

Final - Phase 3

Prepared for:

The National Institute for Coastal and Marine Management (RIKZ) and the Directorate North Sea (DNZ) of the Directorate-General for Public Works and Water Management (RWS)

Morphology of Pits, Channels and Trenches

Part III: Investigation of the longshore and cross-shore impact of various pit designs

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October 2002



CLIENT:	DG Rijkswaterstaat Rijks-Instituut voor Kust en Zee RIKZ							
TITLE:	Morphology of Pits, Channels and Trenches Part III: Investigation of the longshore and cross-shore impact of various pit designs							
ABSTRACT:	For several years the large-scale mining of sand from the Dutch Sector of the North sea is in discussion related to the need of sand for shoreface, beach and dune nourishment and large-scale engineering works at sea (Maasvlakte extension, airport at sea). The mining is considered, basically fall into two categories: wide, shallow or small, deep mining pits. Presently, most sand mining pits with a limited depth, not deeper than about 2 m, are excavated beyond the 20 m depth contour. Deep mining pits have not yet been made extensively. One of the large uncertainties is the morphological response of sand mining pits in different water depths. Although sand mining is not allowed beyond the 20 m depth contour, an onshore migration could result in an increasing morphological response. As a consequence this could adversely affect the stability of the upper parts of the coastal zone. The stability of sand mining pits at deeper water depths is the main focus in this study. From the comparison between a morphodynamic area and 2DV model (Delft3D and Sutrench) it was concluded that the main difference found in the model simulations are caused by the fact that flow contraction was not accounted for in the Sutrench simulation. On the small time scale of 1 year, over which this comparison was made, this primarily results in a different morphological development of the slopes. However, as the backfilling rates are over-estimated in the Sutrench simulations it is expected that this will result in an over-estimation of the migration rates of the pit and an under-prediction of the morphological time scale of pits where flow contraction plays an important role. It emphasises the inherent limitations of the 2DV concept of Sutrench. The Sutrench model can be used to obtain a first order estimate of the occurring bottom changes. However, reliable predictions can only be made if flow contraction is taken into account. Both the longshore and cross-shore morphodynamic simulations have shown that the depth at which pits are constructed has a large influence on the pit stability. Moreover, if the uncertainty of the boundary conditions and model parameters is taken into account, the accuracy ranges show a significant increase for shallower pits. This implies that model predictions for pits in shallower water are associated with an increased uncertainty.							
REFERENCES:	Contract No. RKZ-1079 K2005*ZEEBODEM Generiek Kustonderzoek VOP Project 2							
VER.	ORIGINATOR	DATE	REMARKS	REVIEW	APPROVED BY			
0	D.J.R. Walstra	16 October 2002	Draft	L.C. van Riin	A. Roelfzema			
1	D.J.R. Walstra	01-11-02	Final	L.C. van Riin	A. Roelfzema			
PROJECT IDENTIFICATION:		Z3223						
KEYWORDS:		Morphology of sand mining pits, Delft3D, Sutrench, Unibest-TC						
CONTENTS:	TEXT PAGES	70	TABLES	25	FIGURES	60	APPENDICES	3
CONFIDENTIAL:		☐ YES, until (date) ☒ NO						
STATUS:		☐ PRELIMINARY ☐ DRAFT ☒ FINAL						

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I Introduction

I.1 General

For several years the large-scale mining of sand from the Dutch Sector of the North sea is in discussion related to the need of sand for shoreface, beach and dune nourishment and large-scale engineering works at sea (Maasvlakte extension, airport at sea). The mining methods considered, basically fall into two categories: wide, shallow or small, deep mining pits. Presently, most sand mining pits with a limited depth, not deeper than about 2 m, are excavated beyond the 20 m depth contour. Deep mining pits have not yet been made extensively.

The morphology is affected in the sense that locally the bed level is lowered substantially in the form of a borrow pit (or channel), which influences the local flow and wave fields and hence the sand transport rates due to modification of shoaling, refraction and reflection patterns. The pit area (slopes) may migrate towards the shore over time and/or may act as a sink (trapping) for sediments from the nearshore system. On long term (100 years) the area of influence may extend over tens of km's outside the original mining area. Furthermore, the small-scale and large-scale bed forms (from megaripples to sand waves) may be destroyed locally, which may also have an effect on the hydrodynamic system (less friction and turbulence). Various studies of the morphological consequences of sea sand mining have been performed, but most of these consequences can not yet be fully overseen and further studies are required to line up the positive and negative effects of sea sand mining, so that a rational decision with respect to location and quantity of future sea sand mining can be made.

One of the large uncertainties is the morphological response of sand mining pits in different water depths. Although sand mining is only allowed beyond the 20 m depth contour, an onshore migration could result in an increasing morphological response. As a consequence this could adversely affect the stability of the upper parts of the coastal zone. The stability of sand mining pits at deeper water depths is the main focus in this study which is worked out in three main research questions:

1. What is the morphological response of deep sand mining pits constructed beyond the 20 m depth contour and does the time scale of the morphological response vary significantly for pits in shallower water.
2. Can process based morphodynamic models with one horizontal dimension be used or are morphodynamic area models more applicable.
3. How are the accuracy ranges of the model predictions affected by the water depth at which sand mining pits are constructed and which model parameters cause the largest uncertainties.

I.2 Assignment

In this context WL | Delft Hydraulics was assigned by Rijkswaterstaat/RIKZ (22 October 2001, Overeenkomst RKZ - 1079) to investigate the effect of deep sand mining pits. To that end, the study was sub-divided into three phases:

1. A literature review in which an overview and inventory of the most relevant studies performed up to now, see Van Rijn and Walstra (2002). This review discusses: a) regulations on sea sand mining, b) morphodynamics of offshore mining areas, c) sediment transport and ecological processes in marine conditions, mathematical description of sediment transport and available models, data sets and hindcast studies, mathematical studies related to pits in the North Sea.
2. A model study in which field data obtained from the PUTMOR field campaign is used for the verification of Delft3D. In this phase, the quality of hindcasts made with the Delft3D model are assessed via comparison with measured data from the PUTMOR field campaign. The verification consists of comparison of water level, velocities (depth-averaged, 2DH, and 3 dimensional, 3D) and salinity. A limited morphological sensitivity analysis was carried out in which the predictions made in 2DH and 3D-mode are investigated. Furthermore, the effects of waves on the predicted morphology are investigated. The verification is a first step in the assessment of the quality of predictions made with the Delft3D-model regarding of the possible negative effects of sand mining pits (e.g. morphological stability, water quality, deposition of mud).
3. An assessment of the effects various pit designs may have. With the Delft3D area model and the 2DV Sutrench (longshore) and Unibest-TC (cross-shore) models.

This report constitutes phase 3 of the project.

The study has been done within the Co-operation Framework of Rijkswaterstaat/RIKZ and WL | Delft Hydraulics for Coastal Research (VOP Project 2).

This study was carried out by ir. D.J.R. Walstra (project leader, Delft3D and Unibest-TC simulations) and ir. G. de Boer (Sutrench model simulations). Prof.dr.ir. L.C. van Rijn was the quality coordinator. From R.I.K.Z. the project leaders were ir. M. Boers, ir. J.G. de Ronde and dr. J.P.M. Mulder.

I.3 Approach

In the present study the aim is to investigate the stability of sand mining pits at deeper water depths and how this stability is affected in different water depths. To that end, the morphological impact of pits constructed at water depths of 10 m, 15 m and 20 m where investigated on decadal time scales. The stability of the pits is investigated in both longshore and cross-shore direction with two morphodynamic process models which are specifically designed to simulate the cross-shore and longshore pit development under the influences of waves and tide:

- the Sutrench 2DV-model (applicable to simulate morphology in dominant tidal direction, i.e. longshore direction),

- the Unibest-TC 2DV-model (applicable to simulate the cross-shore profile evolution under the influence of non-breaking and breaking waves).

As the residual longshore transports are several magnitudes larger than the residual cross-shore transports, the morphological development of a pit will primarily occur in longshore direction. Therefore, the main focus of this study is on the longshore stability of pits (situated along the closed coast of The Netherlands). To assess the applicability of the Sutrench modelling concept of considering only one horizontal dimension, a detailed comparison is made with a verified Delft3D area model. The comparison is focussed on the residual longshore transports and the morphological development of a 10 m pit constructed at 25 m water depth one year after construction.

To determine which model parameters cause the largest uncertainties an extensive sensitivity analysis with the Sutrench model is carried out. This analysis comprises an investigation into the effects of varying the wave and tidal forcing conditions and a range of model parameters (all parameters are varied within physically realistic ranges).

To investigate the cross-shore development, the Unibest-TC morphodynamic profile model was used. Cross-shore profile models such as Unibest-TC require a thorough calibration. Although many calibration studies have been performed with the model, the emphasis was usually on the development of the upper part of the bottom profile (surf zone, beach and dune). For the present application a calibration on deeper parts of the bottom profile would be more appropriate. Unfortunately, such a calibration is not possible due to lack of reliable bathymetric data. Therefore, it was decided to apply Unibest-TC model which was calibrated on the long term profile development at Egmond (Boers, 1999).

I.4 Reading guide

The set-up of this report is as follows:

First the Delft3D model simulations are described in Chapter 2. This chapter contains a general description of the designed model and a discussion on the model results. Among others, a comparison is made between the Sutrench and Delft3D model to assess the quality of the Sutrench model.

In Chapter 3, the longshore morphodynamic simulations are made with the Sutrench model. Apart from reference simulations of pits constructed at various water depths, an extensive sensitivity analysis is performed to provide insight in the accuracy ranges of the model predictions.

Chapter 4 deals with the cross-shore morphodynamic simulations, made with the Unibest-TC model. Also here, the development of pits at various water depths is the main interest.

The report is completed with a synthesis of the model study based on which conclusions and recommendations are given.

2 2DH-modelling (Delft3D-Online)

2.1 Introduction

This chapter discusses the morphodynamic simulations that were carried out to hindcast the morphological development of the Lowered Dump Site (LDS) which was monitored in the Putmor project (Svašek, 2001). These simulations were carried out with the Delft3D-Online model which was verified in the previous phase of this project (see Walstra et al., 2002). In addition, the flow module of Delft3D is used to generate water level and tidal velocity boundary conditions for the 2DV Sutrench model (see Chapter 3).

First, the applied model is discussed briefly in Section 2.2. Next, the results of a morphodynamic simulation over a one year period is compared with the measured bathymetric development of the LDS in Section 2.3. Finally, the locations at which the boundary conditions for the Sutrench model are extracted, is described in Section 2.4.

2.2 Delft3D Model Setup

The applied Delft3D model (referred to as the PIT-model) is identical to the model used in the model verification with the PUTMOR data set of Phase 2 (Walstra et al., 2002). Therefore, only a brief description is given of the imposed forcing conditions and the sediment characteristics used in the transport model. In Appendix A, a detailed description of the applied Delft3D models is given.

In the present study representative boundary conditions were used. As these representative conditions were obtained from previous studies only the selected conditions are discussed.

Discharges from inlets and rivers

Below a summary is given of the applied constant, representative, discharge values for all the included inlets and rivers are given

Location	Discharge rate:
Haringvliet	660 m ³ /s
Nieuwe Waterweg	1540 m ³ /s
Sluices of IJmuiden	80 m ³ /s
Sluices of Den Oever	250 m ³ /s
Sluices of Kornwerderzand	200 m ³ /s

Table 2.1 Overview of applied discharges in HCZ model.

Tidal forcing conditions

In Walstra et al. (1997) a representative tidal cycle (referred to as a morphological tide) was selected based on giving an accurate representation of the residual transports over a full neap-spring tidal cycle. The selected representative tide runs from 18 July 1988 3hr20m to 18 July 1988 15hr40m.

Wave climate

For the waves the wave climate from Walstra et al. (1998) is used. This climate consists of a single wave condition from 315 ° N with a height of 2.25 m, a period of 6.6 s occurring 84 % of the time. In Chapter 3, where various representative wave climates were investigated, it is shown that this single wave condition results in approximately similar residual longshore transports than wave climates with 10 or more waves included.

Transport schematisations

The Delft3D-Online model was applied in 2DH-mode. The simulated morphology was scaled to one year (Morphological scaling factor is set to 596.6??). Additional input parameters are summarised in the table below.

Input Parameter	Value
Sediment Density	2650 (kg/m ³)
Median Sediment Diameter, D50	240 (µm)
Dry Bed Density	1600 (kg/m ³)

Table 2.2 Additional model input parameters for morphodynamic simulations.

2.3 One Year Morphodynamic Simulation

A morphodynamic simulation was made with the model described in the previous section and Appendix A. This was primarily done to assess the morphological predictive capabilities of the Delft3D model. However, the Delft3D results are also used in a comparison with the 2DV Sutrench model (with identical boundary conditions) to assess the differences between the two models and to gain insight in the effects that the conceptual 2DV longshore approach, on which the Sutrench model is based. This comparison between Delft3D and Sutrench is presented in the next chapter.

In Figure 2.1 the measured and simulated sedimentation-erosion patterns in and around the LDS are compared after one year. The, in the Putmor project (see Svašek, 2001a, 2001b, 2001c), measured development is shown in the left plot and the simulated results are shown in the right plot are compared. The model result also shows the yearly averaged total transport vectors. The green line indicates the transect which was used by the Sutrench model for the comparison with Delft3D. The measured morphological development had to be derived from a statistical analysis of the available bathymetric surveys as the individual surveys had an accuracy which was smaller then the observed morphological changes. Therefore, the presented sedimentation-erosion is only reliable on the pit slopes (excluding

the southwestern pit slope) and the areas just southeast and northwest of the pit. The outer regions and the landward side of the pit are considered to be too inaccurate for a comparison with the model. In Walstra et al. (2002) a more detailed description is given of the interpretation and accuracy of these measurements.

Taking these limitations into account, the following conclusions were drawn from the measured bottom changes:

- Northeast and Southwest of the pit mainly erosions occurs, whereas the pit slopes experience sedimentation.
- Apart from the erosion of the ridge in the north part of the pit, the pit itself does not show any significant changes although it does seem to experience an overall small sedimentation.
- The southwest pit slope does not show any significant changes, but this is thought to be due to inaccuracies in the measurements.

The modelled bottom changes predict that most changes occur on the pit slopes and just southwest and northeast of the pit which agrees with the trends derived from measured bottom changes. In the pit no significant changes are predicted. However, the ridge in the northern region of the pit is eroded, this sediment is mainly deposited northeast and southwest of this ridge. This erosion was also found in the measurements, although evidence of deposition in the surrounding regions could not be found. Apart from the expected upstream and downstream erosion of the areas just northeast and southwest of the pit, the model also predicts a surprisingly large erosion of the upper areas of the landward pit slope. This seems to be confirmed by the measurements where the landward region just east of the pit is eroded, however this conclusion can not be firm due to the unreliable measurements in this area. For the seaward region, just west of the pit, the model also predicts a limited erosion. The sedimentation of the pit slopes parallel to the dominant tidal motion (i.e. the eastern and western pit slopes) is surprisingly large. This is primarily caused by flow contraction in the pit. As the verification study, carried out in the previous phase of this project (Walstra et al., 2002), showed that the flow contraction is under-predicted in 2DH it is thought that the sedimentation of these parallel pit slopes is under-estimated. Considering the relative small time scale of the morphodynamic simulation it is concluded that cross-shore transports due to flow contraction can not be ignored in long term morphodynamic simulations.

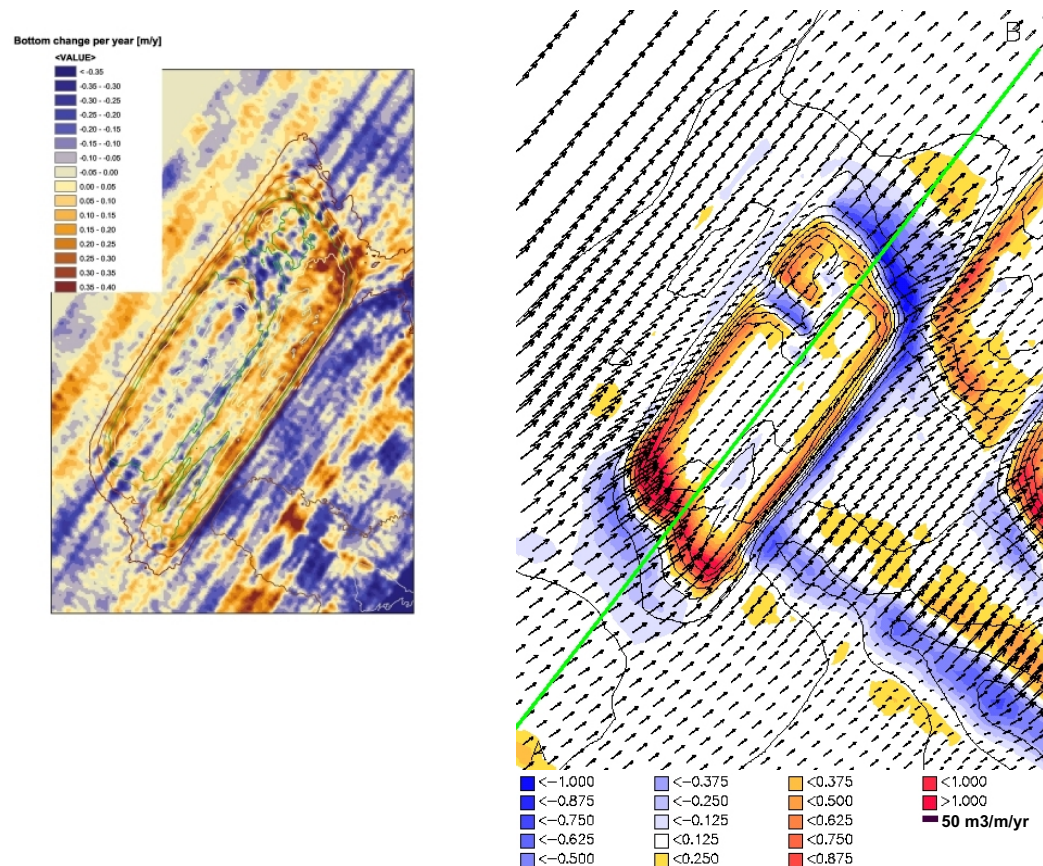


Figure 2.1 Comparison of measured and simulated sedimentation-erosion patterns after one year (left: derived from surveys carried in Putmor project, right: Delft3D model result). The green line indicates the Sutrench transect.

A detailed inspection of the model results is shown in Figure 2.2 where the profile changes, residual longshore transports and residual cross-shore transports are shown along the Sutrench transect (green line in Figure 2.1). The longshore transports (3rd graph in Figure 2.2) inside the trench show the characteristic reduction, but on the slopes the transports show a significant variation. On the southwestern pit slope the residual transports show an increase of about 100% compared to the transports south of the pit. The same effect is present at the northeastern pit slope. As mentioned earlier this is caused by flow contraction on these pit slopes which cause an additional erosion just southwest of the pit and a sedimentation just northeast of the pit. The cross-shore transports also show a significant influence of the pit, although the magnitude is of a smaller order than the longshore transports. Especially, on the southwestern pit slope a significant increased cross-shore transport is predicted which is probably caused by the flow contraction which attracts water offshore from the pit. However the fact that the main tidal motion is not exactly parallel to the orientation of the long axis of the pit can also not be ignored. This could explain the reduction of the cross-shore transports at the northeastern pit slope. In Section 3.2 the Delft3D results are compared in detail with results from a Sutrench simulation with identical boundary conditions.

More information regarding the verification of Delft3D with the Putmor data set can be found in Walstra et al. (2002).

2.4 Generation of boundary conditions for Sutrench simulations

The Sutrench model is used to perform morphodynamic simulations of idealised pits constructed at water depths of 20 m, 15 m and 10 m. The water level and longshore current velocities have been generated by running the Pit-model. In Figure 2.3 the three locations are shown. For a detailed description of the Sutrench simulations is referred to the next chapter.

3 2DV longshore simulations (Sutrench)

3.1 Introduction

3.1.1 General

This chapter contains an investigation into the longshore stability of trenches at depth of 10 m, 15 m and 20 m with the Sutrench model. The dominant forcing in deep water is the tidal motion whereas the waves mainly stir up the sediment and consequently increase the transport capacity. Hence, accurate boundary conditions for waves and tide are vital to make reliable morphodynamic predictions. Therefore, the verified Delft3D model (see Walstra et al., 2002) is used to provide boundary conditions for water level and longshore tidal velocities for the Sutrench model. The required representative tidal forcing conditions and representative wave climate were obtained from earlier studies (Walstra et al., 1997 and Walstra et al., 1998). In addition, an extensive sensitivity analysis with the Sutrench model is carried out to provide insight into the quality of the model predictions and the ranges of accuracy.

In the present study water level and velocity boundary conditions were generated with the Delft3D model verified in Phase 2 of the present project (Walstra et al., 2002) at the investigated water depths. Since the stability of the trench is highly dependent on the water depth, the present study will focus on the sensitivity of the model to boundary conditions and model parameters at various water depths. First the trench design (geometry) parameters are investigated. After that the wave and tidal boundary conditions are varied. Third, the trench is exposed to different values of the physical model parameters. In each of these three investigations, the results of Walstra et al. (1998) are summarised and used, in combination with the findings of the present study, to determine which parameters need further investigation with respect to the water depth. All the simulations are performed for a period of 10 years.

This chapter starts with a summary of the results of the Walstra et al. (1998) study. In Section 3.2 the Sutrench model is compared with the verified Delft3D model for the monitored pit in the Putmor experiment. Next, number of evaluation criteria, to characterise the results, is defined in Section 3.3. This is followed by a description of the base run simulations Section 3.4. Section 3.5 contains an extensive sensitivity analysis in which the wave climate, the tidal schematisation and some physical parameters are thoroughly dealt with. Finally, conclusions are drawn in Section 3.6.

3.1.2 Summary of earlier Sutrench study (Walstra et al., 1998)

An extensive sensitivity analysis in which the morphodynamic behaviour of sand mining pits at deep water were investigated with the Sutrench model was performed by Walstra et

al. (1998). The sensitivity analysis that is presented in this report relies heavily on this earlier study. The approach here is to follow their recommendations and investigate uncertainties of boundary conditions (waves and tide) and model parameters which were not considered in Walstra et al. (1998). In this section the main results and conclusions of this study are summarised.

The central question they answered was: “What will be the effects (on the long term) of large scale sand mining on the lower shoreface of the Dutch coast.” In their study they investigated the effect of three groups of parameters on different time scales (Table 3.1).

Initial geometry	Forcing	Process and model parameters
3 year simulations	3 year simulations	50 year simulations
- trench width	- number of steps in one tide	- thickness of wave mixing layer
- trench depth	- wave height	- wave related mixing coefficient
- trench slope	- wave period	- wave roughness height
- water depth		- current roughness height
		- sediment characteristics
		- reference level

Table 3.1 Model parameters varied in Walstra et al. (1998).

Based on the model simulations summarised in Table 3.1 they concluded that

- The effects of the pit geometry can be considerable. Especially the trench depth and trench width determine the magnitude of the disturbance and hence the backfilling rates. Accordingly, there is an increased morphological interaction between the upstream and the downstream slope with a decreasing trench depth and a decreasing trench width.
- If stability (migration rate) is considered as the main criterion, narrow, relatively deep pits are preferable over wide relatively shallow pits.
- The investigated slope angles as such did not show a significant influence. Differences were mainly due to the fact that the total width of the trench has decreased in case of steep slopes.
- The morphological development of the trench is relatively sensitive to variations of the water depth. The calculated northward directed residual transports were: 80, 50 and 40 m³/m/year for water depths of 15, 20 and 25 m respectively. As tidal velocities were kept constant in the simulation, the resulting transports are largely dependent on the stirring of sediment due to waves. Accordingly, at decreased water depth the sedimentation increases considerably and at increased water depth it decreases.

The main conclusion of the Walstra et al. (1998) study was that: “If the stability (minimum migration rate) is considered as the main criterion, narrow relatively deep pits are preferred over wide relatively shallow pits. Furthermore it was shown that the water depth at which a pit is located can have a dramatic impact on the stability of a trench.”

Limitations of the Walstra et al. (1998) study were:

- The imposed velocity boundaries were identical for the three investigated pit construction depths (15 m, 20 m and 25 m).

- Only a limited sensitivity analysis was performed to investigate variations in the hydrodynamic forcing conditions.
- The sensitivity of the Sutrench model to variations in the parameters listed in Table 3.1 was only investigated for a pit constructed at 20 m water depth.
- Apart from the reference values, only an increased and decreased value were investigated for the model parameters.

3.1.3 Approach

The conclusions and limitations of the Walstra et al. (1998) study were used to set up a study approach which complements their findings:

- The influence of the slope angles is not investigated as it was found they did not have a significant impact on the morphological development. In the present study the width of the pit is kept constant, the focus is on pits with construction depths ranging from 10 m to 20 m at water depths of 10 to 20 m.
- In stead of using constant tidal forcing conditions for the various investigated water depths, the tidal boundary conditions for the Sutrench simulations were obtained from a verified Delft3D-Flow model by means of extracting the water level and velocity data at the appropriate water depths.
- The model settings outlined above were used to perform an extensive sensitivity analysis considering:
 - an investigation into the influence of waves on the residual transports,
 - various representative wave climates used in earlier studies,
 - increased and decreased tidal currents,
 - a complete range of model parameters for which the reference value was varied by 10%, 50%, 150% and 200%.
- To determine the validity of applying the Sutrench 2DV model to simulate the longshore morphology of relative large scale pits, a comparison is made between the Sutrench model and the Delft3D model verified in Phase 2 of this project (Walstra et al., 2002). To that end, the predicted morphological developments of the LDS considered in the Putmor project made by the two model are compared after one year.

3.2 Comparison between Delft3D and Sutrench

To determine the validity of applying the Sutrench 2DV model to simulate the longshore morphology of relative large scale pits, a comparison is made between the Sutrench model and the Delft3D model verified in Phase 2 of this project (of which a summary is given in the previous chapter). To that end, the predicted morphological developments of the LDS considered in the Putmor project made by the two models are compared after one year.

To ensure a reliable comparison between both models, the Sutrench model was set-up by using the forcing conditions and bathymetry from the Delft3D-model. To that end, the tidal boundary conditions for the Sutrench simulation were extracted from the Delft3D model (the boundary conditions for the Sutrench simulation were specified at the southwestern boundary of the model domain). The Sutrench model domain is indicated by the green line in Figure 2.1. This involved water levels and current velocities at the South boundary of the

Sutrench model. The initial bottom profile was also extracted from the Delft3D bathymetry. Lastly, other common model parameters settings were identical.

In Figure 3.1 the results from the Delf3D and Sutrench simulations are compared. In the first (uppermost) plot the initial and final bottom profiles are compared, the second plot shows the calculated bottom changes for both models and the third plot compares the residual longshore sediment transports. As a reference, the residual cross-shore transports of the Delft3D simulation are shown. The predicted bottom changes after one year have the same tendency: a small northward migration of the pit. However, the sedimentation of the southern slope is higher in the Sutrench simulation, whereas at the upper part northern slope the Sutrench model predicts larger erosion rates. The general trends, as shown by the comparison of the bottom changes in the second plot, are very similar. The residual transports of both models have comparable values north and south of the pit. However, on the pit slopes and in the pit itself relative large deviations are present. The transports in the pit, predicted by Delft3D, are significantly higher. This is caused by flow contraction which was not accounted for in the Sutrench simulation. This phenomenon also explains the increased Delft3D transports on the pit slopes.

It can therefore be concluded that the main differences between both models are caused by the fact that flow contraction was not accounted for in the Sutrench simulation. On the relative small time scale of one year this primarily results in a different morphological development of the pit slopes. If longer time scales are considered it is expected that the overall development will show a better agreement between both models as the transport rates outside the pit are very similar. However, as the backfilling rates are over-estimated in the Sutrench simulations it is expected that this will result in an over-estimation of the migration rates of the pit and an under-prediction of the morphological time scale of pits where flow contraction plays an important role.

Although the total transports are comparable between both models, the relative importance of the suspended and bottom transports is approximately opposite. This is to a large extent caused by the difference sediment transport formulas in both models. Delft3D uses the updated transport formulas of van Rijns TRANSPOR2000 model (Van Rijn, 2000), whereas Sutrench uses the original TRANSPOR1993 model formulations. It is recommended to update Sutrench with the improved transport formula of Van Rijn.

3.3 Definition of trench parameters

General

The results will be compared based by means of the transports (1) and the bottom (changes) (2). In order to make an objective comparison between the various applied model settings and investigated trench geometry's it is necessary to formulate some characteristic features (e.g. trench dimension, volumes, slopes, etc.). It is important that the applied method also yields a reliable definition of the slopes, even after a trench has experienced considerable sedimentation and flattening of the downstream slope. Such parameters have already been defined in Walstra et al. (1998). In this section the definition method of Walstra et al.

(1998) is copied. This method will be applied on the resulting bottom profiles and sediment transports. It defines the outer dimensions of the trench, some characteristic locations for determining e.g. the trapping efficiency, the trench volume, width and averaged depth and the subdivision of the trench in three characteristic regions. A few extra parameters solely regarding sedimentation or erosion areas are also introduced.

Definition of trench dimensions

In this sub-section a robust method is described for the definition of the trench dimensions. These trench dimensions are used to define trench features such as the width, average depth and volume of the trench. Furthermore, these trench definitions are, among others, also used to define the trapping efficiency and the sedimentation and erosion in characteristic trench regions.

The angle of the trench slopes is here defined by the inflection points of the first derivative of the trench bottom profile. The trench slopes are thus defined by the inflection points of the slope angle. The first derivative of the bottom profile results in the gradients, the second derivative represents the slope gradients. The zero-crossings of the third derivative then give the inflection points of the slope gradients (i.e. first derivative). In Figure 3.2 this is shown graphically, the graphs show from top to bottom respectively the bottom profile, the bottom gradients (first derivative), the gradients of bottom angles (second derivative) and the third derivative. In all graphs the zero-crossings are indicated.

Based on the derived trench slope angles a logarithmic approximation of the trench slopes can be made. The lower inflection points, defining the transition between the trench bottom and slopes of the trench (see Figure 3.3 points *P2* and *P3*), are used the starting point of the logarithmic approximation. Below the applied logarithmic function is described.

It is assumed that the trench slopes can be approximated by a logarithmic function of the following form:

$$h(x) = h_e \left(1 - e^{\left(\frac{-x}{x_{tau}} \right)} \right) \quad (3.1)$$

where h is the resulting slope profile as a function a horizontal co-ordinate x , h_e is the reference level which acts as a asymptotic limit and x_{tau} which can be interpreted as a horizontal length scale.

This function starts from the lower inflection point (points *P2* and *P3* in Figure 3.3). It is assumed that the trench slope is a good representative of the gradient of the function at the starting point (the line through Points *P3* and *P4* and Points *P1* and *P2* in Figure 3.3). With this assumption the logarithmic function has been defined as the crossing of the line through the inflection points with the reference line, giving x_{tau} . The h_e factor is equal to the vertical distance from the reference line to the bottom inflection point (*P2* and *P3*). The resulting logarithmic approximation is shown in Figure 3.3 as a dashed line. It can be clearly seen that this approximation is in good agreement with the calculated profile which

gives a good indication of the validity of the applied method. The outer dimensions of the trench are now defined by the vertical line from this zero-crossing to the bottom profile (Points *P5* and *P6* in Figure 3.3).

With this simple method, the four points define the trench geometry objectively. These four points can now be used to define some characteristic transport locations, trench volume, width etc. and some characteristic regions of the trench or pit. The next sub-section will be devoted to those definitions.

Definition of transport locations and trench characteristics

To define the volume of a trench, it is necessary to use some definition of the trench. In morphodynamic Sutrench simulations the total trench area does not change because of the conservation of mass. In this study the outer dimensions as defined in the previous sub-section are also used to calculate the trench area. This is shown in Figure 3.3 (third graph), in this graph also the trench width and averaged depth are shown which will be used in the sensitivity analysis. Furthermore, the centre of gravity of the trench (based on the total bottom profile) is used to characterise the migration.

In the sensitivity analysis it is important to study the resulting transports over a trench or pit. For this reason in total six locations will be considered largely based on the trench definition as described in the previous sub-section.

In Walstra et al. (1998) the transports at the up- and downstream boundary of the trench are evaluated by two types of sediment trapping efficiencies. In the results of the present study however, the transports along the main axis of the trench are quite different from the ones in Walstra et al. (1998). This makes them less suited for a description by means of these parameters. Two reasons account for this: (1) inside the middle of the trench the transport are zero for all runs and (2) local maximums and minima are present near the slopes of the trench. Due to the peaks, near the north slope even negative transport occur. Accordingly, the trapping efficiency defined in Walstra (~ transport at south boundary minus transport in trench) et al. (1998) may turn out to be too large. Therefore just the residual transports outside the trench are evaluated to compare the various runs. These residual transports are calculated over the first tide of the simulation. Consequently, the feedback of the bottom changes and the transport is not presented in this data. The initial instantaneous transports during maximum ebb and flood currents are also used to evaluate the results.

The simulation time used in the present study is 10 years. On this short time scale considered, the model resulted mainly in sedimentation of the upstream slope and erosion of the downstream slope. Accordingly the slopes are not morphologically interactive. The autonomous behaviour of the slopes make it possible to define additional parameters, related to the sedimentation or erosion area only: (a) the centre of gravity, (b) the volume and (c) maximum height of a sedimentation /erosion area.

It is noted that in each subsection only a selection of the trench parameters (Table 3.2) is used to investigate the effects of the input parameters studied. Not all the parameters are useful in each case. When for instance the bottom changes are small, which is the case

when the simulation period is short or when the transports are small, the trench mutation parameters are very small and not meaningful. The bottom change parameters on the other hand are only meaningful when the slopes of the trench are morphologically not interactive. Accordingly, these parameters are not meaningful when the transports are large or when the simulation period is long.

Assessment parameter:	Location:	Unit
decrease of wet volume trench	trench	m ³
displacement centre of gravity trench	trench	m
decrease horizontal length trench	trench	m
volume of sedimentation / erosion area on slopes	sedimentation /erosion area	m ³
heights sedimentation / erosion areas on slopes	sedimentation /erosion area	m
location centre of gravity sedimentation / erosion area on slopes	sedimentation /erosion area	m
initial residual transports outside trench	outside trench	m ³ /m/year
initial ebb /flood transports outside trench	outside trench	m ³ /m/year

Table 3.2 Objective parameters used to compare sensitivity runs

3.4 Base run simulations

3.4.1 Set-up base-runs

Design parameters

The main goal of this study is to investigate the behaviour and sensitivity of deep sand pits at different water depths. The design parameters comprise the geometrical parameters (the trench width, the trench depth, the trench slope angle) and the water depth.

In the present study base run simulations are performed for three trench depths: 10, 15 and 20 m. The study by Walstra et al. (1998) showed that the slope has no significant effect on the morphological adjustments. The only effect of the slopes could be attributed to the increased or decreased length of the trench at the reference bottom level. Accordingly, in this study the total trench length is fixed and the slopes are allowed to vary: the slopes become steeper with increasing trench depth.

For the trench geometry idealised profiles are used. These profiles have a smoothly varying bottom gradient at the transitions from the trench slopes to the reference bottom (see Figure 3.5). These rounded transitions reduce the numerical instabilities that may occur at these transitions. Walstra et al.(1998) used the trench geometry of the Euro-Maas channel. They performed runs, both with the real geometry as with an idealised one. Their idealised geometry is less smoothed than the one in the present study. The orientation of the trenches is also different. In the present study an idealised trench off the coast of Scheveningen is used, which has an orientation of the main axis of 35 ° N, while in the Walstra et al. (1998)

study this orientation was 20° N (perpendicular to the Euro-Maasgeul which has an orientation of about 290° N).

Run ID	Trench width [m]	Trench depth [m]	Slope angles [%]	Water depth [m]
b1, b2, b3	1200	10	2.5	10, 15, 20
b4, b5, b6	1200	15	3.75	10, 15, 20
b7, b8, b9	1200	20	5	10, 15, 20

Table 3.3 Base run settings

Since Walstra et al. (1998) conclude that the trench depth has a large influence, this parameters will be varied in the present study as well. Trench depths of 10, 15 and 20 m are used. The trench width is not varied. The water depth at which the trenches are constructed is also varied from 10 to 20 m with accurate tidal forcing conditions obtained from the Delft3D model at each investigated construction depth. The geometrical characteristics are listed in Table 3.3. In order to study the combined effect of the trench depth and water depth nine base run simulations have to be performed in the present study.

Tidal and wave forcing

The tidal and wave forcing depend on the water depth. Wave effects (stirring) are generally less pronounced at deeper water, while tidal velocities are higher at deeper water. The wave effect is calculated by Sutrench, the difference in tidal velocities should be accounted for by imposing the right boundary conditions in Sutrench. Accordingly, these tidal velocities should be different for the three water depths used: 10, 15 and 20 m.

For each water depth, the water levels and depth-averaged velocities as obtained from a Delft3D calculation have been used as input (see Chapter 2 for a description of the Delft3D model). The water depths and velocities in this Delft3D run have been obtained from a morphological tide determined by Walstra et al. (1997) and used in Walstra et al. (1998). This morphological tide is used in the present study as well to be able to compare the results to previous studies. The morphological tide runs from 3hr20 min 18 July 1988 to 15h40m 18 July 1988. In Figure 2.3 the locations at which the hydrodynamic boundary conditions are extracted from the Delft3D model are shown. The velocities of this tide and the water elevations are shown in Figure 3.4. At 20 depth the maximum depth-averaged velocities are up to 0.7 m/s, at 15 m a little over 0.6 m/s and at 10 m slightly below 0.6 m/s. The streamlines cross the trench at 20° at most. In Walstra et al. (1998) the streamlines crossed the trench at 17° .

For the waves the wave climate from Walstra et al. (1998) is used. This climate consists of a single wave condition from 315° N with a height of 2.25 m, a period of 6.6 s occurring 84 % of the time. Since the main axis of the trench is 35° N, the angle between the waves and the current is 100° . This morphological wave climate has been imposed in Sutrench by starting each simulation with a non-stop 8.4 year wave period, followed by 2.6 years without waves.

Physical parameters

All the physical parameters (Table 3.4) are the same as in the study of Walstra et al. (1998).

Model parameter / Boundary Condition	Symbol	Setting	unit
Simulation period		10	year
Number of tides		48	#
Representative wave height	H_{sig}	2.25	m
Wave period	T_{sig}	6.6	s
Wave direction	α	315	° N
Percentage of occurrence representative wave		84	%
Wave related roughness	r_w	0.01	m
Current related roughness	r_c	0.05	m
Reference level	z_a	0.05	m
Median grain size	d_{50}	210	μm
90 % Grain size	d_{90}	310	μm
Sediment fall velocity	w_s	0.0275	m/s
Computational step size	d_x	10	m
Number of computational points in vertical		15	#
Number of time steps per tide		19	#
Coefficient pseudo viscosity	α_{max}	0.0005	#
Correction factor for ca		0.7	#

Table 3.4 Settings of base run

3.4.2 Results base runs

Residual transports

The residual transports (including pores of 40%) during the first tide of the simulation have been investigated/plotted in the bottom panes of Figures 3.5 to 3.13. The values outside the trench are given in Figure 3.14. These figures show that all the tide averaged transports are in the order of $40 \text{ m}^3/\text{m}/\text{year}$. The difference between the transports at deep water (20 m) and at 10 m are small: the total transport at deep water is about 40, while the total transport at 10 m deep water is a little less than 50. Surprisingly, the transport at the intermediate water depth of 15 m is significantly smaller than the transports at 10 and 20 m depth: almost $30 \text{ m}^3/\text{m}/\text{year}$. A possible explanation for this is the following. At 10 and at 20 m different mechanisms are responsible for the large transports. At 10 m depth the wave (stirring) action is strong, while at 20 m depth the tidal velocities are large (Figure 3.4). The decrease in wave effect at 20 m is compensated by the larger tidal velocities at 20 m depth. The difference between the transports at 10 and 20 m is mainly due to the suspended transports. Apparently, at 15 m the combined effect of wave and current is smaller than at 10 and 20 m depth.

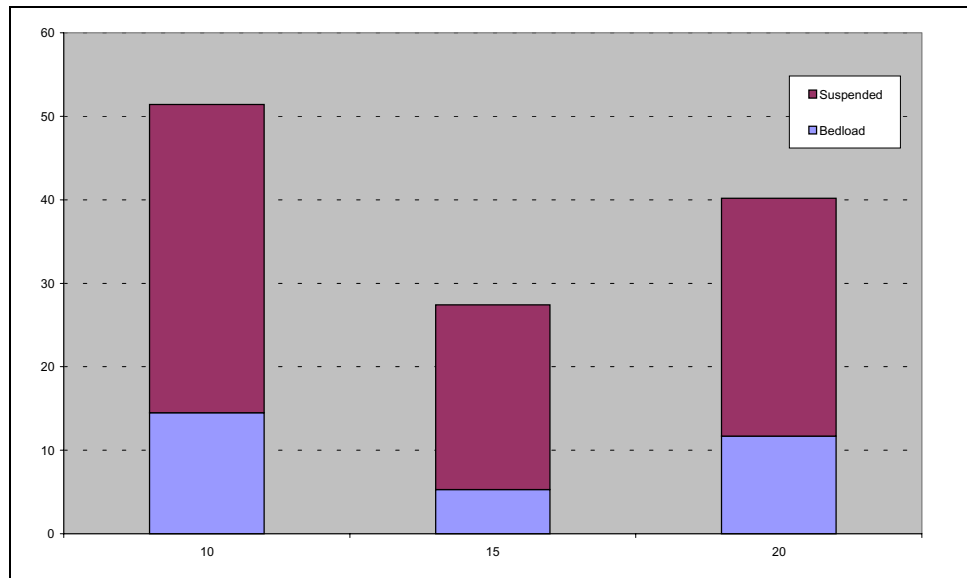


Figure 3.14 Residual transports in m³/m/year outside trench at different water depths.

The values of the tide averaged transport are of the same order as results found in literature. Van Rijn (1997) for instance reports the values given in Table 3.5. When the transports from the present study are compared to the results of Van Rijn we see the following. The transport at deep water are a little high when compared to Van Rijn (1997), while the transports at 10 m depth are a small when compared to the values from Table 3.5. The most surprising difference is that in the present study the transports at 20 m depth and 10 m are more or less the same, while Van Rijn (1997) finds pronounced differences between them.

The transports are also in correspondence with Walstra et al. (1998). Since the same parameter settings are used as in Walstra et al. (1997), this was to be expected. Only the current velocities, the pit geometry and the water depths are different. Walstra et al. (1998) report for the real geometry at a water depth of 20 m : “Just south of the Euro-Maas channel, the residual, yearly transport rate amount 50 to 55 m³/m/year, in the channel itself about 10 m³/m/year. To the north of the channel, transport capacity increases again, yielding transport rates of about 40 m³/m/year. As a result, about 10 to 15 m³/m/year of sediment is trapped by the channel¹. These residual transport rates are in good correspondence with the rates of 30 to 60 m³/m/year reported by Woudenberg (1996) and the rates about 60 m³/m/year, found by Allersma and Ribberink (1992) at a depth of 19 m.”

	Cross-shore		Longshore		
	Depth = 20 m	Depth = 8 m	Depth = 20 m	Depth = 8 m	
incl. Pores	0 ± 8	0 ± 8	25 ± 17	67 ± 42	[m ³ /m/year]

Table 3.5 Yearly – averaged total load transport in m³/m/year in profile 103 (Van Rijn et al., 1997)

In the present study, the suspended transports dominate the bottom transports by a factor 2 to 3 at 10 and 20 m depth, while at 15 m depth the suspended transports the bedload dominate by a factor 4. In Walstra et al. (1998), the suspended transports dominated the

¹ In the present study the transports at both side of the trench are the same, because the bed level is the same at both sides of the trench. In the base run of Walstra et al. (1998) however, the real geometry is used, in which the bottom at the two sides of the trench is not at the same level.

bottom transports by a factor 4 at 20 m depth. This small difference at 20 m is most likely due to the difference in tidal velocities.

In the trench the transports are virtually zero: the dredging trapping efficiency is about 100% (TE_{dredge} in Walstra et al., 1998). Moreover, the residual transports north and south of the trench are the same. This means that all the incoming transport is trapped at one side of the trench, while the same amount is picked up at the other end of the trench. On the time scale considered, this resulted primarily in sedimentation on the upstream slope and erosion on the downstream slope.

Although the steady state transports outside the trench at 10 m and 20 m are comparable in magnitude, the variation of the transport along the x-axis is not comparable for the three water depths. At 10 m water depth, the tide averaged-transport becomes asymmetrical with respect to the middle of the trench: the suspended transport shows a minimum near the north slope of the trench ($x = 2500$) and a maximum near the south slope of the trench ($x = 1000$). This effect is not present at 15 and 20 m depth. This effect is due to the changes in the suspended transport only and can be explained by the relative importance of the different mechanisms responsible for the transport at 10 m depth and deep water. At 10 m depth the relative wave importance in the transport is larger than the relative importance at 20 m depth. The effect of the wave action is explained and studied more thoroughly in the section on the sensitivity due to waves.

This local maximum and minima of the suspended transport at 10 m depth have two main consequences on the transport gradients. First, the gradients at the north and south slope of the trench become larger. Second, the locations of the maximum gradients (the locations of the maximum bottom change) are shifted northwards at 10 m depth.

Instantaneous transports

The third panes in Figures 3.5 to 3.13 show the transports during maximum ebb and flood velocities. The values outside the trench are given in Figure 3.15. These instantaneous transports are about 900 m³/m/year northwards and 400 southwards at 10 m water depth, compared to 400 m³/m/year at 15 and 20 m depth. At 10 m the suspended transport dominate the bedload transports by a factor 2, while at deeper water the suspended and bedload transports are more alike. During the maximum ebb velocities, the bedload transport and the suspended transport are equal. These ratios are in accordance with the ratios found by Walstra et al. (1998).

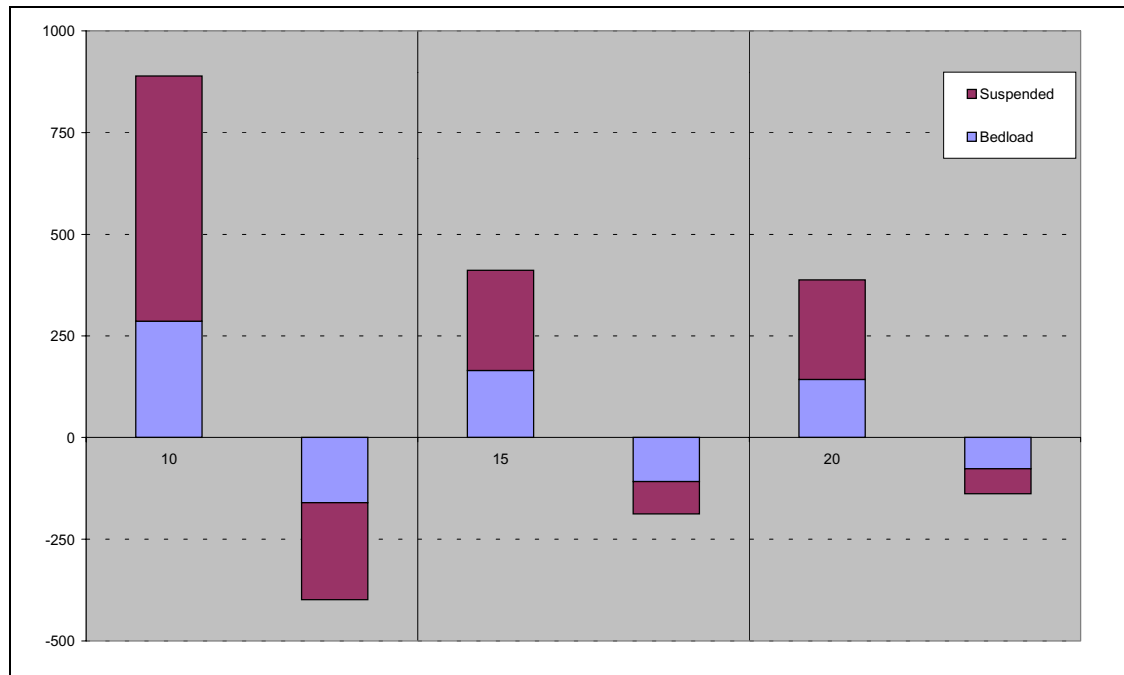


Figure 3.15 Maximum and minimum transports in m³/m/year outside trench at different water depths

Bottom change volumes

The first and second panes in Figures 3.5 to 3.13 show that the bottom changes over the 10 year simulation period are quite small. We can conclude that the morphological time scale of the large sand pits is quite large. The time scale can be estimated by taking the ratio of the pit volume and the residual transports outside the trench (since the trapping efficiency is 100%). With a pit volume of 15000 m³/m this results in time scales of about 290, 530 and 370 years for a pit constructed at 10, 15 and 20 m water depth, respectively.

This time scale is a first order estimate, since the backfilling rates will decrease in time. The time scale is indeed much larger than the simulation period. This explains the small bottom changes observed in 10 years. Note that these backfilling rates are over-estimated by Sutrench due to the fact that flow contraction was not accounted for. The Delft3D simulation showed a trapping efficiency in the order of about 50% (derived from the residual Delft3D transports presented in Figure 3.1). Consequently, the morphological time scales are more likely to be twice as high.

As mentioned earlier, the dredging trapping efficiency of the deep trench is about 100%. Due to the width and large depth of the sand pits, all the trapped sediment settles on the south slope of the trench. Moreover, all erosion happens on the north slopes of the trench. The bottom of the trench itself is not affected. Accordingly the slopes show no morphological interaction. The behaviour on both slopes is autonomous. In smaller trenches and at longer time scales the slopes would interact according to Walstra et al. (1998).

In Table 3.6 the decrease of the wet volume (the sedimentation volume) of the trench is listed. There is no relation between the trench depth and the decrease of wet volume (compare the three rows). There is a relation to the water depth (compare the columns): the

wet volume changes decreases at deeper water. These results surprise for a couple of reasons. First of all, the volume of the trench does not change. The residual transports at both sides of the trench are equal, so there is conservation of mass between the two boundaries of the model. The entire residual transport is trapped at the south slope (trapping efficiency 100%), while the same amount of sediment is picked up at the north slope. No sediment accumulates in the trench.

Trench depth [m]	Water depth [m]		
	10	15	20
10	370	161	111
15	396	131	132
20	373	139	120

Table 3.6 Decrease of wet volume trench in 10 years

Second, if we would expect a wet volume decrease of the trench at all, we would expect the amount of sediment to be equal to the residual transport integrated over 10 years, which for a trench constructed at 20 m water depth is: $40 \text{ m}^3/\text{m}/\text{year} \times 10 \text{ years} = \text{about } 400 \text{ m}^3/\text{m}$. This is more than the values listed in Table 3.6 and is due to the trench definitions applied here. If we have a look at the bottom changes (these are summarised in Figures 3.16 to 3.18 for all investigated geometries) it is clear that there is a close relation between the residual transport outside the pit and volume changes on the pit slopes. The exact values are shown in Table 3.7 from which the symmetrical deposition and erosion is clear for all investigate geometries. In Figure 3.16 to 3.18 the bottom changes for simulations excluding waves is also shown. This provides insight into the tidal residual transports at the investigated water depths. It can be seen that the simulations at 10 m water depth have larger bottom changes than the simulations at 15 m water depth. Apparently, the assumption of reduced tidal residual transports at lower water depths is not true for the tidal conditions specified in this study. In general this assumption does hold, the reduced tidal transport at the 15 m water depth probably are influenced by local effects.

[m ³]	Trench Depth	Water depth		
		10	15	20
Sedimentation Volume south Slope	10	289	181	337
	15	298	182	352
	20	300	183	356
Erosion volume north slope	10	-303	-186	-337
	15	-310	-187	-351
	20	-311	-188	-354

Table 3.7 Volume sedimentation/erosion areas on slopes

Table 3.7 and Figures 3.16 to 3.18 show that the largest sedimentation (& erosion) *volumes* (and *heights*) occur at 10 m depth and 20 m depth. The morphological changes at 15 m are small compared to the changes at 10 and 20 m depth. This is in accordance with the residual transports, which were also highest at 10 m and 20 m depth. The volumes of sedimentation the peak on the south slope and the erosion peak on the north slope are roughly equal to the transport multiplied with the 10 year simulation period. Note that these volumes are not dependent on the trench depth.

As stated earlier, the wet volume figures in Table 3.6 can be explained by the definition of the wet volume given in Walstra et al. (1998). Two basic trench slope definition points are given by the inflection points of the first derivative of the trench bottom profile (See Figures 3.2 and 3.3). Subsequently, a straight line is drawn between these two points. The intersection of this line with the reference level gives the trench dimensions. The wet volume is calculated with these dimensions. So, the figures in Table 3.6 as such cannot be interpreted as a volume loss. The difference between the numbers is interesting. Accordingly, the important conclusion we can draw from Table 3.6, is that the shape of the trench becomes quite different at the three water depths. At 10 m the shape of the trench changes most. The shape of the trench is first investigated by means of the trench shape parameters. Since the sedimentation and erosion on the north and south slopes show no morphological interaction, these areas can also be characterised by objective parameters. Therefore the shape of the trench is also investigated by means of the shape, location and height of the sedimentation/erosion areas.

Trench shape parameters

Table 3.8 shows that the displacement of the centre of gravity of the trench is largest at 10 and 20 m depth. This is in accordance with the findings that the morphological behaviour at these depths is larger than at 10 and 20 m. The table also shows that the migration is larger for a shallower trench. The displacement of the centre of gravity decreases more than linearly with the trench depth. Since for trench depths the same sedimentation/erosion volumes occur on the slopes (Table 3.7), it can be concluded that the shape of the bottom changes differ for all trench depths.

[m]		Water depth [m]		
Trench depth		10	15	20
Northward Migration	10	37.6	22.2	39.5
	15	27.2	15.9	29.2
	20	21.4	12.4	23.0

Table 3.8 Displacement of centre of gravity trench

[m]	Water	depth	[m]
Trench depth	10	15	20
10	85.6	53.4	15.8
15	71.3	15.9	20.1
20	49.0	17.9	3.87

Table 3.9 Decrease horizontal length trench

Table 3.9 shows the horizontal length of the trench (as defined with the points of inflection of the bottom profile). At a water depth of 10 m the horizontal length decreases most, followed the water depth of 15 m. The 20 m depth result is not close to the 10 m results, unlike the residual transports and the bottom change volumes. The horizontal length is also dependent on the trench depth: a deeper length results in a smaller length loss. In a deeper trench more sediment can settle on the slopes (volume above slopes is larger). Accordingly, less sediment will settle in the trench.

The dependence of the trench shape parameters on the trench depth, can be explained by two mechanisms. First, when a volume V deposits on a steep slope, the centre of gravity of this volume will displace less in the direction of the main axis of the trench than with a gentle slope. Accordingly, in sand pits with steeper trenches, the centre of gravity of the trench will displace more than in pits with gentle slopes. Second, the sedimentation volume on the south slope and the erosion volume on the north slope will have less effect on the centre of gravity and the trench length in the deep trenches. The sedimentation and erosion volumes are smaller compared to the larger volumes of the deep trenches. This is also visible in the time scale varying with the trench volume: from 250 years at 10 m to 500 years at 20 m. In fact, to make a fair comparison between the trench depths, one should use trenches with the same reference volume: deep and narrow trenches vs. wide and shallow trenches. Such different trenches all have the same morphological time scale.

Trench bottom height change

In Figures 3.16 to 3.18 the bottom changes at three different water depths are included in one figure. These figures show that the highest sedimentation/ erosion peaks occur at 10 and 20 m depth. In Table 3.10 the exact values of the bottom heights are given. There is also a slight trench depth effect: a deeper trench shows higher peaks due to the stronger acceleration and deceleration rates on the slopes enhancing settling and picking up of sediment (the slopes are steeper in deep trenches).

[m]	Trench Depth	Water Depth		
		10	15	20
Height Sedimentation south Slope	10	1.30	0.65	1.05
	15	1.52	0.74	1.20
	20	1.64	0.76	1.28
Height erosion north Slope	10	-0.53	-0.42	-0.75
	15	-0.55	-0.43	-0.81
	20	-0.59	-0.43	-0.85

Table 3.10 Height sedimentation/erosion area on slopes

Location and shape bottom change

Table 3.11 shows the location of the centre of gravity of the sedimentation/erosion areas. Although the volumes and the height of the erosion and sedimentation areas at 10 m and 20 m depth are the same, the *location* of these sedimentation/erosion areas on the slopes is quite different. Figures 3.16 to 3.18 show that at 10 m depth the north slope is eroded near the sea bottom reference level, while at 20 m depth the erosion starts already halfway the trench slope. This means the north side of the trench keeps the same slope at 10 m depth, while at 20 m depth the slope flattens. At the southern slope little erosion takes place outside the trench at 10 m depth, while this does not happen at 20 m depth. Both the southern slopes at 10 and 20 become steeper.

[m]	Trench Depth	Water Depth		
		10	15	20
Location sedimentation south Slope	10	1324	1234	1170
	15	1271	1184	1124
	20	1235	1151	1090
Location erosion north Slope	10	2704	2589	2498
	15	2736	2636	2534
	20	2765	2666	2566

Table 3.11 Location centre of gravity sedimentation/erosion area on slopes.

Also the *shape* of the sedimentation/erosion areas at 10 and 20 m depth are different. The sedimentation/erosion areas at 10 m depth are more peaked (high and small) at the south slope and more diffuse (wide and low) at the north slope compared to the 20 m results. Due to the differences in location and shape, the trench at 10 m becomes more asymmetrical than the trench at 20 m.

Both the *shape* and *location* of the sedimentation and erosion areas at 15 m depth are the same as the ones at 20 m, while the *height* of the heaps is considerably smaller. Since the shape of the heaps is probably due to the waves, this means that at 15 m the wave effect in the transport is the same as at 20 m, while the current effect is smaller.

3.4.3 Conclusions base runs

- In Section 3.3 a number of parameters were defined to assess the behaviour of the trench. Some of these trench parameters are maximal at a water depth of 10 m and decrease at larger water depths (Table 3.12), while other parameters are maximal at both 10 and 20 m depth and minimal at 15 m depth (Table 3.13). All the morphological changes are small due to the small simulation period with respect to the morphological time scale (order 100's of years). Accordingly, all the sedimentation and erosion occur on the slopes of the trench and the two slopes do not influence each other (no morphological interaction).

Location	max: 10 m / medium: 15 m / small 20 m Parameter
trench	Wet volume change
sed / eros areas on slopes	Location centre of gravity
trench	Decrease horizontal length
outside trench	Transports at maximum ebb and flood current velocity

Table 3.12 Trench parameters defined in Section 3.3 that are maximal at a water depth of 10 m and smaller at 15 m and 20 m.

Location	max: 10 m & 20 m / small: 15 m
sed / seros areas on slopes	Parameter
trench	Volume
sed / seros areas on slopes	Displacement centre of gravity
outside trench	Height
	Residual transports

Table 3.13 Trench parameters defined in Section 3.3 that are minimal at a water depth of 15 m and large at 10 and 20 m.

- The residual transports at 10 m and 20 m water depth are almost equal, while the transport at 15 m is significantly smaller. Also, the magnitude of the morphological changes (the volume of the sedimentation / erosion areas on the slopes) at 10 and 20 m depth more pronounced than at 15 m.
- This effect can be explained by the different dominant transport mechanisms at the three water depths: at 20 m the current is dominant (imposed as boundary condition), while at 10 m the wave effect is dominant. The difference in transports at 10 and 20 m is mainly due to the suspended transports. Apparently, at 15 m the combined effect of waves and current is smaller than at deeper and shallower water. However, this is can not be a general valid conclusion as the tidal velocities at 15 m, as predicted by Delft3D, also resulted in the lowest residual transports.
- At 10 and 20 m the magnitude of the residual transports and the volumes of the bottom changes are almost equal. Consequently, the combined wave and current forcing at 10 and 20 m depth must be equal. Apparently, the smaller wave effect at 20 m is almost fully compensated by the larger current effect.
- Although the magnitude of the morphological activity at 10 m and 20 m depth is the same, the behaviour of the bottom changes is quite different at these depths. At a water depth of 10 m, more erosion occurs near the reference sea bottom level, due to the larger wave effect. At 20 m more erosion occurs on the lower part of the downstream trench slope. As a result, at 10 m depth the trench profile becomes more asymmetrical than at 20 m depth. This asymmetry is reflected in the behaviour of the trench parameters in Table 3.12.
- The results of the present study differ from the results of Walstra et al. (1998). Walstra et al. (1988) used the same depth averaged tidal velocities at water depths of 10, 15 and 25 m. They found that at increased water depth the effects are less pronounced. In the present study the effects are most pronounced at 10 and 20 m and minimal at a depth of 15 m. It can be concluded that using the accurate tidal velocity boundaries gives significant other results than using the same velocities at each water depth.

Location	Dependent on the trench depth	Parameter
trench	n	Wet volume change
trench	y	Decrease horizontal length
trench	y	Displacement centre of gravity
sed / eros areas on slopes	n	Volume
sed / eros areas on slopes	y	Height
sed / eros areas on slopes	y	Location centre of gravity
outside trench	n	Transports at max. ebb and flood current velocity
outside trench	n	Residual transports

Table 3.14 Influence trench depth on trench parameters defined in Section 3.3.

- There is a small effect of the trench depth on the morphological behaviour (Table 3.14). The height and the location of the sedimentation / erosion areas on the slopes of the trench are dependent on the trench depth, but only to a small extent. This influence should be attributed the steeper slopes of the deep trenches.
- The trench shape parameters (centre of gravity, length) are also to a small extent dependent on the trench depth. This effect is mainly due to the different volumes of the shallow and deep trenches. A given morphological change has a smaller effect on the length and centre of gravity of a shallow on a deep than on a deep pit, since the volume, and accordingly the time scale, of a shallow pit are smaller. In fact, to make a fair judgement of the influence of the trench depth, trenches with the equal volume, and hence with an equal morphological time scale should be compared. Moreover, the trenches are constructed to yield a given volume of sand. This volume of sand should be used as reference. This means investigating wide, shallow trenched vs. deep, narrow trenches.
- The effect of the trench depth is not significant with the deep trenches considered in the present study.

3.5 Sensitivity Analysis with Sutrench

This section describes an extensive sensitivity analysis to complement the Walstra et al. (1998) study. This sensitivity analysis considers varying wave conditions and different morphological wave climates, varying tidal forcing conditions and a range of model parameters. In contrast to the referred study, where only one water depth was considered, the sensitivity simulations are carried out for water depths of 10 and 15 m. A detailed description of the sensitivity study can be found in Appendix C, here only a summary of the main findings is given.

3.5.1 Wave parameters

The effects of individual waves is investigated by investigating the incident wave angle, wave period and wave height. To assess the validity of applying a single wave as the representative wave climate, comparisons are made with more complex representative wave climates of previous studies.

The main findings were:

- As could be expected, waves have a significantly larger effect at lower water depths. At a water depth of 10 m, the transports are sensitive to the wave parameters, while at a water depth of 20 m the transports are hardly sensitive to them, since at a water depth of 20 m the current is the dominant forcing type.
- The incident wave angles severely influence transports. The magnitude of the bedload transport can vary a factor 10, and can even switch sign. Moreover, the reactions of the suspended transports are not in accordance with the latest knowledge developments. It can be concluded that the bedload and suspended transport relations in Sutrench require further examination with respect to the wave angle. As concluded from the comparison with Delft3D in Chapter 2, the transport model in Sutrench requires to be updated to the latest version of Van Rijn's Transpor-model.
- The transports results are also very sensitive to the individual wave heights. Not only the magnitude of the transport increases more than linearly with the wave height. Moreover, the suspended transport increase faster than the bedload transports at increasing wave height.
- Since the transports are very sensitive to the wave heights of the contributing wave conditions, it can be concluded that the composition of a wave climate requires great care, especially at small water depths.
- To investigate the amount of care which has to be paid to the composition of the wave climates, different types of well-constructed wave climates have been compared. Surprisingly, the residual transports are not very sensitive to these climates: at 20 m the magnitude of the transports is hardly sensitive to the wave climate and at 10 m depth just a little. Moreover, the residual bedload and suspended transports are not sensitive either. At a depth of 10 m however, some characteristic differences between the different wave climate results can be observed. When a climate includes higher waves, peaks in the transports arises above the slopes. The peaks are most pronounced with the wave climate comprising the highest waves. On the long term these peaks might lead to different morphological behaviour of the pit slopes.
- It can be concluded that Sutrench is not sensitive with respect to well chosen wave climates. The strong sensitivity to the wave heights is well averaged due to the (weighted) composition of the wave climate.
- Since the complex wave climates give such similar results as the wave climate with only one wave condition, the findings of this chapter confirm the validity of the application of one morphological wave in the base run simulations. Moreover, the results are not sensitive to the sequence of the period with waves and the period without.
- However, not simply any wave with any occurrence can be chosen. Even if a higher wave than the wave of Walstra et al. (1998) is chosen ($H_s > 2.25$ m) with a lower occurrence (< 84 %) yields the same total residual transports, two other parameters might be different. These comprise (1) the presence of the local peaks in the transports and (2) the ratio of the suspended and the total transport which is important for the backfilling rates. The selection of a morphological wave should be based on the correct representation of these two parameters. The morphological wave of Walstra et al. (1998) fits these criteria quite well.
- Even though the results are not very sensitive to the wave climate, the largest sensitivity occurs at a water depth of 10 m. Consequently, if the evolution of a trench has to be simulated, the largest differences between model and measurements are expected to arise

at a water depth of 10 m. And vice versa, if one wants to calibrate a model (for a wave climate), one should rather collect data of a trench situated at a water depth of 10 m, than data from a trench at larger depth.

3.5.2 Tidal schematisation

Although an effort was made to use accurate tidal forcing conditions in the base simulations, these will inevitably contain errors. Moreover, the general validity of these tidal conditions is limited as they are extracted at specific locations along the Dutch coast. To gain insight in the morphological response of pits, simulations are made with various tidal forcing conditions which were varied between physically realistic ranges.

The main findings were:

- The Sutrench results are very sensitive to the changes in the velocity, both at 10 and at 20 m depth. The sensitivity at 10 m is more pronounced at 10 m. A 20 % increase of the real local velocity leads to three times larger morphological behaviour. The 20% increase has much more influence at 10 than at 20 m (eventhough the absolute increase in velocity is larger at 20 m depth).
- If the same depth averaged velocities are used at a depth of 10 and 20 m, the morphological changes at a water depth of 10 m are much more pronounced. It can be concluded that the velocity boundary conditions in Sutrench should be derived with great care, and separately for each water depth.

3.5.3 Model parameters

Lastly, the effects of a number of relevant model parameters is investigated. The same model parameters are considered as in Walstra et al. (1998):

- Thickness of mixing layer D_s
- Wave related mixing coefficients $E_{w,bed}$ and $E_{w,max}$
- Sediment characteristics d_{50} , d_{90} , w_s
- Wave roughness height R_w
- Current roughness height R_c
- Reference level Z_a

Walstra et al. (1998) did not investigate the sensitivity to the physical parameters at various water depths. They only investigated 20 m depth. In the present study sensitivity runs are performed at 10 and 20 m depth. Furthermore, the recommendation of Walstra et al. (1998) to apply the sensitivity runs to a whole range of parameter values is followed.

The main findings were:

- The model does not react strongly to variations of the wave and current related roughness heights. However, the residual transports at 10 m water depth show a significant larger sensitivity compared to the calculated transports at 20 m water depth.
- The model does not react strongly to variation of the reference level, the behaviour at both water depths is similar.
- Variations of the sediment characteristics have a significant impact on the residual transports at both water depths

3.6 Conclusions

Comparison between Delft3D and Sutrench

The overall behaviour of both models is very similar, the main differences are caused by the fact that flow contraction was not accounted for in the Sutrench simulation. On the relative small time scale of one year this primarily results in a different morphological development of the pit slopes. If longer time scales are considered it is expected that the overall development will show a better agreement between both models as the transport rates outside the pit are very similar. However, as the backfilling rates are over-estimated in the Sutrench simulations it is expected that this will result in an over-estimation of the migration rates of the pit and an under-prediction of the morphological time scale of pits where flow contraction plays an important role.

Although the total transports are comparable between both models, the relative importance of the suspended and bottom transports is approximately opposite. This is to a large extent caused by the difference sediment transport formulas in both models. Delft3D uses the updated transport formulas of van Rijns TRANSPOR2000 model (Van Rijn, 2000), whereas Sutrench uses the original TRANSPOR1993 model formulations. It is recommended to update Sutrench with the improved transport formula of Van Rijn.

Base run simulations

The present study focussed on three *water depths* (10, 15 and 20 m) and three *trench depths* (10, 15 and 20 m). The influence of the trench depth is small, but not negligible. These influences stem primarily from the larger wet volume of deep trenches. In fact, to make a fair judgement, trenches with equal volume should be compared (note that trenches are designed in the first place to yield a specified volume of sand): deep and small trenches vs. wide and shallow trenches. Note that the depth and the width of the trench have opposite effects on the morphology.

The residual transports become zero in the trench for all base runs: the trapping efficiency of the trench is 100%. The influence of the water depths is strong. When we consider the objective parameters describing the nine base runs, the values are either most pronounced at 10 m and less at deeper water, or the values are most pronounced at both 10 and 20 m and less at 15 m depth. The residual transports belong to the latter group. The volume of the morphological changes is the same at water depths of 10 and 20 m, while the location and shape of the bottom changes is different. Due to the larger relative importance of the wave effect at 10 m depth, the erosion at 10 m occurs on the level of the bottom outside the trench, while at 20 m depth the erosion also happens on the slopes inside the trench.

Sensitivity Simulations

In the sensitivity runs performed on the velocity, the 20 m water depth velocities were applied on a water depth of 10 m and vice versa. It was found that the morphological activity did turn out to be highest at 10 m. The local velocities have also been varied to 80

% and 120 % of the actual values. At 80 % the morphological changes were almost absent, while at 120 % of the base run velocity the morphological behaviour increased by a factor three. At a water depth of 10 m the results are more sensitive than at 20 m. It can be concluded that (1) the model results are very sensitive to the current velocity, accordingly (2) that it is very important to use the real local velocities in Sutrench and (3) that the results at a water depth of 10 m are more sensitive than at 20 m.

The *influence of the waves* has also been investigated. The results are very sensitive to the incident wave angle. This unrealistic sensitivity is caused by the outdated transport formulations in Sutrench. It is therefore recommended to update Sutrench with the most recent version of Van Rijn's transport formula. The results are also very sensitive to the wave height, but not to the wave period. The sensitivity is most pronounced at a water depth of 10 m.

Different types of *complex wave climates* have been imposed on the trench: two wave class exceedence climates, a climate with one morphological wave condition and a climate used in recent MV2 studies. The results are not very sensitive to the various climates, despite the fact that the results are very sensitive to the wave heights of the contributing wave conditions. The sensitivity is most pronounced at a water depth of 10 m. This implies that the climates have been well constructed. It also indicates that one morphological wave condition can be used to replace an extended wave climate schematisation. The sensitivity runs also shows that higher waves lead to local peaks in the residual transports on the slopes of the trench and a higher relative importance of the suspended transport. Accordingly, the single morphological wave condition should be chosen to reproduce these phenomena well.

The sensitivity to some physical parameters has also been investigated. For three parameters the sensitivity is almost negligible at 20 m depth, and reasonable at 10 m depth: up to 50 % variation when the parameters are doubled or halved. The results are very sensitive to variations in the sediment characteristics (grain size and fall velocity of the sediment).

4 2DV cross-shore modelling (Unibest-TC)

4.1 Introduction

This chapter contains an investigation into the cross-shore stability of trenches at depth of 10 m, 15 m and 20 m with the Unibest-TC model. Cross-shore profile models such as Unibest-TC require a thorough calibration. Although many calibration studies have been performed with the model, the emphasis was usually on the development of the upper part of the bottom profile (surf zone, beach and dune). For the present application a calibration on deeper parts of the bottom profile would be more appropriate. Unfortunately, such a calibration is not possible due to lack of reliable bathymetric data. Therefore, it was decided to apply Unibest-TC model which was calibrated on the long term profile development at Egmond (Boers, 1999). The emphasis is on the relative impact of pits to reduce the uncertainty in the model predictions. To that end, the autonomous modelled behaviour for an undisturbed profile is subtracted from the simulations in which the pits were included.

In Section 4.2 the model set up is briefly discussed followed by discussion of model results in Section 4.3. Finally, some conclusions are drawn in Section 4.4.

4.2 Model Set-up

No specific calibration of the Unibest-TC model was made. Instead a model calibrated on the long term profile development at Egmond was used as the basis for the model applied in this study. A detailed description of this model can be found in Boers (1999). Here only a short summary is given of the model settings.

A time series of waves measured at IJmuiden Munitiestortplaats from 1979 to 1997 are used as boundary conditions. In Boers (1999) it was shown that this is a representative wave climate for long term morphodynamic profile modelling. In the model no longshore tidal currents are taken into account.

The basis bottom profile is extracted from the Delft3D bathymetry along the transect located along the locations at which the boundary conditions for the Sutrench model were extracted (see Figure 2.3). In the original bottom profile trenches were constructed with the same (cross-shore) geometric properties as the LDS-pit of the PUTMOR experiments. The resulting profiles are shown in Figure 4.1.

Below a list of the main model parameters is given:

Run Parameters	Explanation	Dimension	Calibrated Value (Boers, 1999)
Nt	number of time steps	-	29360
Dt	time step	days	0.125
Tdry	relative wave period	-	40
Alfac	dissipation parameter	-	1.0
GAMMA	breaking parameter	-	0.57
BETD	roller parameter	-	0.10
FWEE	friction factor	-	0.01
F_LAM	number of wave lengths	-	2
POW	power in weighting function	-	1
TANPHI1	internal friction angle	-	0.28
D50	D50 grain diameter	m	0.284*10 ⁻³
D90	D90 grain diameter	m	0.429*10 ⁻³
DSS	suspended grain diameter	m	0.256*10 ⁻³
FCVISC	viscosity coefficient	-	0.1
RKVAL	roughness height flow model	m	0.05
RC	current roughness height in transport model	m	0.01
RW	wave roughness height in transport model	m	0.02
C_R	correlation wave groups	-	0.25

Table 4.1 Overview model parameters of Unibest-TC model.

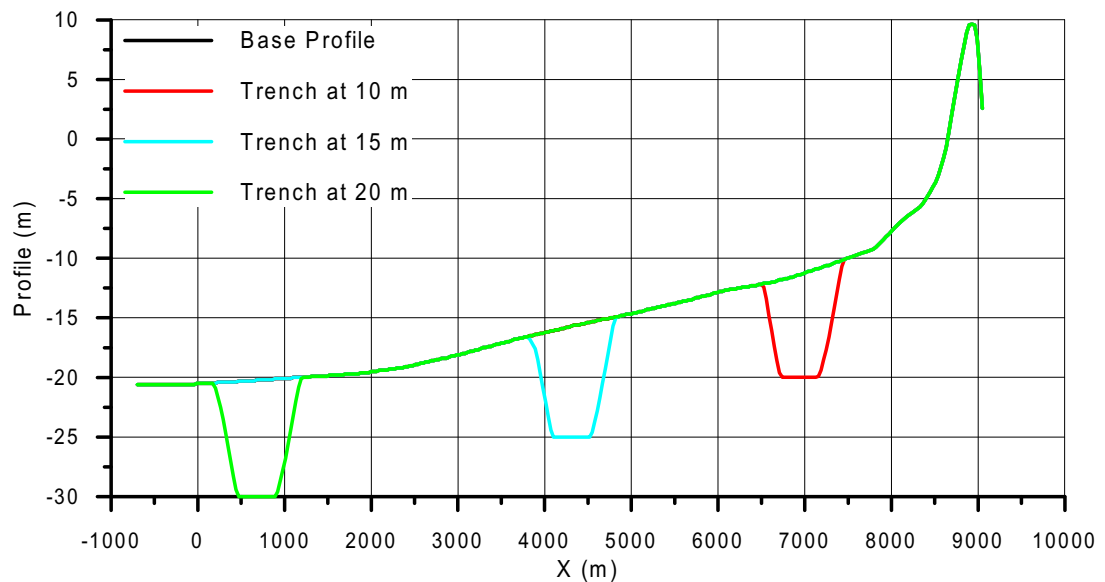


Figure 4.1 Bottom profile with constructed pits at 10 m, 15 m and 20 m water depth.

The pit characteristics are based on the pit monitored in the Putmor project (Walstra et al., 2002). The pit slopes are set to 1:25 and the construction depth of the trenches are defined by the top of the landward slope of the pit. The width of the pit is approximately 450 m.

4.3 Discussion on Results

For all four bottom profiles (the base profile and three trenches) morphodynamic simulations were made for a 18 year period. The results are shown in Figure 4.2. It can be seen that for all simulations a significant, un-realistic, sedimentation occurs at the inter-tidal beach. This is a known artefact which also occurred in the Unibest-TC results presented in Boers (1999). However, the trenches have not accreted significantly, only the trench slopes show a small but consistent shoreward migration which is most pronounced for the trench at 10 m water depth.

In Figure 4.3, Figure 4.4 and Figure 4.5 the resulting profiles are shown relative to the final base run prediction to investigate the impact of the trenches (i.e. $Z'_{trench}(t=18) = Z_{trench}(t=0) + (Z_{trench}(t=18) - Z_{base}(t=18))$). The relative sedimentation-erosion is shown in red. In addition to the profile development vertical cubing regions were defined. The vertical cubing locations were identified by considering the 20 m, 10 m, and 5 m depth contours of the original profile. Furthermore, the trench floor and the seaward and landward trench slopes were also integrated. The resulting cubing locations are indicated by the vertical blue lines in the figures, in Table 4.2 the cubing coordinates are given.

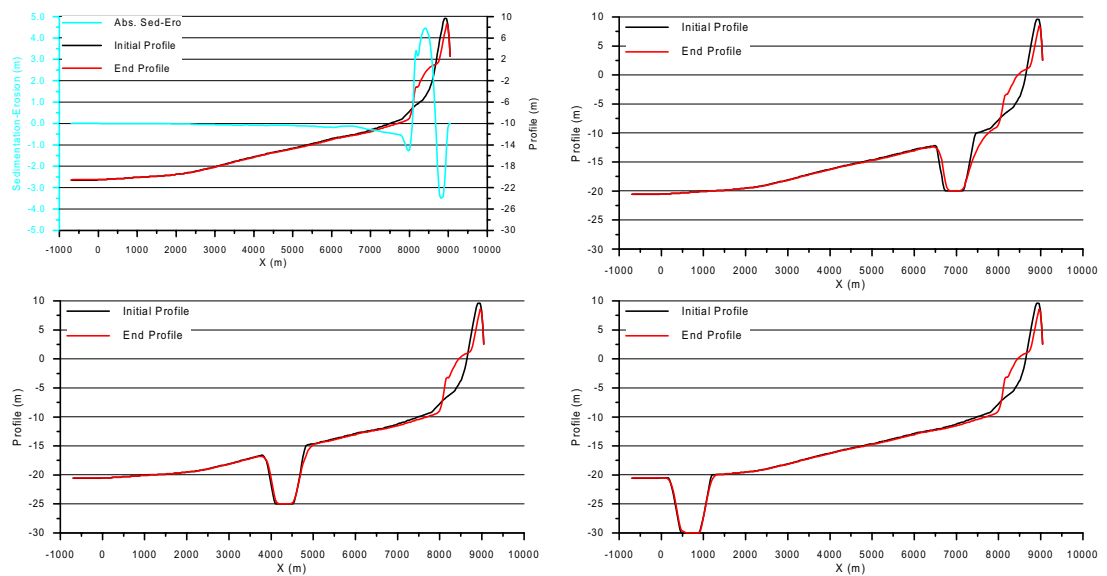


Figure 4.2 Initial and simulated final profiles for the Base Run (top left), a trench at depth 10 m (top right), a trench at depth 15 m (bottom left), a trench at depth 20 m (bottom right).

Region	Pit at 10 m	Pit at 15 m	Pit at 20 m
-20 m to -10 m	-700 to 6530	-700 to 3810 & 4810 to 7440	-700 to 180 & 1180 to 7440
-10 m to -5 m	7440 to 8440	7440 to 8440	7440 to 8440
beach and dune	8440 to 9000	8440 to 9000	8440 to 9000
seaward slope	6530 to 6715	3810 to 4080	180 to 450
trench floor	6715 to 7170	4080 to 4540	450 to 910
landward slope	7170 to 7440	4540 to 4810	910 to 1180

Table 4.2 Cubing coordinates for the 3 pits.

The relative morphological development for the pit at 10 m water depth is shown in Figure 4.3. The pit shows an overall onshore migration, but the sedimentation in the pit is limited. The seaward pit slope has migrated about 50 m onshore without a significant shape change. The upper parts of the landward pit slope primarily experiences erosion. The relative retreat of the 10 m depth contour is about 350 m. The sedimentation of the seaward slope and pit floor and the erosion of the landward slope are more or less equal.

In Figure 4.4 the relative profile development for the pit at 15 m water depth is shown. It can be seen that the sedimentation and erosion patterns have a similar trend as for the 10 m pit but that the magnitude has reduced significantly: 25 m onshore migration of the seaward slope and a landward shift of the 15 m depth contour of about 125 m. The relative changes for the pit at 20 m water depth are again significantly lower, see Figure 4.5. The onshore migration of the seaward pit slope is in the order of 10 m and the landward shift of the 20 m depth contour is about 70 m.

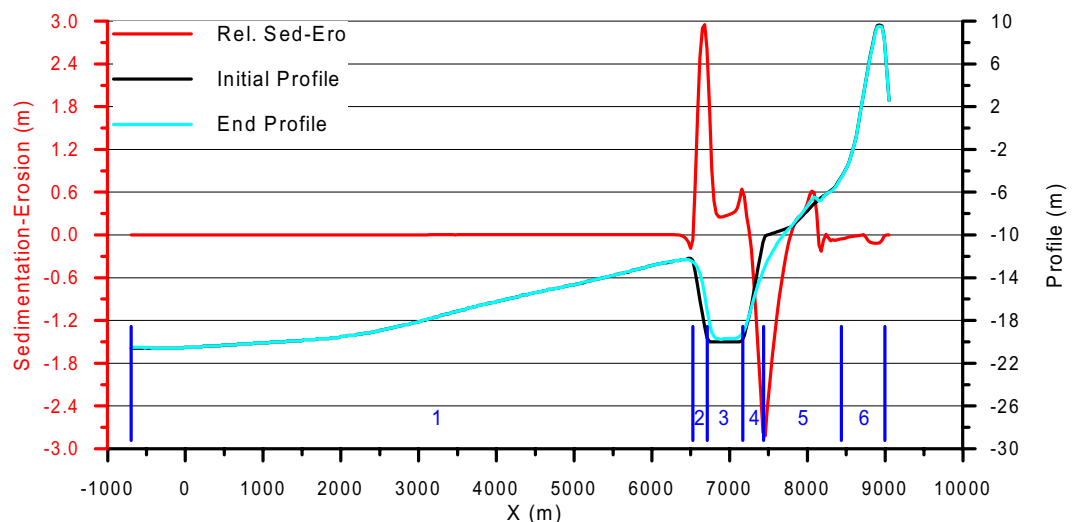


Figure 4.3 Relative profile development for pit at 10 m water depth (vertical lines indicate cubing regions).

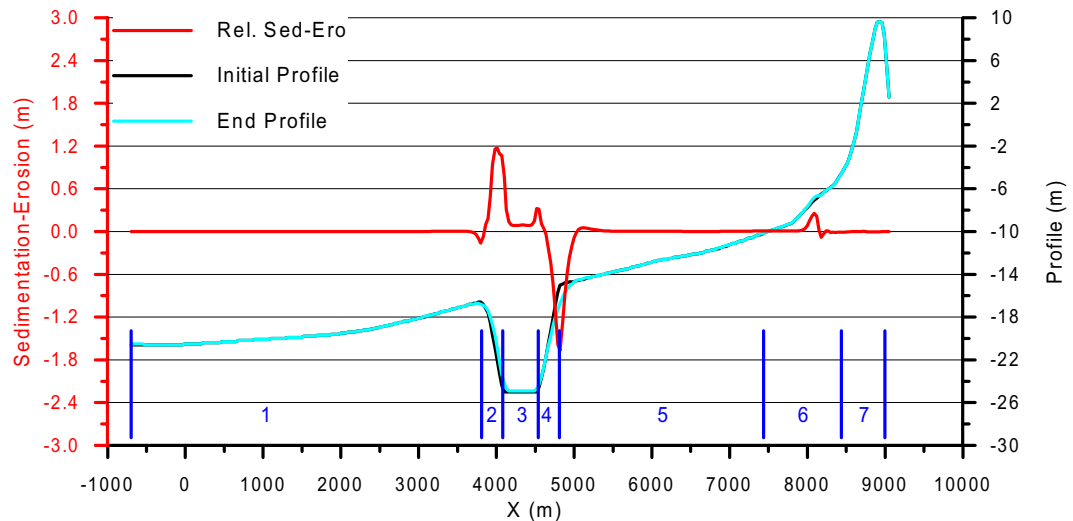


Figure 4.4 Relative profile development for pit at 15 m water depth (vertical lines indicate cubing regions).

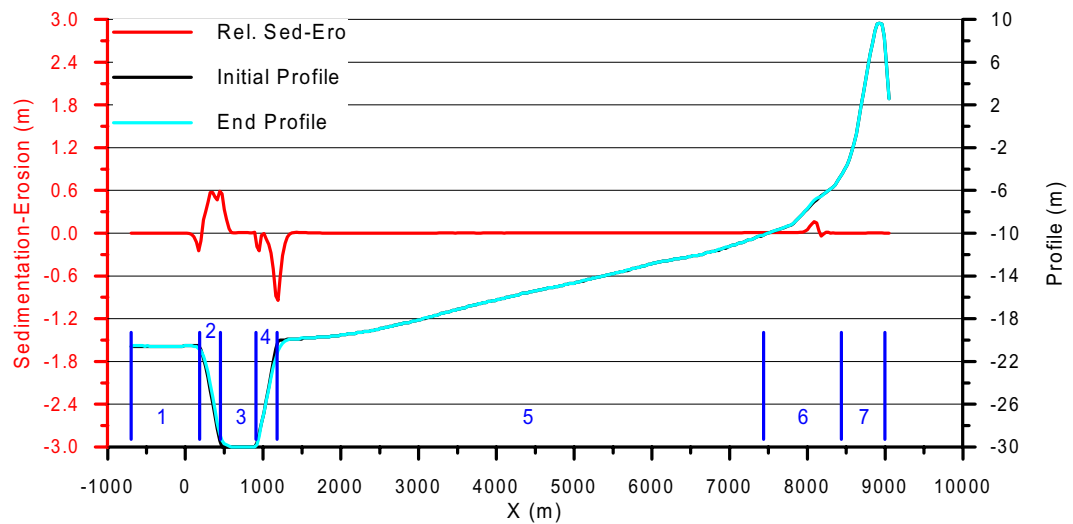


Figure 4.5 Relative profile development for pit at 20 m water depth (vertical lines indicate cubing regions).

In Figure 4.6, Figure 4.7 and Figure 4.8 time series of the volume changes for the various cubing regions are shown. Again the focus is on the relative volume changes which is shown in the bottom plots. Because the cubing regions vary for the various pits, the absolute volume changes for the base run are shown in the top plots, as a reference. The absolute volume changes reveal that the accretion in the region from -10 m to -5 m are primarily caused by erosion of the deeper parts of the profile due to an unrealistic large onshore transport.

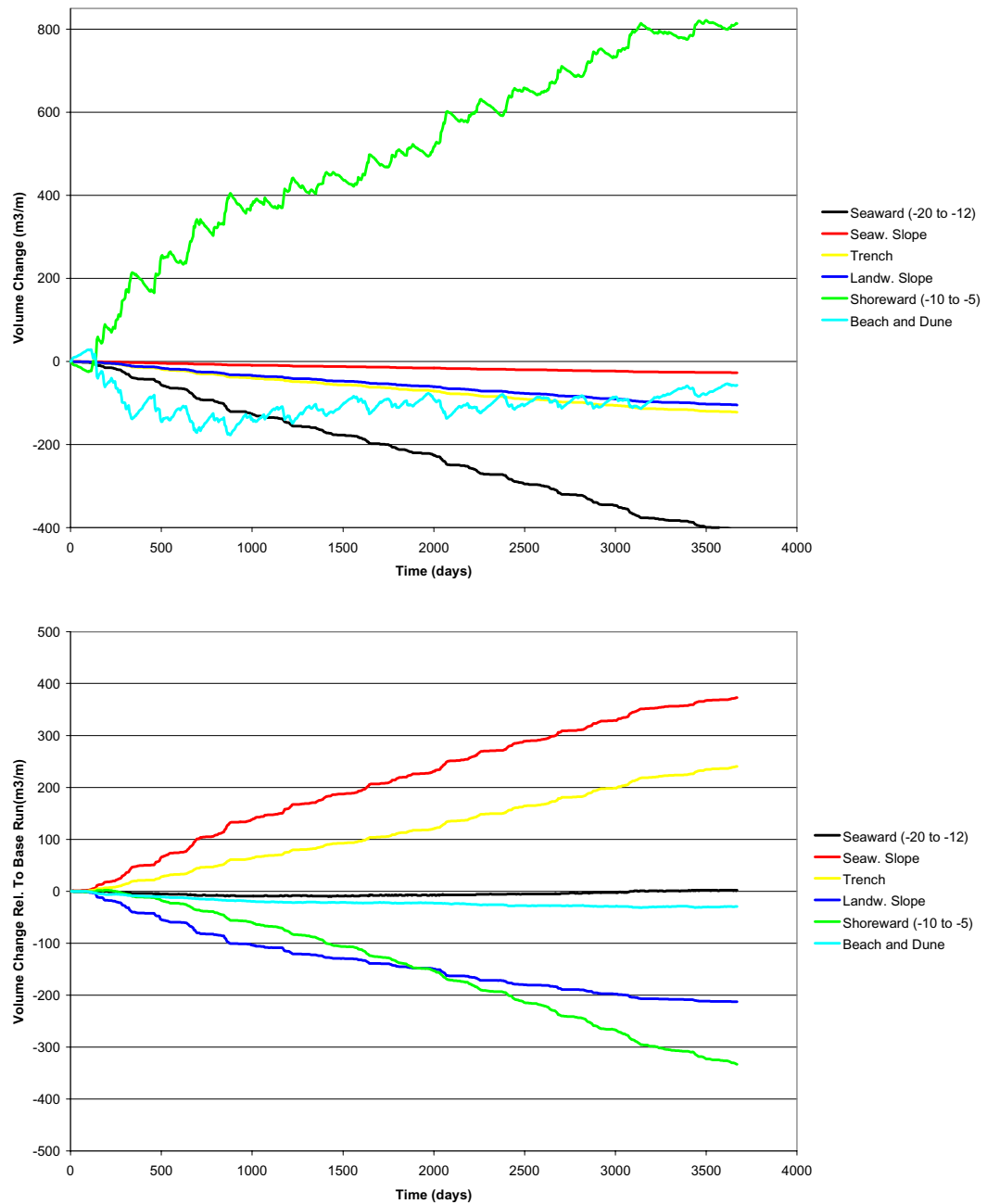


Figure 4.6 Temporal variation of sand volumes for the pit at 10 m water depth (top: absolute changes for base run, bottom: relative changes for pit).

The relative volume changes for the pit at 10 m (bottom plot in Figure 4.6) shows that the amount of sedimentation at the seaward slope and pit floor is approximately similar to the erosion of the landward slope and the shoreward region (-10 to -5). The temporal development of the accretion and erosion volumes is approximately linear.

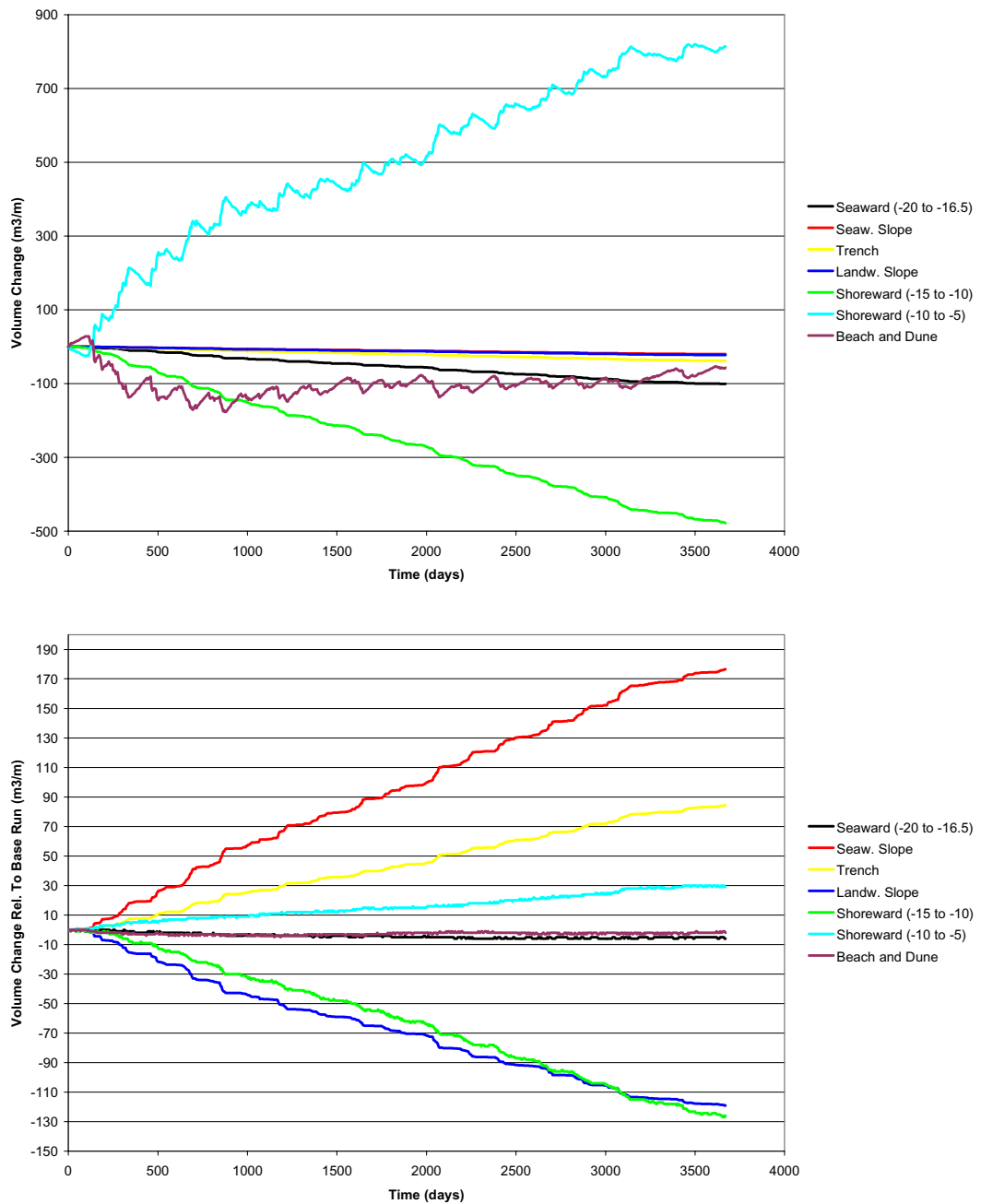


Figure 4.7 Temporal variation of sand volumes for the pit at 15 m water depth (top: absolute changes for base run, bottom: relative changes for pit).

The pit at 15 m water depth (bottom plot in Figure 4.7) again shows the more or less symmetrical migration of the trench, in terms of relative volume changes, although the absolute volume changes are about 60% less compared to the pit at 10 m.

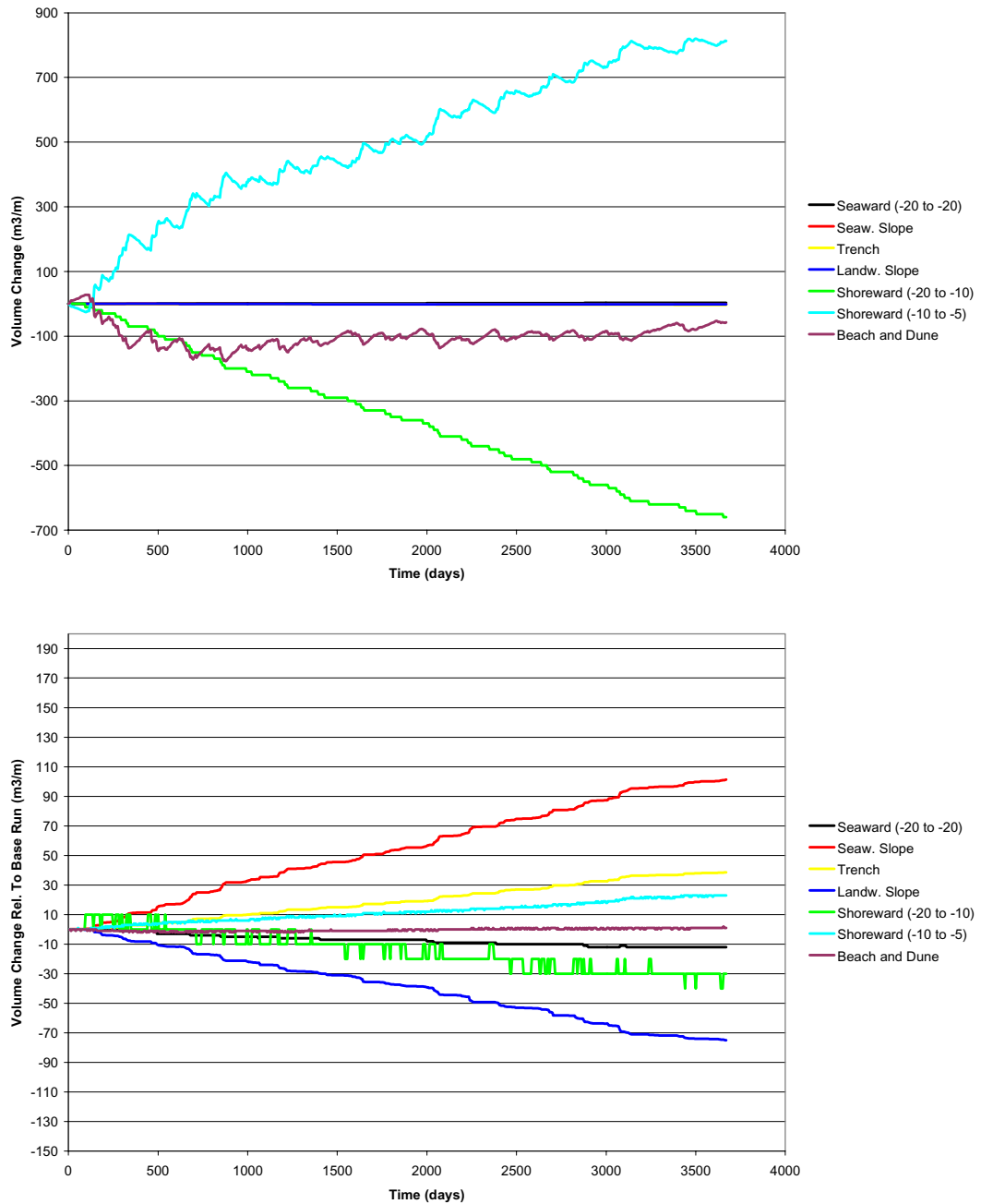


Figure 4.8 Temporal variation of sand volumes for the pit at 20 m water depth (top: absolute changes for base run, bottom: relative changes for pit).

The volume changes for the 20 m pit are shown in Figure 4.8. The total erosion of the landward slope is about $100 \text{ m}^3/\text{m}$ which is about 20% and 40% of the erosion volumes at the pits at 10 m and 15 m, respectively. Similar ratios are found for the sedimentation of the seaward slope and the pit floor. At all three considered pits, the volume changes on the slopes increase or decrease approximately linearly. The morphological time scale for backfilling due to cross-shore transports is about 250, 500 and 1000 years for the pits at a water depth of 10, 15 and 20 m, respectively. These time scales are derived by taking the ratio between yearly sedimentation volumes of the seaward pit slope and the pit floor (respectively: 30, 15 and $8 \text{ m}^3/\text{m}/\text{year}$) and the pit volume (about $7500 \text{ m}^3/\text{m}$).

In Figure 4.9 the resulting relative volume changes for the seaward pit slope, the pit floor, landward pit slope, and the shoreward cubing region compared for the three pit simulations (note that the shoreward region is here the cubing region directly shoreward of the pit). Both the sedimentation and the erosion volumes are approximately similar, indicating a cross-shore trapping efficiency close to 100%. Furthermore, there is a clear non-linear relation with the construction depth of the pit. This emphasises the enhanced migration rates of pits in shallower water and the increased negative impact they may have on the stability of the inter-tidal beach and dune.

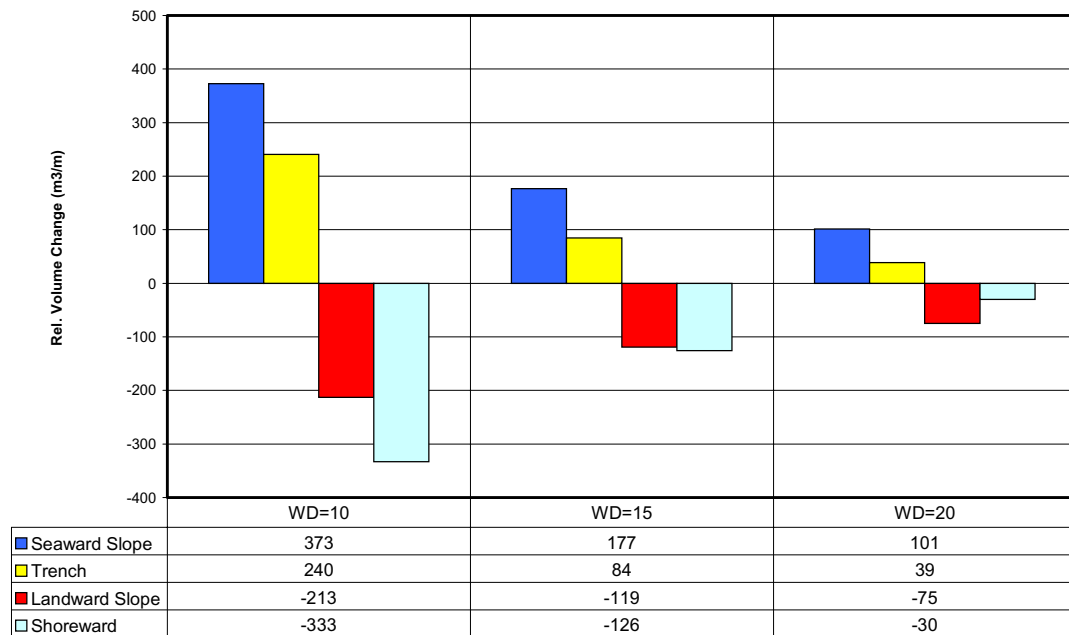


Figure 4.9 Comparison of the relative volume changes for the landward slope, -10 m to -5 m region and the beach & dune region.

4.4 Conclusion of the 2DV cross-shore simulations

Although the interpretation of the model results is based on the relative impact, they still should be considered with great care as no calibration of the model could be performed due to the lack of data.

The cross-shore model simulations show a clear enhanced shoreward migration of trenches constructed in shallower water. The morphological time scale for backfilling due to cross-shore transports is about 250, 500 and 1000 years for the pits at a water depth of 10, 15 and 20 m, respectively. This reflects the non-linear character of the cross-shore transports along the bottom profile. To give a first order indication, the backfilling rates due to cross-shore transports approximately seem to follow the squared ratio between the considered water depths (e.g. backfilling rates for a pit at 20 m water depth is 4 times larger then for a pit at 10 m water depth).

For a more reliable assessment of the cross-shore migration of pits reliable field data is of vital importance. This should provide insight into the residual cross-shore transports along

the bottom profile which is essential for a reliable calibration of any cross-shore morphodynamic profile model.

5 Synthesis, Conclusions & Recommendations

5.1 Synthesis

In the present study the morphological development of pits/trenches, on decadal time scales, in longshore and cross-shore development is investigated with two morphodynamic process models specifically designed to simulate the cross-shore and longshore pit development under the influences of waves and tide:

- the Sutrench 2DV-model (applicable to simulate morphology in dominant tidal direction (i.e. longshore direction),
- the Unibest-TC 2DV-model (applicable to simulate the cross-shore profile evolution under the influence of non-breaking and breaking waves).

In addition, a verified Delft3D-Online area model was used to assess the quality of the longshore morphodynamic simulations with the Sutrench model. From the model comparison it was concluded that the main differences are caused by the fact that flow contraction was not accounted for in the Sutrench simulation. On the relative small time scale of 1 year, over which this comparison was made, this primarily results in a different morphological development of the pit slopes. If longer time scales are considered it is expected that the overall development will show a better agreement between both models as the transport rates outside the pit are very similar. However, as the backfilling rates are over-estimated in the Sutrench simulations it is expected that this will result in an over-estimation of the migration rates of the pit and an under-prediction of the morphological time scale of pits where flow contraction plays an important role.

It emphasises the inherent limitations of the 2DV concept of Sutrench. The Sutrench model can be used to obtain a first order estimate of the occurring bottom changes. However, reliable predictions can only be made if flow contraction is taken into account.

Both the longshore and cross-shore morphodynamic simulations have shown that the construction depth of pits/trenches has a large influence on the pit/trench stability. Moreover, if the uncertainty of the boundary conditions and model parameters is taken into account, the accuracy ranges show a significant increase for shallower pits. This implies that model predictions for pits in shallower water are associated with an increased uncertainty.

An important limitation of the present study is that the longshore and cross-shore development was investigated independently. Especially in shallower water where both cross-shore and longshore transports increase, an area model such as Delft3D-Online would probably more applicable.

5.2 Conclusions

Longshore morphodynamic simulations with Sutrench

The residual transports at 10 m and 20 m water depth are almost equal, while the transport at 15 m is significantly smaller. Also, the magnitude of the morphological changes at 10 and 20 m depth more pronounced than at 15 m. At 10 and 20 m the magnitude of the residual transports and the volumes of the bottom changes are almost equal. Consequently, the combined wave and current forcing at 10 and 20 m depth must be equal. Apparently, the smaller wave effect at 20 m is almost fully compensated by the larger current velocities at this depth.

Although the magnitude of the morphological activity at 10 m and 20 m depth is the same, the behaviour of the bottom changes is quite different at these depths. At a water depth of 10 m, more erosion occurs near the reference sea bottom level, due to the larger wave effect. At 20 m more erosion occurs on the lower part of the downstream trench slope. As a result, at 10 m depth the trench profile becomes more asymmetrical than at 20 m depth.

The results of the present study differ from the results of Walstra et al. (1998). They used the same depth averaged tidal velocities at water depths of 10, 15 and 25 m. They found that at increased water depth the effects are less pronounced. In the present study the effects are most pronounced at 10 and 20 m and minimal at a depth of 15 m. It can be concluded that using accurate tidal velocities is vital when performing longshore morphodynamic simulations with Sutrench.

An extensive sensitivity analysis was performed in which the effect of various wave climates, tidal forcing conditions and model parameters were investigated. The main results from this sensitivity analysis are summarised below.

As could be expected pits constructed at in shallower water are increasingly sensitive to small modifications in the wave climate that is imposed. The present version of Sutrench shows an unrealistic sensitivity to small changes in the wave angle. Moreover, the reactions of the suspended transports are not in accordance with the latest knowledge developments. This is supported by the comparison with Delft3D as significant differences between calculated the bed and suspended transports of both models were found.

It can be concluded that Sutrench yields similar results for the various representative wave climates. Since the complex (i.e. large number of wave conditions) wave climates give such similar results as the wave climate with only one wave condition, it is concluded that reliable long term predictions can be made with one representative wave conditions.

The Sutrench results are very sensitive to the changes in the velocity, at both 10 and at 20 m depth. The sensitivity at 10 m is more pronounced at 10 m. A 20 % increase of the real local velocity leads to three times larger morphological behaviour. From this it can be concluded that the velocity boundary conditions in Sutrench should be derived with great care, and separately for each water depth.

The Sutrench results are not sensitive to the reference level z_a when the variations are within the 50 to 200%. The results are moderately sensitive to the wave and current roughness: the results range by less than 50 % when the variations are kept with a 10 - 200 % range. These variations are all less than the sensitivity to the waves and currents. The results are extremely sensitive to smaller values of the sediment properties, and not sensitive at all when coarser sediment is used. For all three physical parameters, the model results are most sensitive at a water depth of 10 m, only for the sediment size the water depths does not matter.

Cross-shore morphodynamic simulations with Unibest-TC

The cross-shore model simulations show a clear enhanced shoreward migration of trenches constructed in shallower water. The morphological time scale for backfilling due to cross-shore transports is about 250, 500 and 1000 years for the pits at a water depth of 10, 15 and 20 m, respectively. This reflects the non-linear character of the cross-shore transports along the bottom profile. To give a first order indication, the backfilling rates due to cross-shore transports approximately seem to follow the squared ratio between the considered water depths (e.g. backfilling rates for a pit at 20 m water depth is 4 times larger than for a pit at 10 m water depth). However, these findings can not be firm due to the fact that only three construction depths were considered. Moreover, the results should be considered with great care as no calibration of the model could be performed due to the lack of data.

5.3 Recommendations

From the comparison between the Sutrench and Delft3D it became clear that although the total transports are comparable between both models, the relative importance of the suspended and bottom transports is approximately opposite. This is to a large extent caused by the difference sediment transport formulas in both models. Delft3D uses the updated transport formulas of van Rijns TRANSPOR2000 model (Van Rijn, 2000), whereas Sutrench uses the original TRANSPOR1993 model formulations. It is therefore recommended to update Sutrench with the improved transport formula of Van Rijn. However, both transport models have not been validated for deeper water. Therefore, an extensive validation of the TRANSPOR2000 with measurements in deeper water is crucial to improve the offshore morphodynamic modelling capabilities.

Although the interpretation of the Unibest-TC model results is based on the relative impact, they still should be considered with great care as no calibration of the model could be performed due to the lack of data. For a more reliable assessment of the cross-shore migration of pits reliable field data is of vital importance. This should provide insight into the residual cross-shore transports along the bottom profile which is essential for a thorough calibration of any cross-shore morphodynamic profile model.

The independent investigation of the longshore and cross-shore development are an important limitation of the present study. Especially in shallower water, where both longshore and cross-shore transports increase significantly, there will be an increased interaction between cross-shore and longshore processes. Taking the higher uncertainties in the shallower regions into account it is recommended that in follow up studies area models such as Delft3D are also used on longer time scales than applied in the present study.

The considered decadal time scale, is several orders smaller than the morphological time scale (defined as the ratio of the initial pit volume and the residual longshore transports) that were considered in the present study. This is an important limitation which hampers the application of the findings presented in this report in policy and regulations. It is recommended to perform a fundamental investigation on the morphodynamic developments of pits and trenches on time scales of the same order as the morphological time scales of the considered pits. It is thought that with the present models this can be accomplished by considering schematised situations. Ideally such a model investigation should be done in combination with laboratory experiments which can be used to verify the predicted morphology.

5.4 Research Questions

Below an overview is given of answers to some general research questions which were drafted at the start of this project by RIKZ.

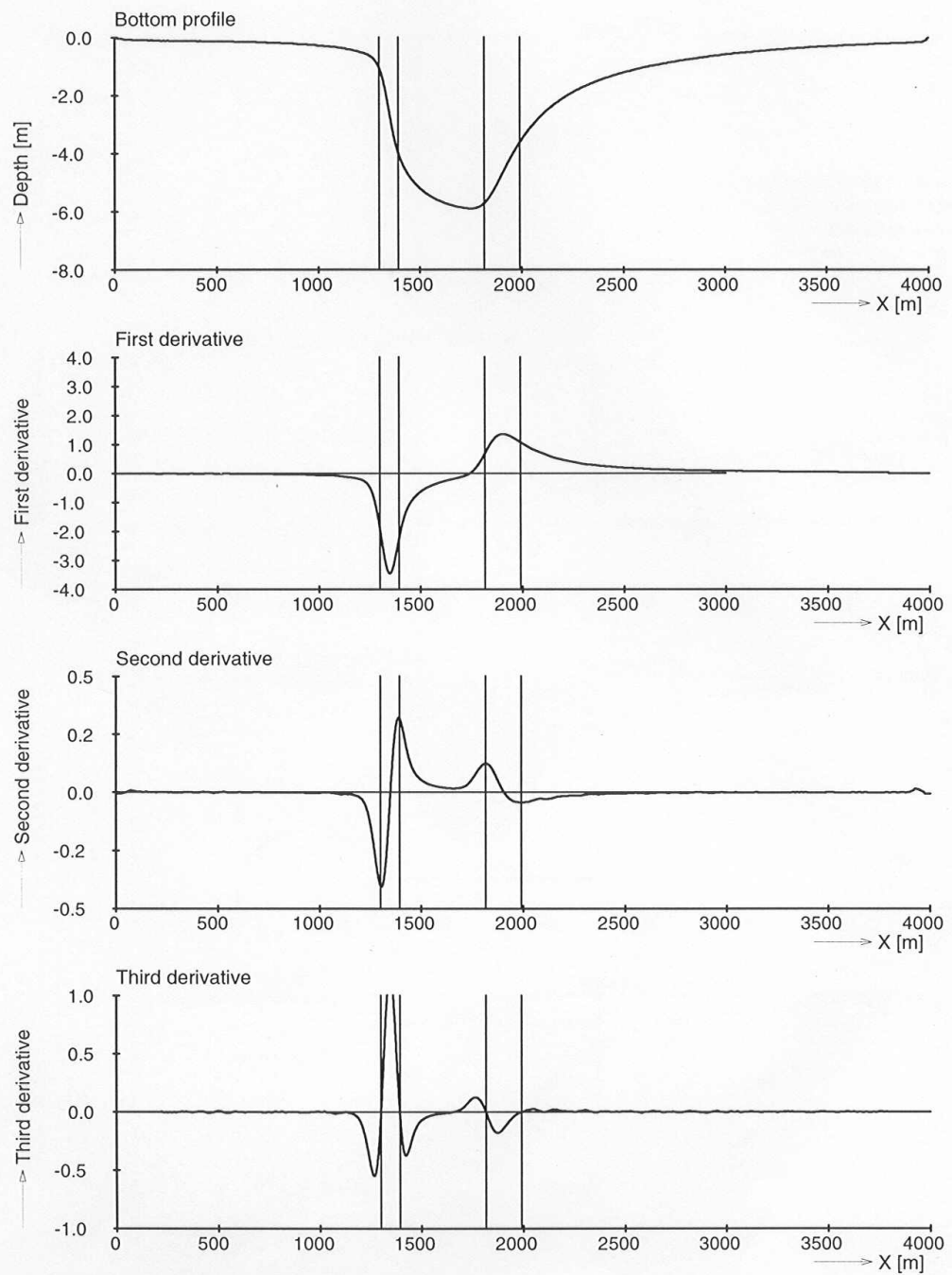
- Q1** There is a concern that pits will be filled with sand from the coastal zone. Therefore, the models should be able to give indications of the sand transport over e.g. the 20 m and 8 m depth contours on various time scales.
- A1** In the morphological verification the Delft3D model gave a reasonable accurate representation of the measured bottom changes for a 10 m deep pit at a water depth of 25 m. The comparison between Delft3D and Sutrench showed that both models gave comparable predictions. However, the fact that flow contraction was not accounted for in Sutrench did result in an under-estimation of the transports inside the pit. The second part of the question can not directly be answered as no verification was carried out for pits at a water depth of 8 m. The sensitivity analysis with the Sutrench model did show that the uncertainties of the model predictions increase significantly for pits in shallower water depth.
- Q2** The morphological development of pits should be investigated (migration and deformation) to determine its effect on other functions (e.g. cables and other constructions). The models should be able to indicate what the bathymetric changes will be at various distances from the original pit (50, 100, 200, 500 en 1000 m) on various time scales (1, 2, 5, 10 en 25 years after construction).
- A2** The morphological verification has shown that the model was able to reproduce the measured bottom changes after one year. Because no verification on longer time scales was made (due to the lack of long term morphological data) no firm conclusions can be drawn for the longer time scales. However, the good performance of the Delft3D model in the hydrodynamic and morphodynamic verification seems to suggest that the model can be applied on these longer time scales with reasonable confidence. The differences between the 3D and 2DH model morphodynamic simulations have revealed significant differences. At present it is thought that the 3D-model is more reliable, but this can not be confirmed with measurements. There is no practical limitation to apply these models on decadal time scales, even in 3D. However, the morphological performance must be assessed first in order to characterise the quality of the predicted morphological changes on such large time scales.

- Q3** Can the morphological development of pits be modelled with 2DH-models or is a full 3D-model required.
- A3** The hydrodynamic verification study has shown that with a 3D-model better agreement is obtained than simulations in 2DH-mode for the PUTMOR data. The differences between the morphological predictions in both modes underlines that there is still some uncertainty regarding the quality of the morphological predictions. The results presented in this report seem to suggest that 3D morphological simulations are necessary. However, due to the lack of morphological data with sufficient accuracy and measured over a longer period this is only a preliminary finding.
- Q4** Oxygen depletion depends on the extent to which the exchange of water between surface and bottom layer is reduced. The models must be able to predict water refreshment rates in the pits and to determine if there are any areas where there is no exchange of water (stagnant water).
- A4** It is thought that the prediction of flow velocities across the vertical is accurate enough to investigate this question. In the LDS the entire water column was refreshed at each tidal cycle (which was both observed and predicted).
- Q5** Are there conditions that deposition of mud occurs on time scales larger than the tidal cycle.
- A5** This can be investigated by investigating the bottom shear stresses in the pit. As the flow predictions are of sufficient accuracy this question can be investigated with good confidence.
- Q6** If mud settles in the pit, will it be removed by the flow and if so how long will it take for the mud to be eroded.
- A6** See **A5**.
- Q7** What will the general applicability be of the findings of this study. To what extent can the conclusions drawn in this study be applied on pits at other locations along the Dutch coast.
- A7** Delft3D is an advanced process based model in which numerous physical phenomena have been implemented. This implies that the presented verification is appropriate at other locations along the Dutch coast with approximately the same characteristics (e.g. non-breaking waves). The model has performed well, taking the complexity of the modelled area into account (e.g. irregular bathymetry and density effects due to fresh water discharges from the Nieuwe Waterweg). This gives good confidence of the applicability of the model at other locations. The applicability of the Sutrench is also generic, but this study has shown that an accurate description of the tidal forcing conditions is vital. Furthermore, the effects of flow contraction can usually not be ignored, which will require additional sensitivity runs if the model is not applied in parallel with an area model. The cross-shore profile model Unibest-TC usually requires a thorough site-specific calibration. Furthermore, the applicability of the cross-shore modelling along one horizontal dimension on pits in deeper water can be questioned. An important limitation of all the morphological models applied in this study is that the fact that transport formulations are used which are not specifically

designed for water depth larger than about 15 m. A systematic validation of the transport formulation in deeper water is crucial for further improvement of the morphological predictive capabilities.

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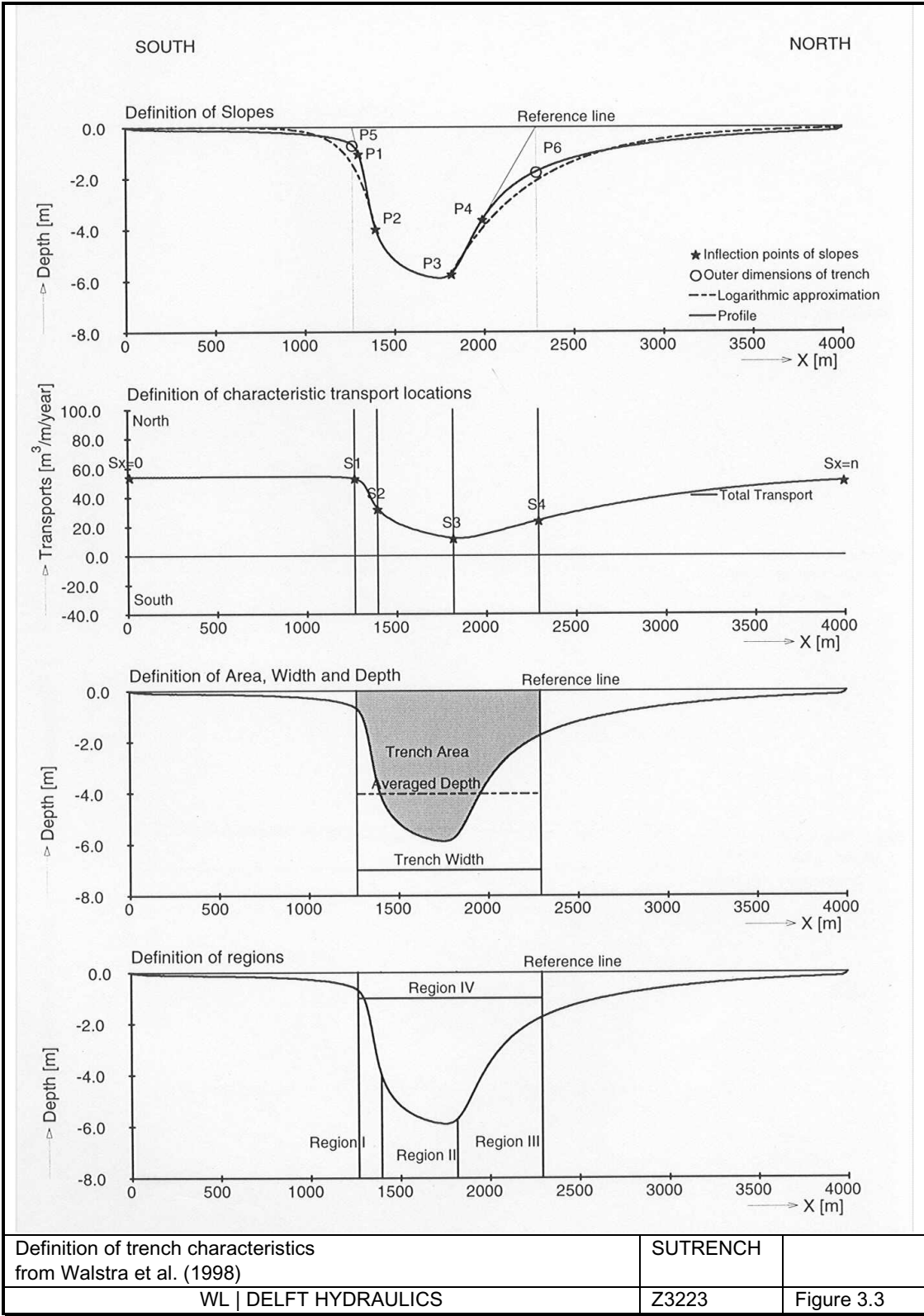
Definition of inflection points
from Walstra et al. (1998)

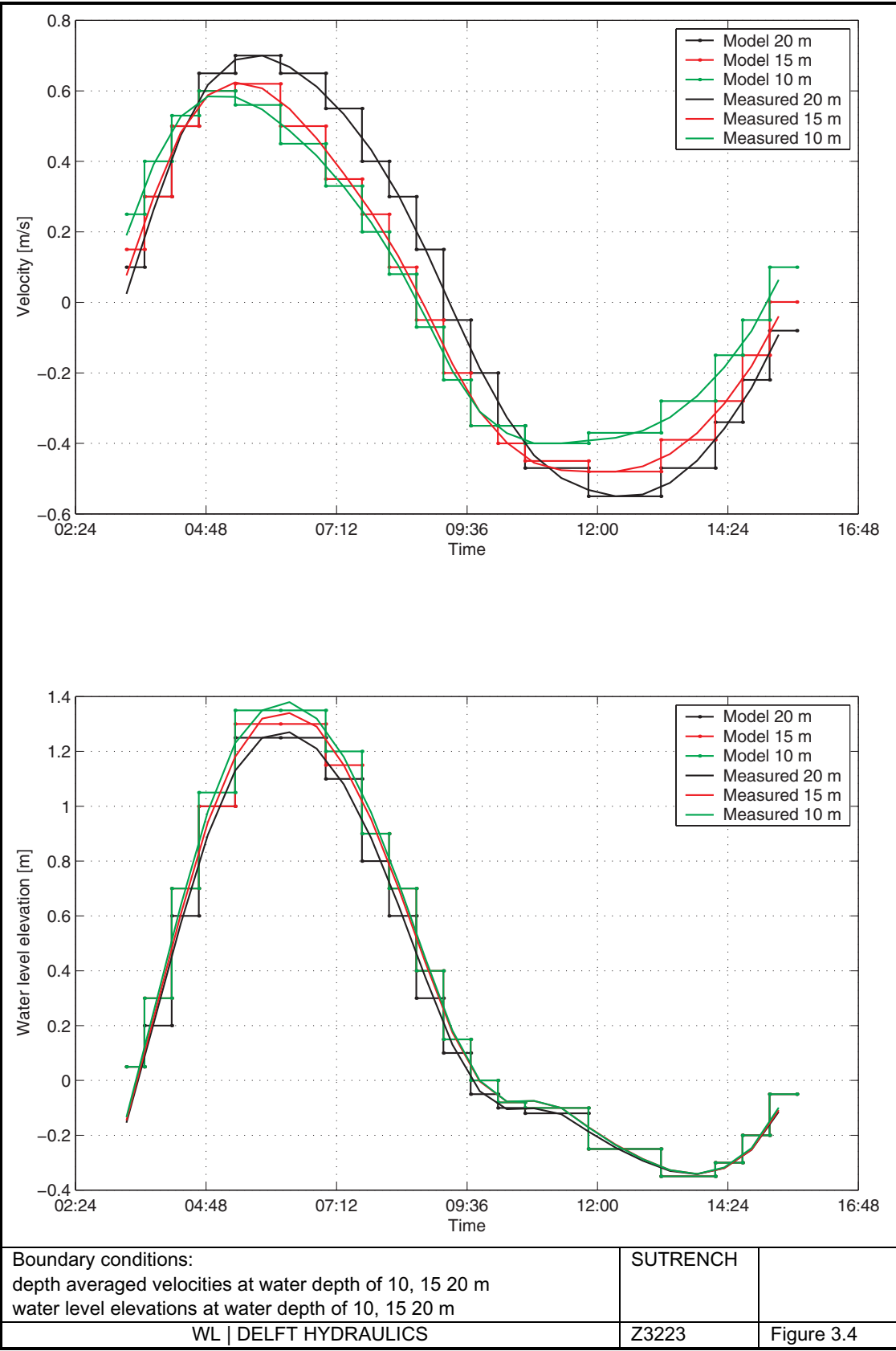
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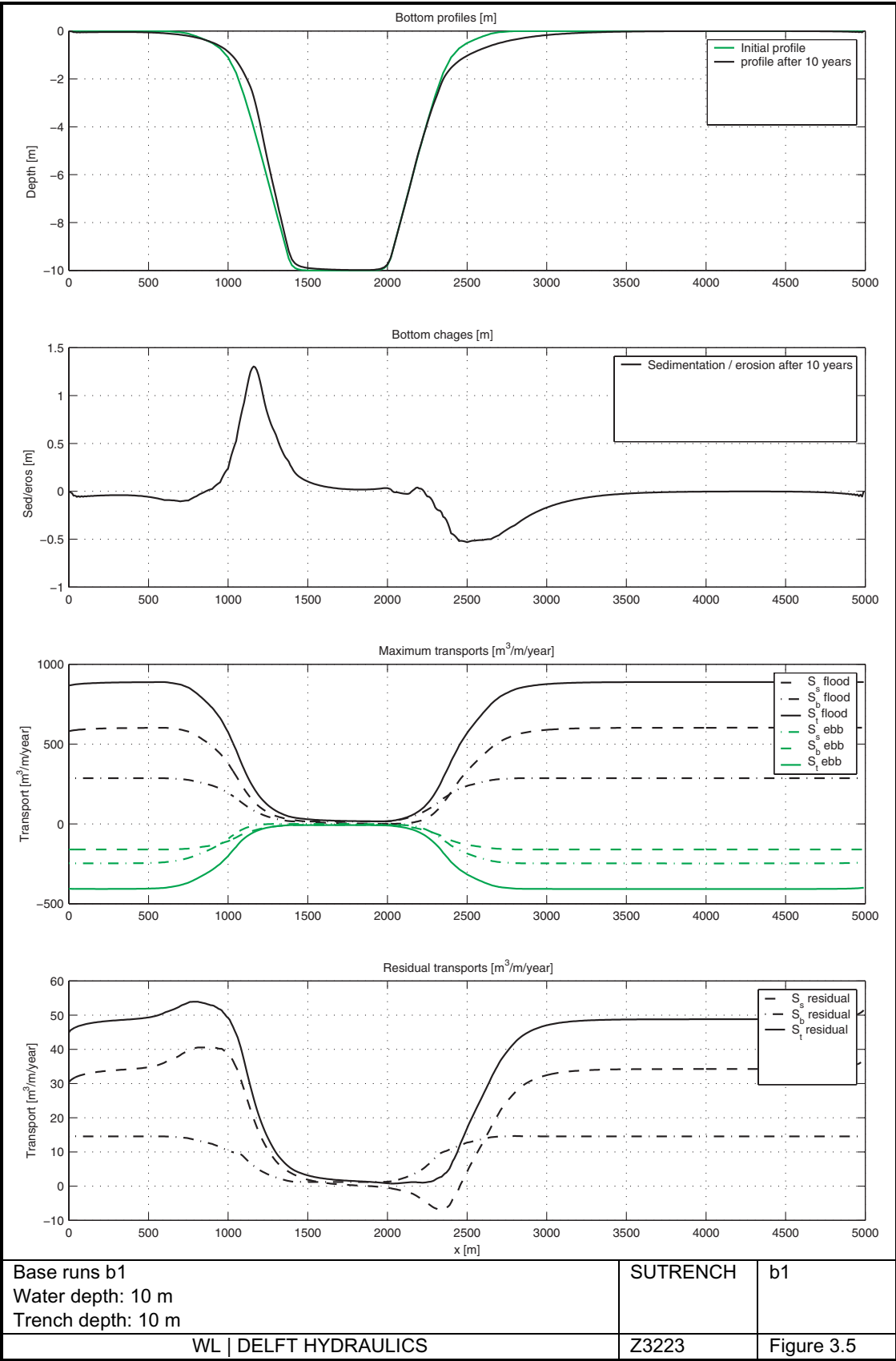
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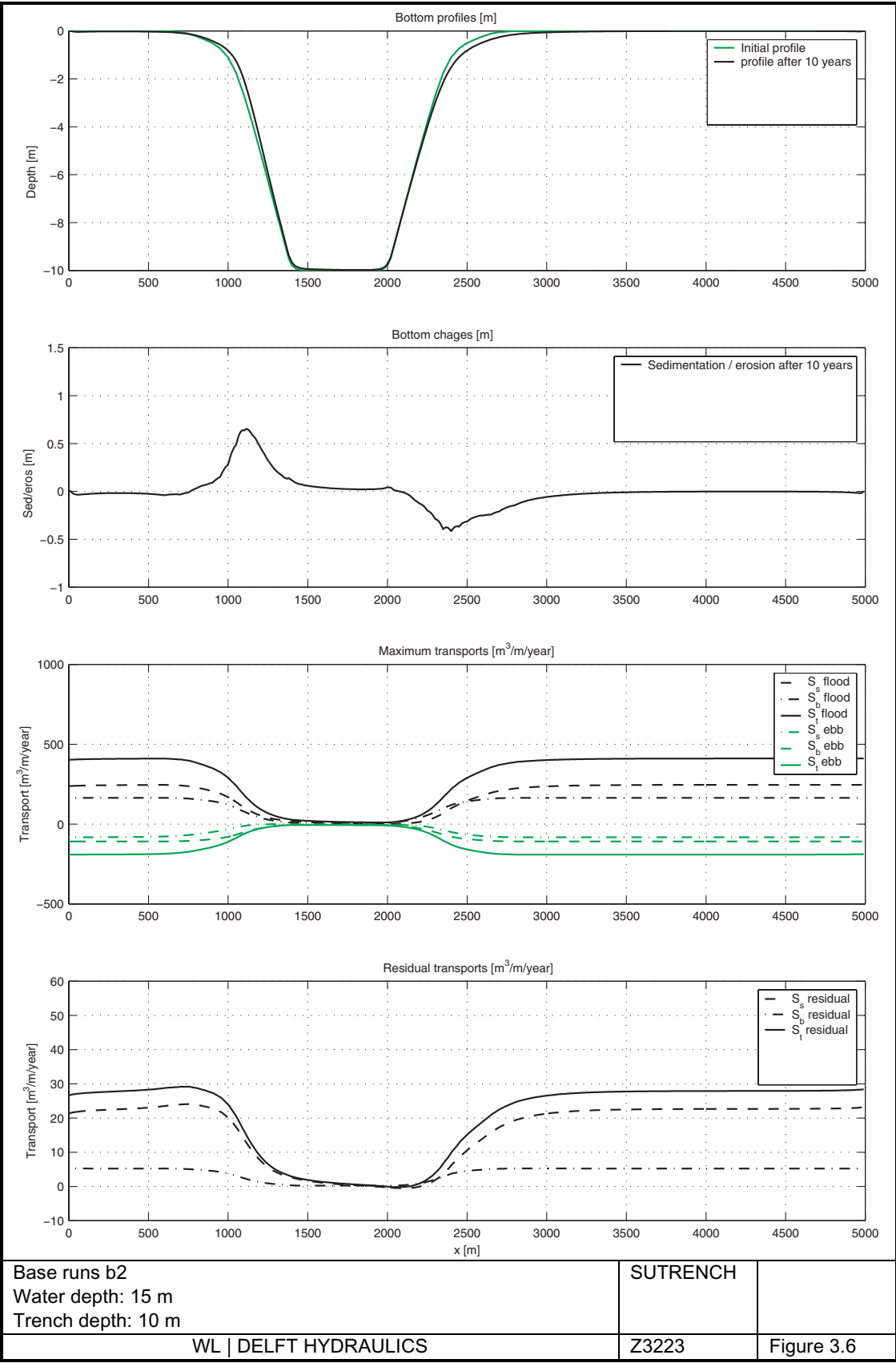
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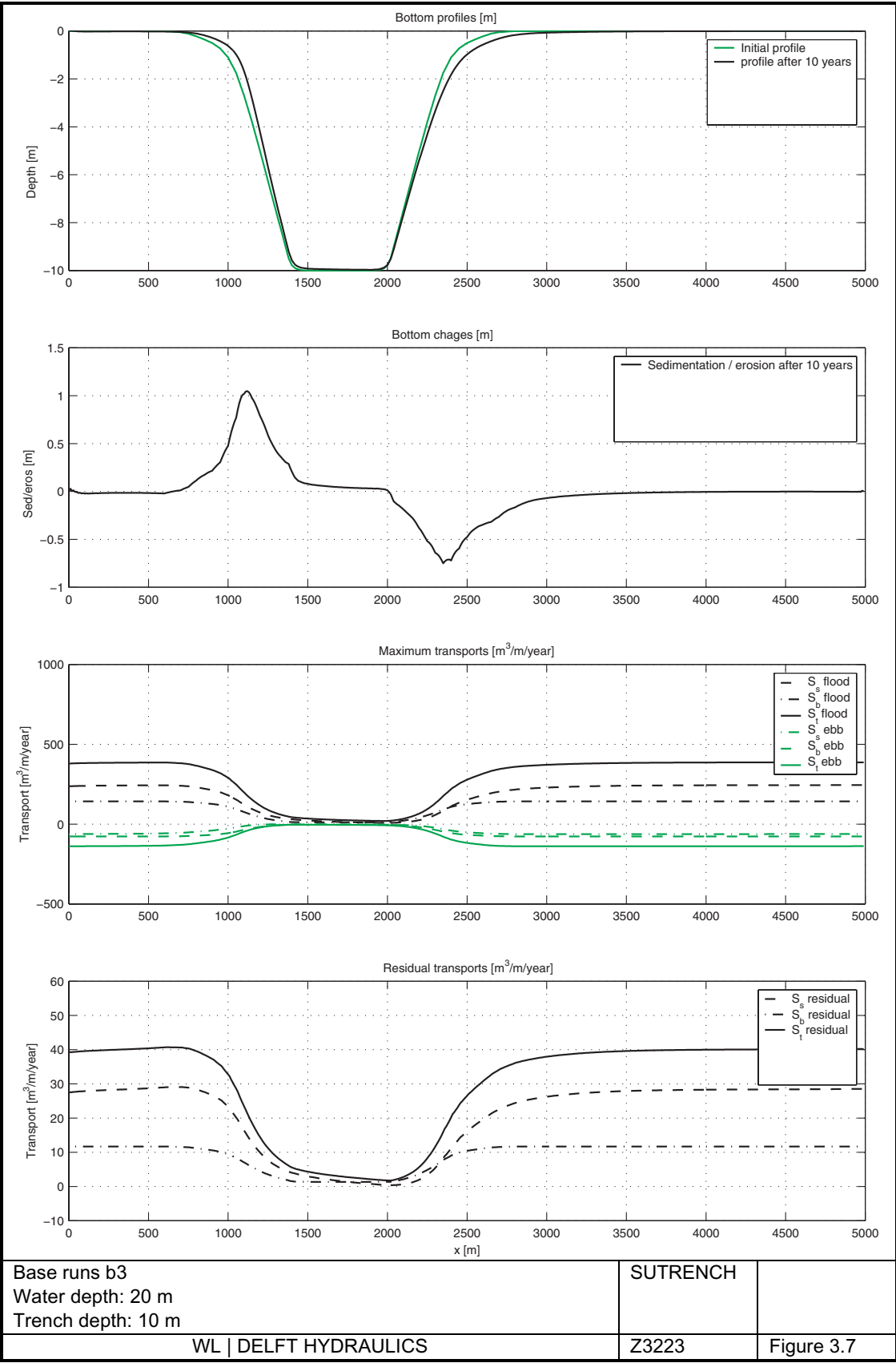
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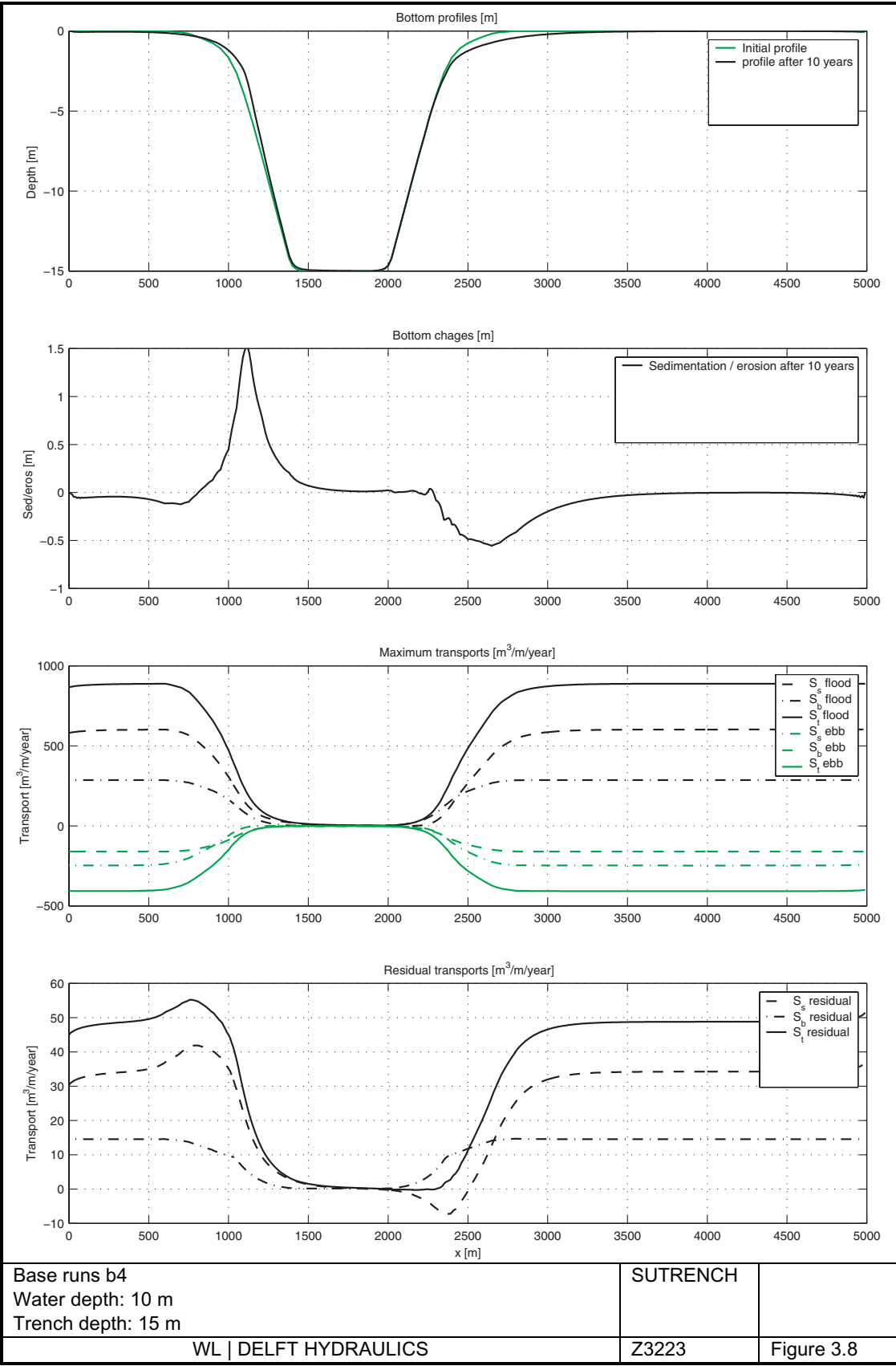


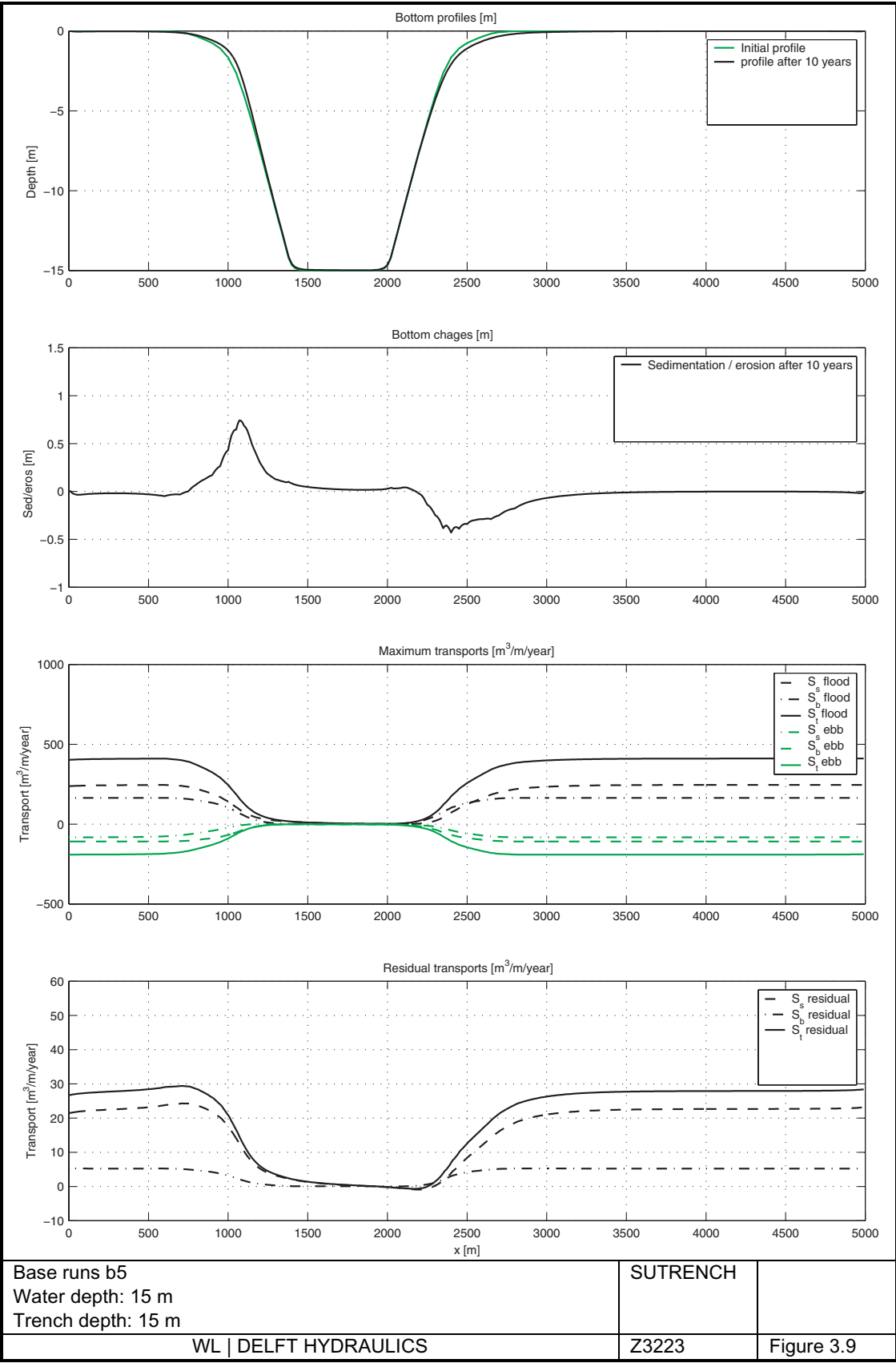


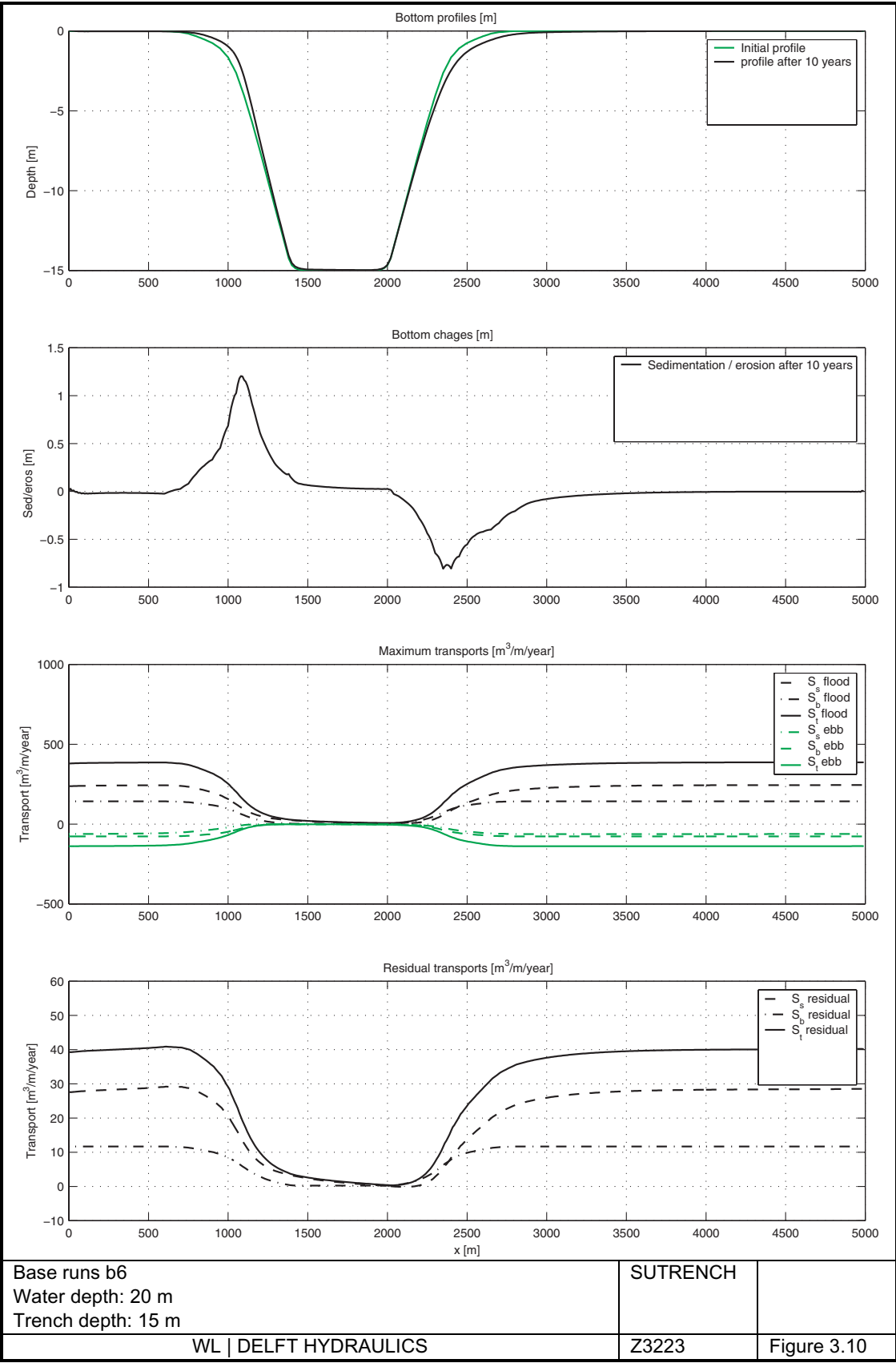


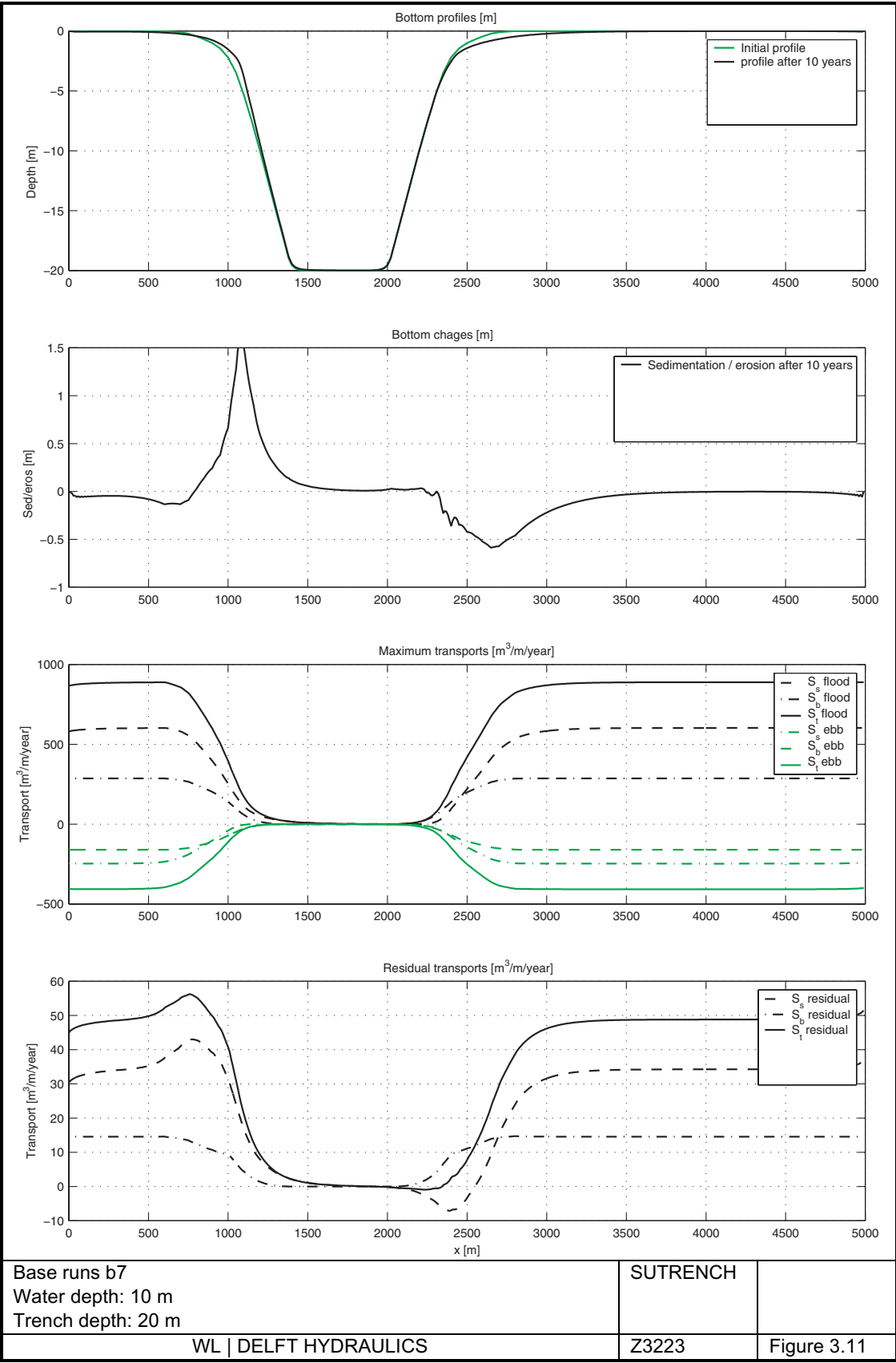


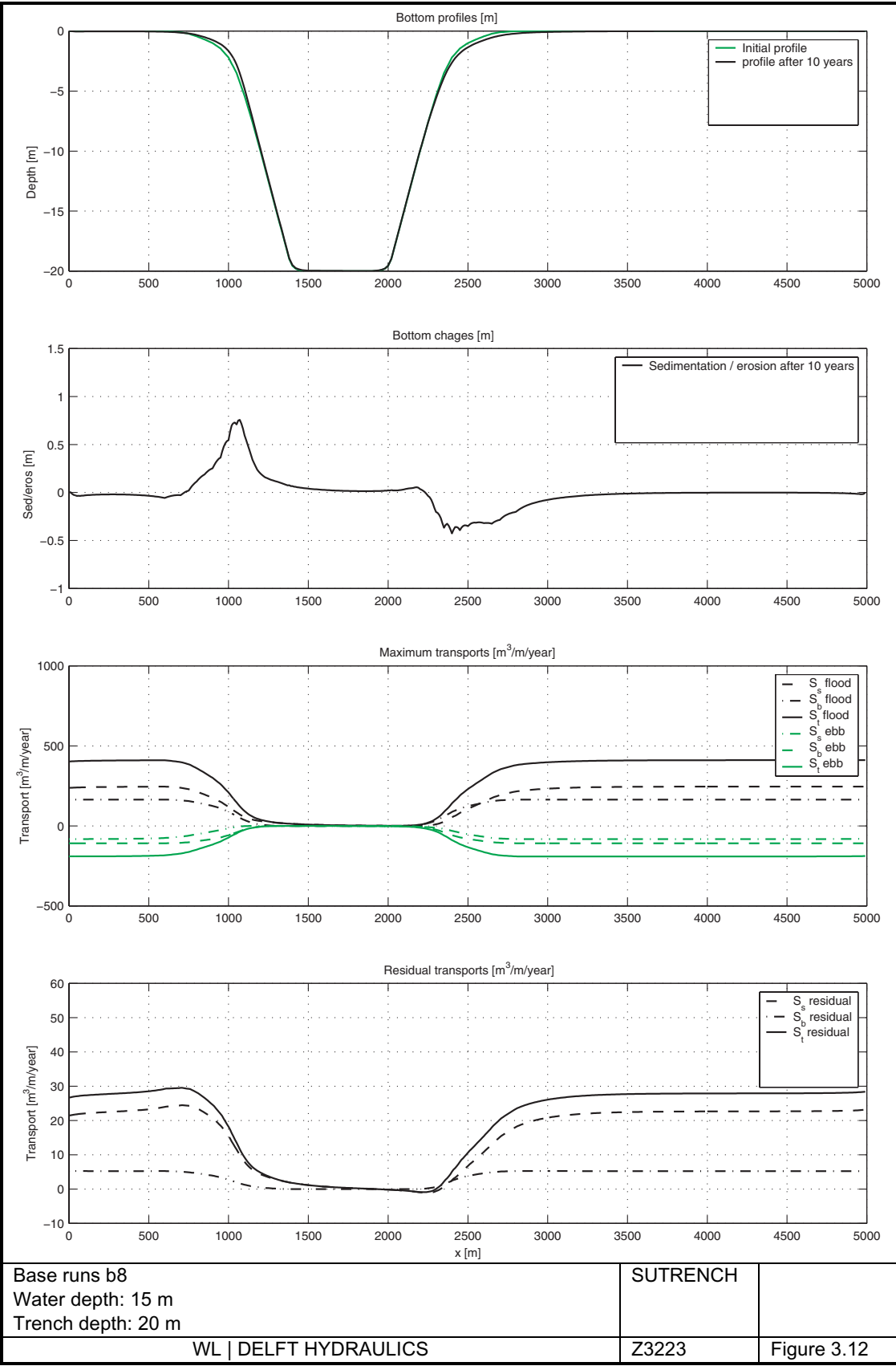


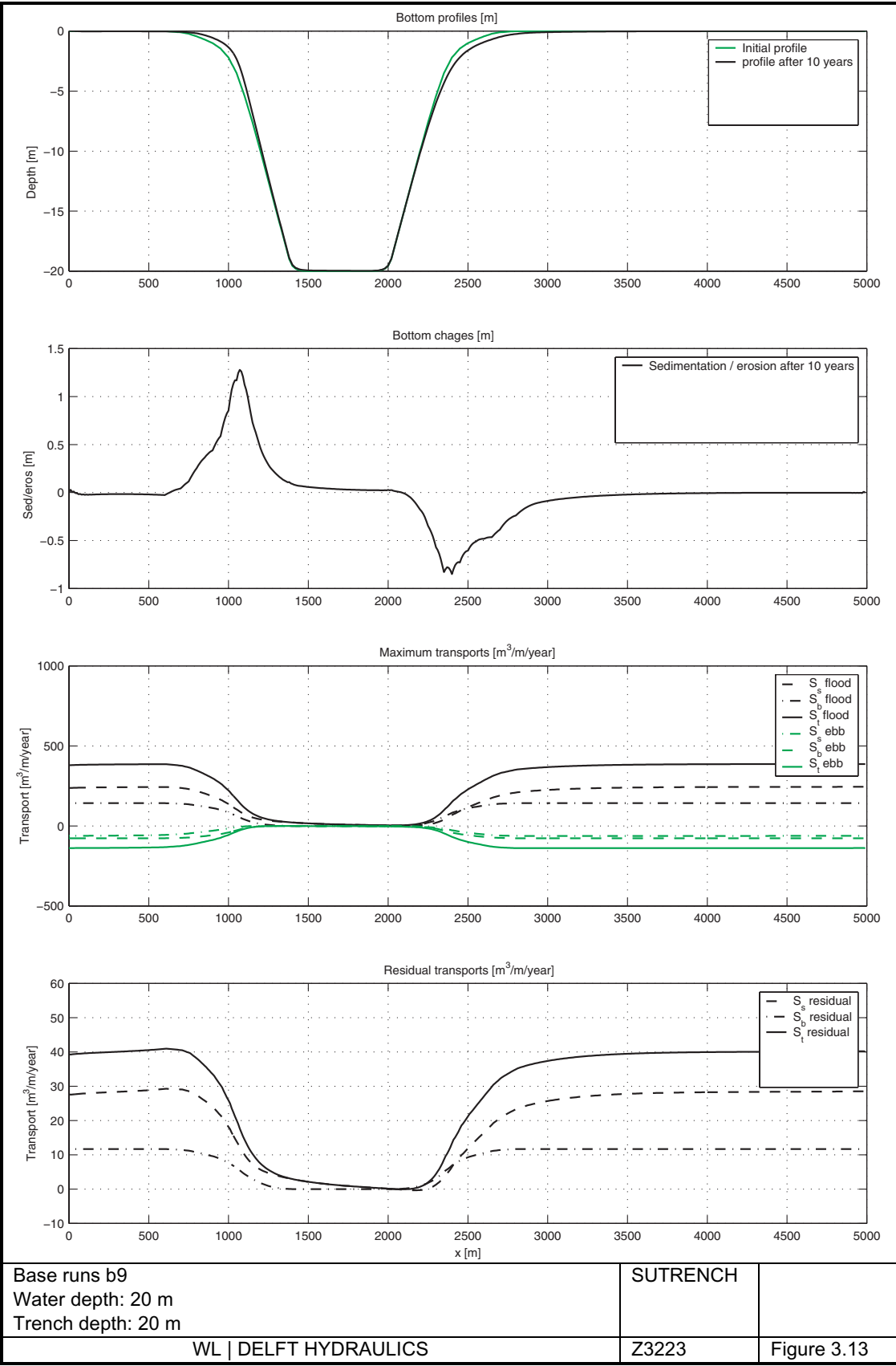


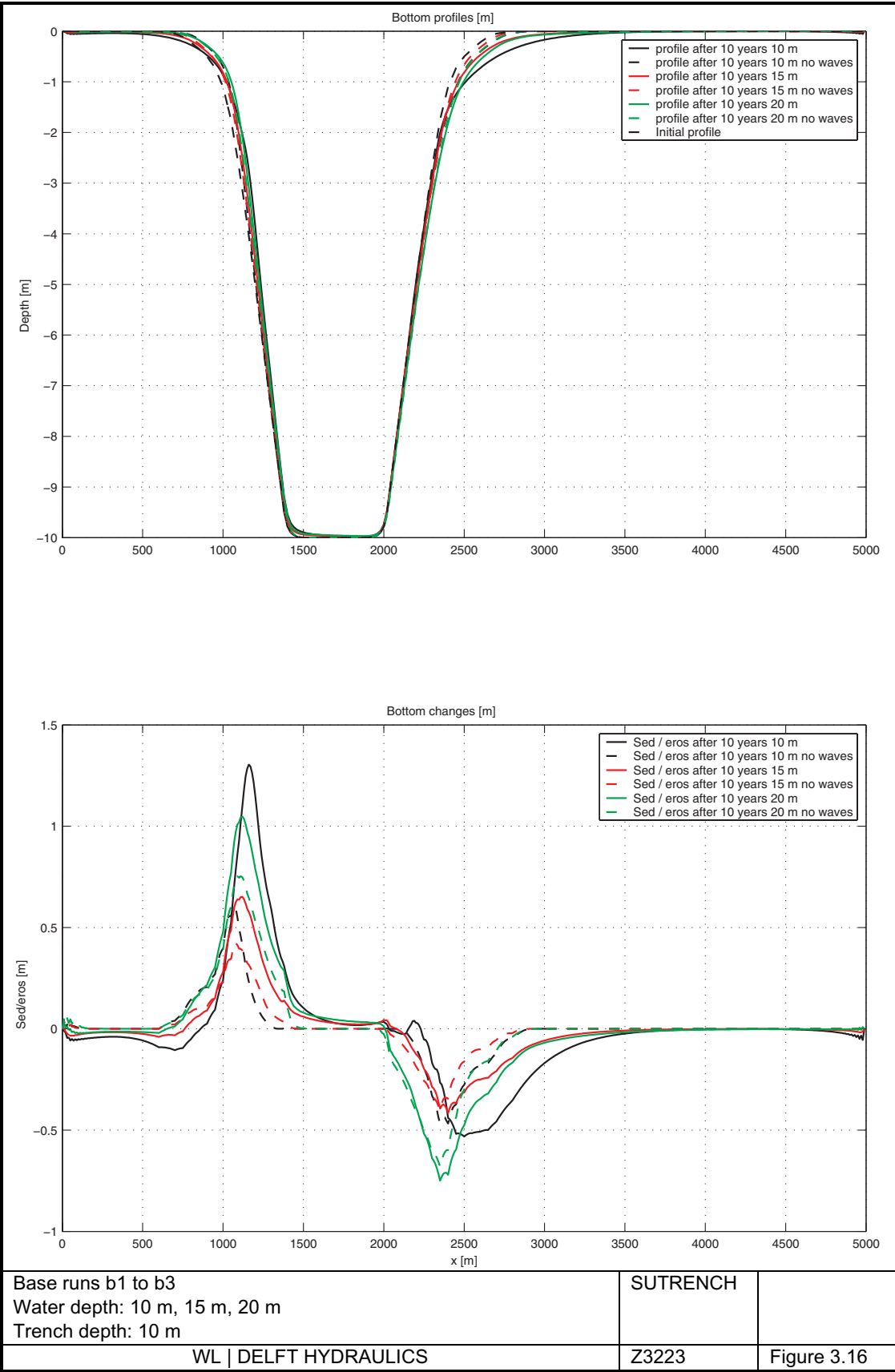


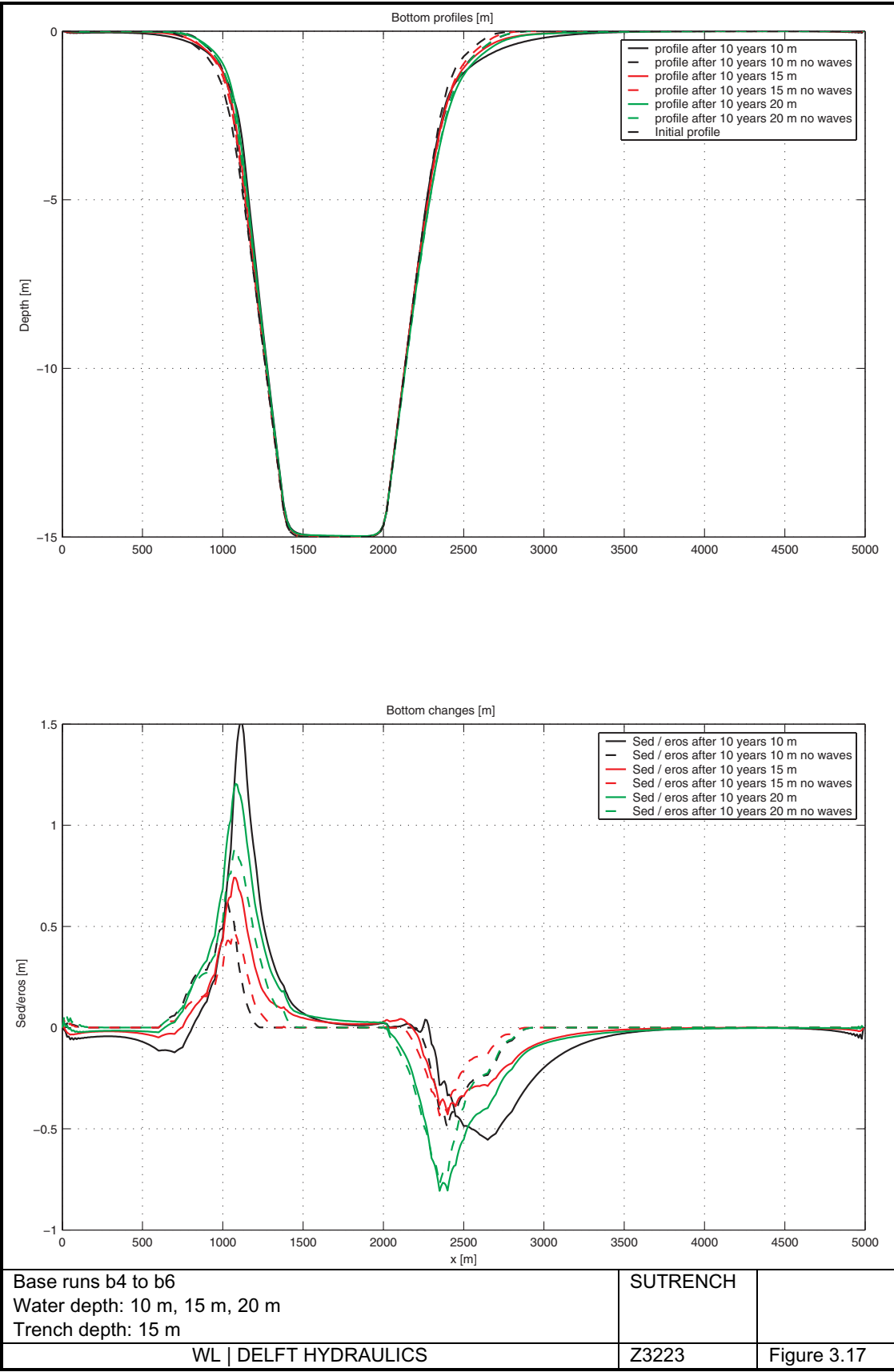


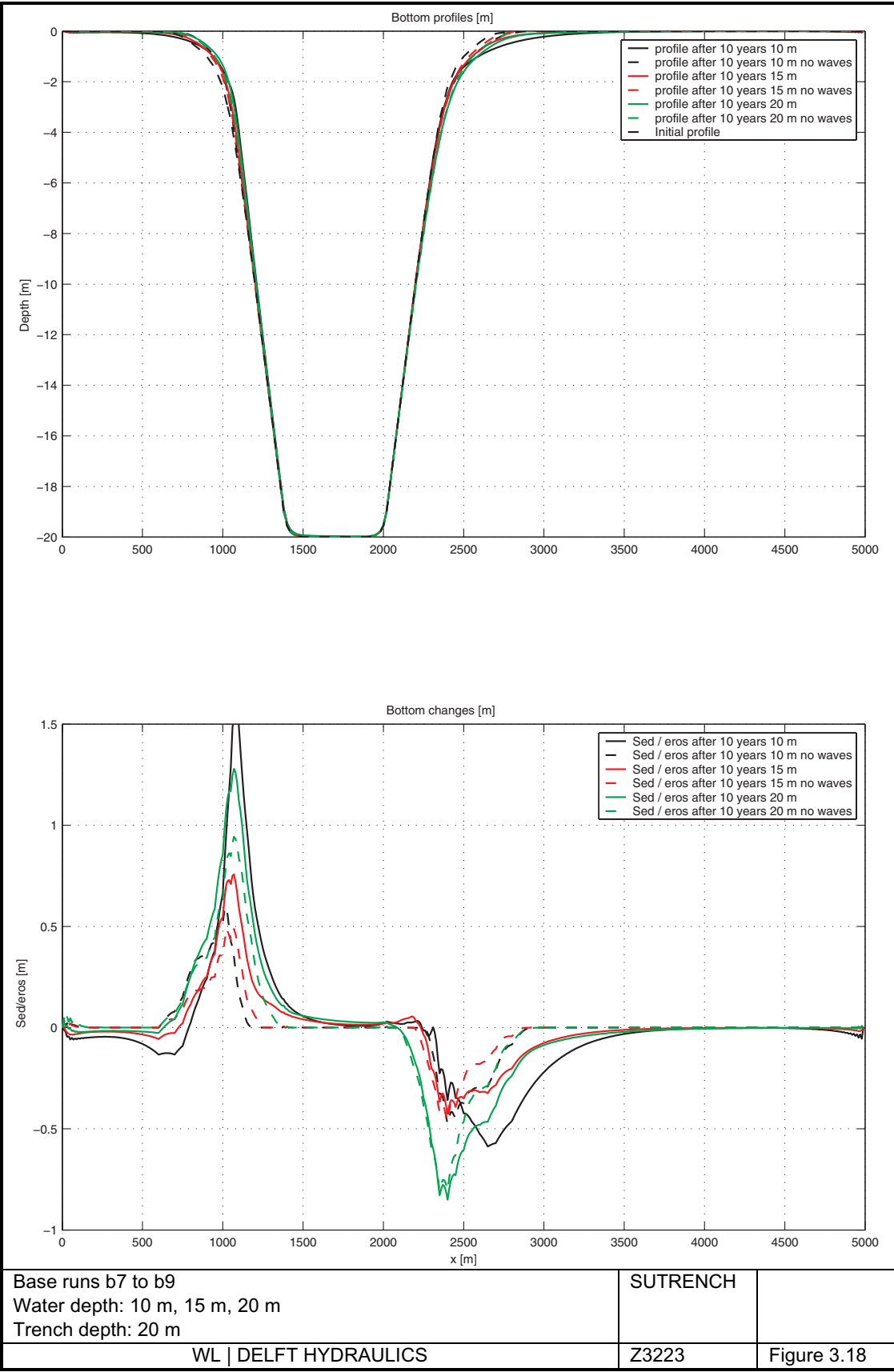












A Description of Applied Delft3D Models

A.1 Introduction

As the applied Delft3D model (referred to as the PIT-model) is identical to the model used in the model verification with the PUTMOR data set of Phase 2 (Walstra et al., 2002), only a brief description is given here with emphasis on the different boundary conditions (waves, tide, etc.).

The PIT-model obtains its tidal boundary conditions from a Delft3D model of the Dutch coast developed in the Flyland project (WL | Delft Hydraulics, 2001) called the Holland Coastal Zone model, abbreviated as HCZ-model. The HCZ-model obtains its boundary conditions from a well calibrated model called the large scale fine grid model covering the entire North-Sea (see WL | Delft Hydraulics, 2001, for details). In the Flyland study it was shown that both models showed excellent agreement with available field data. The PIT-model is characterised by a high resolution at the investigated pit and the surrounding area.

In the following sections model schematisations for the HCZ-model and PIT-model are described. Section A.2 contains a general description of the HCZ-model which is largely taken from WL Delft | Hydraulics (2001). Section A.3 describes the PIT-model, which involves a flow model (Sub-Section A.3.1), a wave model (Sub-Section A.3.2) and a transport and bottom model (Sub-Section A.3.3).

A.2 The HCZ overall model

The model grid of the HCZ-model was derived from the fine grid large scale model of the entire North Sea. A coastal stretch, reaching from “Schouwen Duiveland” to “Terschelling”, with an off-shore extent of 70 km was taken from the large scale model. In the vicinity of the “Marsdiep” the orientation of the grid lines was modified to allow for a better representation of the “Texelstroom”.

By refinement of the grid mesh the required resolution, especially in the near shore zone, was obtained. This results in grid distances in cross-shore direction varying between 50 m at the beach to 5 km at open sea. Alongshore grid distances equal approximately 1 km. In total the computational grid contains approximately 20,000 computational elements.

The model computations aim at predicting the morphological development of the shoreline. To allow for a retrieving coastline, the computational grid also covers some 200 m of the beach/dune area. The resulting computational grid is shown in the left plot of Figure A.1.

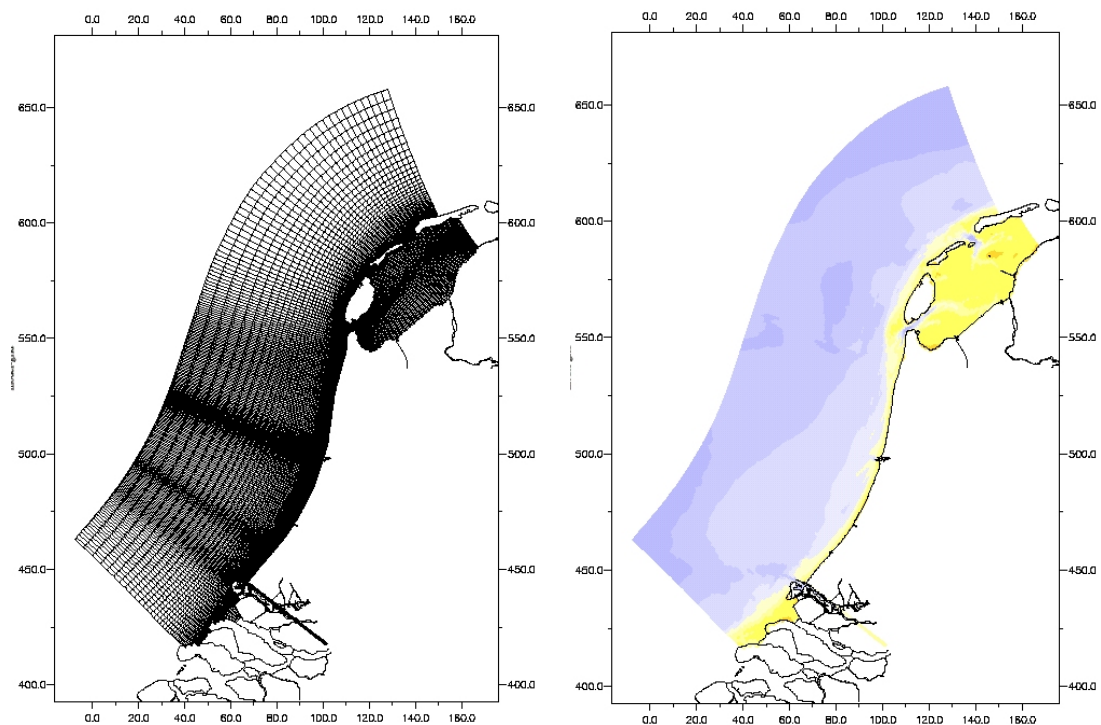


Figure A.1 Computational grid (left) and model bathymetry of present situation (right) of the HCZ-model.

Bathymetry

To represent the present situation, an initial bathymetry was generated using depth data originating from the “Kuststrook” model bathymetry. This depth data covers the area of specific interest for the present study in greatest detail. However, comparison of the depths generated using the Kuststrook data with the model bathymetry of the fine grid large scale model set-up previously (Roelvink et al., 2001) revealed large depth differences, up to 5 m, most pronounced near the open sea boundary of the HCZ model. Therefore, depths in the deeper areas, outside the areas covered by JARKUS and ‘vaklodingen’, were regenerated using recent Dutch Continental Shelf Data supplied by TNO-NITG. This data also served to generate, a part of, the bathymetry of the fine grid large scale model set-up previously. The right plot in Figure A.2 shows the present situation bathymetry (without the LDS).

Open boundary conditions

The open boundary conditions of the HCZ-model were derived from 3-dimensional computations with the large scale fine grid model covering the entire North-Sea. Since the HCZ model was set-up to represent average conditions, the model computation of the fine grid large scale model used for the generation of boundary conditions also represents the average conditions, i.e. a south-westerly wind of 7 m/s and long term average river discharges.

At the cross-shore open sea boundary near “Schouwen Duiveland” a velocity boundary is defined. All of the other open boundaries are defined as water level boundaries. The reason for this type of boundary definition is that the relatively large water level boundary provides more freedom to simulate other wind conditions.

The boundary conditions as generated by the fine grid large scale model are specified as time series of water levels or velocities. Hence, they relate to the simulation period of the fine grid large scale model. To allow for the simulation of any calendar period in time, the original time-series boundary conditions were converted into astronomical boundary conditions by means of a tidal analysis on the time series.

In the present study the constant, representative, discharge values for all discharge locations were used. In the table below an overview is given of the applied discharge rates.

Location	Discharge rate:
Haringvliet	660 m ³ /s
Nieuwe Waterweg	1540 m ³ /s
Sluices of IJmuiden	80 m ³ /s
Sluices of Den Oever	250 m ³ /s
Sluices of Kornwerderzand	200 m ³ /s

Table A.1 Overview of applied discharges in HCZ model.

Other model parameters

- **Computational time step**
Previous modelling exercises with the fine model revealed that the flow rates through the “Marsdiep” appeared to determine the maximum computational time step allowed. From this analysis it was found that a time step of 5 minutes is allowed for the HCZ-model.
- **Bed roughness distribution**
The bed roughness is prescribed by a Manning coefficient. The spatial distribution of bed roughness is taken from the large scale fine grid model set-up previously. For the shallow areas, depths less than 30 m, a Manning value of 0.028 is used. In the deeper areas a Manning value of 0.026 is applied.
- **Salinity**
At the open sea boundaries a constant salinity of 31 ppt was imposed. At the discharge locations the salinity value was set to zero.
- **Wind**
A constant representative wind was applied: windspeed 7 m/s from 240 °N (Southwest).

A.3 The detailed PIT-model

A.3.1 Flow schematisations

The PIT-model was nested in the HCZ-model to enable an increased resolution in the LDS area without having an unacceptable increase of CPU-time. With an automatic nesting procedure an optimal transition between the overall HCZ and PIT model is guaranteed. The PIT computational grid was constructed by taking a selection of the HCZ-model which was locally refined in the LDS area to have an accurate representation. The design criteria of the detailed grid were:

- a minimum of 20 computational grid points should cover the longshore axis of the pit, whereas for the cross-shore axis a minimum of 10 was used,

- the minimal distance of a boundary to the location of the pit 10 km to avoid boundary related disturbances,
- the fresh water discharge and tidal motion of the Nieuwe Waterweg may not be influenced by the boundaries.
- the boundaries of the PIT model should coincide as much as possible with the overall HCZ grid to avoid interpolation errors.

In the left plot of Figure A.2 the computational flow grid of the PIT model is shown.

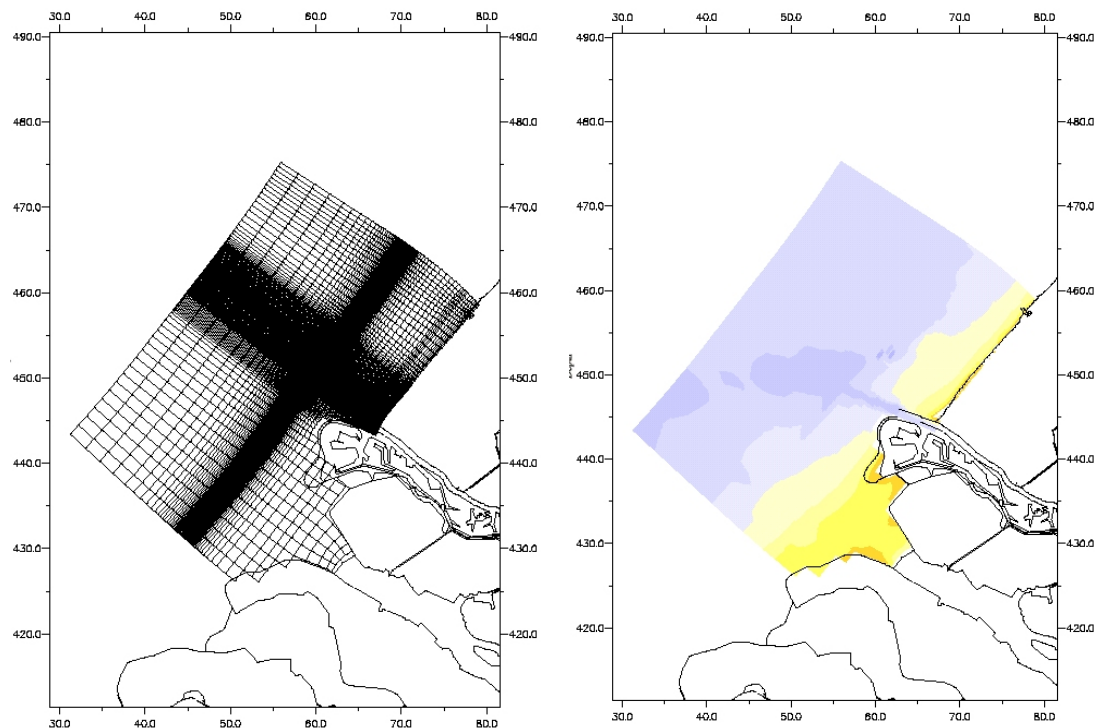


Figure A.2 Computational grid (left) and model bathymetry with LDS included (right) of the Pit-model.

The associated bathymetry was obtained from the PUTMOR survey after construction of the pit. The remaining bathymetry was obtained from the HCZ model bathymetry (right plot of Figure A.2). In Figure A.3 a detail of grid and bathymetry are shown for the LDS area, it can be seen that the resolution is high enough in both longshore and cross-shore direction to meet the standards listed above.

Boundary conditions were obtained from the HCZ-model. Both lateral boundaries were velocity boundaries whereas the coast parallel seaward boundary was largely a water level boundary.

A short overview of the of the PIT-model characteristics is given in the table below.

Unit	Quality
Grid	Curvilinear, originates from HCZ-model. Refined to get better resolution in the LSD vicinity (approx. 50×50 m). Number of grid points: 16000
Bathymetry	Originates from HCZ-model and PUTMOR data.
Time frame	According to period 4, computational time step 0.25 min
Boundaries	Generated by the HCZ-model, mainly current except SW-corner water level.
Roughness	From HCZ-model, Manning

Table A.2 Characteristics of PIT-model.

In Walstra et al. (1997) a representative tidal cycle (referred to as a morphological tide) was selected based on giving an accurate representation of the residual transports over a full neap-spring tidal cycle. This representative tide is also used in the present study. The selected representative tide runs from 18 July 1988 3hr20m to 18 July 1988 15hr40m.

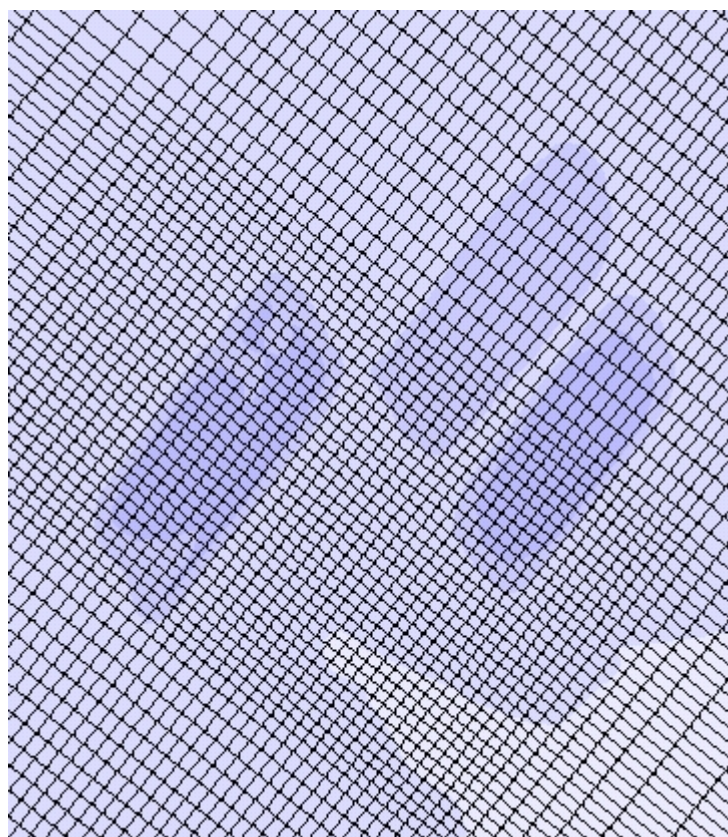


Figure A.3 Detail of Pit-model at the LDS site.

A.3.2 Wave schematisations

In order to simulate the wave propagation and transformation from deep water towards the shore, the wave module of the Delft3D model suite has been used. Two wave models are available within the wave module, i.e. the second generation HISWA wave model and its successor the third generation SWAN wave model. In this study the SWAN model has been

used since it allows for a direct coupling with the FLOW (and MOR) grid due to the availability of curvilinear grids.

In the Flyland study (WL | Delft Hydraulics, 2001) it was found that “in view of the overall uncertainties in morphological modelling it was concluded that the influence of second- or third-generation wave modelling on the resulting transports was very limited. Therefore the SWAN model was run in second generation mode to reduce the overall computing time of the simulations”. Following these conclusions in the present study, the SWAN model was also applied in 2nd generation mode. The following physics were taken into account: wave propagation in space, shoaling, refraction, wind growth, white capping, and depth-induced breaking.

The SWAN model uses the same computational curvilinear grid and bathymetry as used by the flow model (see Figure A.2). This avoids inaccuracies in the interpolation of data between the various Delft3D modules. The harbour moles of Rotterdam were represented in the SWAN model by obstacles with zero transmission (fully blockage of wave energy).

For the waves the wave climate from Walstra et al. (1998) is used. This climate consists of a single wave condition from 315 ° N with a height of 2.25 m, a period of 6.6 s occurring 84 % of the time.

A.3.3 Transport and bottom schematisations

In the morphodynamic simulations the new ‘sediment on line’ version was used. This has recently been introduced in the Flow module, so that the transport components can be calculated during the flow simulation. In this ‘on-line’ mode the transport rates can be computed using:

- a multi-layer model approach (3D) based on the numerical solution of the 3D advection-diffusion equation (Lesser, 2000);
- a one layer model approach (2DH) based on sand transport capacity formulations for bed-load and suspended load transport excluding or including the Galapatti method to account for the lag effects of the suspended load transport (van Rijn et al., 2000).

In the present study Delft3D was applied in 2DH-mode. The morphodynamic model uses the same boundary conditions as applied in the hydrodynamic verification. The simulated morphology was scaled to one year (Morphological scaling factor is set to 596.6). Additional input parameters are summarised in the table below.

Input Parameter	Value
Sediment Density	2650 (kg/m ³)
Median Sediment Diameter, D50	240 (µm)
Dry Bed Density	1600 (kg/m ³)

Table A.3 Additional model input parameters for morphodynamic simulations.

B Description of the Sutrench Model

The Sutrench model (Van Rijn and Tan, 1985) is a two-dimensional vertical (2DV) mathematical model for the simulation of bed-load and suspended load transport under conditions of combined quasi-steady currents and wind-induced waves over a sediment bed. All processes (parameters) in the direction normal to the computation direction are assumed to be constant.

Basic processes taken into account:

hydrodynamic

- modification of velocity profile and associated bed-shear stress due to presence of waves,
- modification of velocity and associated bed-shear stress due to the presence of non-uniform sloping bottom (only for case without waves),

sediment transport

- advection by horizontal and vertical mean current,
- vertical mixing (diffusion) by current and waves,
- settling by gravity,
- entrainment of sediment from bed due to wave- and current-induced stirring,
- bed-load transport due to combined current and wave velocities (instantaneous intra-wave approach),
- slope-related transport components (bed load),
- effect of mud on initiation of motion of sand,
- non-erosive bottom layers.

Basic simplifications are:

hydrodynamic

- logarithmic velocity profiles and associated bed-shear stress in conditions with waves (steep-sided trenches and channels can not be modelled),
- shoaling and refraction of wind waves is not implicitly modelled,
- current refraction (veering) is not implicitly modelled,

sediment transport

- steady state sediment mass conservation integrated over the width of the flow (stream tube approach),
- no longitudinal mixing (diffusion),
- no wave-related suspended sediment transport (no oscillatory transport components),
- uniform grain size (no mixtures),

numerical

- forward-marching numerical scheme (transport due to near-bed return currents can not be modelled),
- explicit Lax-Wendorf numerical scheme for bed level changes (smoothing effects may occur).

Boundary conditions to be specified, are:

- water depth, flow width (stream tube width, discharge is constant) and bed level along computation domain,
- wave heights along computation domain,
- equilibrium or non-equilibrium sediment concentrations at inlet ($x=0$); model has option to generate equilibrium concentrations,
- bed concentration or bed concentration gradient is prescribed as function of bed-shear stress and sediment parameters,
- sediment, settling velocity, and bed roughness.

The Sutrench model is a process-based model to be applied at a space-scale of 1 to 5 km and at a time scale of 1 to 100 years (imposed by computation time and available computer memory). Practical application requires detailed knowledge of the sediment composition along the bed and the incoming sediment transport (at inlet boundary $x=0$).

The Sutrench model is applicable in regions outside the surfzone where wave breaking is limited. Since it is a 2DV model all processes normal to the computational direction are assumed constant. This can impose limitations to the applicability of Sutrench if 2DH or 3D effects play a dominant role.

C Sensitivity Analysis With Sutrench

This appendix contains three kinds of sensitivity runs. First the effect of individual wave conditions is investigated by means of the wave height, the incident wave angle and the wave period. After that the sensitivity to different kinds of wave climates schematisations is investigated. In the second section, the trench is subjected to different current velocities. The last section contains the effect of the physical parameters.

C.1 Wave parameters

The analysis of the effect of the wave on the trench is investigated in a couple of steps. First the influence of the individual wave parameters is investigated: the wave height, the approach angle and the wave period. After that the effect of a well-chosen combinations of waves with different parameters is investigated: the wave climate effect.

Sensitivity to wave period

Walstra et al. (1998) investigated three wave periods (4.4, 6.6 and 9.9 sec.) and conclude: “The influence of variations in the wave period is small. Residual transports show only a weak reaction to variation in the wave period (i.e. smaller relative change than the change of the wave period).”

Sensitivity to wave angle

The initial residual transports have been simulated with wave approach angles varying from 0 ° (along the main current) to 180 ° (against the residual current). The wave heights are set to 2.35 m and the wave period to 6.6 s. The results of the transports are given in Figures A.1 to A.3.

The suspended transport in Figure A.1 are maximal when the waves approach the trench at 0 °. When the waves approach the trench more or less perpendicular, 70 to 120 °, the transports do not change. The transport with perpendicular and parallel waves differ by a factor 2. From experiments it is known that the suspended transport is very sensitive to the incident wave angle. The suspended transport reaches its maximum value when the waves approach the current at 90°. In that case the bed ripples due to waves and the bed ripples due to the current form a kind of honeycomb structure on the bottom, enhancing resuspension. This is obviously not the case in Figure A.1. Apparently the formulations in SUTRENCH are not accordance with this knowledge.

The bedload transports are even more sensitive to the incident wave angle, as can be seen in Figure A.3. The bed load is maximal when the wave approach against the current direction and minimal at an angle of 70 °. The transports at an angle of 180 ° are ten times the transport at 60°. This is due to outdated formulations for calculating the velocity in the boundary layer in Sutrench.

It can be concluded that the bedload and suspended transport relations in Sutrench require further examination with respect to the wave angle.

Sensitivity to wave height

The effect of the wave height effect is investigated in two ways. First, a 10 year simulation is made without waves to investigate the morphological effects of the presence of waves. Second, the initial residual transports are investigated for the 12 different wave heights from a wave class exceedence climate (see next section).

Morphological simulation without waves

To investigate if the waves have any influence at all, a run is made without waves (runid ww6 at 10 m and ww12 at 20 m). Figure A.4 shows that the morphological changes are significantly smaller when there are no waves present. The reduction of bottom changes is more pronounced at 10 m depth (solid lines) than at 20 m depth (dashed lines). At 20 m depth the absence of waves leads to a smaller reduction in morphological changes than at 10 m. Accordingly, at 20 m depth the wave effects are small compared to the current effect. The influence of the waves is not negligible at 20 m however.

Walstra et al. (1998) also investigated the long term effect of the waves used in the simple one condition wave climate. In the sensitivity simulations they performed, the morphological wave of 2.25 m was halved to 1.125 m and increased to 3.375 (150 %). They concluded: "The influence of the increased wave height can clearly be seen in the results; the residual transports have increased considerably and also has the subsequent sedimentation of the trench. At the bottom of the downstream slope negative (southward) transports occur which are caused by an increase of transports in ebb-direction. This is caused by the fact that due to the increased wave height more sediment is stays in suspension which results in a larger lag in the settling of suspended sediment causing a larger transport at the bottom of the slopes. Trapping efficiency is also affected significantly; in case of an increased wave height the total trapping is 98% and the dredge trapping is 100%. The decreased wave heights cause a significant decrease of the sediment trapping which is caused by the lower transports due to ebb-currents on the downstream (northern) slope. This is due to the opposite effect as described for the increased wave heights: lower suspended sediment concentration resulting in a smaller lag. From the relative bottom transports results it can be seen that the bottom transport reacts inversely to changes in wave height. This is due to the fact that the current velocity in the bottom boundary layer decreases in case of increasing wave heights. Variations in wave height affect the resulting morphological behaviour of the trench clearly. The variations in the results are of the same order as the applied changes in wave height."

Wave height effect on residual transports

In Figures A.5 and A.6 the residual transports outside the trench are shown for various wave heights. The transports increase more than linearly with the wave height. The suspended transport increases much faster than the bedload transports. The variation along

the main axis of the trench is shown in Figures A.7 to A.8. These Figures are further analysed in Section C.1.2.

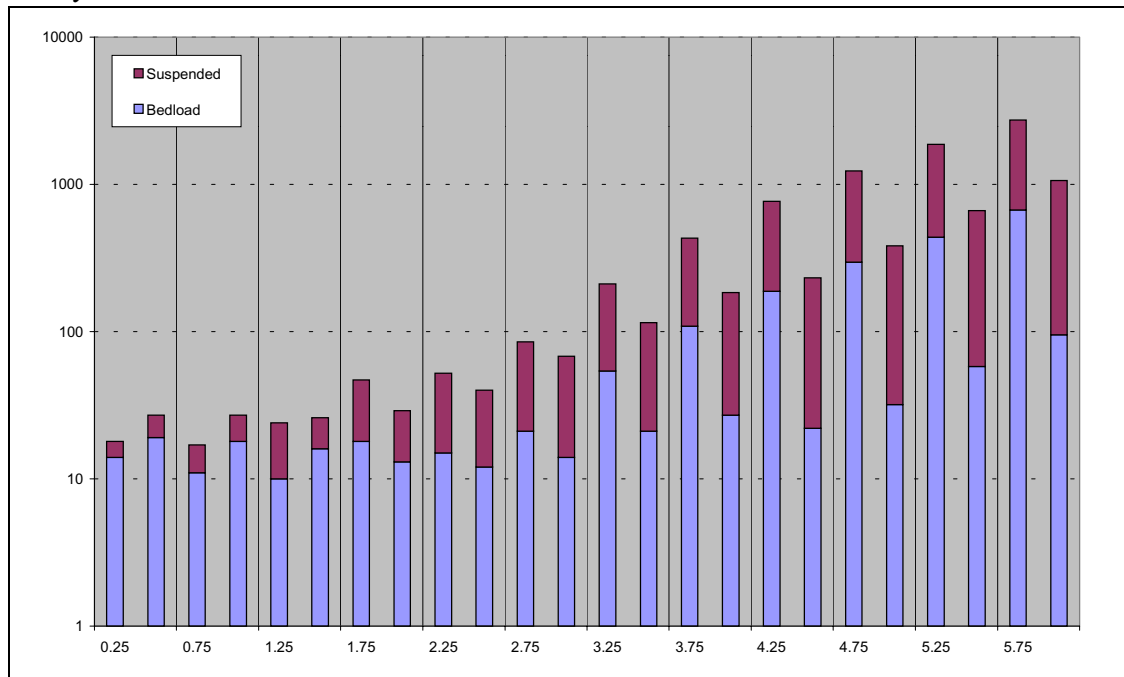


Figure A.5 Initial residual transports as a function of the wave height H_s in m. Left column 10 m depth, right column 20 m depth. (logarithmic scale)

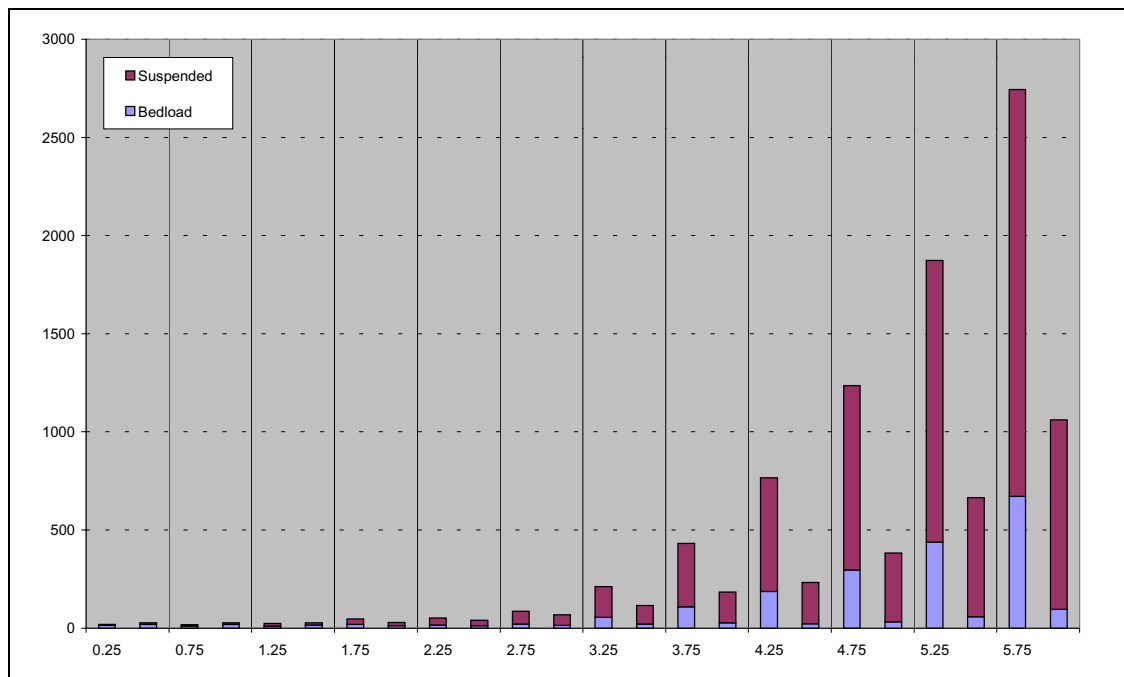


Figure A.6 Initial residual transports as a function of the wave height H_s in m. Left column 10 m depth, right column 20 m depth. (normal scale)

C.1.1 Wave schematisations

In the base run simulations a simple morphological wave climate with only one wave condition is used. To study the effect of this simplification, sensitivity analyses with

complex extended wave climates are performed. These climates are obtained from recent studies. The chronological effect and the effect of different (types of) wave climates are investigated.

The basic assumption of Sutrench does not allow the use of a complex wave climate. Accordingly, for the simulation of every wave condition of a complex climate, a single Sutrench run has to be performed. The transports of these Sutrench runs are then averaged to get the residual transports. After that, the residual transport for all the wave conditions of a complete climate are added, accounting for the right weight (in days per year), to get the yearly residual transports. The transports obtained this way are considered to be the occurring yearly averaged transports. Obviously, this approach does not allow calculating the feed-back of the bottom changes on the transports. This feed-back is only possible with simple wave climates with one morphological wave condition. Consequently, the bottom parameters defined in Section 3.3 can not be applied to assess the results, only the residual transports can be used. The possible influence of the sequence of the waves in a wave climate is therefore investigated with the single wave condition of the base runs. These results can be judged by the bottom change parameters.

Chronology effect

In the base runs a simple wave climate has been used: a 2.25 m wave acting for 84 % of the time. In Sutrench this is represented by starting the simulation with a 8.4 year period with waves, followed by a 2.6 year period without waves. A sensitivity run is made to investigate the sequence effect of this approach. Therefore a run is made starting with a 2.6 year period without waves, followed by a 8.4 year period with the 2.25 m wave (runid: ww5 at 10 m and ww11 at 20 m.). This sequence and the sequence used in the base runs are the most extreme sequences possible. In the base runs the current-only-period at the end of the simulation can smooth the morphological effect of the waves, in the sensitivity run the wave effects cannot be smoothened.

Figure A.4 shows the results of the wave sequence run for the bottom (changes) and the corresponding base run. The sedimentation / erosion patterns at 10 and 20 depth is exactly the same: the lines of the other wave sequence are not even visible. Accordingly it can be concluded that there are no sequence effects with one morphological wave condition.

Set-up wave schematisations effect

1 Wave height frequency exceedence table

The first complex wave climate is the wave height frequency exceedence table derived/composed by Sordedraeger (2002), in which the occurring wave heights range from 0 m to 6 m in wave classes of 0.5 m (runid: ww0). This climate is obtained from data from the Euro-platform measurement station. For the wave period a one to one relation between the wave height and the wave period is used: a higher wave corresponds with a higher wave period.

$$T_p = 1.49H_{rms,0} + 4.2 \quad (7.1)$$

This wave climate does not contain information on the wave direction. Therefore the same direction is used as in the bas runs (315 °N). The wave climate is given in Table A.1.

RunID			ww0 / euro		H1887	
Hs	Tp	deg N	occurrence	exceedence	occurrence	exceedence
[m]	[m]	[deg]	[days]	[days]	[days]	[days]
0.25	4.46	315	55.38	365.25	82.84	365.07
0.75	4.99	315	113.53	309.87	130.07	282.23
1.25	5.52	315	83.85	196.34	73.71	152.16
1.75	6.04	315	51.51	112.49	41.05	78.46
2.25	6.57	315	29.75	60.97	19.47	37.40
2.75	7.10	315	16.04	31.23	10.15	17.93
3.25	7.62	315	8.88	15.19	3.87	7.78
3.75	8.15	315	3.94	6.30	2.05	3.91
4.25	8.68	315	1.48	2.36	1.02	1.86
4.75	9.20	315	0.57	0.88	0.84	0.84
5.25	9.73	315	0.21	0.30	0.00	0.00
5.75	10.26	315	0.09	0.09	0.00	0.00
Total			365.25		365.25	

Table A.1 Wave class frequency exceedence climate Sorigedragger (2002) (runid ww0) and Van Rijn et al. (1995) (runid H1887)

The second wave class exceedence climate used in the present study is the wave climate measured in profile 103, which is the transect perpendicular to the coast at Scheveningen (study H1887, Van Rijn, et al., 1995). Figure A.9 shows that this frequency exceedence wave climate is similar to the climate of Sorigedragger (2002). To get the results of the H1887- climate, the results of the individual wave conditions of Sorigedragger (2002) can simply be used with other weight (days of occurrence). Since the H1887 data do not contain information on the wave period and the approach angle, the periods and incident wave angle of the ww0 simulation are used.

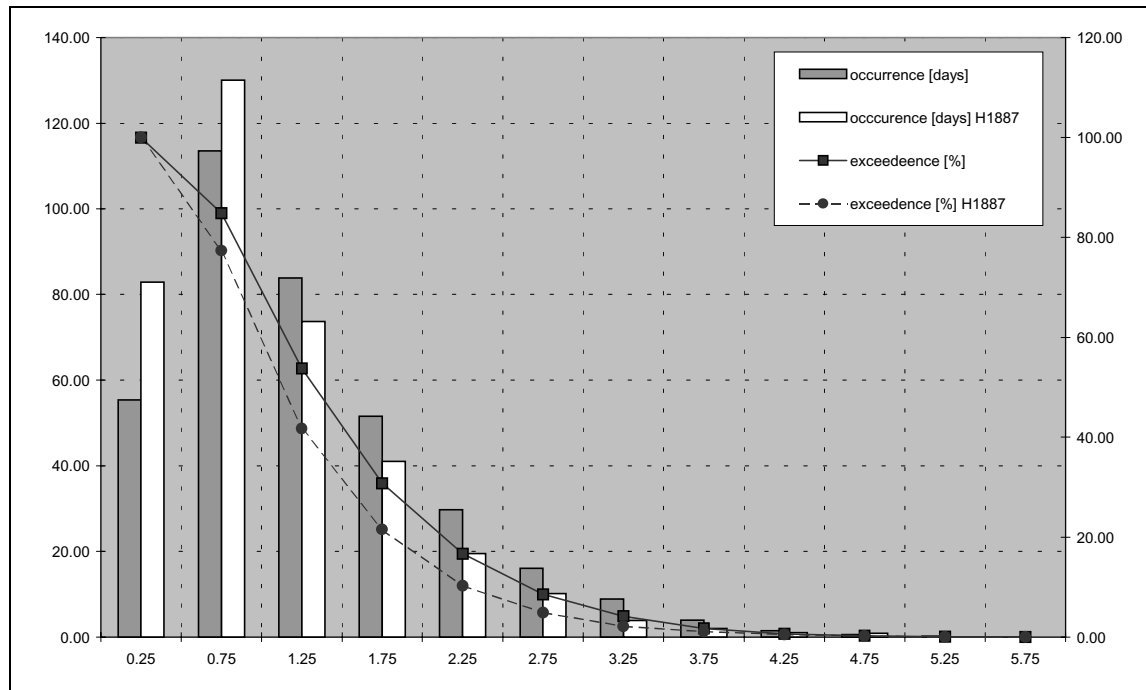


Figure A.9 Wave frequency exceedence climate Hs [m] to occurrence [days/year] and exceedence [%].

2 Morphological wave climate

The second type of complex wave climates used comes from a recent Maasvlakte-2 study (Steijn et al., 2000). This climate contains 11 wave conditions, each of which have a unique wave height, wave period and incident wave angle, which are not correlated. This climate has been adopted for Delft3D and is based on work by Roelvink et al. (1998).

Overall sensitivity test on the incident wave angle have been made by (1) rotating all the angles over 20° in one simulation (runid ww3) and (2) setting all the angles to 315° N in another simulation (runid ww2, see Table A.2). The results of these simulations should be considered with care, bearing the great inherent sensitivity of Sutrench to the wave angles in mind.

Runid:			ww1	ww2	ww3	
Name	H _s [m]	T _p [m]	deg N [°]	deg N [deg]	deg N [deg]	occurrence [days]
w00	0.1	5.00	310	315	290	136.50
z01	1.05	5.00	255	315	235	46.00
z02	2.75	7.20	245	315	225	15.70
z03	1.25	5.30	285	315	265	15.00
z04	2.15	6.50	275	315	255	6.90
w05	1.05	5.00	295	315	275	10.60
w06	2.35	6.80	295	315	275	5.10
n07	1.25	6.30	345	315	325	35.00
n08	2.35	7.20	345	315	325	8.80
n09	1.05	6.00	365	315	345	65.70
n10	2.35	7.10	355	315	335	19.70
Total						365.00

Table A.2 MV2 morphological wave climate

Results wave schematisations effect

Residual transports

Figures A.8, A.9 and A.10 show the residual transports from the simple and complex wave conditions at 10 and 20 m depth. The climates comprise:

- wave class climate Sorgedrager (2002), 12 conditions (runid: ww0, euro)
- wave class climate Van Rijn et al. (1995), 12 conditions (runid: H1887)
- representative wave Walstra et al. (1998), 1 condition (runid: w5, w11)
- a reference run without waves (runid: w6, w12)
- MV2 climate, 11 conditions
 - ◊ with original diverse approach angles (runid: ww1)
 - ◊ with approach angles of 100 ° (runid: ww2)
 - ◊ with original diverse approach angles rotated over 20 ° (runid: ww3)

All the transports with waves are in the order of 32 to 47 m³/m/year at 20 m depth and 35 to 45 at 10 m depth.(first 8 columns of Figure A.10).² The fact that the five various different wave climates give such similar results is very surprising, since the transports are very sensitive to the contributing individual wave heights (Figure A.5). This shows that the wave climates are robust and have been constructed well. However, some differences in transport magnitude and variation along the main axis of the trench can be observed at a water depth of 10 m .

At a depth of 20 m all transports are virtually the same for all the wave conditions: about 35 m³/m/year. One might immediately conclude that this is due to the fact that the current is the only forcing at large water depths. In the run without waves however (w12), the transports are significantly lower (less than 30 m³/m/year) than in the runs with waves. This

² Note that the transports for the morphological wave Z2378 of Walstra et al. (1998) are slightly different than the ones in annex 4 and 6. In figure 5 the 84 % occurrence is taken into account, in annex 4 and 6 the initial residual transport is shown, in which the waves are 2.25 m all the time.

difference is primarily due to the difference in the suspended transports. Accordingly, the waves do influence transports at 20 m, but the current effect certainly dominates.

If the bed load at 20 m water depth for the different wave conditions are compared, it can be seen that without waves larger residual transports occur then for the morphological wave climates. There is no physical explanation for this, it does illustrate that the Transpor model, which has only been tested for surf zone conditions, may yield unexpected results in deeper water. Validation of the Transpor model for deep water conditions is a crucial element for improving the morphological predictive capabilities of not only the Sutrench model, but also the Delft3D and Unibest-TC model.

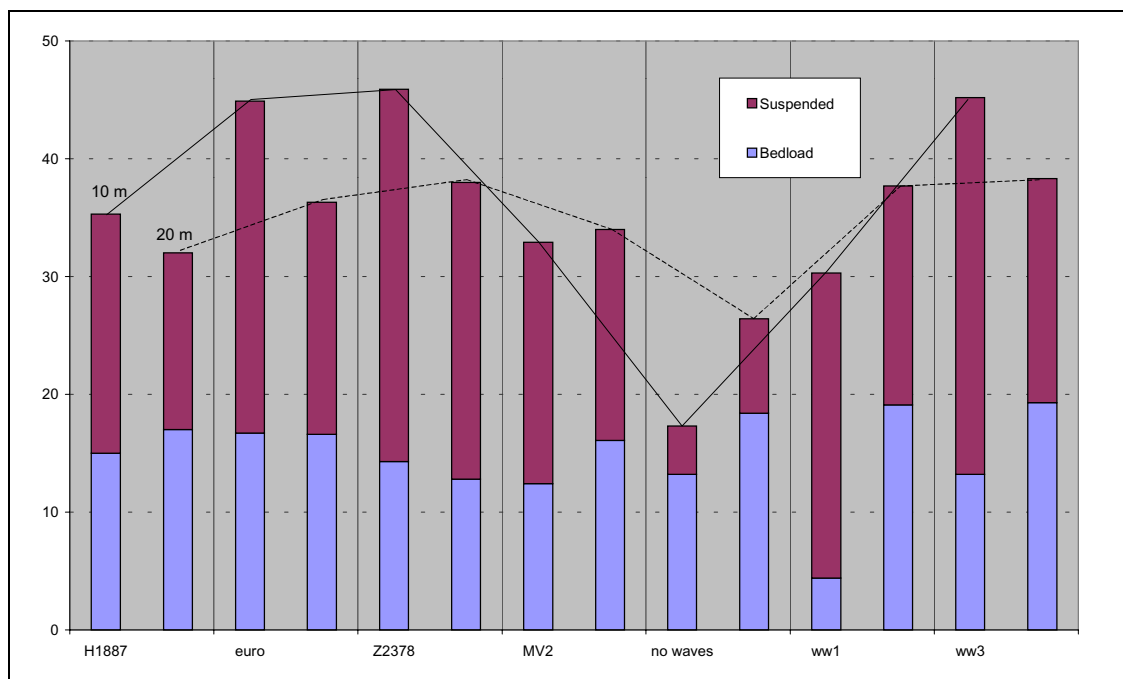


Figure A.10 Residual transports outside trench for different wave climates (water depth 10 m left column, 20 m right column). The two right columns have various wave angles.

At a water depth of 10 m the transports are much more sensitive to the wave climate. The variation due to the wave heights is small however related to the total variation that might be possible due to the wave heights. (see Figures A.11 to A.13)

The first eight columns of Figure A.10 (and Figure A.8 and the second pane of Figure A.9) show the results at a water depth of 10 m for the different wave climates with equal incident wave angles. The total transports are about equal: just over 30 for the MV2 climate to over 40 m³/m/year for the wave class climate. The share of the bedload transport varies moderately about 10 m³/m/year. The suspended transports are responsible for most of the variation in the total transports.

At a depth of 10 m another difference can be observed: the heights of the local transport peak at the south slope and the local minimum at the north slope vary between the various wave conditions. The wave class frequency exceedence climate of Sorgedraeger (2002) gives significantly higher peaks. This is due to the larger share of the high waves present in this climate (see next subsection). The wave class exceedence climate, the single wave climate

and the MV2 climate give peaks with an intermediate height. This stresses that these peaks are only due to the wave heights present in the climate and to the current.

The wave approach angle between the current and the waves has also been investigated. The three panes in Figure A.9 show the results for the MV2 wave climate with three types of angle. At 20 m depth, the wave angles have no influence. At 10 m however, the wave approach angles have a well recognisable effect. The total transports ranges only from below 30 to over 40 m³/m/year, but the share of the bedload transport varies from below 5 to over 10 m³/m/year. The local minimum and maximum of the transports at the slopes do not vary due to the incident wave angles. Inspection of the results of the individual wave conditions of the three MV2 climates (not included), showed that the approach angle has the largest influence at the high waves (2.15, 2.35 and 2.75 m in Table A.2).

Both with respect to the wave climate as with respect to the wave angles one can conclude that the sensitivity to the wave parameters is much more pronounced at a water depth of 10 m than at a water depth of 20 m.

Individual wave conditions

It has been argued that the peaks in the (suspended) transport at the north and south slope are due to the effect of waves. The peaks are most pronounced in the second pane of Figure A.8. This pane shows the results of the only climate with really high waves in it (Table A.1). In the other wave class climate, the H1887 climate of Van Rijn et al. (1995), the waves of 5 m and over are not present, and the exceedence curve is overall lower (Figure A.9). This indicates that mainly the high waves in the climate are responsible for this phenomenon. To analyse this effect further, the tide averaged transports of all the individual wave conditions of the wave class exceedence climate are included in Figures A.11 to A.13.

Figures A.11 to A.13 show the transport along the main axis of the trench for all the wave heights from 0.25 to 5.75 m. Figure A.11 shows that the bedload transports are 15 m³/m/year when the waves are absent, and decrease to 10 when the waves increase to 1.25. With higher waves the bedload increases again. The main increase of the total transports is due to the increase of the suspended transport. As stated earlier, this initial decrease of the bed load transports for low wave conditions is not physically realistic.

With respect to the peaks, Figures A.11 to A.13 show indeed that the large peaks in the transport at the north and south slope are more pronounced with high waves. However, the shapes of these peaks do not change any more at a wave height of about 2.75 m and over. Since the highest wave in the MV2 climate is only 2.75 m, the absence of higher waves can certainly explain the absence of pronounced peaks. The wave class climates of Sorgedragger (2002) and Van Rijn (1995) exceed the 2.75 m limit respectively 31 and 18 days. This small percentage of the year has a pronounced influence of the peaks. With 31 days the peaks are pronounced and with 18 days they are a little flat. With waves of 2 m and lower, the peaks are not present at all in Figure A.11. The single wave condition (third pane in Figure A.8) has a wave higher than 2.25 and accordingly has peaks. The interesting thing now is to explain the local peaks in the transport at high waves.

When the current carries suspended sediment in a stationary situation, there is a dynamic equilibrium situation between the stirring up of sediment and the settling. When the stirring disappears, the sediment will settle and the suspended transport (integral of current velocity and concentration over the vertical) will become zero. The stirring up disappears (1) when the current and the wave action become zero, or (2) when the supply of sediment at the bottom becomes zero. Since inside the trench the bottom is very deep, there is no wave stirring in the trench. Concurrently, when sediment loaded water enters the trench all the sediment will immediately settle. Since the settling velocity of the sediment is 0.0275 m/s, at a water depth of 20 m (10 m + 10 m deep trench) all the sediment settles in about 15 minutes. With a current velocity of at most about 0.5 m/s, the water will contain no sediment within 400 m.

First, at 10 m depth the increased wave stirring keeps the sediment longer in suspension during slack tide. This results in a larger time lag in the settling of suspended sediment. Second, when the waves are higher, the suspended transport increases. This increase in transport is mainly due to the increase in the sediment concentrations and only in small degree due to the changing velocity distribution. The higher concentrations lead to significantly lower settling rates. Accordingly, the current can carry the sediment further into the trench (see Figure A.14 below). Both these phenomena lead to a northward lag in transport at the south slope of the trench during flood, as well as to a southward lag on the north slope during flood. Meanwhile, the recovering of the concentration profile due to resuspension at the downstream side of the trench can only to a small extent be affected by the waves. Resuspension cannot increase but when the waves 'feel the bottom again'. The concentration profile at the downstream slope can not increase before the current has reached the downstream slope. Summarised: with high waves, the transports at the upstream slopes are maintained for a distance into the trench, while the transports at the downstream slopes do not change. Consequentially, when the residual ebb and flood transports are subtracted, the upstream lags in transports arise as an northward peak in the residual transport on the north slope and a southward peak on the south slope.

To illustrate the above explanation graphically, very idealised transport fields are shown for the ebb, flood and residual situation in Figure A.14 (below). The ebb transport field is moved southwards on the north bank for 200 m, and the flood transport is moved northwards 200 m on the south bank. The sum of these shifted transports indeed results in the characteristic profile observed in the Sutrench simulations with high waves.

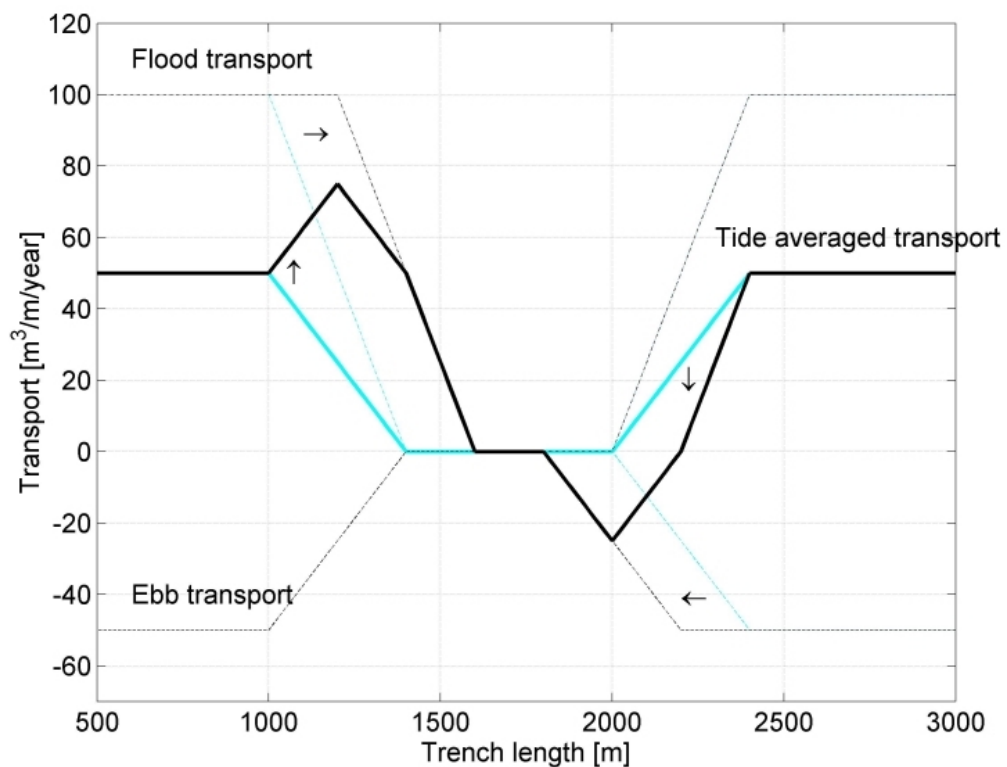


Figure A.14 Principle of settling lag on tide-averaged transport

Conclusions wave climate effect

- At a water depth of 10 m, the transports are sensitive to the wave parameters, while at a water depth of 20 m the transports are hardly sensitive to them, since at a water depth of 20 m the current is the dominant forcing type.
- The transports are not sensitive to the wave period, according to Walstra et al. (1998).
- The incident wave angles severely influence transports. The magnitude of the bedload transport can vary a factor 10, and can even switch sign. Moreover, the reactions of the suspended transports are not in accordance with the latest knowledge developments. It can be concluded that the bedload and suspended transport relations in Sutrench require further examination with respect to the wave angle. As concluded from the comparison with Delft3D in Chapter 2, the transport model in Sutrench requires to be updated to the latest version of Van Rijn's Transport-model.
- The transports results are also very sensitive to the individual wave heights. Not only the magnitude of the transport increases more than linearly with the wave height, also local peaks in the transport arise on the slopes of the trench. Moreover, the suspended transport increase faster than the bedload transports at increasing wave height.
- Since the transports are very sensitive to the wave heights of the contributing wave conditions, it can be concluded that the composition of a wave climate requires great care, especially at small water depths.
- To investigate the amount of care which has to be paid to the composition of the wave climates, different types of well-constructed wave climates have been compared.

Surprisingly, the transports are not very sensitive to these climates: at 20 m the magnitude of the transports is hardly sensitive to the wave climate and at 10 m depth just a little. Moreover, the bedload and suspended transport are not sensitive either. At a depth of 10 m however, some characteristic differences between the different wave climate results can be observed. When a climate includes higher waves, peaks in the transport arises above the slopes. The peaks are most pronounced with the wave climate comprising the highest waves. On the long term these peaks might lead to different morphological behaviour of the trench.

- It can be concluded that Sutrench is not sensitive with respect to well chosen wave climates. The strong sensitivity to the wave heights is well averaged due to the (weighted) composition of the wave climate.
- Since the complex wave climates give such similar results as the wave climate with only one wave condition, the findings of this chapter corroborate the validity of the common use of schematising the wave climate by one morphological wave. Moreover, the results are not sensitive to the sequence of the period with waves and the period without.
- However, not simply any wave with any occurrence can be chosen. Even if a higher wave than the wave of Walstra et al. (1998) is chosen ($H_s > 2.25$ m) with a lower occurrence (< 84 %) yields the same total residual transports, two other parameters might be different. These comprise (1) the presence of the local peaks in the transports and (2) the ratio of the suspended and the total transport. The selection of a morphological wave should be based on the correct representation of these two parameters. (using the panes in Figures A.11 to A.13.) The morphological wave of Walstra et al. (1998) fits these criteria quite well.
- Even though the results are not sensitive to the results are not very sensitive to the wave climate, the largest sensitivity occurs at a water depth of 10 m. Consequently, if the evolution of a trench has to be simulated, the largest differences between model and measurements are expected to arise at a water depth of 10 m. And vice versa, if one wants to calibrate a model (for a wave climate), one should rather collect data of a trench situated at a water depth of 10 m, than data from a trench at larger depth.

C.1.2 Tidal schematisations

In the base runs the real velocities as calculated by Delft3D are used. This resulted in different velocity boundary conditions at 10, 15 and 20 m depth where the velocities at 20 m depth are significantly higher than the ones at 10 m and 15 m. Due to this approach, in the base runs it was not possible to address a phenomenon clearly to the waves or to the current. In the study of Walstra et al. (1998) the same boundary conditions were used at 15, 20 and 25 m depth. Accordingly, they could address phenomena specifically to the waves or to the current. To investigate the effect of the current separately, two types of sensitivity analyses are performed in this section. First, the real velocities from Delft3D are increased to 120 % and decreased to 80% (runid vel2 and vel3). Second, the velocity boundary at a water depth of 20 is imposed on a trench at a depth of 10 m for a 50 year run. As a cross reference, the velocity at 10 m is also imposed on a trench at 20 m depth.

Velocity effect

The velocities have been increased to 120 % and decreased to 80%. In Figure A.15 the results are shown for runs in which the base run velocities are increased to 120%. The transports are very sensitive (more than linear) to the velocity, they increase considerably, both at 10 and 20 m. At 10 m depth the total residual transports increase to as much as 160 m³/m/year (Figure A.16), just as much as the residual transports with waves of about 3.0 m (Figure A.5). With a velocity reduction of 20 % the transports and bottom changes decrease dramatically.

In Table A.3 the trench bottom (change) parameters are given for all the velocity runs. For the small velocities (80 % of base run values) a number of parameters could not be determined due to the small and irregular bottom changes.

The parameters are more sensitive to the velocity at 10 m than at 20 m depth. With the base run velocity (N.B. different for 10 and 20 m depth) the volume of the sedimentation and erosion areas on the slopes were about equal, at an increased velocity the volumes at a water depth of 10 m are considerably larger. So not only for the waves, but also for the velocity the sensitivity is more pronounced at a water depth of 10 m.

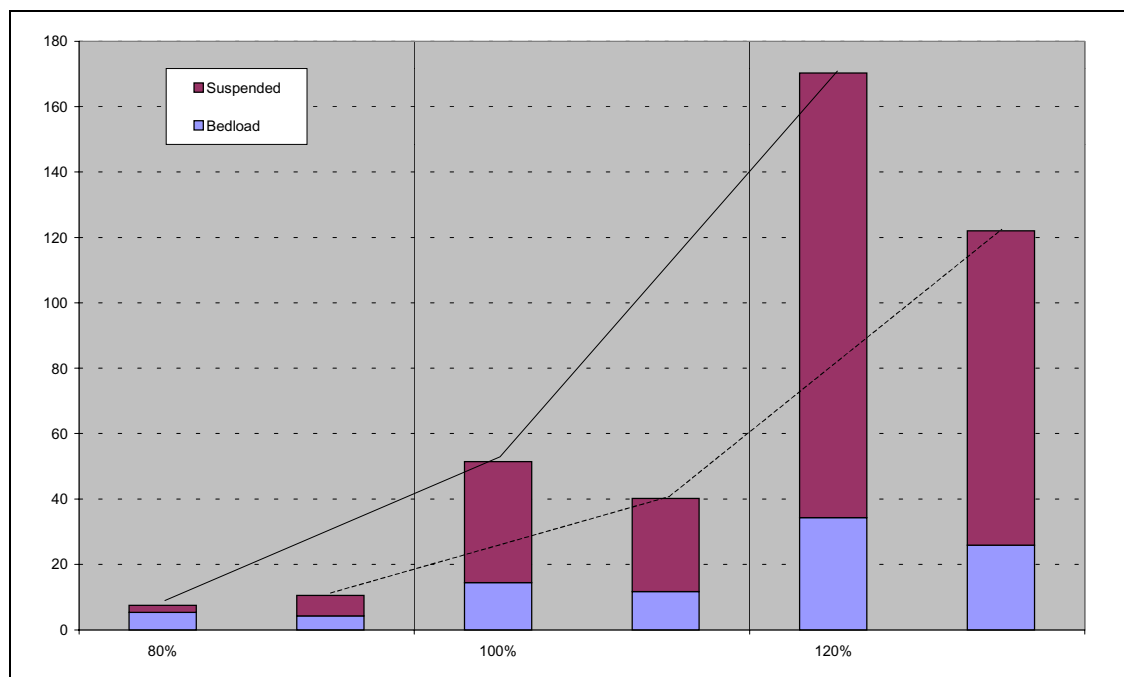


Figure A.16 Residual total transports outside trench (water depth 10 m: left bar, water depth 20 m: right bar).

Velocity	Depth	80%	100%	120%	
Decrease of wet volume	10	186	369	919	[m ³]
	20	24	111	500	
Volume sedimentation/ Erosion areas south slope	10	³⁾ - 289		1101	[m ³]
	20	-	337	935	
Volume sedimentation/ Erosion areas north slope	10	- -303		-1035	[m ³]
	20	-	-311	-895	
Displacement centre of gravity	10	-0.2	37.6	153.0	[m]
	20	11.2	39.5	119.5	
Decrease horizontal Length trench	10	54.8	85.6	204.2	[m]
	20	8.9	15.8	86.8	
Height sedimentation/ erosion south on slope	10	-0.17 / 0.34	1.30	3.90	[m]
	20	0.31	1.05	3.00	
Height sedimentation/ erosion on north slope	10	-0.16 / 0.36	-0.53	-1.47	[m]
	20	-0.28	-0.75	-1.60	
Location centre of gravity Sedimentation/erosion Area on south slope	10	-	1324	1256	[m]
	20	-	1170	1249	
Location centre of gravity Sedimentation/erosion Area on north slope	10	-	2704	2685	[m]
	20	-	2498	2601	

Table A.3 Trench bottom (change) parameters at velocities of 80%, 100% and 120%.

Switching velocity boundary conditions for 50 years

The conclusion of the base runs was that the transports at 10 and 20 depth were almost equal and led to similar morphological changes. The shape of the morphological changes at 10 and 20 m depth was different however. Moreover, in the sensitivity runs with increased velocities, the bottom changes at 10 m depth are larger than at 20 m, while the actual depth averaged velocities at 20 m depth are larger. Due to the different current velocities used at 10 and 20 m depth, it is not possible to attribute effects to either the waves or the currents. In order to be able to judge the current and wave effect more independently, runs are made with the same depth averaged velocity as boundary conditions at 10 and 20 m depth. Four runs are made to have a good cross-reference: both the real 10 m velocities and the real 20 m velocities are used on both depths.

Besides the intertwining of the wave and current effect at 10 and 20 m, the long time scales of the trenches make it hard to draw clear conclusions on the morphology. The bottom changes in the 10 year runs are small. Therefore a simulation period of 50 years is adopted in these sensitivity runs. The results can be found in Figures A.17 to A.21.

³⁾ These parameters could not be obtained with the standardised software routines due to the very small values of the morphological changes.

Table A.4 shows that when the real local velocities are used, after 50 years the trench at a water depth of 10 m looks almost the same and as the trench at 20 m depth. Accordingly, many of the trench parameters are almost same for these two cases. Other parameters do not necessarily have the same value, but their values are closer to each other than to the values of the other two cases. Some parameters however, differ considerably: the wet volume of the trench, the northern trench definition and inflection points.

Water depth:	10	10	20	20	[m]
Velocity obtained from depth of:	10	20	10	20	[m]
Decrease of wet volume	1441	3299	258	733	[m ³]
Volume sedimentation/ Erosion areas south slope	⁴)1505	4466	746	1724	[m ³]
Volume sedimentation/ Erosion areas north slope	-1575	-4225	-748	-1752	[m ³]
Displacement centre of gravity	214	695	89	214	[m]
Decrease horizontal Length trench	253	364	118	168	[m]
Height sedimentation/ erosion south on slope	5.41	9.16	2.82	6.17	[m]
Height sedimentation/ erosion on north slope	-1.59	-3.31	-1.53	-2.5	[m]
Location centre of gravity Sedimentation/erosion Area on south slope	1331	1438	1145	1268	[m]
Location centre of gravity Sedimentation/erosion Area on north slope	2925	3113	2497	2650	[m]
Northward displacement southern trench definition points	304	571	164	301	[m]
Northward displacement northern trench definition points	51	207	46	133	[m]
Northward displacement southern trench points of inflection	280	537	125	247	[m]
Northward displacement northern trench points of inflection	-269	-91	-163	-145	[m]

Table A.4 Trench bottom (change) parameters 50 years for equal velocities at 10 and 20 m depth.

In Figure A.21 the profiles with the real local velocities after 50 years look alike. However, some considerable differences can also be observed. At a water depth of 10 m more erosion occurs near the sea bottom reference level than inside the trench. At a water depth of 20 m more erosion occurs on the (deeper parts of the) northern slope. These differences are not fully reflected in the parameters in Table A.4.

⁴ Note that the parameters referring to the properties of the sedimentation and erosion spots on the slopes are not well-defined at 10 m depth when the velocities are obtained from 20 m depth, since in that run the morphological changes are so large that the slopes are morphologically interacting. The properties are listed though in Table .

Figure A.17 also shows that when equal depth averaged velocities are used, the bottom changes at a water depth of 10 m are significantly larger than the bottom changes at 20 m. This is probably due to the increased wave (stirring) effect at 10 m depth.

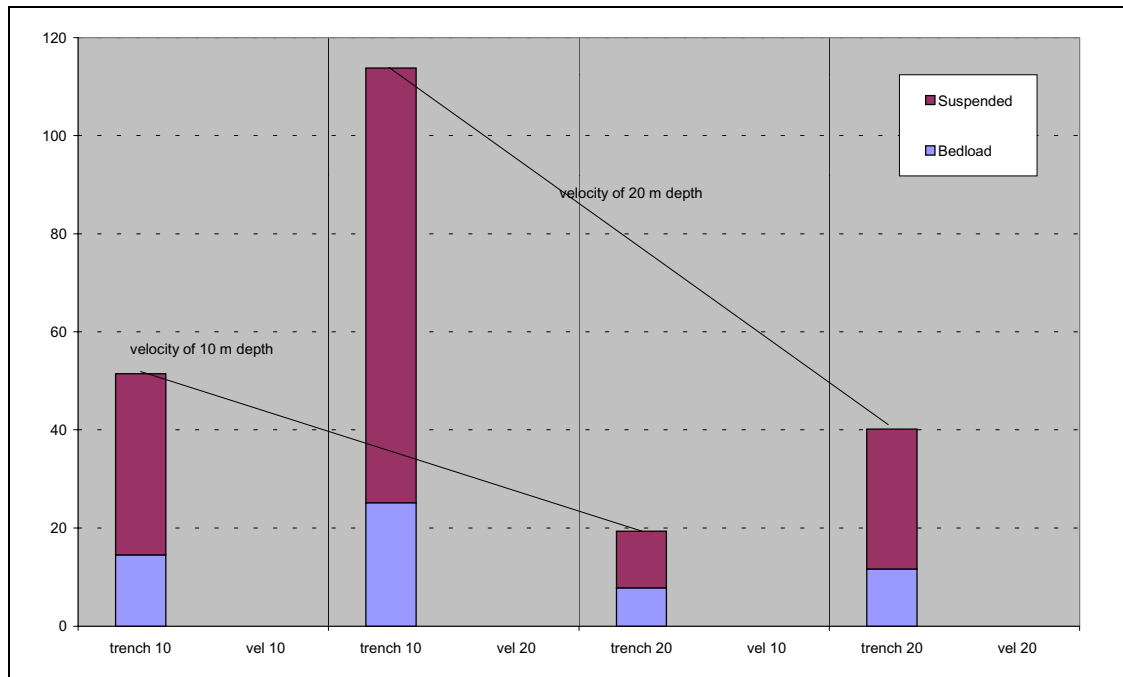


Figure A.22 Residual total transports outside trench.

Conclusions velocity effect

- The Sutrench results are very sensitive to the changes in the velocity, both at 10 and at 20 m depth. The sensitivity at 10 m is more pronounced at 10 m. A 20 % increase of the real local velocity leads to three times larger morphological behaviour. The 20% increase has much more influence at 10 than at 20 m (while the absolute increase in velocity is larger at 20 m depth.)
- If the same depth averaged velocities are used at a depth of 10 and 20 m, the morphological changes at 10 are much more pronounced. If the real local velocities are used, the morphological behaviour at 10 and 20 m are about equal. It can be concluded that the velocity boundary conditions in Sutrench should be derived with great care, and separately for each water depth.

C.1.3 Model parameters

In Walstra et al. (1998) an extensive sensitivity analysis was carried out for physical parameters. Apart from the wave parameters, these parameters included:

- Thickness of mixing layer D_s
- Wave related mixing coefficients $E_{w,bed}$ and $E_{w,max}$
- Sediment characteristics d_{50} , d_{90} , w_s
- Wave roughness height R_w
- Current roughness height R_c

- Reference level Z_a

Walstra et al. (1998) did not investigate the sensitivity to the physical parameters at various water depths. They only investigated 20 m depth. In the present study sensitivity runs are performed at 10 and 20 m depth.

Walstra et al. (1998) recommend to apply the sensitivity runs to a whole range of parameter values (in the referred study only an increased and decreased value were considered). This recommendation will be taken into account. The values are listed in Table A.5.

	value	10%	50%	100%	150%	200%
		x1	x2	Base run	x3	x4
1	r_c	0.002	0.005	0.010	0.015	0.020
2	r_w	0.005	0.025	0.050	0.075	0.100
3	z_a	0.005	0.025	0.050	0.075	0.100
4	D_{90}	77.5	155	310	465	620
	D_{50}	52.5	105	210	315	420
	w_s	0.002	0.0085	0.0275	0.465	0.062

Table A.5 Overview of investigated physical process parameters

Wave roughness r_w

In Figure A.23 the results for the residual transports outside the trench are given. The transports increase by 40 % when the wave roughness is doubled and not when the wave roughness is halved. At a water depth of 10 m the wave roughness has much more effect on the transports and the bottom changes than at 20 m depth.

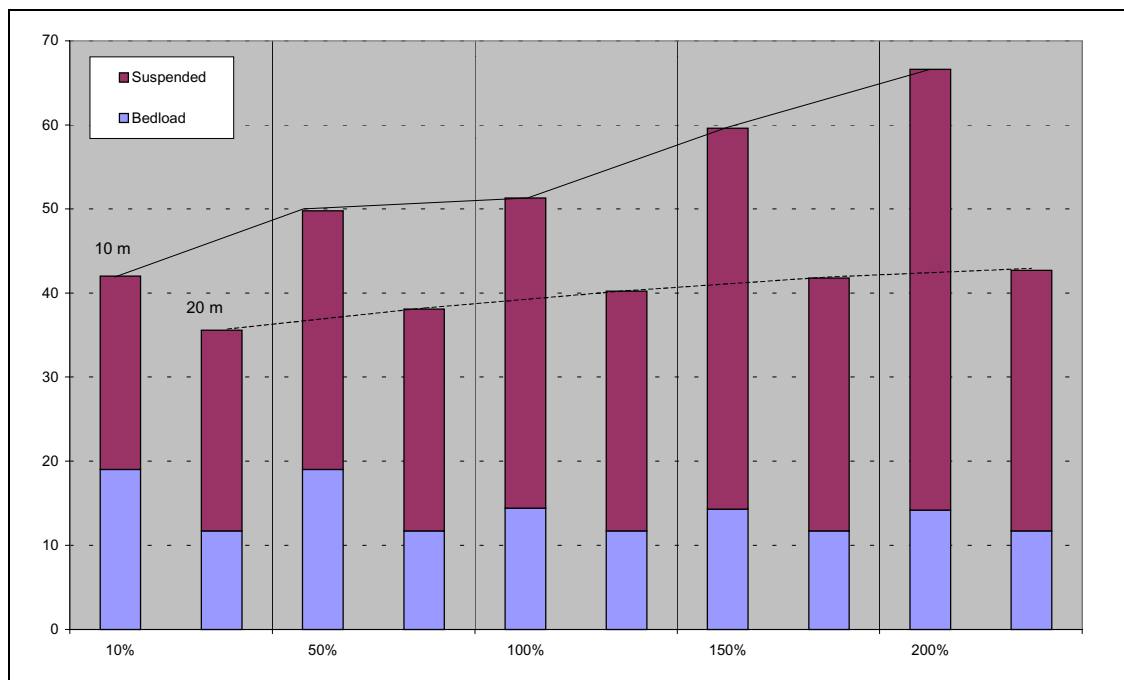


Figure A.23 Residual transports outside trench for 5 values of the wave roughness (water depths 10 m left column, 20 m right column).

Current roughness r_c

Figure A.24 shows that the total transport increase both when r_c increases and when r_c decreases. At a water depth of 10 m, the variation can be 20 % when the wave current roughness is doubled and 40 % when the wave current roughness is halved. At a water depth 20 m the sensitivity is very limited.

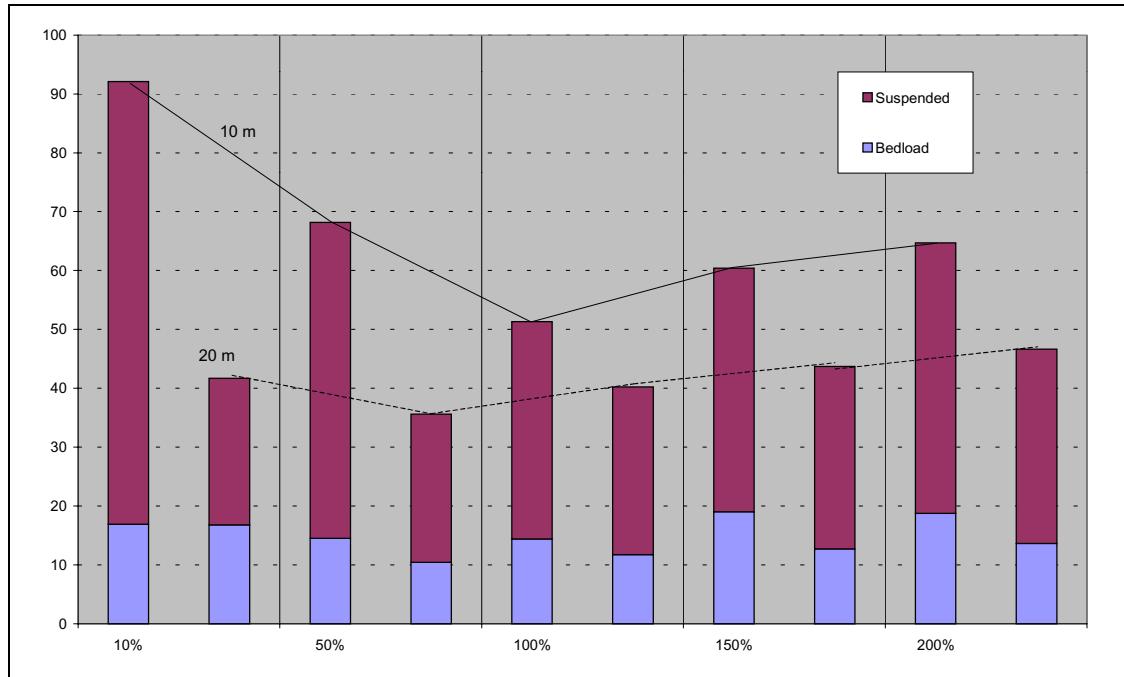


Figure A.24 Residual transports outside trench for 5 values of the current roughness (water depths 10 m left column, 20 m right column).

Reference level z_a

Figure A.25 shows that the results are not very sensitive to the reference level when its value is doubled or halved. When the reference level is set to 10% of the bas run value however, the results show a sudden increase by a factor 5. At a water depth of 20 m the results jump up only with 200%.

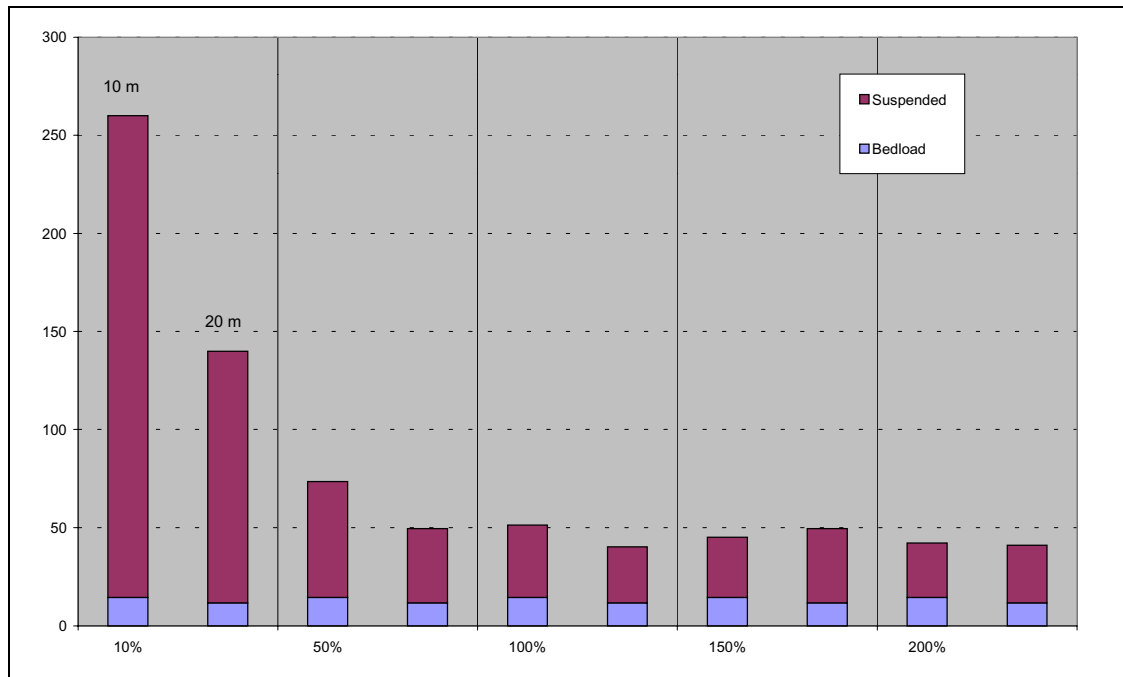


Figure A.25 Residual transports outside trench for 5 values of the reference level (water depths 10 m left column, 20 m right column).

Sediment size (D_{90} , D_{50}) and settling velocity (w_s)

Figure A.26 shows that the results are very sensitive to the sediment properties, both at 10 m and at 20 m (note the logarithmic scale). Already when the settling velocity and the grain diameter are halved, the trench fills up very quickly with sediments: the residual suspended transports increase to over $500 \text{ m}^3/\text{m}/\text{year}$. This is the same value as if 4 m waves were acting all the time at a water depth of 10 m (5 m waves at 20 m, see Figure A.5). When the sediment properties are reduced to 10% (when Sutrench is probably not valid any more), the residual transports increase to $2000 \text{ m}^3/\text{m}/\text{year}$. Surprisingly, in this case transports at 20 m depth are significantly higher than the transports at 10 m.

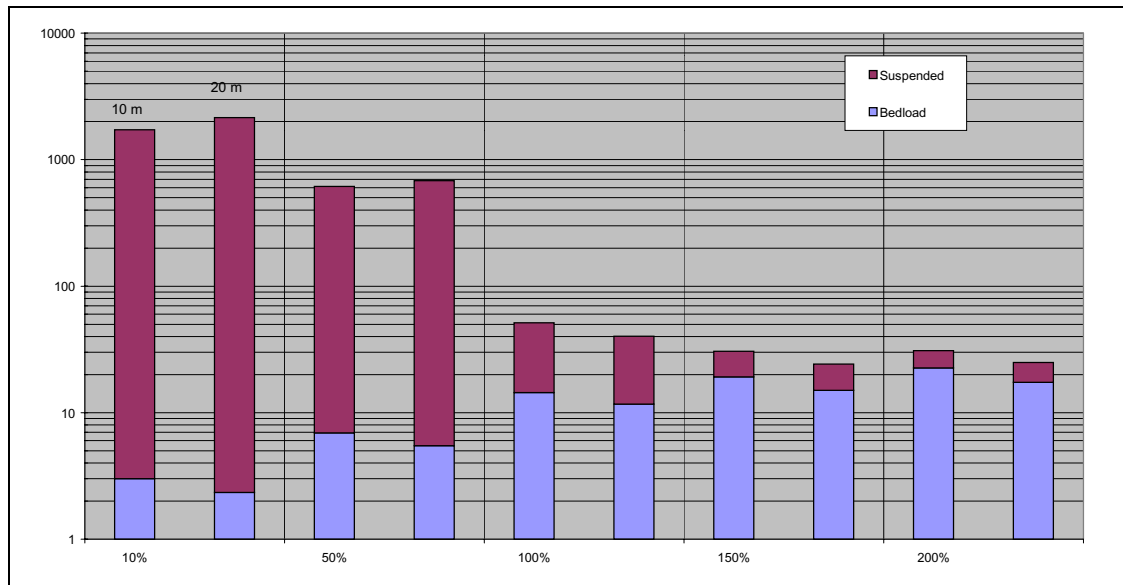
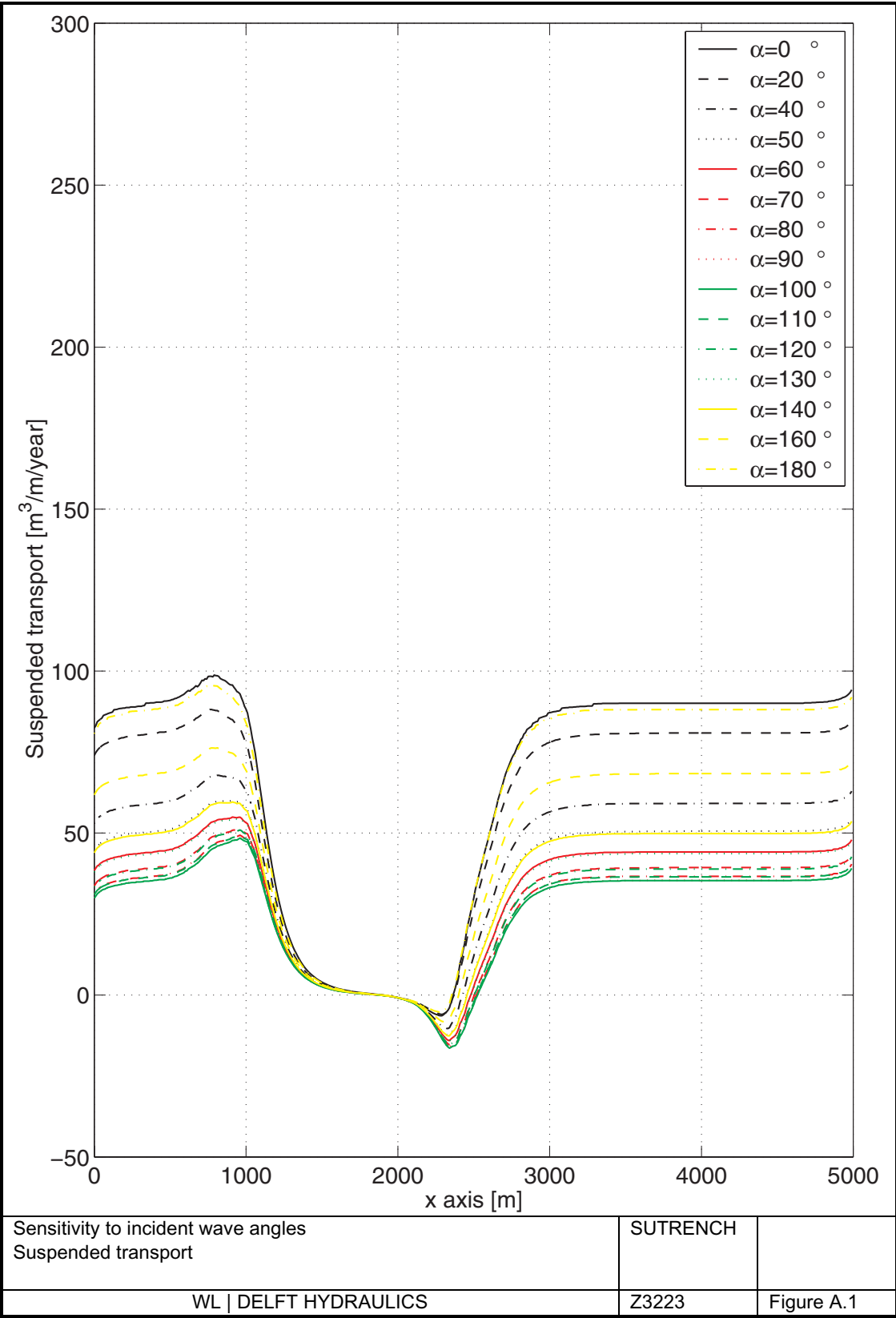
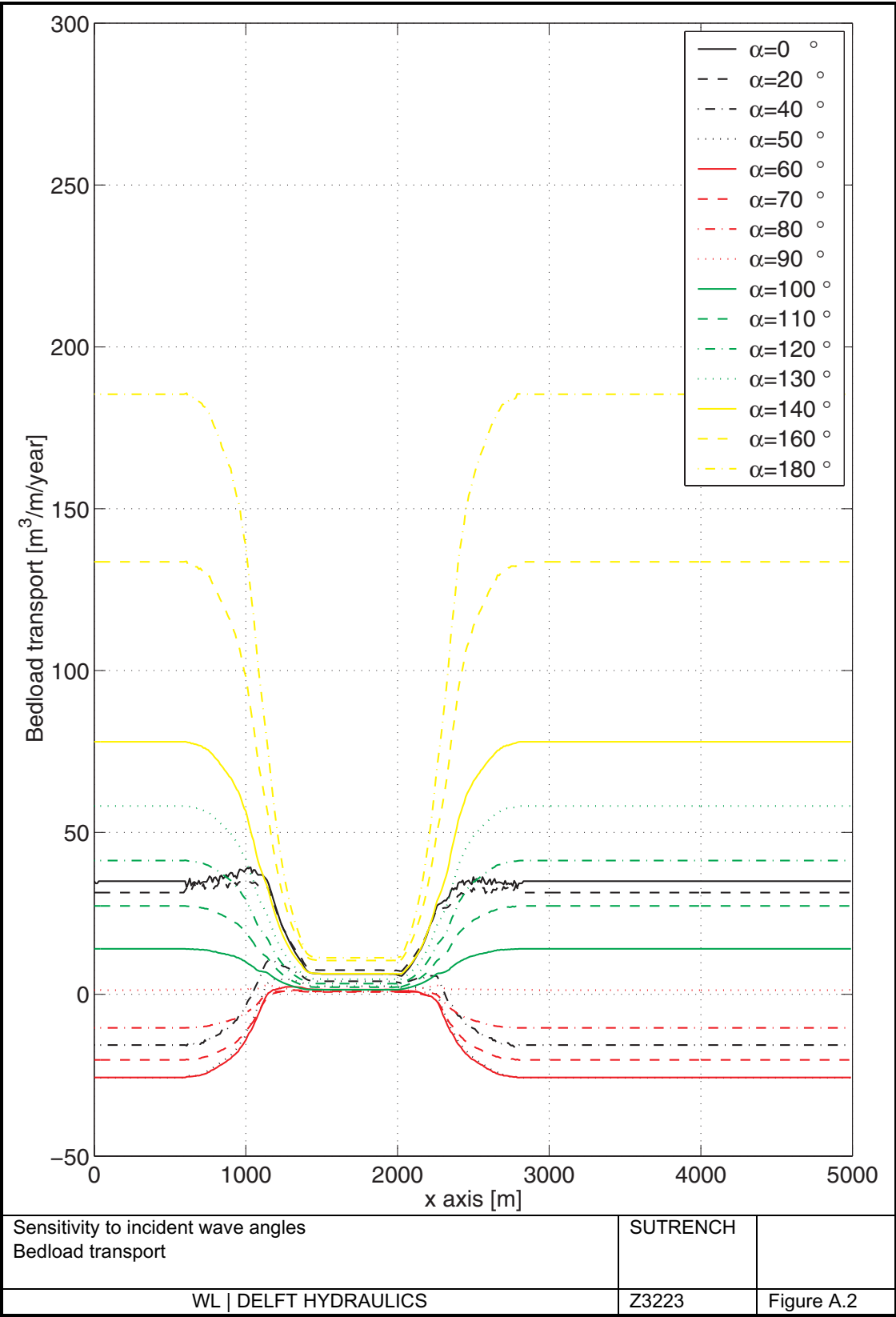


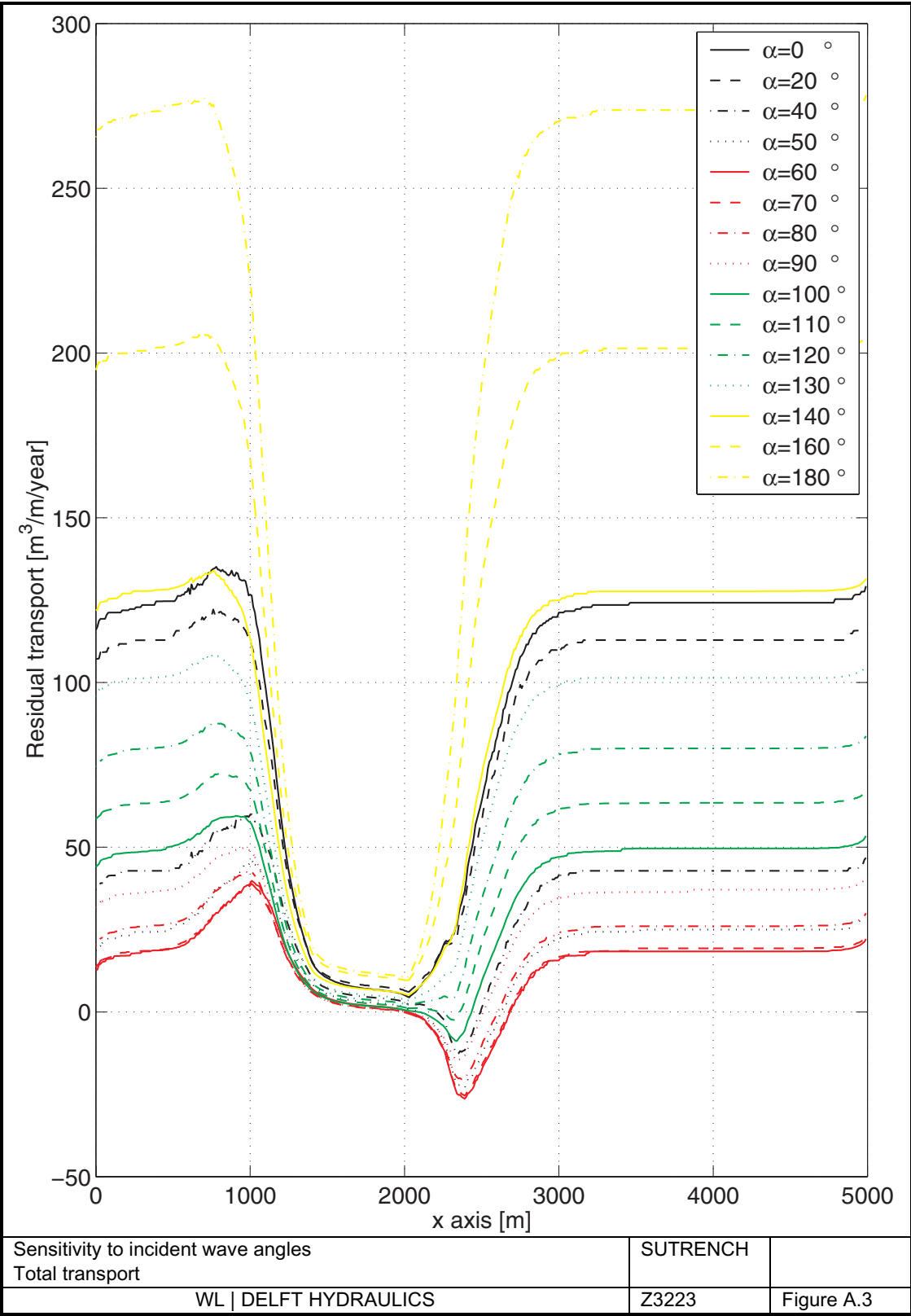
Figure A.26 Residual transports outside trench for 5 values of the sediment properties (water depths 10 m left column, 20 m right column). Note the logarithmic scale.

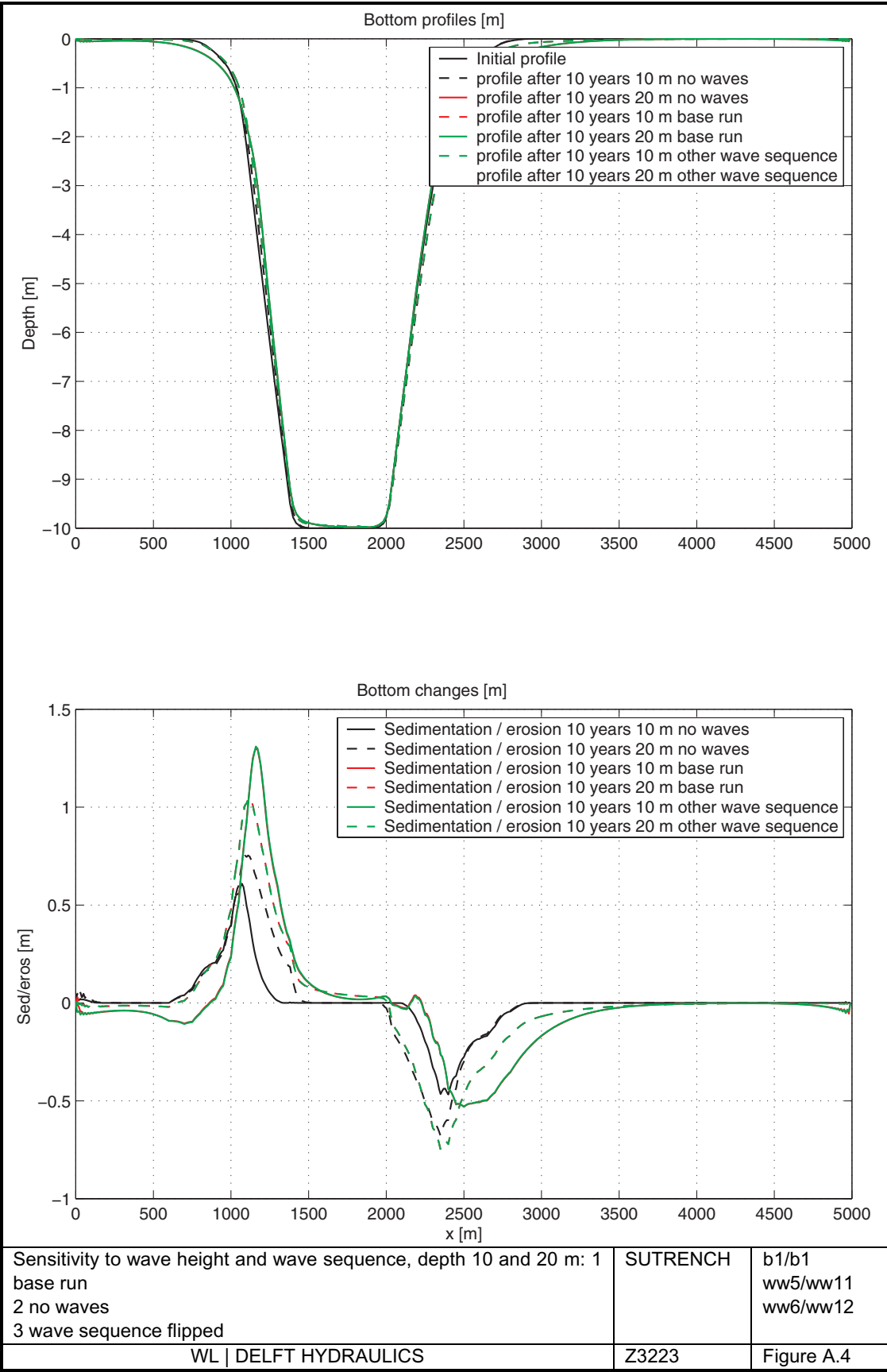
Conclusions

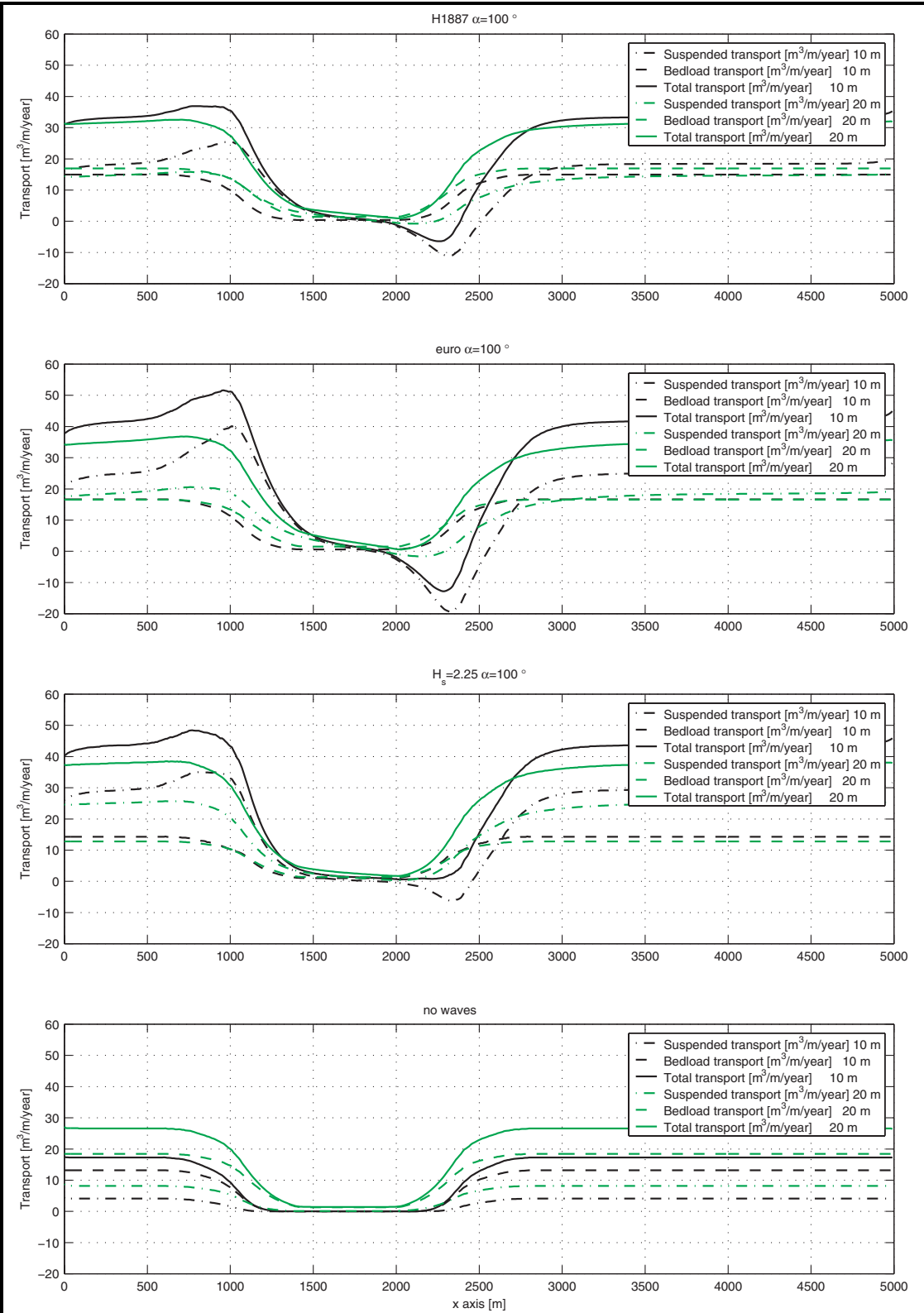
The Sutrench results are not sensitive to the reference level z_a when the variations are within the 50 to 200%. The results are moderately sensitive to the wave and current roughness: the results range by less than 50 % when the variations are kept with a 10 - 200 % range. These variations all less than the sensitivity to the waves and currents. The results are extremely sensitive to smaller values of the sediment properties, and not sensitive at all when coarser sediment is used. For all three physical parameters, the model results are most sensitive at a water depth of 10 m, only for the sediment size the water depths does not matter.



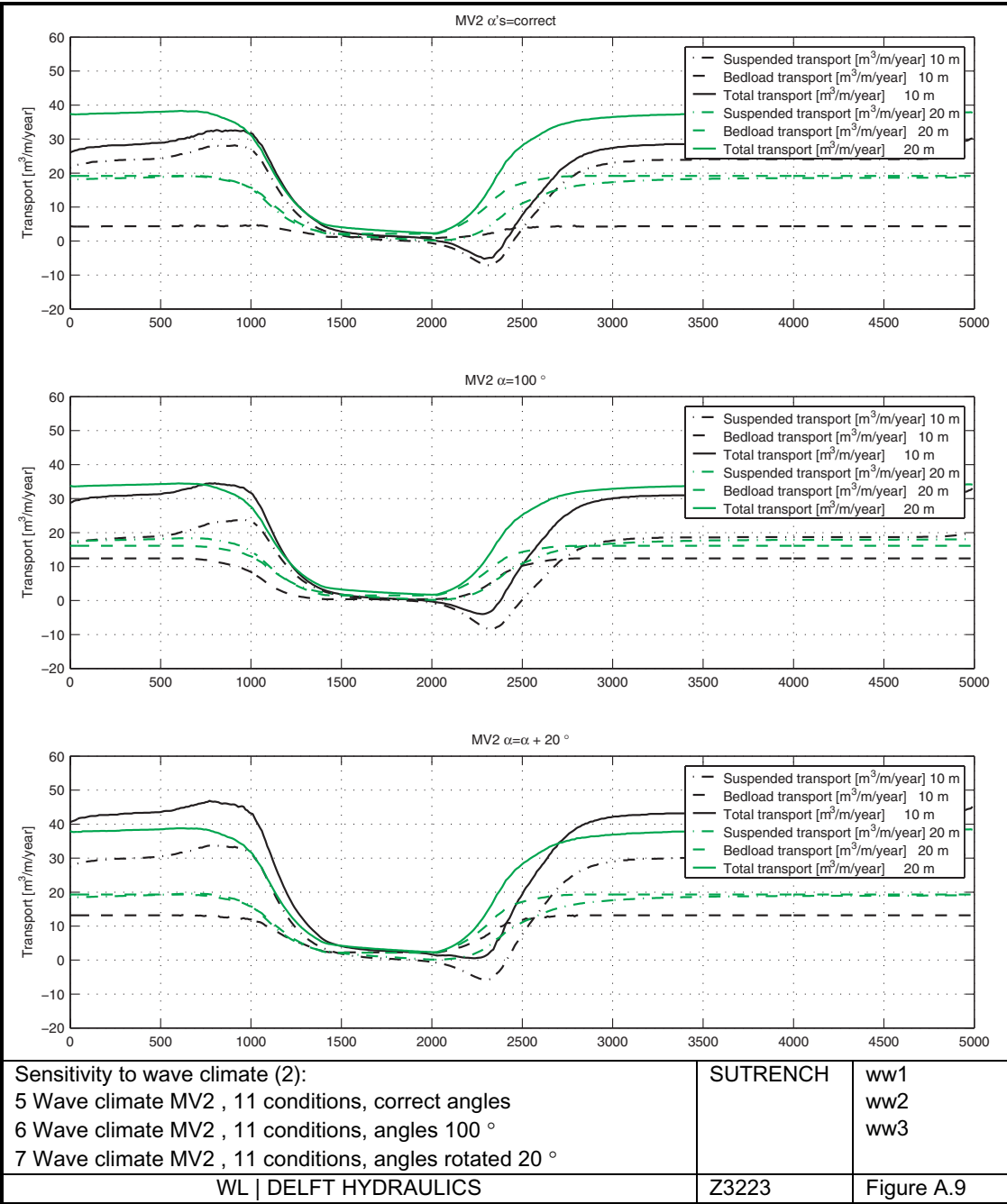


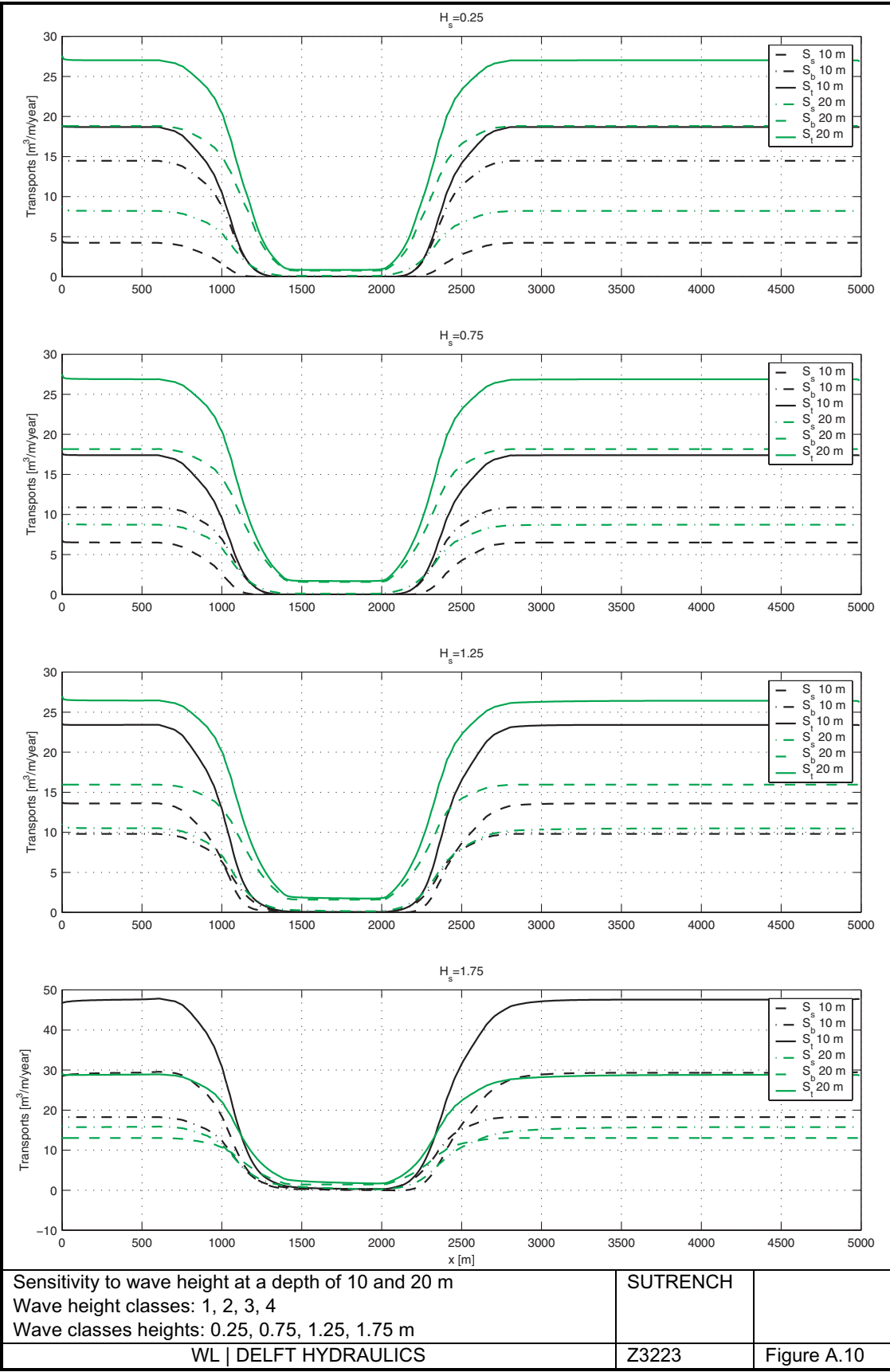


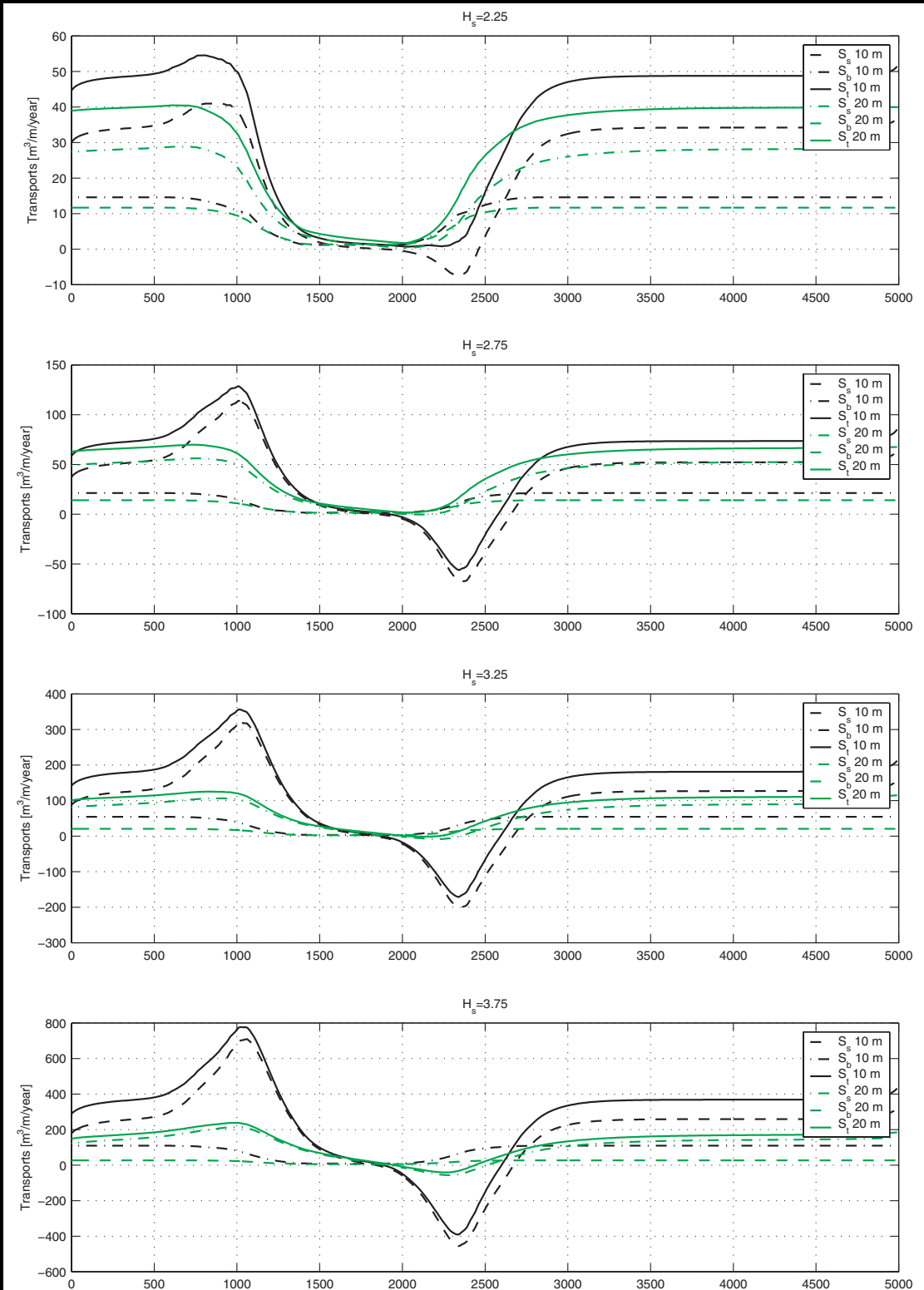




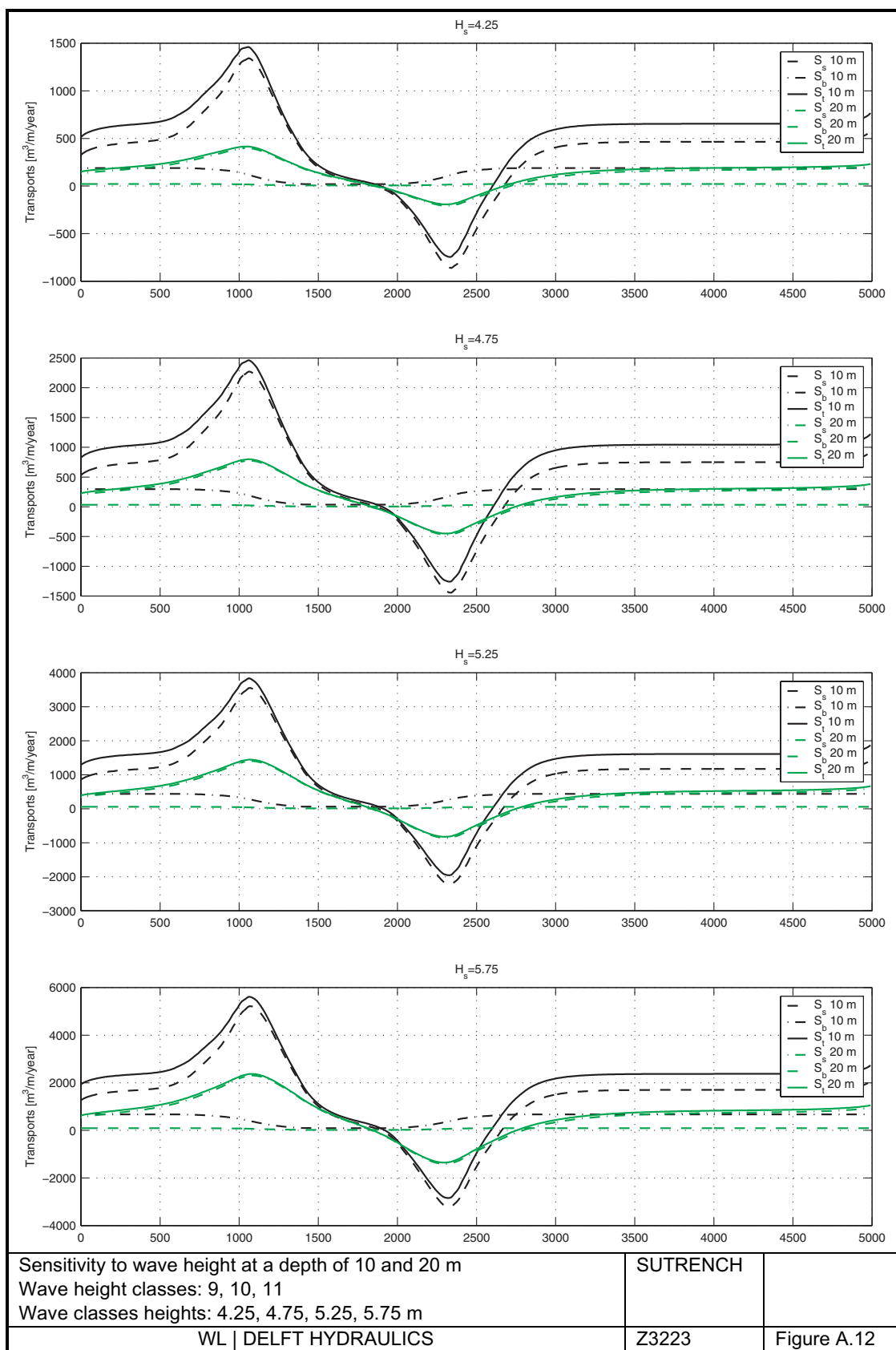
1 Climate Sordedraer (2002), 12 conditions	SUTRENCH	ww0
2 Climate H1887 Van Rijn et al. (1995), 12 conditions		ww0
3 Wave climate Walstra et al. (1997), 2 conditions		b1/b3
4 No waves, 1 condition		ww6/ww12
WL DELFT HYDRAULICS	Z3223	Figure A.8

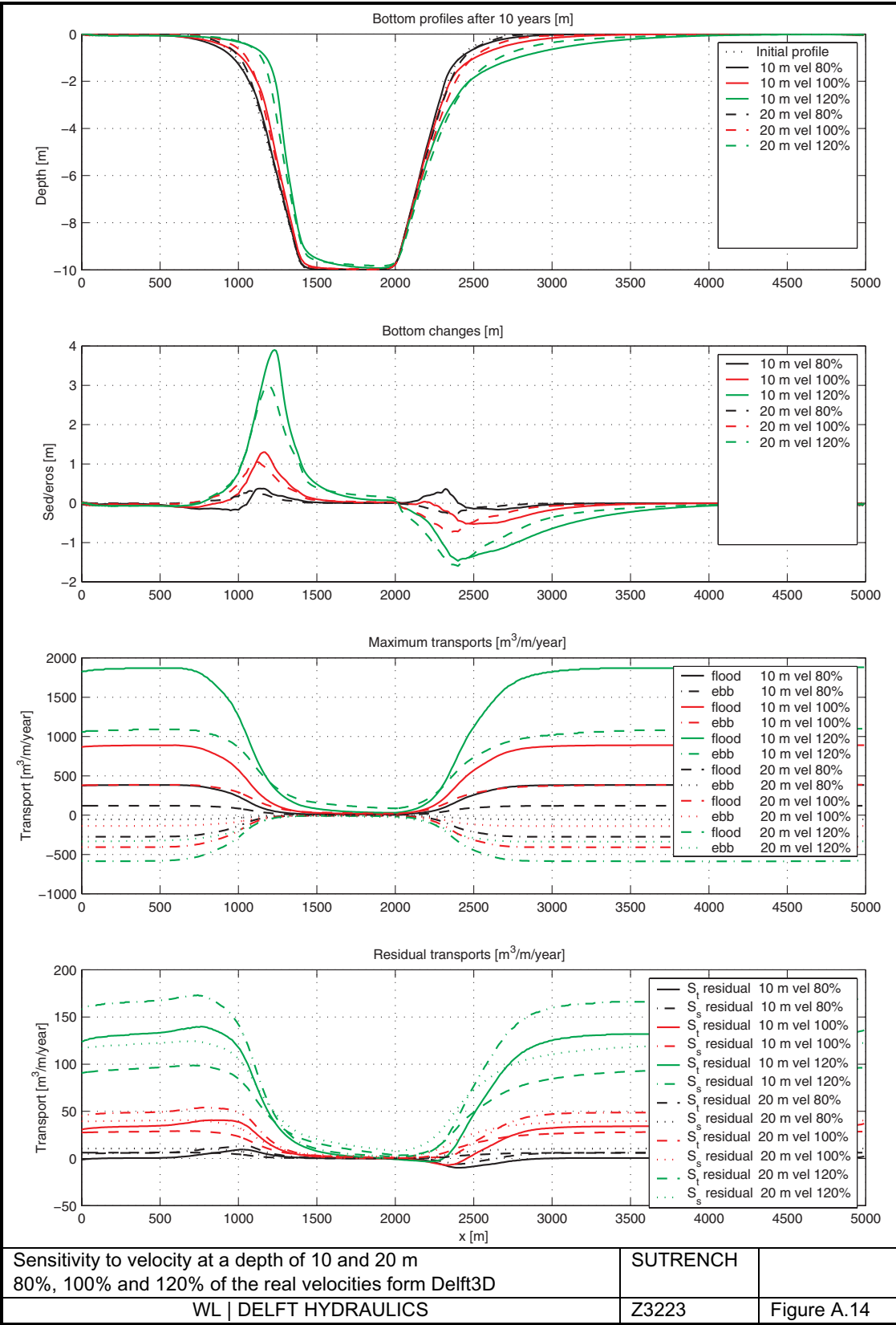


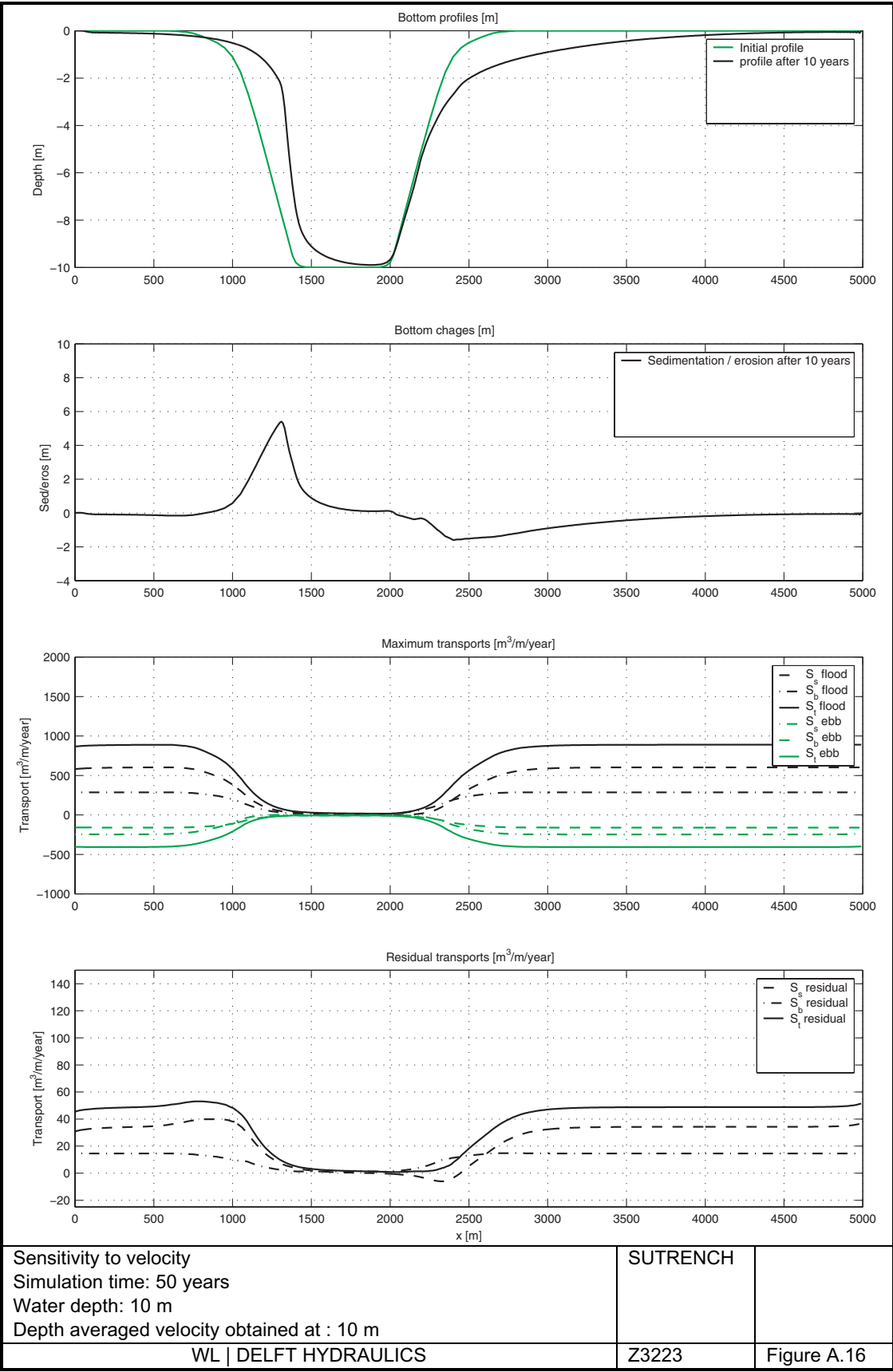


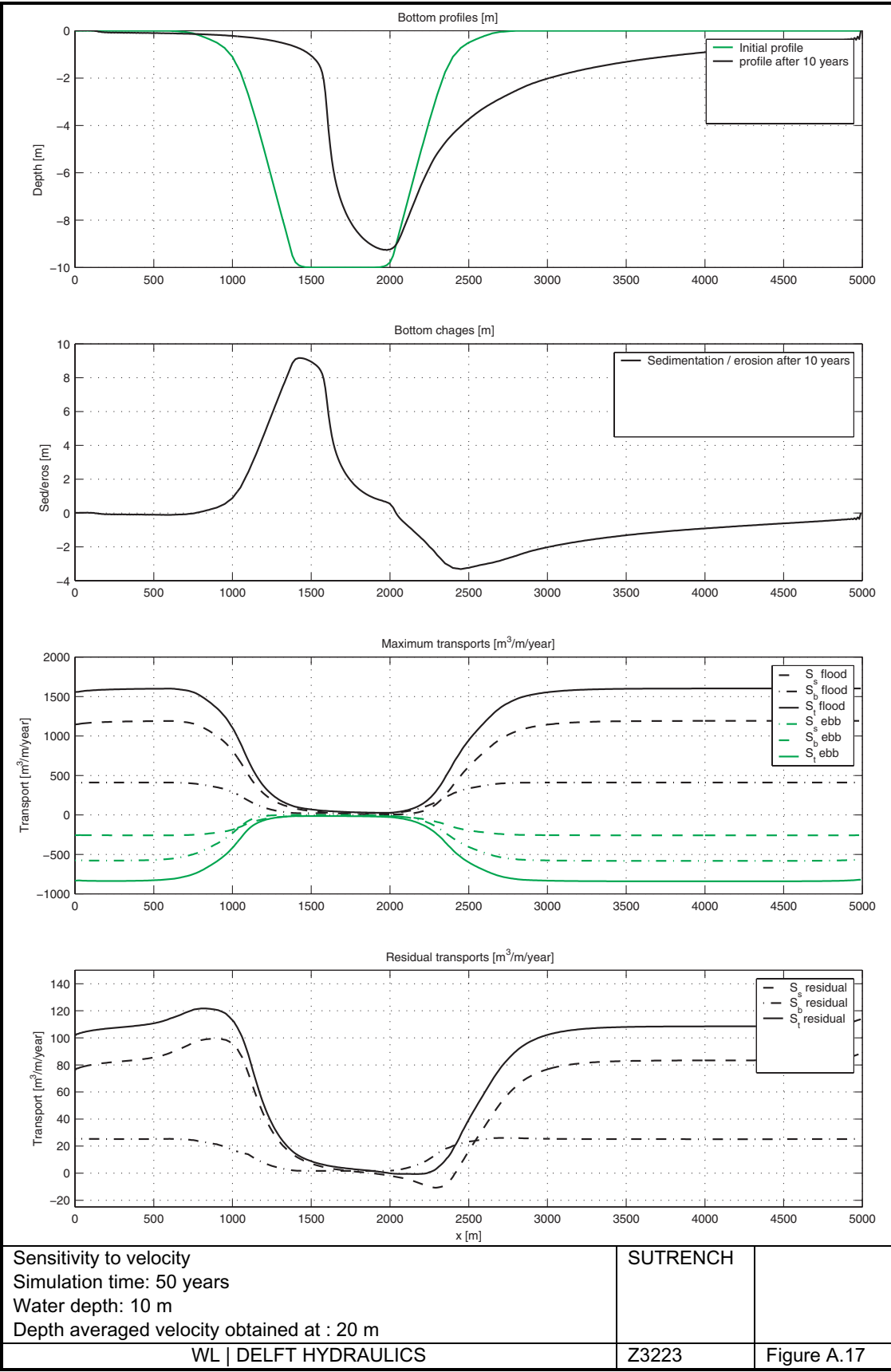


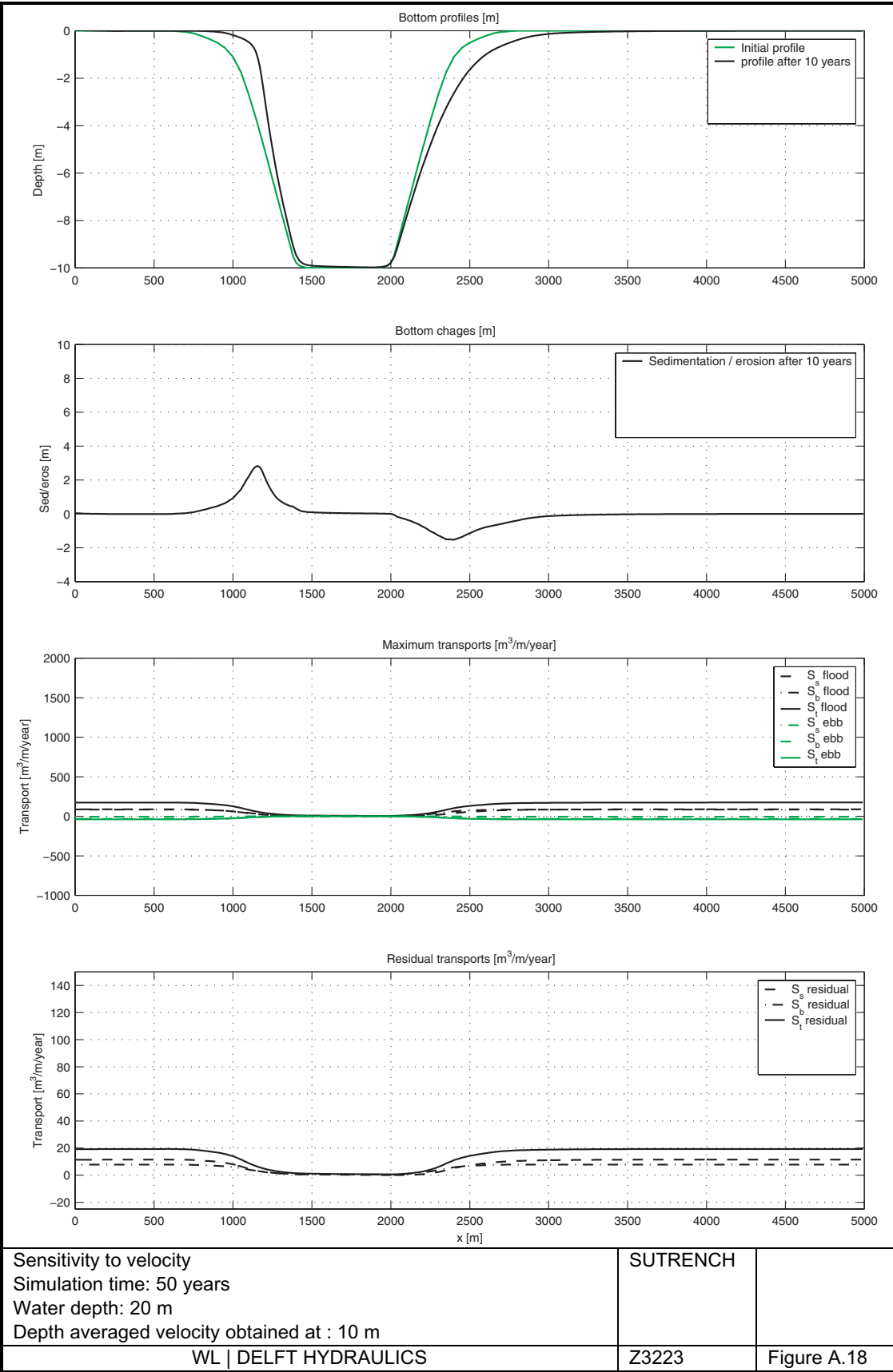
Sensitivity to wave height at a depth of 10 and 20 m Wave height classes: 5, 6, 7, 8 Wave classes heights: 2.25, 2.75, 3.25, 3.75 m	SUTRENCH	
WL DELFT HYDRAULICS	Z3223	Figure A.11

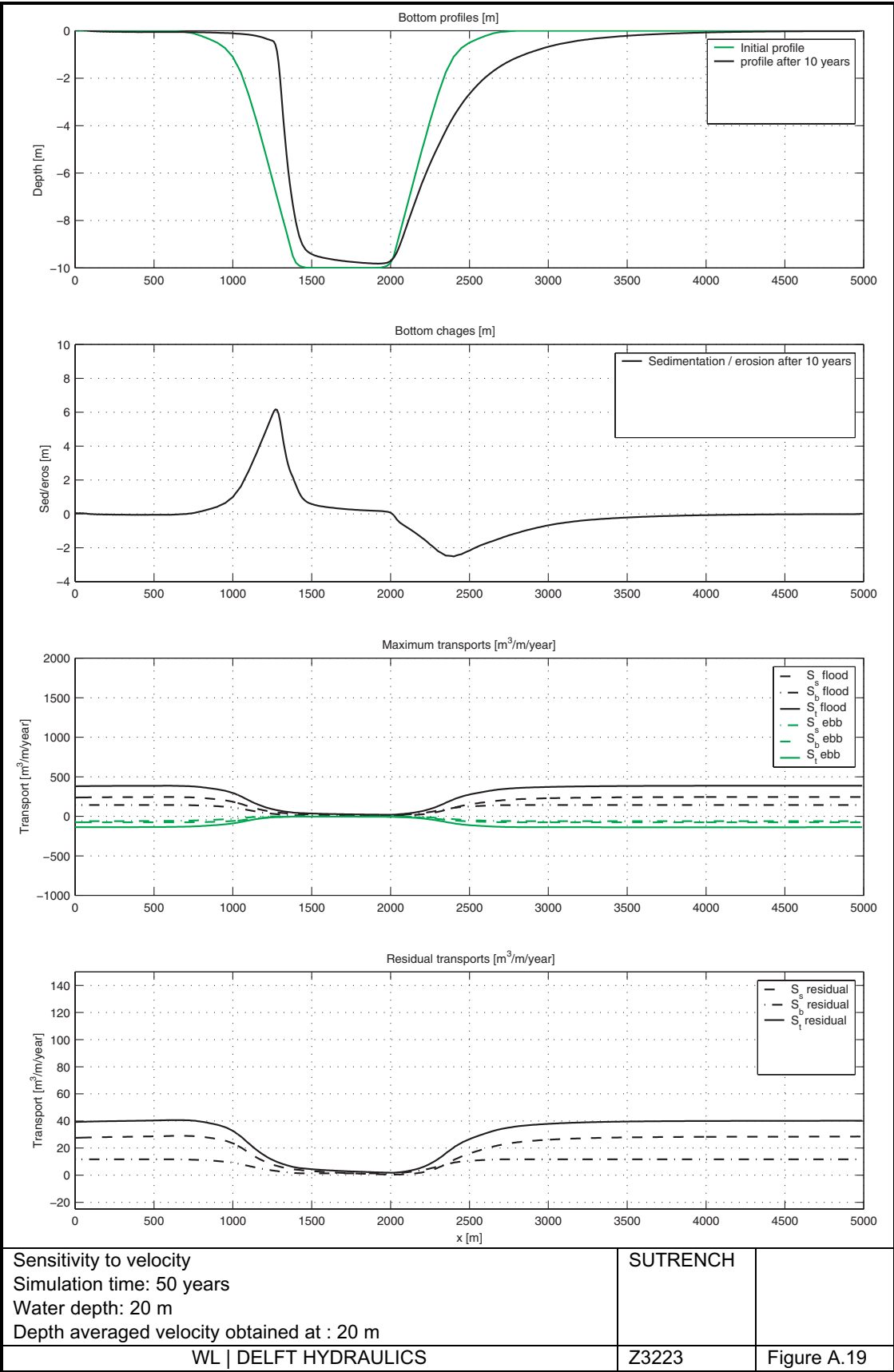


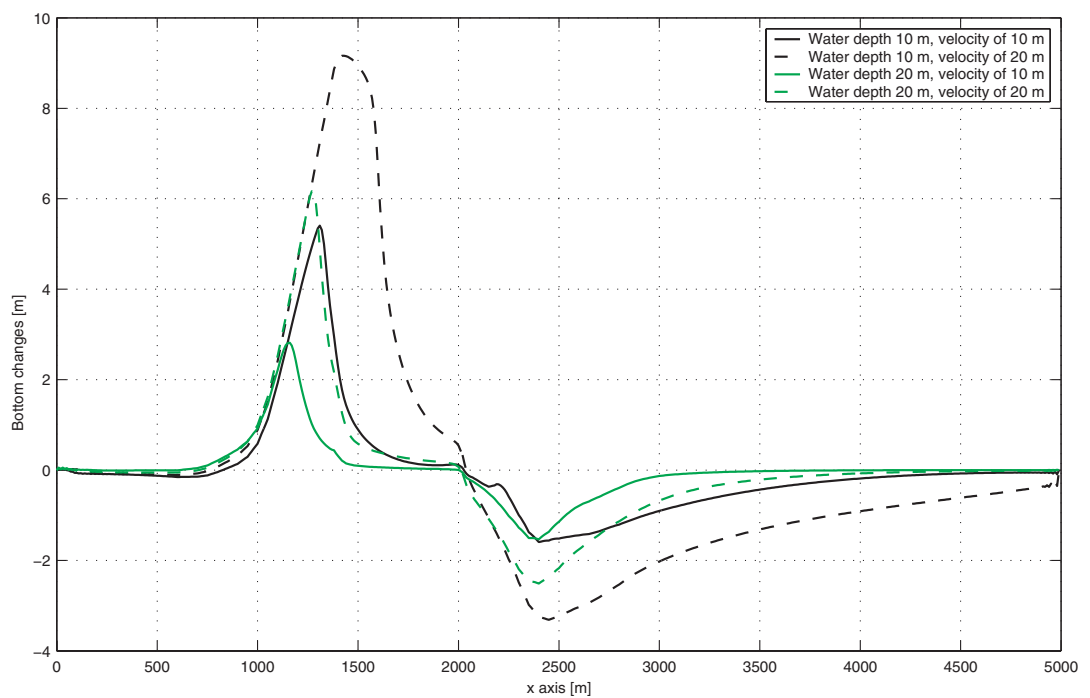
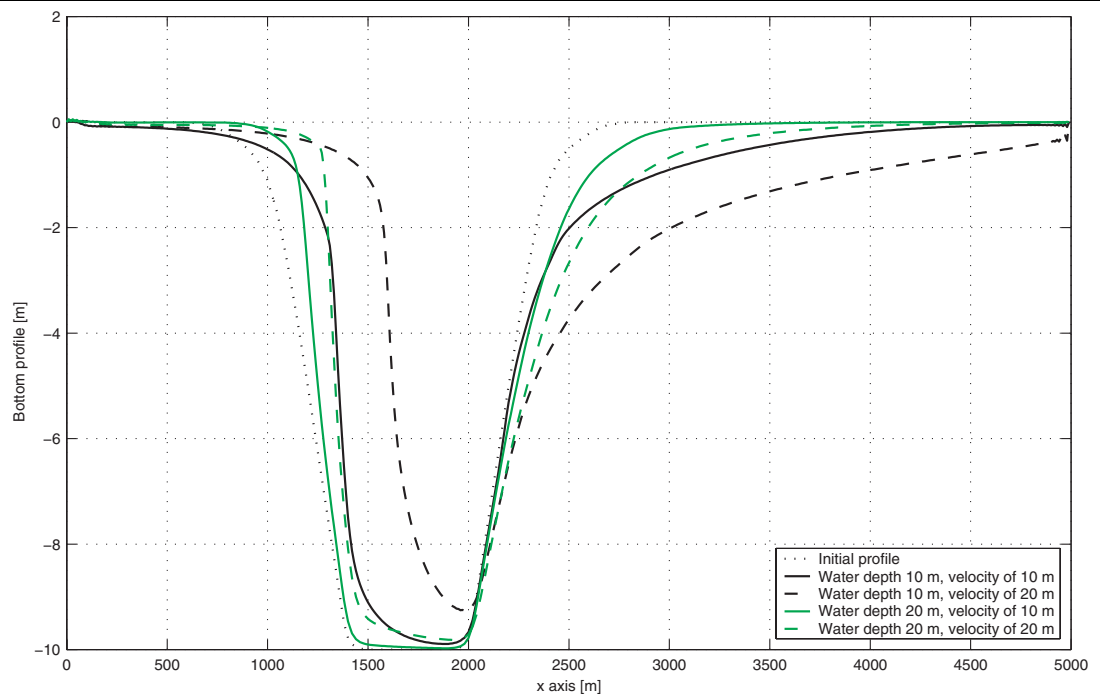












Sensitivity to velocity Simulation time: 50 years Water depth: 10 and 20 m Depth averaged velocity obtained at : 10 and 20 m	SUTRENCH	
WL DELFT HYDRAULICS	Z3223	Figure A.20