University of Twente | HR Wallingford

Bachelor thesis report

To calibrate and validate a 3Dimensional mud model with field data for the Blyth estuary (Suffolk, UK) and determine if the 3D model is an improvement to the existing 2D model.

Willeke van de Wardt

7-5-2016

Supervisors:

Dr. Ir. M.A.F. Knaapen

Dr. Ir. B.W. Borsje

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HR Wallingford
Working with water

PREFACE

This document is the product of my bachelor thesis project, which was carried out to earn a bachelor degree in Civil Engineering at the University of Twente. In this bachelor thesis the 3D model of the Blyth estuary (Suffolk, UK), is calibrated and validated amongst data for a spring tide and a neap tide. This thesis has been carried out during spring 2016, at HR Wallingford. I am very thankful for this opportunity, because this gave me new insights in the world of Civil Engineers. I have been able to develop myself outside the University of Twente, which has been a tremendous learning process.

I could have never booked these results without the help and guidance from a couple of people. First of all, I would like to thank my university supervisor Bas Borsje, for his critical view on my work and the guidance he provided me with, before and during my bachelor thesis project. He has helped me to view my work from a different perspective, which has surely helped me becoming a better researcher.

Secondly I would like to thank my supervisor at HR Wallingford, Michiel Knaapen. He has helped me with my placement at HR Wallingford and has guided me through this bachelor thesis process. He gave me critical feedback on my work, answered numerous questions and has helped me to create a critical view in the world of physical modelling.

I would also like to thank Thomas Benson for his help on my project. His PhD was the basis of my bachelor thesis project, and he taught me many things about modelling. He answered many of my questions and indirectly motivated me to achieve the best results possible, even though this sometimes proved to be very hard.

Last but not least I want to thank everyone at HR Wallingford who welcomed me, helped me and gave me an amazing time at the company. I learned many things and had a great time at HR Wallingford.

Finally, I would like to wish you, the reader, a pleasant time reading this report, and I hope you'll enjoy it as much as I enjoyed working on it.

Willeke van de Wardt

ABSTRACT

In 2003 Thomas D. Benson completed his PhD in which he had analysed the sediment transport of the Blyth estuary (Suffolk, UK). This PhD required building a 2D depth averaged-model of the sediment transport of this estuary (Benson, 2004). However, as the state-of-the-art in modelling sediment transport progressed over time, this 2D model needed to be converted into a 3D model. The 3D sediment transport model has been modified and improved significantly in the last few years, but the model has only partly been tested against a limited amount of measured data. Therefore, in this thesis, the model will be calibrated and validated against the available data, resulting in the following goal:

To calibrate and validate a 3Dimensional mud model with field data for the Blyth estuary (Suffolk, UK) and determine if the 3D model is an improvement to the existing 2D model.

After exploring the properties of the estuary, and the sediment transport within an estuary, a dataset for which the model is calibrated and validated is determined. The data collected during spring tide, which has the highest current speeds and suspended sediment concentrations, will be used for the calibration of the model. The dataset collected during neap tide, which has lower current speeds and suspended sediment concentrations, will be used for the validation of the model.

After calibration and validation, the best results for the model are as shown in Figure 1. The order of graphing is as following:

1. Water level on the spring tide
2. Suspended sediment concentration on the spring tide
3. Water level on the neap tide
4. Suspended sediment concentrations on the neap tide

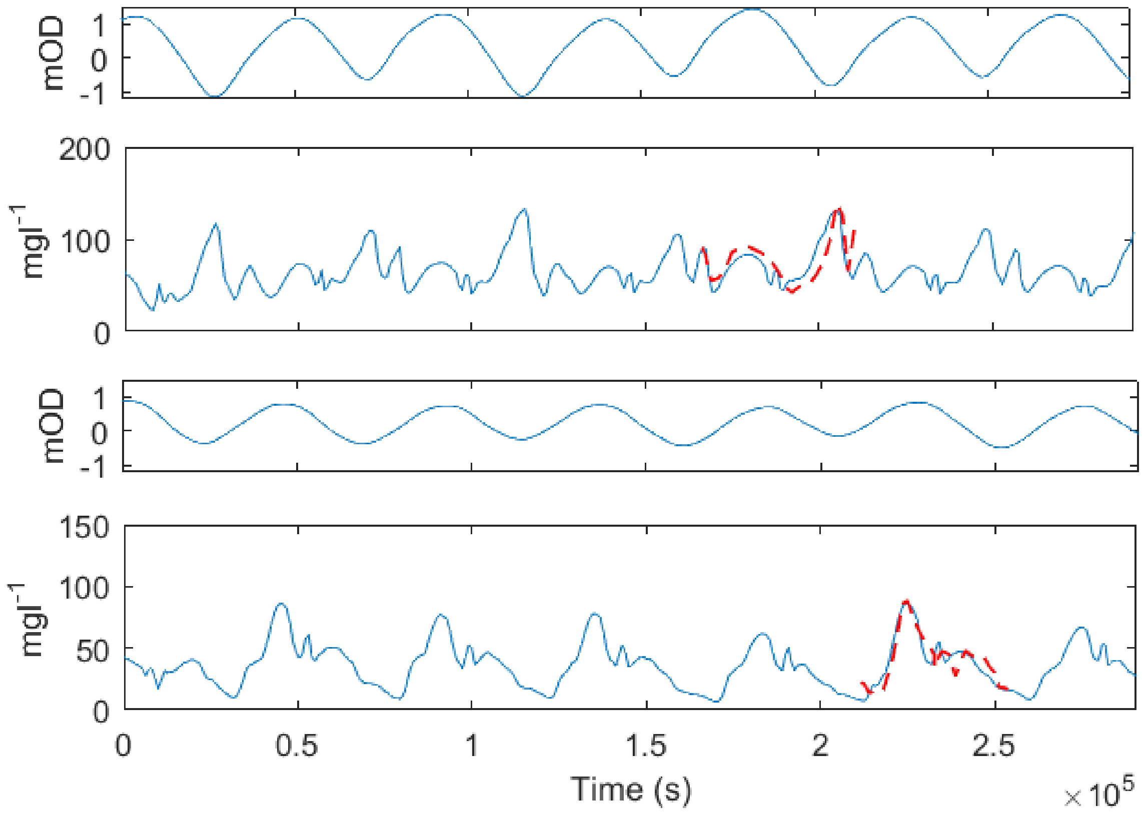

Figure 1: End results calibration (top two figures) and validation process (bottom two figures)

To quantify the quality of the model, the Brier Skill Score is calculated. This Brier Skill Score can be split up in 3 components, respectively the phase error, amplitude error and error in the average mud concentration. This is useful, because it points out where the weaknesses of the model lay. To see if the 3D model is an improvement to the existing 2D model, the Brier Skill Score for both the 2D and the 3D model is calculated. The model quality is also assessed using the Root Mean Square Error of the concentration.

Table 1: Comparison of the 2D and 3D model

Model	Springs (calibration)		Neaps (validation)	
	2D	3D	2D	3D
RMSE	17.23	18.11	18.51	9.45
BSS	0.54	0.49	0.26	0.81
Qualification BSS	Fair	Fair	Bad	Excellent

From the results summarised in Table 1, it can be concluded that the 3D model gives a better fit to the data than the 2D model. Even though it performs slightly worse on the spring tide than the 2D model, possibly due to uncertainties in the 3D model, the model is an excellent fit for the neap tide.

The 3D model can possibly be improved by reducing the uncertainties. This could be achieved by collecting more data about the estuary and use those in the calibration. Important data are the soil type at different locations in the estuary, and the suspended sediment concentrations at these different locations. Since the boundary conditions could play an important role when the current speeds increase during the spring tide, it could also be considered measuring the erosion at the boundaries of the channel, to see how this boundary behaves during these high current speeds. Since it will take a while for the boundaries to erode, the measurements should probably be taken over a couple of tides.

However, it can be concluded that the model works very good for the given data sets, but there are many uncertainties in the model parameters, which can probably be resolved by doing further research.

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LIST OF SYMBOLS

Symbol	Unit	Description
$\boldsymbol{\alpha}$	[-]	Phase error
$\boldsymbol{\beta}$	[-]	Amplitude error
$\boldsymbol{\gamma}$	[-]	Difference between the predicted and measured mud concentration
$\boldsymbol{\varepsilon}$	[-]	Normalization term for the Brier Skill Score
$\boldsymbol{\sigma_X}$	[mgl^{-1}]	Measured standard deviation
$\boldsymbol{\sigma_Y}$	[mgl^{-1}]	Predicted standard deviation
$\boldsymbol{\sigma_{X'}}$	[mgl^{-1}]	Measured standard deviation for the anomalies
$\boldsymbol{\sigma_{Y'}}$	[mgl^{-1}]	Modelled standard deviation for the anomalies
B	[-]	The n^{th} baseline prediction of the suspended sediment concentration at a given time, being the same as the n^{th} value of the prediction and observation Y and X
BSS	[-]	Brier Skill Score
j	[mgl^{-1}]	A prediction/observation in set J
J	[-]	Number of predictions/observations
$\boldsymbol{MAE}(\boldsymbol{Y},\boldsymbol{X})$	[mgl^{-1}]	Mean Absolute Error between predictions Y and observations X
$\boldsymbol{MSE}(\boldsymbol{Y},\boldsymbol{X})$	[$m^2g^2l^{-2}$]	Mean Square Error between predictions Y and observations X
Q	[ms^{-1}]	Current speed
Q_{max}	[ms^{-1}]	Maximum current speed
$\boldsymbol{RMSE}(\boldsymbol{Y},\boldsymbol{X})$	[mgl^{-1}]	Root Mean Square Error between predictions Y and observations X
$\boldsymbol{s_{XY}}$	[-]	Covariance between the observations and the predictions
ssc	[mgl^{-1}]	Suspended Sediment Concentration
x_j	[mgl^{-1}]	Observation at j
$\boldsymbol{X'}$	[mgl^{-1}]	Measured anomalies
$\langle \boldsymbol{X} \rangle$	[mgl^{-1}]	Average of the observations
y_j	[mgl^{-1}]	Prediction at j
$\boldsymbol{Y'}$	[mgl^{-1}]	Modelled anomalies
$\langle \boldsymbol{Y} \rangle$	[mgl^{-1}]	Average of the predictions

1. INTRODUCTION

This chapter will describe the design of this bachelor thesis project. This chapter explains why this research, in the form of a bachelor thesis project, has been carried out and what research approach has been taken.

In section 1.1 a description about the external organisation is given, which is followed by the description of the problem context in 1.2. In section 1.3 the project location is shown and its location on the map. Section 1.4 will elaborate on the research aim of this thesis and the sub topics used to get an answer to this research aim.

1.1. EXTERNAL ORGANIZATION

The company identifies itself as following:

"HR Wallingford is an independent civil engineering and environmental hydraulics organisation.

We deliver practical solutions to the complex water-related challenges faced by our international clients. With a 65-year track record of achievement, our unique mix of know-how, assets and facilities includes state of the art physical modelling laboratories, a full range of numerical modelling tools and, above all, enthusiastic people with world-renowned skills and expertise.

Based in the UK, HR Wallingford has a reputation for excellence and innovation, which we sustain by re-investing profits from our operations into programmes of strategic research and development.

HR Wallingford reaches clients and partners globally through a network of offices, agents and alliances around the world." (HR Wallinford, sd)

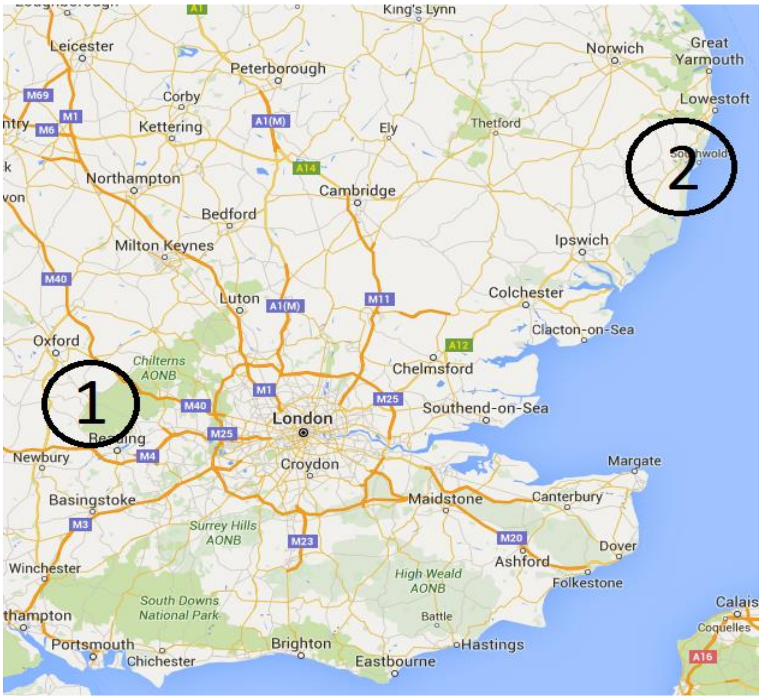

Figure 2: Locations HR Wallingford and the Blyth estuary Suffolk (UK) (Google , 2016)

This bachelor thesis has been carried out in the department of Coasts and Estuaries, within HR Wallingford. This department has 22 employees within the total of the 280 employees working for HR Wallingford.

1.2. PROBLEM CONTEXT

When a water flow interacts with soil, especially grains, sediment transport occurs. This causes estuary beds to change over time. It is important to both understand and be able to predict the estuary bed changes over time. This will allow engineers, to predict whether engineering works are required and what the impact of those works might be.

The Blyth estuary, is an estuary that in the past was turned into a tidal river by land reclamation. Due to natural failure of the dikes, part of the reclaimed land was returned to the natural dynamics of the tides and grassland turned into tidal flats. While the hopeful expectation was that this would quickly turn into a saltmarsh, it still remains a tidal flat. As a result, the Blyth estuary still has a bedding which contains a huge amount of mud, and the sediment transport in the estuary is dominated by mud transport. If an explanation is found of why saltmarshes cannot develop, this knowledge can be used for managed realignments that aim to increase the amount of saltmarsh.

In 2004 a PhD was completed in which 2D modelling of the sediment transport of the Blyth estuary was done (Benson, 2004). In the last couple of years, many new features have been added to this model, though it was never calibrated and validated properly after these new properties had been added. As at the start of this bachelor thesis a 3D model was up and running. In this bachelor thesis, this model is calibrated and validated for the available data. A comparison to both the dataset and the old 2D model is done as well, to determine how much of an improvement this 3D model is compared to the existing 2D model.

1.3. PLACES

The Blyth estuary in Suffolk, UK is the focus in this bachelor thesis project. The location and a picture of this estuary are shown in Figure 3 at the end of this chapter.

1.4. RESEARCH AIM AND RESEARCH TOPICS

The research aim of this bachelor thesis is:

To calibrate and validate a 3Dimensional mud model with field data for the Blyth estuary (Suffolk, UK) and determine if the 3D model is an improvement to the existing 2D model.

This main research aim is split up into the following six topics:

(1) *Understand the properties of the 3D model and the important differences between 2D and 3D modelling of mud transport.*

(2) *Decide how to quantify model errors.*

(3) *Analyse the data set from measurements and select calibration and validation period.*

(4) *Calibration of the model to a part of the measured data.*

(5) *Validation against remaining data and initial analysis of the results.*

(6) *Detailed comparison between model results and measurements, analyse weak and strong points of the model.*

1.5. METHODS AND MODELS

This section elaborates on the methods and models to use per topic.

(1) Understand the properties of the 3D model and the important differences between 2D and 3D modelling of mud transport.

Since the model embraces a large variety of properties and data, literature review is done in order to determine the physical concepts which are relevant for mud transport. These are determined qualitatively in order to know how mud transport works and to be able to understand what the model performs. The model parameters are studied, as well as the settings that are used.

(2) Decide how to quantify model errors.

This section starts with the description of the quantification of the model errors. Three methods have been chosen to test the model's performance. The methods concerning the bias, accuracy and Brier Skill Score are described in this chapter, since these three tests will be used to test the model's performance.

(3) Analyse the data set from measurements and select calibration and validation period.

The characteristics of the data available are analysed in this chapter. It is important to know which data are available and what their characteristics are. The eventual model is going to be calibrated and validated against these data and to have a reliable model, it has to be known what the data represent. The data are graphed together with the free surface elevation, such that it is clear for which part of the tides the model is calibrated and validated.

(4) Calibration of the model to a part of the measured data.

For the calibration, the data set with the highest current speeds and suspended sediment concentrations is used. This is the data collected during a spring tide. Springtide occurs when the sun and moon are in line with the earth. When this occurs, the high waters are at its highest and low waters are on its lowest (The Open University , 1989). The model is calibrated against both current speeds and suspended sediment concentrations. This is done by parameterization and altering the properties of the estuary bed.

(5) Validation against remaining data and initial analysis of the results.

After the model is calibrated against the data of the spring tide, the part of the data that was collected during the neap tide is used to validate the model. The current speeds and suspended sediment concentrations during the neap tide are lower than those during the spring tide. During the validation it becomes clear whether the model has been over-parameterized for the outliers in the spring tide data, or whether the model is as good of a fit for the neap tide data as it is for the spring tide data.

(6) Detailed comparison between model results and measurements, analyse weak and strong points of the model.

This part of the thesis brings all the sub topics from the research together, and answers the research aim of this bachelor thesis. The strong and the weak points from the 3D model are analysed and the performance of the 3D model is compared to that of the 2D model. This makes clear whether the 3D model is an improvement to the existing 2D model, and where the 3D model can still use some improvement.

Figure 3: Location of the Blyth estuary (Suffolk, UK) (Google, 2016)

2. MUD MODELLING

When a water flow interacts with soil, especially grains, sediment transport occurs. This causes estuary beds to change over time. It is important to both understand and be able to predict the estuary bed changes over time. As the mud transport in the Blyth estuary is examined, it is important to know the properties of mud and sediment transport.

First of all, the properties of the Blyth estuary are examined. The formation of the estuary over time is explained and what its properties are nowadays. Secondly, the phenomenon of the s transport in the estuary is examined.

2.1. DESCRIPTION OF THE ESTUARY GEOMETRY

Figure 4 displays the geometry of the Blyth estuary. As can be seen in this figure, there are three accesses to the estuary. The mouth of the channel is in the south east, channel 2. There are two river streams flowing into the estuary, the River Blyth and the River Wang, respectively numbered 1 and 3. The discharge from stream 1, the River Blyth, has a mean monthly discharge of $0.46 m^3 s^{-1}$ (Centre of Ecology & Hydrology , 2015). Therefore, stream 2 can be identified as being the main entrance and exit of the estuary.

The channel on the east of the estuary, is connected with the North Sea, therefore the estuary is directly influenced by the tides of the sea. The tidal range at the mouth, at Southwold, varies from 1.2 m at neaps to 2.0 m at springs. Due to this influence, the estuary is well-mixed (French, et al., 2008).

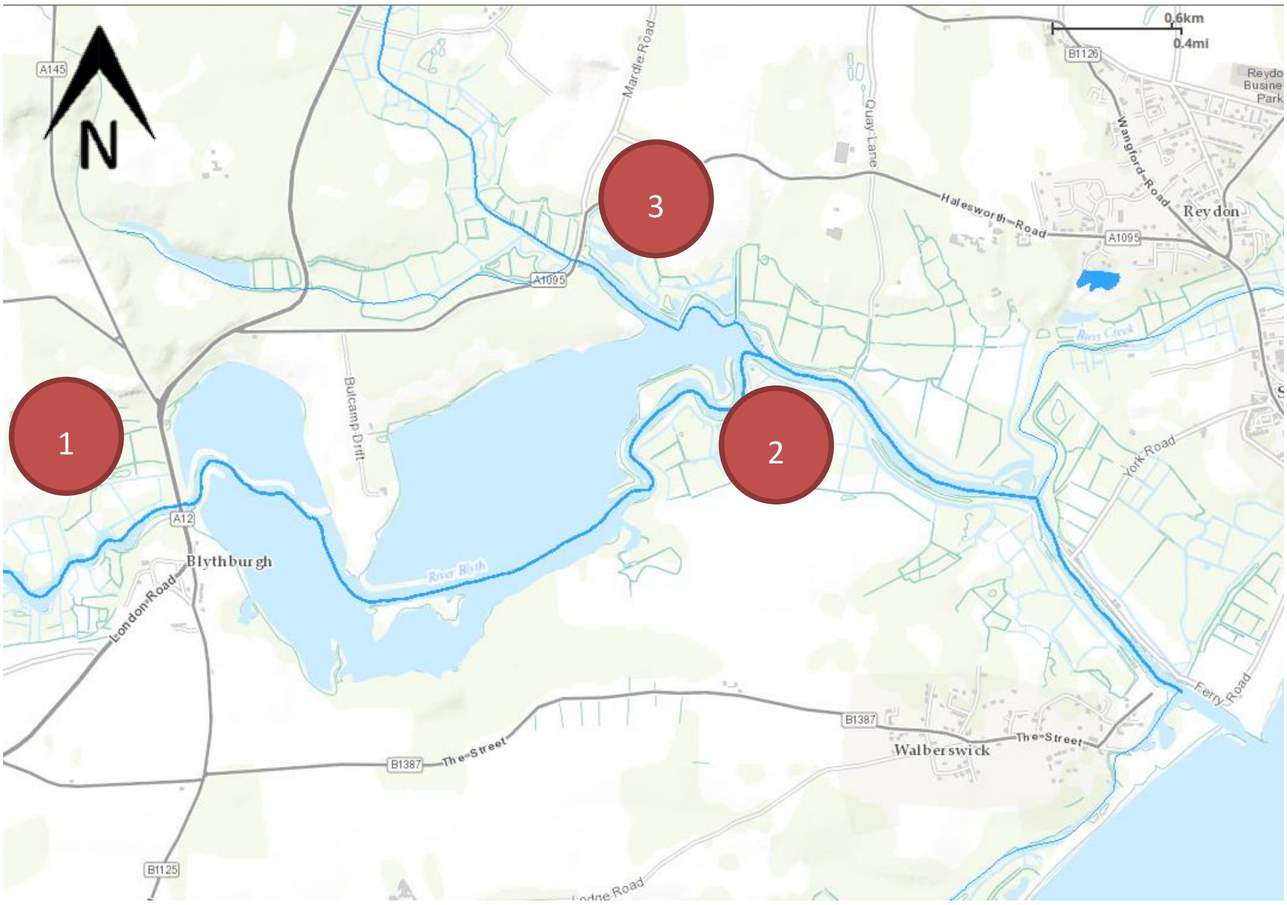

Figure 4: Estuary Geometry (Centre of Ecology & Hydrology , 2015)

2.2. SEDIMENT TRANSPORT IN THE ESTUARY

In this chapter the sediment transport in the estuary will be described. First of all, the sediment zonation on the tidal flats will be explained to reach a better understanding of the sediment in these zones.

Additionally, this chapter will explain the estuary type and the flocculation of the Blyth estuary.

2.2.1. SEDIMENT ZONATION ON TIDAL FLATS

Within estuaries, intertidal flats are formed. These intertidal flats have tidal channels, which are gradually filled when the water level rises. When the water level exceeds the height of the channel, the flats are flooded. When the water level drops again, the water drains back and sediment is left behind.

As can be seen in Figure 5, there are four different zones in an estuary that can be distinguished (The Open University , 1999).

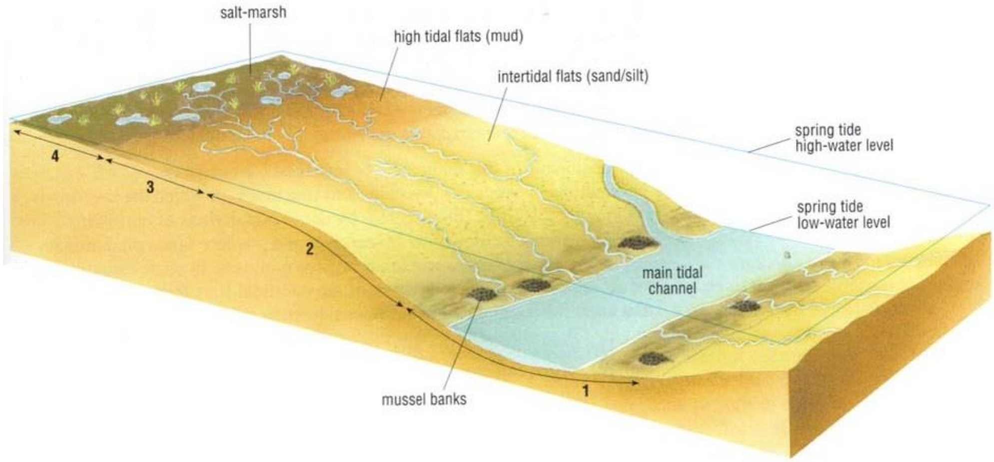

Figure 5: Sediment zonation on tidal flats (The Open University , 1999)

THE MAIN TIDAL CHANNEL

The main tidal channel is the deepest part of the estuary, and is directly affected by de tides and currents of the sea. The sediment in this channel consists mainly out of sand and some gravel (French, et al., 2008).

THE INTERTIDAL FLATS

The region of the intertidal flats is the widest zone in the estuary. These flats are submerged and exposed for almost the same amount of time. These flats are submerged, when the strongest tidal currents occur. Therefore, deposition of sand and the forming of ripples are the most dominant form of sediment transport in this region. When the strong currents disappear and a period of high slack water starts, fine mud suspension settles and cover the earlier sand formed ripples on the flat.

THE HIGH TIDAL FLATS

These high tidal flats are only submerged when high tide occurs and the current speeds are close to zero. During this period, there is little bed load transport and deposition. Once the critical depositional shear velocity is reached, the sediments start to settle down. The sediments, in this estuary the muds, settle out of suspension to form the mud-flats due to the lack of a current. The amount of sediment which settles down, is determined by the settling velocity. The settling velocity is the rate at which a grain settles out of suspension back to the bed (The Open University , 1989).

The deposition of the mud is encouraged by the settling lag. The settling velocities of sediments are related to their size: The larger the sediment, the faster the settling velocity. It takes the coarser sediments longer to settle down, so that they might settle down long after the critical depositional shear velocity has been reached. This is the so-called settling lag. Because there is still a slight current during the slack water period, the muds do not settle down vertically, but they are transported to more shallow waters closer to the shore, where they eventually settle. Once the muds are settled down, they will not easily erode, because muds are cohesive sediments which can endure a very high shear stress before its critical shear stress is reached.

SALT MARSHES

Salt marshes are flats that are exposed for a sufficiently long time period, such that plants start to grow. The growth of these plants ensures that the sediments are bound and that further erosion is prevented. On top of that, due to the roots of the plants, the flow is decelerated, resulting in even more deposition of sediments. Due to the deposition of these sediments and the growth of land plants, the flat is only flooded during high spring tides. This development, causes the salt marsh to extend towards the river or sea and the region further land inwards is even flooded less frequently (The Open University, 1989).

2.2.2. ESTUARINE TYPE

The Blyth estuary in Suffolk, is a generally well-mixed estuary. In this kind of estuaries, the salinity varies hardly as a function of the depth of the estuary. Though the salinity can vary along the width of the estuary because of lateral mixing. In this estuarine type, the deposition of marine sediments finds place on the left-hand bank, and the river-borne sediments on the right hand bank, facing downstream (The Open University, 1989).

2.2.3. FLOCCULATION

Flocculation is the binding of sediments due to Van der Waals forces. These forces do not occur in fresh water, because the particles are negatively laden and repel each other. In saline sea waters however, the minerals are neutralized, such that the van der Waals forces dominate and flocculation does take place. Logically, as the mud flocs grow, they will settle down more easily than the fine-grated muds. Since the main water type in this model is saline sea water, it is assumed that flocculation takes place.

3. QUANTIFICATION OF MODEL ERRORS

A model error is a discrepancy between the model and reality (Cornford, et al., 2010). It is important to quantify model errors because these model errors are the weaknesses of the model, for they are the discrepancy with the reality and it is the reality that should be modelled properly. However, it must be realized that a model never is an exact copy of reality, but only a mere representation of reality. 'It is the mediator between theory and the world, as theories do not provide any measurable physical variables until a model is built' (MacLeod, 2016). As the model is the connection between the theory and the real world, it is very important to understand what the model executes and how the theory is implemented in this model. Even though the underlying theory and assumptions might be right, a wrong implementation may result in a bad model. To test the correctness of the implementation of this theory in the model and the parameterization of the parameters in the model, the model should be examined for model errors. These model errors need to be quantified in a proper and thorough way, to establish whether the model is reliable or not. The quantification of model errors will be carried out in section 7.1 after the model is properly calibrated and validated.

3.1. METHODS TO QUANTIFY MODEL ERRORS

3.1.1. BIAS

The main purpose of the bias is to determine whether the model has a tendency to under- or over-predict the observations (Sutherland, et al., 2004). A positive bias indicates that the model over-predicts the observations. The bias in the mean is calculated by the following equation:

$$Bias_a = \frac{1}{J}\sum_{j=1}^{J}(y_j - x_j) = \langle Y \rangle - \langle X \rangle$$

Where y_j is the prediction and x_j the observation at the exact same point at the exact same time. J is the total amount of predictions/observations and the angular brackets denote the mean.

3.1.2. ACCURACY

The accuracy of the model can be determined with various methods. The most common measures of accuracy are the Mean Absolute Error, the Mean Square Error and the Root Mean Square Error, respectively the MAE, MSE and RMSE.

The MAE, MSE and RMSE express how accurate the model is and how close the modelled values are to the observed values. The MAE and MSE are defined as:

$$MAE(Y,X) = \frac{1}{J}\sum_{j=1}^{J}|y_j - x_j| = \langle |Y - X| \rangle$$

$$MSE(Y,X) = \frac{1}{J}\sum_{j=1}^{J}(y_j - x_j)^2 = \langle |Y - X|^2 \rangle$$

However, instead of using the MSE, most of the time the RMSE is used, as it is preferred to the MSE, since it has the same units as the values in J. The RMSE is defined as:

$$RMSE(Y,X) = \sqrt{\frac{1}{J}\sum_{j=1}^{J}(y_j - x_j)^2}$$

The distinction between the MAE and the RMSE is that the RMSE squares the difference and hence amplifies the difference between the predicted and observed values. Therefore, the RMSE is more sensitive for outliers in the data than the MAE. In Figure 6 the PhD modelling of the neap tide has been plotted. The dashed line is the data that the model is going to be validated for.

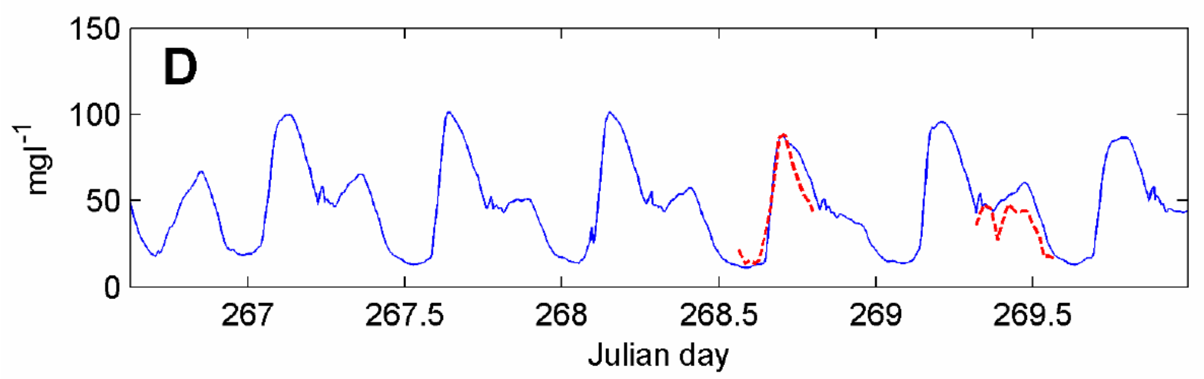

Figure 6: Comparison between modeled and measured suspended sediment concentrations from Benson, (Benson, 2004), during the neap tide

As can be seen in Figure 6, the model has large peaks, and therefore it is assumed that the model is sensitive for outliers in the data. This means that the RMSE is used to determine the accuracy of the model.

3.1.3. BRIER SKILL SCORE

In a model like this, it is often the case that the observed and the modelled data show a lot of similarities, but that they do not perfectly match because they are different in amplitude, phase and mean. For these situations the Brier Skill Score, hereafter referred to as BSS, is extremely helpful (Sutherland, et al., 2004).

The calculation of the BSS is given by the following equation:

$$BSS = \frac{\alpha - \beta - \gamma + \varepsilon}{1 + \varepsilon}$$

Table 2: Parameter description Brier Skill Score

Term	Formula	Description
$\boldsymbol{\alpha}$	$\alpha = r^2_{Y'X'}$	This term denotes the phase error and therefore the time at which a given concentration occurs. Perfect phasing gives $\alpha = 1$.
$\boldsymbol{\beta}$	$\beta = \left(r_{Y'X'} - \frac{\sigma_{Y'}}{\sigma_{X'}}\right)^2$	This term denotes the amplitude error and therefore the concentration of the mud. Perfect modelling of phase and amplitude gives $\beta = 0$.
$\boldsymbol{\gamma}$	$\gamma = \left(\frac{\langle Y' \rangle - \langle X' \rangle}{\sigma_{X'}}\right)^2$	If $\gamma > 0$, then the predicted average mud concentration is different than the measured concentration.
$\boldsymbol{\varepsilon}$	$\varepsilon = \left(\frac{\langle X' \rangle}{\sigma_{X'}}\right)^2$	This is a normalization term, which is affected by the observed anomalies and its standard deviation.

This results in the following formula:

$$BSS = \frac{r^2_{Y'X'} - \left(r_{Y'X'} - \frac{\sigma_{Y'}}{\sigma_{X'}}\right)^2 - \left(\frac{\langle Y' \rangle - \langle X' \rangle}{\sigma_{X'}}\right)^2 + \left(\frac{\langle X' \rangle}{\sigma_{X'}}\right)^2}{1 + \left(\frac{\langle X' \rangle}{\sigma_{X'}}\right)^2}$$

The qualification of the BSS is given in Table 3 (Van Rijn, et al., 2003).

Table 3: Qualifications of the Brier Skill Score

Qualification	BSS
Excellent	1.0 – 0.8
Good	0.8 – 0.6
Reasonable/fair	0.6 – 0.3
Poor	0.3 – 0
Bad	< 0

It should be taken into account that this qualification of the BSS was designed for morphological models, which models the change of bathymetry over time. In this particular model, not the change of bathymetry over time is modelled, but the suspended sediment concentration over time. Therefore, the qualification of the BSS for this particular model could be slightly different. However, in this thesis it is assumed that this qualification of the BSS for the bathymetry over time, will work for the suspended sediment concentration over time as well.

4. ANALYSIS OF THE MEASURED DATA

The characteristics of the data available need to be analysed. It is important to know what data are available and what their characteristics are. The eventual model is going to be validated against these data and to have a reliable model, it has to be known what the data represent.

Not only the knowledge about the available data is important to the reliability of a model. Another aspect, namely the 'robustness of the model' is quite important to have a reliable model.

4.1. ROBUSTNESS OF THE MODEL

When calibrating the model, it is important to realise that a model should never be too sensitive to the parameterisation, since this may cause over parameterization.

'The model is robust if the results or prediction it gives holds independently of changes in its underlying assumptions. When the model's parameters are changed, idealizations or abstractions are swapped out and are replaced with other or more sophisticated representations, and the same results or predictions still occur, the model is robust. Models with a lot of parameters are easily over-fitted to the data. To be robust, they should be resistant to noise or error in the data. Therefore, a decision should be made whether the model is calibrated for the outliers or not. If it is calibrated for the outliers, there is a danger of over parameterization' (MacLeod, 2016).

To avoid over-parameterization, the model will be calibrated and validated amongst data collected during respectively a spring tide and a neap tide.

4.2. THE DATASET

Field data were collected from the Blyth estuary for a spring and a neap tide. The data for the spring tide were collected on 19-20th of October 2001 and the data for the neap tide were collected on the 26-27th of September 2001 (Benson, 2004). This collected dataset contains data about the suspended sediment concentration, hereafter referred to as ssc, which is to be used to calibrate and validate the model. The data were collected in the main channel at point 'A', outside the estuary, as can be seen in Figure 7.

Figure 7: Location of the data collection (Google, 2016)

4.3. DETERMINATION CALIBRATION PERIOD

The data collected during spring tide, which has the highest current speeds and ssc's, will be used for the calibration of the model. The model will be calibrated against the ssc. The tide input for the model is the water depth measured during spring tide. The total time simulated by the model is 291000 seconds (3 days, 8 hours and 48 minutes). In Figure 8 the measured water level, in meter Ordnance Datum, has been plotted in the upper graph, as well as the measured ssc in milligram per litre in the lower graph.

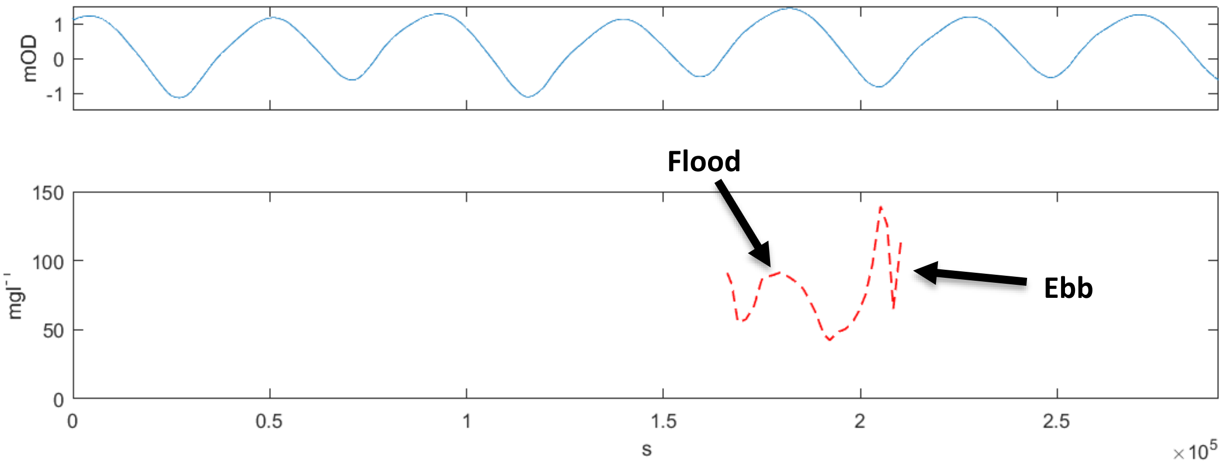

Figure 8: Dataset calibration period

4.4. DETERMINATION VALIDATION PERIOD

The data set collected during neap tide, which has lower current speeds and ssc's, will be used for the validation of the model. This will be the data collected during a neap tide since this period has the lowest current speeds and ssc's. Again, the ssc will be used to compare the model with the measured data. In Figure 9 the measured water level, in meter Ordnance Datum, has been plotted in the upper graph, as well as the measured ssc in milligram per litre in the lower graph.

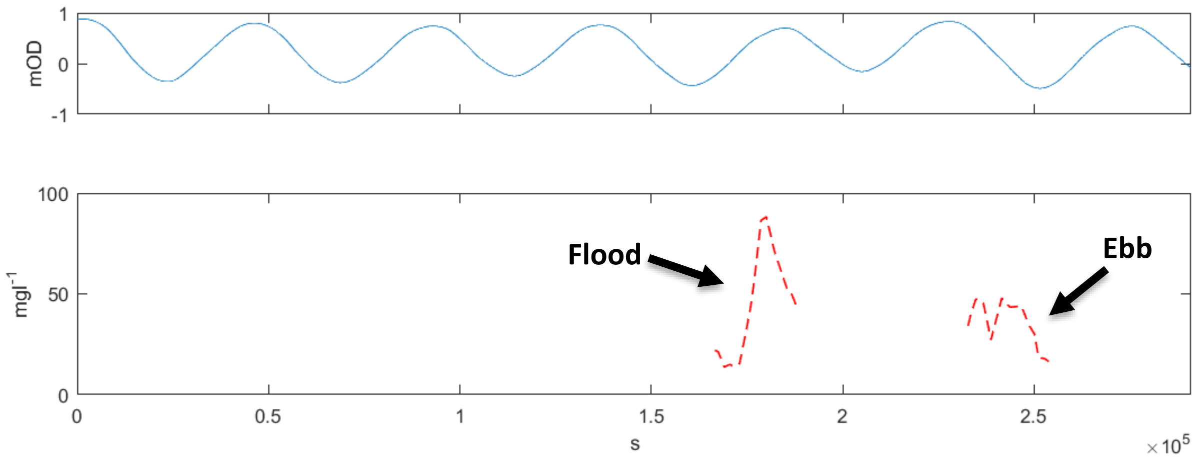

Figure 9: Dataset validation period

5. CALIBRATION OF THE MODEL

This chapter describes the calibration of the sediment transport during the spring tide period, using the in situ measurements for the same period.

5.1. CHOICE OF MODEL GEOMETRY

Initially, it was planned to use the model with the re-meshed geometry that was generated for this thesis project (the Demo model) for the calibration and validation (Appendix A., section 10.1.1). However, initial model runs using the PhD model geometry proved to be better than the Demo model because the results fitted the observed current speeds and elevation (Appendix A., section 10.1.1, Figure 25). The main reason for this was because the original raw bathymetry data used for the PhD model were not available for the current project, so the bed levels for the Demo model needed to be interpolated from the PhD model geometry, making them less accurate. In addition, it was decided that a direct comparison between the 2D and 3D models would be more useful if it was performed using the same mesh. Therefore, the model results using the PhD-model geometry are used for the final calibration.

5.2. CALIBRATION OF THE ELEVATION AND THE CURRENT SPEEDS

In this section the process of the calibration of the hydrodynamics is described. Before the 3D model can be calibrated for the mud concentrations, the current speeds and elevation as function of the time must be calibrated. If the current speeds and the elevations are not calibrated, it means that the hydrodynamics in the estuary are not modelled properly in the model, which would make the correct calibration of the ssc's an impossible task.

5.2.1. BOTTOM FRICTION

To get a realistic representation of the hydrodynamics, bottom friction needs to be parameterised in the model. The friction coefficient used in this model is the Nikuradse friction coefficient. Nikuradse is used because it allows for a friction that varies with water depth. The Nikuradse parameter values vary between 0.001 m and 0.1 m (Appendix A., section 10.1.2, Figure 27) for representing regions with a smooth muddy bed or saltmarsh on the high intertidal areas.

5.2.2. SMOOTHING OF THE ESTUARY

In the final calibration of the elevation and the current speeds, three scenarios are developed, which are presented in Table 4. The only parameter changed in these runs, is the parameter which determines the smoothness of the model's bathymetry. Since the new model is run in 3D, the smoothness of the bathymetry is more important than in the 2D model since steep bed slopes can affect the vertical velocity and therefore influence model stability. This makes the smoothness of the bathymetry considerably more important than in 2D modelling.

Table 4: Three scenarios for elevation and current speeds calibration

Scenario	Description
No smoothing	In this scenario no smoothing has been applied to the bathymetry of the model.
Smoothed mouth	In this scenario, only the mouth of the estuary has been smoothed. Near the mouth of the estuary there is a sharp step in the bed level, resulting in a sudden change of height of nearly three meters over a distance of approximately eight meters. (Appendix A., section 10.1.3, Figure 28 and Figure 29).
Smoothed estuary	In the third scenario, the whole model has been smoothed with a smoothing factor of 1 (Appendix A., section 10.1.3, Figure 30 and Figure 31).

From the plotting of the three scenarios it is visually decided that the smoothed estuary gives the best results compared to the field data.

5.2.3. EXTRACTING DATA FROM MULTIPLE LOCATIONS IN THE CHANNEL

Unfortunately, the exact location where the field data have been collected was not recorded in the PhD thesis. Since no coordinates are available, the data for the tidal elevation and the current speeds derived from the models are taken from an approximate point inferred from a location map in the PhD (section 4.2, Figure 7). Therefore, it is useful to extract model data from a number of slightly different locations in the channel (Appendix A., 10.1.4, Figure 34), to see if this makes a substantial difference.

The data extracted from 23 points proves that location X (648575;276221) is the best location (Appendix A., section 10.1.4, Figure 35, Figure 36, Figure 37, Figure 38, Figure 39). The tidal elevation and current speeds for the spring tide, measured at location X, are presented in Figure 10.

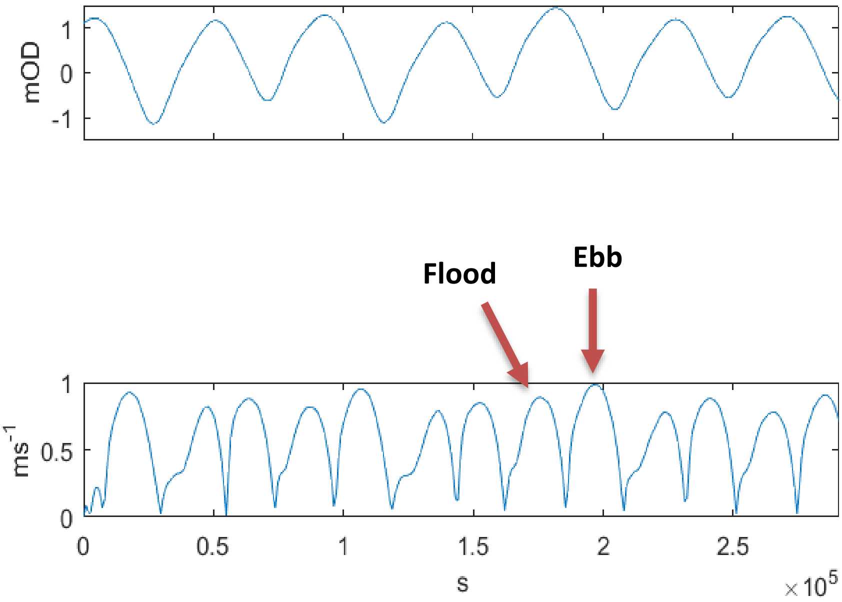

Figure 10: Tidal elevation and current speeds for the spring tide

5.3. CALIBRATION OF THE MUD CONCENTRATION

The calibration process has been carried out in five steps, which will be described as five separate models in this chapter. For each model, the changes are made sequentially, in addition to the changes made to the preceding run. The added features in every model are shown in Table 5.

Table 5: Calibration settings

Model #	Title	Change
Calibration model 1	Initial model set up	This model uses the default settings.
Calibration model 2	Parameterization	In this model parameterization takes place, as to improve the model's performance.
Calibration model 3	Spatially varied critical shear stress for erosion based on spring tide hydrodynamics	In this model, a spatially varied critical shear stress for erosion (bed plane 2) is recalculated for spring tide flow conditions. Its lower limit is 0.2 $kgm^{-2}s^{-1}$.
Calibration model 4	Variable ssc	In this model, the ssc at the seaward boundary is scaled according to a lower discharge at the mouth to give a maximum ssc of 100 mgl^{-1} at a peak discharge of 200 m^3s^{-1} (approximately the peak spring tide discharge).
Calibration model 5	Initial bed sediment removed from the channel and saltmarshes	In this model the thickness of the sediment layer of the channel and saltmarshes is set to 0.0 m.

In the following paragraphs the different steps in the calibration process of the model will be presented and explained. In each paragraph a new calibration step is presented, with its corresponding graphed ssc. The elevation is shown above every graphed ssc.

5.3.1. CALIBRATION MODEL 1 – INITIAL MODEL

In this model, the settings are mainly set the same as in the 2D model. The initialised ssc for the spring tide is set to 75 mgl^{-1} and the ssc at the seaward boundary is set to 70 mgl^{-1}. There is a single bed layer, with a thickness of 0.2 m and a concentration of 500 kgm^{-3}.

The Parthenaides erosion coefficient (the rate at which erosion takes place once initiated, Appendix A., section 10.1.5) is set to 0.00004 $kgm^{-2}s^{-1}$. The bed uses a uniform critical erosion shear stress of 0.2 $kgm^{-2}s^{-1}$ and a critical erosion shear stress for deposition of 1000 $kgm^{-2}s^{-1}$. This value of the critical erosion shear stress for deposition has been set to 1000 $kgm^{-2}s^{-1}$, because the probability of depositing sediments is very high. In the initial model, no flocculation takes place.

The variables which define sediment transport, are shown in Table 6.

Table 6: Model parameters

Parameter	Unit	Value
SSC AT THE SEAWARD BOUNDARY	[mgl^{-1}]	70
FLOCCULATION	[-]	No
EROSION COEFFICIENT	[$kgm^{-2}s^{-1}$]	4.E-5
NUMBER OF SEDIMENT BED LAYERS	[-]	1
READ CRITICAL BED SHEAR STRESS PER LAYER	[-]	No
CRITICAL EROSION SHEAR STRESS OF THE MUD LAYERS	[$kgm^{-2}s^{-1}$]	0.2
CRITICAL SHEAR STRESS FOR DEPOSITION	[$kgm^{-2}s^{-1}$]	1000
INITIAL THICKNESS OF SEDIMENT LAYERS	[m]	0.2
MUD CONCENTRATIONS PER LAYER	[kgm^{-3}]	500.0

It can be seen in Calibration model 1, Figure 11, the modelled concentration on the flood tide exceeds the data, while the modelled concentration on the ebb tide highly underestimates the data.

5.3.2. CALIBRATION MODEL 2 – PARAMETERIZATION

In Calibration model 2, the model has been parameterized. The parameterization process is described in Appendix A., section 10.1.6. The new parameter settings are shown in Table 7.

Table 7: Model parameters - parameterization

Parameter	Unit	Value
SSC AT THE SEAWARD BOUNDARY	[mgl^{-1}]	100
FLOCCULATION	[-]	Yes
EROSION COEFFICIENT	[$kgm^{-2}s^{-1}$]	8.E-5
NUMBER OF SEDIMENT BED LAYERS	[-]	2
READ CRITICAL BED SHEAR STRESS PER LAYER	[-]	0.05;0.2
CRITICAL EROSION SHEAR STRESS OF THE MUD LAYERS	[$kgm^{-2}s^{-1}$]	0.0;0.2
CRITICAL SHEAR STRESS FOR DEPOSITION	[$kgm^{-2}s^{-1}$]	100
INITIAL THICKNESS OF SEDIMENT LAYERS	[m]	Yes
MUD CONCENTRATIONS PER LAYER	[kgm^{-3}]	8.E-5

This model is better in proportion, compared to Calibration model 1. The peak on the ebb tide is higher than the peak on the flood tide, as are these peaks in the data set. The ssc's might be higher than in Calibration model 1, but now that the proportions are right, the overall amount of the ssc's should be reduced.

5.3.3. CALIBRATION MODEL 3 – SPATIALLY VARIED CRITICAL SHEAR STRESS FOR EROSION

There are two layers of sediment in the model. A thin, low density (or *fluffy*), top layer, and a thicker, more solid, lower layer. After running the model with the new meshing for the very first time, it is observed that a lot of erosion takes place at certain locations in the estuary, especially at the mouth of the channel. The cause for this phenomenon, is that the estuary bed has not been corrected for different kinds of bed forms. The bed in the channel, can endure a higher shear stress before eroding, than the bed somewhere in the middle of the estuary. This bed has been hardened by the fast flows over the years and has therefore adapted to the high critical shear stresses exerted on the estuary bed.

The model is therefore corrected by using spatially varied critical shear stress for erosion values amongst the estuary. The upper limit is set, such that the estuary bed can endure a higher critical shear stress before it starts eroding, such that it is consistent with the actual estuary bed.

Since the model should not be overly sensitive for erosion, a minimum critical shear stress of 0.2 $kgm^{-2}s^{-1}$ is set. The layer that is calibrated for the spatially varied critical shear stress for erosion is the underlying, second layer (Appendix A., section 10.1.7, Figure 41).

The result of this spatially varied critical shear stress for erosion, is that the overall ssc is a lower than before and that the modelled values match the observed values more closely. Whereas the minima of the graph almost already resemble the minima of the data set, the maxima are still too high. However, the peaks on the ebb tide have a steeper slope than before, which is an improvement compared to the observed data. This steep slope on the ebb tide happened, because all the sediment close to the data extraction point was removed. There is only sediment further upstream in the estuary, and it takes longer for this sediment to reach the data extraction point. This means that there is a lag in the ssc and when this ssc passes the data collection point, a steeper peak occurs.

5.3.4. CALIBRATION MODEL 4 – VARIABLE SSC

In the previous models it is assumed that the ssc at the seaward boundary has a constant concentration of 100 mgl^{-1}. However, with varying current speeds and elevations, the ssc will fluctuate as well. Only when the current speeds reach their maximum value, the prescribed ssc of 100 mgl^{-1} will be reached. Therefore, the ssc will be normalized with the cross-sectional integrated flood tide discharge (Q) divided by an approximate maximum discharge (Q_{max}), expressed by the following equation, introduced by Thomas Benson:

$$SSC = Prescribed\ SSC * (Q/Q_{max})$$

Where (Q/Q_{max}) has a maximum value of 1, and a minimum value of 0.

For the spring tide, Q_{max} is 200 m^3s^{-1}. In Calibration model 4, applying the above equation mainly affects the ssc on the flood tide. As can be seen in Figure 11, the plotted observed and the modelled data for Calibration model 4 qualitatively have almost the same shape. Since the ssc at the beginning and end of the flood tide is lower due to discharge dependent ssc's, a dip occurs at the beginning and the end of the flood tide, after which the ssc increases again. Apart from the height of the peek on the ebb tide, the observed and the modelled graphs look very similar.

5.3.5. CALIBRATION MODEL 5 – THICKNESS SEDIMENT LAYER CHANNEL AND SALTMARSHES

Over time, the repeatedly high current speeds have caused any soft, easily erodible sediment in the channel to be eroded, thus exposing a harder bed. This means that there is very little sediment to erode in the channel during the spring tide. Therefore, the thickness of the sediment layer in the channel is set to 0.0 m.

Other locations with no sediment to erode, are the salt marshes. Due to the vegetation on the saltmarshes, it is impossible for the sediment to be eroded. The thickness of the sediment layer on the salt marshes has therefore also been set to 0.0 m. The spatial distribution of the sediment layer thickness is shown in Appendix A. section 10.1.8, Figure 42.

This last model fits the data very well and gives the best result compared to the other models. Since a lot of sediment on the ebb tide came from the channel and the salt marshes, the ebb tide peak in ssc was very high in the earlier models. However, since the sediment in these regions is now removed, there is less sediment to erode, which leads to a lower ssc peak on the ebb. The ssc on the flood tide is a bit too low now, but it is judged to be good enough, especially since the shape of the curve fits the beginning and the end of the flood tide perfectly. This difference can be explained by the fact that the initial bed sediment within the outer channel was completely removed. In reality a small amount of sediment will have been available for erosion from the bed in this area, thus increasing the concentrations slightly. However, in the scope of this project the schematised spatial distribution of bed deposits is sufficient for understanding the main influences on the tidal concentrations. Further fine tuning of the bed model could be carried out in future investigations if deemed necessary.

5.3.6. CALIBRATION RESULTS

The settings and results of the calibration are presented in Table 8 and Figure 11 on the next page.

Table 8: Model settings calibration

Parameter	Unit	Calibration model 1	Calibration model 2	Calibration model 3	Calibration model 4	Calibration model 5
SSC SEAWARD BOUNDARY	[mgl^{-1}]	70	100	100	100	100
FLOCCULATION	[-]	No	Yes	Yes	Yes	Yes
EROSION COEFFICIENT	[$kgm^{-2}s^{-1}$]	4.E-5	8.E-5	8.E-5	8.E-5	8.E-5
NUMBER OF SEDIMENT BED LAYERS	[-]	1	2	2	2	2
READ CRITICAL BED SHEAR STRESS PER LAYER	[-]	No	No	Yes	Yes	Yes
CRITICAL EROSION SHEAR STRESS OF THE MUD LAYERS	[$kgm^{-2}s^{-1}$]	0.2	0.05;0.2	0.05;0.2	0.05;0.2	0.05;0.2
CRITICAL SHEAR STRESS FOR DEPOSITION	[$kgm^{-2}s^{-1}$]	1000	1000	1000	1000	1000
INITIAL THICKNESS OF SEDIMENT LAYERS	[m]	0.2	0.0;0.2	0.0;0.2	0.0;0.2	0.0;0.2
MUD CONCENTRATIONS PER LAYER	[kgm^{-3}]	500.0	500.0;500.0	500.0;500.0	500.0;500.0	500.0;500.0
		Initial model with the default settings.	Parameterization of the model.	Spatially varied critical shear stress for erosion.	Variable ssc at the seaward boundary.	Thickness of the sediment layers in the channel and at the saltmarshes has been set to 0.0 m.

Visually, the concentrations plotted in Figure 11 do not show a long term trend (apart from during the model start up over the first few tides). The model is in equilibrium with no significant net build up or loss of sediment from the bed occurring. The model is not a perfect fit for the data, but unfortunately it is not possible to achieve a perfect calibrated model in the timescale of this project. At some point it should be decided that the model does fit the data well enough. Since there is not any spatial data available about the estuary, only the general characteristics can be prescribed, whereas the actual characteristics might be different for different locations in the estuary. Since in this 3D model, physical processes also take place in the dimension of depth, it is very difficult to prescribe these events perfectly, as no specifics are known about these events amongst the different places of the estuary. It must be said however, that the phasing of the model and the amplitude of the ssc on the ebb tide appears to be very consistent with the measurements.

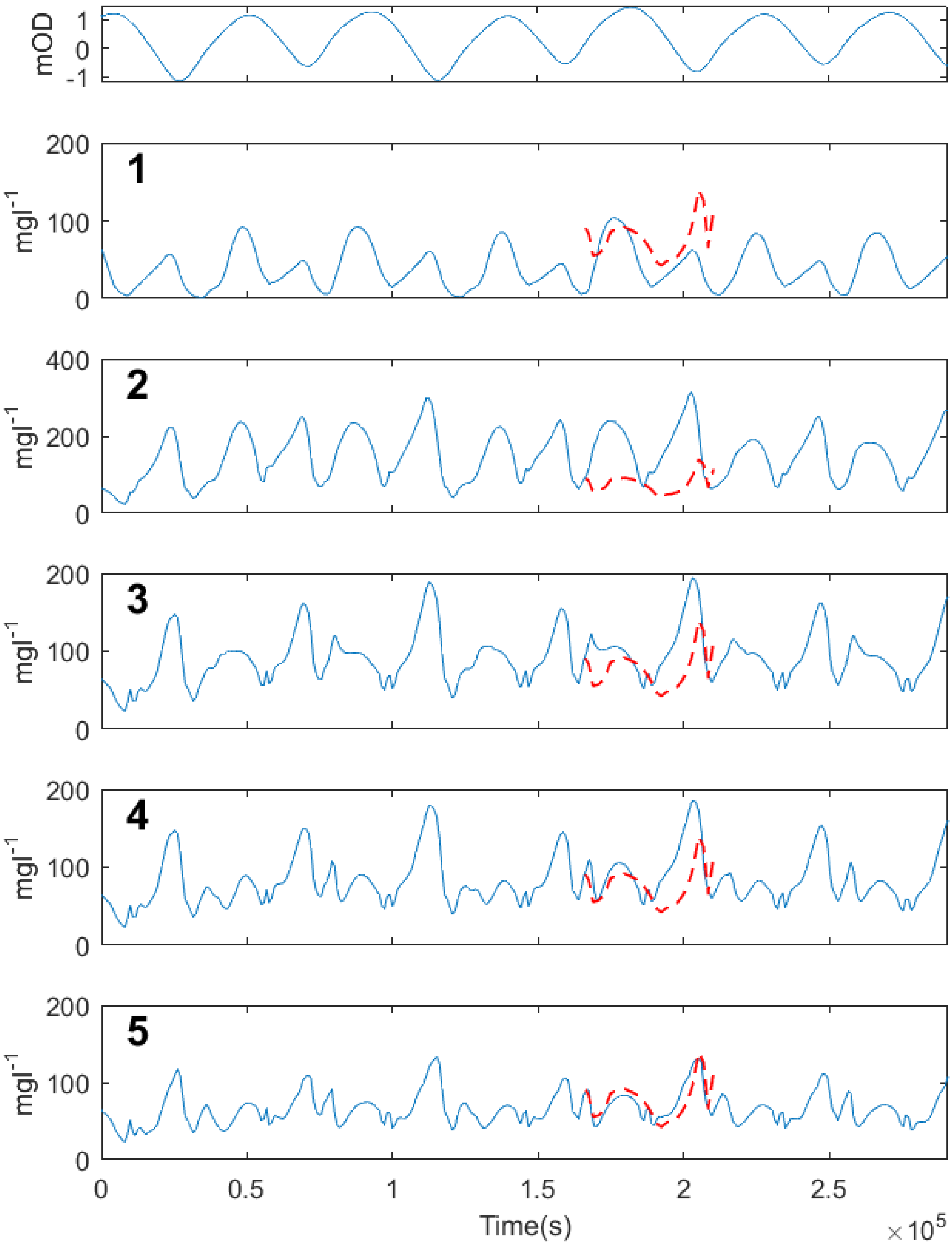

Figure 11: Calibration graphs for each of the five models

6. VALIDATION OF THE MODEL

This chapter describes the validation of the previously calibrated sediment transport model using the neap tide measurements.

6.1. VALIDATION DATA

It was originally planned to validate the modelled ssc against the measurements given in Figure 9, section 4.4. However, it was found that the current speeds from the thesis model during flood tide do not fit the current speeds given in the dataset properly (Appendix B., section 10.2.1, Figure 43). One flood tide later gives a better fit between the modelled and the observed current speeds, therefore these data have been shifted by one tide (12 hours and 29 minutes), as shown in Figure 12.

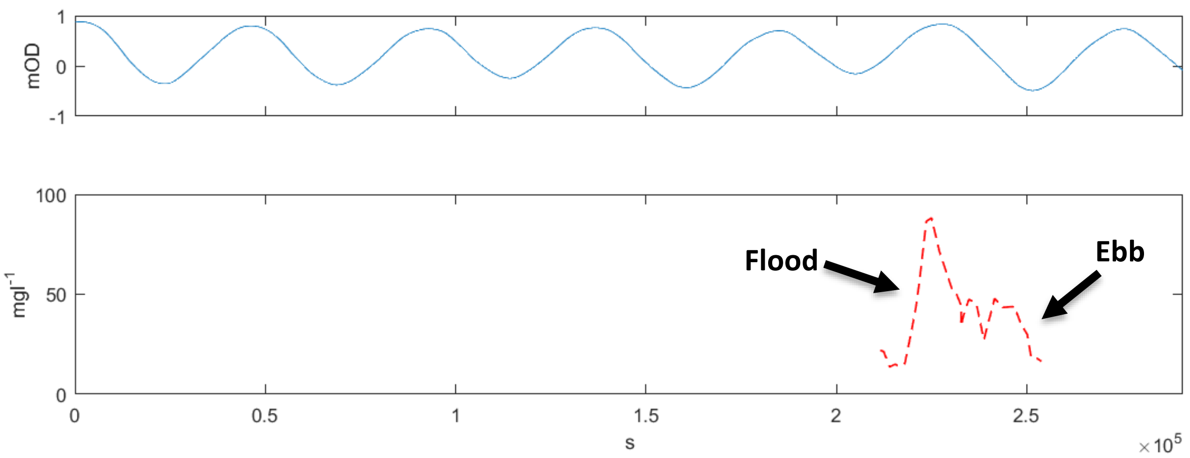

Figure 12: Observed suspended sediment concentration neaps

6.2. VALIDATION MODELS

The validation process has been carried out in five steps, which will be described as five separate models in this chapter. The main aim of the validation is to keep the parameters the same between the calibration and the validation process, such that the same model setup can be used for the two different tidal situations, without altering too many settings. In this thesis project the model has been calibrated for the spring tide data and will in this chapter be validated for the neap tide data. The added features in every model run are shown in Table 9. Once again, for every model, the changes are made sequentially, in addition to the changes made to the preceding run. Note that apart from the changes described all other parameters are the same as used for the spring tide calibration model (as described in section 0). The results of each validation can be seen in Figure 13 at the end of this chapter.

Table 9: Validation settings

Model #	Title	Change
Validation model 1	Initial model set up	This model uses the calibration settings, with the ssc and elevation for the neap tide.
Validation model 2	Increased ssc	In this model, the ssc at the seaward boundary is scaled according to a lower discharge at the mouth to give a maximum ssc of 100 mgl^{-1} at a peak discharge of 120 m^3s^{-1} (approximately the peak neap tide discharge).
Validation model 3	Spatially varied critical shear stress for erosion based on neap tide hydrodynamics	In this model, a spatially varied critical shear stress for erosion (bed plane 2) is recalculated for neap tide flow conditions. Its lower limit is 0.2 $kgm^{-2}s^{-1}$.
Validation model 4	Spatially varied critical shear stress for erosion for neap tide with an increased lower limit	In this model, the lower limit of the spatially varied critical shear stress for erosion is set to 0.4 $kgm^{-2}s^{-1}$.
Validation model 5	Thickness sediment layer channel	In this model the thickness of the sediment layer of the channel is set back to 0.2 m.

6.2.1. VALIDATION MODEL 1 – CALIBRATION SETTINGS

The first model mainly uses the same settings as the final model from the calibration process (Calibration model 5). The ssc at the seaward boundary is changed to 60 mgl^{-1}, which is the same as used in the PhD model. A new liquid boundary file is used as well, as the elevation has changed due to the use of neap tide data.

As can be seen in Validation model 1 in Figure 13, the modelled ssc is a lot lower than the observed ssc. This could be due to the fact that the peak neap ssc at the mouth (at peak flood tide discharge) is 60 mgl^{-1} instead of the 100 mgl^{-1} used for the spring tide calibration. It could also be due to the fact that the spatially varied critical shear stress for erosion is too high, so not a lot of sediment transport is going on.

6.2.2. VALIDATION MODEL 2 – INCREASED SSC

As the ssc at the seaward boundary was set to 100 mgl^{-1} in the calibration model for the spring tide, this is done for the validation model as well. As described in section 5.3.4, the ssc at the tidal boundary is prescribed relative to tidal discharge during the flood tide. Therefore, to achieve the same peak ssc as the spring tide model, the peak neap tide discharge (120 m^3s^{-1}) is used as the value at which the ssc reaches 100 mgl^{-1}.

In Validation model 2, it can be seen that the correctness of the modelled data compared to the observed data has increased qualitatively by changing the ssc at the seaward boundary. The conclusion can be drawn, that the North Sea probably has a sediment concentration of 100 mgl^{-1}, during both spring and neap tide (although there are no measurements available to verify this).

6.2.3. VALIDATION MODEL 3 – SPATIALLY VARIED CRITICAL SHEAR STRESS FOR EROSION – NEAPS

Up until now a spatially varied critical shear stress for erosion used for the spring tide calibration model, has been used. Since there are high current speeds during the spring tide, the shear stress is very high at some locations. The spatially varied critical shear stress for erosion for the spring tide calibration ranged in value between 0.2

$kgm^{-2}s^{-1}$ to 2.51 $kgm^{-2}s^{-1}$. However, since the current speeds are lower during the neap tide, the critical shear stress for erosion may be reduced as well, since no erosion will take place when the critical shear stess is set too high (this will be discussed further in section 7.1.1). The lower limit is still 0.2 $kgm^{-2}s^{-1}$, which is the same as for spring tide, but the upper limit is reduced to 0.80 $kgm^{-2}s^{-1}$ (Appendix B., section 10.2.2, Figure 44).

In Validation model 3, Figure 13, it can be seen that the ssc has increased for some periods. There is a higher ssc at the beginning of the flood tide, which actually makes the model slightly worse qualitatively, than Validation model 2. However, the ssc has gone up for the ebb, which is an improvement of the model. Since the critical shear stress for erosion is now lower at many places, more erosion is going on, which is, in this case, favourable for the ebb tide.

6.2.4. VALIDATION MODEL 4 – SPATIALLY VARIED CRITICAL SHEAR STRESS FOR EROSION WITH LOWER LIMIT 0.4 $KGM^{-2}S^{-1}$

Since the new spatially varied critical shear stress for erosion in Validation model 3 gave too high values at the beginning of the flood tide, and also during the neap tide, the lower limit of the critical shear stress for erosion has been set to 0.4 $kgm^{-2}s^{-1}$ (Appendix B., 10.2.2, Figure 45). This is two times the value used in validation model 3 and reduces the ssc in the estuary. As can be seen in Figure 23, for Validation model 4 the sediment at the beginning of the flood tide is reduced, as well as the concentration during the ebb tide. As can be seen in this model, the slope at the beginning of the flood tide matches the data very closely. There is just not enough erosion going on at the flood tide and at the end of the ebb tide, this problem may be solved by adjusting the thickness of the sediment layer.

6.2.5. VALIDATION MODEL 5 – INITIAL THICKNESS SEDIMENT LAYER CHANNEL

For the spring tide calibration model, the initial thickness of the sediment layer in the channel and on the saltmarshes was set to 0.0 m. However, since the current speeds at neap tide are lower than at spring tide, a sediment layer will be formed in the channel. Therefore, the initial thickness of the sediment in the bottom layer of the channel has been set to 0.2 m for neap tide again. The situation on the saltmarshes does not change, since there is still vegetation in these regions which prevents the sediment from eroding (Appendix B., section 10.2.3, Figure 46).

The sediment in the channel causes higher peaks, since now there is sediment in the channel to erode. The peak on the flood tide fits the data very well, and also the modelled ssc concentration on the ebb tide is better than in the previous models.

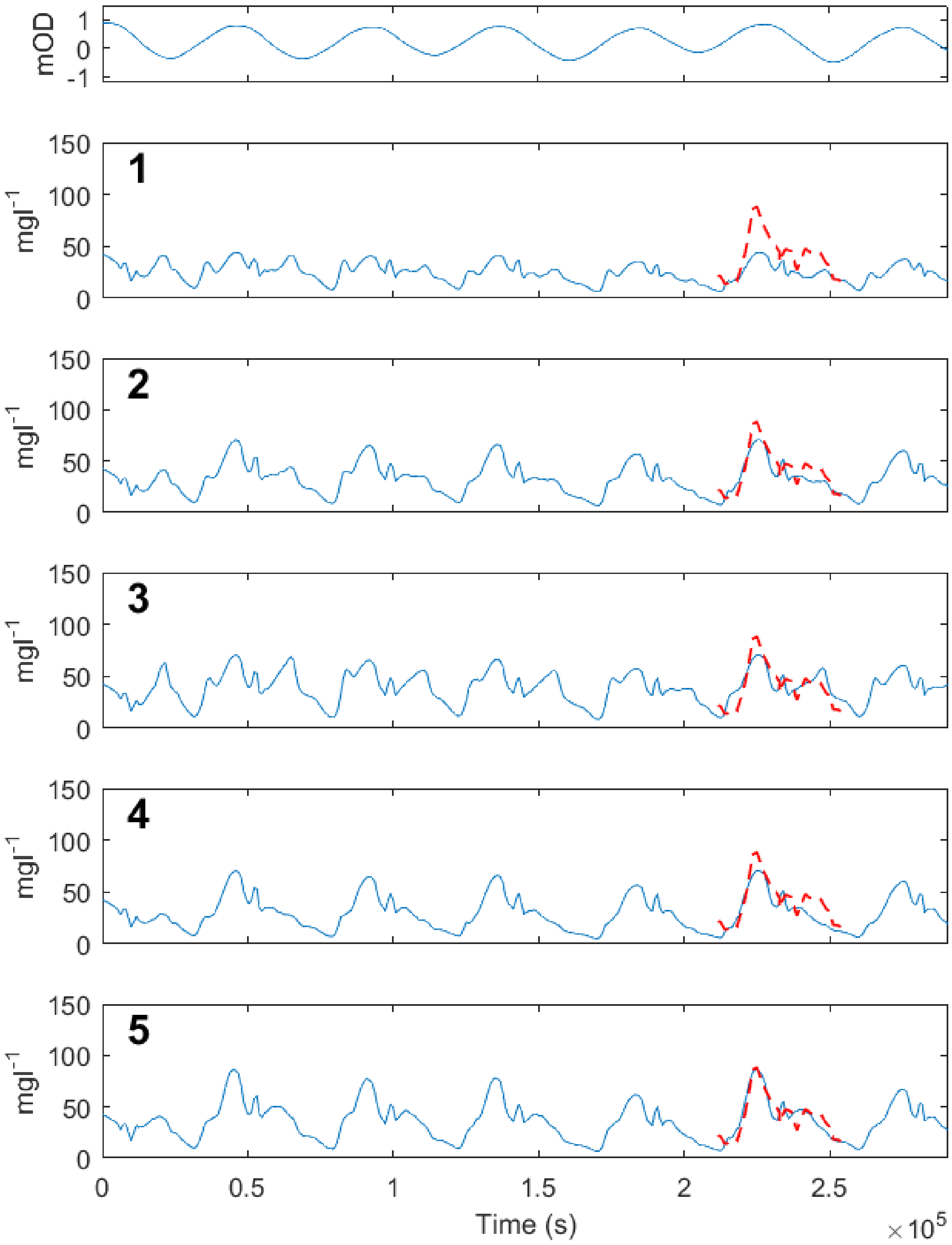

Figure 13: Validation graphs for each of the five models

7. COMPARISON OF MODEL RESULTS

In this chapter the settings from the calibration and the validation period, and the differences between these two periods will be compared and discussed.

7.1. COMPARISON OF CALIBRATION AND VALIDATION SETTINGS

The calibration and validation models both use the same parameter settings, as can be seen in Table 10. This is quite interesting, because it means that besides a different spatially varied critical shear stress for erosion and initial thickness of the second bed layer, nothing has changed between the models. Therefore, it can be concluded that the estuary bed does change between the spring and the neap tide.

Table 10: Comparison parameter settings calibration and validation

Parameter	Unit	Calibration	Validation
SSC SEAWARD BOUNDARY	[mgl^{-1}]	100	100
FLOCCULATION	[-]	Yes	Yes
EROSION COEFFICIENT	[$kgm^{-2}s^{-1}$]	8.E-5	8.E-5
NUMBER OF SEDIMENT BED LAYERS	[-]	2	2
READ CRITICAL BED SHEAR STRESS PER LAYER	[-]	Yes	Yes
CRITICAL EROSION SHEAR STRESS OF THE MUD LAYERS	[$kgm^{-2}s^{-1}$]	0.05;0.2	0.05;0.2
CRITICAL SHEAR STRESS FOR DEPOSITION	[$kgm^{-2}s^{-1}$]	1000	1000
INITIAL THICKNESS OF SEDIMENT LAYERS	[m]	0.0;0.2	0.0;0.2
MUD CONCENTRATIONS PER LAYER	[kgm^{-3}]	500.0;500.0	500.0;500.0

7.1.1. SPATIALLY VARIED CRITICAL SHEAR STRESS FOR EROSION

The spatially varied critical shear stress for erosion does change for the spring and the neap tide, as can be seen in Table 11.

Table 11: Spatially varied critical shear stress for erosion - limits

	Lower limit	Upper limit
Spring tide	0.20 $kgm^{-2}s^{-1}$	2.51 $kgm^{-2}s^{-1}$
Neap tide	0.40 $kgm^{-2}s^{-1}$	0.80 $kgm^{-2}s^{-1}$

When the bed is not corrected for a spatially varied critical shear stress (Calibration model 3, section 5.3.3), the resulting rates of erosion are too high on the spring flood tide. Therefore, a spatially varied critical shear stress for erosion was used for the second layer.

The difference in the *upper* limit of critical shear stresses for erosion between the spring and the neap tide (given in Table 11), is caused by the higher current speeds during the spring tides. The larger tidal ranges, and hence higher current speeds, lead to higher shear stresses exerted on the estuary bed. Consequently, more bed material is both eroded and deposited each tide during the springs. In addition, the slack water period is shorter on spring tides than on the neap tides (Appendix C., section 10.3.1, Figure 47), which means the sediment spends less time on the bed and therefore does not have time to consolidate. At slack water during spring tides this results in the formation of a relatively thick, low density (or *fluffy*), top layer of mobile sediment as compared with the neap tides. Moving from springs into neaps, the reducing shear stresses mean that less of this fluffy top layer is eroded on each consecutive tide. This means that a build-up of soft muddy deposits gradually forms in places where, during springs, there was a hard bed. Hence the upper limit for the erosion threshold is reduced during neaps.

The increase in the *lower* limit for the erosion threshold during neap tides can be explained by consolidation. In the run-up to neaps, the longer residence time of the mud in the bed, means it is allowed time to consolidate. Therefore, it becomes harder to erode the sediment. The lower limit for the erosion threshold for this mud layer is therefore higher than for the spring tides. This explains the difference in the lower limits for the spring and the neap tide, i.e. the mud is generally more consolidated during the neaps. During the spring tide again, the current speeds rise again, such that sediment is eroded due to the high shear stresses exerted on the estuary bed, thus completing the cycle. A schematic drawing is shown in Appendix C, section 10.3.2, Figure 48.

This suggests that perhaps more layers in the bed model are required, with a consolidation model to move sediment down to the lower, more resistant, layers over time. However, it was not possible to test this in the time frame of this project.

7.1.2. INITIAL THICKNESS SEDIMENT LAYER – CHANNEL

Since the current speeds on the neap tide are lower than those on the spring tide, sediment will settle down in the channel during the neap tide. This sediment also erodes again, so more sediment is moved around in the channel during neap tide. It is assumed that during the spring tide the current speeds in the channel are very high, and will therefore erode all in the sediment in the channel, such that only a hard, non-erodible layer, bed layer is left.

7.2. QUANTIFICATION OF THE MODEL ERRORS

To quantify the model errors and therefore its performance, the tests as explained in chapter 3 will be used.

7.2.1. QUANTIFICATION OF THE MODEL ERRORS – CALIBRATION

The model results of the calibration process are listed in Table 12.

Table 12: Quantification of the model errors - Calibration

	Calibration model 1	Calibration model 2	Calibration model 3	Calibration model 4	Calibration model 5
Setup	Initial model with the default settings.	Parameterization of the model.	Spatially varied critical shear stress for erosion.	Variable ssc at the seaward boundary.	Thickness of the sediment layer in the channel and at the saltmarshes has been set to 0.0 m.
Bias	-29.74	103.45	26.21	20.94	-2.16
RMSE	46.19	129.98	44.22	39.21	18.11
BSS	-2.07	-30.64	-2.58	-1.78	0.49
Qualification BSS	Bad	Bad	Bad	Bad	Fair
Alpha	0.06	3.5E-03	0.13	0.19	0.53
Beta	0.97	8.83	1.25	1.03	0.04
Gamma	1.17	21.90	1.48	0.94	2.0E-3
Epsilon	2.8E-03	2.8E-03	2.8E-03	2.8E-03	2.8E-03

It is interesting to see that the parameterization did not have a positive effect on the model, as can be concluded from the statistics. However, this parameterization was needed to get the right sediment proportions between the flood and ebb tide. After the parameterization the model's performance got better to an ultimate BSS of 0.4924.

The applied spatially varied critical shear stress for erosion in Calibration model 3 improves the model massively, with a BSS improved from -30.64 to -2.58 All the segments of the BSS have been improved. In Calibration model

2 there was an overall critical shear stress of 0.2 $kgm^{-2}s^{-1}$, with too high values for the ssc. In Calibration model 3, this value has been increased at places where a lot of erosion was going on, resulting in less erosion occurring in these places and therefore a lower ssc.

In Calibration model 4, a variable ssc on the seaward boundary was implemented. This especially improved the gamma, the average value for the ssc.

In Calibration Model 5, the thickness of the sediment layer in the channel and on the salt marshes has been set to 0.0 m. Unfortunately, the BSS of this model is the only positive number for the calibration models. This BSS is not as high as hoped, since the qualification of its value according to Table 3 is 'Fair'. This might be due to the fact that the value for alpha is only 0.53, whereas a value of 1 means perfect modelling of the phase. This means that there is still a significant phasing error in the model.

7.2.2. QUANTIFICATION OF THE MODEL ERRORS – VALIDATION

The model results of the validation process are listed in Table 13.

Table 13: Quantification of the model errors - Validation

	Verification model 1	Validation model 2	Validation model 3	Validation model 4	Validation model 5
Setup	Initial model with the settings from calibration but with a ssc from neap tide.	Increased ssc at the seaward boundary.	Spatially varied critical shear stress for erosion for neap tide with a lower limit of 0.2 $kgm^{-2}s^{-1}$.	Spatially varied critical shear stress for erosion for neap tide with a lower limit of 0.4 $kgm^{-2}s^{-1}$.	Initial thickness of sediment layer in the channel is set back to 0.2 m.
Bias	-15.48	-4.27	0.88	-6.50	0.08
RMSE	20.03	10.58	11.71	12.19	9.45
BSS	-9.7E-3	0.73	0.67	0.61	0.81
Qualification BSS	Bad	Good	Good	Good	Excellent
Alpha	0.73	0.80	0.69	0.76	0.82
Beta	0.16	9.3E-3	0.01	7.17E-04	0.01
Gamma	0.58	0.06	7.3E-3	0.14	1.26E-04
Epsilon	2.09E-04	2.09E-04	2.09E-04	2.09E-04	2.09E-04

The overall performance of the validation model is good, with an even excellent final model. Only the very first model with a negative BSS is bad, but the rest is good. It is notable that especially an increased ssc at the seaward boundary improves the model quite a lot.

Though the alpha, and therefore the phase error does not significantly change between Validation model 1 and Validation model 2, the beta and gamma are improved significantly between these two models. This means that a higher ssc has a positive impact on the amplitude and the average ssc value, which seems reasonable with a higher ssc entering the estuary.

It seems that the applied spatially varied critical shear stress for erosion in Validation model 3 worsens the model, looking at the RMSE and BSS. However, the gamma has actually improved, which means that the modelled average ssc is more accurate than in Validation model 2.

Setting a higher lower limit for the spatially varied critical shear stress for erosion in Validation model 4, only impacts the alpha and beta positively. Therefore, it can be concluded that the model has better phasing and that is amplitude is more accurate. This improvement of phasing can be explained by the fact, that due to the increased lower limit for the spatially varied critical shear stress for erosion, sediment only erodes further upstream. So when the tide turns around, it takes longer for this sediment to reach the data extraction point than the sediment further downstream the estuary. Since this sediment further downstream has not eroded, and therefore does not pass the data extraction point, the ssc peak is slightly shifted to a later period. This gives better phasing and therefore a better value for the alpha. This shifting of the ssc also explains the improvement of the beta, the amplitude.

The adding of sediment in the channel in the last model, gives the model an excellent value for the BSS. Due to the availability of sediment in the channel, more sediment is moved around resulting in larger peaks in the model. The phasing and average of the model have both been improved, whereas the amplitude error is slightly worse than in the previous model. Especially on the ebb tide the model exceeds the data, causing a worse score for the amplitude. Overall it must be concluded that the neaps model is an excellent fit to the data.

7.3. COMPARISON OF THE 2D AND 3D MODEL RESULTS

The research aim of this bachelor thesis was formulated as following:

To calibrate and validate a 3Dimensional mud model with field data for the Blyth estuary (Suffolk, UK) and determine if the 3D model is an improvement to the existing 2D model.

In Table 14 the model results of the 2D and 3D model are displayed. For every model error quantification parameter, the 2D result is compared to the 3D result, after which the best result is coded with a green colour, and the worst with a red colour. This is done for both the spring tide and the neap tide.

Table 14: Comparison of the 2D and 3D model results

Model	Springs (calibration) (Appendix C., section 10.3.4, Figure 49)		Neaps (validation) (Appendix C., section 10.3.4, Figure 50)	
	2D	3D	2D	3D
Bias	-0.42	-2.16	11.58	0.08
RMSE	17.23	18.11	18.51	9.45
BSS	0.54	0.49	0.26	0.81
Qualification BSS	Fair	Fair	Bad	Excellent
Alpha	0.61	0.53	0.72	0.82
Beta	0.07	0.04	0.11	0.01
Gamma	1.6E-3	2.0E-3	0.34	1.26E-04
Epsilon	2.8E-3	2.8E-3	2.09E-04	2.09E-04

As can be clearly seen above, the 2D model gives better results for the spring tide, whereas the 3D model gives a better estimation for the neap tide.

7.3.1. COMPARISON SPRING TIDE

The 2D model gives better results for the spring tide than the 3D model. However, the difference between the models is not very large, with the RMSE less than 1% of the measured concentrations, and the values which quantify the model errors are close to each other for the 2D and the 3D model. Both the models slightly under-predict the data and have almost the same RMSE. Earlier it was concluded that the 3D model does not give a good or excellent value for the BSS, which is surprising, because as far as can be seen by the bare eye, the model fits the data fairly well. However, the 2D model only gives a slightly better result for the BSS, so it is not necessarily a fault in the 3D model, which results in a fair BSS value. It is interesting to see that the 2D model has a higher value for alpha, which means that the 2D model has a better phasing than the 3D model. However, the 3D model has a beta which is halve as large as the beta for the 2D model. The beta denotes the amplitude error, which means that the 3D model estimates the volume of the ssc better than the 2D model. In both the 2D and the 3D model, the gamma has a higher value than 0, which means that that the modelled average ssc is different from the observed ssc.

7.3.2. COMPARISON NEAP TIDE

First of all, it should be noted that the data for the flood tide during the neap tide, has been shifted by one tide when the 3D model was validated for the neap tide. This has been done, because the modelled current speeds for this tide were a better fit to the data than one tide earlier. However, this has not been done for the 2D model, which means that this model has been fitted for one flood tide earlier. Both the 2D and 3D model in this chapter are compared to the dataset used for the 3D model. This means that the 2D model has been calibrated for a different flood tide than the flood tide to which it is compared in this chapter. This might be the reason why the 2D model does not give good overall results.

The bias of the 2D model is fairly high, which means that the model over predicts the data. The RMSE for the 3D model is halve the value of the RMSE for the 2D model. This means that the overall error in the 2D model is higher than the error in the 3D model. The BSS for the 2D model is bad, but this might be due to the fact that the 2D model has been fitted to a different tide, with lower current speeds, than used for the 3D model. The phasing of the 2D model is worse than the phasing of the 3D model, though a value of 0.72 does not seem to be too bad. However, the beta and the gamma of the 2D model are a lot higher and therefore worse than those of the 3D model. This means that the volume of the ssc in the 2D model is considerably different than the data and the 3D model. The difference in the gamma means that the average ssc value in the 2D model is significantly than the data and the 3D model.

7.3.3. CONCLUSION COMPARISON

It is concluded that the 3D model is a better fit for the neap tide but a worse fit for the spring tide compared to the 2D model.

That the 3D model is a worse fit for the spring tide, may be due to the fact that the 3D model is more simplistic compared to the 2D model. In the 2D model the estuary was split up in zones (Appendix C. section 10.3.5, Figure 51). These zones had their own critical shear stress for erosion, such that it was very well prescribed where erosion and deposition would happen, such that the model fitted the data as good as possible. Since the 3D model has not been split up in zones and uses a spatially varied critical shear stress for erosion without zonation, instead of a critical shear stress per zone, the 3D model does not fit the data as well as the 2D model. However, as can be seen in Table 14, the 2D model is only slightly better with a slightly lower RMSE and a higher BSS. Therefore, it can be concluded that the 3D model is a good fit to the data regarding the fact that the 3D model is a lot more simplistic than the 2D model.

That the 3D model is a better fit to the neap tide than the 2D model, might be due to the fact that the 2D model has been fitted for one flood tide earlier. This flood tide had lower current speeds, so less sediment was entering the estuary. Therefore, the other parameters have been set to compensate for the lower current speeds, such that the ssc of the model during this specific flood tide fitted the data. Now the model is rerun with the same parameter settings but with higher current speeds. This causes the overall ssc in the estuary to be too high.

7.4. ANALYSIS OF STRONG AND WEAK POINTS OF THE MODEL

In this chapter the strong and the weak points of the model and the measured data are discussed. In Table 15 the strong and the weak points of the model and the measured data are presented. These points have not been quantified by a value, because these points are very different in their nature and cannot easily be compared to one another.

Table 15: Strong and weak points of the model

Strong points	Weak points
There are no differences in the parameter settings for the springs and neaps. Only the spatially varied critical shear stress for erosion and the thickness of the second layer vary.	There is not a lot of spatial knowledge about the estuary. All the measurements have been done in one place, but there is no specific knowledge about the estuary bed.
The model gives a fair BSS result for the spring tide and a good BSS result for the neap tide. Though the outcome for the spring tide is slightly disappointing, it should be noted that no further improvement was possible in the time span of this BSc thesis project. When the BSS for the spring tide is put in this perspective, the given score is good enough. On the other side, the BSS for the neap tide is excellent and therefore the scores for the model can be mentioned as a strong point.	The exact place from where the measurements were taken stays unknown. The data extraction point in the model is about the same as where the measurements were taken in the field. Though model data has been extracted from different locations in the channel to find the best place according to the field data measurements, the exact location stays unknown.
The 3D model is a better fit for the neap tide data than the 2D model.	The 3D model is a worse fit for the spring tide data than the 2D model.
The model is in equilibrium with no significant net build up or loss of sediment from the bed occurring. The only entrance and exit is the channel from the estuary to the North Sea.	No specific knowledge about the North Sea has been found, regarding the suspended sediment concentration. In this model the ssc at the seaward boundary is a parameter used to parameterize the model with. Though this parameter stays the same for both the springs and the neaps, there is no foundation for this value other than the calibration.
	The weather conditions have not been taken into account in this model. When there is a storm and there are high wind velocities, more sediment will move around because of higher waves occurring both at the mouth of the estuary at the North Sea and in the estuary.

The model gives good overall results for the calibration and the validation process. From the analysis done above, it can be concluded that points mentioned as strong point, mainly judge the model’s performance, whereas the weak points mainly regard the input for the model and the uncertainties in the input. From the weak points it can be concluded that the model can be improved by gaining more knowledge about the estuary itself.

8. CONCLUSION AND DISCUSSION

In this chapter the conclusion of this project will be drawn on basis of the research aim. This research aim is formulated as following:

To calibrate and validate a 3Dimensional mud model with field data for the Blyth estuary (Suffolk, UK) and determine if the 3D model is an improvement to the existing 2D model.

This with the ultimate goal to determine the performance of the 3D model compared to the 2D model and whether it was at least as good of a fit to the data.

8.1. CONCLUSION – COMPARISON OF THE 2D AND 3D MODEL

The 3D model is a slightly worse fit for the spring tide data in the calibration phase, but a much better fit for the neap tide data than the 2D model in the validation phase.

With these results, the Brier Skill Score has been calculated. Since the aim if this bachelor thesis is to determine whether the 3D model is an improvement to the old 2D model, the Brier Skill Score for both the 2D and the 3D model is calculated. The Root Mean Square Error is a measure of the volume error between the data and the model, which has been used as well to compare the 2D and 3D model.

Table 16 shows the performance of both the 2D and 3D model for a spring tide and neap tide.

Table 16: Conclusion - comparison of the 2D and 3D model

Model	Springs (calibration)		Neaps (validation)	
	2D	3D	2D	3D
RMSE	17.23	18.11	18.51	9.45
BSS	0.54	0.49	0.26	0.81
Qualification BSS	Fair	Fair	Bad	Excellent

Both the 2D and 3D model provide only a fair fit for the spring data with the 3D model marginally worse than the 2D model. This might be caused by the fact that a lot of sediment transport takes place during spring tide and that too little is known about the estuary. The suspended sediment concentration (ssc) is only measured at one point in the channel, which exact coordinates are unknown. Whereas the 2D model was split up in different zones with different critical shear stresses for erosion, the 3D model is more simplistic with spatially uniform values for the estuary bed. There is not any spatial data available about the model, which makes it very difficult to determine where all the sediment comes from. During the spring tide the current speeds are high and all the sediment is removed from the channel. This is the point where the boundary conditions for the sediment concentrations get important. No information on the sediment concentrations at the seaward end of the model domain is available for the period of the measurements. Therefore, this boundary condition is used as a calibration parameter as a function of the discharge at the boundary. As the concentration will be varying with the tidal and wave conditions, this could be a significant source of the model error, in particular during the flood tide.

The 3D model is an excellent fit to the neap data, whereas the 2D model gives a bad result. The 2D model has originally been fitted to another tide than for which it is tested in this thesis. Due to a shift in the data from the flood tide in the 3D model, the performance of the 2D model has now been tested with the original parameter settings, but against another tide than to which it was fitted originally, with slightly higher current speeds. Therefore, the average value of the ssc in the 2D model is too high compared to the data, which makes it difficult to judge whether the 3D model is actually an improvement compared to the 2D model.

8.2. CONCLUSION – STRONG AND WEAK POINTS OF THE 3D MODEL

Strong points are that there are no parameter changes between the spring and neap tide. Only the spatially varied critical shear stress and the thickness of the sediment layer change between the two tides. Another strong point is that the model is in equilibrium with no significant net build up or loss of sediment from the bed occurring.

A weak point of the model is that there is not much known about the estuary. The ssc only passes one data extraction point and there is no spatial measured information about the estuary, since data measurement were only taken from one location in the channel. Unfortunately, the exact location where the field data have been collected was not recorded in the PhD thesis (section 5.1). The last weak point of the model is that the weather conditions are not taken into account in this model. Since wind will produce higher waves and thus more sediment transport, weather conditions can have a huge impact on the sediment transport and ssc in the estuary.

8.3. CONCLUSION – PERFORMANCE 3D MODEL

From section 7.3 it can be concluded that the 3D model in itself performs really good compared to the 2D model. The 3D model is a more advanced model with an extra dimension, increasing the model complexity and adding a third dimension with additional uncertainties. New features were added to the 3D model over the years, but the model was never properly calibrated and validated. The main difference between the 2D and 3D model is that in the 3D model sediment transport are also computed in the depth dimension, which introduces additional computations in the model making it more complicated. Therefore, it was uncertain whether the 3D model performed as well as the 2D model, let alone that it would be an improvement to the 2D model.

It can be concluded that the 3D model is as good of a fit as the 2D model. Even though it performs slightly worse on the spring tide than the 2D model, possibly due to uncertainties in the model, the model is an excellent fit for the neap tide. The 3D model can possibly be improved by reducing the uncertainties. This could be achieved by collecting more data about the estuary and use those in the calibration. Such as collecting data about the soil type in at different locations in the estuary, and measuring the suspended sediment concentrations at these different locations. Since the boundary conditions could play an important role when the current speeds increase during spring tide, it could also be considered measuring the erosion at the boundaries of the channel during a couple of spring tides, to see how this boundary behaves during high current speeds.

8.4. DISCUSSION

As mentioned in section 7.4 there are still a lot of uncertainties in the model. These uncertainties are listed below:

- The bed composition in the estuary is assumed to be uniform over the entire estuary, which might in reality not be true. The properties of the estuary bed will be different at different locations (and over time).
- The different weather conditions have not been taken into account, though this might have a huge effect on the sediment transport in the estuary. Since no data was taken during a storm, the model could not be calibrated for situations where wave effects are important.
- When high current speeds occur during the spring tide and the channel is eroded out, the boundaries might start to erode as well. However, in this model is assumed that the boundaries do not erode under any condition.
- The exact location of the data extraction point in the channel is still unknown. It has been tried to find the best location, but the exact location is unknown.
- No specific knowledge about the ssc in the North Sea has been found. The concentration of ssc at the seaward boundary has been used as a parameter to calibrate the model with, assuming a relationship

between the discharge and the concentrations. within reality the concentrations are far more variable, depending on tidal velocities offshore, and the prevailing wave conditions.

Another point of discussion is that at some point the model should just be accepted, without it being a perfect fit to the data. Since a lot of physical processes take place in the estuary and only little is known about this estuary, it is almost impossible to model every characteristic of the estuary. This especially is an issue in a bachelor thesis project where there is only a certain time frame to do the modelling. This model has been calibrated as well as possible within the time frame, but it may well be possible to get a better fit, especially for the neap tide period. However, as only limited data is available, one should be careful to avoid over calibration of the model.

9. FURTHER RESEARCH

During this project the problem arose that too little is known about the estuary and there are too many uncertainties in the model. Therefore, the model can easily be improved by doing further research.

First of all, measurements could be taken in the actual estuary instead of one data extraction point in the channel. When more properties are known about the estuary, there will be a better estimate of where all the eroded sediment comes from. This will likely result in better phasing of the model and therefore a more accurate result.

Additionally, it would be useful to do measurement amongst the boundary of the estuary. In this model it is assumed that no erosion takes place amongst the boundary. However, as the flow velocities tend to become very high during the spring tide and the channel is completely eroded out, erosion amongst the boundary might occur in the channel. It would be very interesting to do research in this area, to see what happens to the boundary during spring tide.

Secondly, it would be useful to collect data during a storm surge. Since this might have a huge impact on the model it would be interesting to see how the model and sediment behaves during these extreme weather conditions. However, the model can also be calibrated for less extreme weather conditions. Since the estuary is likely to be exposed to wind, rain and other conditions, it would be useful to model these situations. Especially the wind can have an important impact on the model, since the estuary will frequently be exposed to winds, and winds can produce waves in the estuary. The sediment transport in the estuary will likely be effected by these waves. During windy weather, sediment from the land around the estuary could end up in the estuary, causing more sediment transport.

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10. APPENDICES

Appendix A. Calibration of the model

Appendix B. Validation of the model

Appendix C. Comparison of the model results

10.1. APPENDIX A. CALIBRATION OF THE MODEL

10.1.1. REMESHING

In the model, meshes are used to split up the area into smaller subareas. This makes the model manageable and exact. However, too small meshes will take the model too long to run, therefore there needs to be a consensus between the exactness of the model and the running time. Since the capacity of computers has grown over the years, a finer mesh can be used in this 3D model, compared to the old 2D model. The model is remeshed and a finer mesh has been used in this 3D model than in the initial 2D model. To remesh the estuary, the different zones, as described in section **2.2.1**, need to be distinguished in the model. It is important that the meshes are of the right proportion. They should not be too large or small in volume, but they should also not be too thin and stretched out. Equilateral triangles would be perfect, however, due to the shape of the estuary this cannot be realized. The most important thing about the remeshing, is that the mesh should follow the water streams in the estuary. There should not be a bumpy channel, since this would not be in accordance with the reality.

THE MAIN TIDAL CHANNEL

The main tidal channel, has the highest current speeds. It is important that this zone is very detailed, because there is a large variety of current speeds, and most of the sediment transport takes place in the main channel. The most important aspect of meshing in this zone, is that the mesh gets the shape of the channel right. Since a channel with many sharp edges due to large meshes is undesirable, the sizes of the meshes need to be chosen such that it results in a smooth channel without any sharp edges. The meshes are shown in Figure 18, Figure 19, Figure 20, Figure 21, Figure 22, and Figure 23

FINAL RESULT

The final result of the bathymetry is shown in **Figure 24**. Whereas the old 2D model has some very angular transitions, the transitions in the new 3D model are more smoothly and gradually.

INTERIM SUMMARY

In this chapter, the process of remeshing has been described. However, after this process of improvement, it was revealed that the 2D model which had been improved in this thesis, was an old version of the model. In the final PhD report by T. Benson a more sophisticated version of the 2D model had been used, one that was even better than the newly improved 3D model. This more sophisticated 2D model had a spatially varying critical shear stress for five sedimentary zones in the main tidal channel, and an improved bathymetry of the estuary. This 2D model had been converted into a 3D model, so its outcome could be compared to the outcome of the newly improved 3D model. When the sophisticated 2D and newly improved 3D model were both compared to the observed data, it came to light that the 2D model was a better fit to the data than the 3D model. Therefore, it has been decided that the settings of the old 2D model will be used in this thesis. The mesh that will be used in the 3D model, and was used in the 2D model as well, can be seen in **Figure 26**, at the end of this chapter.

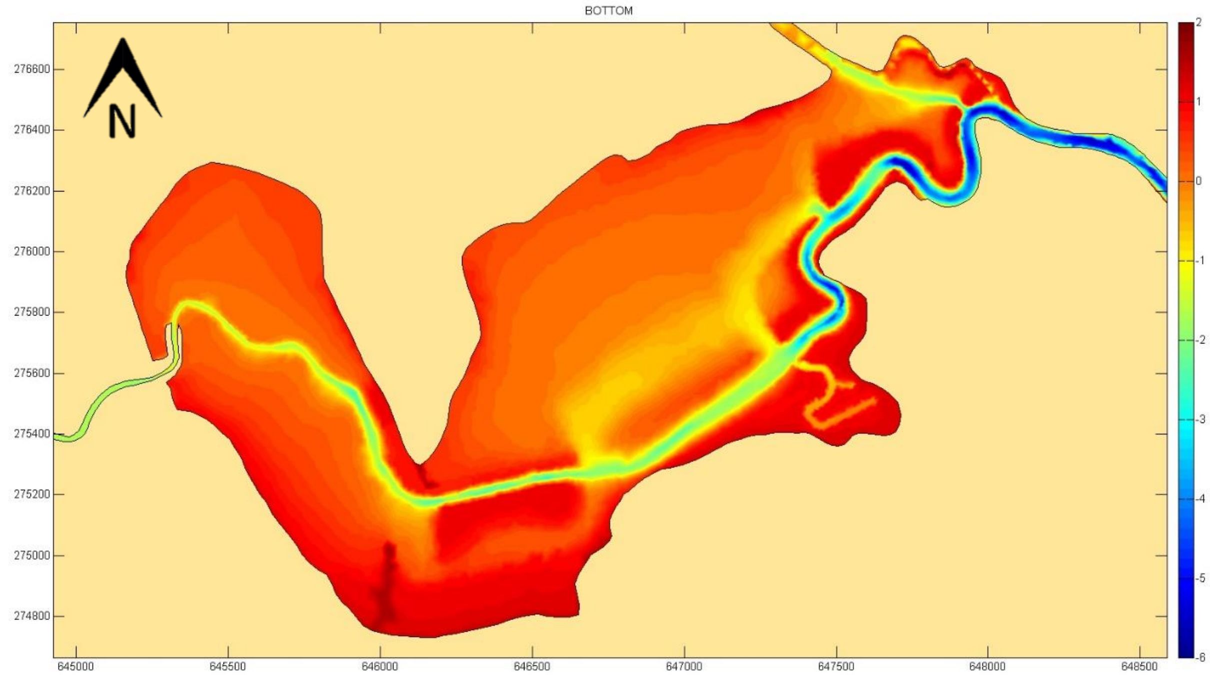

Figure 14: Geometry 2D model (scaling in meters)

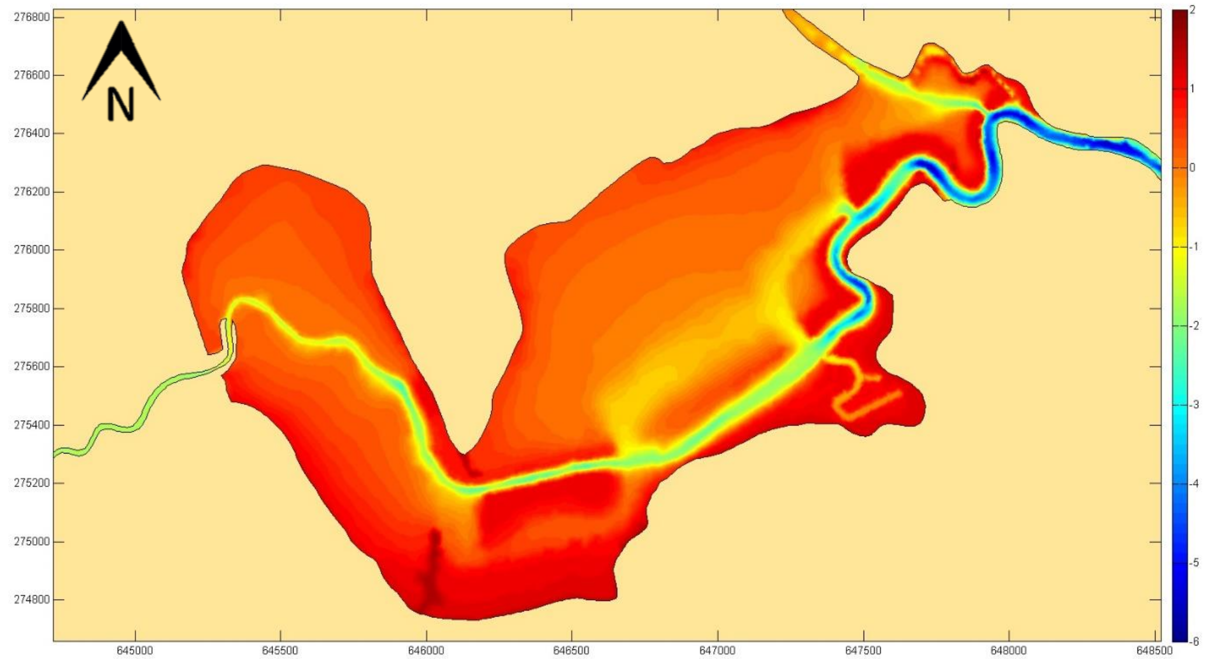

Figure 15: Geometry 3D model (scaling in meters)

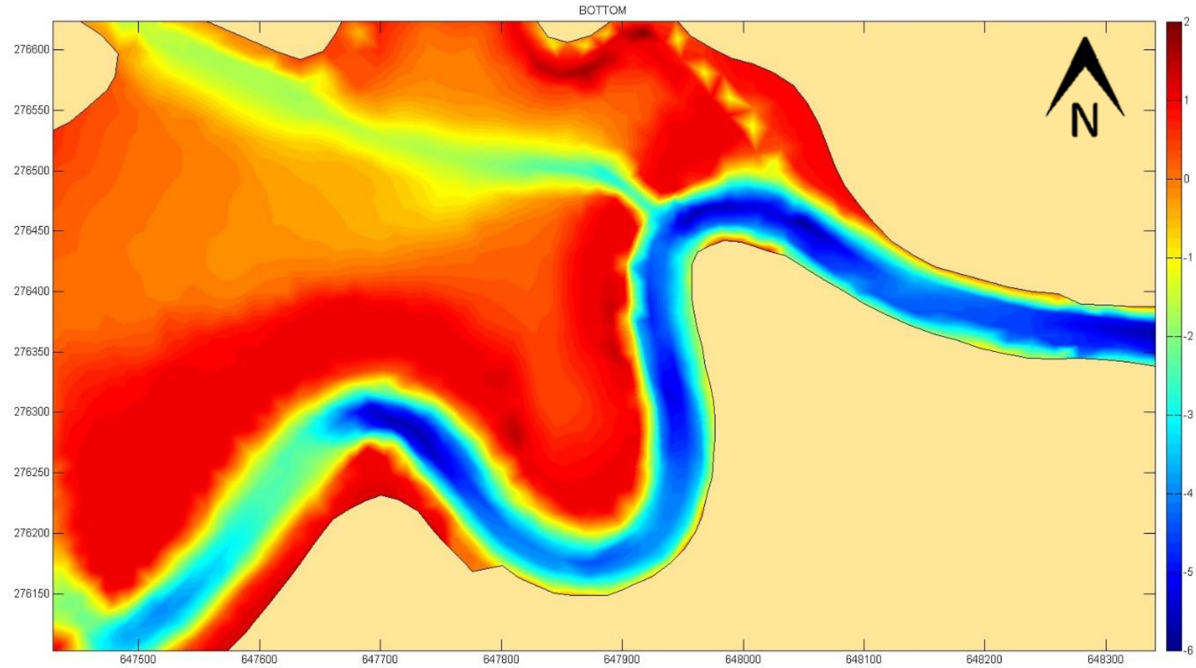

Figure 16: Main tidal channel with sub flow (2D model) (scaling in meters)

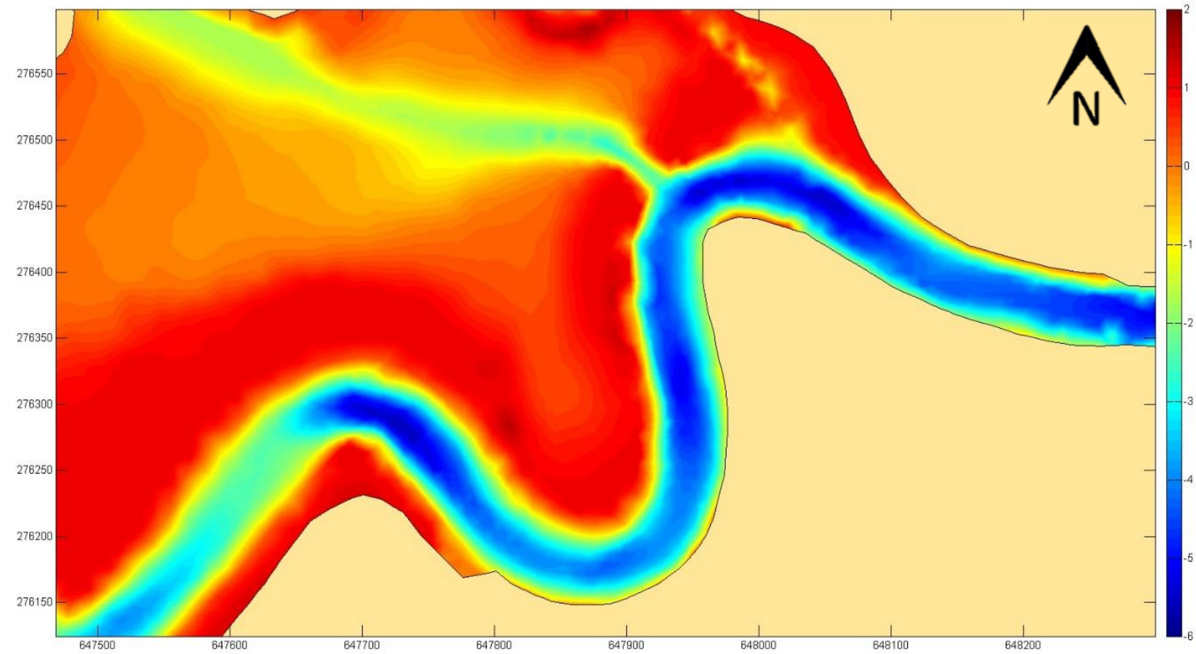

Figure 17: Main tidal channel with sub flow (3D model) (scaling in meters)

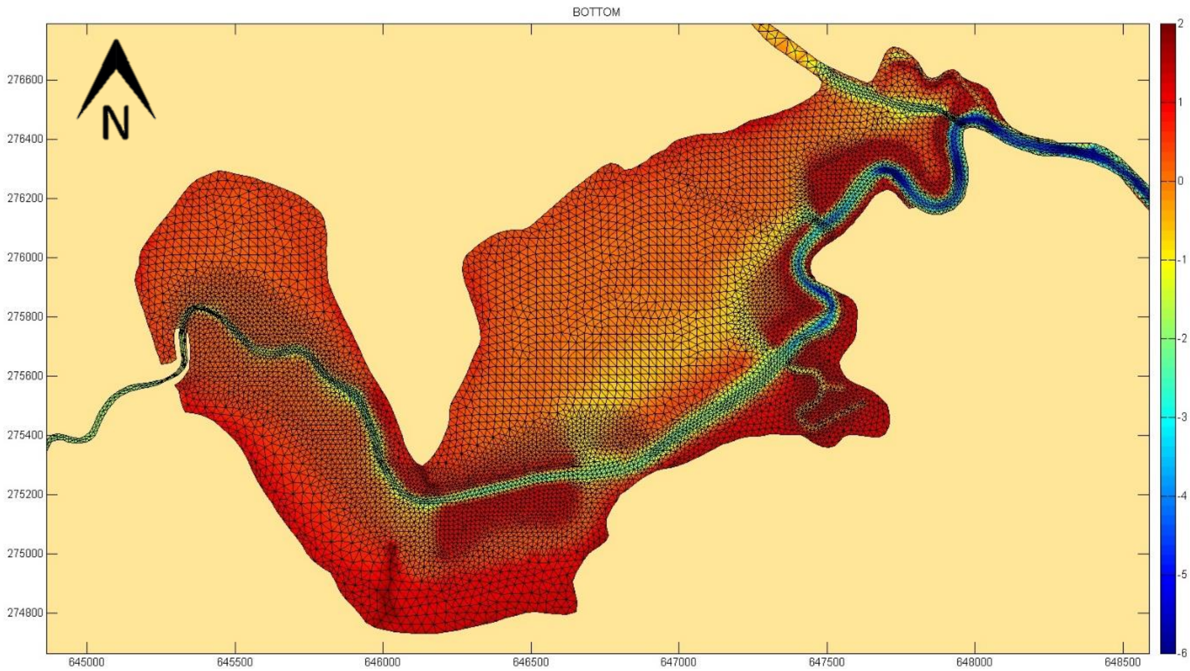

Figure 18: Meshing (2D model) (scaling in meters)

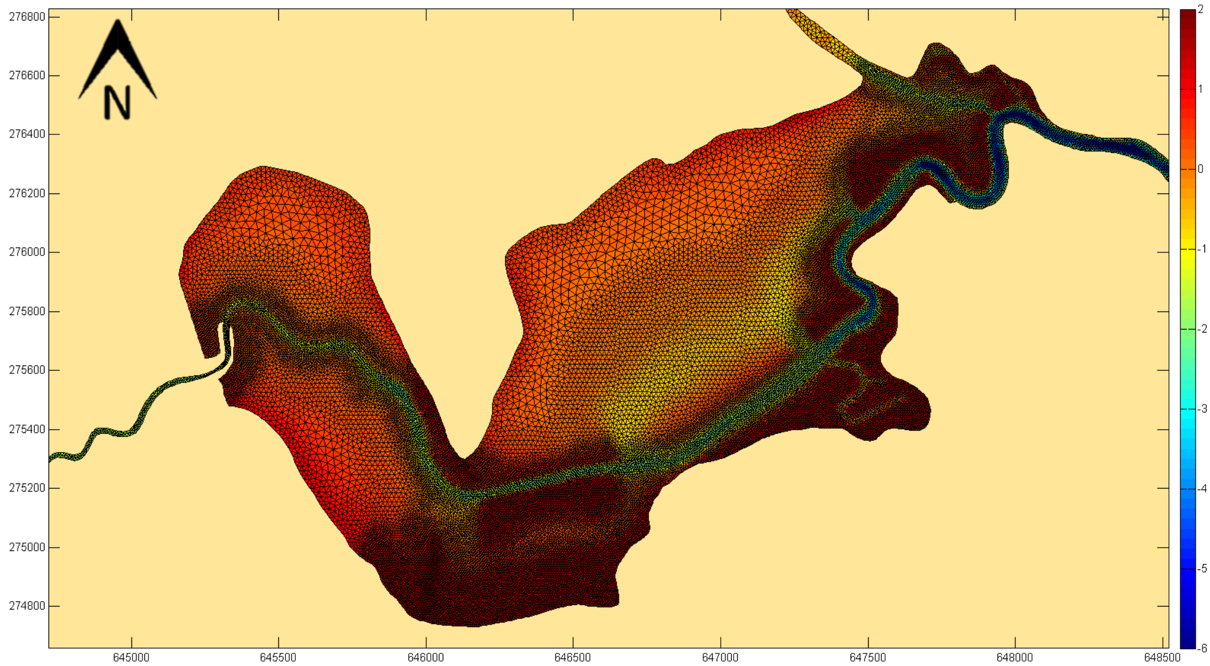

Figure 19: Meshing (3D model) (scaling in meters)

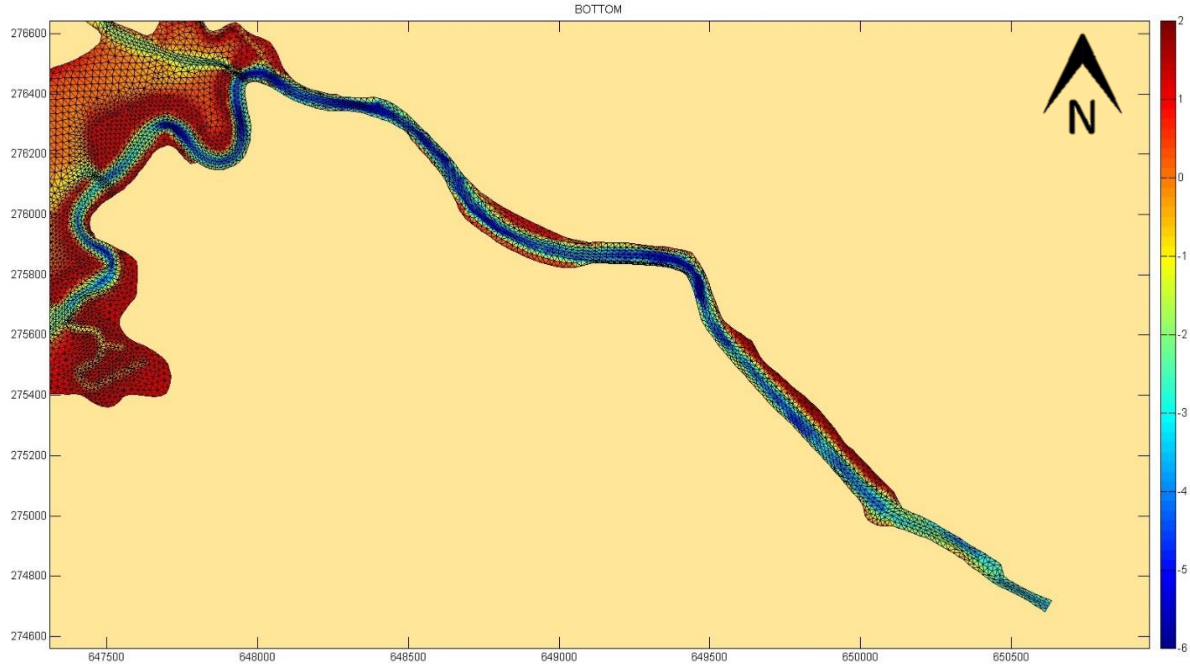

Figure 20: Meshing channel (2D model) (scaling in meters)

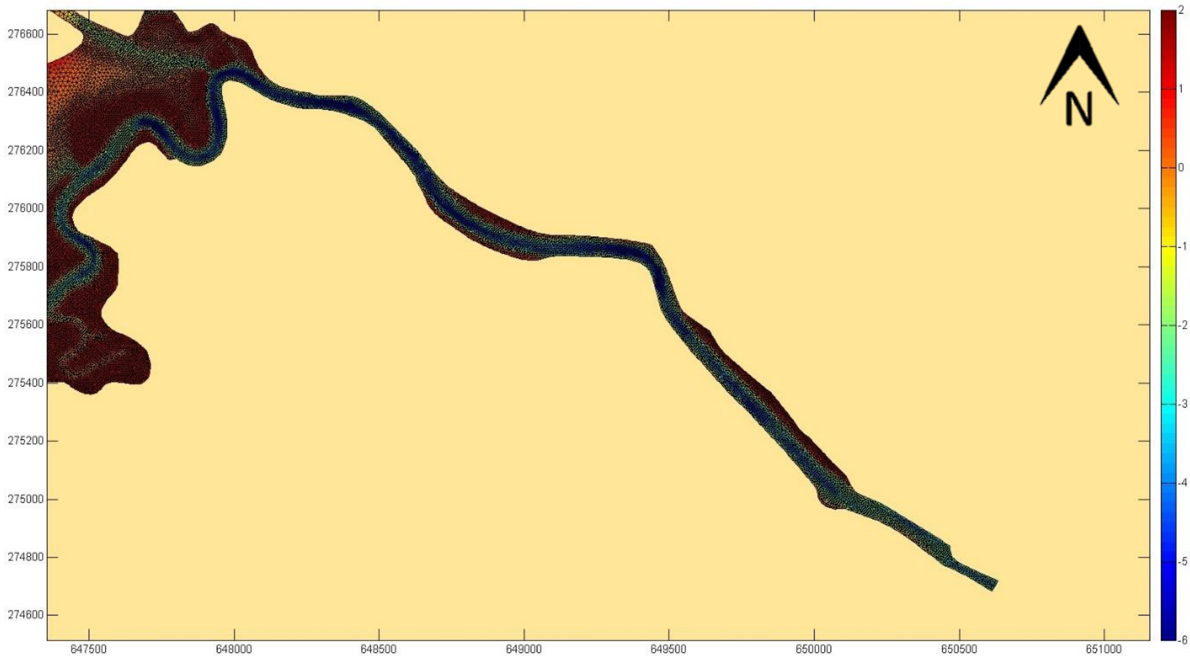

Figure 21: Meshing channel (3D model) (scaling in meters)

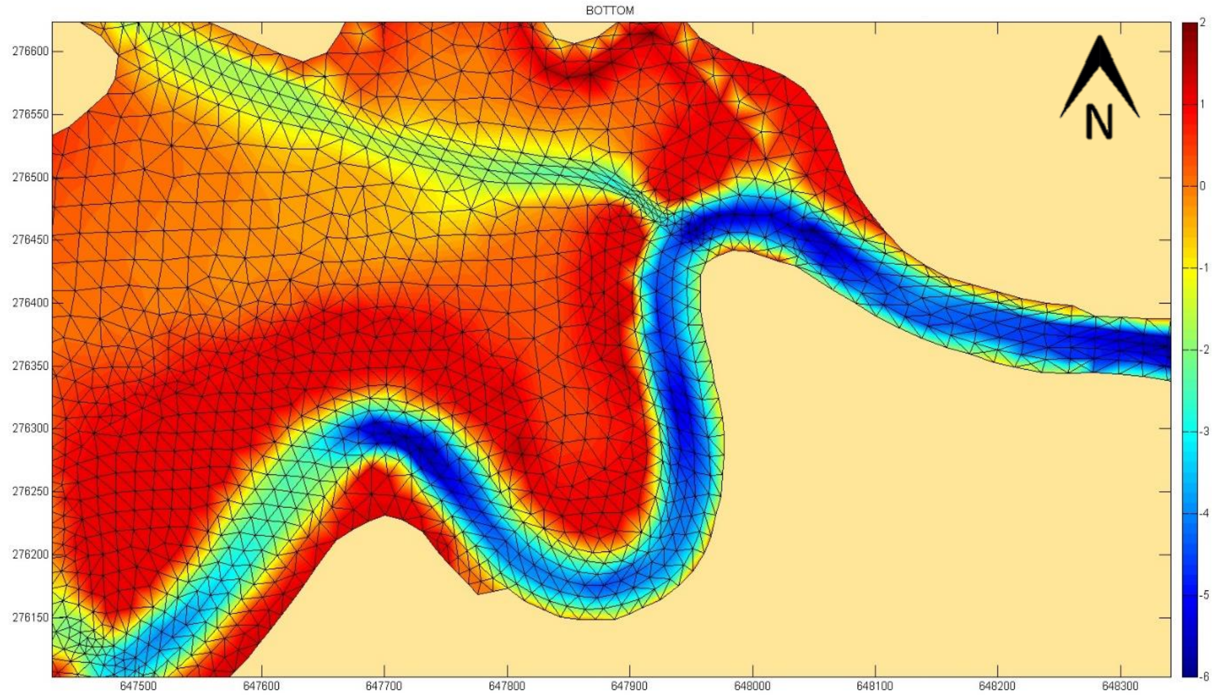

Figure 22: Meshing main tidal channel with sub flow (2D model) (scaling in meters)

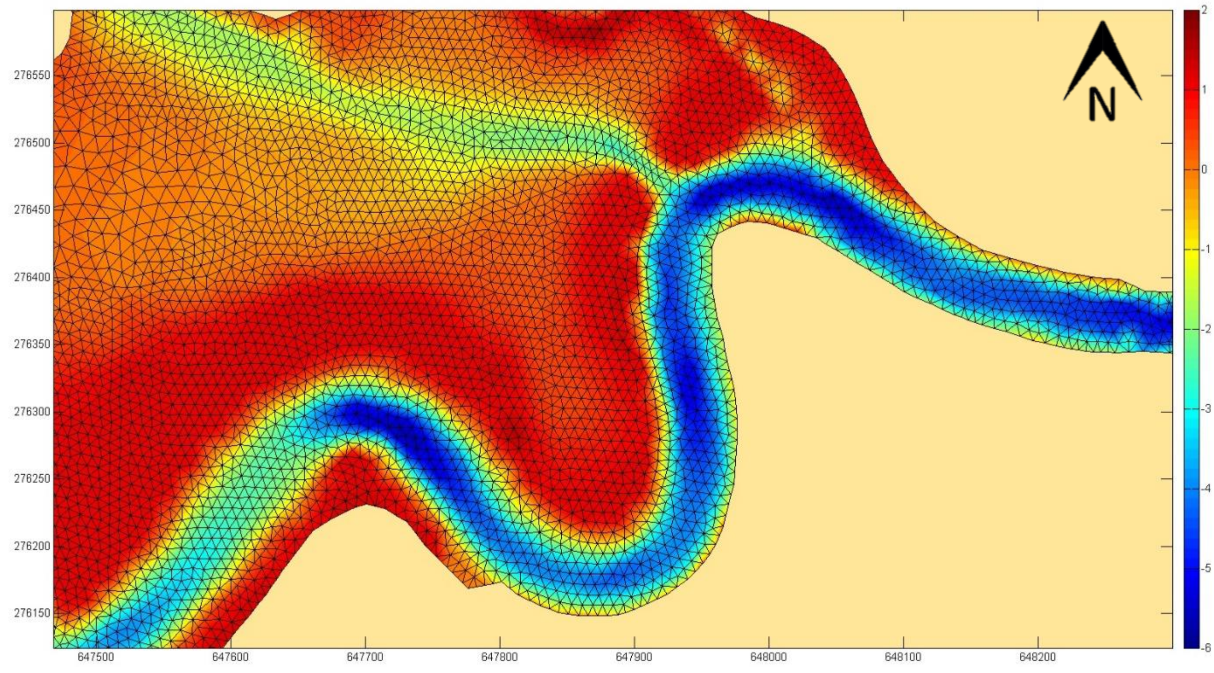

Figure 23: Meshing main tidal channel with sub flow (3D model) (scaling in meters)

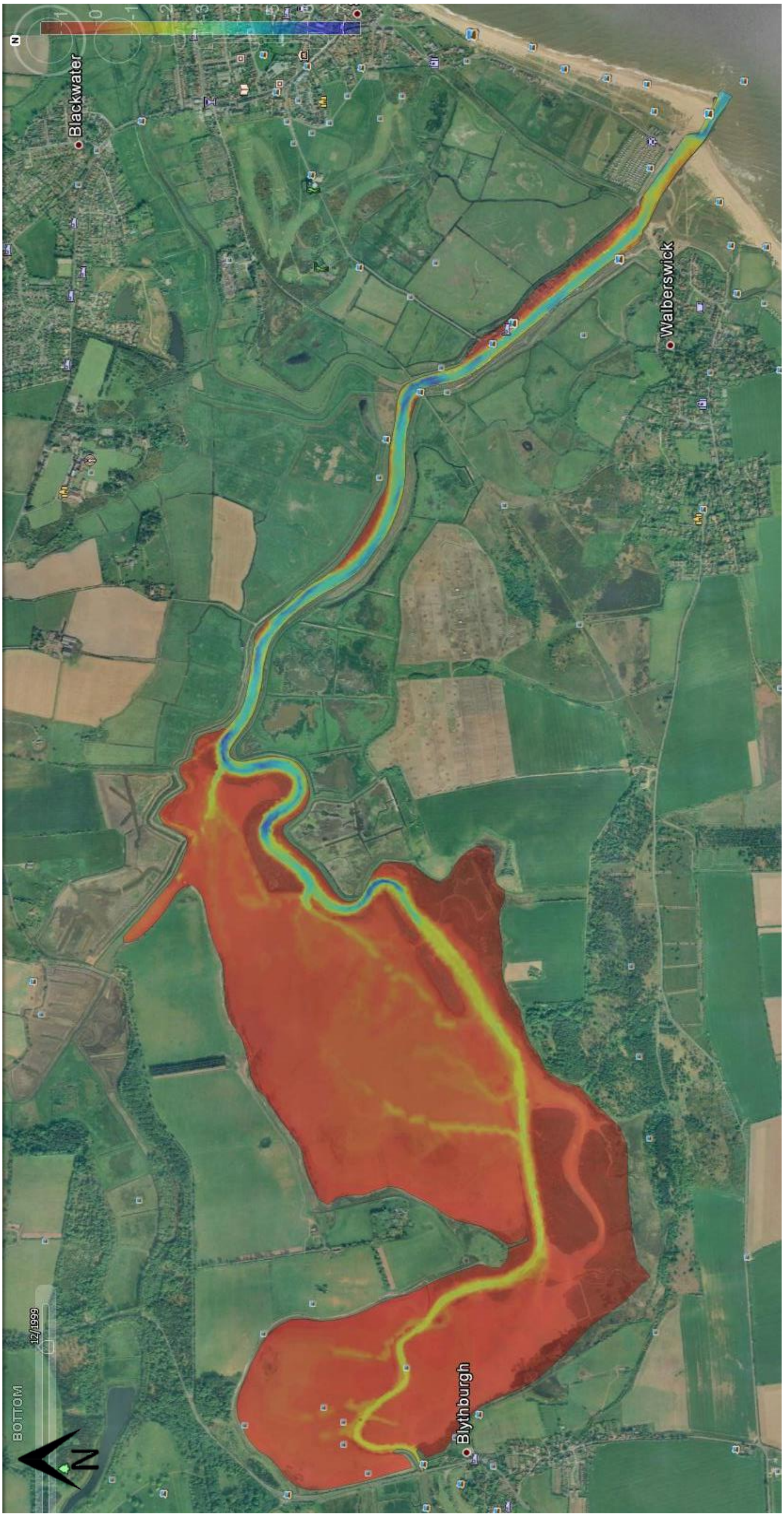

Figure 24: Bathymetry of the 3D model (Google, 2016) (scaling in meters)

CURRENT SPEEDS COMPARISON PHD MODEL AND DEMO MODEL

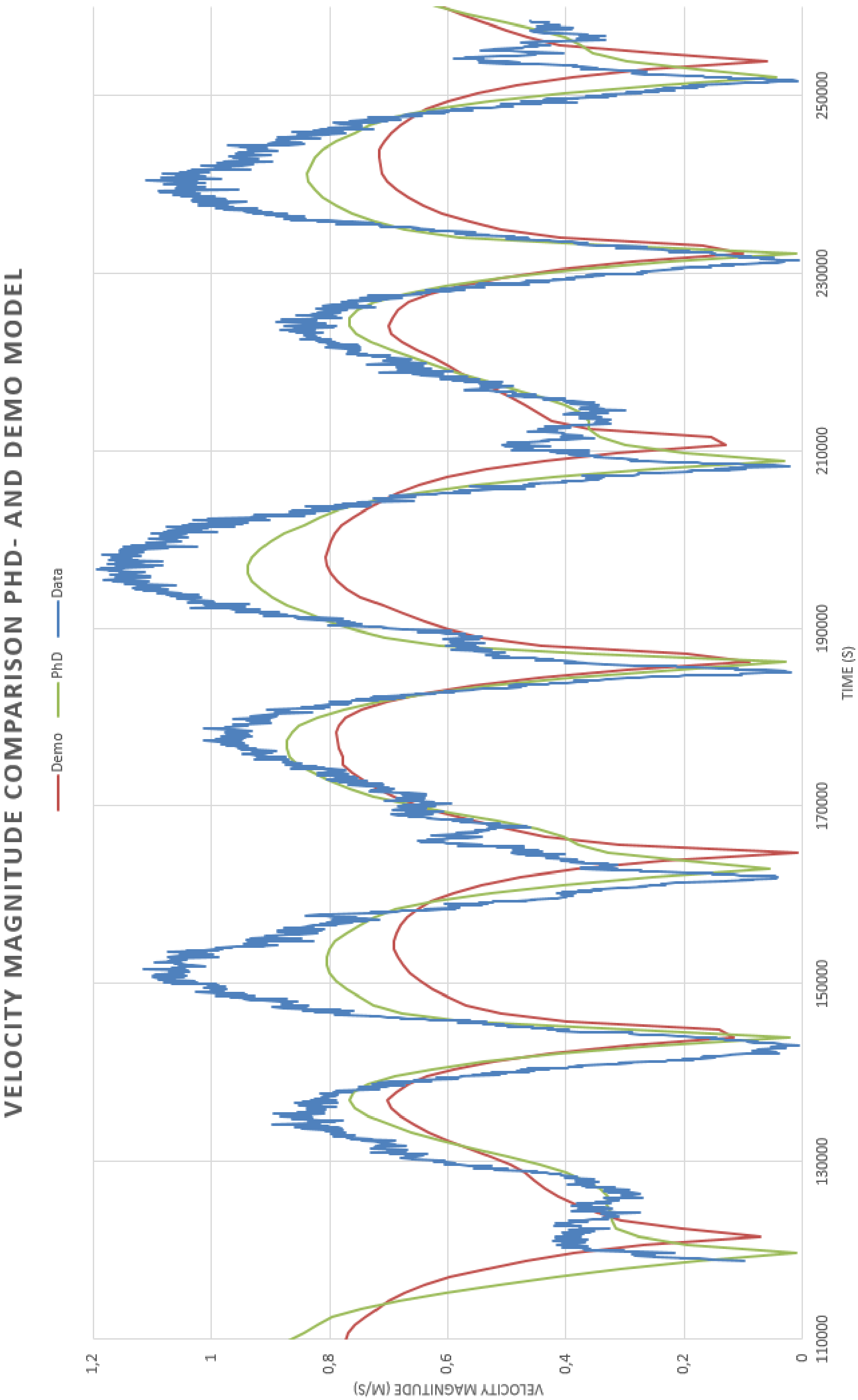

Figure 25: Current speeds comparison PhD model and Demo model

Figure 26: Mesh to be used in the 3D model (Google, 2016)

10.1.2. NIKURADSE FRICTION COEFFICIENT

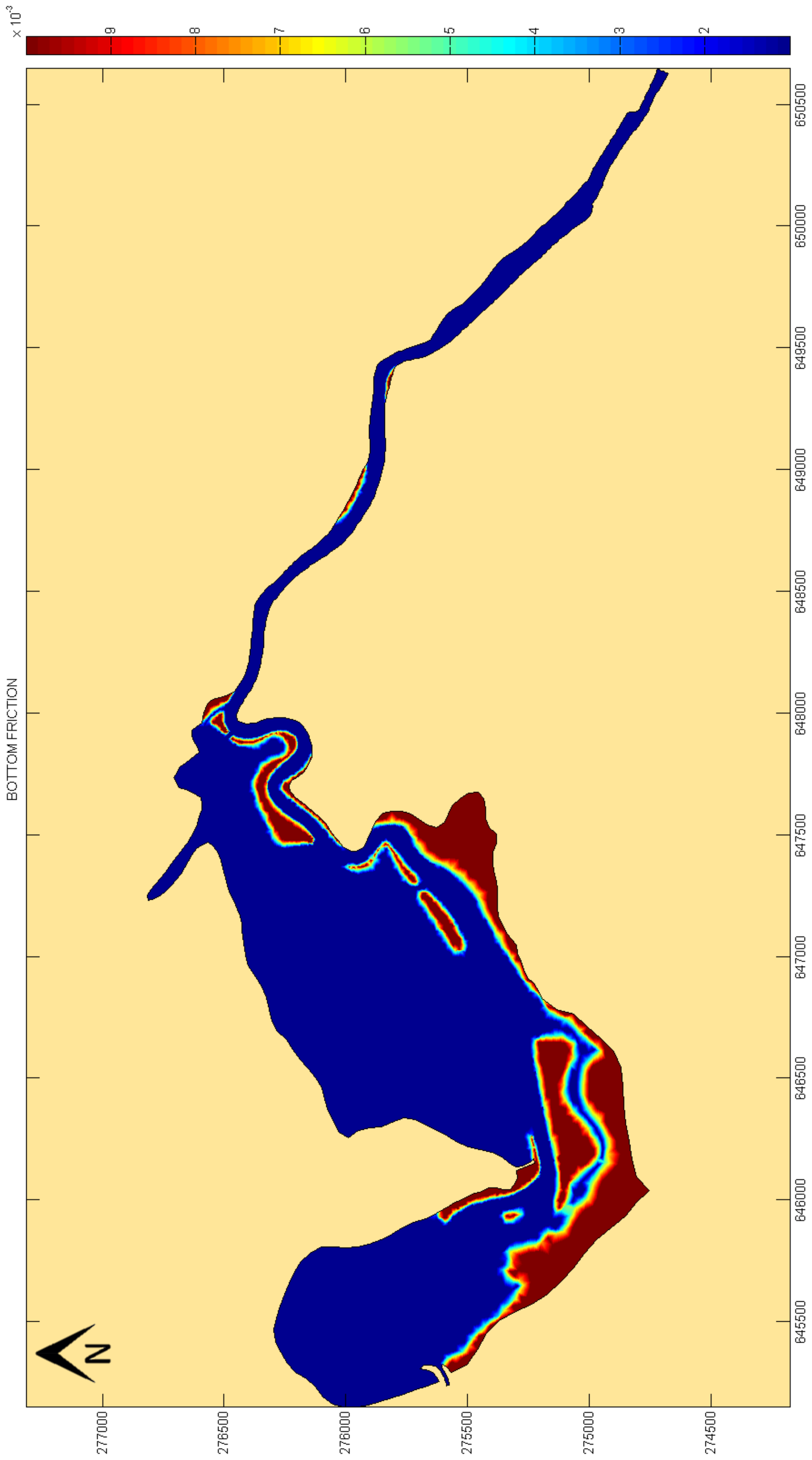

Figure 27: Nikuradse bottom friction (scaling in meters)

10.1.3. SMOOTHING OF THE ESTUARY

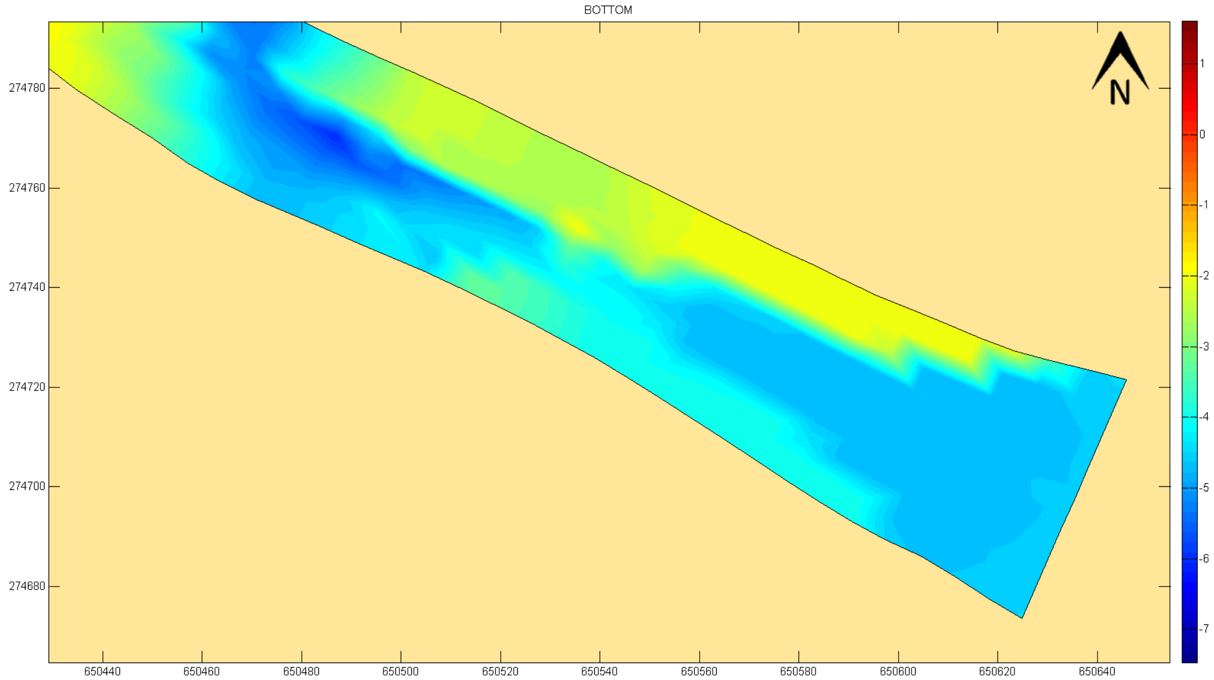

Figure 28: Unsmoothed mouth of the channel (scaling in meters)

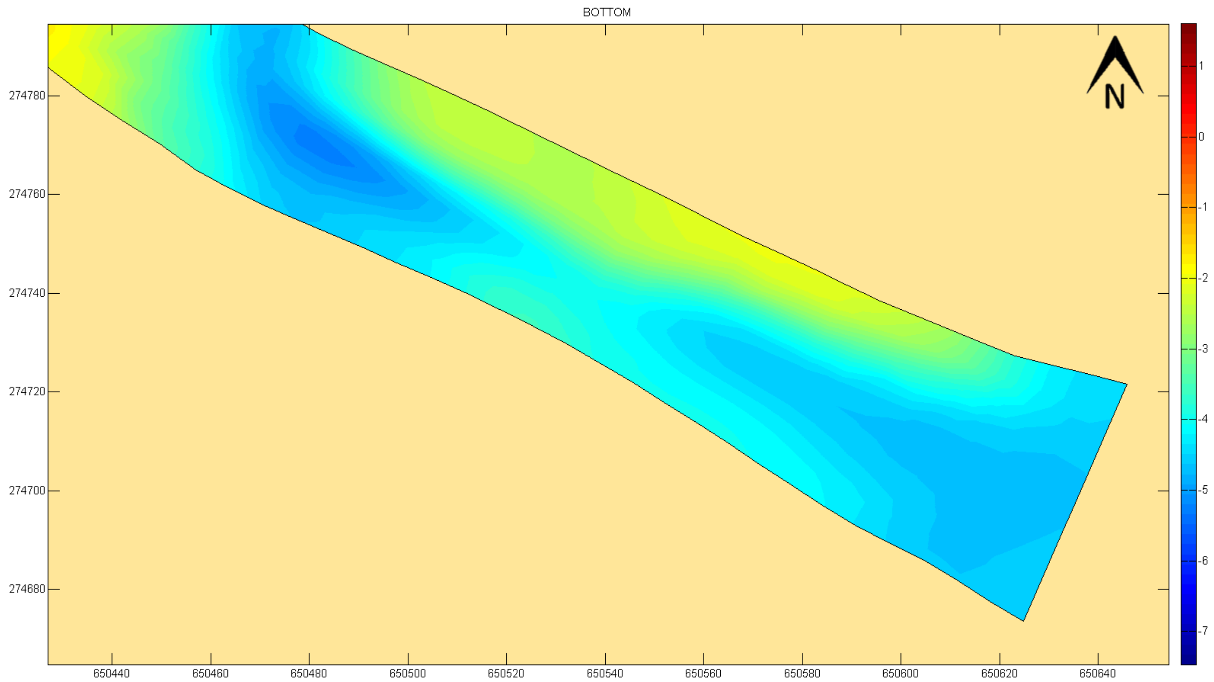

Figure 29: Smoothed mouth of the channel (scaling in meters)

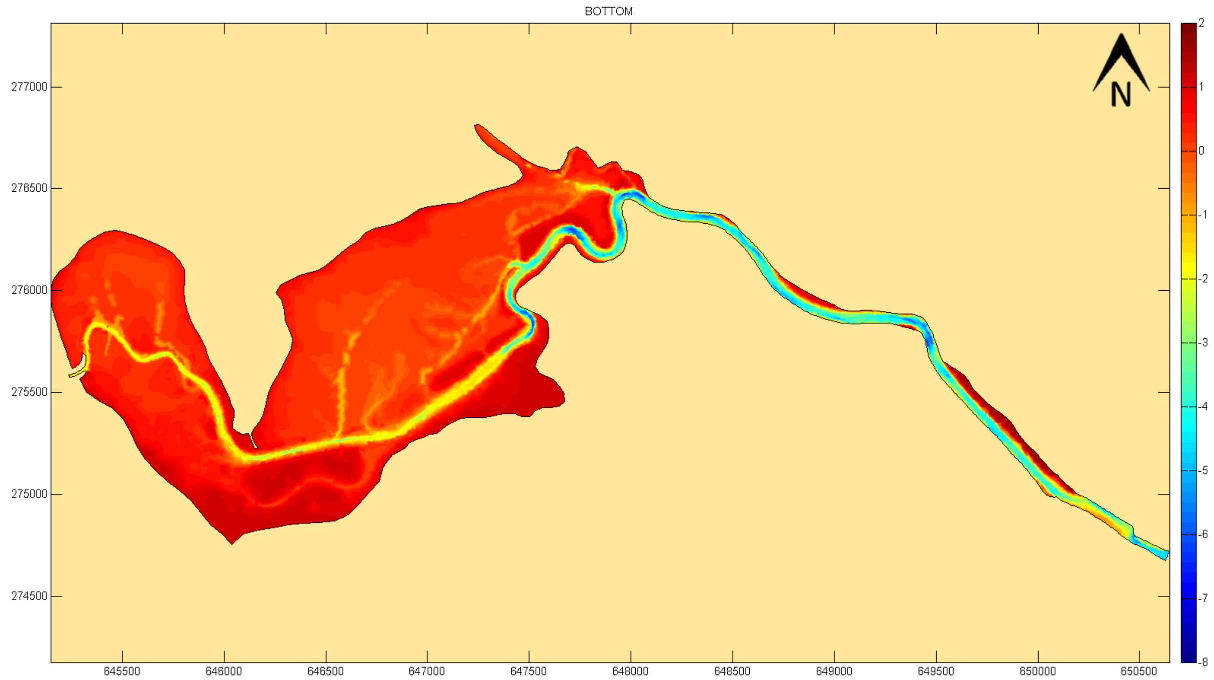

Figure 30: Unsmoothed bottom (scaling in meters)

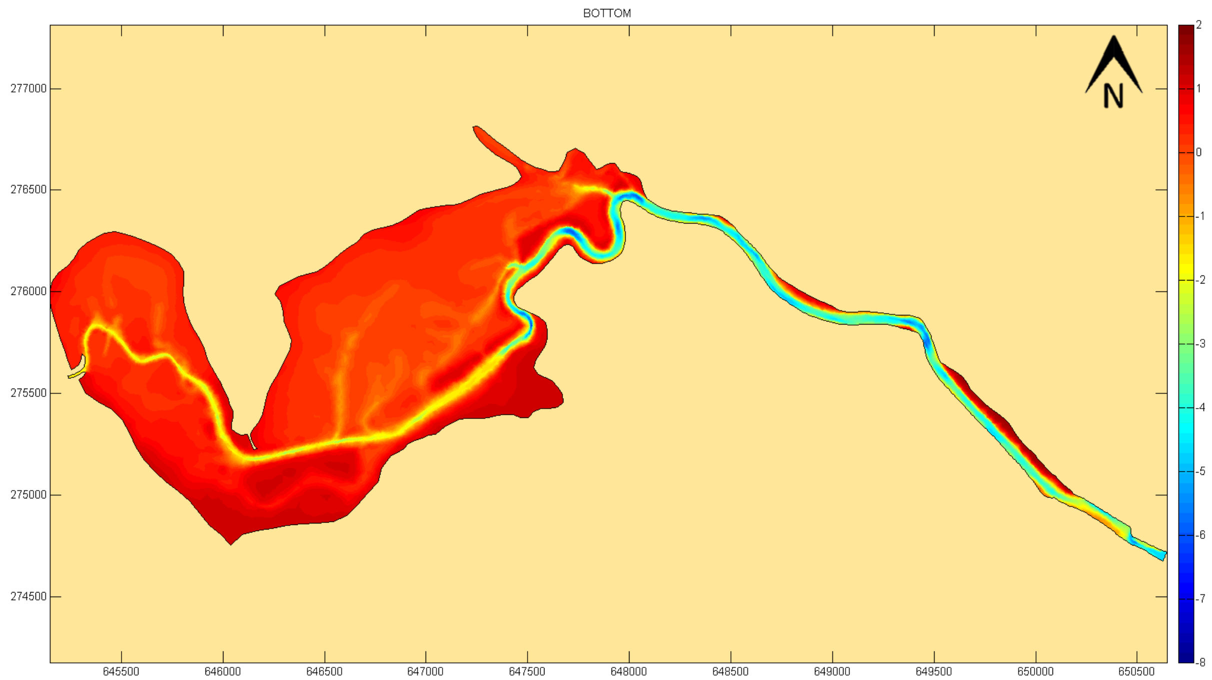

Figure 31: Smoothed bottom (scaling in meters)

COMPARISON OF THE ELEVATION AND CURRENT SPEEDS FOR THE SMOOTHED ESTUARY

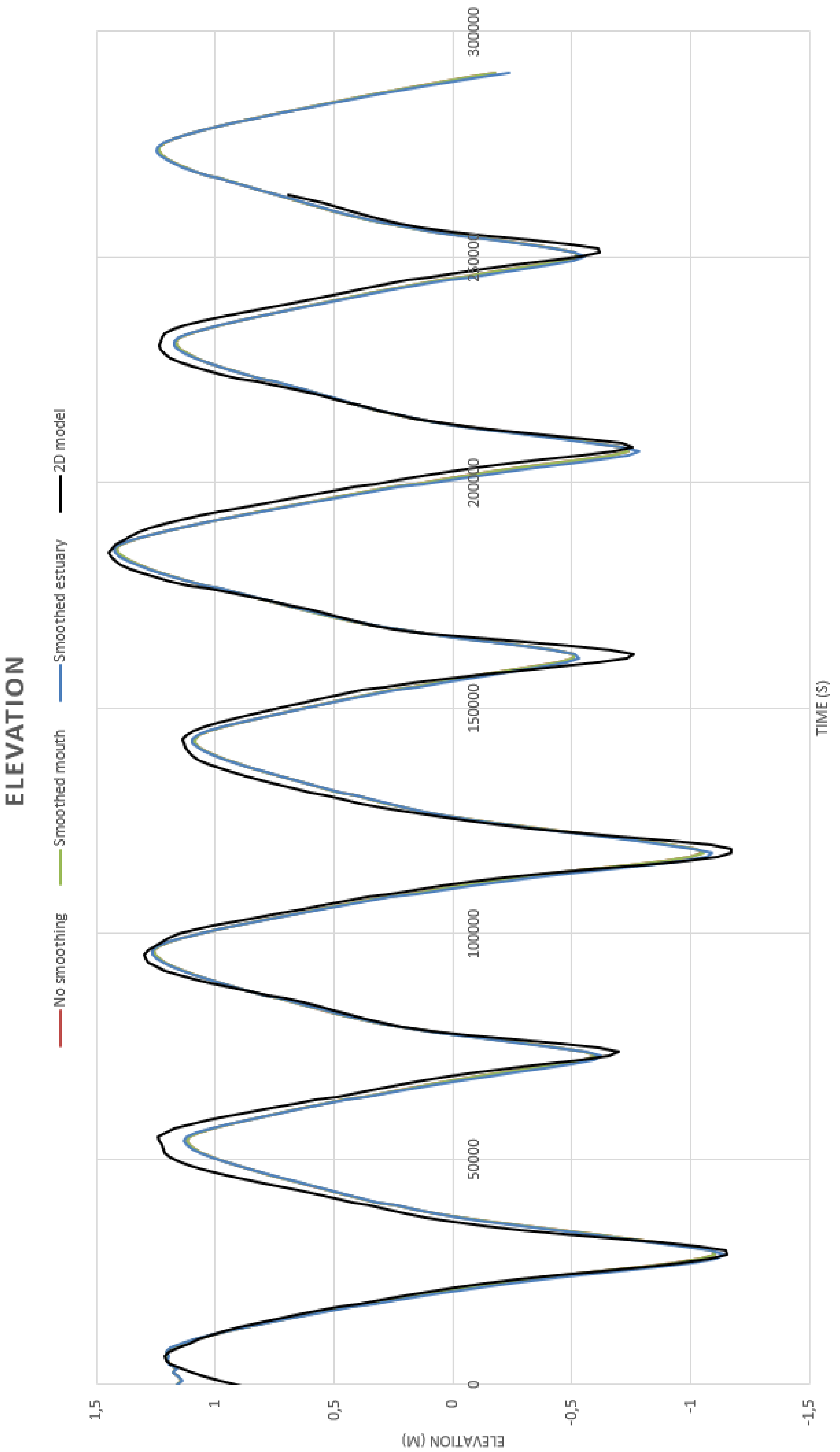

Figure 32: Comparison of the elevation of the three smoothness scenarios

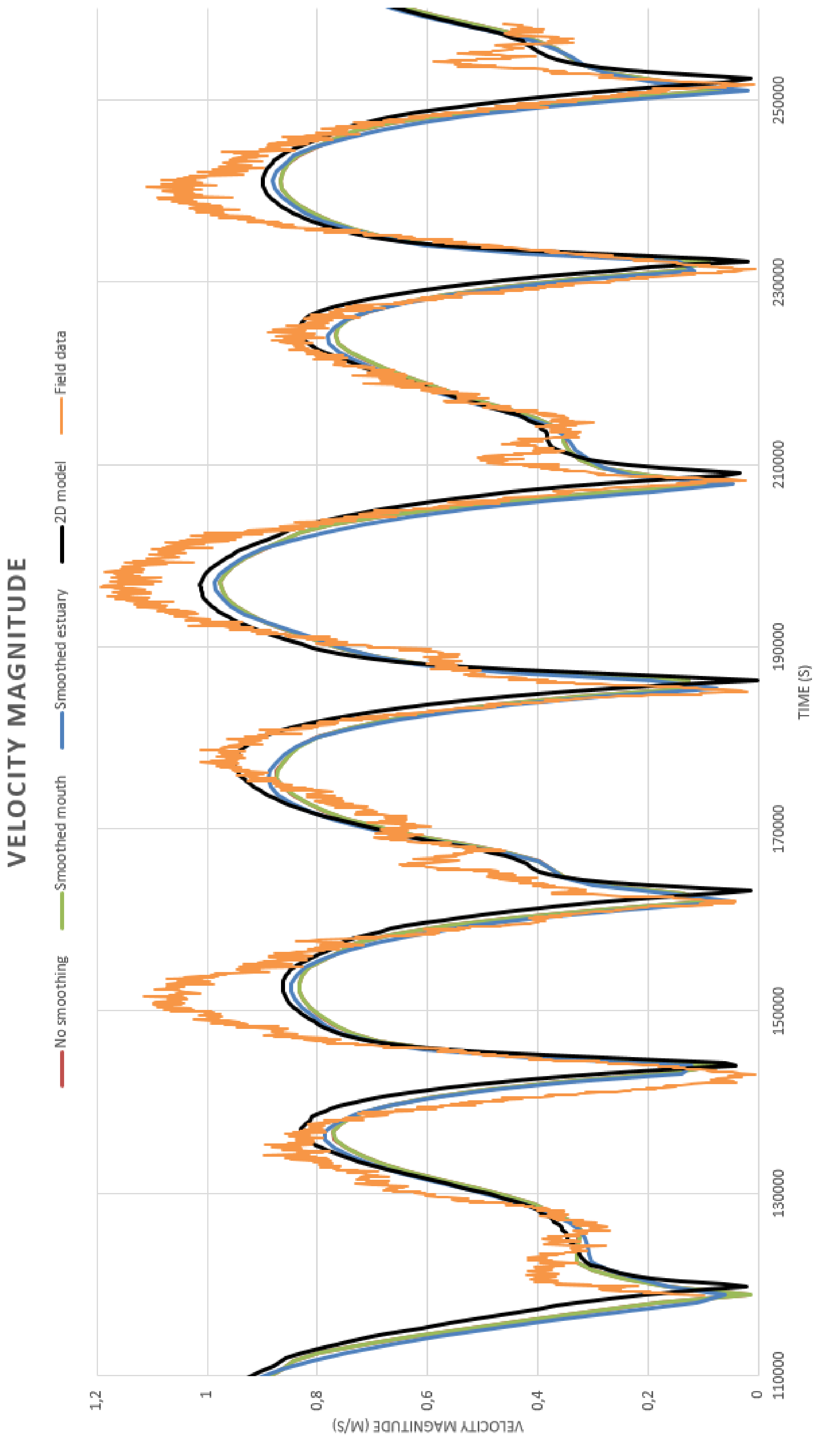

Figure 33: Comparison of the current speeds of the three smoothness scenarios

10.1.4. MULTIPLE DATA EXTRACTION POINTS

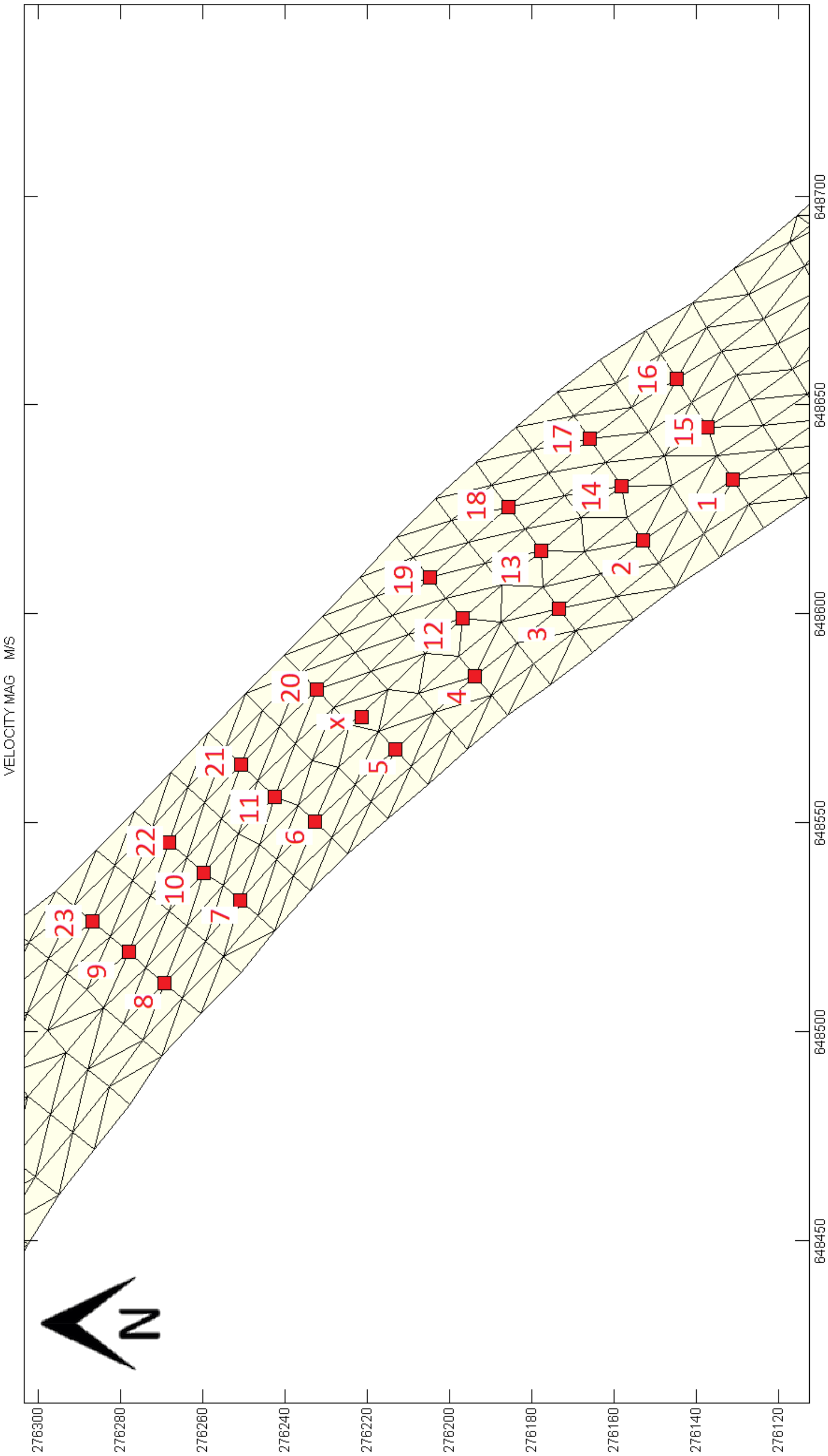

Figure 34: Multiple data extraction points channel

COMPARISON OF THE CURRENT SPEEDS AND ELEVATION FOR THE MULTIPLE DATA EXTRACTION POINTS

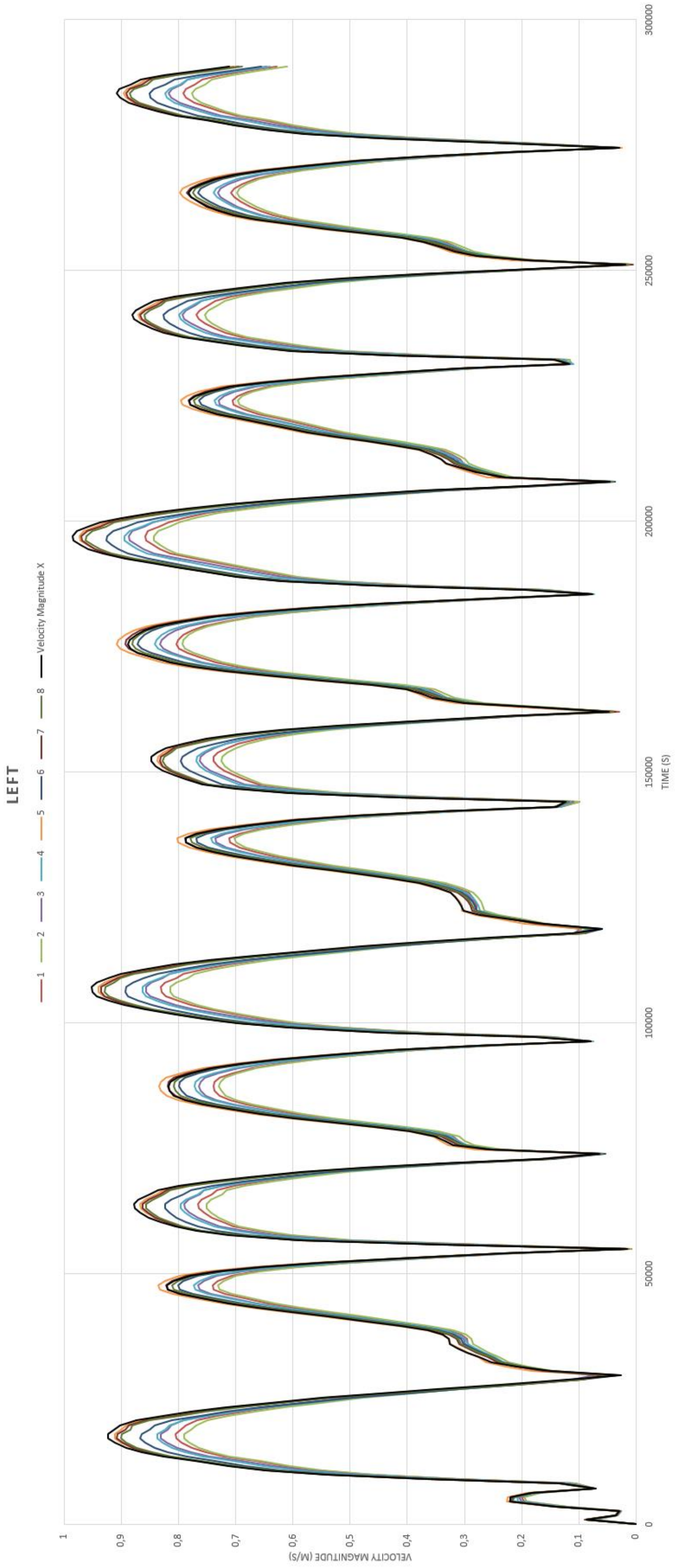

Figure 35: Multiple data extracting locations: Left

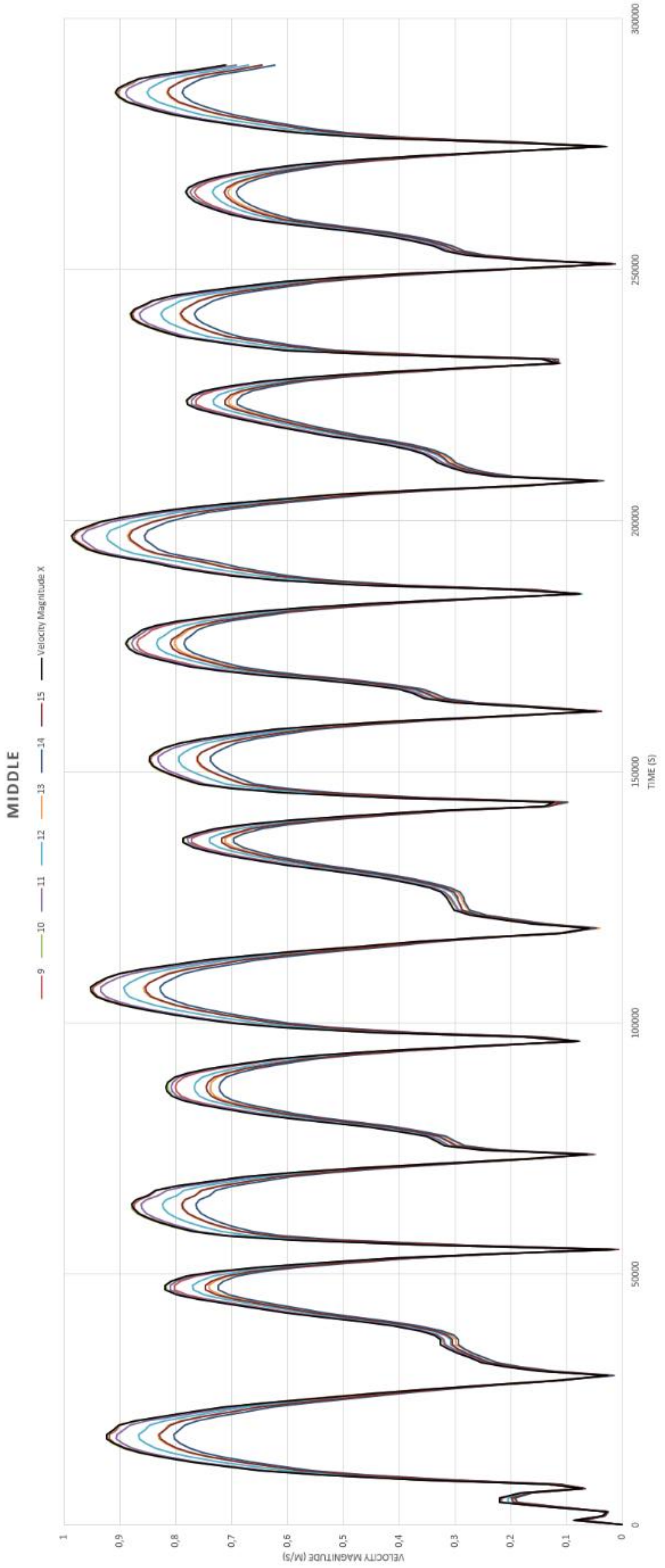

Figure 36: Multiple data extracting locations: Middle

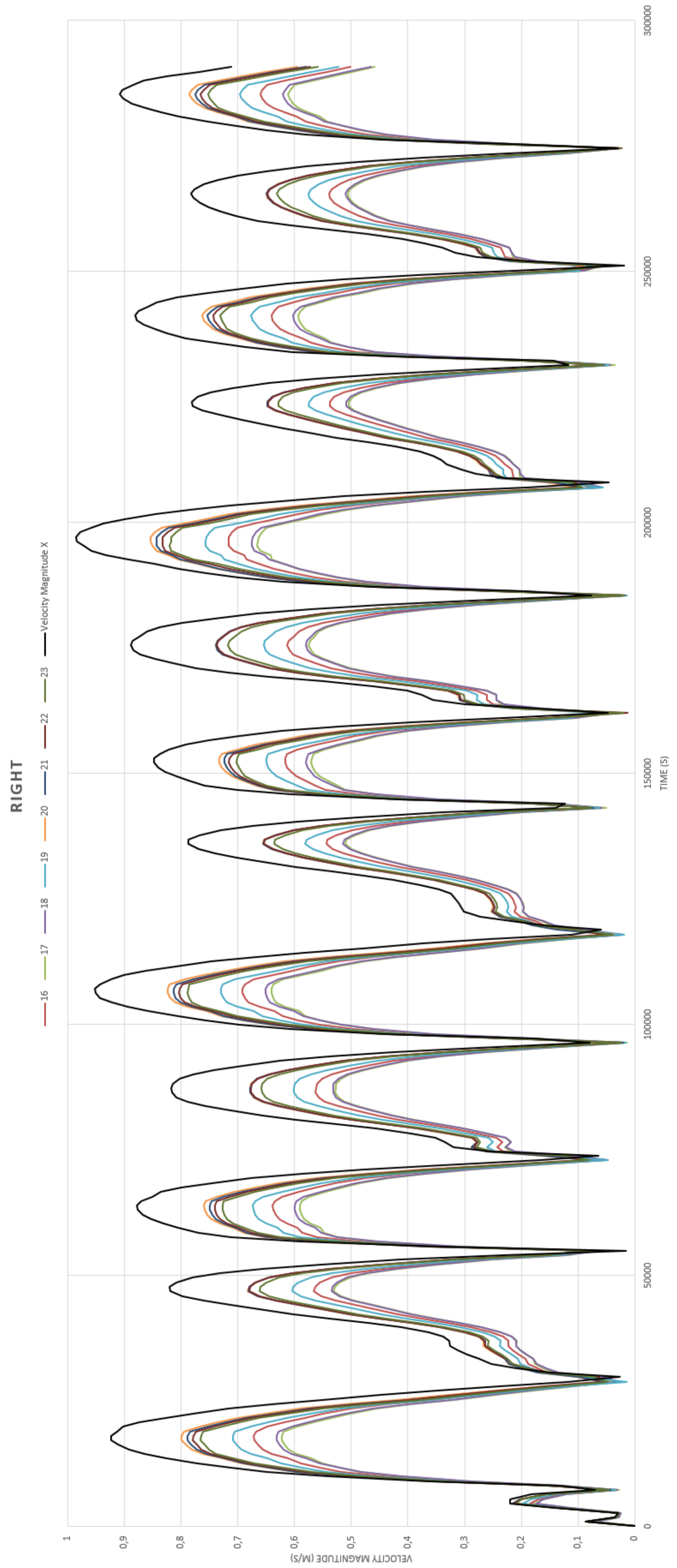

Figure 37: Multiple data extracting locations: Right

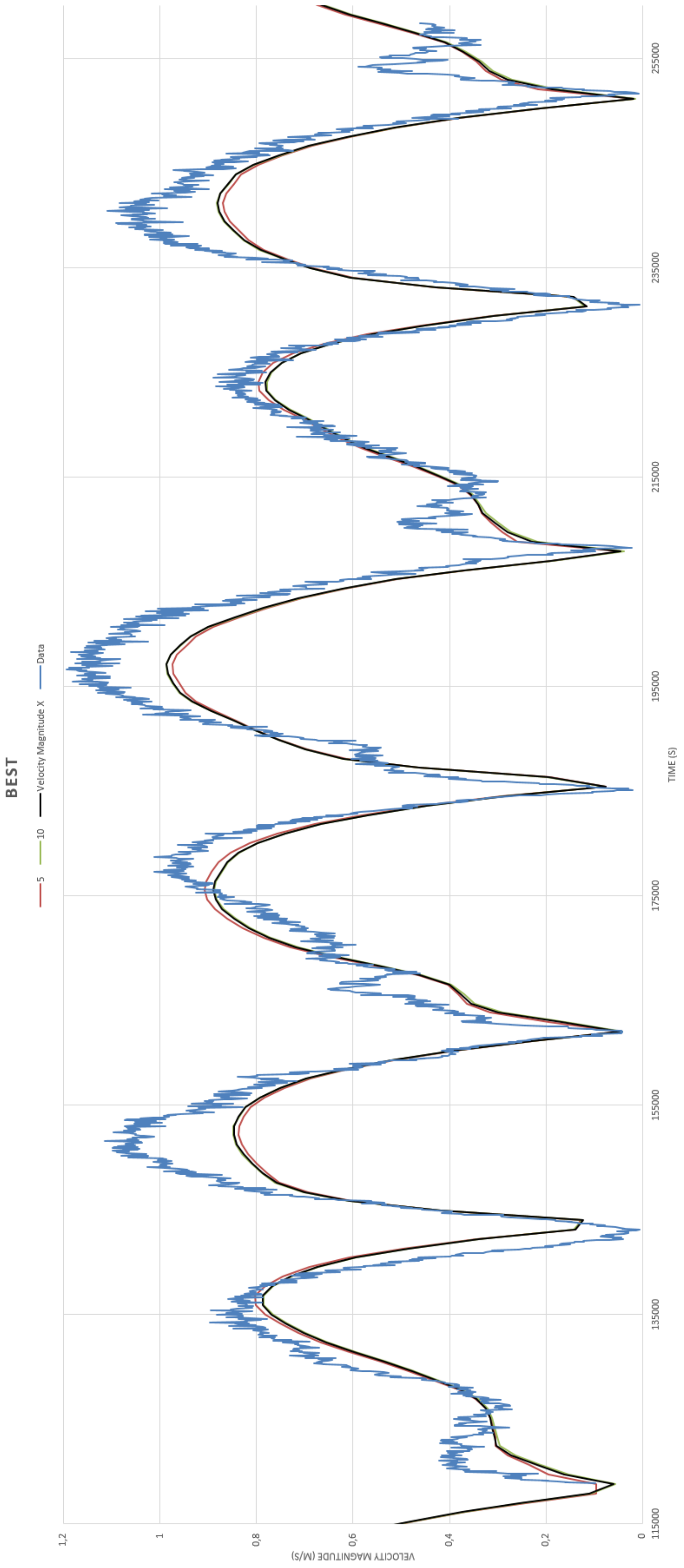

Figure 38: Multiple data extracting locations: Best results compared to the data

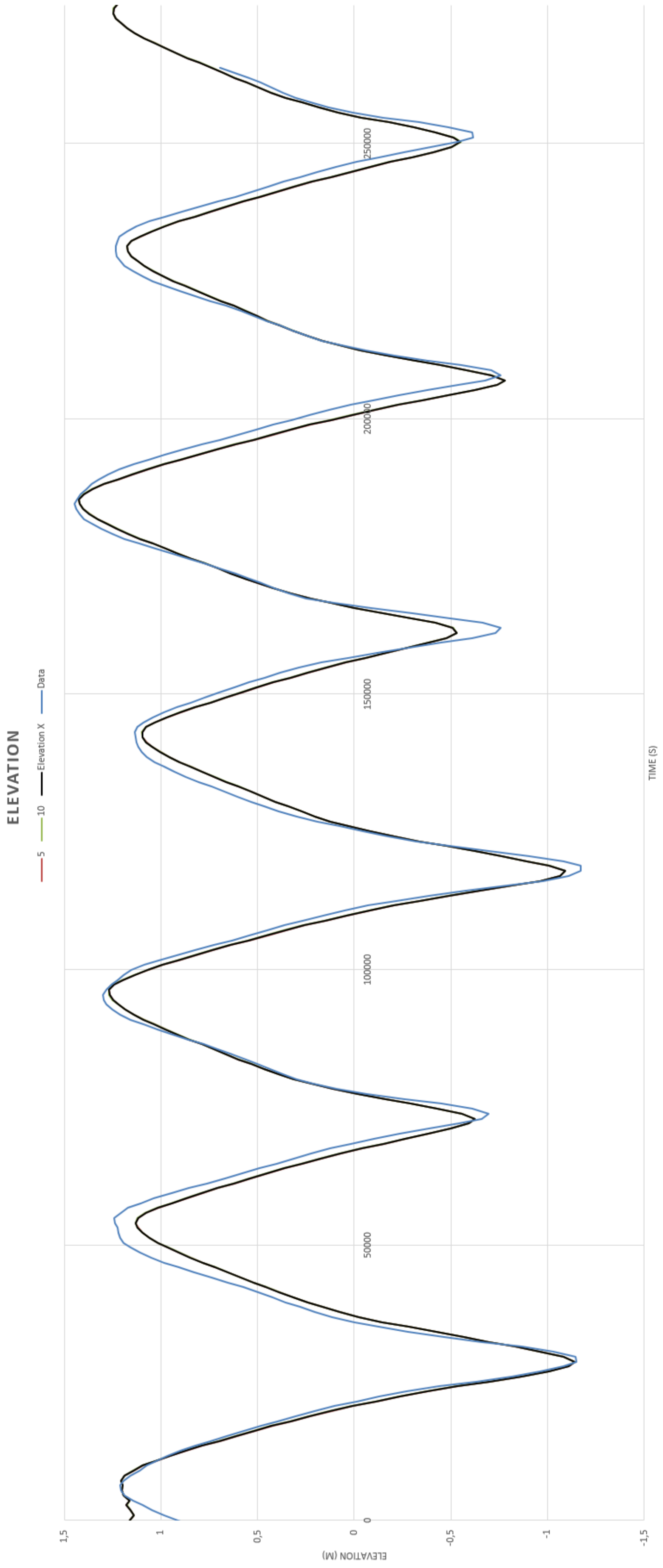

Figure 39: Multiple data extracting locations: Elevation of the best results, compared to the data

10.1.5. PARTHENIADES EROSION COEFFICIENT (BENSON, 2004)

$$Q_E = M\left(\frac{\tau_b}{\tau_e} - 1\right) \text{ when } \tau_b > \tau_e$$

Where:

- Q_E = flux of sediment by erosion and deposition ($kgm^{-2}s^{-1}$)
- τ_b = bed shear stress (Nm^{-2})
- τ_e = critical shear stress for erosion and deposition (Nm^{-2})
- M = erosion rate constant ($kgm^{-2}s^{-1}$)

10.1.6. PARAMETERIZATION

PARAMETERIZATION PROCESS

The model is parameterized with the parameters shown in Table 17. The final result of the parameterization is shown in the first column, named final result. Since the model is going to be assessed by the BSS it is interesting to see how the performance of the model changes, and therefore the score, by changing one parameter at a time. In run A until F a single parameter is changed every time, to see how this effects the BSS.

Table 17: Parameterization

Parameter	Unit	2 - Final result	2A	2B	2C	2D	2E	2F
SSC AT THE SEAWARD BOUNDARY	[mgl^{-1}]	100	70	100	100	100	100	100
FLOCCULATION	[-]	Yes	Yes	no	Yes	Yes	Yes	Yes
EROSION COEFFICIENT	[$kgm^{-2}s^{-1}$]	8.E-5	8.E-5	8.E-5	4.E-5	8.E-5	8.E-5	8.E-5
NUMBER OF SEDIMENT BED LAYERS	[-]	2	2	2	2	1	2	2
CRITICAL EROSION SHEAR STRESS OF THE MUD LAYERS	[$kgm^{-2}s^{-1}$]	0.05;0.2	0.05;0.2	0.05;0.2	0.05;0.2	0.2	0.2;0.2	0.05;0.2
INITIAL THICKNESS OF SEDIMENT LAYERS	[m]	0.0;0.2	0.0;0.2	0.0;0.2	0.0;0.2	0.2	0.0;0.2	0.01;0.2

In Figure 40 on the next page, the parameterization graphs are shown.

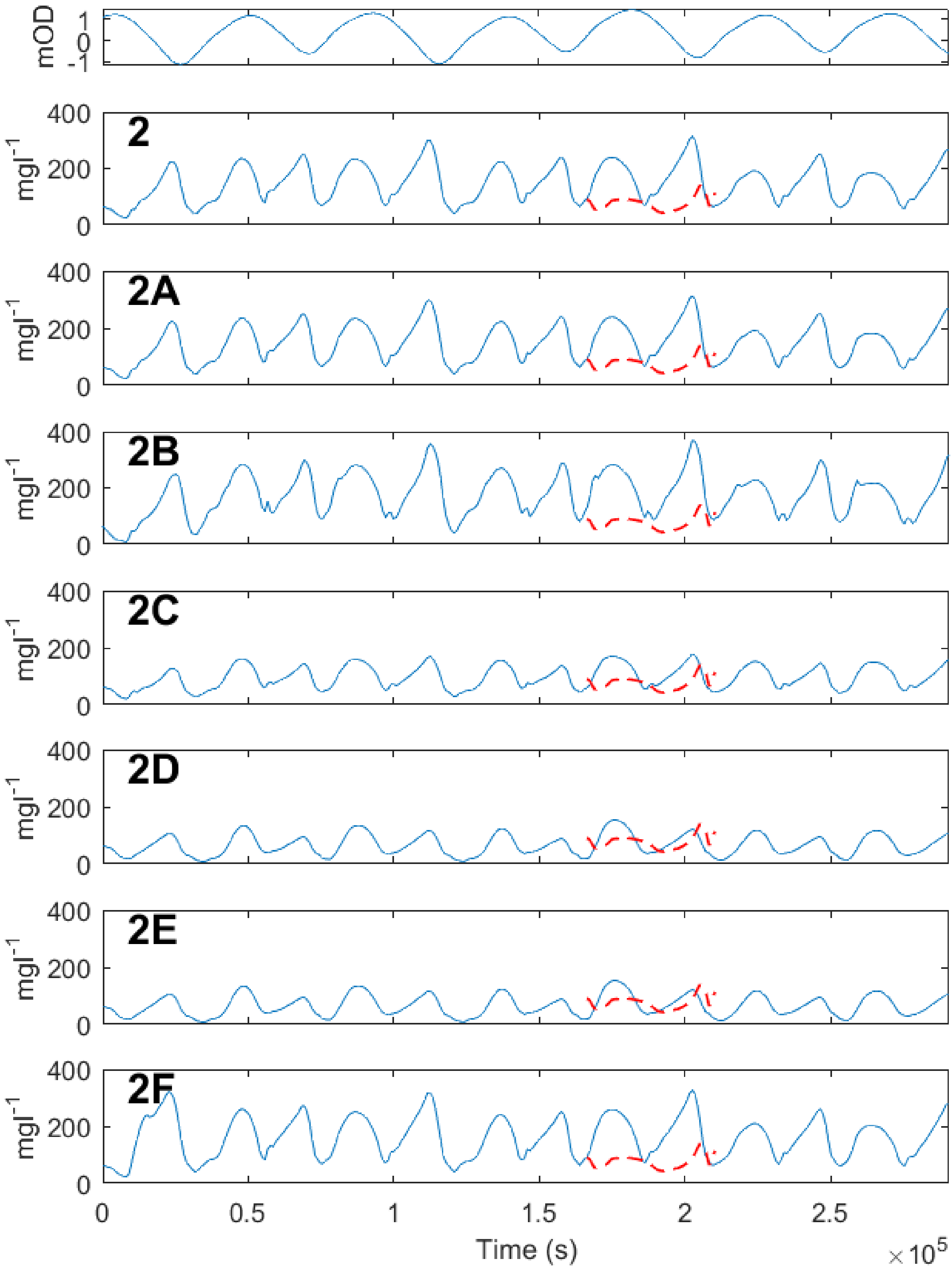

Figure 40: Parameterization graphs for each of the six models

Model 2 is the final model after the parameterization has taken place. The main difference between model 1 and 2, is that model 2 has a higher average of ssc. Whereas the modelled peaks are too high compared to the observed data, the proportion between the ssc on the ebb and flood tide is better than in model 1. It should be noted that the value on the y-axis goes to 400 mgl^{-1}, instead of the 200 mgl^{-1} used for model 1. Below the effects of the different parameter settings will be described per sub model of model 2.

CALIBRATION MODEL 2A – SSC AT SEAWARD BOUNDARY

It is interesting to see that there is not a noticeable difference between 2 and 2A. It could be possible that the changes are minimal and can therefore not be noticed by the bare eye. The BSS should point out whether there are any differences between model 2 and 2A.

CALIBRATION MODEL 2B – FLOCCULATION

In model 2B the flocculation model has been switched off. This resulted in higher peaks, because the sediment does not settle down as fast as it did before. Since the sediment particles do not stick together when the flocculation is turned off, the particles are smaller than they were before. As smaller particles do not settle down as fast as large particles, more sediment stays in suspension, instead of settling down on the estuary bed. So when the water level rises after slack water, all the sediment particles that are still in suspension start to move around, resulting in higher peaks.

CALIBRATION MODEL 2C – EROSION COEFFICIENT

In model 2C the erosion coefficient has been halved, resulting in an overall lower graph.

CALIBRATION MODEL 2D – NUMBER OF SEDIMENT LAYERS

In model 2D only 1 bed layer has been used to see its effect on the model. The model is flatter than model 2, because there is less sediment moving around in the estuary. As explained before, there is a solid lower layer, and a top layer with loose sediment, which easily goes into suspension. This top layer produces the high peaks in the model, since this sediment goes into suspension when the water level rises. As this layer is taken out in model 2D and the only layer that remains has a critical erosion shear stress of 0.2, there is not a lot of sediment that moves around in the estuary. Therefore, the model is lower than it was before.

CALIBRATION MODEL 2E – CRITICAL EROSION SHEAR STRESS OF THE MUD LAYERS

In model 2E the critical erosion shear stress of the top layer is set to 0.2. This is four times as large as the old value. Almost the same thing happens as in 2D, as there is not a lot of sediment in the estuary to move around anymore, and the graph is flatter than model 2.

CALIBRATION MODEL 2F – INITIAL THICKNESS OF THE SEDIMENT LAYERS

In model 2F the thickness of the upper layer has been increased to 0.01 m. The exact opposite happens as in model 2D and 2E. Since there is more sediment in the top layer, there is more sediment that is moved around in the estuary, which results in higher peaks. It should be noted that especially the first peak is a lot higher than in model 2. The reason for this to happen, is that the sediment that is in the top layer, immediately starts to move around when the water level rises. Since this top layer is thicker than in the other models, the first peak is incredibly high compared to the other models.

PARAMETERIZATION RESULTS – SUMMARY

The results of the parameterization are presented in Table 18. The effects are qualitatively measured by visual analysis. In section **7.1** the performance of the models will be measured by the Brier Skill Score, for a quantitative analysis.

Table 18: Results parameterization

Graph	Effect	Performance compared to model 2
2A	The effect of this measurement is barely noticeable by the bare eye. The BSS will point out whether there is any difference between model 2 and 2A.	Neutral
2B	The peaks on the ebb tide get higher, which makes the model worse than model 2.	Worse
2C	The average concentration is a lot lower than in model 2, it seems to be about halve the value of model 2. This makes the model a better fit to the data.	Better
2D	This model does almost the same as model 2C and is a better fit to the data than model 2. The peak on the ebb tide is even smaller than the peak in model 2C. This makes the model even a better fit to the data.	Better
2E	This model is in line with model 2C and model 2D. There is no difference noticeable with the bare eye between model 2D and 2E.	Better
2F	This model gives a very high value on the very first ebb tide. However, when the rest of the tides is compared to model 2, there are barely any differences noticeable with the bare eye. Therefore, it is considered that the performance of this model compared to model 2 is neutral.	Neutral

10.1.7. SPATIALLY VARIED CRITICAL SHEAR STRESS FOR EROSION – CALIBRATION

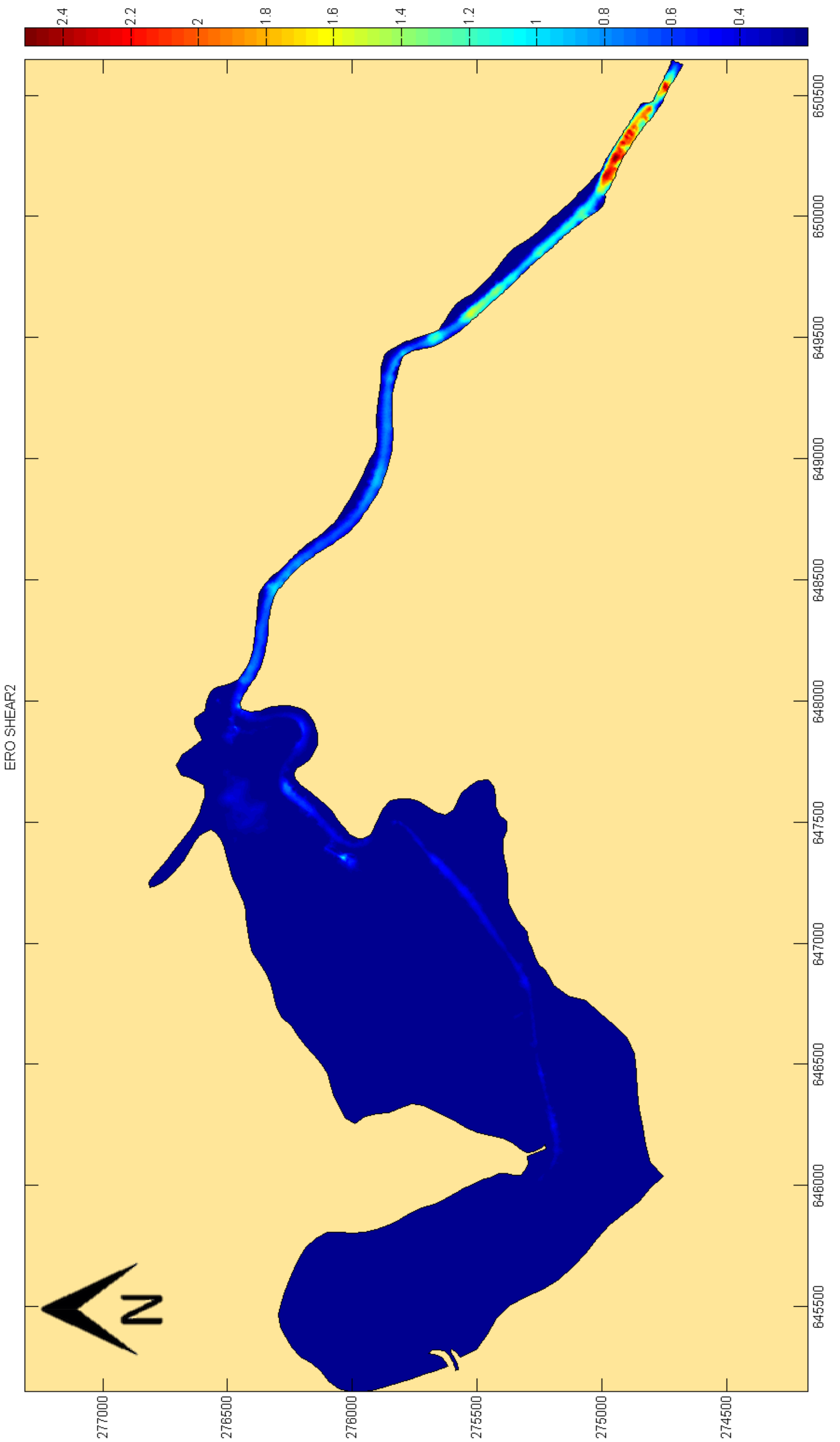

Figure 41: Spatially varied critical shear stress for erosion for the spring tide with lower limit 0.2 $kgm^{-2}s^{-1}$ (scaling in $kgm^{-2}s^{-1}$)

10.1.8. THICKNESS SEDIMENT LAYER CHANNEL AND SALTMARSHES – CALIBRATION

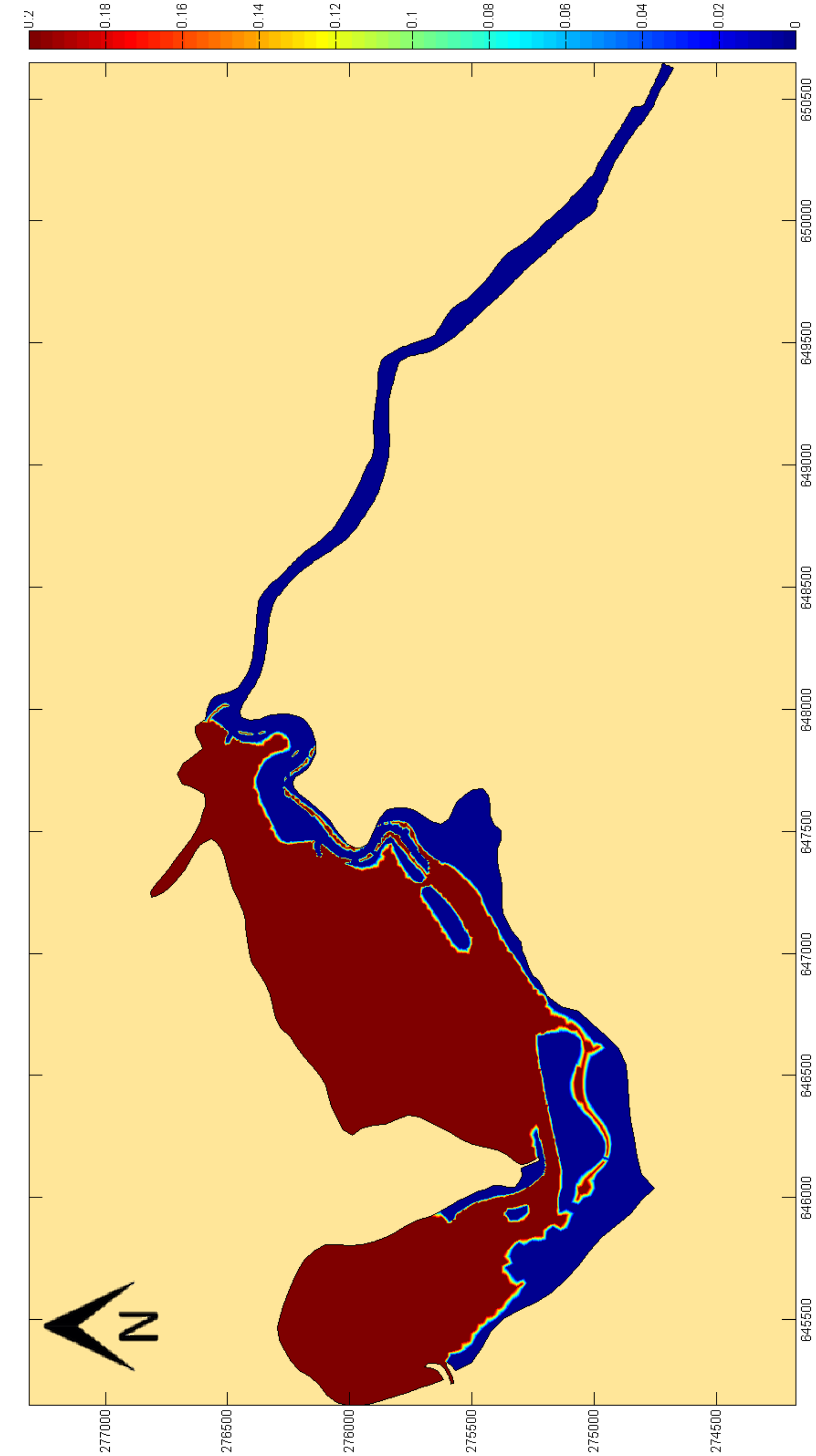

Figure 42: Initial thickness spring tide (scaling in meters)

10.2. APPENDIX B. VALIDATION OF THE MODEL

10.2.1. COMPARISON OF THE CURRENT SPEEDS FROM THE DATA SET FOR THE VALIDATION PERIOD WITH THE MODELLED CURRENT SPEEDS FOR THE VALIDATION PERIOD

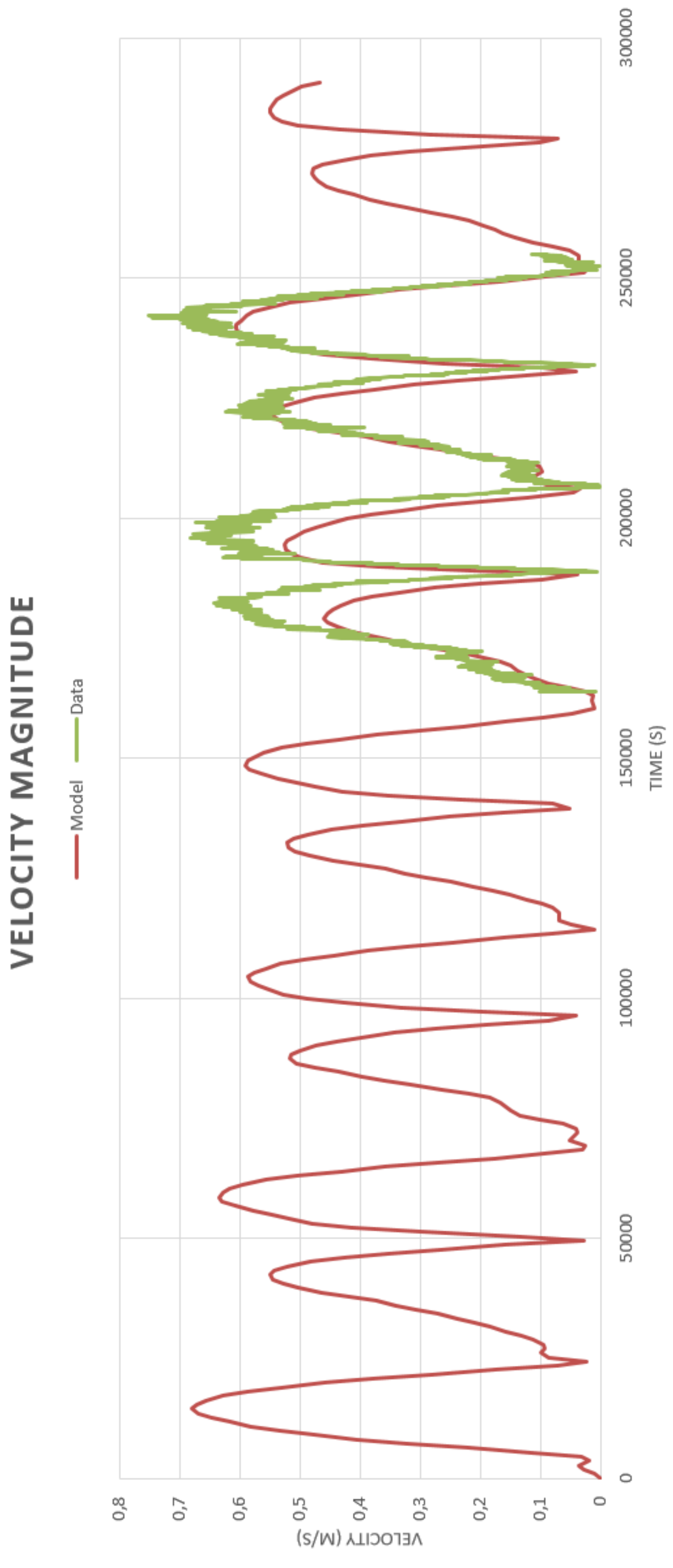

Figure 43: Current speeds validation

10.2.2. SPATIALLY VARIED CRITICAL SHEAR STRESS FOR EROSION – VALIDATION

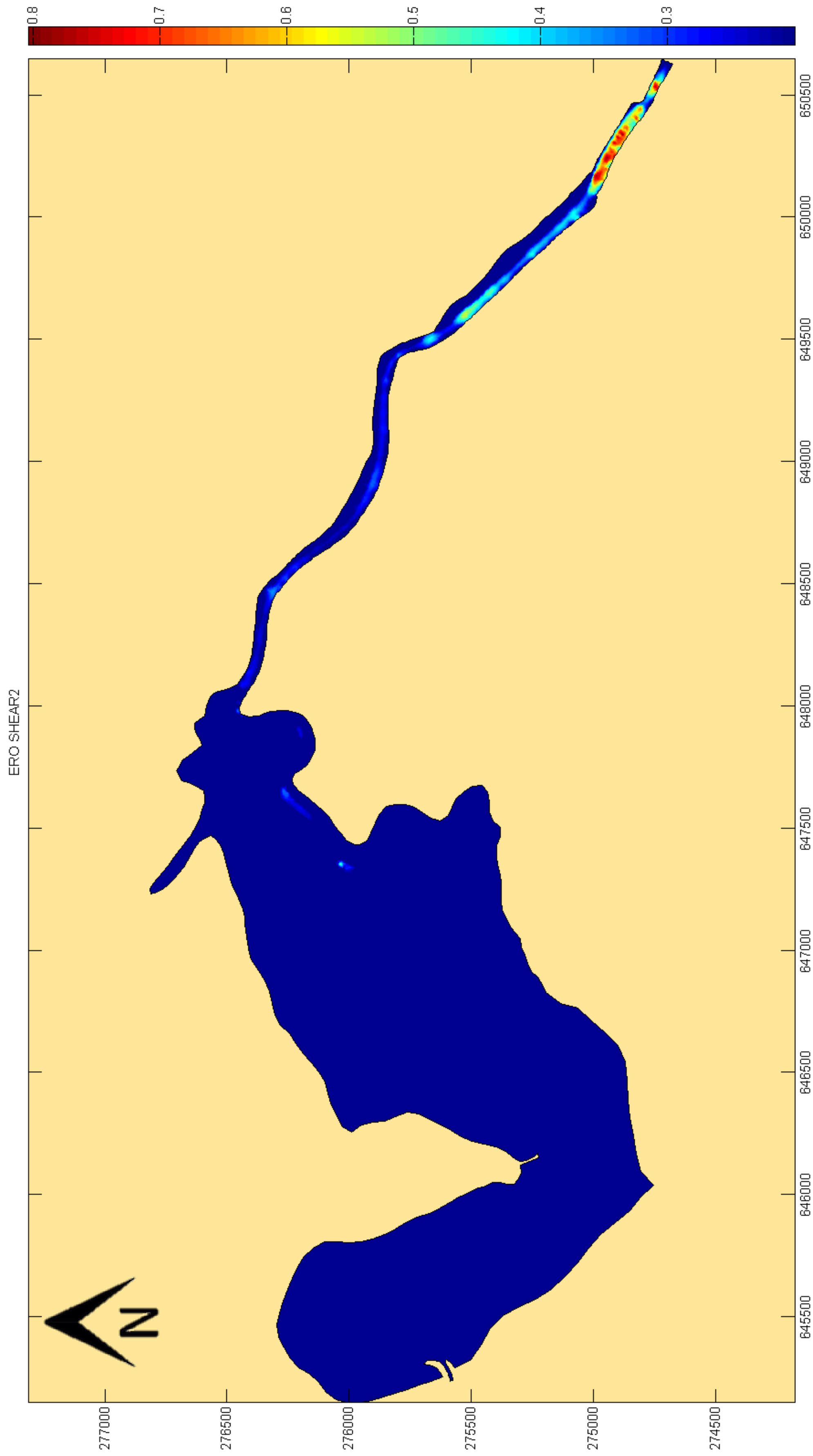

Figure 44: Spatially varied critical shear stress for erosion for the neap tide with lower limit 0.2 $kgm^{-2}s^{-1}$ (scaling in $kgm^{-2}s^{-1}$)

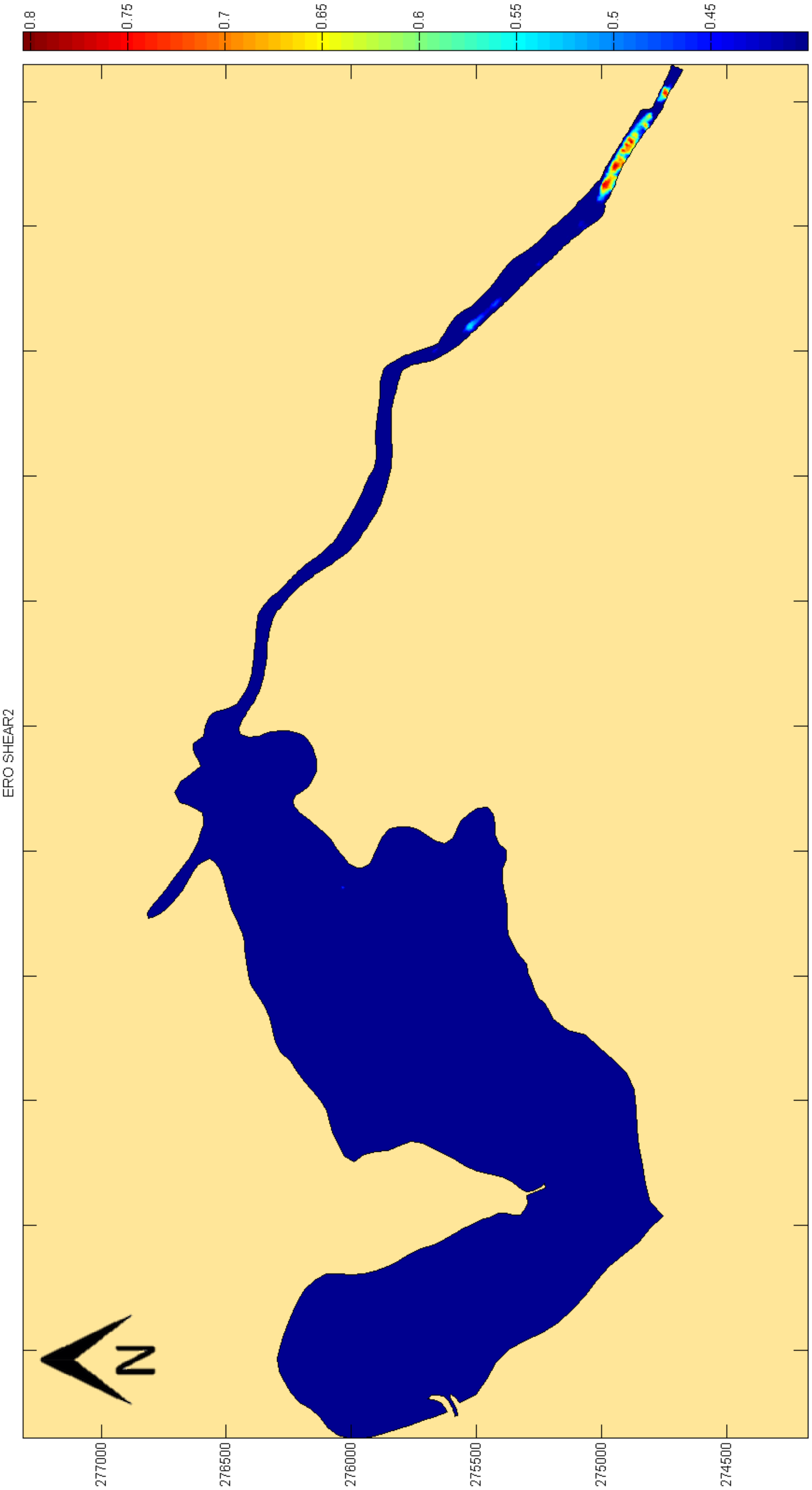

Figure 45: Spatially varied critical shear stress for erosion for the neap tide with lower limit 0.4 $kgm^{-2}s^{-1}$ (scaling in $kgm^{-2}s^{-1}$)

10.2.3. THICKNESS SEDIMENT LAYER CHANNEL AND SALTMARSHES – VALIDATION

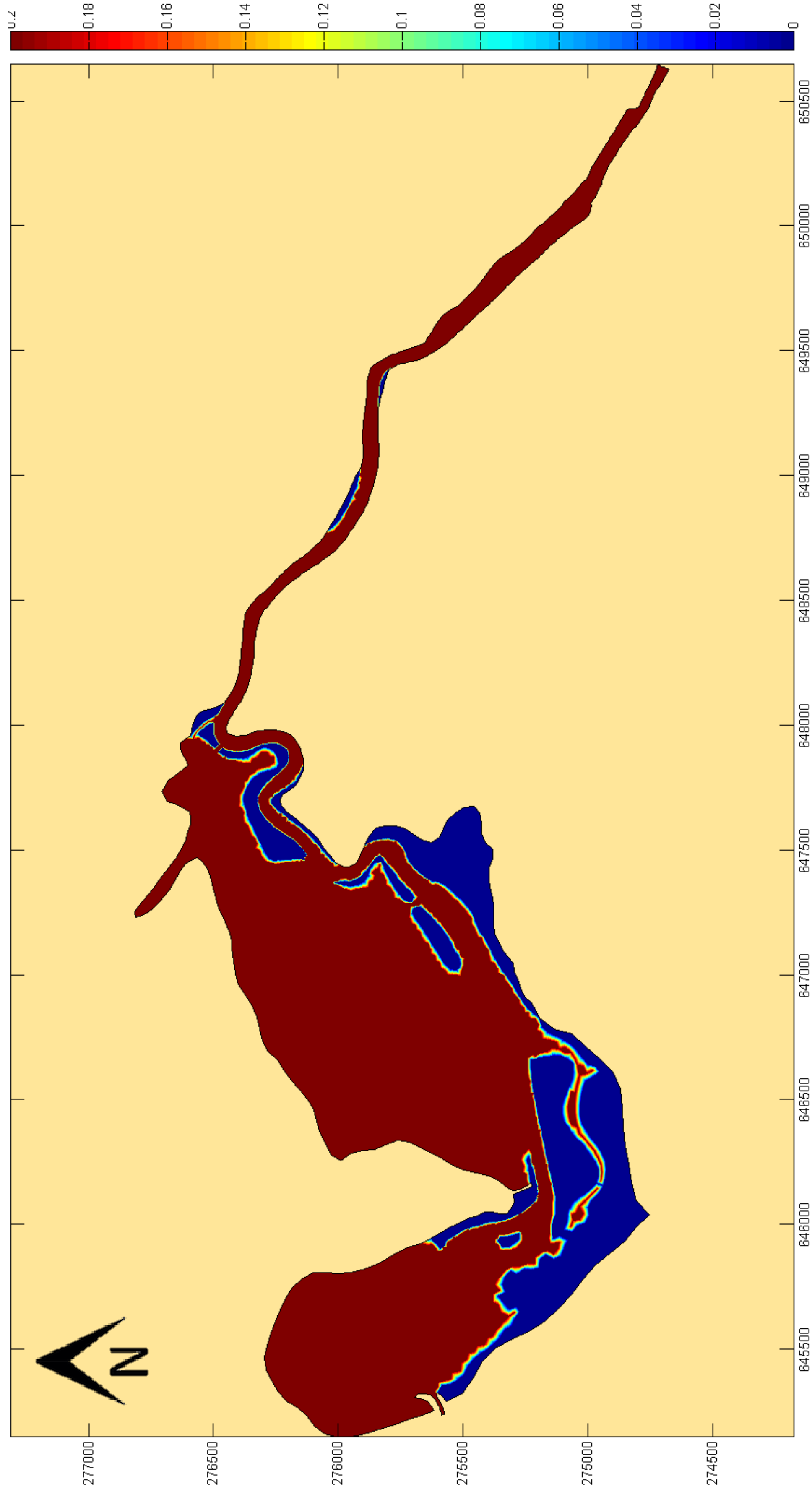

Figure 46: Initial thickness neap tide (scaling in meters)

10.3. APPENDIX C. COMPARISON OF THE MODEL RESULTS

10.3.1. SLACK WATER PERIOD

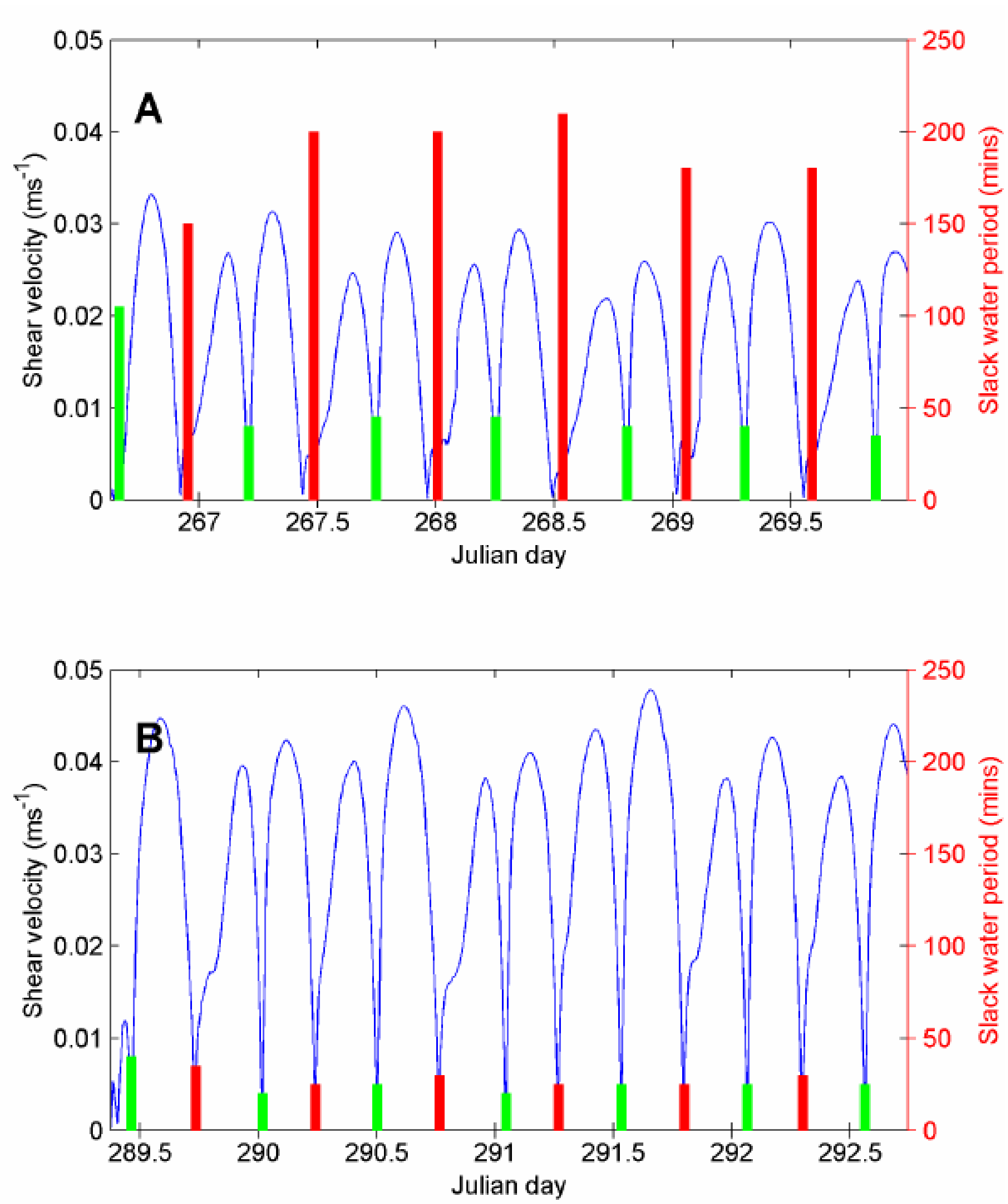

Figure 47: Settling periods for high (green) and low (red) slack water (Benson, 2004).

10.3.2. BED LAYERS

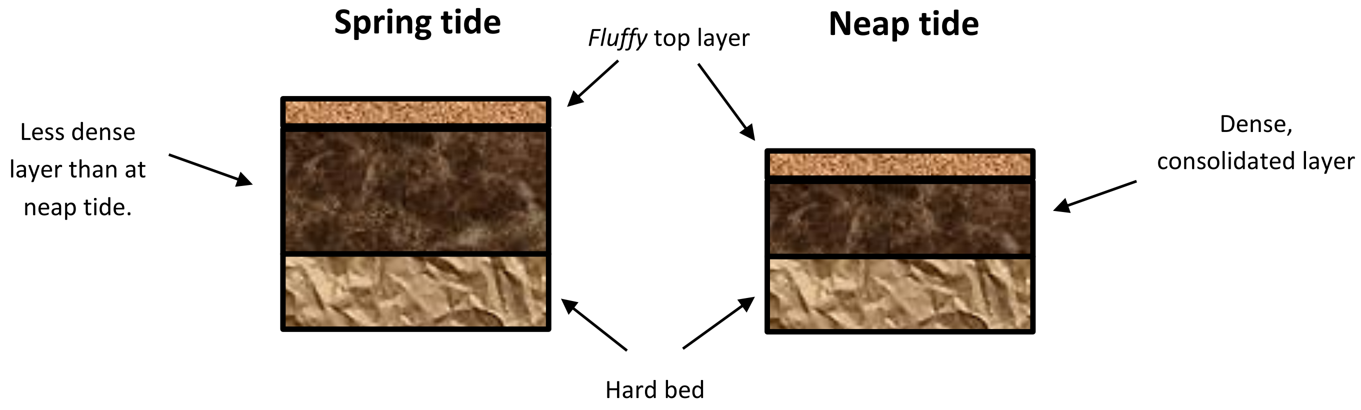

Figure 48: Bed layers

10.3.3. QUANTIFICATION OF MODEL ERRORS

To quantify the model errors and therefore its performance, the tests as explained in chapter 3 will be used. In Table 19 a short explanation can be found of the different quantification formulae.

Table 19: Short explanation quantification of model errors

		Short explanation
Bias		A positive bias indicates that the model over predicts the observations
RMSE		Expresses how accurate the model is and how close the modelled values are to the observed values
BSS		Performance of the model with its qualifications given in **Table 3**.
	Alpha (α)	This term denotes the phase error and therefore the time at which a given concentration occurs. Perfect phasing gives $\alpha = 1$.
	Beta (β)	This term denotes the amplitude error and therefore the concentration of the mud. Perfect modelling of phase and amplitude gives $\beta = 0$.
	Gamma (γ)	If $\gamma > 0$, then the predicted average mud concentration is different than the measured concentration.
	Epsilon (ε)	This is a normalization term, which is affected by the observed anomalies and its standard deviation.

QUANTIFICATION OF THE MODEL ERRORS – PARAMETERIZATION

The model results of the parameterization process are listed in Table 20.

Table 20: Quantification of the model errors - Parameterization

	Calibration model 2	**Calibration model 2A**	**Calibration model 2B**	**Calibration model 2C**	**Calibration model 2D**	**Calibration model 2E**	**Calibration model 2F**
Changed parameter	Final model	Decreased ssc	Flocculation turned off	Halved erosion coefficient value	1 layer	Increased critical shear stress top layer	Increased thickness of the top layer
RMSE	119.1530	119.1530	148.8186	57.8680	47.0414	47.0422	129.9796
BSS	-25.5610	-25.5610	-40.5313	-5.0661	-2.4166	-2.4167	-30.6430
Qualification BSS	Bad	Bad	Bad	Bad	Bad	Bad	Bad
Alpha	0.0044	0.0044	0.1058	0.0321	0.0308	0.0308	0.0035
Beta	7.7082	7.7082	8.4029	2.4194	2.3677	2.3677	8.8300
Gamma	17.9308	17.9308	32.3492	2.5957	0.0891	0.0892	21.9042
Epsilon	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028	0.0028
Performance compared to model 2, as seen by the bare eye	-	Neutral	Worse	Better	Better	Better	Neutral

Unfortunately, the BSS's for all the parameterization models are bad, though the different parameter settings do have an effect on the performance of the model.

The decreased ssc in model 2A does not have an impact on the model, which could already be seen in its graph.

In model 2B, where the flocculation has been turned off, the model has worsened, which can be seen in both the graph, BSS and RMSE. The alpha, which denotes the phase error, has actually become slightly better, due to the better phasing of the model. However, the beta and gamma, which both depend on the volume of the sediment, have worsened, due to higher concentrations and less settling of the sediment.

Model 2C, with a lower value for the erosion coefficient, gives better results than the final model 2. All the values are better for this model than for the final model 2.

Model 2D also gives better results than model 2, but is not realistic since the model only has one layer. Especially the gamma has greatly improved, compared to the previous models. This is due to the fact that the average value of ssc of the model, fits that of the data better. The main difference between model 2D and model 2C is the peak on the ebb tide. Reducing this peak in model 2D impacts the average ssc in the model.

Model 2E gives almost the same results as model 2D. This has been accomplished by increasing the critical shear stress for the top layer, which has almost the same effect as having one layer, because it is more difficult for the sediment in the top layer to erode in model 2E.

Model 2F gives comparable results to model 2. The BSS has slightly worsened, as well as the RMSE, but there are no major differences between these two models. This is mainly because the thicker top layer only has a massive effect on the first ebb tide. The rest of the model is quite the same as model 2.

QUANTIFICATION OF THE MODEL ERRORS – VALIDATION

The model results of the validation process are listed in Table 21.

Table 21: Quantification of the model errors - Validation

	Verification model 1	Validation model 2	Validation model 3	Validation model 4	Validation model 5
Bias	-15.4807	-4.2724	0.8839	-6.4966	0.0814
RMSE	20.0326	10.577	11.7078	12.1887	9.4526
BSS	-0.0097	0.7308	0.6693	0.6149	0.8060
Qualification BSS	Bad	Good	Good	Good	Excellent
Alpha	0.7325	0.7970	0.6910	0.7603	0.8195
Beta	0.1591	0.0093	0.0145	7.17E-04	0.0134
Gamma	0.5833	0.0569	0.0073	0.1448	1.26E-04
Epsilon	2.09E-04	2.09E-04	2.09E-04	2.09E-04	2.09E-04

10.3.4. COMPARISON OF THE 2D AND 3D MODEL

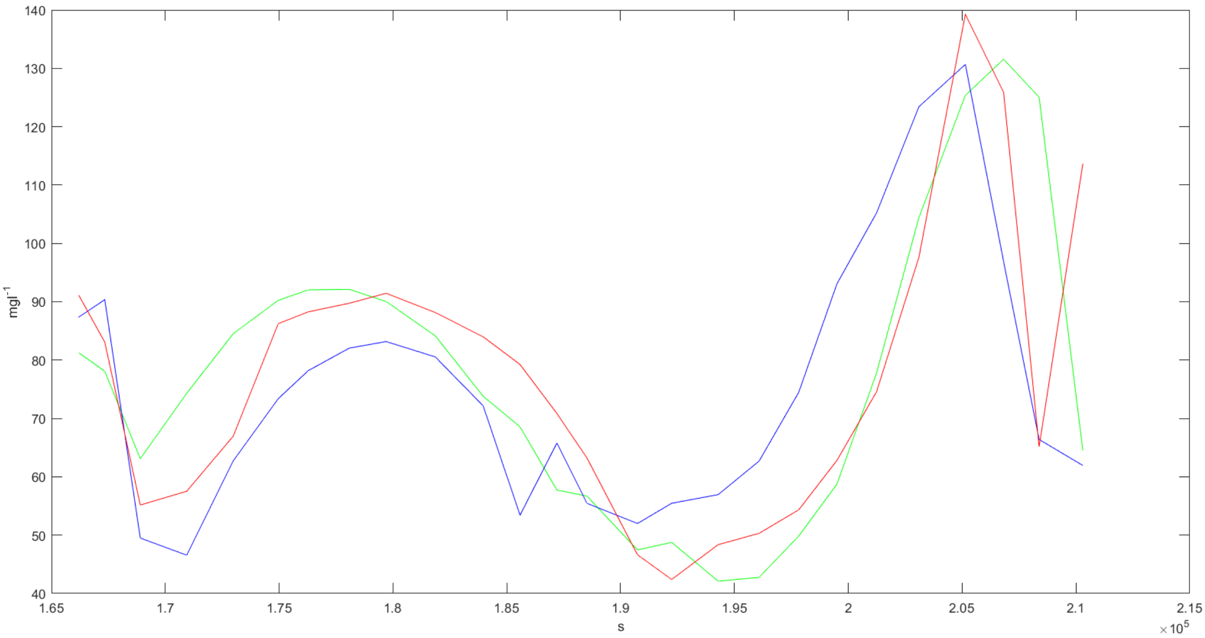

Figure 49: Comparison of the 2D and 3D model for the spring tide. With red is observed, green is 2D model, blue is 3D model.

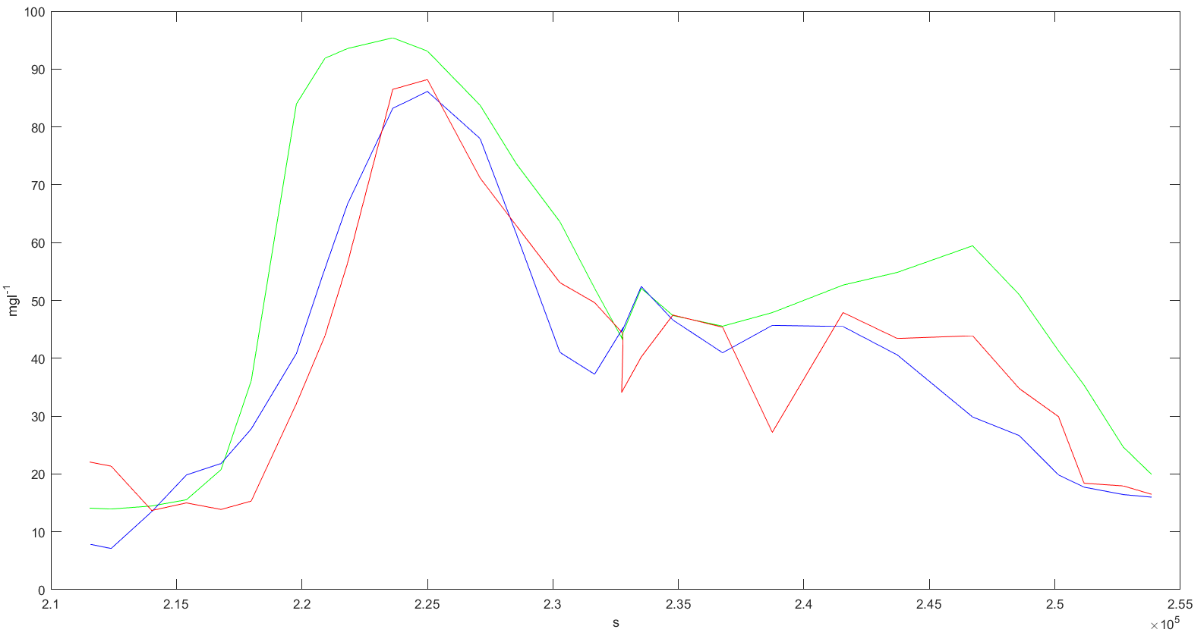

Figure 50: Comparison of the 2D and 3D model for the neap tide. With red is observed, green is 2D model, blue is 3D model.

10.3.5. ZONATION OF THE 2D MODEL

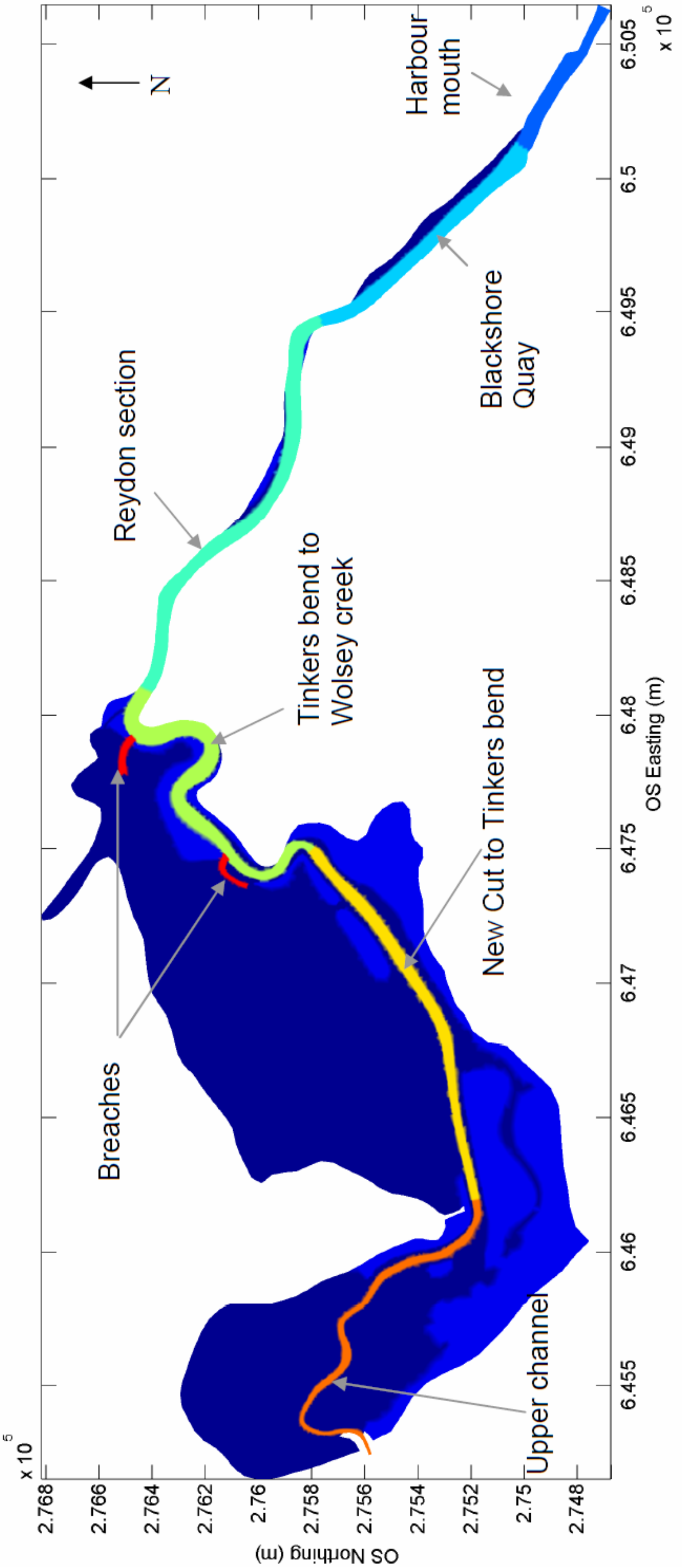

Figure 51: Zonation 2D model (Benson, 2004).