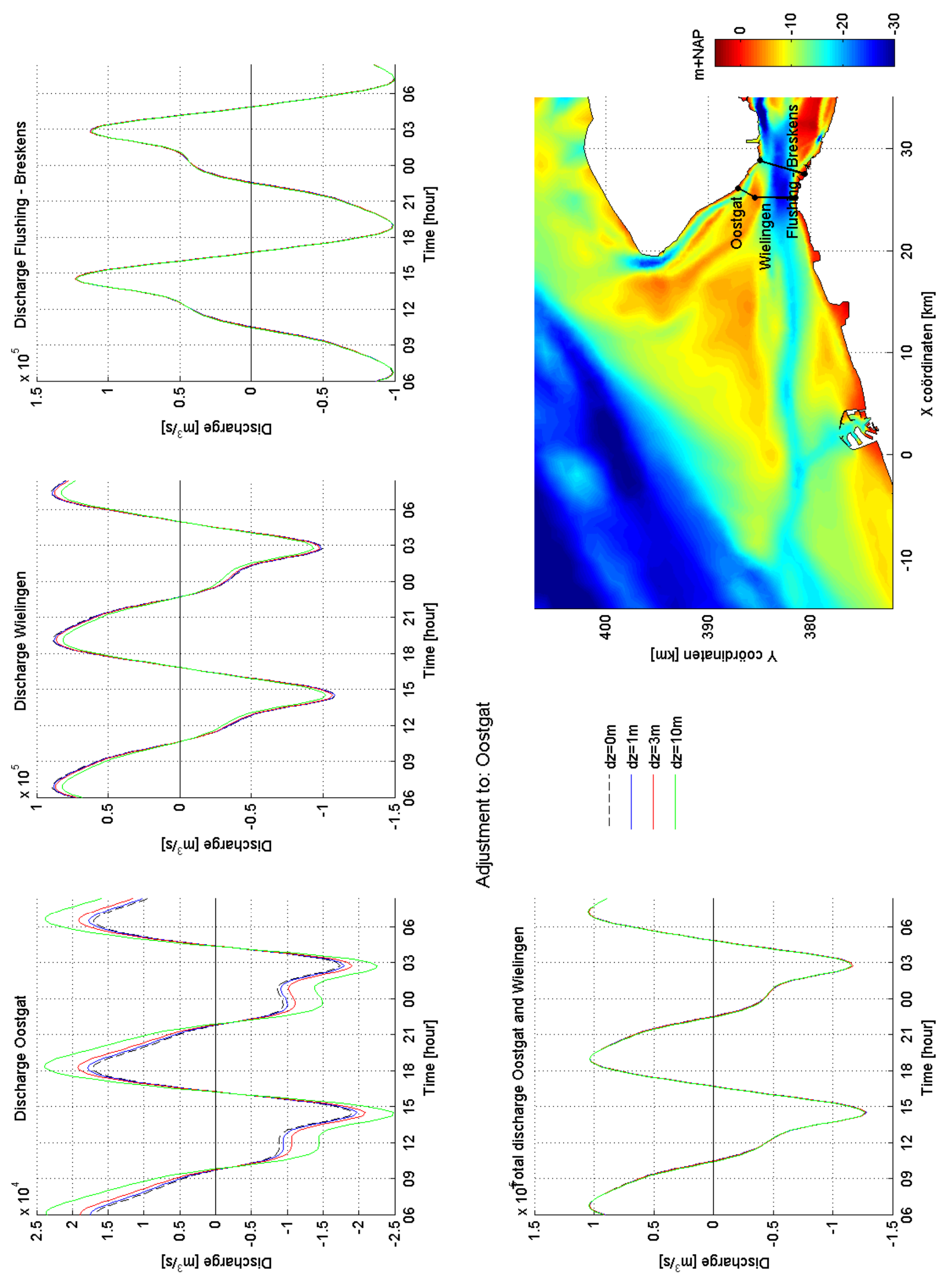

Figure 3.7: Discharge distribution in the Western Scheldt for scenario T0 (dz=0 m) and T1 (dz=1 m, dz=3 m, dz=10 m).

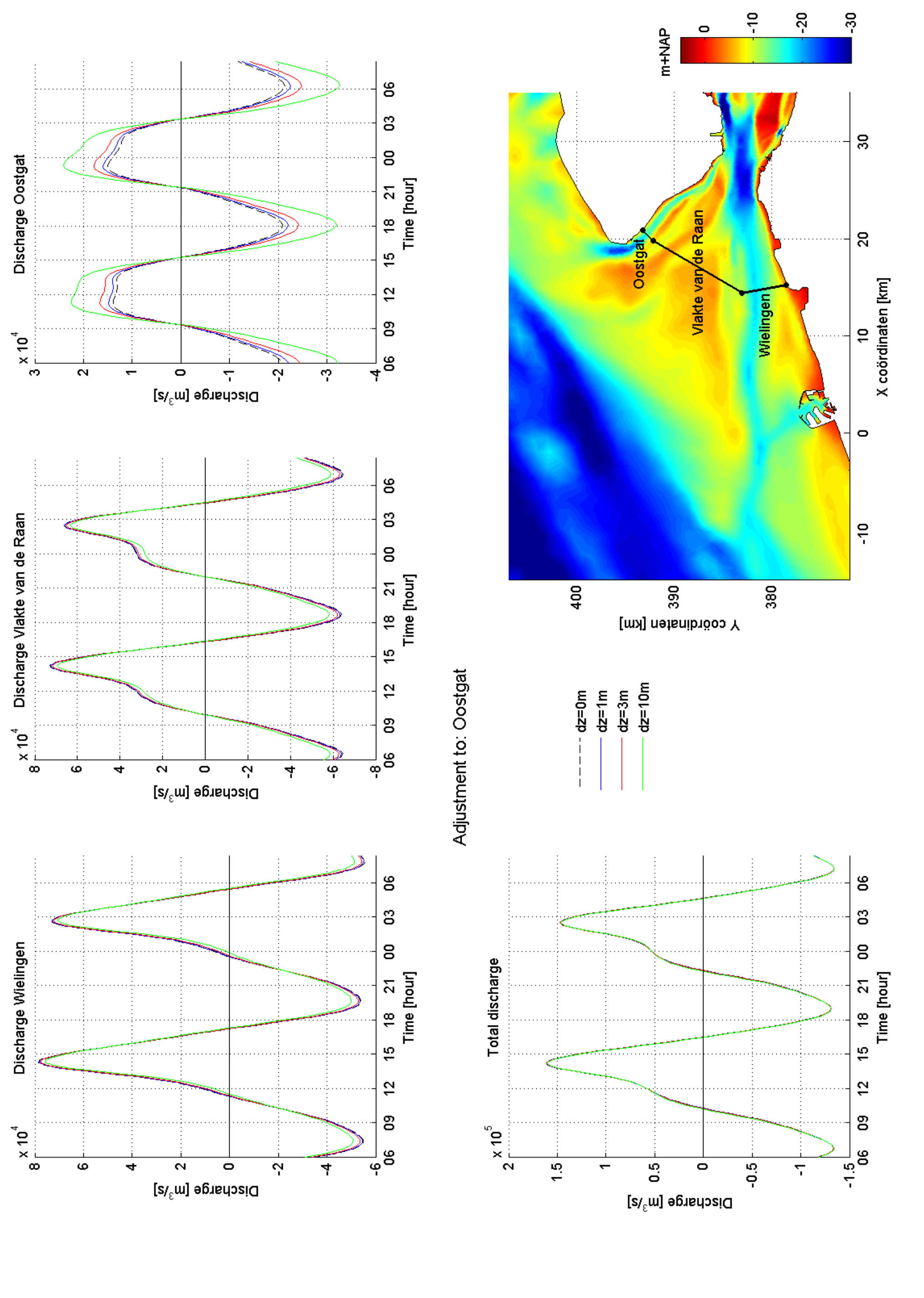

Figure 3.8: Discharge distribution in the estuary mouth of the Western Scheldt for scenario T0 (dz=0 m) and T1 (dz=1 m, dz=3 m, dz=10 m).

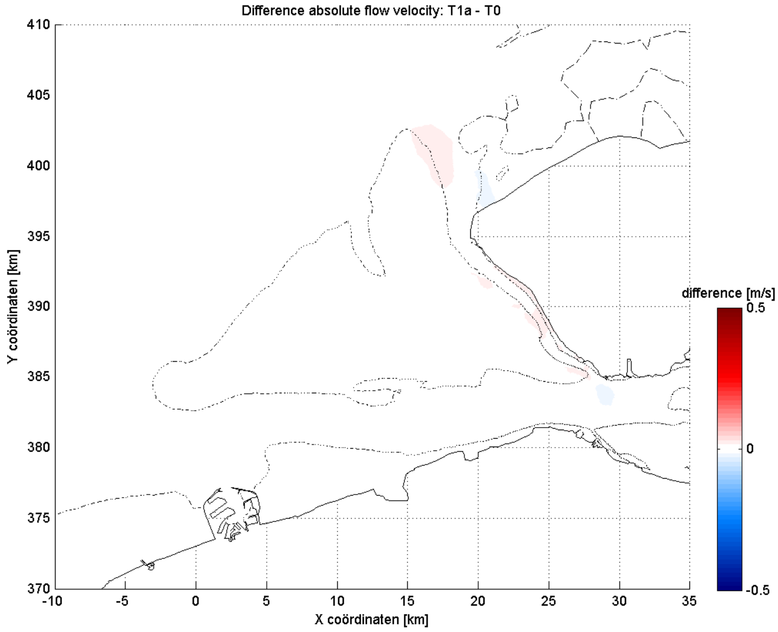

Figure 3.9: Difference in flow velocity between scenario T0 and scenario T1a around maximum flood flow. Red indicates where the flow velocity of scenario T1a is higher than in scenario T0; blue indicates where the flow velocity is lower.

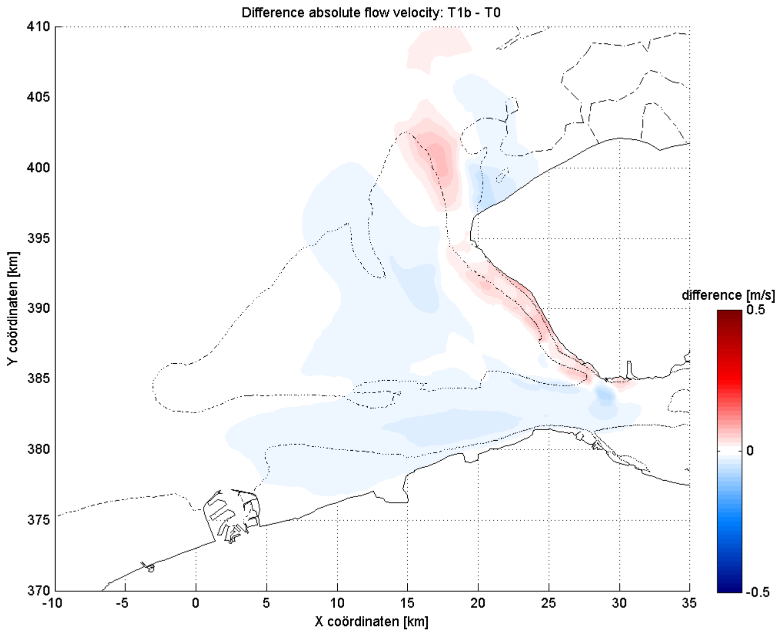

Figure 3.10: Difference in flow velocity between scenario T0 and scenario T1b around maximum flood flow. Red indicates where the flow velocity of scenario T1b is higher than in scenario T0; blue indicates where the flow velocity is lower.

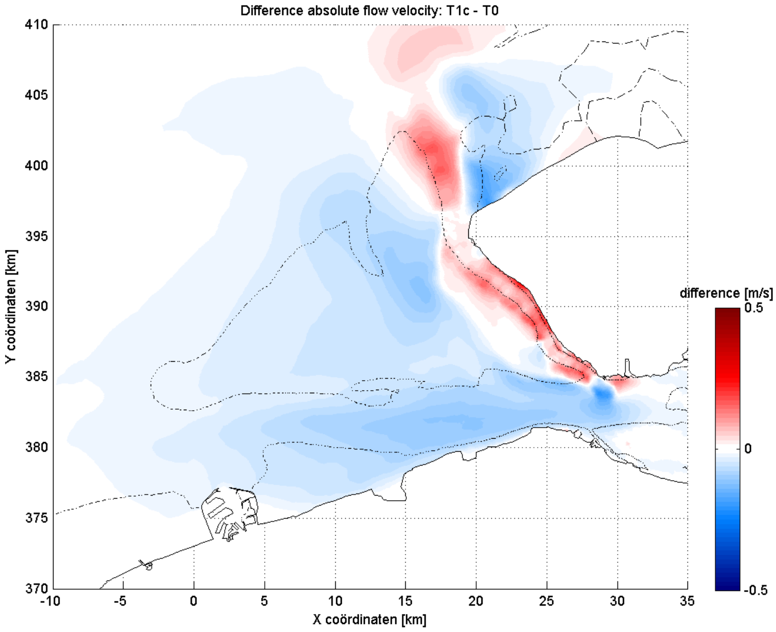

Figure 3.11: Difference in flow velocity between scenario T0 and scenario T1c around maximum flood flow. Red indicates where the flow velocity of scenario T1c is higher than in scenario T0; blue indicates where the flow velocity is lower.

4 RESULTS SCENARIO T2

In scenario T2 the depth of the Vlakte van de Raan is decreased. In scenario T2a this is defined by 1 m (Figure 4.1), in scenario T2b by 3 m (Figure 4.2) and in scenario T2c by 10 m (Figure 4.3). An overview of the scenarios is given in Table 4.1.

Table 4.1: Adjustments with respect to the basic model bathymetry for the different scenarios.

Scenario	Area	Bed level adjustment	Volume
T0	N.a.	N.a.	0 Mm^3
T2a	Vlakte van de Raan	+1 m	277 Mm^3
T2b	Vlakte van de Raan	+3 m	833 Mm^3
T2c	Vlakte van de Raan	+10 m	2775 Mm^3

Figure 4.4 shows the tidal range of the main tide gauge stations in the Western Scheldt for scenario T0, T2a, T2b en T2c. The difference in tidal range with respect to scenario T0 is also included in the figure. The figure shows that heightening the Vlakte van de Raan results in an increase of the tidal range, except at Westkapelle (Oostgat), which shows a distinct decrease of the tidal range. Probably the Oostgat is somewhat 'squeezed' as a consequence of the adjustment at the Vlakte van de Raan, as can be seen in Figure 4.1, Figure 4.2 and Figure 4.3 and the reduction of the discharge through the Oostgat channel (Figure 4.6 and Figure 4.7).

In both scenario T2a and T2b the increase in tidal range is rather constant throughout the Western Scheldt, and amounts 1 cm respectively 2 cm. In scenario T2c the effect on the tidal range varies, from a maximum increase of 9 cm at Hansweert to no effect at Antwerp. In this scenario the adjustment in the morphology is so large, that the shape of the tidal curve is strongly influenced. The reasoning that the difference in tidal range in the estuary mouth equals the difference in tidal range at Antwerp can therefore not be applied in this case.

Figure 4.5 presents the mean phase difference in the tidal propagation in minutes with respect to scenario T0 at Flushing. The phase difference between scenarios T2a, T2b, T2c and scenario T0 is shown in the figure as well. The heightening of the Vlakte van de Raan leads to a lag in propagation in the estuary mouth. The lag which originates in the estuary mouth remains approximately constant along the Western Scheldt. The lag amounts about 2 minutes, 6 minutes and 30 minutes for scenario T2a, T2b and T2c respectively.

The discharge at the Vlakte van de Raan, the Oostgat and the Wielingen, as well as the total discharge through the estuary mouth, are depicted in Figure 4.6 and Figure 4.7. Figure 4.7 shows that the discharge of the Vlakte van de Raan reduces as a result of the heightening of the sea bed. For scenario T2c, in which the Vlakte van de Raan is heightened by 10 m, this results in a discharge of almost 0. The discharge reduction at the Vlakte van de Raan is almost entirely compensated by an increase of the discharge at the Wielingen. The total discharge in the estuary mouth reduces as a result of the decreasing of the bed level of the Vlakte van de Raan.

Figure 4.8, Figure 4.9 and Figure 4.10 shows the difference in flow velocity. It should be noted that the velocity is compared at the same moment in time, by which the comparison is not exact because phase differences occur up to 30 minutes.

In both scenario T2a, T2b and T2c an increase of the flow velocity at the Wielingen channel is visible. The reason why the flow velocity is increased is that the discharge in the Wielingen has increased, while the cross-sectional area remains constant. The increase of the flow velocity in the Wielingen becomes larger when the depth of the Vlakte van de Raan is decreases more.

At the Vlakte van de Raan both an increase (Figure 4.8, scenario T2a, and Figure 4.9, scenario T2b) as well as a decrease (Figure 4.10, scenario T2c) of the flow velocity is visible. In the time series (not shown here) at the Vlakte van de Raan the increase (scenario T2a and T2b) and the decrease (scenario T2c) of the flow velocity is visible as well.

At the Oostgat an increase of the flow velocity is visible for all three scenarios in Figure 4.8, Figure 4.9 and Figure 4.10. The time series at Westkapelle, show that the increase in flow velocity is mainly due to the phase difference between the scenarios T2a..T2c and scenario T0 (time series not shown). In reality, the flow velocity in the Oostgat decreases.

From the preceding it is concluded that the Vlakte van de Raan, like the Oostgat, is mainly important to the outflow of the tide, see Figure 3.1. By heightening the bed level of the Vlakte van de Raan this outflow has become more difficult, which results in an increase of the tidal range. Deepening the Vlakte van de Raan on the other hand, could lead to a reduction of the tidal range.

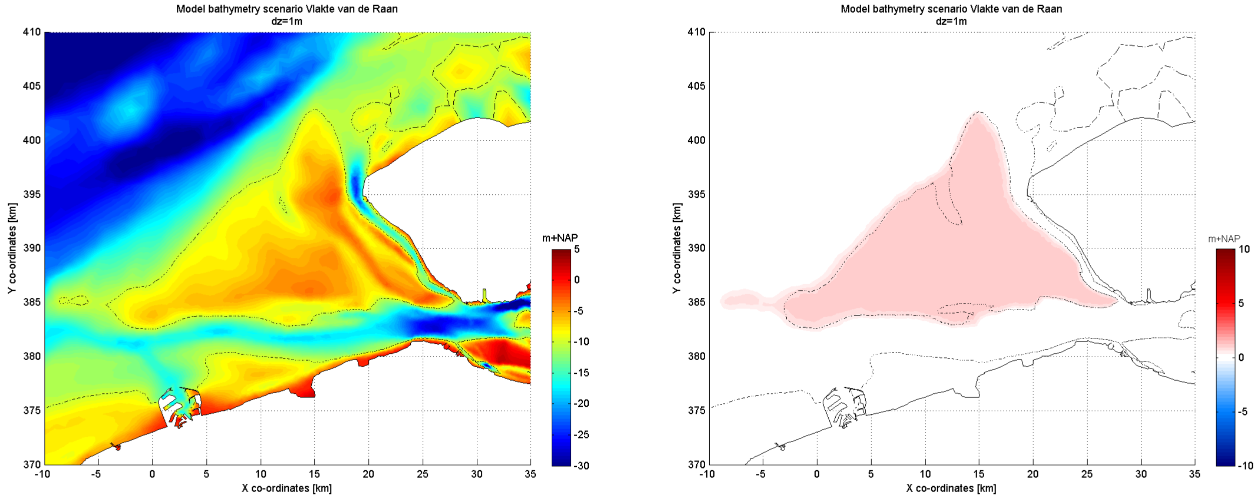

Figure 4.1: Model bathymetry for scenario T2a, and the difference with respect to scenario T0.

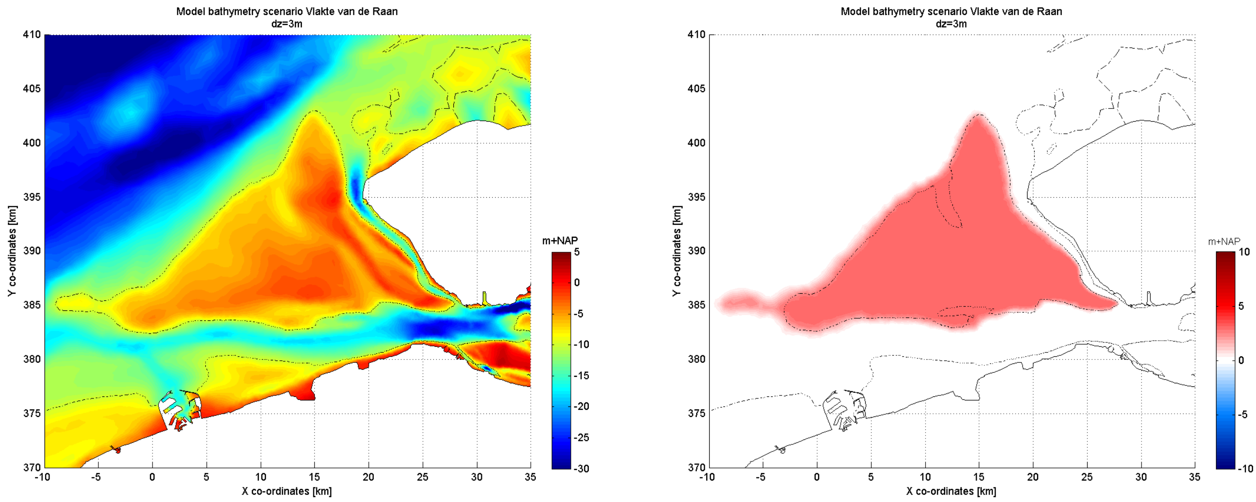

Figure 4.2: Model bathymetry for scenario T2b, and the difference with respect to scenario T0.

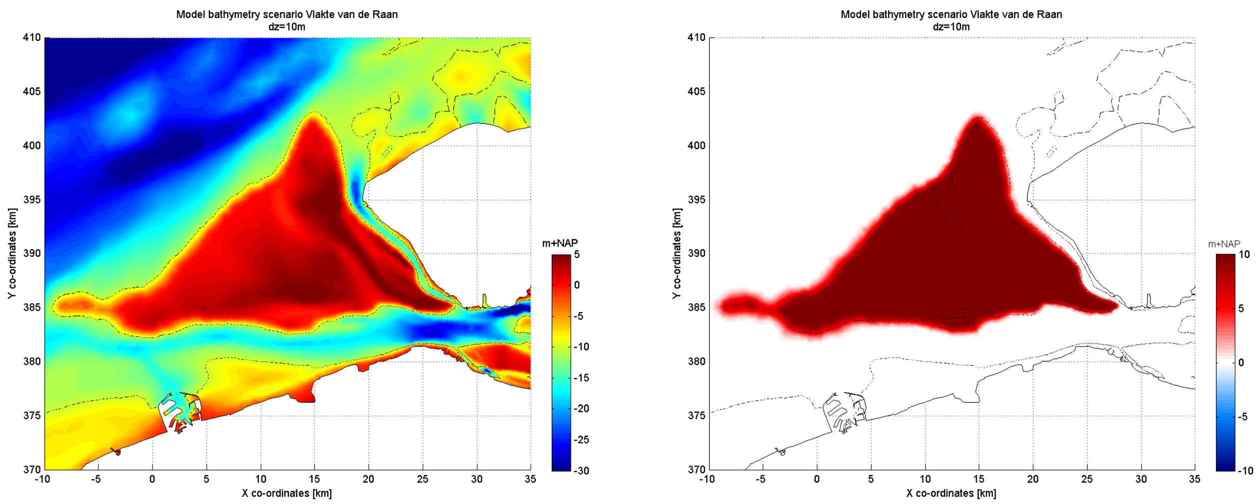

Figure 4.3: Model bathymetry for scenario T2c, and the difference with respect to scenario T0.

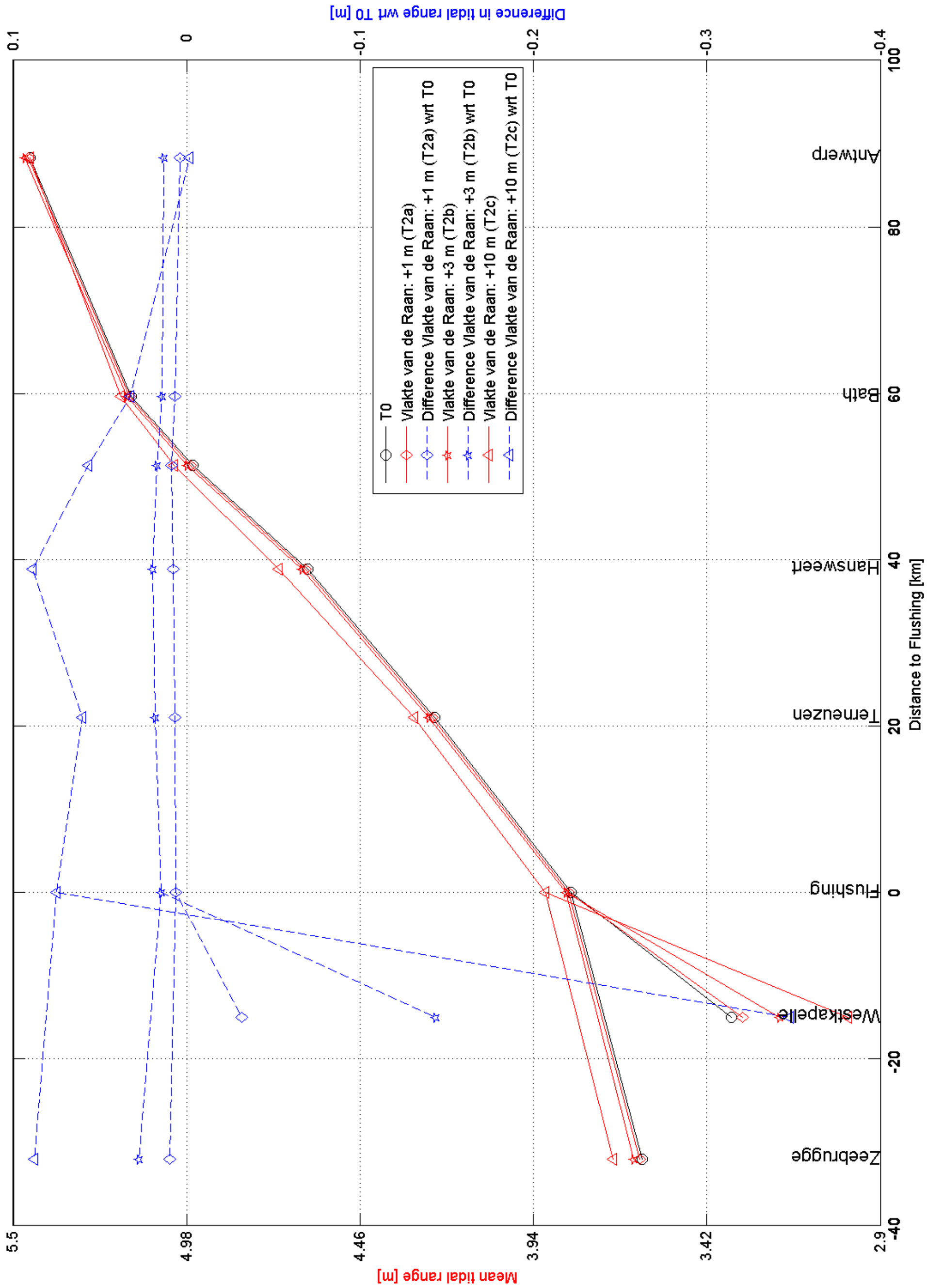

Figure 4.4: Tidal range for scenario T2 along the main tide stations in the Western Scheldt. Scenario T0 and the difference of scenario T2 with respect to scenario T0 are included in the figure as well.

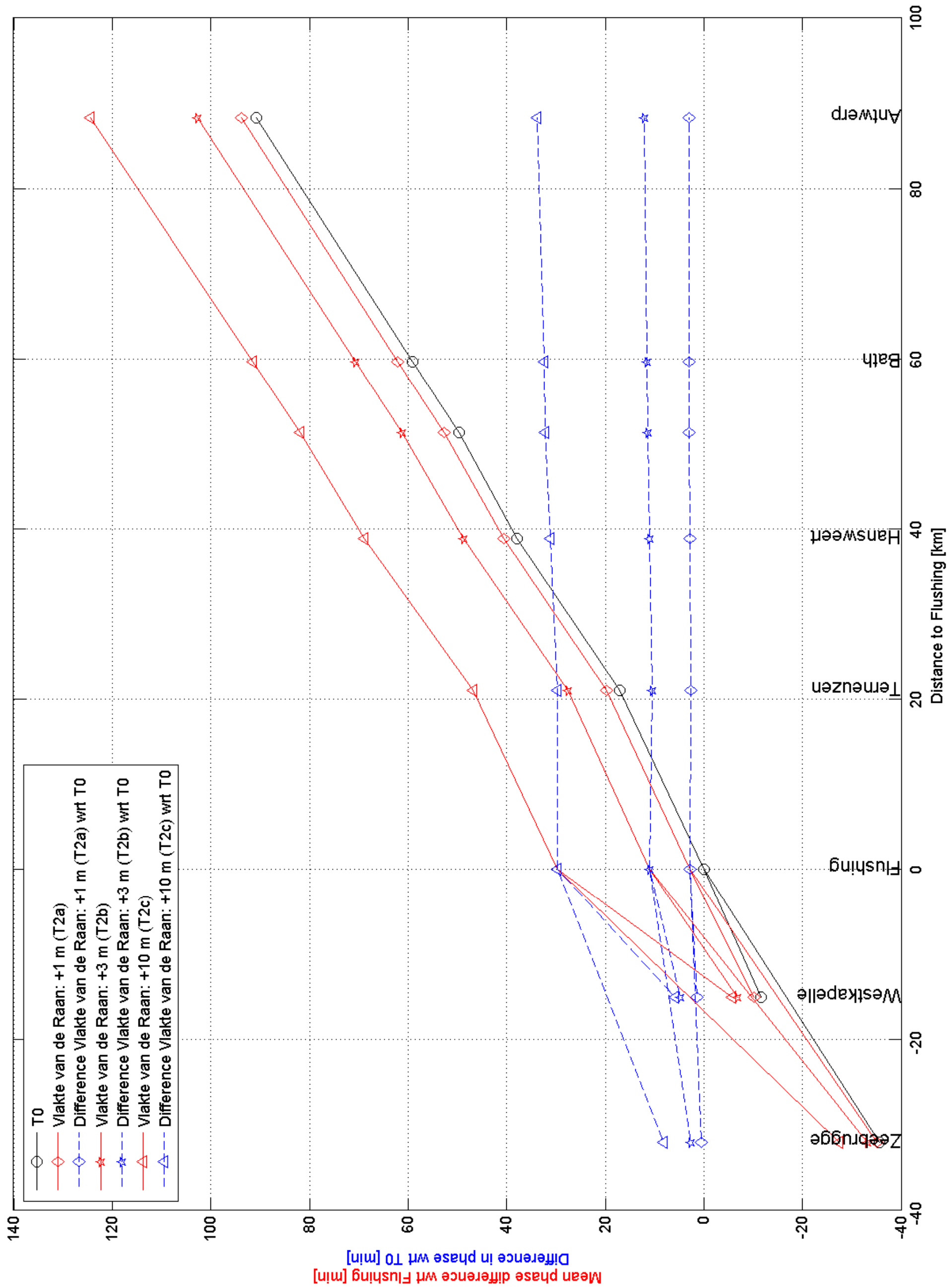

Figure 4.5: Phase difference with respect to T0 at Flushing for scenario T2 along the main tide stations in the Western Scheldt in minutes. Scenario T0 and the difference of scenario T2 with respect to scenario T0 are included in the figure as well.

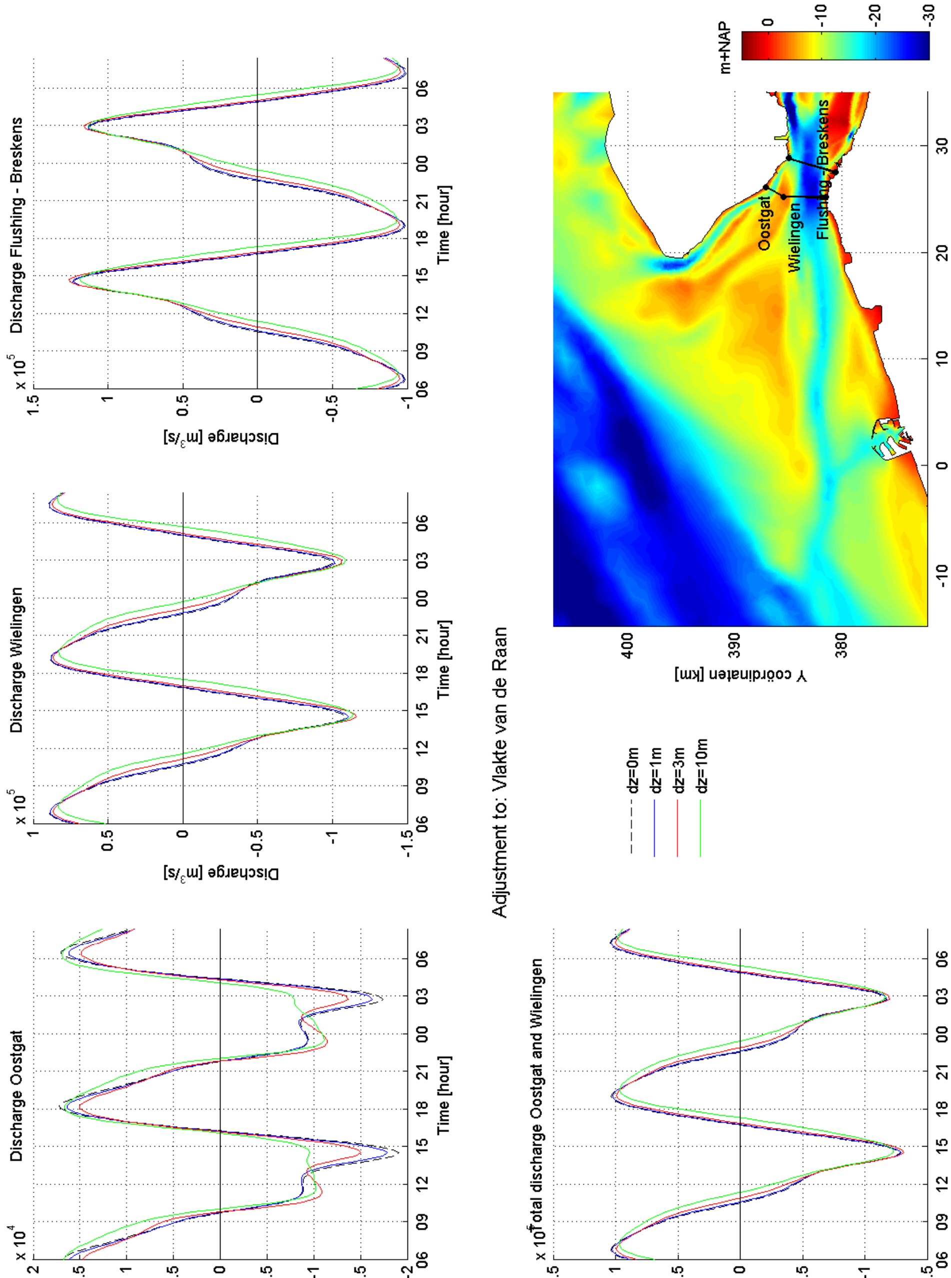

Figure 4.6: Discharge distribution in the Western Scheldt for scenario T0 (dz=0 m) and T2 (dz=1 m, dz=3 m, dz=10 m).

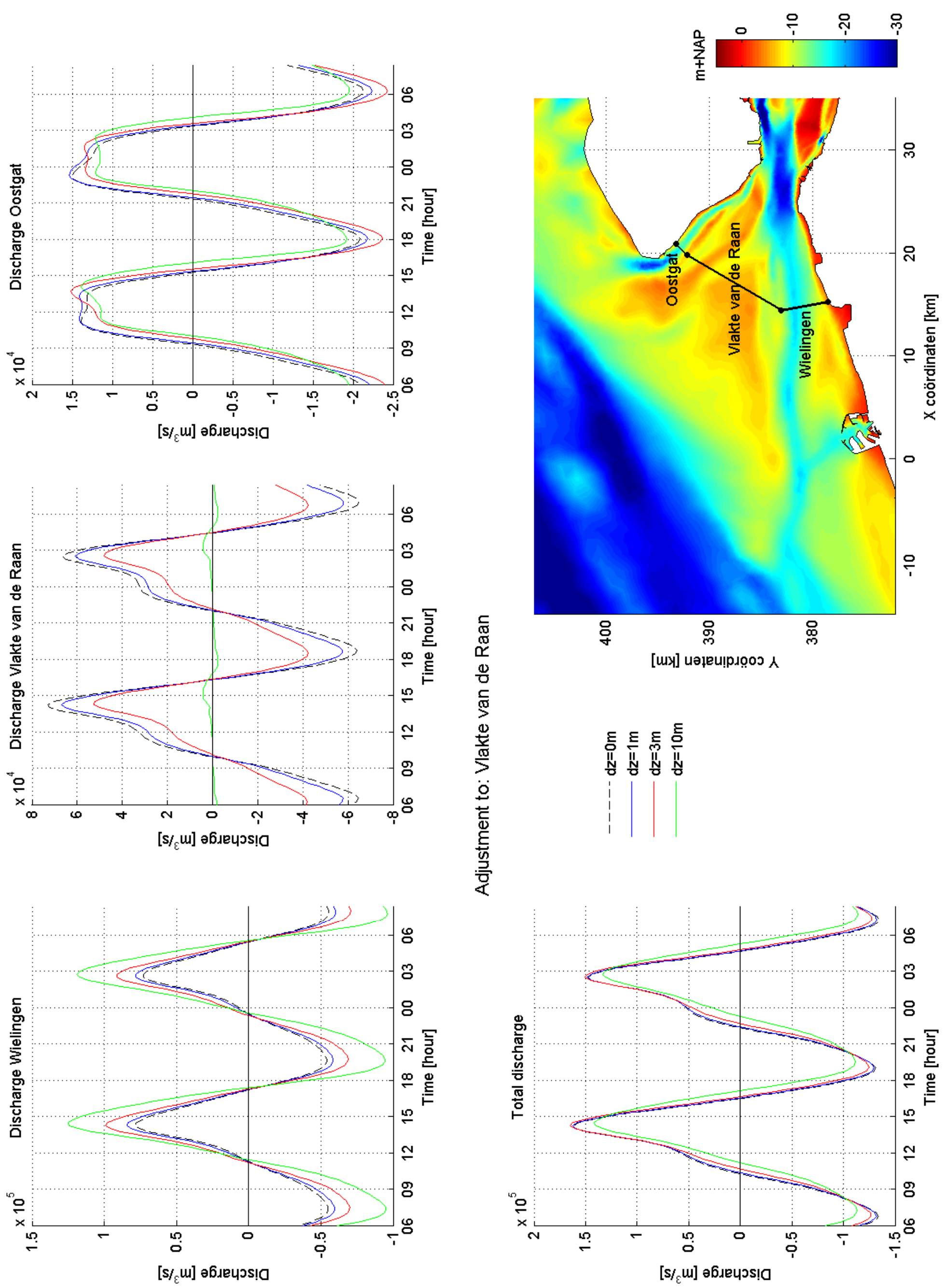

Figure 4.7: Discharge distribution in the estuary mouth of the Western Scheldt for scenario T0 (dz=0 m) and T2 (dz=1 m, dz=3 m, dz=10 m).

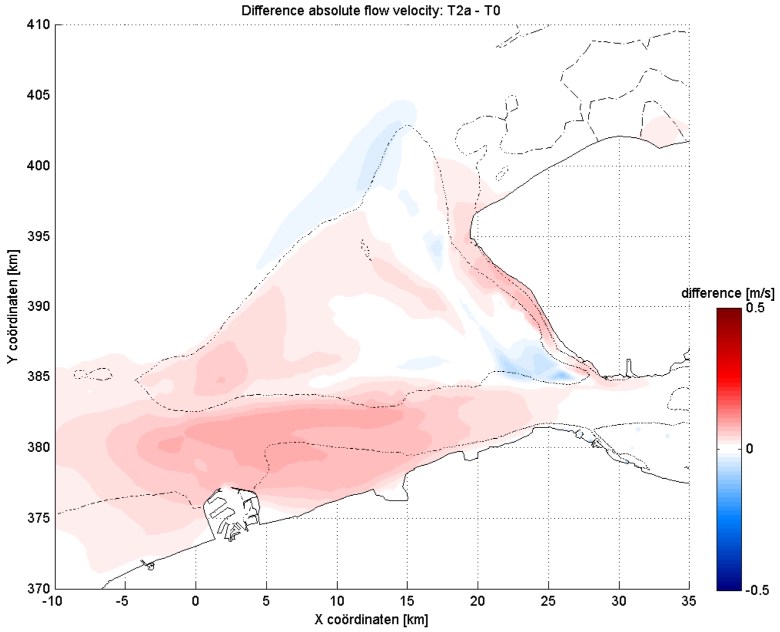

Figure 4.8: Difference in flow velocity between scenario T0 and scenario T2a around maximum flood flow. Red indicates where the flow velocity of scenario T2a is higher than in scenario T0; blue indicates where the flow velocity is lower.

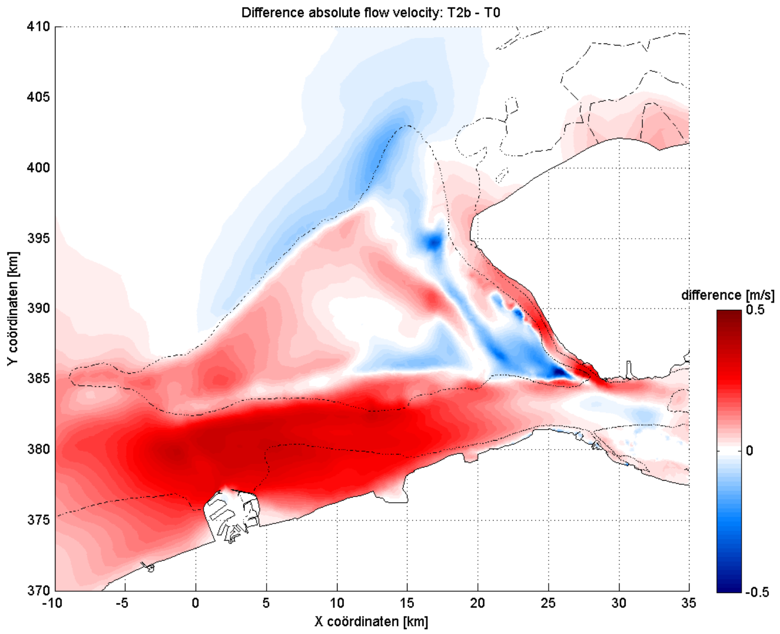

Figure 4.9: Difference in flow velocity between scenario T0 and scenario T2b around maximum flood flow. Red indicates where the flow velocity of scenario T2b is higher than in scenario T0; blue indicates where the flow velocity is lower.

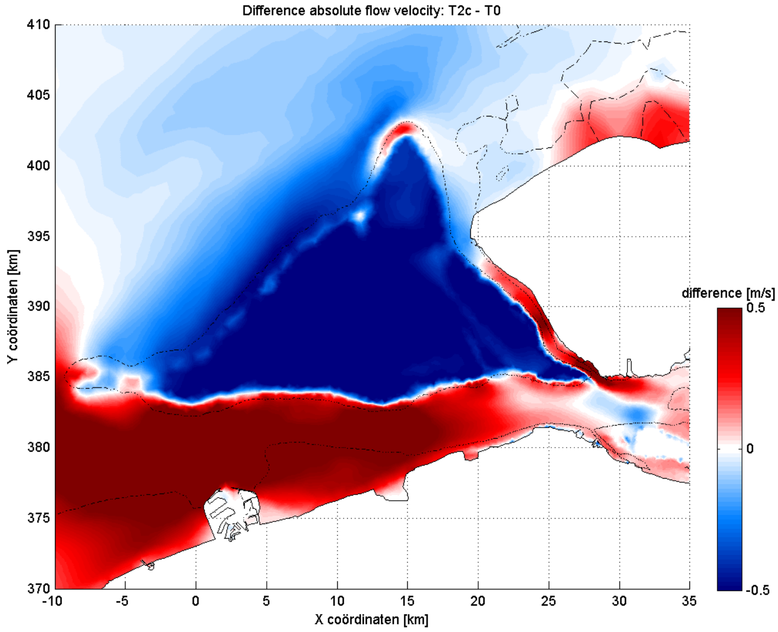

Figure 4.10: Difference in flow velocity between scenario T0 and scenario T2c around maximum flood flow. Red indicates where the flow velocity of scenario T2c is higher than in scenario T0; blue indicates where the flow velocity is lower.

5 RESULTS SCENARIO T3

In scenario T3 the Wielingen is deepened. For scenario T3a this is defined by an increase of the depth of 1 m (Figure 5.2), for scenario T3b this increase is 3 m (Figure 5.3) and for scenario T3c 10 m (Figure 5.4). The adjustments are summarised in Table 5.1.

Table 5.1: Adjustments with respect to the basic model bathymetry for the different scenarios.

Scenario	Area	Bed level adjustment	Volume
T0	N.a.	N.a.	0 Mm^3
T3a	Wielingen	-1 m	-79 Mm^3
T3b	Wielingen	-3 m	-239 Mm^3
T3c	Wielingen	-10 m	-802 Mm^3

Figure 5.5 shows the tidal range at the main tide gauge stations in the Western Scheldt for scenario T0, T3a, T3b and T3c. The difference in tidal range between scenarios T3a, T3b, T3c and scenario T0 is given in the figure as well. The three scenarios result in an increase of the tidal range in the Western Scheldt, which originates in the estuary mouth. At Zeebrugge, which is located close to the Wielingen channel, no difference in tidal range is present. In the Western Scheldt itself, the difference is constant. The increase of the tidal range in the Western Scheldt amounts approximately 1 cm, 2 cm and 4.5 cm for scenario T3a, T3b and T3c respectively.

In Figure 5.6 the average phase difference in the propagation of the tide with respect to scenario T0 at Flushing is presented, as well as the phase difference of scenarios T3a, T3b and T3c with respect to scenario T0. The deepening of the Wielingen leads to an acceleration of the tidal propagation for all three scenarios. The difference are small however, and amount approximately to 0.5 minute, 1 minute and 3 minutes. The phase difference originates in the estuary mouth and remains constant in the Western Scheldt itself.

Figure 5.7 and Figure 5.8 shows the tidal discharge of the Wielingen, Oostgat and the Vlakte van de Raan, as well as the total discharge of the estuary mouth. The discharge of the Wielingen channel increases, mainly at the expense of the discharge of the Vlakte van de Raan. The total discharge is slightly increased.

As a result of the adjustments to the morphology in the estuary mouth, the flow velocities are also affected. The difference in flow velocity between scenarios T3a, T3b and T3c with respect to scenario T0 is presented in Figure 5.9, Figure 5.10 and Figure 5.11. It should be noted that the velocity is compared at the same moment in time, by which the comparison is not exact. Time series of the flow velocity show that the differences in the figures are mainly caused by the phase differences (time series not shown here).

The deepening of the Wielingen results in an increase of the tidal range. Contrary to the Vlakte van de Raan and the Oostgat channel, the Wielingen is mainly important for the inflow of the tide. Decreasing the depth of the Wielingen could lead to a decrease of the tidal range. This is investigated further in the next chapters. The propagation of the tide in the Western Scheldt is schematised in Figure 5.1.

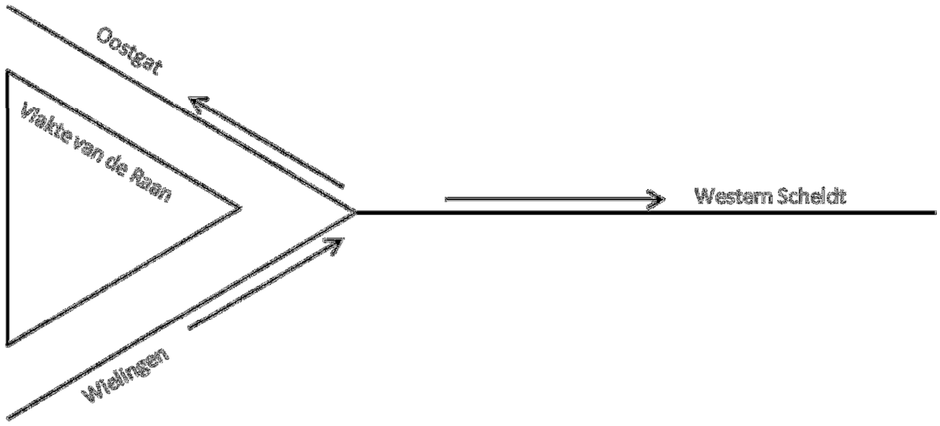

Figure 5.1: Schematisation of the propagation of the tide in the Western Scheldt.

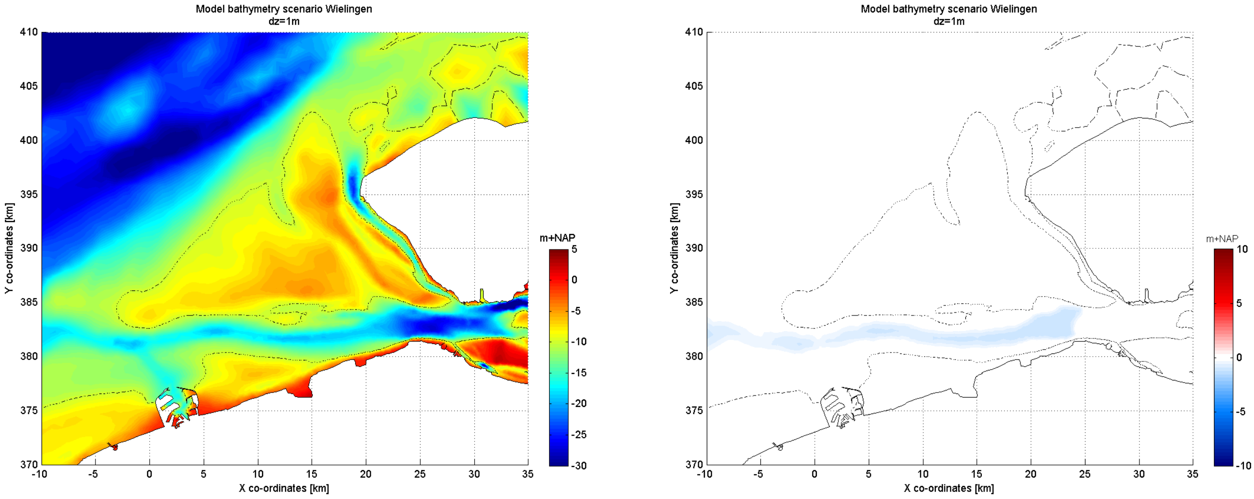

Figure 5.2: Model bathymetry for scenario T3a, and the difference with respect to scenario T0.

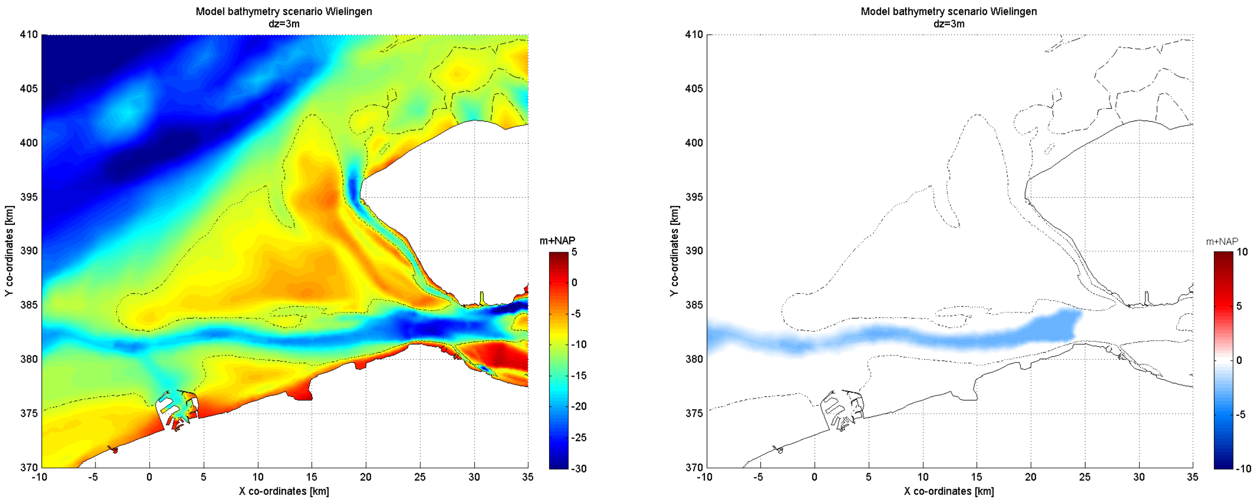

Figure 5.3: Model bathymetry for scenario T3b, and the difference with respect to scenario T0.

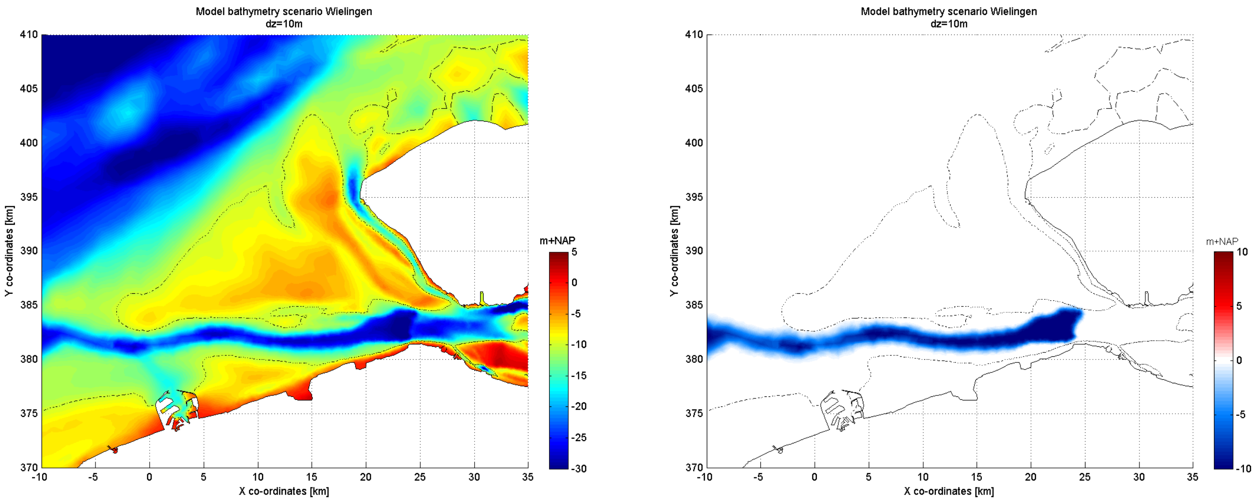

Figure 5.4: Model bathymetry for scenario T3c, and the difference with respect to scenario T0.

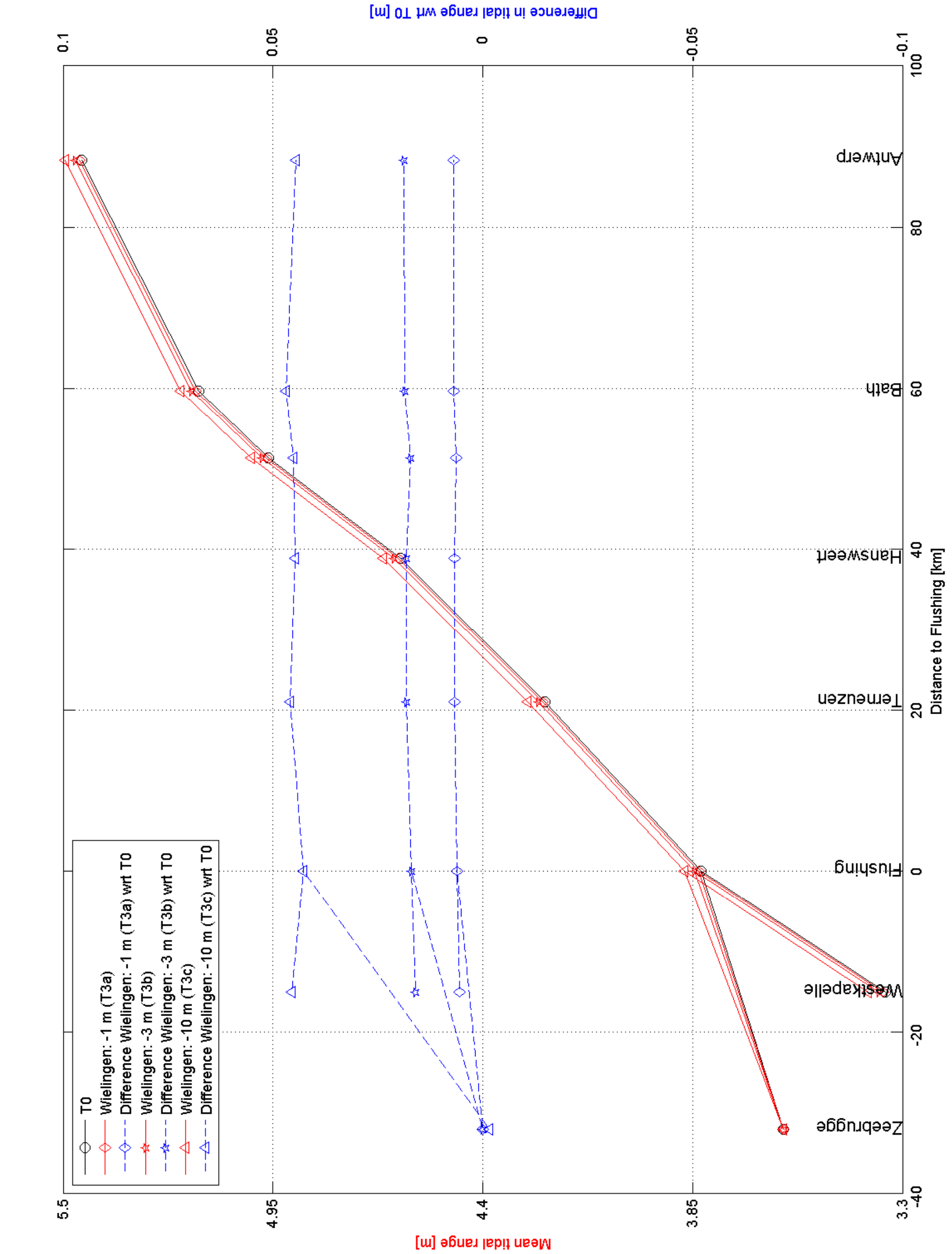

Figure 5.5: Tidal range for scenario T3 along the main tide stations in the Western Scheldt. Scenario T0 and the difference of scenario T3 with respect to scenario T0 are included in the figure as well.

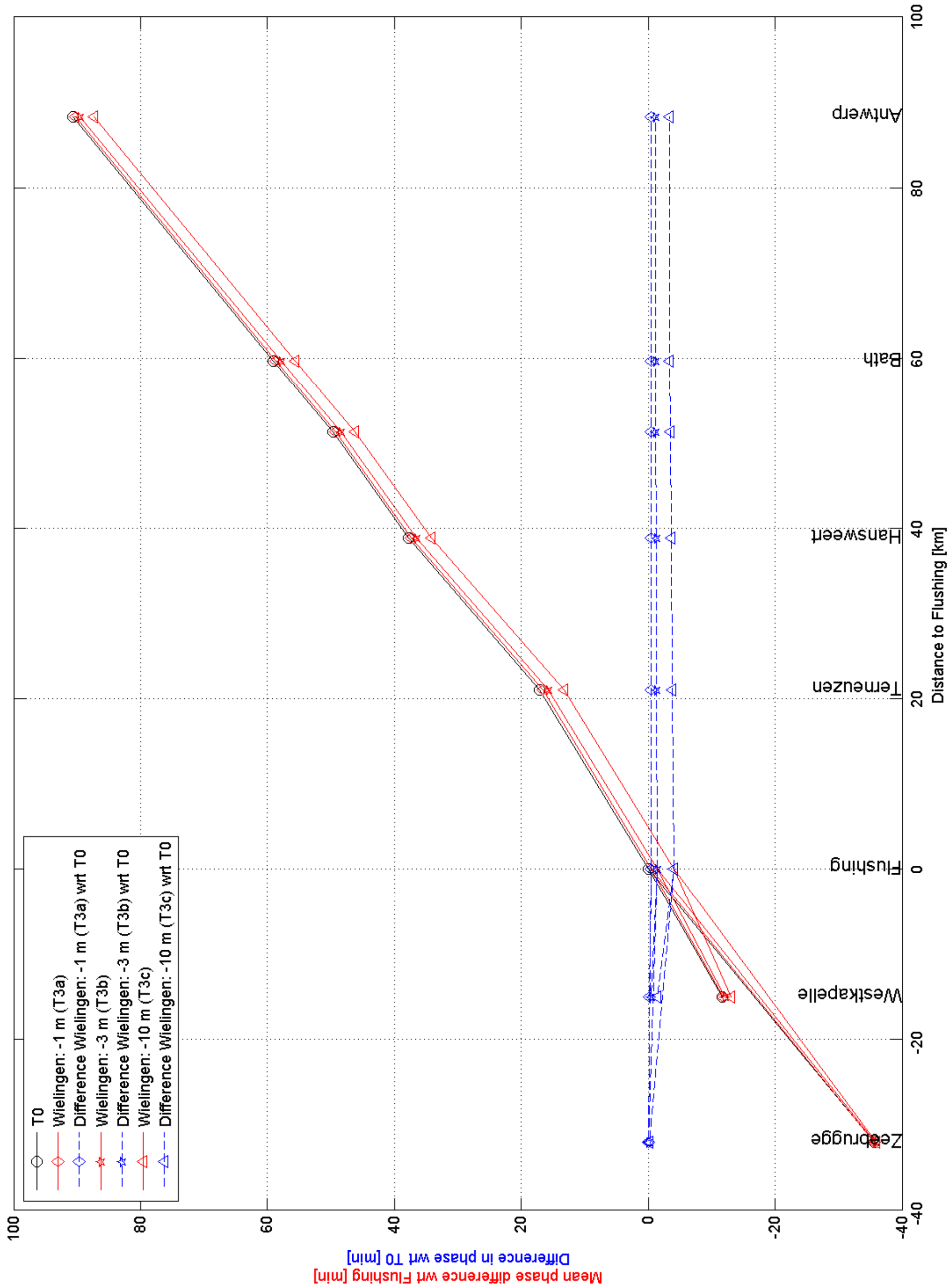

Figure 5.6: Phase difference with respect to T0 at Flushing for scenario T3 along the main tide stations in the Western Scheldt in minutes. Scenario T0 and the difference of scenario T3 with respect to scenario T0 are included in the figure as well.

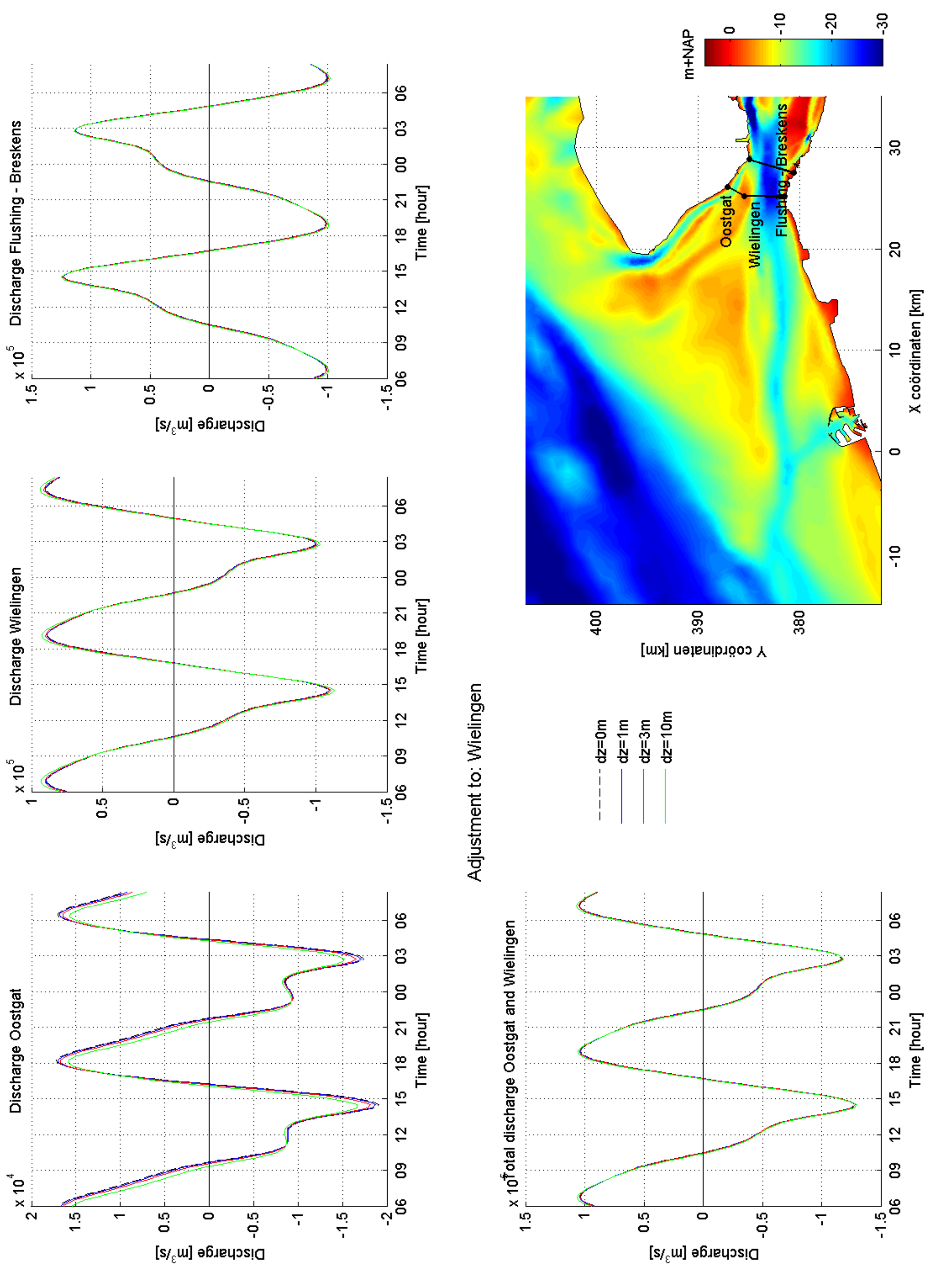

Figure 5.7: Discharge distribution in the Western Scheldt for scenario T0 (dz=0 m) and T3 (dz=1 m, dz=3 m, dz=10 m).

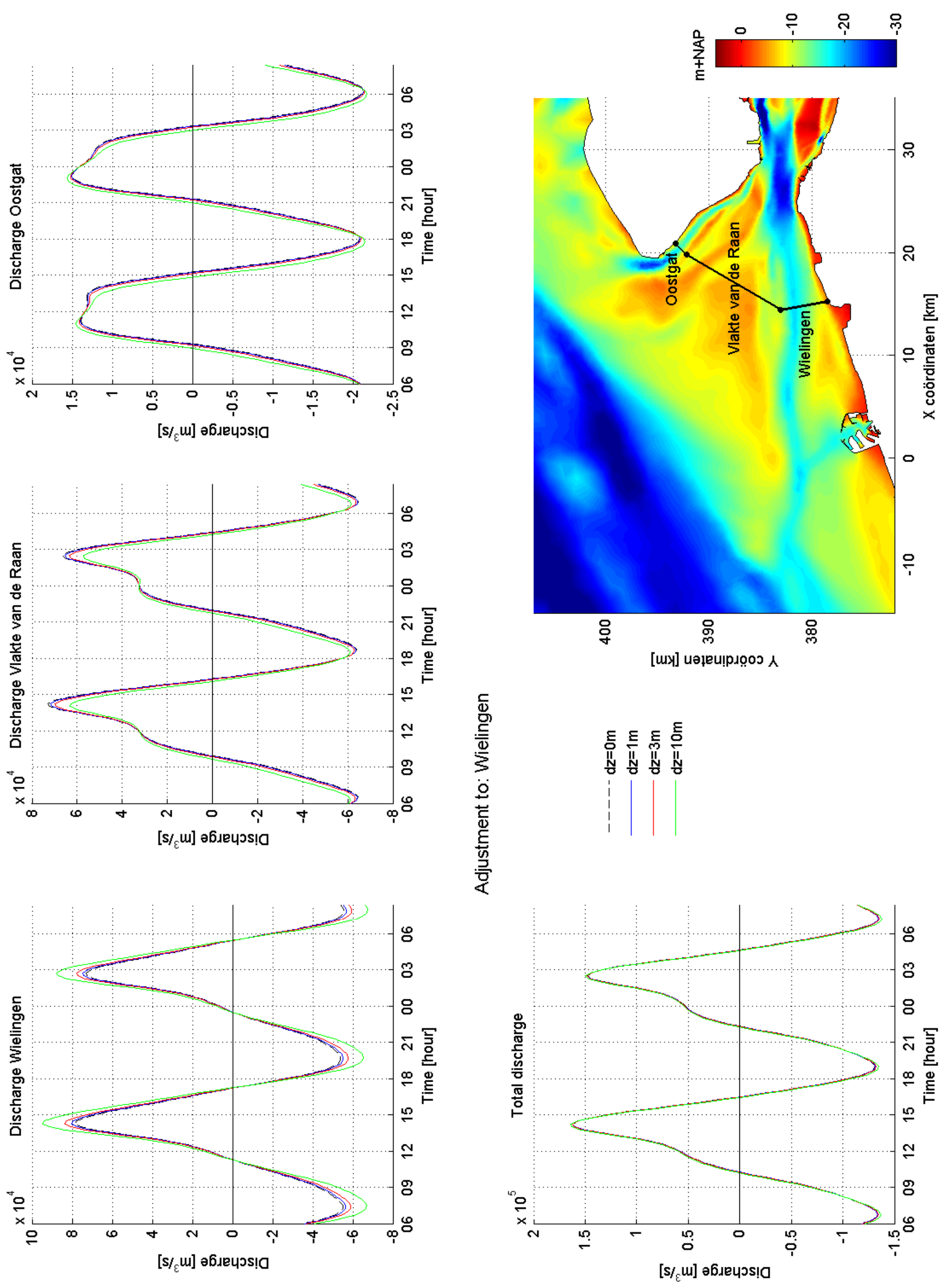

Figure 5.8: Discharge distribution in the estuary mouth of the Western Scheldt for scenario T0 (dz=0 m) and T2 (dz=1 m, dz=3 m, dz=10 m).

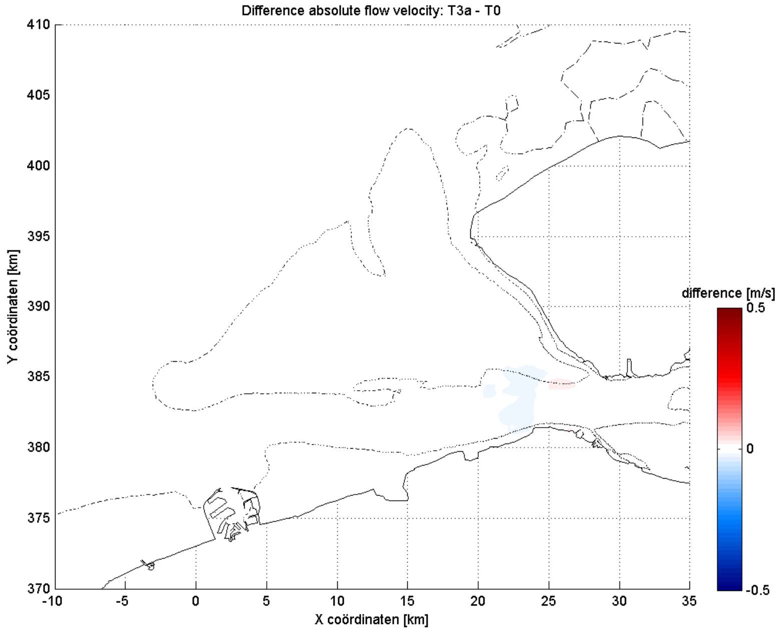

Figure 5.9: Difference in flow velocity between scenario T0 and scenario T3a around maximum flood flow. Red indicates where the flow velocity of scenario T3a is higher than in scenario T0; blue indicates where the flow velocity is lower.

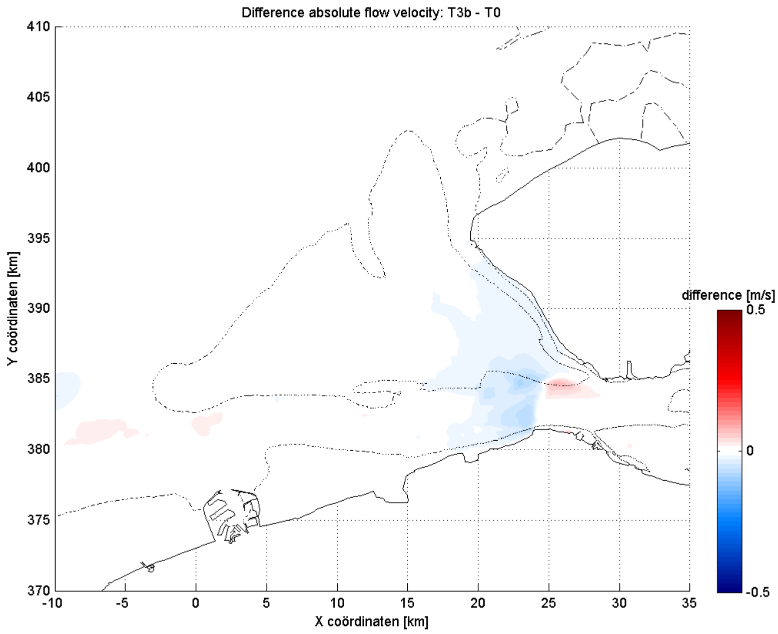

Figure 5.10: Difference in flow velocity between scenario T0 and scenario T3b around maximum flood flow. Red indicates where the flow velocity of scenario T3b is higher than in scenario T0; blue indicates where the flow velocity is lower.

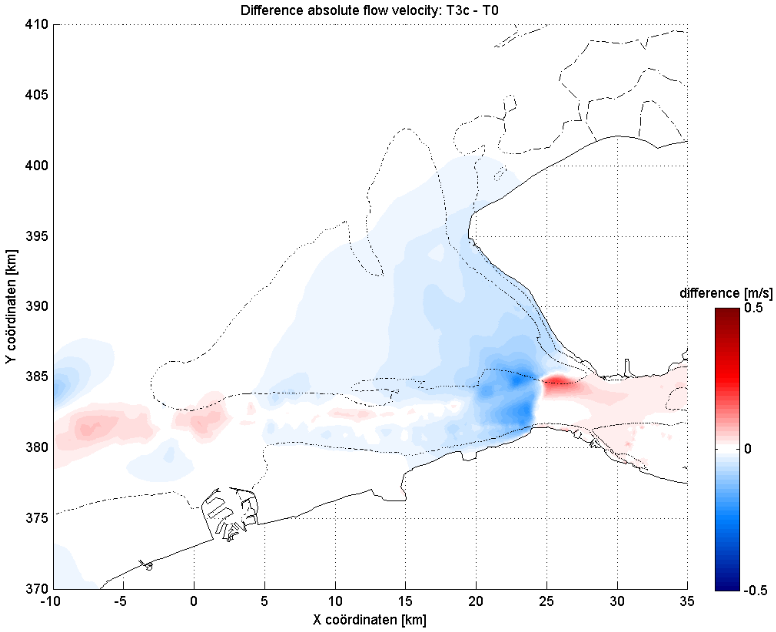

Figure 5.11: Difference in flow velocity between scenario T0 and scenario T3c around maximum flood flow. Red indicates where the flow velocity of scenario T3c is higher than in scenario T0; blue indicates where the flow velocity is lower.

6 RESULTS SCENARIO T4

A heightening of the bed level of the Oostgat channel to NAP (approximately Mean Sea Level) is investigated in scenario T4, see Figure 6.1 and Table 6.1. Figure 6.2 presents the tidal range in the Western Scheldt for scenario T4 and scenario T0, and the difference between the scenarios. Westkapelle is not taken into account in the analysis because the tidal station Westkapelle is dry during most of the simulation and therefore the results are not representative. The shallowing of the Oostgat leads to an increase of the tidal range, which originates in the estuary mouth. In the Western Scheldt itself, the increase of the tidal range varies slightly, between 8 and 9 cm.

Table 6.1: Adjustments with respect to the basic model bathymetry for the different scenarios.

Scenario	Area	Bed level adjustment	Volume
T0	N.a.	N.a.	0 Mm^3
T4	Oostgat	Filled to NAP	648 Mm^3

The influence on the phase difference with respect to scenario T0 is visible in Figure 6.3. The intervention causes a phase lag, which originates in the estuary mouth, similar to the increase in tidal range. The phase difference is constant throughout the Western Scheldt and amounts approximately 3 minutes.

The tidal discharge of the Oostgat, the Wielingen and the Vlakte van de Raan is shown in Figure 6.4 and Figure 6.5. The total discharge of the estuary mouth of the Western Scheldt is presented as well. The figure shows that logically the discharge of the Oostgat is strongly reduced. This is compensated by an increase of the discharge at the Wielingen and the Vlakte van de Raan. The total discharge is slightly increased, because of the increase in tidal range of the Western Scheldt.

Figure 6.6 shows the influence on the flow velocity. In the Oostgat channel logically a large decrease in the flow velocity occurs, while in the Wielingen and the Vlakte van de Raan a velocity increase occurs, because the water is diverted to these areas. Again the velocity is compared at the same moment in time, by which the comparison is not exact due to phase differences. Because the phase difference between the two scenarios is small, the overall conclusion is not affected. The time series of the flow velocities at several locations confirm this (not shown here).

The results of the simulation confirm the conclusions of scenario T1, in which the Oostgat is deepened. The Oostgat is important for the outflow of the tide, and by shallowing the Oostgat, this outflow is limited and as a result the tidal range increases.

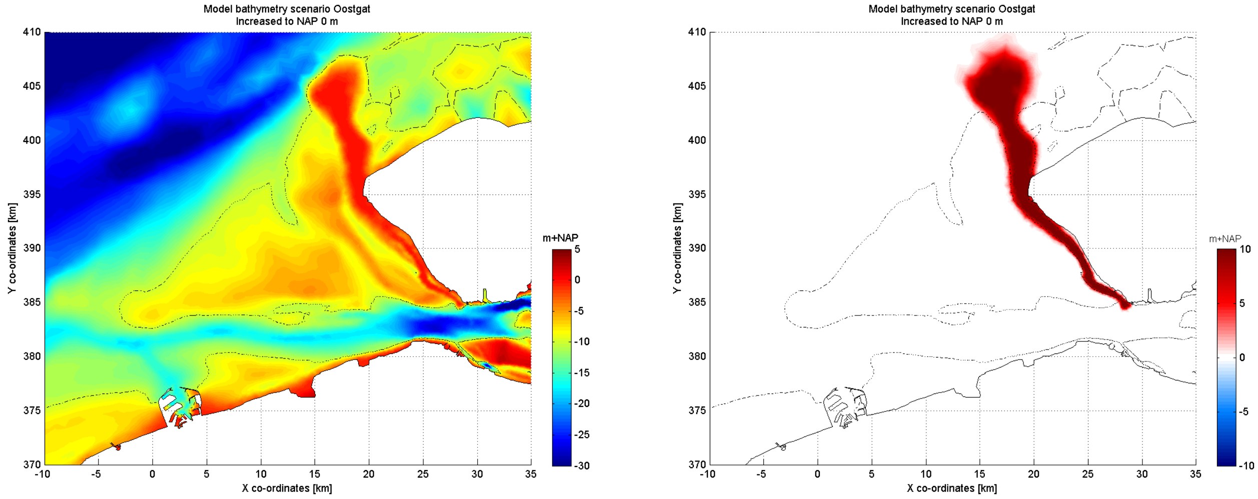

Figure 6.1: Model bathymetry for scenario T4, and the difference with respect to scenario T0.

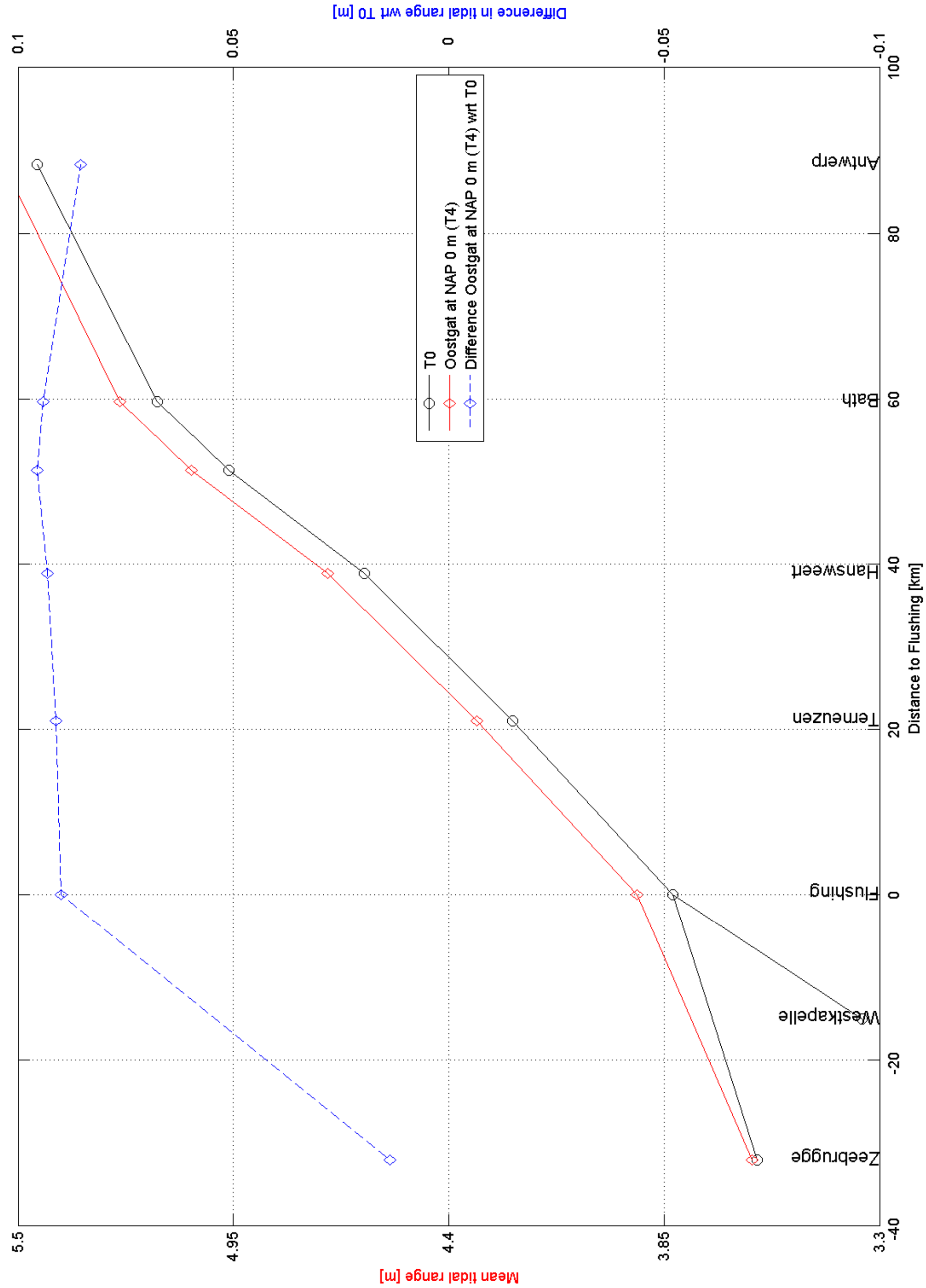

Figure 6.2: Tidal range for scenario T4 along the main tide stations in the Western Scheldt. Scenario T0 and the difference of scenario T4 with respect to scenario T0 are included in the figure as well.

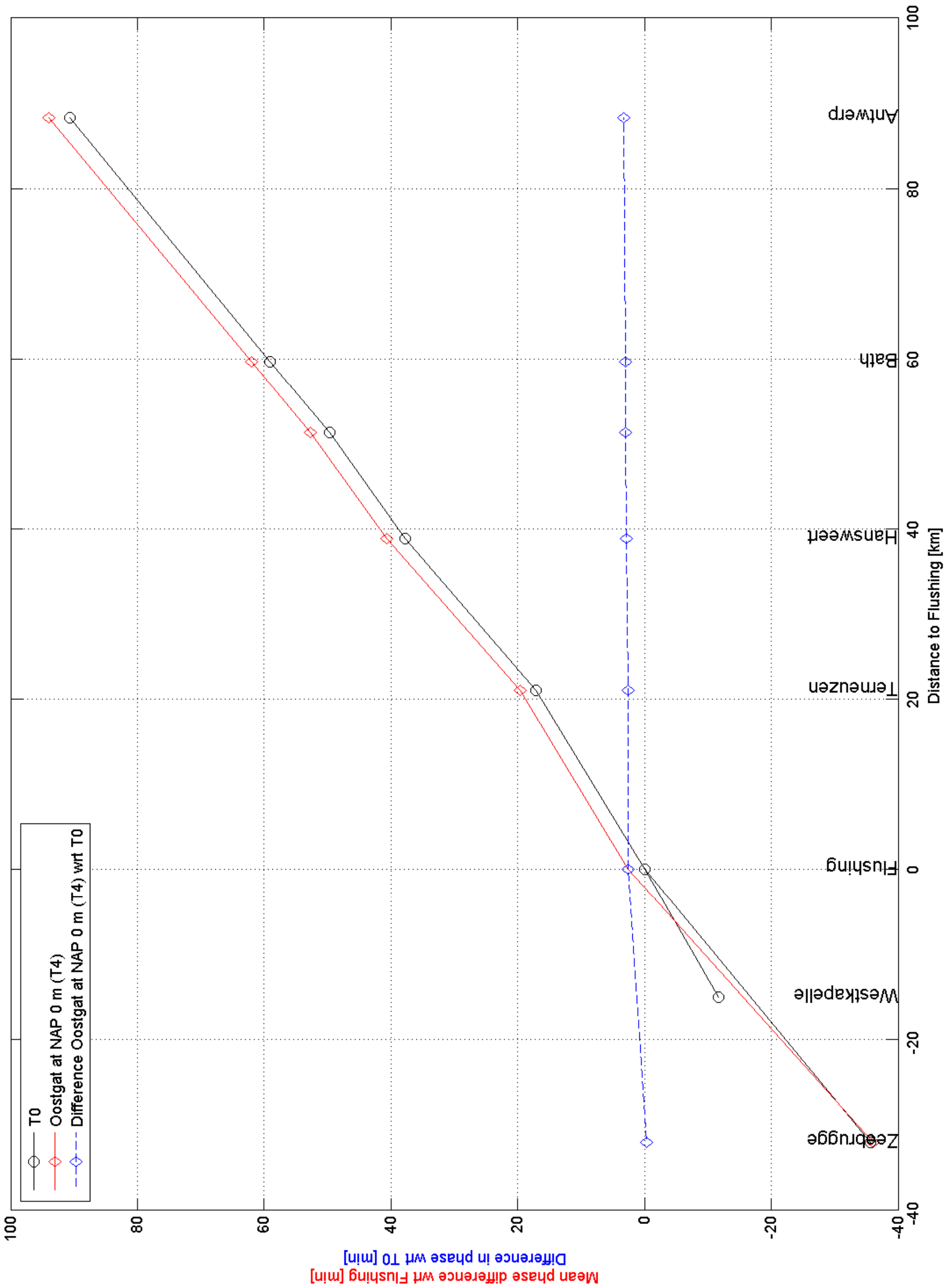

Figure 6.3: Phase difference with respect to T0 at Flushing for scenario T4 along the main tide stations in the Western Scheldt in minutes. Scenario T0 and the difference of scenario T4 with respect to scenario T0 are included in the figure as well.

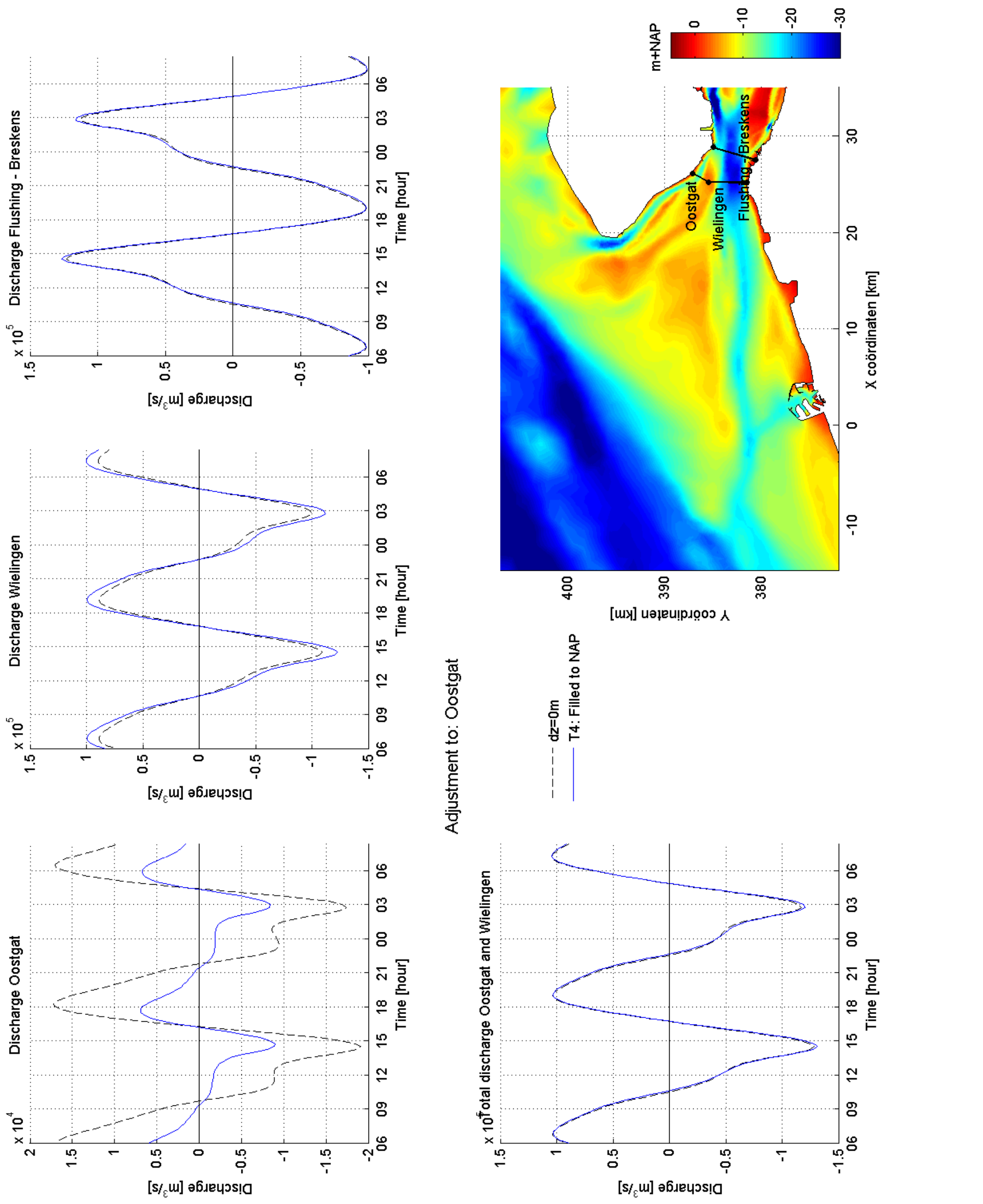

Figure 6.4: Discharge distribution in the Western Scheldt for scenario T0 (dz=0) and T4.

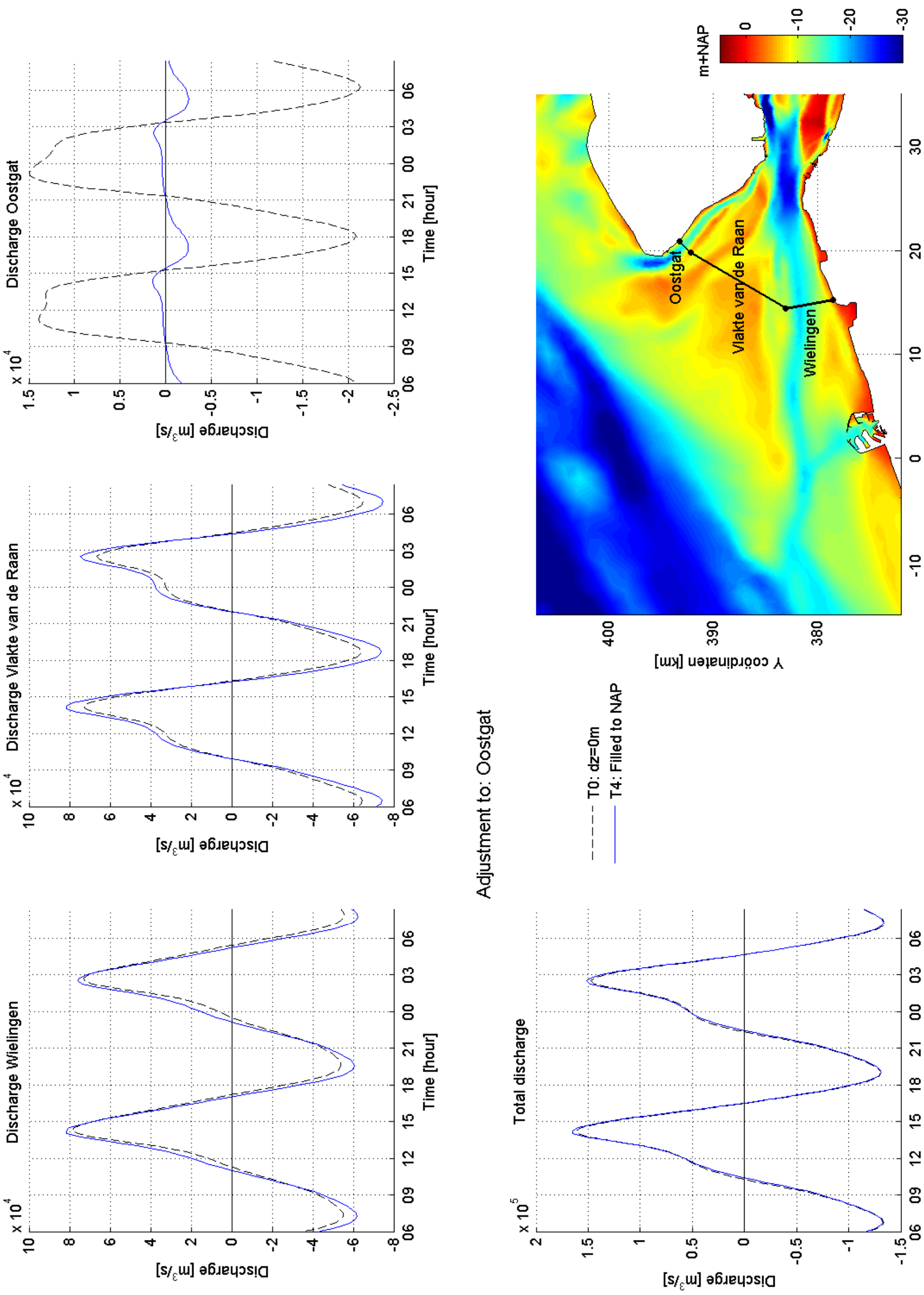

Figure 6.5: Discharge distribution in the estuary mouth of the Western Scheldt for scenario T0 (dz=0) and T4.

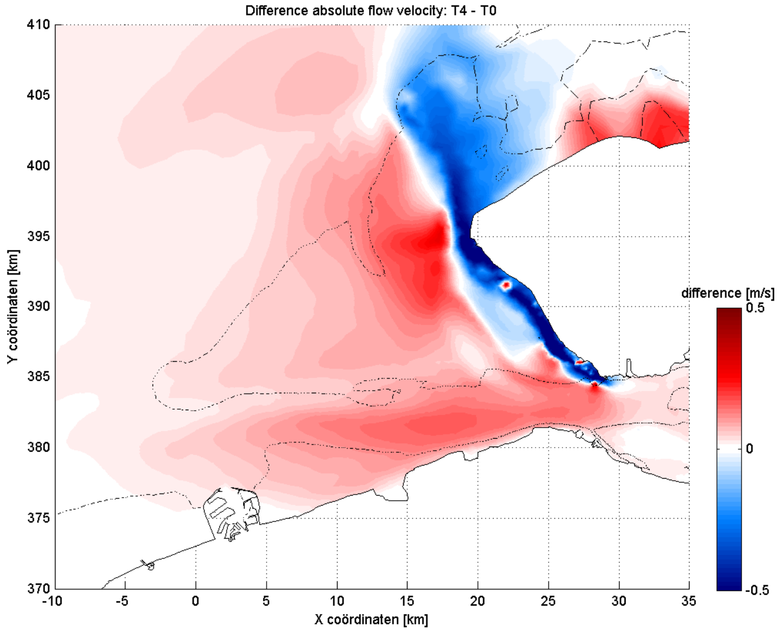

Figure 6.6: Difference in flow velocity between scenario T0 and scenario T4 around maximum flood flow. Red indicates where the flow velocity of scenario T4 is higher than in scenario T0; blue indicates where the flow velocity is lower.

7 RESULTS SCENARIO T5

The Wielingen is the main navigational channel in the estuary mouth. The channel requires regular dredging in order to maintain the navigational depth. In scenario T5, the deep parts of the Wielingen are filled up to the maintenance depth of the navigational channel, which is NAP -17 m. See also Figure 7.1 and Table 7.1. Figure 7.2 presents the tidal range of scenario T5 and scenario T0 of the tide gauge stations in the estuary. The intervention causes a decrease of the tidal range, but the difference only amounts 0.5 cm. The difference in tidal range between scenario T5 and T0 is constant throughout the Western Scheldt.

Table 7.1: Adjustments with respect to the basic model bathymetry for the different scenarios.

Scenario	Area	Bed level adjustment	Volume
T0	N.a.	N.a.	0 Mm^3
T5	Wielingen	Filled to NAP -17m	51 Mm^3

Figure 7.3 shows the phase with respect to Flushing for both scenarios. From Figure 7.3 it is concluded that this scenario has a negligible influence on the phase of the tide.

The discharge at the Wielingen, the Oostgat and the Vlakte van de Raan is shown in Figure 7.4 and Figure 7.5. The figures show that the discharge does not change.

The difference in flow velocity of scenario T5 with respect to scenario T0 is presented in Figure 7.6. Since the intervention causes no phase shifts, the figure compares the flow velocity at the same moment of phase. At the locations where the depth is slightly decreased, the flow velocity shows a small increase. In the areas of the Wielingen channel, between the elevated parts, the flow velocity slightly decreases. The differences amount no more than a few cm/s.

In both scenario T3 and scenario T5 the Wielingen is shallowed, and in both cases this leads to a reduction of the tidal range. The Wielingen is therefore mainly important for the inflow of the tide.

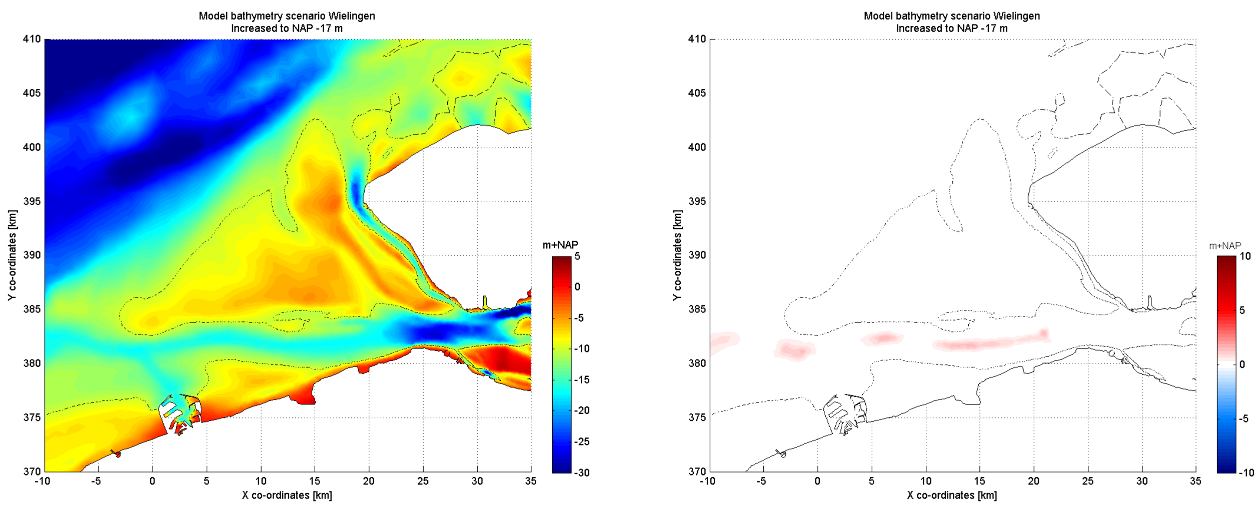

Figure 7.1: Model bathymetry for scenario T5, and the difference with respect to scenario T0.

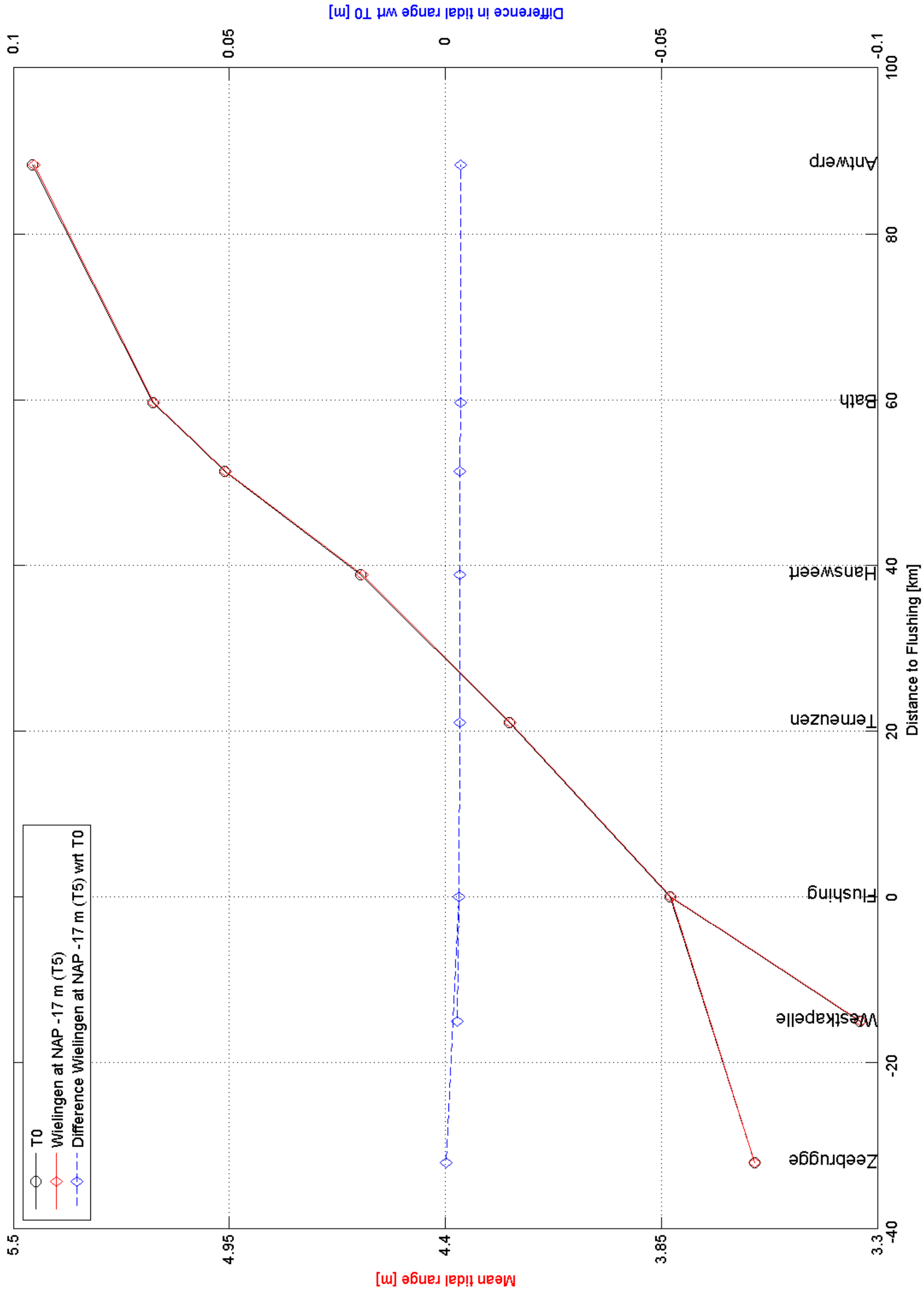

Figure 7.2: Tidal range for scenario T5 along the main tide stations in the Western Scheldt. Scenario T0 and the difference of scenario T5 with respect to scenario T0 are included in the figure as well.

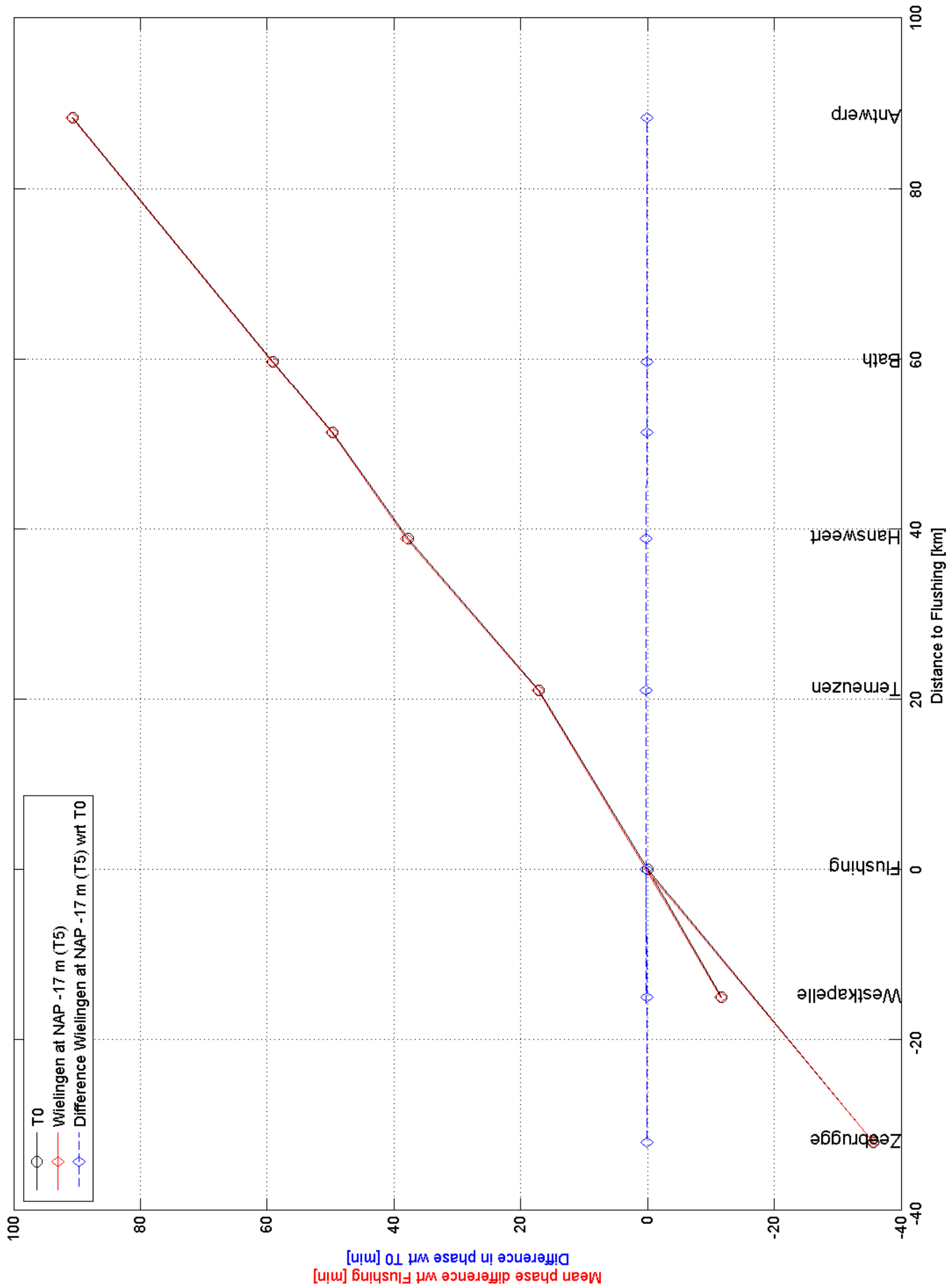

Figure 7.3: Phase difference with respect to T0 at Flushing for scenario T5 along the main tide stations in the Western Scheldt in minutes. Scenario T0 and the difference of scenario T5 with respect to scenario T0 are included in the figure as well.

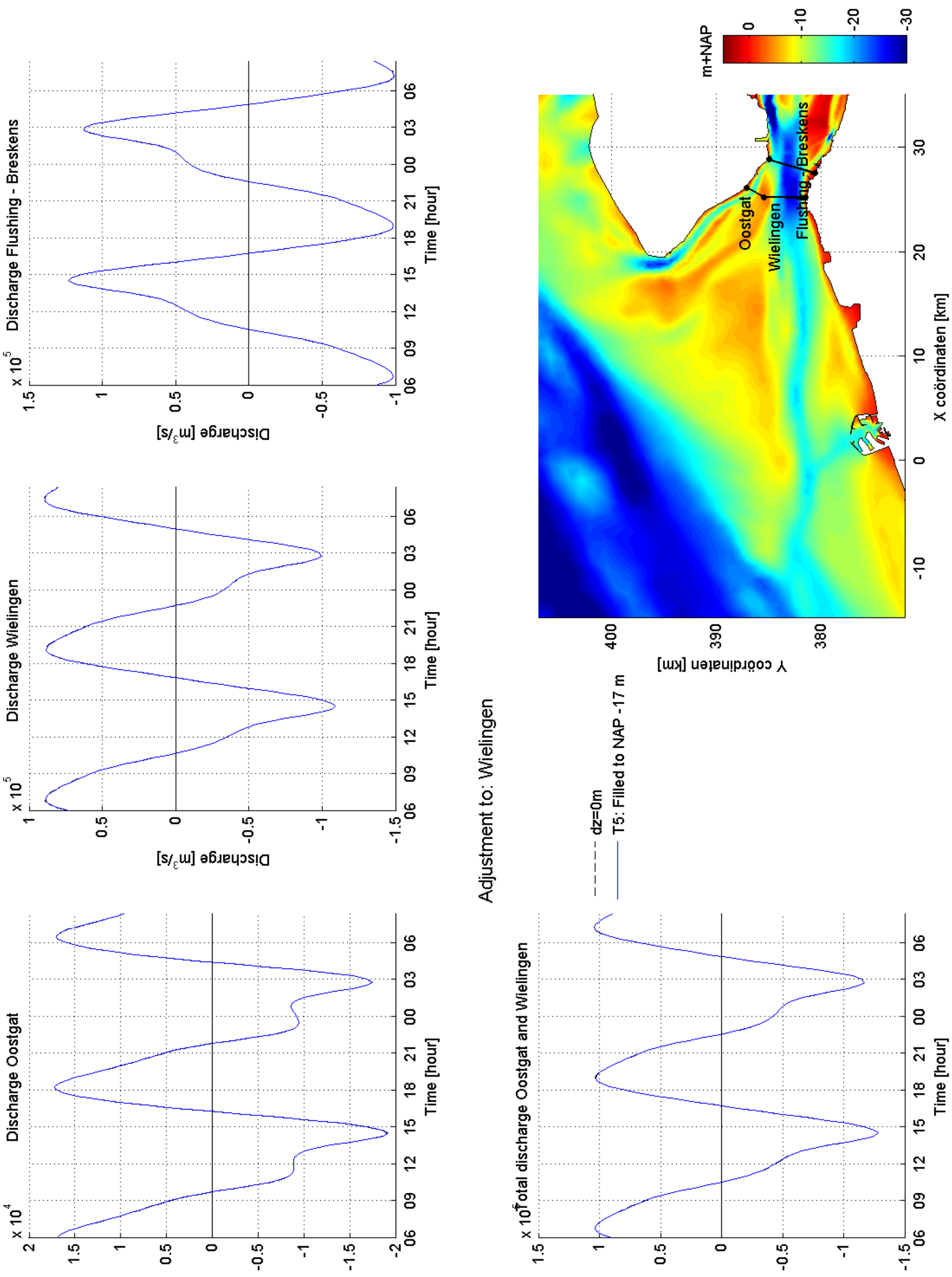

Figure 7.4: Discharge distribution in the Western Scheldt for scenario T0 (dz=0) and T5.

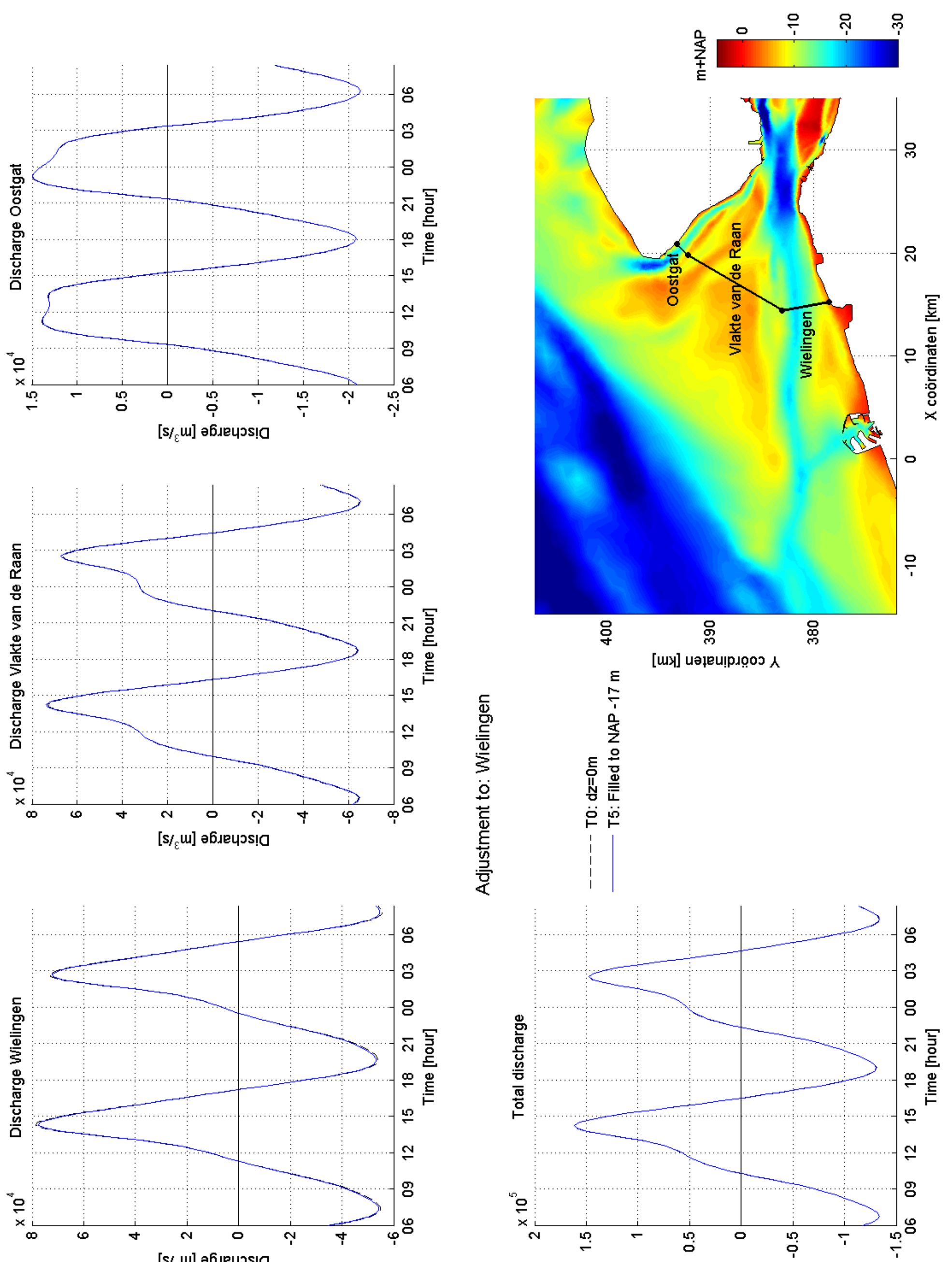

Figure 7.5: Discharge distribution in the estuary mouth of the Western Scheldt for scenario T0 (dz=0) and T5.

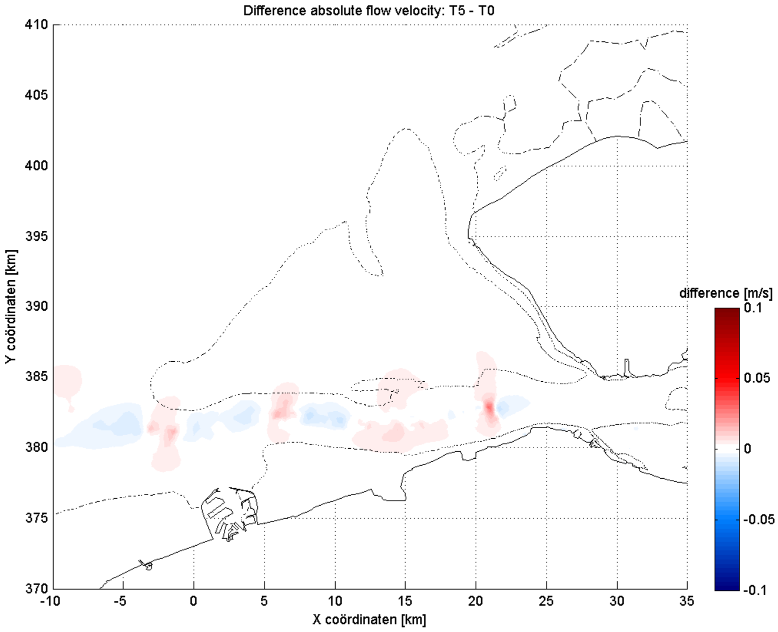

Figure 7.6: Difference in flow velocity between scenario T0 and scenario T5 around maximum flood flow. Red indicates where the flow velocity of scenario T5 is higher than in scenario T0; blue indicates where the flow velocity is lower.

8 RESULTS SCENARIO T6

For scenario T6 a shoal is defined in the Wielingen navigational channel. For scenario T6a the height of the shoal is NAP -10 m (Figure 8.1), and for scenario T6b NAP -5 m (Figure 8.2). The scenarios are summarised in Table 8.1.

Table 8.1: Adjustments with respect to the basic model bathymetry for the different scenarios.

Scenario	Area	Bed level adjustment	Volume
T0	N.a.	N.a.	0 Mm^3
T6a	Wielingen	Shoal at NAP -10m	31 Mm^3
T6b	Wielingen	Shoal at NAP -5m	116 Mm^3

Figure 8.3 shows the tidal range at the main tide gauge stations along the Western Scheldt. The difference in tidal range between scenario T6a and T6b with scenario T0 is included as well. The figure shows that (partly) blocking of the Wielingen results in a decrease of the tidal range. In scenario T6a the reduction amounts approximately 1.5 cm. In scenario T6b the reduction varies throughout the Western Scheldt, between 10 cm and 12 cm. When time series of the water level at several of the tide stations are analysed (not shown here), it appears that the intervention results in a change of the tidal curve. The theorem that the difference in tidal range is constant throughout the Western Scheldt (and originates in the estuary mouth), can therefore not be applied.

The phase difference with respect to scenario T0 at Flushing in minutes is for scenario T6a and T6b presented in Figure 8.4. The difference with respect to scenario T0 is shown as well. A lag of the tidal wave occurs due to the intervention. The tidal wave is slowed down due to the frictional effect of the shoal. In contrast to the difference in tidal range, the phase difference is constant throughout the Western Scheldt. The phase lag amounts less than a minute for scenario T6a and approximately 3 minutes for scenario T6b.

The discharge through the Wielingen, the Oostgat and the Vlakte van de Raan is shown in Figure 8.5 and Figure 8.6. The total discharge is indicated as well. Figure 8.6 shows that the discharge in the Wielingen reduces in both scenario T6a and scenario T6b. The reduction in scenario T6b is significantly larger than the reduction in scenario T6a. The reduction of the discharge in the Wielingen is largely compensated by an increase of discharge at the Vlakte van de Raan. The total discharge through the estuary mouth slightly decreases because of the reduction in tidal range in the rest of the estuary.

The intervention affects the flow velocity in the estuary mouth. The difference between the flow velocity of scenarios T6a and T6b with respect to scenario T0 are presented in Figure 8.7 and Figure 8.8. The figures present the differences at the same moment in time, not at the same moment of phase. The figures show that the velocity at the location of the shoal increases and east and west of the shoal decreases. In scenario T6b, this effect is stronger, and the flow velocity in the entire Wielingen reduces. At the Vlakte van de Raan and the Oostgat an increase of the flow velocity is visible. Time series of the flow velocity show however that this increase is mainly due to phase differences (not shown here). The flow velocities at the Vlakte van de Raan and the Oostgat Channel are approximately equal to the flow velocities in the T0 scenario.

From scenario T3 it was concluded that the Wielingen is important for the inflow of the tide in the Western Scheldt. Deepening led to an increase of the tidal range. In this scenario, the depth of the Wielingen is locally decreased. In both scenario T6a and T6b, a decrease of the tidal range occurs. So the results of all the Wielingen scenarios show that the Wielingen is indeed important for the inflow. An increase of the depth leads to an increase in tidal range, while a decrease of the depth leads to a decrease in tidal range, see also Figure 5.1.

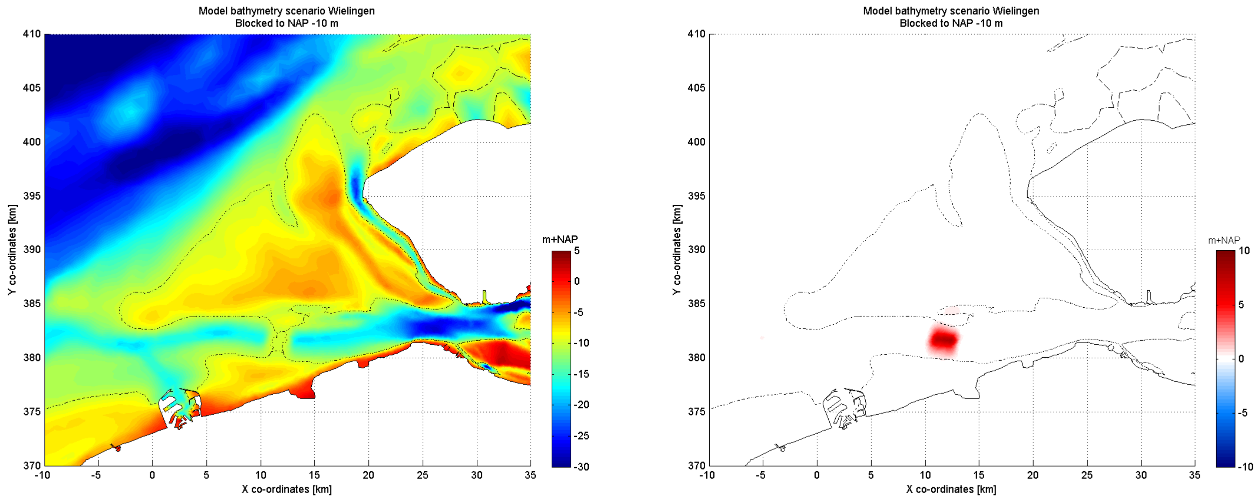

Figure 8.1: Model bathymetry for scenario T6a, and the difference with respect to scenario T0.

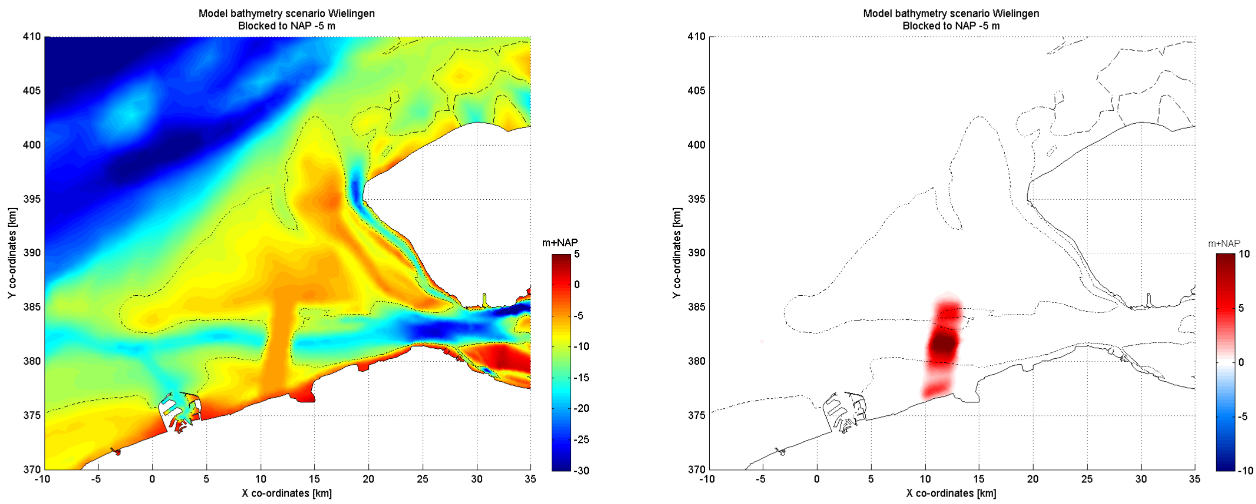

Figure 8.2: Model bathymetry for scenario T6b, and the difference with respect to scenario T0.

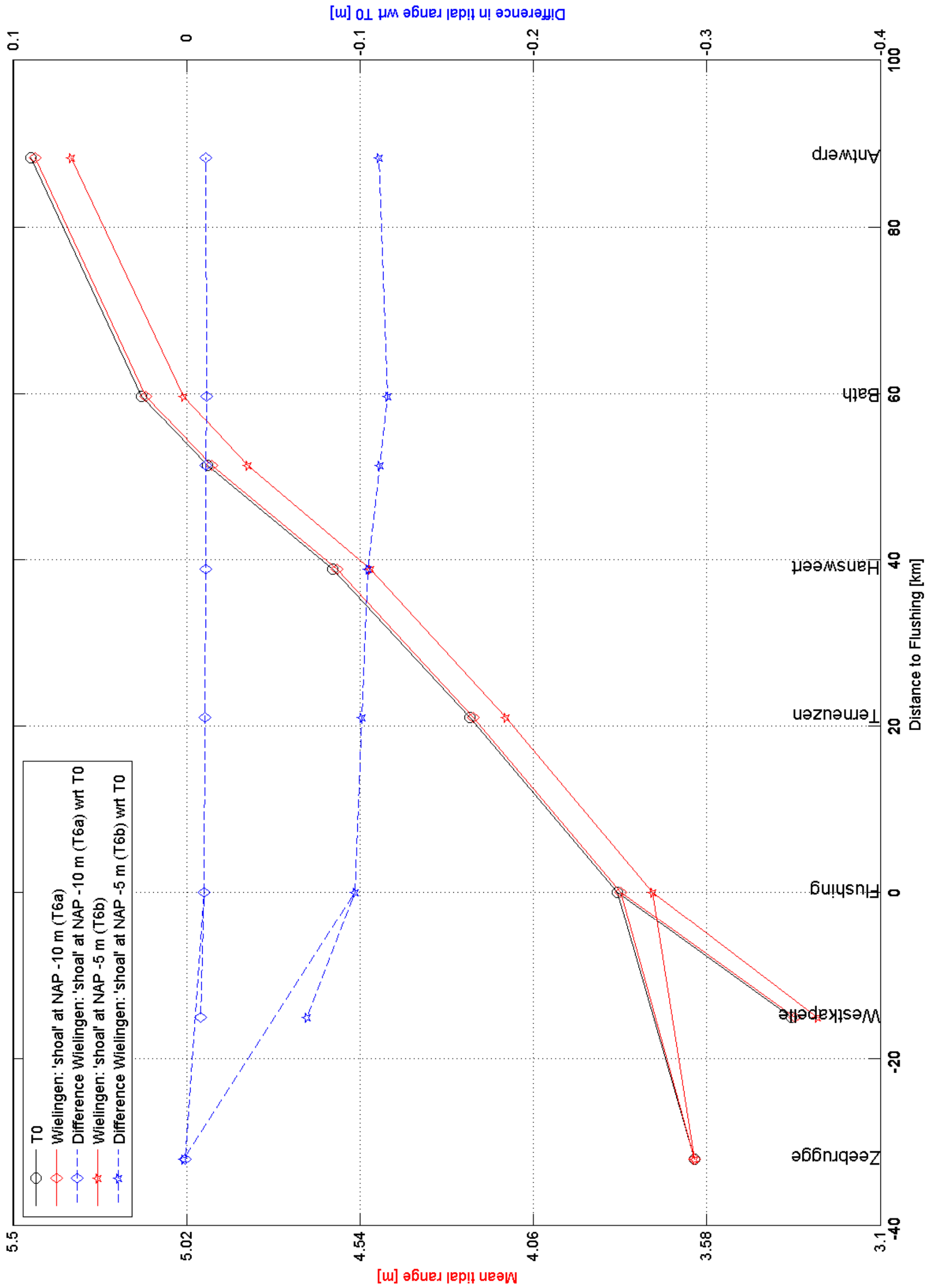

Figure 8.3: Tidal range for scenario T6 along the main tide stations in the Western Scheldt. Scenario T0 and the difference of scenario T6 with respect to scenario T0 are included in the figure as well.

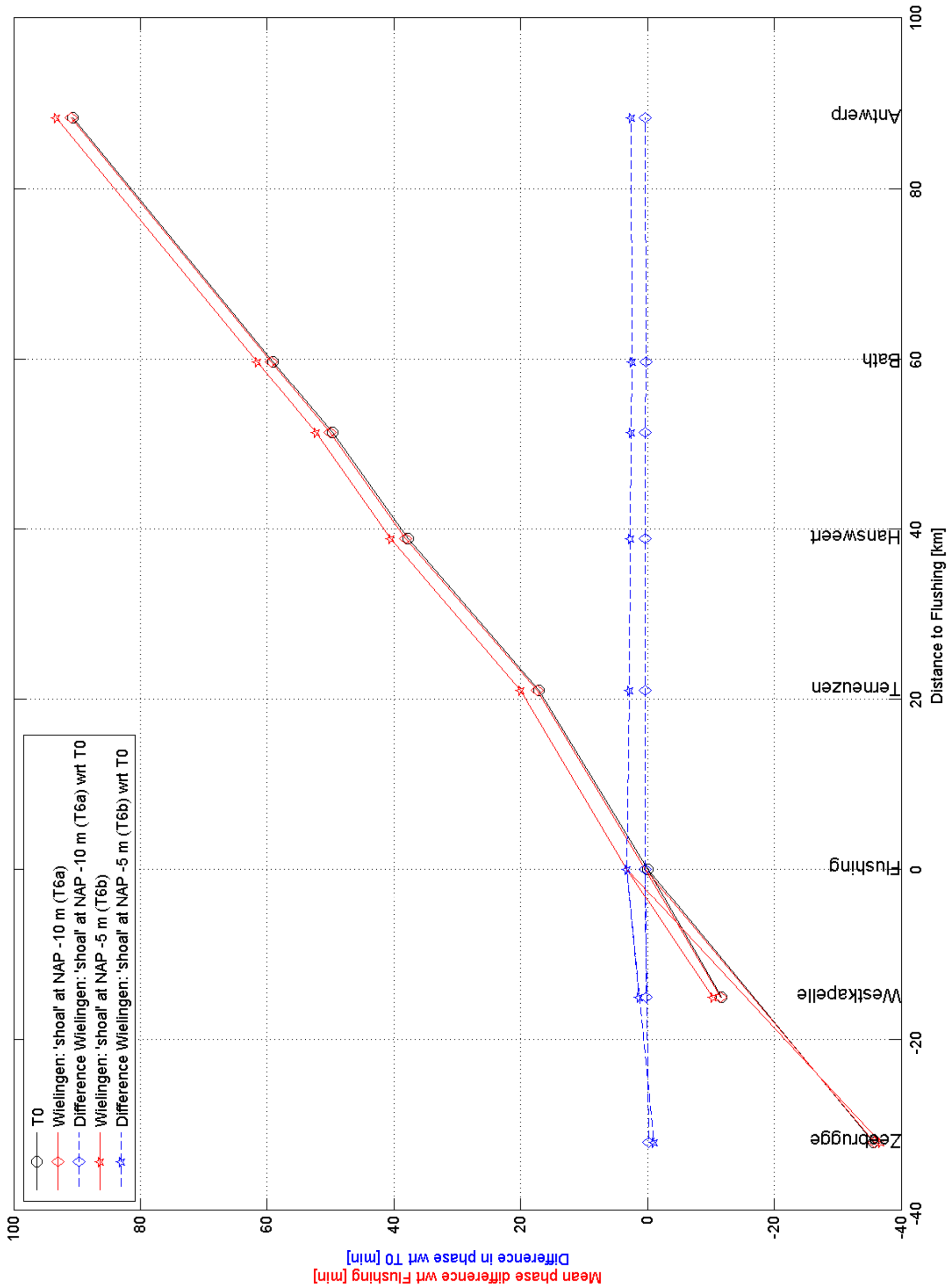

Figure 8.4: Phase difference with respect to T0 at Flushing for scenario T6 along the main tide stations in the Western Scheldt in minutes. Scenario T0 and the difference of scenario T6 with respect to scenario T0 are included in the figure as well.

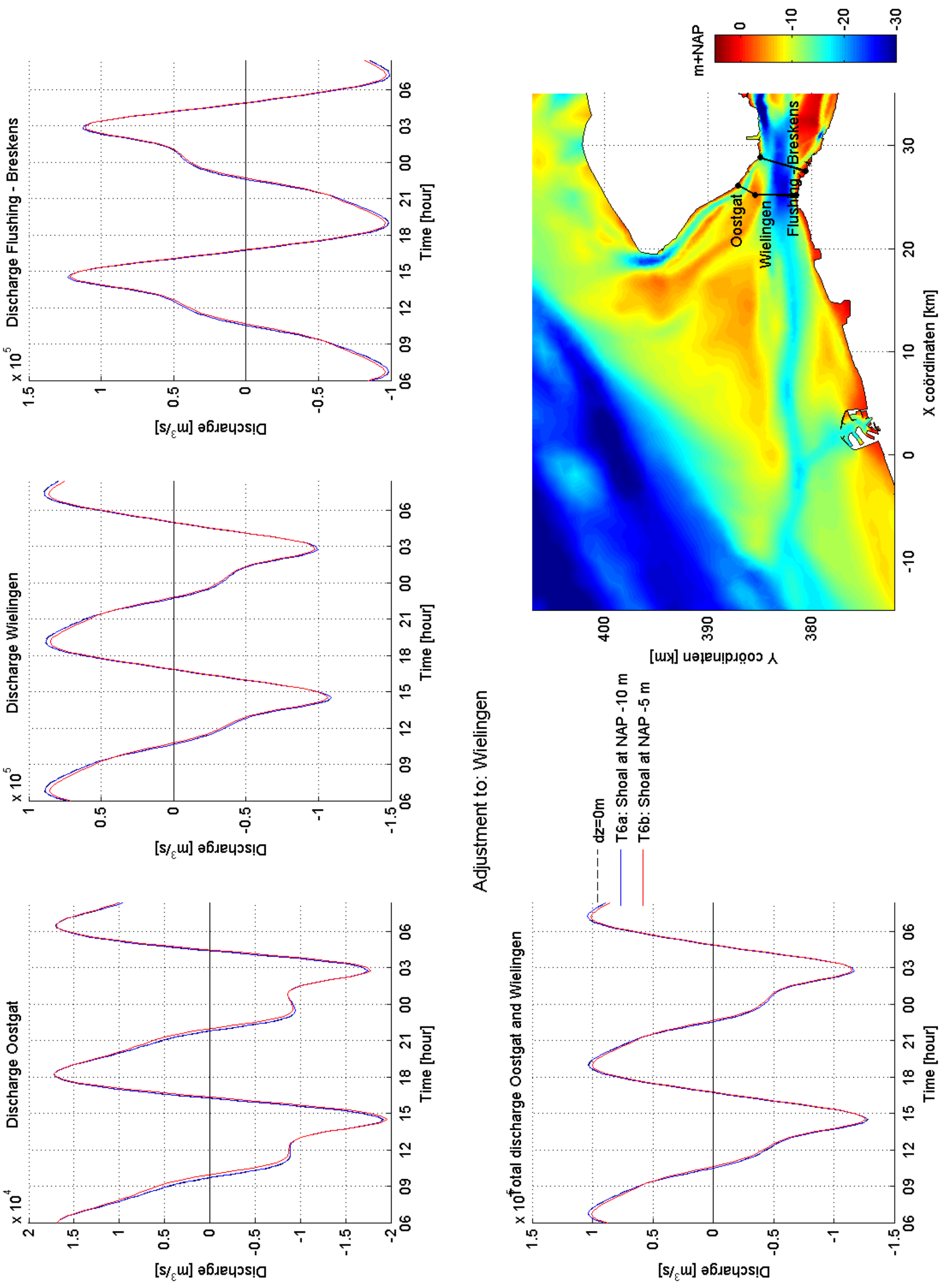

Figure 8.5: Discharge distribution in the Western Scheldt for scenario T0 (dz=0) and T6.

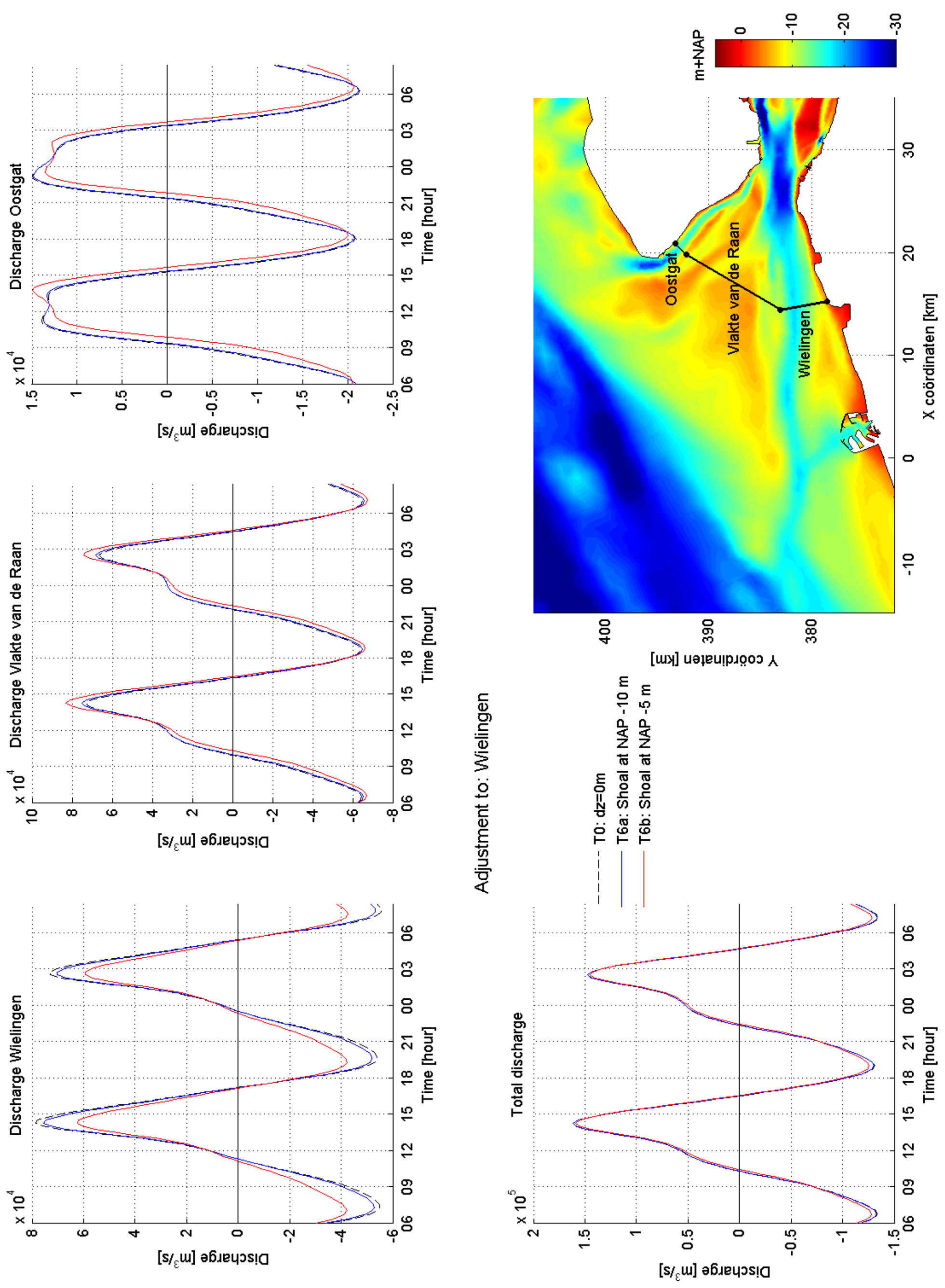

Figure 8.6: Discharge distribution in the estuary mouth of the Western Scheldt for scenario T0 (dz=0) and T6.

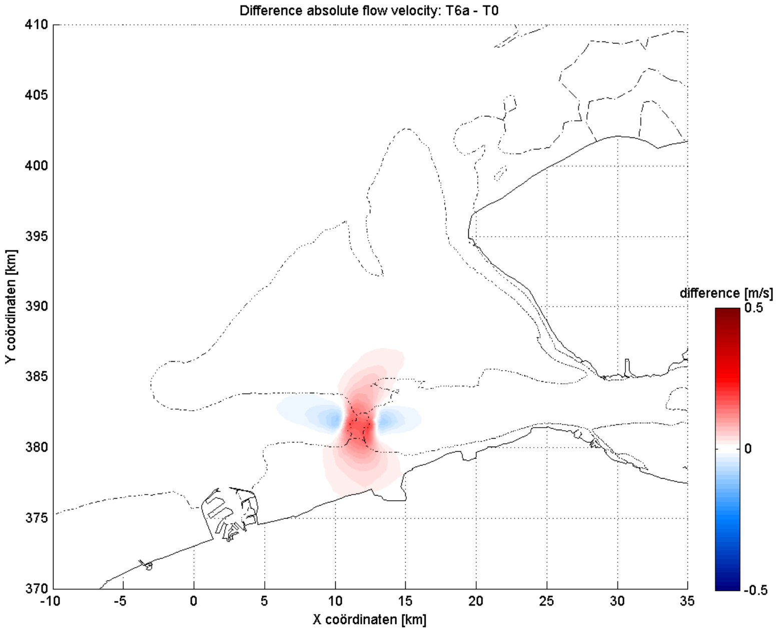

Figure 8.7: Difference in flow velocity between scenario T0 and scenario T6a around maximum flood flow. Red indicates where the flow velocity of scenario T6a is higher than in scenario T0; blue indicates where the flow velocity is lower.

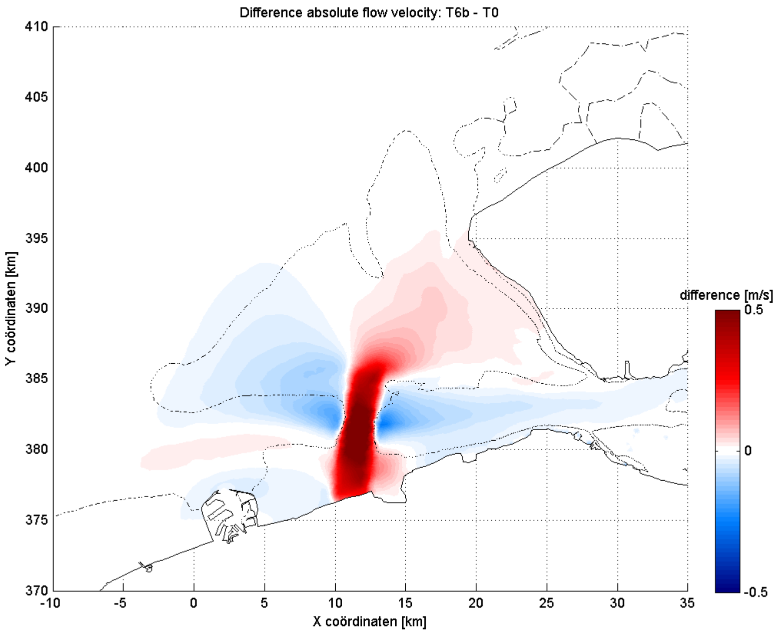

Figure 8.8: Difference in flow velocity between scenario T0 and scenario T6b around maximum flood flow. Red indicates where the flow velocity of scenario T6b is higher than in scenario T0; blue indicates where the flow velocity is lower.

9 RESULTS SCENARIO T7

In scenario T7 two bed levels are applied in the Scheldt estuary mouth : NAP -18 m and NAP -2 m. In scenario T7a (Figure 9.2) the entire estuary mouth is defined at a bed level of NAP -18 m. In scenario T7b (Figure 9.3) the bed level of the Wielingen is defined at NAP -2 m. The remaining part of the estuary mouth is defined at NAP -18 m. In Table 9.1 the interventions are summarised.

Table 9.1: Adjustments with respect to the basic model bathymetry for the different scenarios.

Scenario	Area	Bed level adjustment	Volume
T0	N.a.	N.a.	0 Mm^3
T7a	Entire estuary mouth	NAP -18m	-4881 Mm^3
T7b	Entire estuary mouth	Estuary mouth NAP -18m, Wielingen NAP -2m	-1932 Mm^3

Figure 9.4 presents the tidal range in the Western Scheldt of scenario T7a, T7b and T0 along the Western Scheldt, as well as the difference in tidal range with respect to scenario T0. The intervention results in a reduction of the tidal range, except for Westkapelle, because at Westkapelle the bed level is locally increased. In Chapter 3 it turned out the Oostgat is important for the outflow of the tidal wave. Due to the local increase of the bed level, this is counteracted, which leads to a small increase of the tidal range.

At the other tidal stations a decrease of the tidal range is observed. In the Western Scheldt the difference in tidal range with respect to scenario T0 is constant, except for Antwerp. Since the geometry of the estuary mouth has changed drastically, the shape of the tidal curve has changed as well (not shown here). The reduction of the tidal range amounts 14 cm up at Flushing to 17 cm at Antwerp in case of scenario T7a, and amounts 18 cm at Flushing to 17 cm at Antwerp in case of scenario T7b.

The phase difference with respect to scenario T0 at Flushing is for scenarios T7a, T7b and T0 presented in Figure 9.5. Both scenario T7a and T7b show an acceleration of the propagation of the tide with respect to scenario T0. This acceleration of the tidal celerity is constant throughout the Western Scheldt, and amounts approximately 15 minutes for scenario T7a and approximately 8 minutes for scenario T7b.

At Zeebrugge distinct differences are visible between the phase shift of scenario T7a and T7b. Scenario T7a results in a small acceleration, whereas scenario T7b results in a phase lag of about 8 minutes. This is caused by the large difference in the intervention in the southern part of the estuary mouth. In scenario T7a the area is deepened, whereas it is shallow in scenario T7b. The phase shift with respect to scenario T0 is for scenarios T7a and T7b significantly larger than in scenarios T1 to T6. On the other hand the intervention in scenario T7 is larger.

The discharge at the Oostgat, the Wielingen and the Vlakte van de Raan, and the total discharge in the Western Scheldt estuary mouth is shown in Figure 9.6 and Figure 9.7. The total discharge reduces slightly for both scenarios, which corresponds with the decrease of the tidal range. The distribution of the discharge over the three morphological units changes drastically.

The difference in flow velocity with respect to scenario T0 is presented in Figure 9.8 and Figure 9.9. The velocities are compared at the same moment in time, and not at the same moment of phase, by which the comparison is far from reality. Figure 9.8 shows that the flow velocity decreases in almost the entire Scheldt estuary mouth, due to the large increase of the cross sectional area. This reduction of the flow velocity appears to be independent of the phase shifts caused by the intervention. The phase shift may cause an error in the velocity difference, but the conclusion that the flow velocities decrease holds. Remarkably a local increase of the flow velocity at the Vlakte van de Raan is present. This might be caused by the phase shift differences.

Figure 9.9 shows approximately the same pattern as Figure 9.8. However, in scenario T7b an increase of the flow velocity is observed at the transition between the deep and the shallow part of the estuary mouth as well. This increase is probably caused by an abrupt change in the bed level.

The functioning of the three morphological units has again clearly been recognised by the two scenarios presented in this chapter. The Vlakte van de Raan and the Oostgat are mainly important for the outflow of the tide, see Figure 9.1. Since both morphological units are deepened in these scenarios, the outflow is enhanced, and the tidal range reduced. The Wielingen on the other hand is mainly important for the inflow of the tide. For scenario 7a there are two counter acting effects on the tidal range. On the one hand there is the deepening of the Vlakte van de Raan and Oostgat, which causes a decrease in tidal range. On the other hand the deepening of the Wielingen causes an increase of the tidal range. Since the tidal range is reduced in the Western Scheldt it becomes clear that the deepening of the Vlakte van de Raan and Oostgat prevails over the deepening of the Wielingen. Scenario T7b shows that by decreasing the depth of the Wielingen in comparison to Scenario T7a, and keeping the Vlakte van de Raan and Oostgat at -18m NAP the tidal range becomes lower with respect to Scenario T7a. This again proves the function of the Wielingen as being important for the tidal inflow.

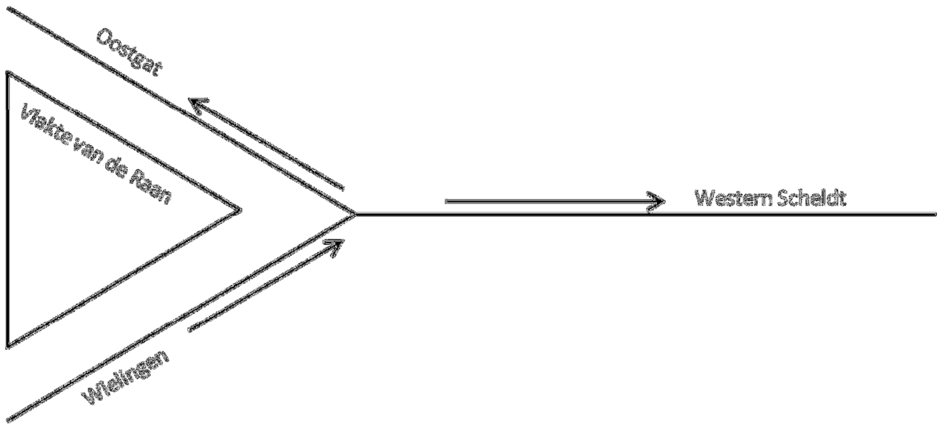

Figure 9.1: Schematisation of the propagation of the tide in the Western Scheldt.

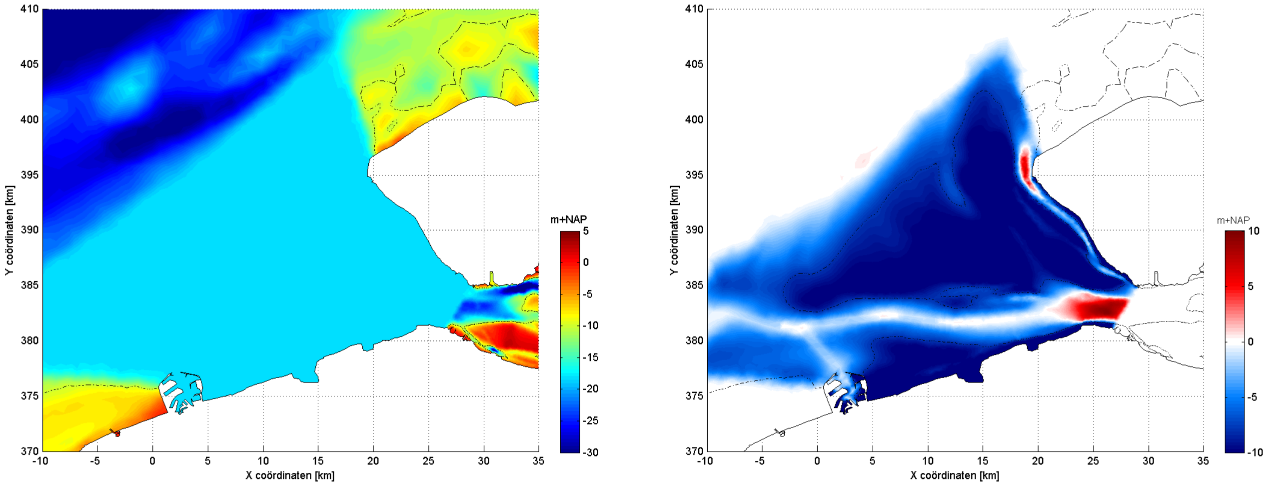

Figure 9.2: Model bathymetry for scenario T7a, and the difference with respect to scenario T0.

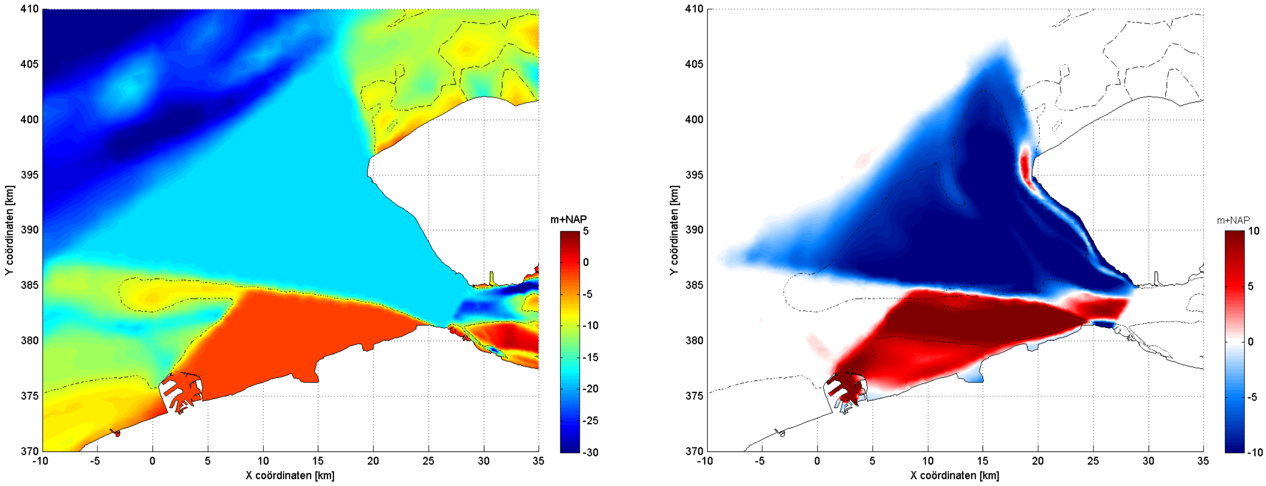

Figure 9.3: Model bathymetry for scenario T7b, and the difference with respect to scenario T0.

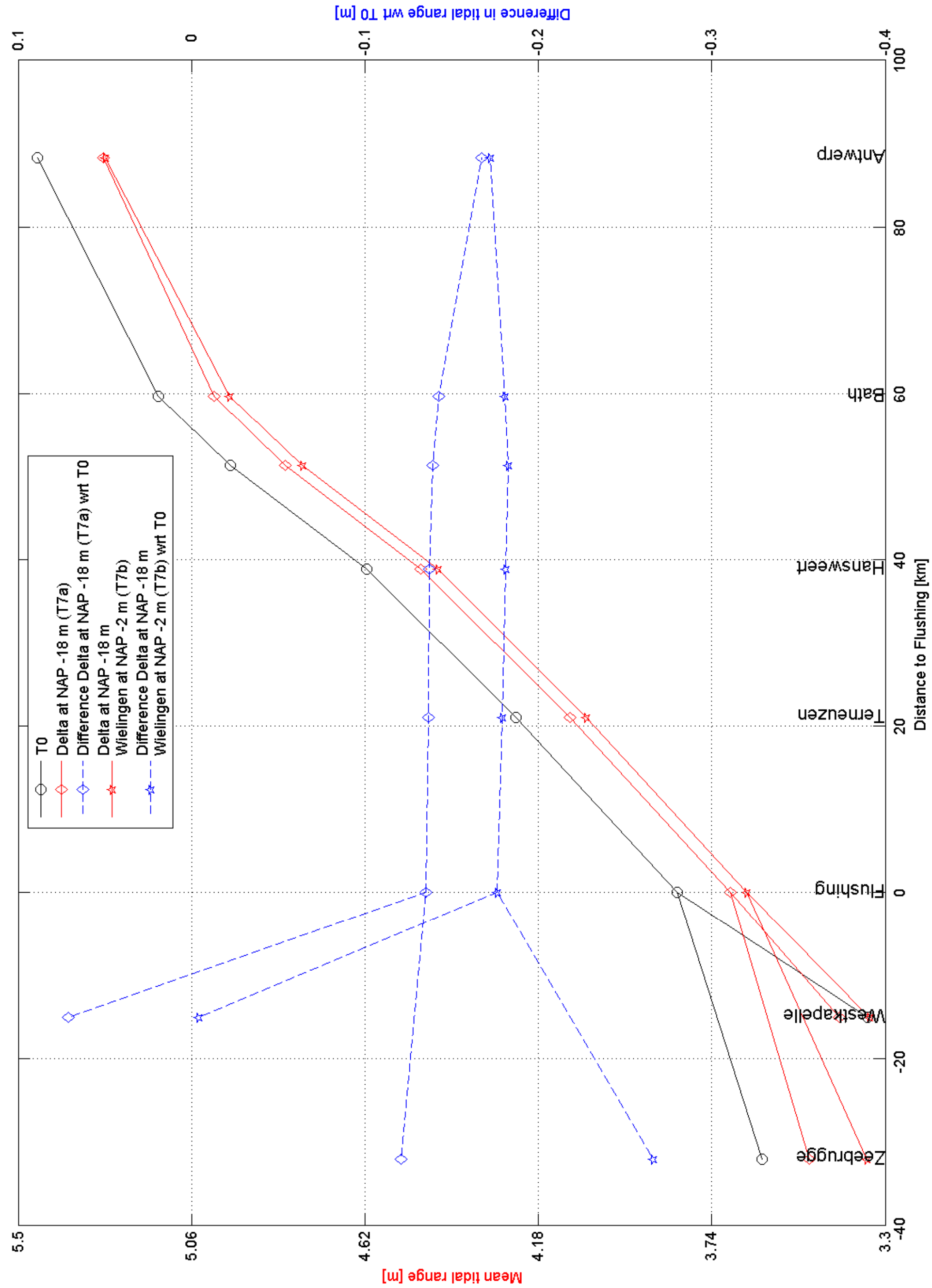

Figure 9.4: Tidal range for scenario T7 along the main tide stations in the Western Scheldt. Scenario T0 and the difference of scenario T7 with respect to scenario T0 are included in the figure as well.

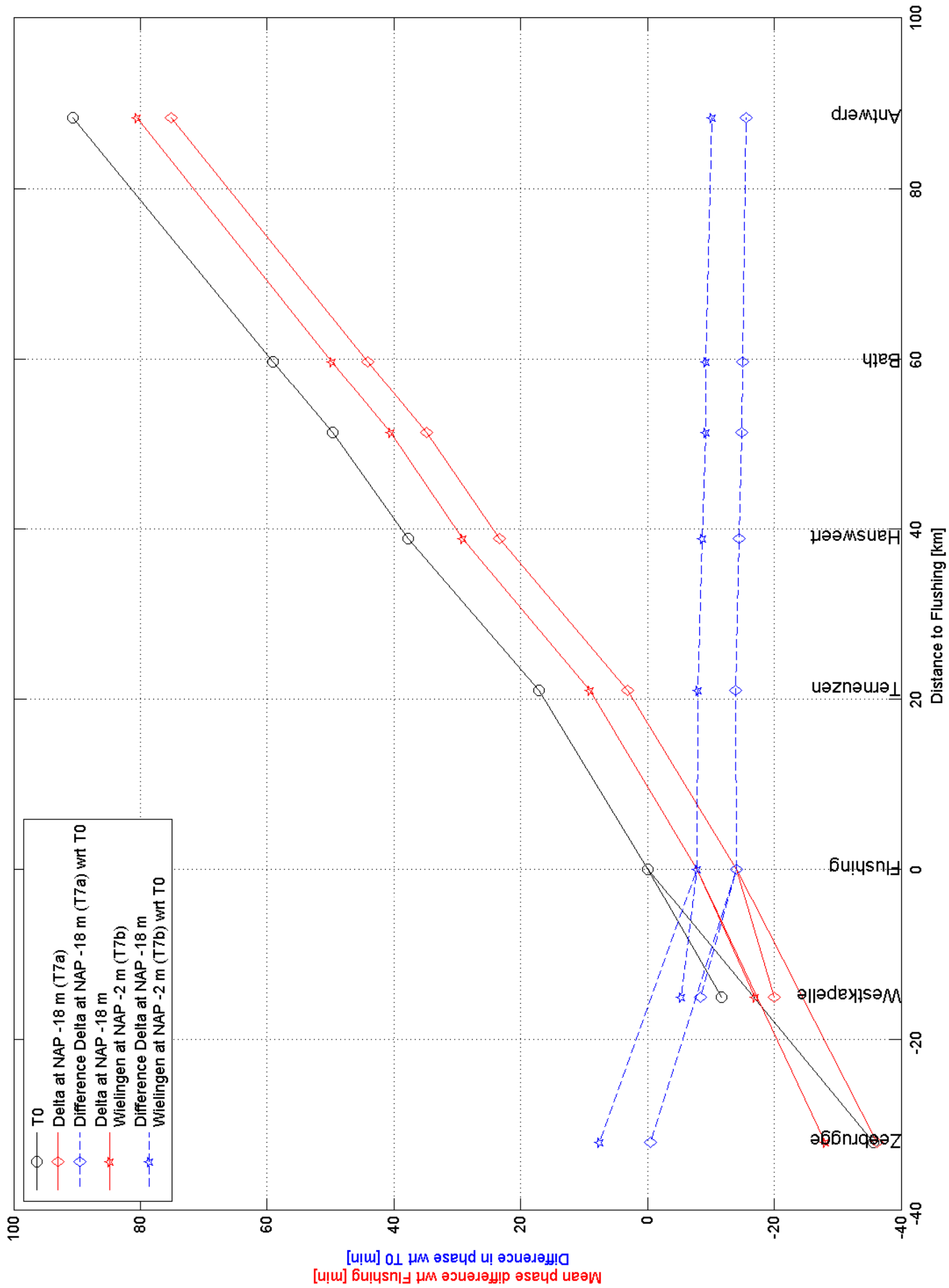

Figure 9.5: Phase difference with respect to T0 at Flushing for scenario T7 along the main tide stations in the Western Scheldt in minutes. Scenario T0 and the difference of scenario T7 with respect to scenario T0 are included in the figure as well.

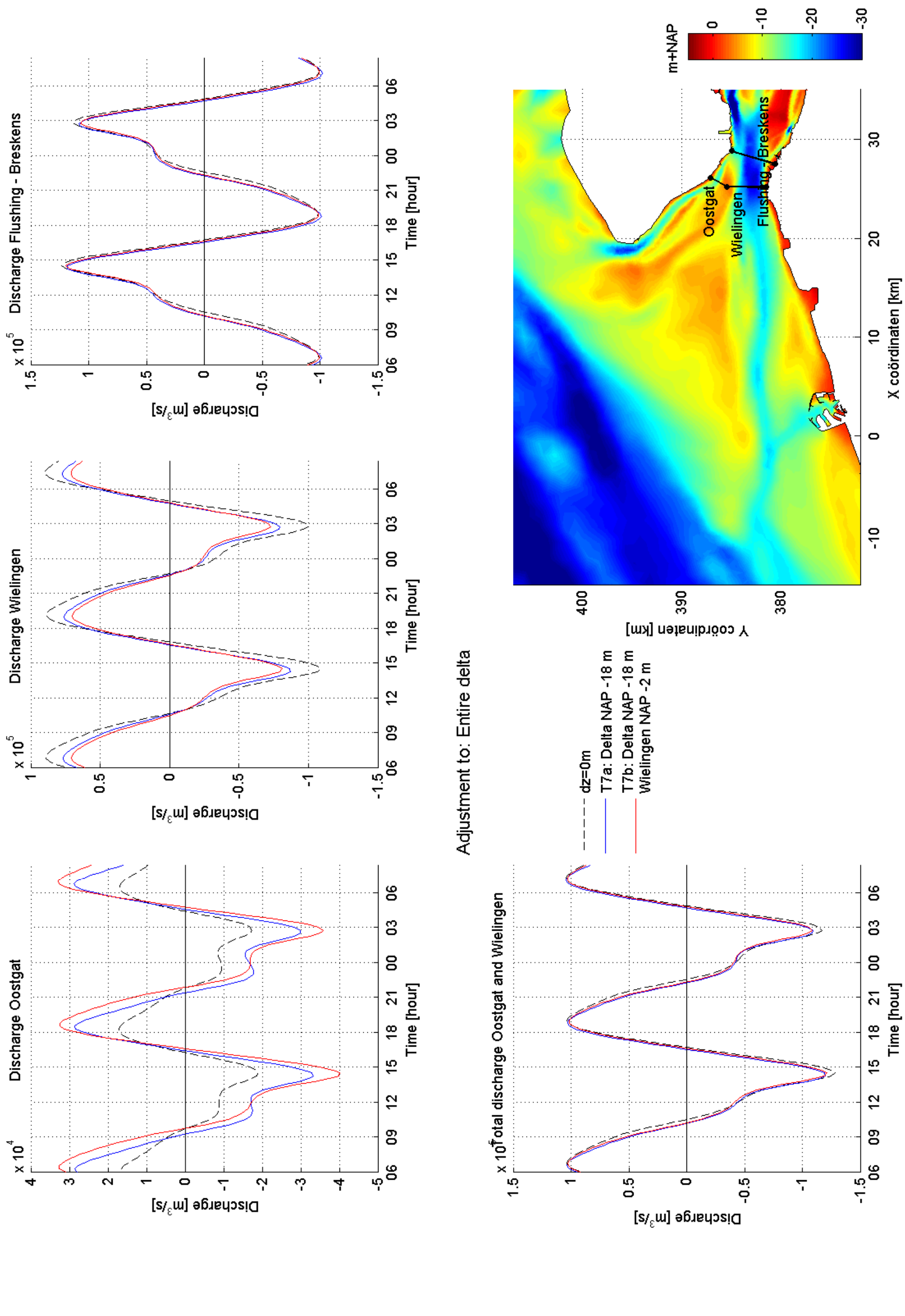

Figure 9.6: Discharge distribution in the Western Scheldt for scenario T0 (dz=0) and T7.

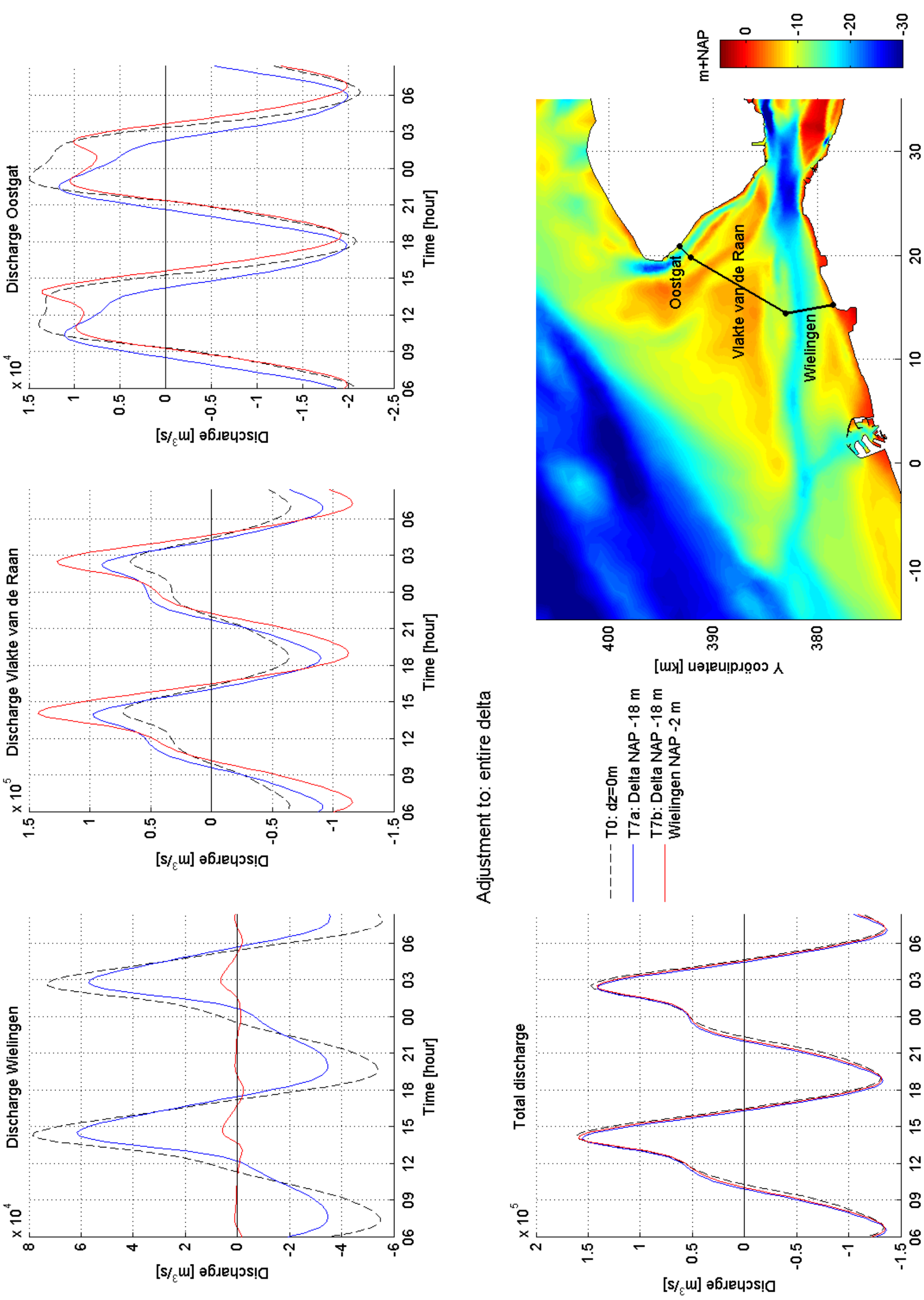

Figure 9.7: Discharge distribution in the estuary mouth of the Western Scheldt for scenario T0 (dz=0) and T7.

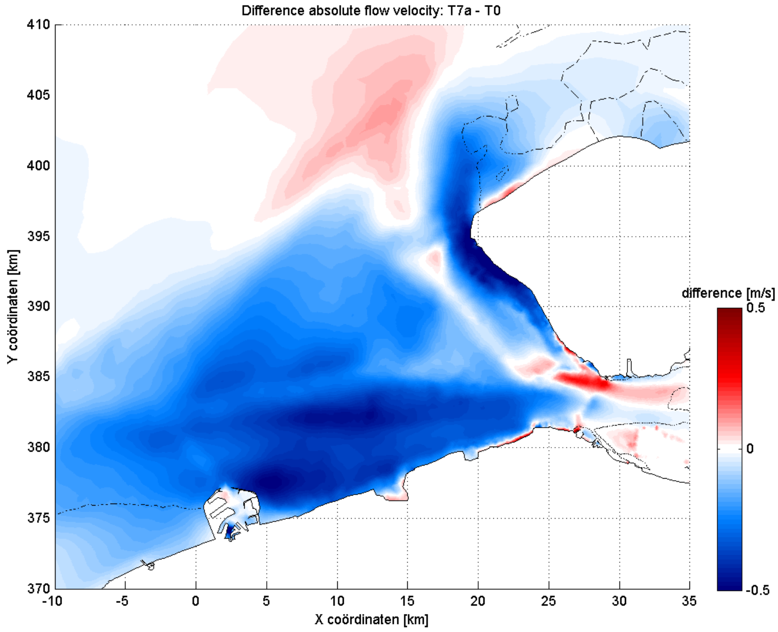

Figure 9.8: Difference in flow velocity between scenario T0 and scenario T7a around maximum flood flow. Red indicates where the flow velocity of scenario T7a is higher than in scenario T0; blue indicates where the flow velocity is lower.

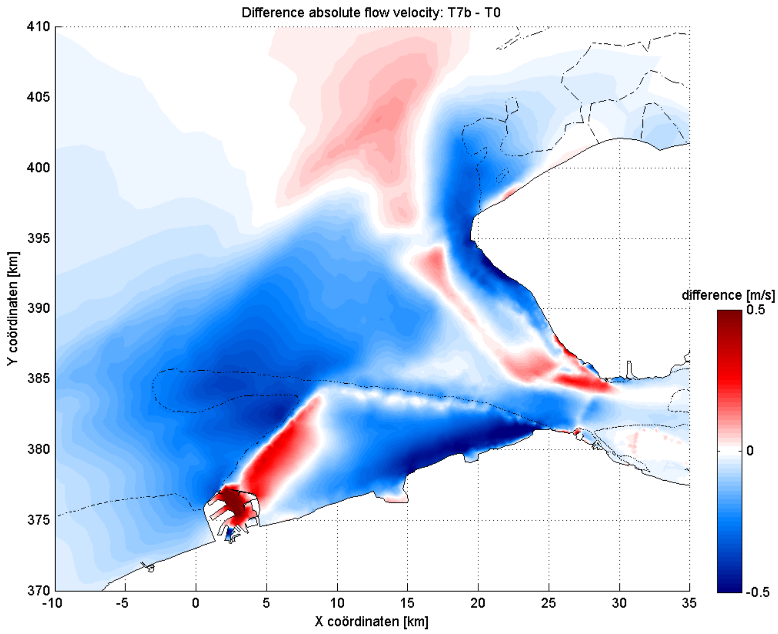

Figure 9.9: Difference in flow velocity between scenario T0 and scenario T7b around maximum flood flow. Red indicates where the flow velocity of scenario T7b is higher than in scenario T0; blue indicates where the flow velocity is lower.

10 RESULTS SCENARIO T8

In scenario T8, again only two bed levels are applied: NAP -18 m and NAP -2 m. In scenarios T8a, T8b and T8c the entire estuary mouth area is defined at a bed level of NAP -2 m. A navigational channel of 500 m wide at a depth of NAP -18 m (approximately the current width and depth of the navigational channel at the Wielingen) is applied at the Oostgat location for scenario T8a (Figure 10.1), the Wielingen for scenario T8b (Figure 10.2) and the Vlakte van de Raan for scenario T8c (Figure 10.3). Scenario T8d (Figure 10.4) is a combination of scenarios T8a and T8c, and contains therefore two navigational channels. Scenario T8e is comparable to scenario T8b, but has a navigational channel of 2000 m wide. An overview of the scenarios is given in Table 10.1.

Table 10.1: Adjustments with respect to the basic model bathymetry for the different scenarios. 'Small' indicates a channel of 500 m wide. 'Wide' indicates a channel of 2000 m wide.

Scenario	Area	Bed level adjustment	Volume
T0	N.a.	N.a.	0 Mm^3
T8a	Oostgat	Estuary mouth NAP -2m, Oostgat 'small' NAP -18m	1924 Mm^3
T8b	Vlakte van de Raan	Estuary mouth NAP -2m, Vlakte van de Raan 'small' NAP -18m	1884 Mm^3
T8c	Wielingen	Estuary mouth NAP -2m, Wielingen 'small' NAP -18m	1862 Mm^3
T8d	Oostgat and Wielingen	Estuary mouth NAP -2m, Wielingen and Oostgat 'small' NAP -18m	1666 Mm^3
T8e	Vlakte van de Raan	Estuary mouth NAP -2m, Vlakte van de Raan 'wide' NAP -18m	1361 Mm^3

The tidal range along the Western Scheldt is for scenarios T8a, T8b and T8c presented in Figure 10.6. Figure 10.7 shows the tidal range for scenarios T8d and T8e. The difference with respect to scenario T0 is indicated in both figures as well. The largest reduction of the tidal range occurs in the estuary mouth. At Flushing, the tidal range has decreased approximately 2.8 m for scenarios T8a, T8b and T8c. In the Western Scheldt a further reduction is observed, caused by a change in shape of the tidal curve (not presented in this report). In total a tidal range reduction of 4.7 m at Antwerp is reached.

Scenario T8d and T8e also lead to a significant reduction of the tidal range (Figure 10.7), however less than scenarios T8a, T8b and T8c. For scenario T8d the reduction amounts approximately 1.7 m in the estuary mouth and 2.9 m at Bath. At Antwerp, the tidal range has increased again; the reduction however is still 2.8 m. In scenario T8e, where the navigational channel in the estuary mouth is wider than the previous scenarios, the reduction of the tidal range is significantly less, with a reduction of 0.7 m at Flushing and 0.9 m at Antwerp.

Figure 10.8 and Figure 10.9 shows the mean phase difference in the tidal propagation, as well as the difference with respect to scenario T0. The impact of scenarios T8a, T8b and T8c are approximately equal, which is also found for the tidal range. The scenarios cause a significant phase lag. At Flushing, the lag amounts approximately 140 minutes. Further in the Western Scheldt, the phase lag reduces to 95 minutes.

Scenarios T8d and T8e show a similar pattern, however the differences with scenario T0 are smaller. At Flushing, the lag amounts 60 and 105 minutes respectively. This is reduced to a lag of 80 and 50 minutes respectively at Antwerp. The phase shift in scenarios T8a to T8e is significantly larger than all the preceding scenarios. With respect to the preceding scenarios, the intervention in the estuary mouth is significantly larger as well.

Figure 10.10 and Figure 10.11 show the discharge for several locations in the estuary mouth. The figures show that the total discharge in the Western Scheldt decreases. The reduction is largest for scenarios T8a, T8b and T8c, which show the largest reduction in the tidal range as well. The discharge of the several morphological units change significantly in all scenarios and each scenario leads to a different distribution of the total discharge over the three units. This can be explained by the strongly varying location of the navigational channel in the different scenarios.

The difference in flow velocity of scenarios T8a, T8b, T8c, T8d and T8e with respect to scenario T0 is presented in Figure 10.12, Figure 10.13, Figure 10.14, Figure 10.15 and Figure 10.16. The figures present the difference in flow velocity at the same moment in time, and not at the same phase. Considering the large phase differences, conclusions about the development of the flow velocity by means of the figures have to be drawn with care. Considering the large reduction of both the tidal range and the discharge, the reduction of the flow velocity as presented in the figures is realistic. The increase of the flow velocity which is visible in scenario T8e in the navigational channel on the Vlakte van de Raan is also realistic, since a relatively large discharge passes through a relatively small opening.

In scenarios T8a to T8e it seems not important where the navigational channel is located in the estuary mouth, the cross sectional area of the navigational channel is normative for the tidal propagation. When the cross sectional area is enlarged, for instance with a factor two in scenario T8d and with a factor four in scenario T8e, the reduction of the tidal range is significantly smaller. In scenario T8e, where the navigational channel is 2000 m wide, the tidal range reduces only 20 cm more than in scenario T7a, where the entire estuary mouth is defined at a bed level of NAP -18 m.

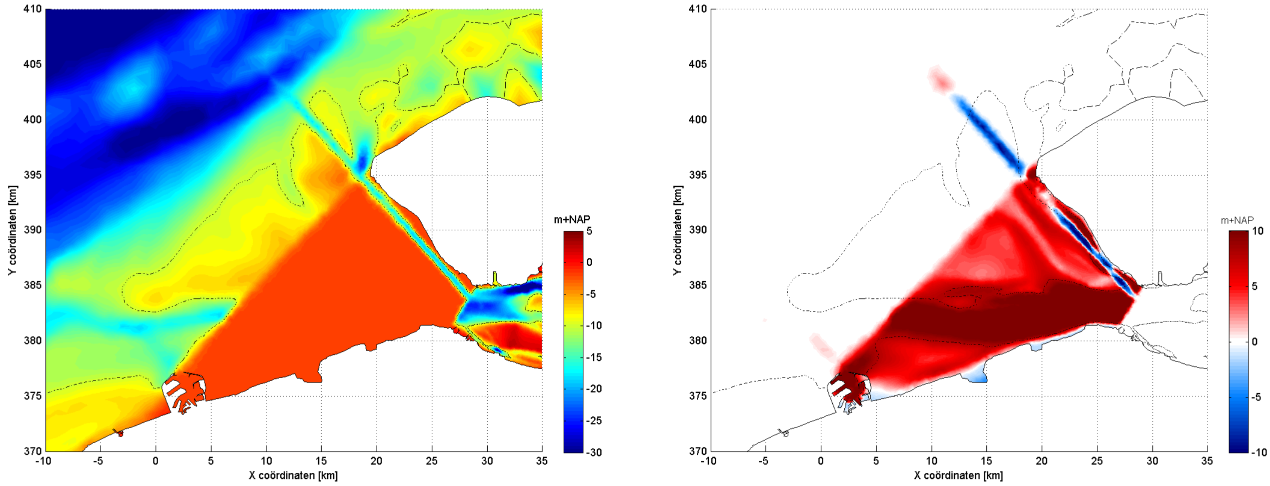

Figure 10.1: Model bathymetry for scenario T8a, and the difference with respect to scenario T0.

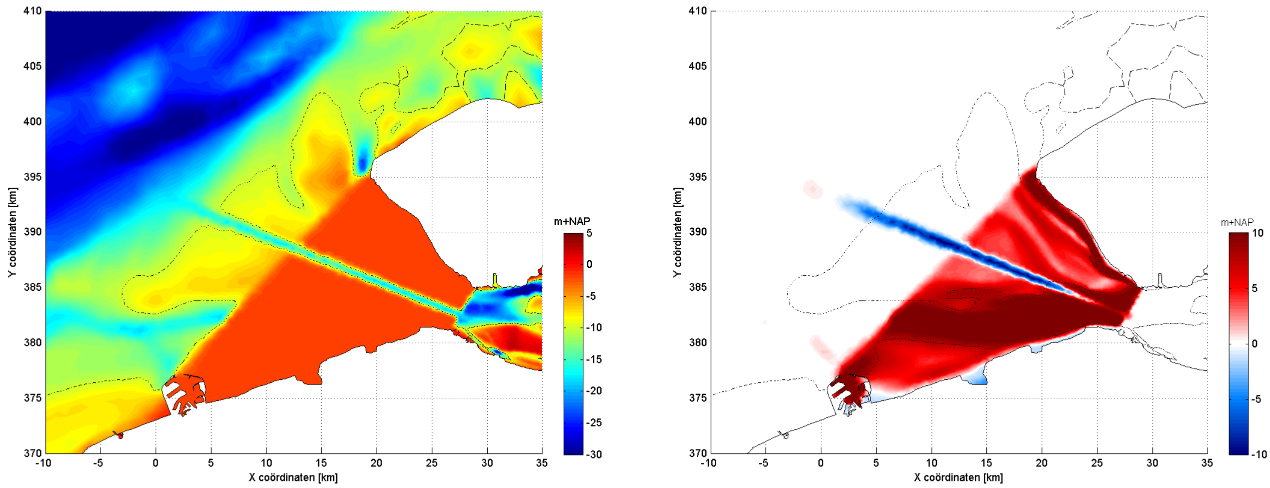

Figure 10.2: Model bathymetry for scenario T8b, and the difference with respect to scenario T0.

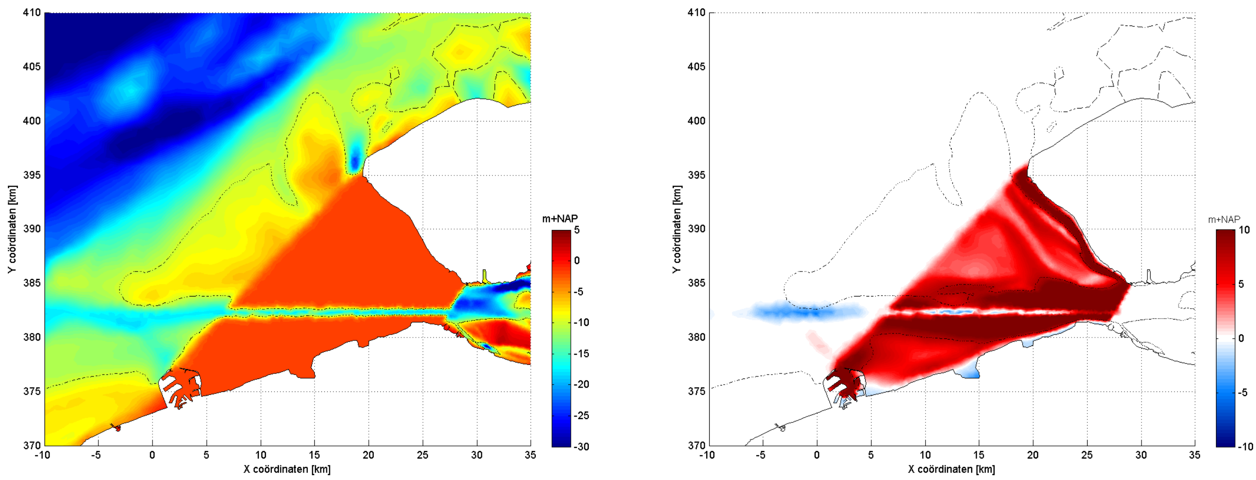

Figure 10.3: Model bathymetry for scenario T8c, and the difference with respect to scenario T0.

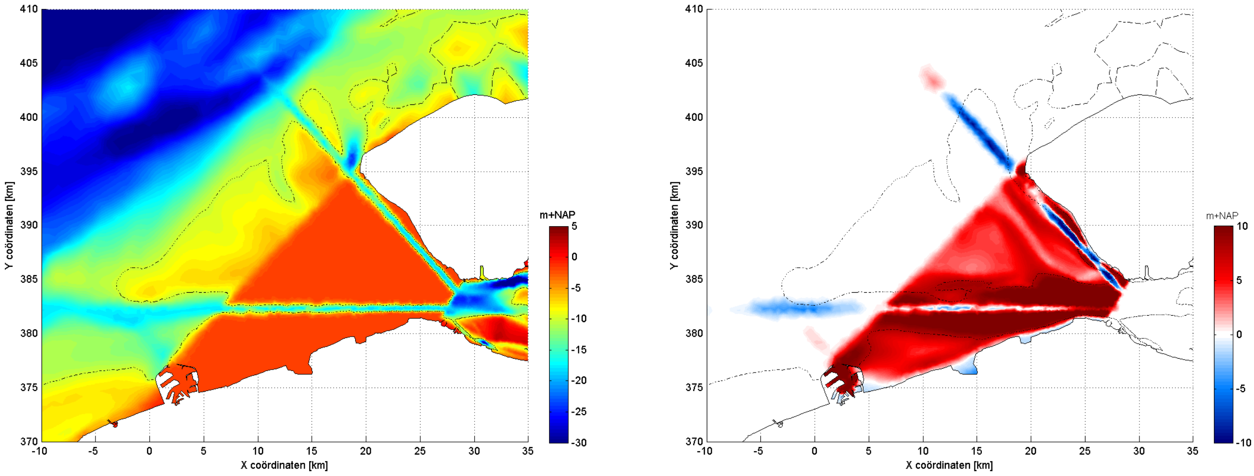

Figure 10.4: Model bathymetry for scenario T8d, and the difference with respect to scenario T0.

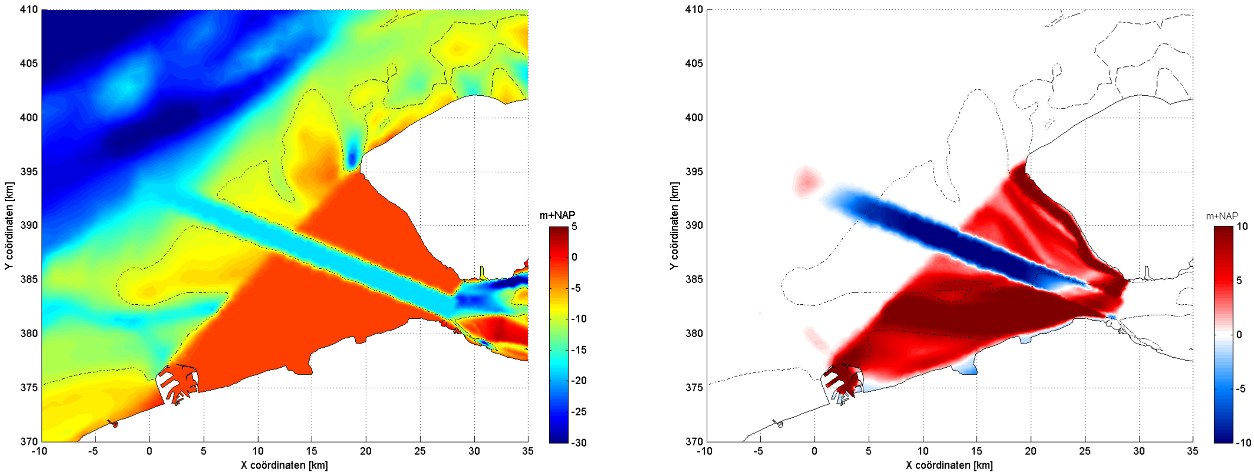

Figure 10.5: Model bathymetry for scenario T8e, and the difference with respect to scenario T0.

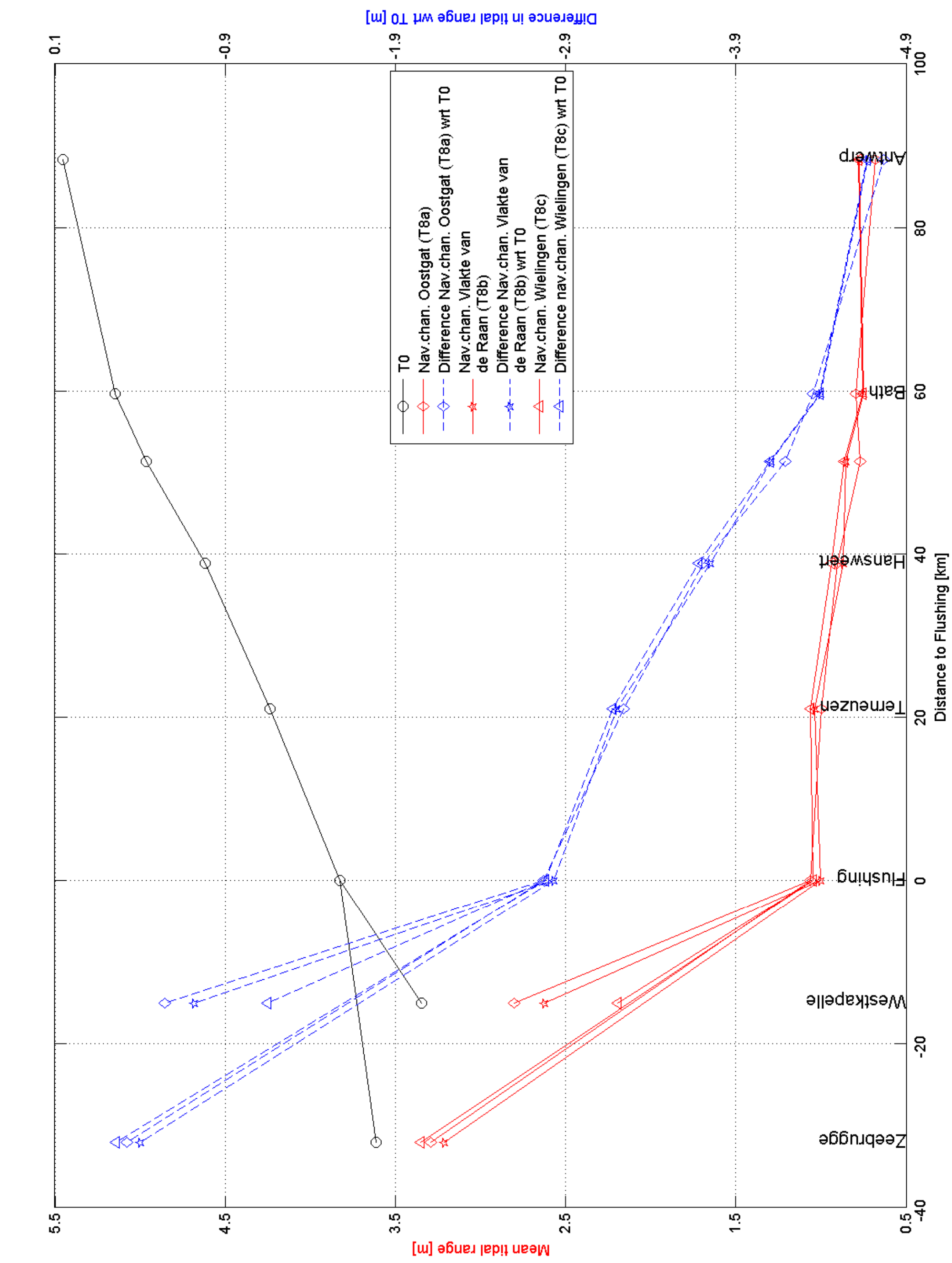

Figure 10.6: Tidal range for scenario T8 (part 1) along the main tide stations in the Western Scheldt. Scenario T0 and the difference of scenario T8 with respect to scenario T0 are included in the figure as well.

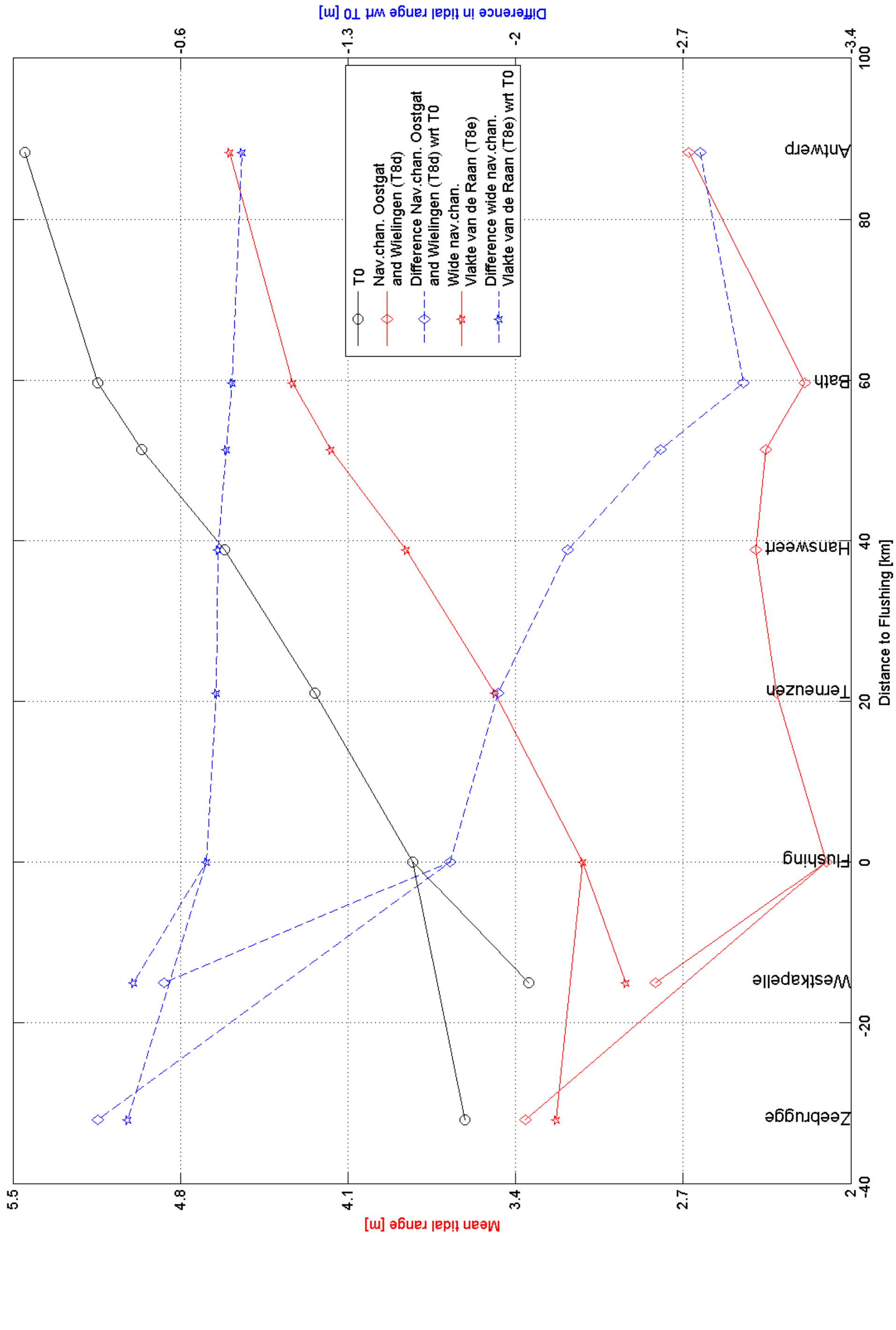

Figure 10.7: Tidal range for scenario T8 (part 2) along the main tide stations in the Western Scheldt. Scenario T0 and the difference of scenario T8 with respect to scenario T0 are included in the figure as well.

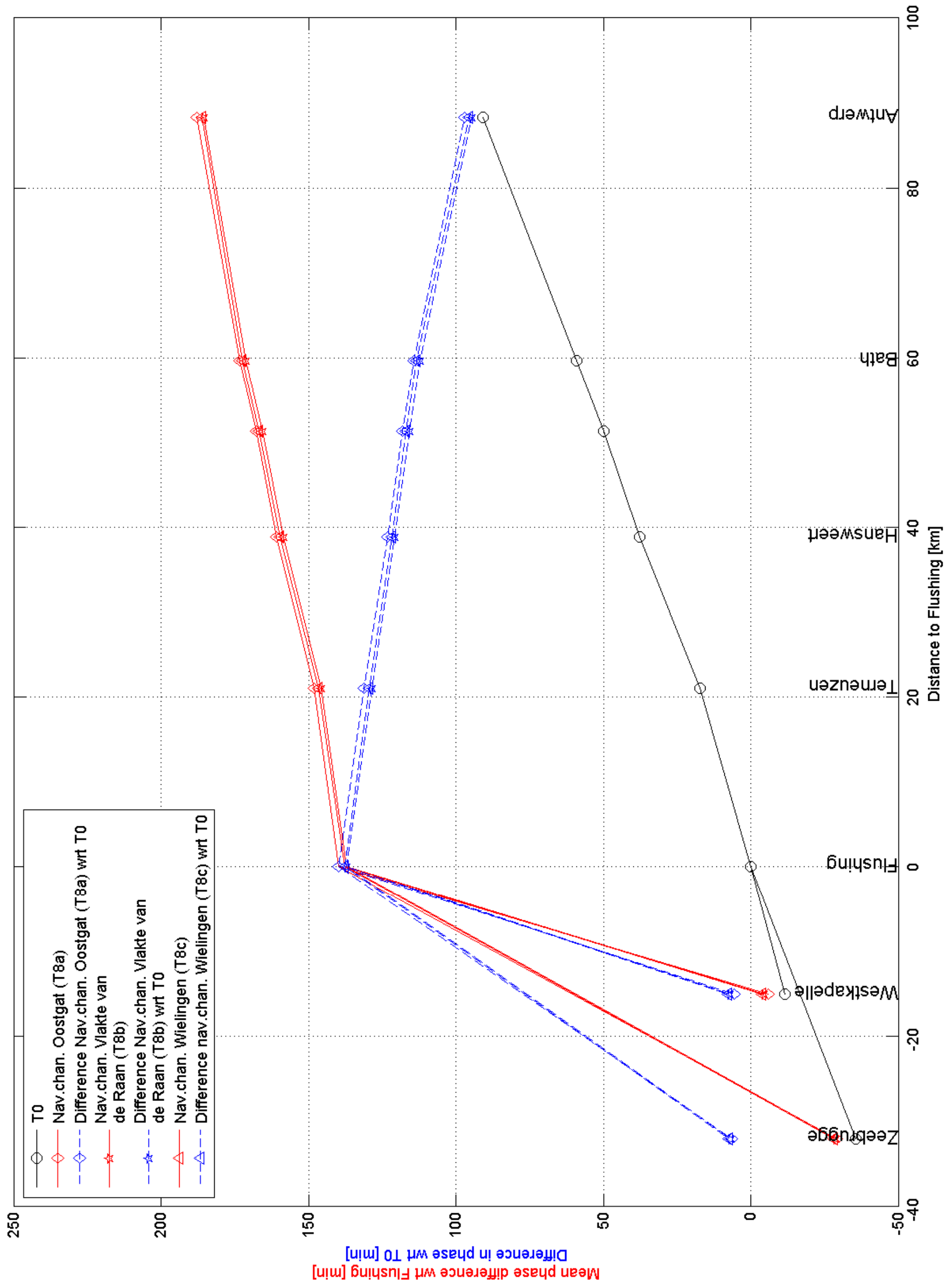

Figure 10.8: Phase difference with respect to T0 at Flushing for scenario T8 (part 1) along the main tide stations in the Western Scheldt in minutes. Scenario T0 and the difference of scenario T8 with respect to scenario T0 are included in the figure as well.

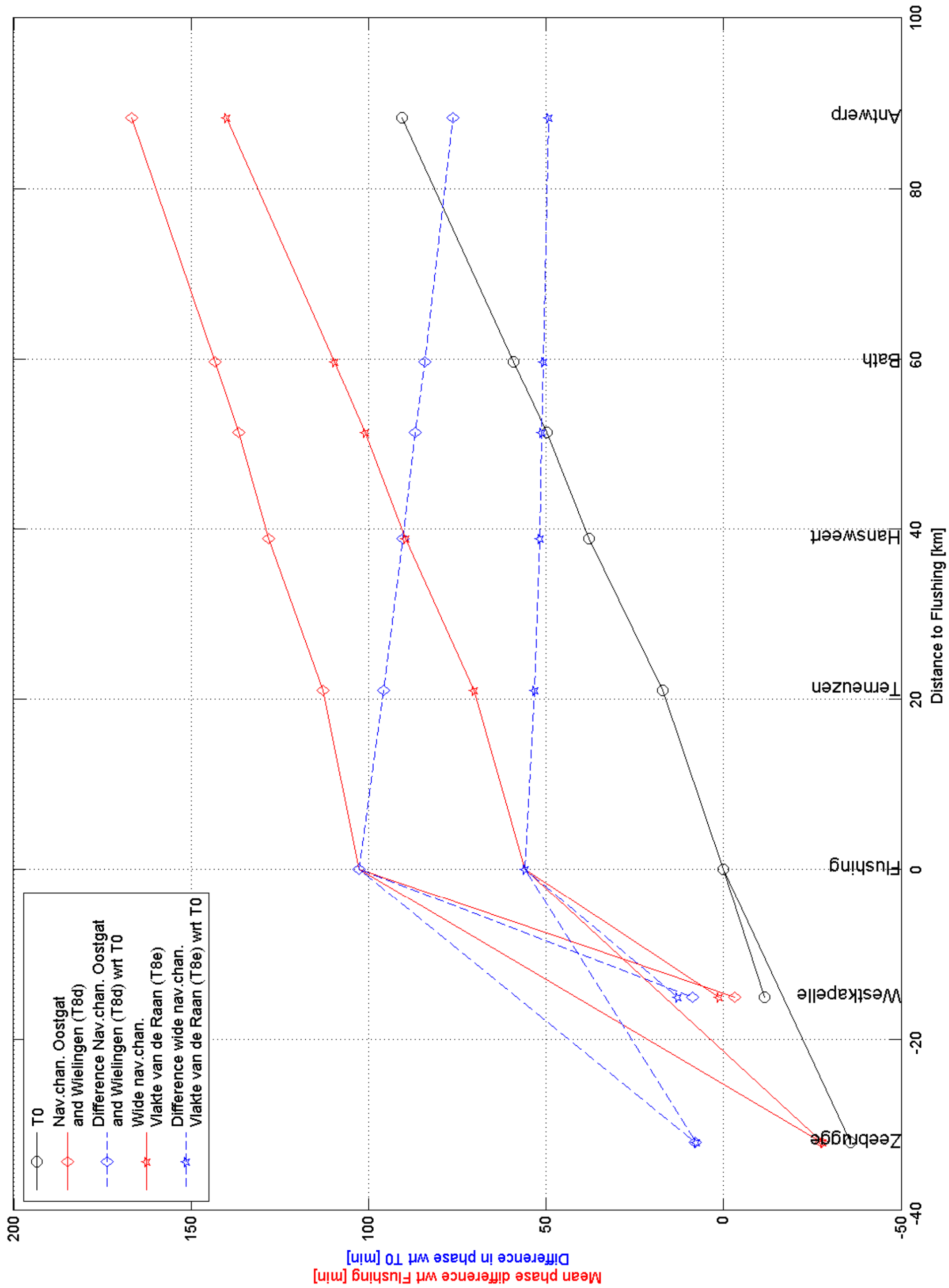

Figure 10.9: Phase difference with respect to T0 at Flushing for scenario T8 (part 2) along the main tide stations in the Western Scheldt in minutes. Scenario T0 and the difference of scenario T8 with respect to scenario T0 are included in the figure as well.

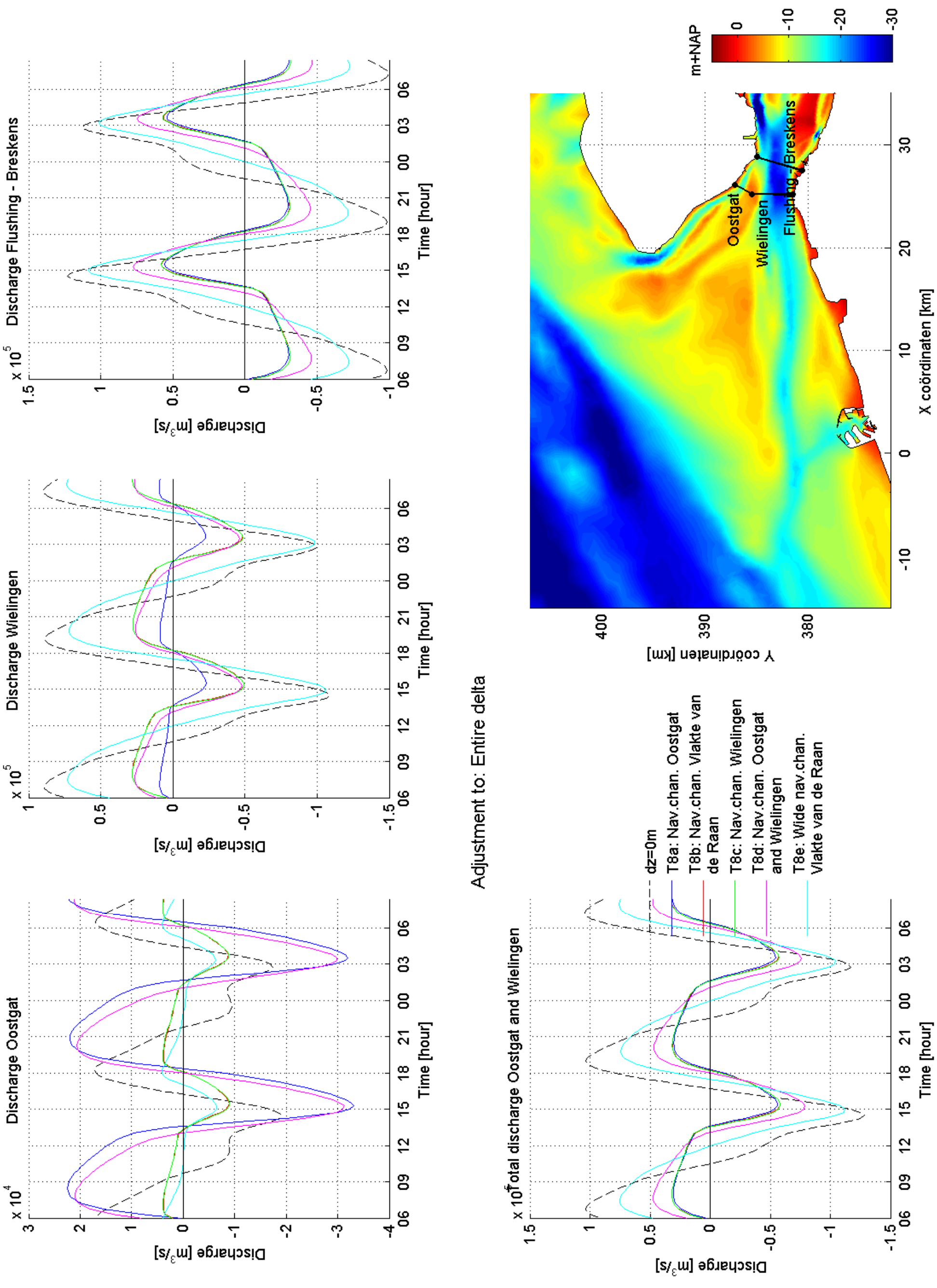

Figure 10.10: Discharge distribution in the Western Scheldt for scenario T0 (dz=0) and T8.

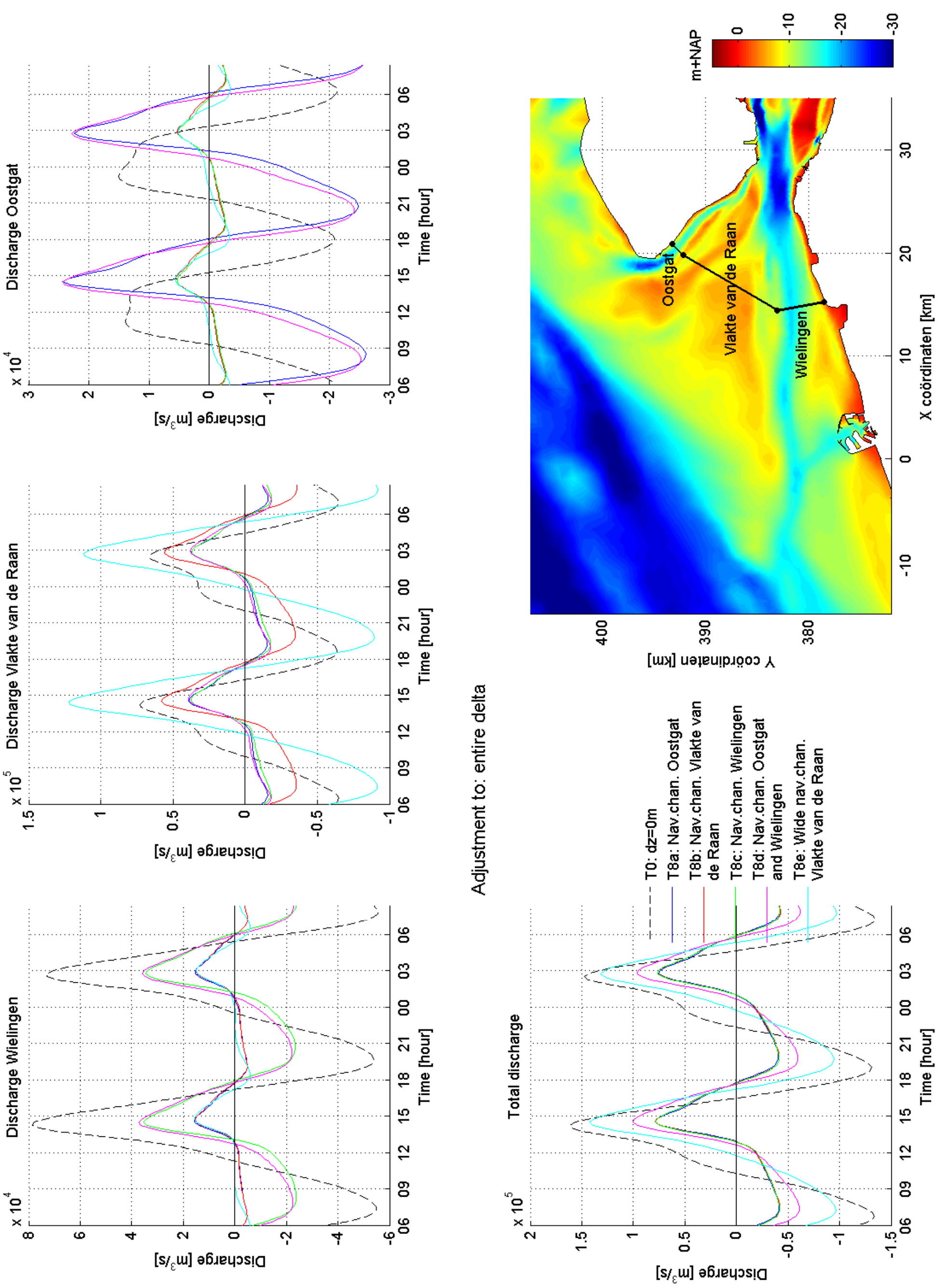

Figure 10.11: Discharge distribution in the estuary mouth of the Western Scheldt for scenario T0 (dz=0) and T8.

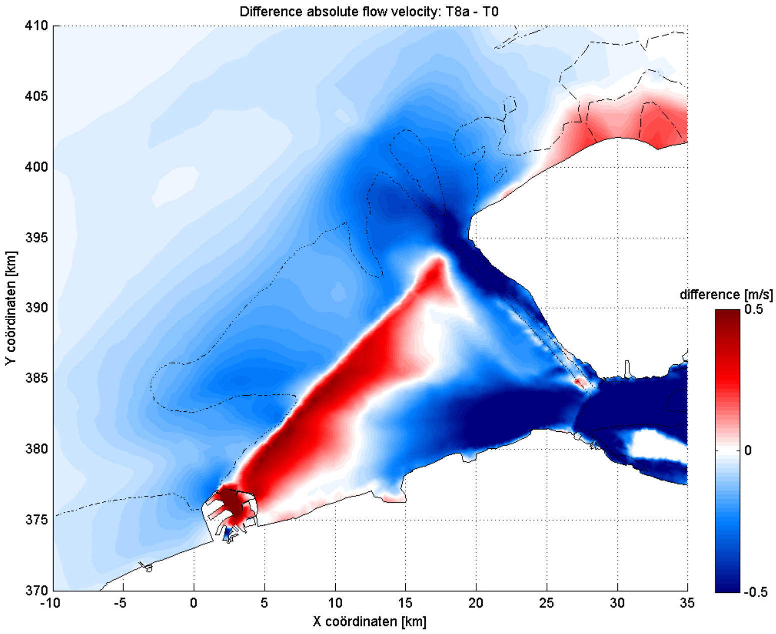

Figure 10.12: Difference in flow velocity between scenario T0 and scenario T8a around maximum flood flow. Red indicates where the flow velocity of scenario T8a is higher than in scenario T0; blue indicates where the flow velocity is lower.

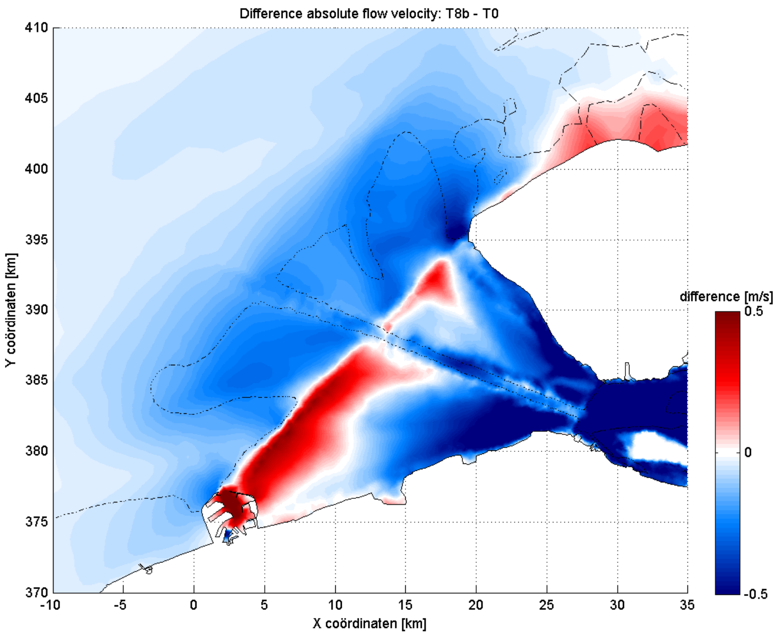

Figure 10.13: Difference in flow velocity between scenario T0 and scenario T8b around maximum flood flow. Red indicates where the flow velocity of scenario T8b is higher than in scenario T0; blue indicates where the flow velocity is lower.

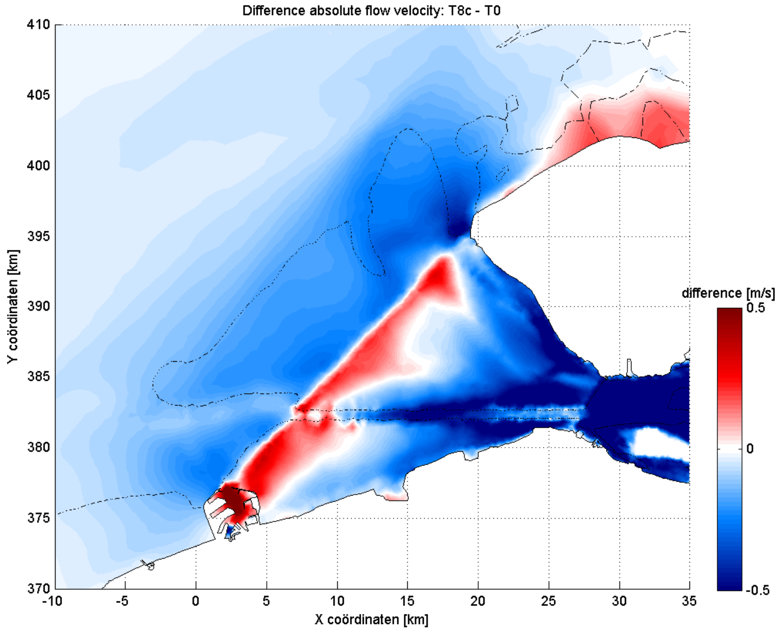

Figure 10.14: Difference in flow velocity between scenario T0 and scenario T8c around maximum flood flow. Red indicates where the flow velocity of scenario T8c is higher than in scenario T0; blue indicates where the flow velocity is lower.

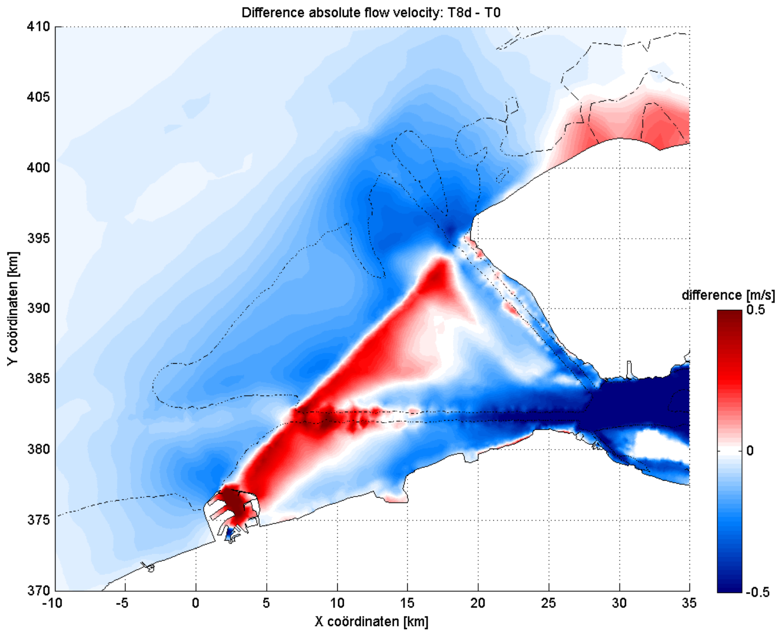

Figure 10.15: Difference in flow velocity between scenario T0 and scenario T8d around maximum flood flow. Red indicates where the flow velocity of scenario T8d is higher than in scenario T0; blue indicates where the flow velocity is lower.

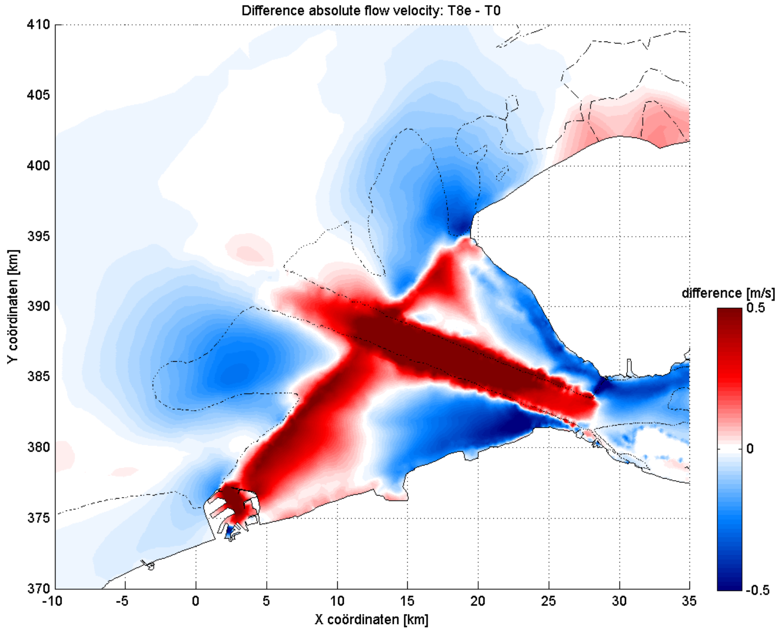

Figure 10.16: Difference in flow velocity between scenario T0 and scenario T8e around maximum flood flow. Red indicates where the flow velocity of scenario T8e is higher than in scenario T0; blue indicates where the flow velocity is lower.

11 CONCLUSIONS AND RECOMMENDATIONS

The past decades the tidal range in the Scheldt estuary has increased. In order to gain insight in the role the Scheldt estuary mouth can potentially play in case of mitigating measures, several exploratory scenarios have been investigated. The effect of the interventions on the tidal range and the phase for the different scenarios are summarised in Table 11.1 and Table 11.2.

The functioning of the tide in the estuary mouth area can be described as follows: the Wielingen, which is used as navigational channel, is mainly important for the inflow of the tide. Deepening this channel results in a larger tidal range in the Western Scheldt. A decrease of the depth of the Wielingen results in a smaller tidal range. The Oostgat channel however is mainly important for the outflow of the tide. Deepening the Oostgat therefore results in a reduction of the tidal range. The Vlakte van de Raan functions similar to the Oostgat. Lowering of the Vlakte van de Raan results in a reduction of the tidal range. The propagation of the tide is schematised in Figure 11.1.

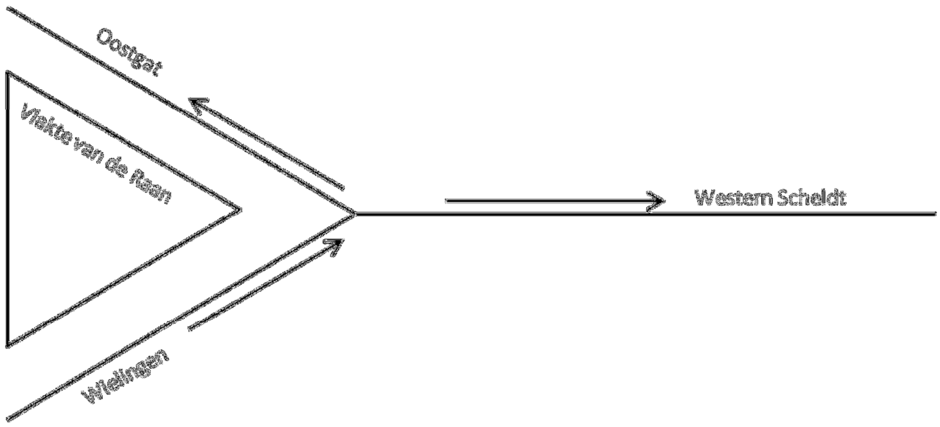

Figure 11.1: Schematisation of the propagation of the tide in the Western Scheldt.

From the simulations it follows that the interventions in the estuary mouth have to be considerably large in order to obtain a significant effect on the tidal range. Filling the full estuary mouth to a bed level of NAP -2 m, except for a navigational channel of 500 m wide at approximately the depth of the current main navigational channel (NAP -18 m), results in a large reduction (over 50%) of the tidal range. The cross-sectional area of the estuary mouth is reduced in such a way, that the discharge decreases significantly. By doubling the cross sectional area, the reduction of the tidal range becomes significantly smaller, with only a limited effect on the tidal range compared to the scenarios with a navigation channel of 500 m wide.

Deepening the Oostgat and applying a 'shoal' in the Wielingen also result in a reduction of the tidal range, however to a limited extend compared to the amount of sediment involved in such a measure. Deepening the Wielingen and heightening the Vlakte van de Raan on the other hand, result in an increase of the tidal range. Lowering the Vlakte van de Raan could lead to a reduction of the tidal range, however the intervention needs to be considerable in order to obtain any significant effect. Besides, this intervention can potentially enhance the export of sand from the Western Scheldt.

Table 11.1: Effect on the tidal range [cm] for the different scenarios and tide stations along the Western Scheldt. A negative difference means a decrease of the tidal range; a positive an increase.

Station / Scenario	Zee-brugge	West-kapelle	Flushing	Terneuzen	Hansweert	Bath	Antwerp
T1a	-0	-1	-0,5	-0,5	-0,5	-0,5	-0,5
T1b	-0,5	-2,5	-1	-1	-1	-1	-1
T1c	-1	-4	-3,5	-3,5	-3,5	-3,5	-3,5
T2a	1	-3	1	1	1	1	1
T2b	2,5	-14	2	2	2	2	2
T2c	9	-34	8	7	9	4	0
T3a	0	1	1	1	1	1	1
T3b	0	2	2	2	2	2	2
T3c	0	4,5	4,5	4,5	4,5	4,5	4,5
T4	2	n.a.	8	8	9	9	8
T5	0	-0,5	-0,5	-0,5	-0,5	-0,5	-0,5
T6a	0	-1,5	-1,5	-1,5	-1,5	-1,5	-1,5
T6b	0	-8	-10	-10	-11	-12	-12
T7a	-12	8	-14	-14	-14	-14	-17
T7b	-26	0	-18	-18	-18	-18	-17
T8a	-60	-70	-280	-320	-370	-440	-470
T8b	-60	-80	-280	-320	-370	-440	-470
T8c	-60	-110	-280	-320	-370	-440	-470
T8d	-30	-50	-170	-190	-230	-290	-280
T8e	-40	-40	-70	-70	-80	-80	-90

Table 11.2: Effect on the phase [minutes] of the tide for the different scenarios and tide stations along the Western Scheldt. A negative phase shift means an acceleration of the tide; a positive one a deceleration.

Station / Scenario	West - kapelle	Zee- brugge	Flushing	Terneuzen	Hansweert	Bath	Antwerp
T1a	0	0	-0,5	-0,5	-0,5	-0,5	-0,5
T1b	0	0	-1	-1	-1	-1	-1
T1c	0	0	-3	-3	-3	-3	-3
T2a	0	1	2	2	2	2	2
T2b	1	4	6	6	6	6	6
T2c	9	4	30	30	30	30	30
T3a	0	0	-0,5	-0,5	-0,5	-0,5	-0,5
T3b	0	-0,5	-1	-1	-1	-1	-1
T3c	0	-1	-3	-3	-3	-3	-3
T4	0	n.a.	3	3	3	3	3
T5	0	0	0	0	0	0	0
T6a	0	0	0,5	0,5	0,5	0,5	0,5
T6b	0	1	3	3	3	3	3
T7a	-1	-8	-15	-15	-15	-15	-15
T7b	8	-6	-8	-8	-8	-8	-8
T8a	10	10	140	140	140	140	140
T8b	10	10	140	140	140	140	140
T8c	10	10	140	140	140	140	140
T8d	10	10	105	105	105	105	105
T8e	10	10	60	60	60	60	60

REFERENCES

Consortium Deltares-IMDC-Svasek-Arcadis (2013). LTV V&T-report: Actualisatierapport Finel 2D Schelde-estuarium (A-26). (In Dutch)

SVAŠEK
HYDRAULICS
COASTAL, HARBOUR AND RIVER CONSULTANTS