Tidal Meanders in the Ameland Basin

A study to the underlying processes in the evolution of tidal meanders

S. W. van Til
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A study to the underlying processes in the evolution of tidal meanders

by

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Until recently my family was in the possession of a Waarschip 10.76 m sailing boat with which we have sailed on almost all Dutch waters. As can be expected from the title of this report, the Wadden Sea was also overcome. Thinking back to that time, I have many good memories like sailing backwards as the result the tidal currents, or seals that swam besides our boat. On the other hand, I certainly have not forgotten about the storms that we got into. During a storm on the Wadden Sea not only the currents and the waves try to get a grip on the boat, but also the waves created by fishing boats and ferries were shaking us up to every imaginable direction. When we arrived in calmer waters behind an island, the currents were still strong enough to push the boat onto a tidal flat. Actually, safety was only assured when being moored in the harbor and with land beneath our feet.

This thesis completes the Master of Science program in Civil Engineering at the Delft University of Technology. While working on this thesis, I came to realize once again that a lot of different things are going on in the Wadden Sea. Many natural and non-natural influences are continuously changing the environment. It is therefore difficult to keep track of which processes govern in changing the meandering extent of the tidal channels. However, this is what makes researching the Wadden Sea both exciting and challenging. I am very grateful for the opportunity to research the dynamic character of the Wadden Sea behind Ameland. Therefore, I would like to thank Zheng Bing Wang for introducing me to the subject and for sharing his knowledge and experiences with me in the past months. Your critical questions during meetings and your help with evaluating the results have helped a lot in improving this report. I would like to thank Han Winterwerp for providing valuable and constructive feedback during meetings. I want to thank Jelmer Cleveringa for the inspiring conversations we had about the geographic analysis of the channel evolution. And I want to thank Bram van Prooijen for his valuable feedback on my report and all his advise within and outside the scope of this thesis.

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The fairway connecting Holwerd and Nes forms the main transport route between Friesland and Ameland (the Dutch Wadden Sea). It consists of several tidal channels that funnel the majority of the tidal currents propagating through the tidal basin. Over the past decades, several channel bends have expanded leading to a fairway length-increase of about 1 km, and the channel in front of Holwerd has become subject to sedimentation. Since 1990 this channel was dredged and the volume of dredged material has increased exponentially. A relation between dredging activities, channel migration and frequent delays of the ferry has been suggested. The main goal of this thesis is therefore to explain the difference in evolution between the non-natural (intervened) and natural tidal meanders in the Ameland basin. To achieve this goal, the evolution of geographic channel dimensions are analyzed by assessing bathymetric data and the outcome is linked to the physics by means of hydrodynamic modeling.

Channels have been classified based on their locations and dimensions. Three meandering stages have been identified that describe the basic channel behavior. The first meandering stage is the developed meander, characterized by a clear sinusoidal shape and with flood chutes. In this stage, the depth at a cross-over is approximately two times smaller than at the channel section with a maximum curvature (the "channel top"), where the width profile is funnel shaped. The developed, variable meander has similar characteristics, but differs by a lower correlation in width and bed level, and closer to the tidal watershed the ebb channel location varies more in time. The third stage is the undeveloped meander, which is characterized by small and relatively straight channels, the absence of flood chutes, and a rather constant bed level and width profile along the channel. In this study, the channels are evaluated that have similar meandering features and distance from the Ameland inlet as the dredged channels. In general, the examined channels showed a width reduction that dominates over the bed level increase. An irregularity in the width and/or bed level along the channel is an indicator for the development of a bifurcation or flood chute.

Numerical modeling of the tidal currents revealed a correlation between the depth averaged velocity and the funnel shaped channel top. From the depth averaged velocities it is found that flow accelerates around the channel tops, where flood dominance prevails and flood chutes (are able to) develop. During ebb, a similar acceleration occurs towards the point of inflection, where ebb dominance prevails. Increasing meanders correspond to a shift towards ebb dominance in both natural and non-natural channels. By evaluating the secondary flow velocities along the channels, an eastward shift of the cross-over location is observed. Whether the shift corresponds to the channel migration, or that it strengthens the potential for channel splitting is not proven. However, an indication is found that a correlation exists between the distance between channel tops and the cross-over location shift. When the meanders develop, the distance between the tops increases, enabling a larger area over which the direction of the secondary flow can change. Furthermore, the orientation of the currents over the tidal flats and the angle under which they flow into the channel seems to be correlated. Also the importance of flood chutes to the meandering development is brought forward. The development of a chute increases the flow area and reduces the flow velocities in the ebb channel adjacent to the flood chute, which thereafter becomes shallower. After a flood chute is established, and it obtained a more west-east orientation, the flood currents over the tidal flat are deflected towards the ebb channel. As a consequence flow velocities increase in the ebb channel, resulting in a westward migration of the ebb channel.

Comparing the natural and non-natural channels, the meandering extent (average sinuosity) is approximately 10% larger for the non-natural channels. This sinuosity also increases over time in the natural channels, but to a lesser extent. By dredging, irregularities in width and bed level are flattened out and the flow during ebb as well as during flood is concentrated through the ebb channel. This resulted in the non-natural development of the eastern Kikkertgat-bend and the stagnation of the flood chute development. Therefore it is concluded that a non-natural tidal meander in the Ameland basin is distinguished by developing meanders, where the flood chutes are not restricting the development of the meandering ebb channels.
CONTENTS

1 Introduction .......................................................... 1
  1.1 Local Conditions .................................................. 3
  1.2 Fairway Development .............................................. 4
  1.3 Scope of the Research ............................................ 5
  1.4 Research Questions .............................................. 7
  1.5 Thesis Outline .................................................. 7

2 Meandering Theory .................................................. 9
  2.1 The Concept of Meandering Channels ................................ 9
  2.2 Comparison between River and Tidal Meanders .................. 13
  2.3 Channel Classification Methods ................................ 14
  2.4 FlowVelocities ................................................ 15
    2.4.1 Tidal Currents ........................................... 15
    2.4.2 Secondary Flow .......................................... 17

3 Tidal Channel Classification ...................................... 19
  3.1 Available Data ................................................ 19
  3.2 Methodology .................................................. 20
  3.3 Channel Dimensions Results .................................. 25
    3.3.1 Macro-Scale Developments ................................. 25
    3.3.2 Meso-Scale Developments ................................. 26
    3.3.3 Micro-Scale Developments ................................. 35
  3.4 Conclusions .................................................. 42
  3.5 Other Characteristics ........................................ 45

4 Numerical Modeling ................................................ 49
  4.1 Methodology .................................................. 52
    4.1.1 General Model Set-Up ..................................... 52
    4.1.2 Simulation Specific Set-Up ............................... 53
  4.2 Results Depth Averaged Flow Velocities ....................... 58
  4.3 Meandering Development ...................................... 60
  4.4 Secondary Flow Results ....................................... 62
    4.4.1 Kikkertgat Results ....................................... 62
    4.4.2 Noorder Spruit Results ................................ 64
    4.4.3 Other Channels .......................................... 66
  4.5 Conclusions .................................................. 68

5 Discussion .......................................................... 69
  5.1 Assumptions and Approach ..................................... 69
    5.1.1 Limitations Data Resolution ............................. 69
    5.1.2 Tidal Channel Classification ............................ 70
    5.1.3 Hydrodynamic Modeling ................................ 71
  5.2 Interpretation of the Results ................................ 72
  5.3 Study Applications ........................................... 74

6 Conclusions and Recommendations ................................ 77
  6.1 Conclusions .................................................. 77
  6.2 Recommendations ............................................. 80

Bibliography .......................................................... 81

List of Figures ........................................................ 85
List of Tables

A  Bathymetry Maps  
B  Tidal Channel Classification  
  B.1  Morphological Scales  
  B.2  Sailing Time Ferries  
  B.3  Coriolis  
  B.4  Curvature derivation  
  B.5  Sinuosity  
  B.6  Outlier Removal Procedure  
  B.7  Hypsometric Curve of the Ameland Basin  
  B.8  Curvature plot  
  B.9  Bottom Slope  
  B.10  Micro-Scale results  
  B.11  Probability Distributions Channel Cross-Sections  
C  Numerical Modeling  
  C.1  Time-Step and Threshold Depth Calculation  
  C.2  Two-Dimensional Model  
  C.3  Three-Dimensional Model  
  C.4  Location Observation Points  
D  Numerical Modeling Results  
  D.1  Observation Points along the channels  
  D.2  Difference Plots 2DH  
  D.3  Difference Plots 3D  
  D.4  Kikkertgat  
  D.5  Noorder Spruit  
  D.6  Zuider Spruit  
  D.7  Noorder Kikkertgat  
  D.8  Zuider Kikkertgat
I N T R O D U C T I O N

The fairway between Holwerd and the island Ameland forms the only connection between the island and the mainland. It is therefore of vital importance to the inhabitants of Ameland and the tourists visiting the island. However, the positioning of the fairway is dynamic and it is prone to sedimentation and meandering. Over the past decades, sedimentation in the fairway increased significantly resulting in a large increase in required dredging activities. Due to the meandering evolution, the fairway length increased by 1 km. Previous studies (e.g. [1], [2] and [3]) indicate that a relation exists between the meandering evolution and the dredging activities. This thesis will further focus on this relationship by examining the evolution of the channels in and around the fairway. Throughout this thesis, the analyses are elaborated by describing the developments from the large-scale towards the small-scale developments. According to this principle, first a description of the study area and the local conditions are presented in this chapter. Thereafter, the problem is defined and the goals and research questions are presented.

The international Wadden Sea covers an area of approximately 10,000 km$^2$ and spans a distance of nearly 500 km of coast (Elias et al. [4]). Thereby, the Wadden Sea is the world’s largest coastal wetland, consisting of a large stretch of tidal flats and barrier islands. During low tide, more than two-third of the Wadden Sea runs dry. Tidal flats and salt marshes then expose a great biodiversity, which attracts a large variety of birds. This great biodiversity and the ecological importance of this area resulted in 2009 in the designation of the Wadden Sea as a Natura-2000 protected area (RWS [5]).
Five islands form the barrier of the Dutch Wadden Sea against hydrodynamic forcings from the North Sea (see Figure 1.1). The island of Texel belongs to the province of Noord-Holland and Schiermonnikoog is part of the province of Groningen. Islands Vlieland, Terschelling and Ameland belong to Friesland and are referred to as the Frisian barrier islands. The tide enters the basin through the inlets between the islands. The semi-diurnal constituent M2 is the main component driving the tides. Inside the basin the tidal currents are mainly discharged through a system of channels, which are defined as the parts of the Wadden Sea that are permanently submerged. With the rising tide, first the channels and eventually the tidal flats will become flooded. This process is associated with currents and therefore movement of sediments. The result is a dynamical system in which the geometry is reshaped continuously.

As time proceeded, human interventions in the coastal region and in the Wadden Sea have become more important in the changing system. Levees were built, salt marshes were drained and the coasts were reinforced with hard and soft solutions (Beets and Van der Spek [7]). In 1932 the construction of the 30 km long Afsluitdijk was completed (Wang et al. [8]). This dam separated the Zuiderzee from the Wadden Sea, causing large changes in the Wadden Sea system. The propagation of the tide and the sediment balance in the basin have changed, i.e. the system was driven away from its morphological equilibrium.

A part of the imported sediments are deposited in the tidal channels and on the tidal flats. Zooming in on the Ameland basin, i.e. the area between the tidal watershed (Dutch: wantij) behind Ameland and Terschelling, this forms a problem for the ferry that sails between Holwerd and Nes. This ferry forms the main means of transportation between the mainland and Ameland and it sails through a series of tidal channels. Approximately 650000 passengers, 79000 vehicles and 93000 trucks were transported in 2015 [9], which highlights the importance of the ferry. As a result of the sedimentation, the navigability of the fairway was threatened and in 1990 dredging activities were initiated.

![Figure 1.2: The rapid growth of the volume of dredged material, source: Rijkswaterstaat, original figure: Cleveringa [10].](image-url)
From the dredging data it was found that the volume of dredged material has increased by a factor 4 over the last 10 years, as can be seen in Figure 1.2 [10]. In addition, the fairway length has increased by a kilometer since 1990, resulting in a 10 minute longer sailing time. This is especially important as longer sailing times could mean that the same ferry cannot make the return journey. The delayed departures of the ferry (25.5% in 2014 [11] and 34.9% in 2015 [9]) caused much discontent among passengers. The (socio-) economic impact of these aspects form the reason why the cause of the length- and dredged volume increase has to be researched. Compared to the other channels in the basin, the fairway channels show non-natural meandering patterns.

Whether this is the case has to be investigated to understand the future development of the fairway channel. The goal of this research is therefore to:

*Explain the difference in evolution between non-natural and natural tidal meanders, to understand the future behavior of channels that are intervened.*

In order to converge to a research question corresponding to this goal, a description of the study area will be presented in Section 1.1 and the conclusions from recent studies to the channel development will be presented in Section 1.2. The scope of the research is defined in Section 1.3, the research questions are presented in Section 1.4 and the outline of the rest of the report is described in Section 1.5.

### 1.1. Local Conditions

Ameland is the fourth barrier island that forms the border in between the Dutch Wadden Sea and the North Sea. The shape, orientation and location of the barrier islands is dependent on several factors. Historical studies showed that the Wadden Sea was formed mainly under the influence of river outflow, waves and the tide (Beets and Van der Spek [7]). The barrier islands largely dampen the North Sea waves and the closure of the Zuiderzee and the Lauwerszee largely reduced the river discharge. Therefore, the tide is the major hydrodynamic forcing that enables morphological changes in the Wadden Sea.

The North Sea tides entering the basin are driven by the tidal (Kelvin) waves that rotate anti-clockwise around two amphidromic points in the North Sea (Pugh [13]). This principle is shown in Figure 1.3, from Kvale [12]. The tidal wave travels Northwards along the Dutch coast, entering the Wadden Sea through the tidal inlets in between the barrier islands. The Ameland basin is influenced by the tide entering at the Borndiep and Pinkegat inlets, which are presented in Figure 1.4. The basins boundaries are prescribed by two tidal watersheds. A tidal watershed is the location in the basin where the incoming tides from the tidal inlets meet. Due to the basin’s topography, the location of the inlets and the length of the islands, there is a tidal phase difference is between inlets. Vrooom [14] discovered that this phase difference can be related to the location of the tidal watershed, which causes the watershed to be located more to the east.

Dronkers [15] found that the ebb period is longer than the flood period. The same volume of water flows in- and out of the basin, so on average the flood currents are stronger than the ebb currents, resulting in a net import of sediment. The flow velocities are at a minimum during transition from ebb to flood (and vice versa). This is called the slack water period, during which sediment settlement is enhanced due to the lower flow velocities. The mean tidal range in the Dutch Wadden Sea is approximately 2 m and the dominant wind direction is southwest to west, see Duran-Matute *et al.* [16]. In Dronkers [17] it was described that a close relationship exists between the flow area, $A$ [m$^2$], and the tidal prism, $P$ [m$^3$]. The flow area consists of the wetted part of a channel cross-section and the tidal prism is the volume of water that is transported through
1.1. INTRODUCTION

The channel per half tidal cycle (Bosboom and Stive [18], p. 408). A simplification of this relation is depicted by:

\[ A \propto P^b \]

in which \( b \) is a value close to one. The average flow velocity can give an indication of the channel dimensions and vice versa. The simplified equation

\[ u = \frac{P}{A \cdot T} \]

describes this relation for a tidal period \( T \). It implies that if the flow area \( A \) reduces, the average velocity increases with the same tidal volume. When the velocity is reduced, its ability to pick-up sediments from the bed reduces. So if a channel is naturally reducing its flow area, it means that less water \( P \) is being transported through the channel. When the channel is then dredged to improve the navigability, flow velocities will drop and the calmer conditions increase the sediment deposition rate. In this way the channel is striving for an equilibrium between the depth averaged velocity and the tidal volume.

1.2. FAIRWAY DEVELOPMENT

This Section summarizes the main conclusions from the Alkyon-studies ([1] and [3]). In Steijn [3] the aim was to find the cause of the increasing dredging volume and to present a prediction of the dredged volumes in the future. The relation between the cross-sectional area and the amount of water flowing through the channel was therefore highlighted. If the volume of water decreases, the flow velocities reduce and the channel adapts by reducing the width and the depth. Two mechanisms were identified that influenced the development of the Kikkertgat channel (see Figure 1.5). The first mechanism is the reduction of the water volume that flows through the channels. This is described as a consequence of the stronger meandering Dantziggat channel, and this mechanism is held responsible for about 1/3 of the sedimentation in the Kikkertgat (see Figure 1.4). The changing orientation of the Dantziggat creates a redistribution of the water over the channels, which has a negative effect for the volume of water flowing through the Kikkertgat.

The second mechanism is responsible for the remaining 2/3 of the problem and beholds the movement of the tidal watershed. Increasing meanders in all channels is causing a westward movement of the tidal watershed. This movement is reinforced by the morphological developments in the Pinkegat inlet and it reduces the storage capacity of the Ameland basin. The storage capacity of tidal channels can be described by the tidal prism. Therefore the study by Alkyon [1] consisted of the behavior of the tidal watershed over time. Hydrodynamic model simulations were performed to determine the location of the tidal watershed and an eastward transition was found. Because several sources described contradicting developments of the tidal watershed regarding its influence on the tidal prism, no uniform conclusion could be drawn from the watershed movement. The morphological analysis Alkyon [1] exposed several other mechanisms that could
influence the reduction of the tidal prism. Besides the mechanism described before, the sedimentation on the tidal flats and salt marshes, the local change of the tidal watershed between the catchment areas of the Noorder Kikkertgat and the Zuider Kikkertgat (the channel names are presented in Figure 3.1), and the separation of the ebb- and flood currents at the ebb- and flood-chutes, can influence the reduction of the tidal prism. The influence of these mechanisms to meandering is difficult to determine, and therefore it is needed to further extend the knowledge of these mechanisms.

1.3. **Scope of the Research**

In this research, the processes that describe the development of tidal meanders are examined from two different perspectives. First, the available bathymetry data is used to examine trends and characteristic dimensions of the tidal channels. The second part of the research consists of a hydrodynamic modeling study. Delft3D is used to examine how the hydrodynamics in the channels have changed over the years. The main research objective is split-up into the following goals for respectively the parts Tidal Channel Classification and Numerical Modeling:

A. **Tidal Channel Classification:**

Classifications of tidal channels have been proposed for the Western Scheldt estuary (e.g. Jeuken [19] and Winterwerp *et al.* [20]). For the Wadden Sea basin, correlations between characteristic channel dimensions have been examined by Cleveringa and Oost [21]. Van Veen [22] presented a classification of tidal channels on the level of individual ebb and flood channels. A general classification of the tidal channel system in the Wadden Sea has not been established yet and therefore a combination of classification methods will be used to classify the tidal channels per basin. This leads to the research goal for this part of the research:

*Classify the system of channels to their locations and dimensions and find the characteristic properties that describe a natural meander.*

Many different processes affect the evolution of tidal channels, each at a different spatial scale (see De Vriend [23] and Appendix B.1). On the scale of the entire basin the strongest forcing is the tide and sediment im- or export defines the large-scale channel development. Individual channels are more dependent on the volume of water that flows through the channel every tide. Finally, channels are bifurcating and flood chutes develop. More understanding of these processes would contribute to the explanation of the local channel evolution. Because these scales cannot be elaborated at once, they will be described in the subsequent order. This will ease the narrowing down of relevant properties to find the characteristic ones. A schematic overview is presented in Figure 1.6 to clarify the scope and the approach to the classification of the tidal channels.
B. Hydrodynamical Modelling:
When the characteristic properties of the system of channels in the Dutch Wadden Sea have been assessed, the influence of the hydrodynamics on the Micro-scale channel evolution will be examined. The focus of this Section is on distinguishing trends in the development of Micro-scale channel sections. The main goal is therefore described as:

*Determine the trends in depth averaged- and secondary flow velocities that relate to the origin and development of tidal meanders in the Ameland basin.*

The influence of the secondary flow can be examined by performing 2DH and 3D simulations. In the 2DH simulations, depth averaged flow velocities can be calculated and the secondary flow intensity can be approximated. In 3D simulations, variations over the depth are taken into account and the bed shear stresses can then be evaluated. Both simulations will be executed and the effect of flow velocities on channel migration will be discussed.

Figure 1.6: Flow chart that represents the approach of and the converging procedure of the channel classification analysis. Blue indicates data analysis and red indicates numerical modeling.
1.4. RESEARCH QUESTIONS

Why and How the tidal channels are developing in time form the core interest of this research. In the first part of the research, the tidal channel classification, multiple years of topographic data will be examined to examine the channel development in time. The three spatial scales that are used in this respect contribute to the distinguishing of trends and hypotheses for the numerical modeling part of this research. The main research question for this part is therefore formulated as (RQ A):

What are the trends in the development of tidal channels that characterize natural meandering behavior in the Ameland basin?

To specify this research question, the following subquestions are defined:

a.1 Which channels can be used for the comparison between natural and non-natural meandering channels?

a.2 Which channel dimension was affected the most by the changes in the system?

a.3 How do the channel dimensions change in a channel bend and are these dimensions influenced by a bifurcation or flood chute?

a.4 In what way are the dredged channel and the adjacent Kikkertgat channel different from natural meanders?

Bathymetry maps provide data that is static in time and the dynamic aspects can therefore not be tested in this way. Wind, waves and currents are driving the hydrodynamic and morphodynamic changes in the basin. To indicate how these affect the evolution of a tidal meander, numerical model simulations are applied. Only the hydrodynamics are modeled to provide an indication how they are related to meandering development. In rivers, flow velocities in a bend are found to have a strong three-dimensional character and a circulatory water movement (secondary flow) is formed [24]. The influence of the secondary- and depth averaged flow velocities on the meandering development are therefore analyzed. The following research question is proposed for the hydrodynamic modeling part of the thesis (RQ B):

What trends in the depth averaged- and secondary flow velocities can be distinguished that could influence the development of a tidal meander?

The answers to the following subquestions will support the main research question of this part:

b.1 How does the depth averaged flow relate to the changing channel dimensions?

b.2 How does the secondary flow relate to the changing channel dimensions?

b.3 How are the tidal currents related to channel bifurcations?

1.5. THESIS OUTLINE

For the understanding of the evolution of meandering tidal channel development, background information to the concept of meandering and a literature review are presented in the Chapter 2. In Chapter 3, Tidal Channel Classification, the channel dimensions are determined for several years with data and a comparison is presented how the non-natural channels differ from the natural channels. The description of these differences result in the proposition of several hypotheses in Section 3.5. By applying numerical modeling in Chapter 4, the hypotheses are tested and the development of depth averaged- and secondary flow velocities in the channels are described. Both Chapters 3 and 4 are elaborated according to the structure presented in Figure 1.6. This means that first a data description is presented, followed by the methods that are applied for obtaining the results. Subsequently, the results are presented and discussed, and each chapter ends with a description of the main conclusions. Chapter 5 features a discussion of the findings and methods and finally the conclusions and recommendations of the entire study are merged and summarized in Chapter 6.
Meandering is the term used to describe a series of bends in a stream channel. A meandering pattern is formed when water flows through an erodible environment. In riverine environments meanders have been studied in more detail than for tidal environments. In tidal environments like the Wadden Sea, meandering patterns can be found at three different kinds of systems: 1) at salt marshes; vegetated areas in the inter-tidal zone [25]; 2) at tidal flats, which are sandy/muddy areas that are only submerged during high water and 3) tidal channels, which form the main transporting body for the tidal currents. Each tidal system is related to different flow velocities, grain size and location in the basin. In order to understand the relation between these parameters and the evolution of meandering tidal channels, the underlying processes are explained first in Section 2.1. Principles from river meanders will be used in the analyses, so Section 2.2 will describe the applicability in a tidal environment. Thereafter, tidal channel classification methods are revised. This Chapter concludes by describing the theory of the description of the tidal currents, which is applied in numerical modeling in Chapter 4.

2.1. THE CONCEPT OF MEANDERING CHANNELS

A meandering channel consists of a system of bends. In channel bends, variations are found in the bottom profile, flow distribution and water level. Several processes are related to variations in these aspects. To begin with, stable flow conditions will change once it arrives at a bend. A centrifugal force is directed towards the outer bend and generates a water level gradient over the cross-section. This gradient is often described as a pressure gradient that is balanced by a downward directed flow [18]. A circulatory water motion is initiated that has the ability to transport sediment. Erosion takes place at the outer bend and sediment is deposited at the inner bend (see Figure 2.1). As a result, a non-linear bottom profile is formed in the transversal direction, i.e. perpendicular to the channel centerline.

Figure 2.1: Schematization of the origin of the circulatory motion in a channel bend, Figure obtained from Bosboom and Stive [18]
The circulatory water motion is analogous to the Coriolis-induced circulation and therefore the shallow water equations can be applied to describe the transversal force balance [18]. When stationary uniform flow is assumed, the force balance yields

\[
\frac{-u^2}{R} + f u + \frac{1}{\rho} \frac{\partial p}{\partial y} - \frac{\partial}{\partial z} \left( \frac{\partial v}{\partial y} \right) = 0
\]

\[\text{(2.1)}\]

In this equation the first term represents the centrifugal force, which is derived from \( F = \frac{m v^2}{R} \) in which \( m \) has been left out of the equation and \( R \) is the radius of the channel bend in meters. The second term represents the effect due to Coriolis and is described as \( f = 2 \Omega \sin(\phi) \), in which \( \Omega \) represents the angular velocity of the earth \((72.9 \cdot 10^{-6} \text{ rad/s})\) and the latitude, \( \phi \), is approximately \( 45^\circ \) at the location of interest. The third and fourth terms represent the pressure gradient and the turbulent viscosity. This force balance was derived by applying the assumptions that the Coriolis force is balanced in a depth averaged sense by a water level gradient. The flow (both ebb and flood) is assumed to have adapted to the channel bend under the influence of bottom friction and the mean surface slope. Furthermore, it is assumed that the channel and the flow structure are angle-independent in a cylindrical coordinate system. When also stratification is neglected and it is assumed that the Coriolis force is negligibly small (see Appendix B.3), the pressure gradient is formed by the water level slope and counteracts the centrifugal force:

\[
\frac{1}{\rho} \frac{\partial p}{\partial y} = \frac{u^2}{R}
\]

\[\text{(2.2)}\]

The circular water motion in a river can erode and deposit sediments from the outer and inner bends (banks). According to Thorne [26], bank erosion and accretion is caused by two distinct mechanisms: fluvial erosion and geomechanical instability. Consequences due to geomechanical instability (bank mass failure) are assumed to be small in an area that is submerged on a regular basis. Therefore only fluvial erosion is considered, which is the erosion of sediment particles by the water flow. Apart from the flow and pressure gradients, many other factors influence the migration and growth of meanders. An overview of these influencing factors was presented by Leopold and Wolman [24] and are discussed now.

To begin with, there is still no general relationship that describes the meandering initiation. Several possible processes are described, such as the relevance of helical flow, i.e. the circulatory water motion in the longitudinal channel direction. Dey [27] brings forward the Coriolis effect on the initiation of flow velocity gradients, Inglis [28] described the concept of excess flow energy and Werner [29] highlighted the importance of local disturbances in the bed. In this regard De Vriend and Struiksma [30] presented a relation for the channel length after which the flow has adapted to the local disturbances, i.e. the flow adaptation length:

\[
\lambda_w = \frac{h}{2C_f} = \frac{h}{2 \cdot g/C_s^2}
\]

\[\text{(2.3)}\]

where \( h \) is the total water depth (see Figure 2.5), \( g \) is the gravitational acceleration and \( C_s \) is the Chézy coefficient. However, whether this is related to the meandering initiation is uncertain. Although each of these theories describe plausible causes for meandering initiation, a distinct relation has yet to be found (see e.g. [24] and [27]). Furthermore, correlations between channel dimensions of different groups of data showed that the meandering length and the channel width formed the most consistent relation in developed (river) channels [24].

\[
L = 10.9 B^{1.01} = 4.7 R^{0.98}
\]

\[\text{(2.4)}\]

When assuming that the exponents are equal to one, one can write the ratio of radius of curvature to width by:

\[
\frac{R}{B} = \frac{10.9}{4.7} = 2.3
\]

\[\text{(2.5)}\]

This ratio was calculated for 50 rivers and resulted in a mean of 3.1 and a standard deviation of approximately 1.3. The amplitude of a stream channel, however, appeared to show a poor correlation with the meander length. Friedkin [31] supports the argument of Leopold and Wolman [24] that the amplitude is more determined by the erodibility of stream banks and by other local factors, so a simple relation was not found. However, the existence of meanders during stream experiments on ice contradicts this argument. Therefore it was concluded that sediments may alter or affect the meandering pattern, but it does not cause the meandering pattern. This is interesting to keep in mind, as in the Ameland basin a combination of sand, mud and silty
sediment compositions are present [2]. If the main course of the channels is not primarily originating from differences in sediment composition, other governing factors in the channel evolution are expected.

Besides geographic, also dynamic features have been examined for meandering channels in rivers. In that sense Leopold and Wolman [24] continued by describing that flow velocities and sediment transport in meandering channels are much reduced compared to straight channels of similar dimensions. This means that more energy is dissipated along the meandering channel than in straight channels. The increase in channel length could therefore be related to the energy expenditure per unit channel length, which decreases with a length increase. By this argument, it could be stated that a channel bend is always striving to a morphologic equilibrium and that the bend is most stable when the energy loss due to curvature is at a minimum.

**Idealized planform for a meandering stream channel**

To find an answer to research question A., the geometric channel features are analyzed in Chapter 3. The idealized planform from Dey [27] is adopted for the description of the meandering channel dimensions. In Figure 2.2 a meandering river section is presented, including of the relevant geometric channel features. The x-axis describes the centerline of the meandering planform downstream of the valley slope in a rectilinear coordinate system, and the n-axis is the centerline of the meandering path in a curvilinear coordinate system. The points of inflection for changing curvatures are called cross-overs, i.e. $I^{-1}$, $I_0$, $I_1$ and $I_2$. A meander is defined as any portion of the channel along the n-axis containing three cross-overs (Marani et al. [32]). The deflection angle $\theta$ is maximum at a cross-over ($\theta_0$). The meandering wavelength, arc length, belt width and amplitude (or meandering width) are represented by $\lambda_m$, $L$ (or $L_{arc}$), $B_m$ and $a_m$. The radius of curvature is represented by $R$ and the average flow width is $B$.

![Figure 2.2: Idealized planform for a meandering channel section. This figure presents the definitions of the channel dimensions that are used throughout the report. Figure obtained from Dey [27].](image)

In literature these channel dimensions are applied to describe the meandering evolution. Often this is done by looking at ratios between dimensions and one ratio in particular is important for the description of a meander: the sinuosity, $S$. Sinuosity in this report is defined as the ratio between the length of the stream channel along its centerline, and the length between the start and end of the channel (Rust [33]):

$$S = \frac{L_{arc}}{L_{abs}}$$  \hspace{1cm} (2.6)

in which

$S$ = Sinuosity [-];

$L_{arc}$ = The arc-length of the channel, i.e. the distance between the start and end point of a channel along the centerline [m];

$L_{abs}$ = The distance between start and end point of the channel [m].
For meandering rivers, different definitions of sinuosity exist to describe the degree of meandering. In Appendix B.5 several definitions of sinuosity are presented. In general, each definition describes the channel stage by the following rules:

\[
\begin{align*}
S > 1.5 & \quad \text{Meandering channel} \\
1.1 \leq S \leq 1.5 & \quad \text{Braiding channel} \\
S < 1.1 & \quad \text{Straight channel}
\end{align*}
\]

The circulatory water motion is inverted when water flows from one bend into the other. Around the cross-over, this inversion takes place. Here, the flow velocities are distributed more evenly over the channel width, after which they are transposed to the other side of the channel into the next bend. The location in the bend with a maximum curvature, is referred to in this thesis as the channel top. Furthermore, channels can bifurcate and, in case of a tidal channel, create flood chutes. The difference between these two types of splitting is that a bifurcation results in two separate channels with meandering features, while with a flood chute the largest body of water is still discharged through the ebb channel. An overview of these definitions is presented in Figure 2.3.

Figure 2.3: A presentation of the definitions bifurcation, flood chute, channel top (CT) and cross-over, which are used throughout the report. The two branches of a bifurcation show meandering features. For flood chutes the largest body of water is still discharged through the channel.
2.2. COMPARISON BETWEEN RIVER AND TIDAL MEANDERS

River meanders and tidal meanders are different on several aspects. The main difference can be found in the bi-directional flow which is related to the tide, and the tidal flat or salt marsh run-off during the falling tide. Besides the different flow direction, the basin's geometry is an important factor in determining the volume of sediment available for transport. In rivers, the size and amount of sediment particles is more dependent on the distance from the river origin and the erosion of the flood plains. Whereas flood plains generally become submerged several times per year, the tidal flats in the Wadden Sea are submerged every high water, i.e. twice per day. Wind waves are also presumed to be of larger influence than in a riverine environment, because of the larger available area (fetch) for wind waves to develop. However, the tidal flats and salt marshes can reduce the formation of wind waves and the Frisian barrier island largely dampen the waves originating from the North Sea. Waves with a significant height may be of influence on the erosion of banks as they dissipate energy in the shallower sections of the channel and on the flats.

Another important difference can be found in the evolution of meandering bends. Unrestricted river bends evolve until two bends collide and a bend is cut-off. The abandoned river sections thereafter accrete and the straightened channel will restart the meandering process. This is not - or very rarely - experienced in tidal meanders. However, they do show a phenomenon that was described by Van Veen [22] as ebb- and flood chutes (see Figure 2.3). These chutes are formed in a bend and look like the flow shoots out of the bend. These chutes seem to occur at locations where the bend has reached a maximum length. Van Veen [22] describes further that the created flood chute (or channel) seldom breaches, which is probably because sediment is transported towards the upstream bar of the channel, causing it to maintain its elevation (see Figure 2.4).

When the radius of curvature in a meander becomes too small, the flow will erode the banks. Eventually the channel will split up into an ebb and a flood channel. A bar is formed in between and the splitting is a consequence of the excessive local width of the channel (Van Veen [22], see also Figure 2.4a). The radius of curvature, sediment properties and flow velocity are also of influence on the splitting of channels into ebb and flood channels. Hence, the splitting in this way will only occur in untrained bends where sand transport and bank erosion occurs. After splitting, the sediment transport most likely dominates in the ebb and flood tidal channels. If a channel is bifurcated, the flood velocities are damped by the submersion of the tidal flats. The ebb tidal channel exhibits larger flow velocities, because the water from the tidal flats is discharged towards the

Figure 2.4: Three different bar formations are presented. Channel splitting according to Van Veen [22] is presented in graph a. Source figure: Leuven et al. [34]
channels and thereby concentrating the flow to the ebb channels. The stronger flow in the ebb tidal channel have therefore a higher potential to erode sediments from the banks, and hence increase the meandering of the channel.

Lanzoni and D’Alpaos [35] argued that the width-to-depth ratio, $\beta$, is a key factor in the characterization of the tidal channel morphology, but that a process-based relationship for predicting $\beta$ is still missing. This is acknowledged by Marciano et al. [36], who argues that the large variability in morphologic and hydrodynamic processes complicates the establishment of a process-based model. Describing meanders based on their behavior is therefore more convenient. Marani et al. [32] presented that salt marshes in the Venice Lagoon have a width-to-depth ratio ($\beta$) in the range of 5 − 7, while for meandering rivers $\beta$ varies between 8 and 48. Furthermore, in environments with tidal flats it was found that this ratio showed river-like patterns ($8 < \beta < 50$).

The origin and development of tidal channels are described in a detailed literature study by Hughes [37]. Regarding the channel development, it is stated that channels within the same system may originate from different processes and they may also function differently, depending on their origin. According to Zeff [38], a distinction can be made between ‘through-flowing’ channels that connect two channels, and ‘dead-end’ channels which end in the salt marsh. Between these two types of channels notable differences can be found regarding the channel dimensions and width-to-depth ratio. Besides the dimensions, a significant difference was found in hydrodynamics. At dead-end channels, the peak currents occur close to bank-full conditions (i.e. close to high water). The currents in the through-flowing channels are an order of magnitude larger and the peak currents occur at mid- to low water. This will be taken into account in the description of the differences between the results of non-natural and natural meanders.

2.3. CHANNEL CLASSIFICATION METHODS
Trends in channel evolution in the Dutch Wadden Sea have been examined for the last time approximately 10 years ago. Because in this thesis the channel dimensions are analyzed, a classification of the results will create a better overview of the results. Several classification methods are available for analyzing the tidal channels. These methods are consulted to form a deliberate choice in the classification of the channels in the Amealand basin. An overview of these methods is presented here and will be used in Chapter 3 to describe the results.

Jeuk [19] classified the tidal channels in the Western Scheldt estuary according to their size, location and orientation. In between the ebb tidal channels, connecting channels are present that were subdivided into bar channels (BC), cross channels (CC) and margin channels (MC). The presented method divided the estuary into six sections and for each section the connecting channels and dimensions were described. Thereafter, the morphological channel behavior was studied and comparison was made between the characteristics of the sections.

Horton [39] applied a morphological analysis to determine the number of branches of different size. For that purpose the largest channels are defined as first-order channels. A first-order channel bifurcates and the two resulting branches are then defined as second-order channels (etcetera). The summation of the different channel-orders results in the detection of a branching pattern. The study of Cleveringa and Oost [21] was the first to apply this method to the Dutch Wadden Sea. It was found that the number of channel branches increases logarithmically with decreasing channel order, and that the tidal channel geometry is comparable with a three- to four- times branching network. This means that channels generally bifurcate two to three times. In this study a fractal analysis was also applied to identify the length of the channel-system circumference. This circumference length is related to the tidal flat submersion and runoff towards the channels, and it was found that below the scale of 500 m the circumference does not increase anymore, implying that channels stop bifurcating below this scale.

A method to automatically derive the fractal geometry of tidal channels from bathymetry maps is proposed by Fagherazzi et al. [40]. A certain reference elevation is used below which the channels are detected. The vertical elevation of each point is represented by a colored dot (gray-scale is used), which is darker at deeper sections and lighter at shallower sections. By tuning the brightness and contrast of the gray-scale of these dots, the channels are identified. When the remaining dots are linked, the channel patterns can be derived. By this method the bottom slope and the width of the channels were calculated for several tidal lagoons.
and creeks in the Venice Lagoon, Italy. Marani et al. [32] applied this method to describe the morphological characteristics of meandering channels in three different tidal systems. It was found that the width-to-depth ratio of the channels varied substantially for each location and for different conditions. Meander wavelengths, radii of curvature and width showed a strong non-stationary pattern. The ratio of local width to local radius of curvature, however, fluctuated around rather constant values. This is different from what was found in river meanders [24]. By assessing these dimensions for the Ameland basin, the ratios can be compared to those found in other tidal environments or locations.

2.4. Flow Velocities
Tidal currents are assumed to be the dominant forcing mechanism in the generation and maintenance of tidal channels. The tidal currents in the Ameland basin are bi-directional, i.e. the flood currents are directed landward and the ebb currents are directed seaward. These velocities vary both in magnitude and in comparison to each other, depending on their position within the tidal system [37]. Compared to fluvial systems, the bed slope in the tidal channels is also dependent on the tidal flat runoff and the number of bifurcations. Therefore, the flows in the tidal basin are rather driven by gradients in the water slope than in bed slope (Rinaldo et al. [41]). As the tide proceed mainly through a system of channels, a description of the currents in tidal channels are presented here. The main flow direction is described in Section 2.4.1 as the strongest flow influencing the transport of sediments. Section 2.4.2 describes the curvature induced secondary flow, which is described as one of the factors responsible for channel migration in river bends. In Chapter 4 the hydrodynamics in the Ameland basin are evaluated, mainly focusing on the depth averaged- and secondary flow velocities. The background information of the hydrodynamic aspects are therefore presented in the subsequent Sections.

2.4.1. Tidal Currents
The Ameland basin can be considered as a shallow water basin, because the water depth is much smaller than the tidal wave length. When this is the case, the shallow water approximations to the Navier-Stokes equations can be applied for the description of the tide. These equations are known as the shallow water equations and assume that vertical variations in the water can be ignored by averaging over depth:

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -g \frac{\partial \zeta}{\partial x} - g \frac{u \sqrt{u^2 + v^2}}{C^2} \frac{u}{h} \tag{2.10}
\]

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -g \frac{\partial \zeta}{\partial y} - g \frac{v \sqrt{u^2 + v^2}}{C^2} \frac{v}{h} \tag{2.11}
\]

\[
\frac{\partial (uh)}{\partial x} + \frac{\partial (vh)}{\partial y} = 0 \tag{2.12}
\]

in which
- \(x, y\) = Cartesian co-ordinates in the horizontal plane;
- \(u, v\) = depth-averaged velocity components in x- and y-direction;
- \(h\) = water depth;
- \(\zeta\) = water level elevation;
- \(g\) = gravitational acceleration;
- \(C\) = Chézy coefficient.
The Chézy coefficient describes the hydraulic resistance, which beholds a logarithmic relation. The White-Colebrook formulation of the Chézy coefficient applies an equivalent geometrical roughness of Nikuradse, $k_s$ [m]:

$$C = 18 \log \left( \frac{12h}{k_s} \right)$$

(2.13)

in which the $h$ is the water depth. Another option to determine the Chézy coefficient is by applying the Manning coefficient, $n$:

$$C = \frac{h^{1/6}}{n}$$

(2.14)

Typical value for the Manning coefficient is 0.02 [s/m$^{1/3}$], see Deltares [42]. Both equations are only applicable for depth averaged computations.
2.4.2. Secondary Flow

In Section 2.1 it is described that in river bends a water level difference occurs along width of the channel. As this is the result of the channel bends, it is often referred to as bend-action. Compared to straight channel sections this bend-action adds a flow pattern in the transversal direction, referred to as circulatory flow. When this is combined with the main flow, a spiraling flow field is created and is referred to as spiral flow. The terms spiraling or circulatory motion are merged by the term secondary flow. Secondary flow is defined as the water motion that is deviating from the main flow and to explain its effect on the meandering of tidal channels, the underlying principles are clarified first.

For the understanding of these principles, simplifications have to be adopted. First, an infinitely coiling bend with a fixed bed and a rectangular cross-section is assumed. When axially symmetrical potential flow is assumed, there are no velocity gradients in the downstream (tangential) direction and therefore only transversal water motions are considered. Finally, it is assumed that the secondary flow originates solely from the tidal currents. This means that the shallow water equations (see equations 2.10 to 2.12) can be used, and in order to derive the secondary flow in terms of the primitive variables \( u, v \) and \( \zeta \) the SWE’s are expressed in polar coordinates. The continuity equation yields

\[
\frac{1}{r} \frac{\partial (uh)}{\partial \phi} + \frac{\partial (v h)}{\partial r} + \frac{v h}{r} = 0 \tag{2.15}
\]

Assuming frictionless and axially symmetrical flow, the continuity equation (eq. 2.15) yields

\[
\frac{\partial (v h)}{\partial r} + \frac{v h}{r} = \frac{1}{r} \frac{\partial (r v h)}{\partial r} = 0 \tag{2.16}
\]

The momentum equations in polar coordinates are written as

\[
\frac{u}{r} \frac{\partial u}{\partial \phi} + \frac{v}{r} \frac{\partial u}{\partial r} + \frac{u v}{r} = -g \frac{\partial \zeta}{\partial r} - g \frac{u \sqrt{u^2 + v^2}}{C^2} \frac{u^2}{h} \tag{2.17}
\]

\[
\frac{u}{r} \frac{\partial v}{\partial \phi} + \frac{v}{r} \frac{\partial v}{\partial r} - \frac{u^2}{r} = -g \frac{\partial \zeta}{\partial \phi} - g \frac{v \sqrt{u^2 + v^2}}{C^2} \frac{v^2}{h} \tag{2.18}
\]

In which \( u \) and \( v \) are the velocity components in the \( \phi \)- and \( r \)-direction, see Figure 2.6.

Figure 2.6: The secondary flow is directed to the outer bend in the upper part of the water column and towards the inner bend in the lower part of the water column. The polar coordinate system is presented in this figure and the figure is obtained from Jansen [43].

Assuming that water cannot proceed through the channel sidewalls, the net horizontal velocity over the entire width equals zero. Applying this condition to the momentum equation 2.17, it reduces to

\[
\frac{-u^2}{r} = -g \frac{\partial \zeta}{\partial r} \tag{2.19}
\]
Taking into account the velocity variations in the vertical, a third term is added to the equation which does include a horizontal velocity component $v$.

\[- \frac{u^2}{r} = -g \frac{\partial \zeta}{\partial r} + \frac{\partial}{\partial z} \left( v \frac{\partial v}{\partial z} \right) \]  

(2.20)

In which the eddy viscosity is described by $\nu_t$ and the vertical coordinate is $z$. Averaging this equation over depth yields

\[- \frac{\overline{u^2}}{r} = -g \frac{\partial \zeta}{\partial r} + \frac{\tau_{br}}{\rho h} \]  

(2.21)

The secondary flow in the cross-sectional plane can then be described by subtracting equation 2.20 from 2.21. By doing this, the water level $\zeta$ can be excluded and the secondary (horizontal) flow is described in terms of the main flow.

\[- \frac{u^2 - \overline{u^2}}{r} = - \frac{\partial}{\partial z} \left( \nu_t \frac{\partial v}{\partial z} \right) + \frac{\tau_{br}}{\rho h} \]  

(2.22)

Figure 2.7: Schematization of the secondary flow in the transversal flow direction. Figure obtained from de Vriend et al. [44]

With the theory described above, the secondary flow can be computed from the three-dimensional hydrodynamic model output. Then the horizontal velocity (x- and y-) components are used to calculate the main flow velocity vector, $\vec{u}$, at every level in the vertical. The vertical distribution of the secondary flow can be determined by solving $v(z)$ from equation 2.22. The depth-integrated velocity component $v$ equals zero. See Jansen [43] for the exact vertical distribution of the horizontal velocity component.

Concluding  The channel classification methods, definitions of tidal channel features and the flow velocity concepts will be applied and referred to throughout the report. Theory from Section 2.2 will be used mainly to discuss the results. Section 2.3 will be applied in determining the approach to classifying the channel dimensions and in the elaboration of the channel classification results. The last Section (2.4) is mainly applicable to the hydrodynamic modeling chapter.
Classification of the channels in the Ameland basin will contribute to the understanding of natural channels as the intervened channels show deviating meandering patterns. In Table 3.1 an overview of channel properties and forcings is presented that are found in the Wadden Sea. The scope of this Chapter is defined by the assessment of the channel bed level-, length-, width-, and radius of curvature-evolution. Other channel properties are not discussed in much detail, but may be of influence on the tidal channel evolution. By assessing these properties, the aim is to find the characteristic properties and trends that describe a natural meander. It is contemplated to achieve this goal by examining the channel development on the Macro-, Meso- and Micro-scale, as is presented in Figure 1.6. These scales are slightly different from morphological scales described by De Vriend [23] (see Appendix B.1), i.e. they are describing the channel sections that are evaluated. The classification presented in this chapter resembles the analysis of geographical aspects and is derived from the methods of Jeuken [19] and Fagherazzi et al. [40].

Before the results of the channel development analysis are presented, the available data is described in Section 3.1. Thereafter, the methodology is described in Section 3.2. The results will be described in Section 3.3 according to the different scales that are presented in Figure 1.6.

Table 3.1: Overview of tidal channel properties and forcings that can be found in the Wadden Sea. It represents the large amount of factors that can influence the tidal channel evolution.

<table>
<thead>
<tr>
<th>Channel Properties</th>
<th>Forcings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Channel depth</td>
<td>Radius of curvature</td>
</tr>
<tr>
<td>Channel length</td>
<td>Tidal prism</td>
</tr>
<tr>
<td>Channel width</td>
<td>Geological history</td>
</tr>
<tr>
<td>Wavelength</td>
<td>Salt marsh dimensions</td>
</tr>
<tr>
<td>Bottom slope</td>
<td>Tidal flat dimensions</td>
</tr>
<tr>
<td></td>
<td>Currents</td>
</tr>
<tr>
<td></td>
<td>Sediment properties</td>
</tr>
<tr>
<td></td>
<td>Tidal asymmetry</td>
</tr>
<tr>
<td></td>
<td>Human interventions</td>
</tr>
<tr>
<td></td>
<td>Wind</td>
</tr>
<tr>
<td></td>
<td>Tidal range</td>
</tr>
<tr>
<td></td>
<td>Waves</td>
</tr>
</tbody>
</table>

3.1. AVAILABLE DATA

The channels are classified by their geometrical features, which are obtained from analyzing the Vaklodingen-data. This data is provided by Rijkswaterstaat [6] and consists of bathymetry maps of the Dutch coastal areas. Since 1987, the Vaklodingen-data are measured for the Dutch Wadden Sea with single beam echo sounders on an interval of 6 years (Elias and Wang [45]). Rijkswaterstaat processes, corrects and interpolates the data to a 20 x 20 m grid. Thereafter the interpolated datasets are saved and made available as Vaklodingen-cells with an area of 10 x 12.5 km. Before 1987 only hard-copy maps were available and these have been digitalized with a maximal grid resolution of 100 x 100 m. Oost [46] provided reconstructions of historical bathymetry maps of the Frisian inlet and these will be used in the evaluation of the results. The 2016 data was also measured with echo sounders, but deviates from the other maps with a 10 x 10 m grid resolution. It concerns an additional dataset which is specifically measured for the analysis of the sedimentation problems in the fairway in front of Holwerd. Because the study area is covered by several Vaklodingen of 10 x 12.5 km, the relevant areas have been merged to provide a single map per year. It is assumed that the merged data is representative for the
considered year, even though the acquisition might take several months.

Elias and Wang [45] describe that the measuring error in the Vaklodingen-data is difficult to determine. First of all, different measuring techniques have been used and combined to form the Vaklodingen. The transition between datasets in the same Vakloding and the different methods for the water level correction can cause errors. If the maps are carefully examined, some errors can be noticed which are found in Appendix A. These errors will be taken into account in the analysis of the channel dimensions. The years that are evaluated in this study are presented in Table 3.2, in which the spatial resolution of the data is included as well.

Table 3.2: Overview of the years and the spatial resolution of the used bathymetry maps.

<table>
<thead>
<tr>
<th>Year</th>
<th>Spatial resolution [m x m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1971</td>
<td>100 x 100</td>
</tr>
<tr>
<td>1975</td>
<td>100 x 100</td>
</tr>
<tr>
<td>1981</td>
<td>100 x 100</td>
</tr>
<tr>
<td>1989</td>
<td>20 x 20</td>
</tr>
<tr>
<td>1993</td>
<td>20 x 20</td>
</tr>
<tr>
<td>1999</td>
<td>20 x 20</td>
</tr>
<tr>
<td>2005</td>
<td>20 x 20</td>
</tr>
<tr>
<td>2011</td>
<td>20 x 20</td>
</tr>
<tr>
<td>2016</td>
<td>10 x 10</td>
</tr>
</tbody>
</table>

3.2. METHODOLOGY
As described in Section 1.3, the development of the tidal channels will be evaluated in three levels of detail. The focus in this thesis lies on the development of the tidal meanders. To find the extent of meandering, the channel centerlines will be determined and analyzed. Subsequently, meandering channels that are comparable to the Kikkertgat are analyzed and finally the scope is narrowed down to the origin and development of certain channel sections. For this purpose the geometrical features that will be evaluated per channel are the width, bed level, length and curvature.

The first step in the extraction of these geometrical features is the determination of the channel centerlines. Fagherazzi et al. [40] described a method to automatically extract a channel network, based on digital elevation maps. A similar method has been implemented in the program Quantum GIS (henceforth: QGis). In stead of reproducing these network extraction models, the methods of QGis is used. QGis is an open source Geographical Information System (GIS) and provides numerous tools for geographical data analysis. These tools, named ‘models’ in QGis documentation, are developed with the programming language Python. With Python, relevant QGis-models have been linked to automatize the extraction of the geometrical features. Which models were used, the model-principles and the way they were applied to the Ameland basin are discussed now.

To begin with, several Vaklodingen datasets were merged into one geographical map that covered the entire study area. This was repeated for each year that is presented in Table 3.2. Thereafter, three QGis models have been combined in order to automatically extract the centerline of the channels:

1. Fill Sinks: A sink in the data is identified when the bottom slope between two grid cells exceeds 0.01 degrees. Data points identified as sinks are converged to Not-a-Number (NaN) values, -999 by default.
2. Catchment Area: This model is used to linearly interpolate the NaN-data points. The model output is a GeoTiff-file, which is a Tagged Image File in which bed level information is included. The image output shows the bed level elevation by means of a gray-scale with a range of 0 – 400.000 (white - black). The gray-scale range has a larger variation than metric-data, making it possible to detect channel sections based on the color range. The interpolation of the NaN-values prevents that the Channel Network-model detects only the extreme values, which results in a large inaccuracy.
3. Channel Network: This model combines the output of the previous two models and detects only the data-points below a predefined threshold value. All data points with a gray-scale value below 50.000
(chosen by expert judgment) are detected by the model. By applying a minimum segment length of 10 data points, continuous line are constructed between the detected points.

Because these models have been developed for environments where larger gradients in elevation are present, the models introduced some difficulties regarding the accuracy. Each year showed some variation in the gray-scale range, causing the threshold value to consist of a different percentage of the total range. Because the threshold cannot be defined as a percentage of the total range, it is decided to choose a fixed value of 50.000 and to manually reduce the noise that was produced by the model.

Noise is defined as the line segments that are not contributing to the description of the channel centerline. The largest noise reduction is obtained by subdividing the system of channels into smaller areas. Based on the location, origin, and the bifurcation locations the sections were determined. Figure 3.1 presents an overview of this subdivision, including channel names that will be used throughout the remainder of this thesis. The centerlines are determined for every year with data and for each channel section separately. In Appendix B.6, an example of a raw model output and the noise reduction procedure is presented. The remaining noise in the channel network was thereafter removed manually in four steps: 1) the outliers are removed by superimposing the network to the bathymetry maps; 2) channel sections with a bed level larger than $-1$ m+NAP are removed; 3) gaps in the resulting network are filled up by creating extra line sections and 4) different channel sections are connected to create a continuous link between channels. After these adjustments bifurcations and flood chutes are still present. For the automatic extraction of the width, bed level and length, one channel centerline has to be chosen. Therefore, the longest continuous centerline is used in the analysis and other, possibly interesting, channel sections are excluded.

The extracted network consists of an irregular pattern as it does not include an interpolation method to find the bed level in the grid cell centers. For determination of the curvature and the channel length a smooth centerline is required. One-dimensional Gaussian smoothening is therefore applied to prepare the centerline for further analysis. The one-dimensional smoothing for the \(x\)- and \(y\)-coordinates is described by:

\[
G(x) = \frac{1}{\sqrt{2\pi\sigma}} e^{-\frac{x^2}{2\sigma^2}} \tag{3.1}
\]

where \(\sigma\) is the standard deviation of the distribution, \(\sigma^2\) is the variance, \(x\) is the \(x\)- or \(y\)-coordinate of a point along the channel, and a 4-point window is used in the smoothing. Due to the different spatial resolutions (see
Table 3.2), the distance between data points varies between 9 and 20 m. Therefore the $\sigma$ represents a number of data points in stead of a distance. By examining several $\sigma$-values, it was found that a rather high $\sigma = 4$ (data points) is needed to provide the smoothest results. If the channel is less smooth, the curvature determination will present many wiggles. For some channels a smaller $\sigma$ could be used, but a uniform standard deviation is applied for consistency of the results. This variance did cause the channel length to reduce by 20 to 80 m, which is approximately 5% of the total channel (arc-) length. For the determination of the width and bed level, cross-sections were created along each channel. The chosen cross-sectional width is 3000 m, which covers the entire channel width for the secondary and tertiary channels. Where the cross-sections did not cover the entire width, it was excluded from the analysis. Histogram plots of the bed level were created to examine whether a probability distribution could be distinguished. In Appendix B.11 it can be observed that no clear distribution can be distinguished. Therefore it is chosen to use a cross-sectional interval of approximately 40 m, because with a spatial resolution is 20 x 20 m a closer interval would not generate much more accurate results.

Figure 3.2: Subplots $a$ and $b$ present an overview of the determination of the width ($B$) and bed level ($D$), $L_{arc}$ and $L_{abs}$. Subplots $c$ and $d$ show an example of the fitted radii of curvature (in meters) in the channel and the curvature along the channel. The used cross-section in $a$ and $b$ is visualized in subplot $c$ with an orange line. In subplot $d$ it becomes clear that the smallest irregularity in the channel can create an outlier. Therefore the radius of curvature is only determined at the channel tops.
With the cross-sections, the width and the bed level can be calculated. For the determination of the channel width, the following criteria have been applied:

- Only the channel sections with a bed level lower than -1 m+NAP will be used in the analysis.
- Every meter along the cross-section the bed level is measured and saved, resulting in 3000 data points per cross-section.
- Because of the 20 x 20 m grid size, flat sections are present in the bed level plot of the cross-section. Therefore, double values are removed from the dataset, i.e. the middle data point in a flat section is kept and the rest is removed.
- Linear interpolation is applied to obtain one value at every centimeter in the vertical.
- As the QGis models should have defined the centerline at deepest point in the channel, the bed level is calculated in the middle of the cross-section (at \( x = 1500 \) m). The width is determined for every cm in the vertical. To prevent the detection of minor irregularities at the bottom, the lowest 10% of the maximum bed level is not included in the calculation.

The channel bed level is defined as the average bed level (in m+NAP) at the same location where the width is determined (see Figure 3.2a). Sinuosity (eq. 2.6) describes whether the channel meandering length increases compared to the absolute length. The average sinuosity is used here, which is defined as the entire length of the channel divided by the arc-length (see equation 2.6). In order to examine the extent of meandering, the curvature and the radius of curvature are calculated. Due to disturbances in the data, the network extraction does not always present clear meandering features. Therefore the meandering extent in this analysis is defined as the difference in evolution of the arc- and absolute length of the entire channel (see Figure 3.2b). This was also the reason only to calculate the radius of curvature for the channels with meandering features and of those that showed considerable changes over time. The curvature is determined following Kreyszig [48]:

\[
\kappa = \frac{d\phi}{ds}
\]

(3.2)

and the radius of curvature is defined as the inverse of the absolute curvature:

\[
R = \frac{1}{|\kappa|}
\]

(3.3)

In Appendix B.4 an elaboration of these equations is presented. With the curvature, the radius of curvature (henceforth: Roc) can be calculated at every point in the channel. Because the most interesting Roc is located at the channel top, there the Roc has been determined. When the channel is described as a wave, the maximums and minimums can be determined by calculating the first derivative. The automatically extracted channel centerlines, however, do not always show a wave-like pattern and therefore several maximums were not detected. In order to improve the accuracy, a second approach was applied. First a line was drawn from the beginning to the end of the channel. Then the maximum distance between this line and the point on the channel perpendicular to the line was determined. The two methods resulted in a set of coordinates for the tops. When both methods described the same wave top, the top from the second method was removed. That was, because the derivative was determined with the smoothed line and the second method used the non-smoothed channel line. An example of a Roc-output is presented in Figure 3.2c. Variations in the width, bed level, length, curvature and bed slope may indicate a reason for change in the meandering pattern. The results and analysis of the channel dimensions are elaborated in the preceding sections.
3. Tidal Channel Classification
3.3. CHANNEL DIMENSIONS RESULTS

From the extent of meandering (see Figure 3.3) it is decided to only look at the tertiary channels and the Kikkertgat (Kik) channel. The Kik is included because it shows a clear meandering pattern which is expected to be caused by the dredging activities. By implementing this channel it is possible to draw conclusions between the behavior of dredged and natural channels.

Examining the channel evolution in Figure 3.3, the meandering tidal channels show a large variability. Some unexpected channel patterns, probably originating from the measuring accuracy, produce or remove meanders that can be distinguished in the bathymetry maps (e.g. the 2011 map in Figure 3.1). Because the aim of this thesis is to find an explanation of the meandering channel behavior, the figures and conclusions that are presented will only make use of the channels that showed meandering features. Bathymetry data of the years 2005, 1993 and 1981 are excluded form the analysis, as they contained many measuring errors in the channels of interest. An overview of the remaining years is presented in Table 3.3.

Table 3.3: Channels that are used in the dimensional analysis. Years presented in italics are used in the analysis, but do show errors in the data that may influence the results.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Abbreviation</th>
<th>Data used</th>
</tr>
</thead>
</table>

In the preceding Sections, the development of the channel dimensions are assessed from three different scales. First, the Macro-scale is applied to examine the meandering extent of the tidal channels and to determine which meanders will be evaluated in more detail. These details are evaluated in the section Meso-scale developments, which focuses on the channel length, width, bed level and how these are correlated. The Micro-scale zooms in on the width- and bed level developments around a channel top and/or flood chute.

3.3.1. MACRO-SCALE DEVELOPMENTS

Macro-scale developments include global channel developments of all channels in the Ameland basin over a period of 40 years. Figure 3.3 presents the channel centerlines that have been obtained with the data analysis in QGis. The expansion of the bends in the Kik can be seen clearly, as well as the variation in the NSp and the ZSp. Whereas the channel tops of the Kik have expanded about 500 m, the MG shows very little variation over time. Furthermore, dynamic meandering development is observed and channels have a more west-east orientation from $x = 1.83 \cdot 10^5$ towards the tidal watershed in the east.

Sedimentation problems occurred in the ZKik-West. As time proceeded, more intensive dredging took place and the length of the fairway increased by one kilometer. Since the start of the dredging in 1990, the ZKik-West meander stopped evolving and the Kik meander evolved the more. During this process, NKik formed and grew from a small flood chute to a meandering channel. Figure 3.3 furthermore shows that the length scale, orientation and meandering extent of the NSp, ZSp, NKik and ZKik-West and -East are comparable. The development of these channels will be studied, in order to examine the differences in natural and dredged channel behavior. Also, Kik will be included as this meander seems to have an non-natural development over time.
3.3.2. Meso-Scale Developments

The Meso-scale channel developments consist of the developments on the scale of individual channels. Developments in this level of accuracy include the changes in width, bed level, length and radius of curvature. Analysis of these dimensions are elaborated for the Kik, NSp, ZSp, ZKik-West and ZKik-East.

Channel Length

For each channel the wavelength and amplitude can be determined based on the channel center line. As described in Section 2.1, a single wave is defined as the combination of three consecutive points of inflection. The assessed channels show a variable pattern over time, which is partly caused by the data accuracy and partly by the channel network extraction model. Therefore it is difficult to determine the wavelength and to compare the results. The meandering extent is therefore determined by calculating the absolute length and the arc-length of the channel as a whole. The results of both lengths are presented in Figure 3.4, in which the ratio between the arc- and the absolute length is included as well. This ratio is referred to as the average sinuosity and it provides an indication of the meandering extent by showing the relative growth or decay of the meander.

Generally speaking, the absolute and the arc-length of all channels in Figure 3.4 show an increasing trend until 1990. Considering the Spruit channels, ZSp is growing at a more constant rate than NSp. The overall increase in meandering length ($L_{arc}$) relative to $L_{abs}$ is larger in the NSp. This is mainly due to a reducing $L_{abs}$ in NSp and in ZSp $L_{abs}$ keeps growing with about the same rate as $L_{arc}$. However, the bifurcation point of these channels moved westward with about 800 m since 1993. The channel also developed at the east end, but its influence on the trends in Figure 3.4 is negligible compared to the movement of the bifurcation point. By taking into account these deviations, the length development would rather be constant or decreasing. This finding is supported by the fact that the NSp meander seems to have reached a limit in the first two bends in 2005, which can also be observed in Figure 3.3. So the channel length increased until 1993, after which the meandering in the NSp stagnated.
3.3. CHANNEL DIMENSIONS RESULTS

From Figure 3.3 it was expected that the meandering of the Kik increases to a greater extent than the NSp and the ZSp. Even though this expectation is met, it should be noted that the eastern end (bifurcation point) moved northwards with about 500 m over the years, which altered $L_{arc}$ with about 70 m each year. In addition, the western end of the Kik 1999 and 2005 centerline is located approximately 650 m more to the east than the other years. Correcting for this alteration would lead to a decreasing $L_{abs}$ 1999 relative to 1993, and an $L_{abs}$ 2005 similar to 1993. Also in 2016, the channel start and -end showed a deviation of about 350 m compared to 2011, which would not affect the global trend visible in the results. So, even though $L_{abs}$ reduced since 1999, $L_{arc}$ was still growing. This means that the erosion-sedimentation pattern in these channels comes closer to an equilibrium.

Figure 3.4: The absolute- and arc- channel lengths over time. The blue line represents the length along the centerline of the channel (the arc-length) and the red line represents the absolute length between the beginning and end of the channel. The black line with triangular markers corresponds to the axes on the right and represents the average sinuosity, i.e. the ratio between the arc- and the absolute length. Note: the vertical axes of subplots d to f have a different scale.
From the remaining plots, it is observed that the NKik seems to grow much faster than the ZKik. In the years considered, the NKik developed from a small, straight channel to a channel with comparable length features as the ZKik-East. As its length increased, it started to show meandering features in 1981. The cause of this development could be pointed to the northward movement of the bifurcation point Kik-NKik-ZKik, which can lead to a growing tidal prism in the NKik. Except for this northward moving bifurcation point, the ZKik-West length development has stagnated which can be appointed to the dredging activities. As its channel length remained remarkably constant, ZKik-East absolute length has reduced by 11% since 1993. Where the length decrease takes place the hydrodynamic conditions have reduced, resulting in sedimentation at the end of the channel. From Figure 3.4 the suspicion arises that the NKik slowly replaces the ZKik-East as sediment is accreting in the latter and eroding in the NKik. By only examining the lengths, this expectation cannot be proven. Therefore, the other channel dimensions have to be examined in order to determine to which extent this happens.

If the sinuosity rules (eq. 2.7) applicable for river environments are applied here, no channels are classified as meandering. Although an averaged sinuosity is presented in the figures, the ratio $L_{\text{arc}}/L_{\text{abs}}$ is still low. The Kik does show a large increasing trend compared to the other channels. However, it consists of one channel wave, whereas the other channels consist of more meandering sections. The channel ends are meandering less, which reduces the average sinuosity. ZKik-West and Kik do not contain channel ends and have a higher sinuosity value. The small, but noticeable NSp sinuosity-increase is dedicated to the stabilizing of the first two meanders.

Cleveringa and Oost [21] described that the branch length (i.e. $L_{\text{arc}}$ between two bifurcations or channel end) of each channel decreases logarithmically. Even though this is not tested here explicitly, it can be observed that the Kik and the ZKik do not share a logarithmic relation anymore. The lengths are now comparable and less bifurcations are present in the ZKik-West than in the past. For the NSp and ZSp this logarithmic scale still seems to hold when the bathymetry maps in Appendix A are examined. If the bifurcation at the end of the Kik is seen as a new branch, the NKik and ZKik would have to consist of meandering sections including flood chutes. The length of the meanders would be in the order of 2 km before splitting up again. With this information, it can be confirmed that the dredging activities have influenced the natural meandering pattern and the bifurcation potential of the ZKik-West and the Kik.

Channel Width
Trends in the width development along the channels can provide an indication of the development of the flow area and therefore the tidal prism. Ebb- and flood chutes are often present resulting in the presence of bars in the channel, which makes it complicated to determine the channel width and bed level. Because of this high dimensional variability in the cross-section, the width and bed level have been determined for the deepest channel section of the flow area. It is assumed that this section transports most water during a tidal cycle and it is therefore used as the governing channel section in the analysis of the width and bed level.

Figure 3.5 presents the width along the channel. By examining the results in general, several aspects come forward. To begin with, the width fluctuates around a constant value along the entire channel. For the NSp, ZSp, Kik and ZKik-West this value is approximately 200 m and for the NKik and ZKik-East it is about 100 – 150 m. The width along the channel appears to be mostly influenced by the meandering development and the existence of bifurcations or flood chutes. The relation with meandering development follows from the width profiles in the NSp and the Kik. In the NSp, the width is showing relatively small variations at the first two meanders and thereafter the channel directly widens. The Kik is a strongly meandering channel and shows the same trend as in the first two meanders of the NSp. The ZSp is a less stable channel and shows variations from the beginning until the end, comparable to the final 2000 m of the NSp. The relation between bifurcations and width comes forward in the graph of the NKik in which the width variation is almost zero near the non-meandering and non-bifurcating channel end in 2016.
3.3. CHANNEL DIMENSIONS RESULTS

Figure 3.5: In these graphs the width along the channel is presented. Due to the large amount of oscillations of the width, only $1/3$rd of the data points is plotted to improve the visibility of the trends. The black triangular markers designate the approximate locations of a bifurcation or flood chute.
**Channel Bed Level**

The bed level is determined for the part of the cross-section where the width has been determined and its development is presented in Figure 3.6. As expected, the bed level increases along the channel until $-1 \text{ m+NAP}$ (the channel threshold depth), except for Kik and ZKik-West which continue in a subsequent channel. The NSp shows a rather consistent bed level development over the years. In general, the channel bed level seems to have increased in time and in more recent years a more distinct profile has developed. The most probable reason for this is the stagnating meandering length, causing the channel adjustments to take place in a different dimension; the bed level. The bed level of the ZSp appears to be lower (deeper) than in the NSp along the entire channel. Peaks in the bed level around 2000 m are not an error caused by a definition. The bathymetry maps of these years show that this location is at the beginning of a flood chute, which has disappeared as time proceeded. The large bed level decrease at this location and the peaks in the Kik are all visible on the bathymetry maps, see Appendix A.

Similar to the NSp, the bed level profile in the Kik also becomes more distinct as the meandering increased. The channel sections located west of the first bifurcation are generally deeper and rapidly become shallower towards the location where the flood chute and ebb channel confluence. This result will be discussed in more detail in Section 3.3.3, where the smaller scale developments are elaborated. Apart from the fluctuating bed level pattern, a bed level increase from the beginning to the end of the channel is still taking place.

The NKik and ZKik-West are the split-off channels of the Kik, but show a different bed level pattern. The development of the NKik is visible by the bed level decrease and the length increase in time. Both developments are ongoing in 2016, so erosion is still taking place in the channel. Furthermore, bed level fluctuations become more as the bed level decreases and they dampen towards the channel end. The bed of the ZKik-West is clearly being dredged in the recent years. Irregularities in the bed profile have been removed, whereas they were still present in 1989. The horizontal section in 1999 represent inconsistencies in the bathymetry data. The maps in Appendix A show the bed level increase at this location, resulting in the horizontal planes. The bed level in ZKik-East is remarkably similar to NKik. However, there are two differences between these two channels. The first is that more fluctuations are present in sections with similar bed levels (see 1999), but as the channel becomes shallower (2016) they tend to dampen out. And secondly, the length and bed level development of this channel is opposite to the NKik. So if the length and bed level increases, meanders and flood chutes start to appear.

In general, the bed level has increased (shallowing) over time. Except for the Kik the bed level seems to develop according to an exponential trend. The Kik shows a more wave-like trend which corresponds to its meandering bends. Also the bed level peaks are more profound in the more recent years, except for the dredged ZKik-West. NKik shows a rather constant profile as the meandering length increases. It is interesting to see that this channel does not contain flood chutes, which highlights the effect of bifurcations on the channel dimensions.

The ZKik presents a rather constant bottom slope (see Appendix B.9) and bed level. Before the start of dredging, it did not show bifurcations and therefore did not show large peaks in the bottom slope. On the contrary, NSp and ZSp present large variations, even with the more recently measured data. In between the peaks (hence bifurcations) the channel bed seems to become more flat. From a bed level of approximately $-200 \text{ cm+NAP}$ to $-100 \text{ cm+NAP}$ no clear flood chute is formed; a threshold for bifurcation seems to be found. If this threshold bed level for potential channel splitting is evaluated on the other channels, ZKik-West should have formed a bifurcation a long time ago. The year before the dredging started (1989) the bed level showed a large variation at $x = 1200$, indicating a possibility of bifurcating. The same holds for ZKik-East, which showed a starting bifurcation in the middle of the channel (at $x = 1000, 1989$). The bed level at that location was lower than $-200 \text{ cm+NAP}$ at that time, whereafter it increased and the channel displayed a clean meander.
Figure 3.6: The bed level development along the channel is presented in these graphs. To improve the visibility of bed level trends along the channel, only 50% of the points are plotted to reduce the oscillations. The black triangular markers designate the approximate locations of a bifurcation or flood chute.
3. Tidal Channel Classification

Curvature
With the smoothed channel centerlines, the curvature can be determined by applying equation 3.2. For channels where a clear meander is present, the radius of curvature can be plotted at the location of the channel tops (the bend sections where a maximum curvature is found). The plot of the curvatures along the channels is placed in Appendix B.8. The main conclusions that can be drawn from this figure is that the curvature fluctuates between $-0.005 \text{ m}^{-1}$ and $0.005 \text{ m}^{-1}$, which corresponds to a $\text{Roc}$ of $\pm 200 \text{ m}$. Furthermore it can be seen that the NSp and ZSp have a mirrored orientation and that the fluctuations are much larger than in the Kik.

When determining the radius of curvature, inaccurate results are found at most locations. This inaccuracy is caused by small disturbances in the extracted channel centerlines after smoothing. The location of the channel tops is highly variable over time due to channel migration and therefore it is difficult to present the results clearly in a figure. The only channel that showed results with enough comparable radii was the Kik, which is presented in Figure 3.7. Because of the irregular channel top output, it was almost impossible to automatically calculate the wavelength. Therefore, the wavelength of this channel was measured manually by calculating the length from the cross-over west of the Kik-West bend to the cross-over east of the Kik-East bend (see Figure 3.7c).

This figure shows that, when the 2005 results are excluded (inconsistent data, see Table 3.3), the eastern bend radius reduced as the arc-length increased. The western bend, however, fluctuated around a $\text{Roc}$ of 500 m. Furthermore, the location of the channel top was rather constant for the eastern bend. It is not clear why this occurs, but hypothesis for this channel behavior are presented in Section 3.5.

![Figure 3.7: The evolution of the radius of curvature in the Kik-channel are presented in the upper graphs for the years 2016, 2011, 2005, 1999 and 1993. Besides the wavelength, the Table in (c) presents the relation between the circles and the years. The wavelength was determined manually and the 2016 bathymetry is plotted on the background of (a) and (b).](image-url)
3.3. CHANNEL DIMENSIONS RESULTS

Yearly Averaged Trends

Figure 3.8 presents an overview of the change in dimensions relative to 1971. An indication of the channel volume is included as well, by defining the volume as $V = L \cdot B \cdot D$. For the analysis of Figure 3.8 it important to understand that each data point represents a value averaged over the entire channel and yearly averaged. Therefore, steep gradients in the figure can be related to a bifurcation, the origin of a flood chute, a measuring error, or to a result from the definition of a channel. Also, the NSp and ZSp are larger channels than e.g. NKik, meaning that averaging is performed over a larger dataset. Still, the average development of the arc-length ($L$), width ($B$), bed level ($D$) and volume ($V$) can advance trends in the sensitivity of the parameters. The aim of this section is to find which parameters are adjusted the most in the development of a meander.

![Figure 3.8: Percentual changes of the arc-length (L), width (B), bed level (D) and volume (V). Each point in this figure represents a value averaged over the entire channel and yearly averaged.](image-url)
In Steijn [3] it was described that the ZKik channel volume decreased after 1998 and this is also clearly visible in Figure 3.8. As the volume decreased, the volume of the dredged material increased exponentially (see Figure 1.2). The main conclusion that can be drawn in this respect is that the largest contributor to the volume decrease was the width reduction in the ZKik-West from 1993 onward. For ZKik-East the same holds, but the width reduction had already started in 1981. In the period that dredging activities engaged, also the length of this channel reduced almost linearly compared to 1971. In the Alkyon-reports ([11] and [3]) it was argued that the meandering of the Dantziggat caused a redistribution of the water volume through the channels. The only channels that showed a volume increase since 1998 are the NKik and the ZSp. Here too, the influence of the width is the governing factor in the change. As the NSp and the ZSp are larger and more developed channels than NKik, it is possible that these channels have taken over a certain amount of water from the kik-channels.

Besides the volumetric changes, other trends can be observed. First of all, the channel lengths in the tertiary channels has increased since 1971. The large increase in length for the NKik can be explained by the 1971 channel length, which increased from approximately 1000 m to approx. 3000 m. The other channels were in a more developed state in 1971, resulting in a more gradual variation. Even though the ZSp length increased linearly, the NSp shows a larger net growth. Also, the length development seems insensitive to changes in the width and bed level. Generally, the channels show a width reduction and a bed level increase.

From Figure 3.8 it can be seen that the channel volume of the ZKik decreased since 1990, which corresponds to the start of dredging the channel. The decreasing channel volume corresponds to siltation and/or the formation of larger shallower areas at the end of the channel. The NKik, however, presents a large increase in storage volume which is mostly due to the increase in length. The percentual variation in dimensions in the ZKik is of the same order of magnitude as in the NSp, which supports the probability of the effect of the land boundaries. In the eastern part of the ZKik, the width, depth, length and therefore channel storage volume reduced since 1999.

**Main Conclusions Meso-scale Developments** In general, the length of all channels increased until 1990. Thereafter, the channel lengths decreased, except for the NKik and the ZSp. The NKik is growing because it is only just arisen, and the ZSp is most probably growing because the starting location of the channel moved westward. Furthermore, the NSp and the Kik showed an increasing average sinuosity as the meandering behavior became more profound. The sinuosity of the Kik was the largest ($S = 1.4$), confirming the observations in Figure 1.5. Also, the increase of the NKik length seems to correspond to the decreasing length of the ZKik-East.

Besides the length developments, a channel width reduction and bed level increase is observed in the years that are examined. The width along the channels fluctuates around a constant value. For the NKik and ZKik-East this value is around 100 – 150 m and for the other channels it is approximately 200 m. This too shows that the NKik and ZKik-East are comparable. The bed level generally increased for all channels in the evaluated years. Dredging of the ZKik-West is clearly visible, because few bed level variations are observed after the dredging was initiated. Channels that have not been dredged show that if flood chutes or meanders are present, the bed level profile is more variable than when they are not present. When ruling out the bed level fluctuations, the bed level consists of an exponential trend along the channel. Only for the Kik the bed level consists of a sinusoidal shape, corresponding to its meandering lay-out. Furthermore, from analyzing the channel bifurcation locations, it is found that no profound flood chute can be distinguished when the bed level is larger (i.e. shallower) than approximately −200 cm+NAP. These findings are examined and described in more detail in Section 3.3.3.
3.3.3. Micro-Scale Developments

In the developed meanders (Kik and NSp), a trend in width and bed level has been observed. Therefore these meanders will be highlighted to see how the meandering, bifurcations and flood chutes are related to the channel dimensions. If trends can be distinguished in a developed channel, a prediction can be made regarding the development of less developed channels. In order to describe a prediction, the observations in the Kik and NSp will be projected on less developed channels which show the potential to evolve into a developed meander. In this paragraph the bathymetries of 1971 and 1975 are excluded, because the 100 x 100 m spatial resolution is too inaccurate for the distinction of Micro-scale developments. The aim of this section is to find trends in dimensions and the relation with the meandering behavior.

The Kik is the first meander to be assessed, because it contains the largest meanders in the system of channels. Its two channel tops contain flood chutes and therefore the analysis of the Kik will be performed for each top separately. In the same way, the development of the first two bends in the NSp and the ZSp are examined. The development of the NSp stagnated over time and the difference in bed level with relation to Kik is used for describing the parameters’ influence.

The meanders and flood chutes are presented in the upper plane of Figures 3.10 to 3.15. The main trends are observed around the flood chutes, which are therefore highlighted by a continuous line. The channel bend to be assessed is defined manually by ensuring that some part before- and some part after the flood chute is included. For clarity, the end of the 1st bend and the beginning of the 2nd bend is highlighted by a black marker. The circular marker in the lower figures represents the estimated bifurcation locations. Furthermore, the same years are applied in this figure as has been applied in the previous sections. The presentation of the flood chutes is derived manually by defining a line in QGis through the deepest section of the chute. As the start- and endpoint of the chutes is drawn by visual inspection, no conclusions regarding the flood chute length, the start- and the endpoint can be drawn. However, the orientation is rather accurate and is taken into account in the analysis.

Figure 3.9 clarifies the most relevant aspects that can be derived from the figures on the following pages. In several occasions the channel width and bed level show similar developments. The width reduces at a channel top and the bed level decreases, which is depicted in the first graph of Figure 3.9. The second graph shows the first bend of the Kik, which contains a developed flood chute. The angle between the flood chute and the ebb channel increased, and the ebb channel became more defined. This results in a more defined bifurcation which is detected closer to the bifurcation location.

Figure 3.9: The first graph highlights the width reduction and the bed level decrease around a channel top with a bifurcation. There, the dotted lines are inserted to show similarities in the width and bed level development. The second graph highlights the distance between the bifurcation location and the rapid decrease in width.
The channel width in Figure 3.10 is increasing along the channel and suddenly decreases some distance after the splitting off to a flood chute (see a.). This distance has become shorter in the course of time. That is, as the angle between the ebb channel and the flood chute increases, the ebb and flood channel become more separated. In the first bend, the peak width at c relates to the switch between ebb and flood channel. Here the definition of which channel is examined is causing the irregularity in the data. The second bend also shows a width increase towards the bifurcation location, but does not show such a distinct width reduction after splitting. This channel behavior could be explained by the distance between the flood chute and the bifurcation at the end of the Kik (see b.), which reduces the length over which the ebb channel can develop.

Two observations stand out regarding the channel bed level: 1) The variations in the bed level follow the variations in the width and 2) The depth before splitting up is larger than after splitting up. The first observation is explained by the link in definition of the channel width and bed level (see Section 3.2), which states that the bed level is calculated where the width was determined. The second observation can be explained by the tidal prism (see equation 1.1). When a channel splits up, the flow area reduces resulting in a decrease in water volume flowing through the channel. This corresponds to a reduction in flow velocity and hence sedimentation.
3.3. CHANNEL DIMENSIONS RESULTS

Figure 3.11: The development of the width and the bed level at the NSp channel tops. The 1\textsuperscript{st} bend is the channel top on the left (west) and the 2\textsuperscript{nd} bend is the top on the right (east). In the two lower graphs only years 2011 and 2016 are presented. The location where the channel is subdivided into two bends is highlighted by a black marker and the approximated location of the flood chute is shown by a red marker.

The first bend of the NSp is in a more developed state than the second bend, because the ebb channel remains at the same location. Similar to the Kik, a clear similarity exists between the width and the bed level. The 2011 and 2016 plots show a width reduction and a bed level decrease around the channel top. Right before and right after the top, an opposing trend is visible (see a\textsuperscript{.}). At the channel top, the bed level decreases and right after the bifurcation it increases again. The depth just before a channel top is approximately twice as large as in the foregoing section. In the second bend, the changes in width and bed level are less similar than in the first bend and the Kik. This points towards a possible limit in dimensions for which a distinct bifurcation can occur.
The ZSp presents a variable channel with an instable meander, as can be seen in the migration pattern in the upper graph of Figure 3.12. In 1989 and 1999, the channel was more stable, resulting in more distinct width and bed level patterns in the lower figures (see a.). The unstable meanders consist of channels separated from the ebb channel, resulting in a larger flow area and hence a tidal prism reduction. Looking at the shallower channels, flow velocities are expected to decrease. The first bend is more profound in 2011 and 2016, resulting in a lower width and an average bed level comparable to the other years. The second bend became more irregular by forming several channels, which results in a width- and bed level increase.

Interesting is the bed level decrease at the first bend of 1989 and 1999, because no flood chute is present there. So it is not necessarily the flood chute causing the bed level decrease, but it could also be the meandering extent. Bathymetry maps (Appendix A) show that the tidal flat runoff-area around the first bend was much larger in 1989 and 1999. This implies that the development of tidal flats is an important factor in the development of the tidal meander.
In Figures 3.13, 3.14 and 3.15 the evolution of three cross-sections along the channel are presented. The evolution of two channel tops and a cross-over is presented in the three lower figures for which the blue marker in the upper graph corresponds to $x = 0$. By assessing these figures the aim is to determine the channel migration velocity and to find trends in meandering extent between the three cross-sections.

![Kikkertgat Development](image)

**Figure 3.13**: The cross-sectional development at the two channel tops and the cross-over of the KIK. Cross-sections 1 to 3 are depicted from left to right in the upper graph by the black lines. The blue marker in the upper graph corresponds to $x = 0$ in the lower graphs.

In Figure 3.13 several observations can be made. To begin with, the upper graph shows that the flood chutes migrate together with the migrating bend. Also the chutes preserve their west-east orientation over time (see a.). Due to an error in the automatic extraction of the channel centerline the 2011 chute at a. seems to be positioned south of the ebb channel and is not connected to the designated flood chute location. In the bathymetry maps in Appendix A it is shown that the channel top is positioned close to the 2016 top. This deviation does not hold for the second bend and it does not influence the results regarding the width, bed level and cross-sections.

Further, in both the first and third cross-section, the bend migration is clearly visible. The migration velocity in CS1 is reducing from 20 m/yr in the period 1989 – 1999 to 17 m/yr in the period 1999 – 2011. The migration speed in the third cross-section is comparable to the first. From CS2 it is observed that the bed level and the width have increased. The cross-sectional (flow-) area does thereby not deviate much from CS1. Furthermore, the migration of the bends influences the lay-out of CS2. CS2 of 1989 shows a rather uniform profile that evolved into a separation of ebb and flood channels by a bar in the center of the channel. The arc length of the channel and the distance between the channel tops increased, which could provide an explanation for the changing profile of CS2.
Similar to the flood chutes in the Kik, the flood chutes in the first bend of the NSp develop with the migrating ebb channel. They obtain a more west-east orientation and in 2011 and 2016 the chute is located at approximately the same location (see a.). The flood chutes in the second bend show a parallel development over time and show a similar migration pattern as the first bend (see b.).

Compared to the Kik, the bed level variation between cross-sections is much smaller in the NSp (see the red dashed lines). During the channel location shift in CS1 from $x = 750$ to $x = 400$, the maximum depth increased with 200 cm. Besides, the migration velocity in recent years is much lower than for the Kik. In the period 1999 – 2011 the migration velocity was approximately 8.5 m/yr and between 2011 and 2016, the movement stagnated almost completely. The centerline in the upper figure shows different results, which is due to the error in the centerline determination. Like for the first bend of the Kik, the small deviation in the flood chute location proves this error.

CS2 presents a clear difference in the main channel development between 1999 and 2011. The two troughs in 1999 have changed into a single deeper section in 2011. So the meandering (arc-) length has grown and the intermediate section between CS1 and CS3 has deepened. Presumably, the 1999 profile is also found if CS2 was drawn more to the south. CS3 lies closer to the bifurcation point in 2011 and 2016 than in 1999. Therefore, the shallow channel section left of the deepest channel section differs in CS3 between 1999 and 2011. The straight orientation of the 1989 channel presents cross-sectional symmetry, while later years show
3.3. CHANNEL DIMENSIONS RESULTS

an asymmetrical profile due to the bend migration.

Figure 3.15: The cross-sectional development at the two channel tops and the cross-over of the ZSp. Cross-sections 1 to 3 are depicted from left to right in the upper plot by the black lines. The blue marker in the upper graph corresponds to \( x = 0 \) in the lower graphs.

At the ZSp, the west-east flood chute orientation is found as well. Different from other channels is the absence of flood chutes in 1989 and 1999. The bifurcations in 2011 and 2016 are not marked as flood chutes, but represent an ebb-flood channel development as presented by Van Veen [22] in Figure 2.4a. The width and bed level in the first bend of 1999 show similar trends as were found at other channels, which means that the width reduction and bed level decrease also occurs without the presence of a flood chute. Another difference with Kik and NSp is that the flood chute in the second bend originates from the cross-over at location \( a_1 \) and not from the cross-over at location \( a_2 \).

The irregular ZSp bathymetry clearly comes forward in the cross-sections of Figure 3.15. In CS2 it is observed that the depth of the split-off channel (2016) is greater than the ebb channel (see \( a_1 \)). In earlier years, the channel had a more consistent location resulting in a lower bed level in CS2. For the last two years plotted the cross-over area is larger and the channel pattern of CS2 is more irregular. In general, the average depth decreases from CS1 to CS3. However, the bed level between CS2 and CS3 differs only mildly, forming an intermediate development compared to Kik and NSp. Furthermore, the migration velocity in CS1 is much larger than in CS3. From 1989 to 1999 the migration velocity was 10 m/yr and between the other years 20 m/yr. The top at CS3 migrated with approximately 7.5 m/yr.
3. Tidal Channel Classification

The histogram in Figure 3.16 presents the temporal averaged maximum channel depth that is depicted by a red dashed line in the figures above. The ratios between CS1 and the other cross-sections are presented on top of the histogram bars. These show that only in the Kik the depth increases again after CS2, while for the NSp and ZSp this remains approximately the same. As the NSp and ZSp are assumed to represent natural meanders, this forms a way to identify the natural behavior of a meandering tidal channel.

![Figure 3.16](image)

Figure 3.16: The temporal averaged maximum channel depth for the cross-sections of the channels Kik, NSp and ZSp. The numbers on top of the histogram bars represent the ratios between the depth relative to CS1.

3.4. Conclusions

The aim of this chapter was to explain the difference in evolution of natural and non-natural tidal meanders in the Ameland basin. To achieve this goal, the channels in the Ameland basin have been classified to their locations and dimensions. Because the developments are dependent on the scale that is applied, the channels are classified by substantiating three different scales; Macro, Meso and Micro. Four subquestions were proposed to guide the elaboration of the main research question. The conclusions corresponding to each subquestion is elaborated separately:

a.1 Which channels can be used for the comparison between natural and non-natural meandering channels?

By assessing the channel centerline developments in the Macro-scale analysis, the evolving meandering channels were distinguished from the more geographically fixed channels. It is concluded that the smaller channels located near the tidal watershed showed the largest meandering development. These channels were therefore examined in the Meso-scale section, where the channel length, width, bed level and radius of curvature have been analyzed.

a.2 Which channel dimension was affected the most by the changes in the system?

By comparing different channels, the meandering behavior in the Ameland basin is described by three different dimensions. To begin with, an increasing trend is found in the (arc-) length for all channels until 1990. Thereafter, a decreasing trend is observed at all channels, except for the NKik which kept on growing. Furthermore, a general trend of decreasing channel widths and decreasing bed levels is observed between 1989 and 2016. Along the channels, the bed level increases towards the location of the tidal watershed and the reduction can be described best by an exponential trend. The channel widths are reduced the most in time and because the bed level decreased to a lesser extent, it can be concluded that the channels became more distinguished from the tidal flats in time.

a.3 How do the channel dimensions change around a channel top and are these dimensions influenced by a bifurcation or flood chute?

Before and after a channel top, the width increases and the bed level increases. The channel top itself is defined by a bed level reduction of factor 2 and a reduced width, resulting in a funnel shaped geometry that can be observed in more detail when the meanders develop. These dimensions are found regardless of the presence of a flood chute. The flood chutes are found to migrate simultaneously with the channel top and they strive for a west-east orientation.
a.4 In what way are the dimensions of the dredged channel and the adjacent Kikkertgat channel different from natural meanders?

The Kik and ZKik-West are considered as the non-natural meanders. The meandering extent of these channels is approximately 10% larger than for natural meandering tidal channels. The sinuosity increase in the NSp shows that also in natural channels meanders develop, but in a lesser extent than the non-natural channels. Furthermore, the length between two bifurcations decreases logarithmically for natural channels (see [21]). For the non-natural meanders, this logarithmic relation is not observed anymore. It is also found that natural meanders contain flood chutes, which can be detected by an irregular width and bed level profile. Although the Kik contains these irregularities, the dredged ZKik-West does not show this. This channel therefore does not contain flood chutes or ebb-flood channel developments.

Combining all results and the conclusions of these subquestions, it can be concluded that the geographic development of a meander can be described by distinguishing three meandering stages (see also Figure 3.17 and Figure B.8 in Appendix B.10):

- **Developed meander (Kik):** This is a meander with a clear sinusoidal shape and with flood chutes. In this stage, the depth at a cross-over is approximately two times smaller than at the location of a channel top. The temporal averaged maximum channel depth between the seaward channel top, the cross-over and the landward channel top has a ratio $1 : 0.5 : 0.75$. The width is smaller at the channel tops compared to the rest of the channel.

- **Developed, variable meander (NSp, ZSp):** This stage is defined by a clear sinusoidal channel shape, flood chutes and a variable ebb-channel location towards the end of a channel. Characteristic for this stage is a lower correlation between width and depth, and the temporal averaged maximum channel depth between the seaward channel top, the cross-over and the landward channel top has a ratio $1 : 0.6 : 0.6$ for the NSp and $1 : 0.8 : 0.8$ for the ZSp.

- **Undeveloped meander (NKik):** Small and straight channels like the NKik develop into longer channels with initial meanders. This stage is defined by little meandering features and the absence of flood chutes. In this stage, a rather constant width and depth are observed.

By applying the ratios of the temporal maximum averaged channel depth for consecutive cross-sections and cross-overs, the meandering stage can be distinguished. The ratios of the Kik are clearly different from the NSp and ZSp, in the way that the channel deepens after a cross-over. For the **developed, variable meanders**, the temporal averaged channel depth remains rather constant after a cross-over. This forms an indicator of a characteristic of a natural meandering channel. Furthermore, a width reduction and/or depth increase in a channel is an indication for the development of a flood chute or bifurcation. At the location of this change, a bifurcation will occur. In case of a non-natural meander, the depth increase occurs before the bifurcation location and the width reduction further away (after) the bifurcation location.
Overview of the Meandering Stages

*Developed meander:*
1. Clear sinusoidal shape
2. Funnel shaped width at channel top
3. Flood chutes
4. Depth at cross-over ±2x smaller than at channel top
5. Correlation B and D

*Developed, variable meander:*
1. Clear sinusoidal shape
2. Flood chutes
3. Variable ebb channel location towards end of channel
4. Lower correlation B and D

*Undeveloped meander:*
1. Small, straight, and developing channel
2. Initial meandering features
3. No flood chutes
4. B and D rather constant along the channel

Figure 3.17: Overview of the meandering stages and where they are defined. For the correlation between the width and the bed level a reference is made to Section 3.3.3.
3.5. OTHER CHARACTERISTICS

In this Chapter, the flood channel developments have not been discussed as extensively as the ebb channel developments. Furthermore, the processes related to the initiation and development of bifurcations have not yet been discussed in great detail. In this Section relevant developments other than ebb-channel developments are therefore described. Alongside this description, a look ahead is presented of how the processes related to these developments can be proven by modeling the hydrodynamics.

In case of the Kik and the development of the NKik and ZKik, an interesting phenomenon takes place. In 1989, a flood chute initiation was observed in ZKik-West. After its formation it migrated northwards to a more west-east orientation, which is in agreement with the findings in the previous Section. However, since 1990 the ebb channel (ZKik-West) was being dredged and the flood chute disappeared. Furthermore, the NKik developed and the Kik meanders became much larger than in the natural channels is observed.

The flood chute developed (see Figure 3.18) at the transition of the Kik into the ZKik-West, which is defined as a meandering cross-over. It indicates that currents over the tidal flat were large enough to transport sediments. By the disappearance of the chute, it can be hypothesized that either the currents decreased, or that the run-off direction of the flats changed. In Herman et al. [2] it is described that the degeneration of the flood chute is directly related to the rising tidal flat elevation, which plays a key role in the location of the local tidal watershed (see also Figure 3.19b) and for reduction of the ebb-flood circulation.

Observing the developments in the NSp and ZSp, a new flood channel develops which becomes more important in discharging the ebb- and flood currents. Due to channel splitting, the cross-sectional area increases and if a similar volume flows through a larger area, the velocities decrease. As a result, the bed level increases in the ebb channel and decreases in the flood chute until an equilibrium bed level is reached in both channels. This process could be reinforced by the reduced catchment area of the ebb channel, which has partly been taken over by the flood chute. In Figure 3.19 an overview of these processes is presented.

The hypotheses presented in Figure 3.19 beholds the reduction of the catchment area, which is sketched by the dashed line. After a flood chute formation, a part of the flood currents through the ebb channel are redirected to the flood chute. The location where the water flows onto the tidal flats changes and a local tidal watershed is formed (see a in Figure 3.19). In the NSp and ZSp it is observed that due to this process, the flood channel becomes wider and shallower. The bed level around the tidal watershed lowers resulting in an earlier submersion during flood. Also, the flow area at the bifurcation location increased due to the flood
chute formation, reducing the tidal prism. The calmer flow conditions then enhance sedimentation of the ebb channel and eventually a new channel will be formed in the area between the ebb- and flood channel. In this way a new (more straight orientated) channel is formed, which obtains a more west-east orientation and in the old, shallow, ebb- and flood channels sediment is being deposited. The new channel starts to meander under the influence of currents and tidal flat runoff, and the process repeats itself.

Returning to the disappeared flood chute at the ZKik-West, the dredging of the ebb channel can largely influence the development of the flood chute. Dredging increases the cross-sectional area, and thereby the volume of water that the channel can discharge. By the increased cross-sectional area, flood currents are redirected to the dredged channels, reducing the currents at the surrounding areas. This flow reduction on the tidal flats enhances sediment deposition and therefore the flood-chute disappeared. Due to this process, the location of the local tidal watershed is expected to migrate northward. From equation 1.1 follows that if the volume decreases, the tidal prism decreases and sedimentation is likely to occur with the reduced flow velocities. Because ZKik-West dredging started at the moment the flood chute development started, it was not able to develop into a new channel.

As the ebb channel was dredged in the years that passed, the flood currents were forced to be discharged through the ebb channel. Because the ebb currents were thereby also discharged through the "old" ebb channel, it could have caused the continuous growth of the eastern bend of the Kik. If the magnitude of the ebb velocities do not decrease, bend migration continues until the dimensions have adjusted towards a new equilibrium. The increasing Kik bends, and the fixed orientation of the ZKik-West (as a result of dredging), are expected to have created the clockwise channel rotation at the cross-over between Kik and ZKik-West. Thereby it is expected that more water will flow through the NKik, of which the length increase supports this hypothesis.

**Cross-overs**

Another interesting finding in this regard is the location where bifurcations take place. From Figures 3.1 and 3.3 it seems as if the channel orientation before the point of bifurcation determines the orientation after the bifurcation. Channels with a west-east orientation (e.g. ZSp and NSp) split-up at the channel top and form two channels with a mirrored orientation. In case of a north-south orientation, a parallel orientation is found after splitting-up at the cross-over.

The origin of flood chutes and bifurcations on the micro-scale lies in two bifurcation mechanisms. The first is caused by a meandering channel that "shoots-out" when the bends and velocities increase in magnitude. The second principle is presented in Figure 2.4a and describes a separation between ebb and flood channels in the main (ebb-) channel. Until now, flood chutes are described only by the "shoot-out" principle, while in the Ameland basin the other principle is encountered more often. In Figure 3.20, the mechanism of flood chute development originating in the cross-over is presented. The cross-over is the location where the flow shifts from one bend into the next. The secondary flow changes orientation at the cross-over, and there the lowest secondary flow velocities are expected. In fluvial systems, the cross-over location often corresponds to a higher bed level and a larger width. In case of a tidal channel, this shallower section is expected to be more sensitive to the development of a new channel.

The processes in Figure 3.20 can be described as follows: As the channel starts to meander, some channel sections become flood dominated and some ebb dominated. Flood dominated indicates that the flood currents are larger than the ebb currents in a specific channel section. If a bend is generated, secondary (curvature induced) flow is generated perpendicular to the channel axis. At the top of the water column, the secondary flow is directed to the outer bend and from one bend to the other, the secondary flow direction reverses. This reversal occurs at the cross-over, which is presented in the figure (graph a)) as the Area of interest (Aoi). In graph c) it is shown that the cross-over location during flood is expected to lie more to the east and more to the west during ebb. The different (secondary) flow conditions at the Aoi result in a separation of the channel into an ebb- and flood channel, which is shown in graph b). When the channel meandering increases, the flood channel obtains a more west-east orientation and the ebb channel reattaches to the first bend, as is shown in graphs c) and d).
3.5. Other Characteristics

Figure 3.20: Schematic overview of a meandering tidal channel with the ebb and flood cross-over at a different location. The area of interest (Aoi) seems to be the most unstable channel section, which is susceptible to variations in (secondary) flow velocities. Graph a) indicates the initial meandering stage, where small bends introduce secondary flow. As the meander evolves, the channel splits at the Aoi into an ebb and a flood channel, graph b). In graph c) the reattachment of the ebb channel to the flood channel is shown. The lower graph, d), describes a fully evolved meander. The ebb channel reattached to the flood channel, while the flood channel developed to a more west-east orientation, as is depicted by the red arrow.

The processes described above, indicate the onset of a channel bifurcation. If this moment is known, conclusions can be drawn for the maximum channel bend migration. Therefore, hydrodynamic model simulations should provide insights in the probability of occurrence and effect of these processes. The development of tidal currents through the channels would indicate the cross-over location during ebb and flood by calculating the secondary flow. Furthermore, the depth averaged flow velocities can present which channel sections are ebb- or flood dominated and how this develops in time. How the flows develop and their relation with the channel dimensions is discussed in the next chapter.
After assessing the channel dimensions at different spatial scales, the observed Micro-scale developments are to be substantiated by the use of a hydrodynamic model. The aim is to define the role of hydrodynamics in the origin and development of a meandering tidal channel. As was hypothesized in Section 3.5, the understanding of the bifurcation locations and moment of bifurcating is expected to be the key in the description of the maximal channel migration. In order to prove this hypothesis, the depth averaged- and secondary flow velocities are simulated in two- and three dimensions.

The hydrodynamics in the Ameland basin have already been modeled by Herman et al. [2]. A 2DH model was set-up and among others, the depth averaged velocity and bed shear stresses were evaluated for the fairway. Most sedimentation occurred in the ZKik-West and because of the growth of the Kik meanders, the hydrodynamic part of the study focussed on these two channels. The main conclusion of the model simulations were that in the ZKik-West the tidal volume reduces and that the flood dominance locally increases (Herman et al. [2]). In the Kik, the tidal volumes and the flow velocities increased in 2011 in comparison to 1999 and 1993. In general the flow velocities reduced, whereby it becomes possible that sediments are deposited in the fairway channels. Because the ebb velocities reduced more than the flood velocities, it is less likely that sediment can be exported from the channels. To obtain these conclusions, depth averaged flow velocities have been determined along the channel and the overview plots of Figure 4.1 were presented. In these graphs, the flow development in the flood channel (see also Figure 3.18) is clearly observed. Later years showed that this development stagnated and eventually disappeared.
The hypothesis that flood chutes and bifurcations are formed at cross-overs seems more plausible when examining Figure 4.1. Also, the flood channel formation determines the size and dimensions of the meander. The bend migration of a tidal channel is therefore expected to be dependent on bifurcations. By examining the ebb- and flood velocities in the channels, the relation between flow velocities and channel dimensions are tested. The main research question of the modeling study is therefore described by:

*What trends in the depth averaged- and secondary flow velocities can be distinguished that could influence the development of a tidal meander?*

Secondary flow is relatively weak, but it has the ability to redistribute the flow momentum over the cross-section (de Vriend *et al.* [44], p. 8-8). If the (secondary) flow velocity magnitudes deviate between ebb and flood, the peak velocities may deviate as well over the cross-section. At the point of the cross-over, the channel becomes wider and there is less asymmetry in the cross-sectional bed level. If the cross-over location is different for ebb- and flood situations, an unstable channel section is created. It is expected that the strongest (secondary) flow velocities (ebb or flood) in this channel section then become governing in reshaping the dimensions of this section. If this is translated into subquestions, the purpose is to find answers to the following questions:

b.1 *How does the depth averaged flow relate to the changing channel dimensions?*

b.2 *How does the secondary flow relate to the changing channel dimensions?*

b.3 *How are the tidal currents related to channel bifurcations?*

From these questions, several hypotheses are tested. In Section 2.1 it was described that more energy is dissipated along a meandering channel than in straight channels. The increase in channel length could therefore be related to the energy expenditure per unit channel length, which decreases with a length increase [24]. It is expected that this will also come forward in the distributions of the magnitude of the flow velocities and the secondary flow along the channel. Subsequently this raises the expectation that there is also a relation between the channel (arc-) length and the (secondary) flow velocities for which the bifurcation will take place.

The developments of the channel dimensions are examined for the Kik, NSp and ZSp in Chapter 3. These channels show a different meandering behavior with flood chutes and bifurcations at different locations. The NSp and ZSp are found to be in the same stage and therefore only the NSp will be examined together with the Kik. The focus of this chapter will be on smaller (Micro-scale) development in these channels. The examined locations are shown in Figure 4.2. At these locations, the clearest trends in channel dimensions are observed and they show consistent and comparable developments over time. The modeling analyses are performed for all channels that are discussed in Section 3.3.2; Meso-scale developments. But for the sake of brevity, only the figures with the results of these channels are included in Appendix D.

A 2DH hydrodynamic model for the Ameland basin is made available by Deltares and is used and extended to be able to assess the secondary flow velocity. In Section 4.1 a description of this model is presented, including the case-specific model configurations. While only the secondary flow intensity can be calculated in the 2DH Delft3D model, a three dimensional modeling is applied to evaluate the secondary flow to a larger extent. The methods applied in the 2DH and 3D modeling are discussed separately in Section 4.1.2. The results for the depth averaged- and secondary flow velocities are presented separately in Sections 4.2 and 4.4. In each section the results are presented for the Kik and the NSp channel. The final discussion of the results and conclusions are presented together with the Channel Classification results in the next Chapter.
Figure 4.2: The two locations that will be examined by the hydrodynamic model. Area i. covers the first bend of the NSp and area ii. covers the Kik meanders. The background is formed by the 1999 bathymetry.
4.1. METHODOLOGY

This Section discusses the set-up of the model that is used to examine the historical development of the meandering channels in the Ameland basin. With the historical bathymetry records and meteorological data, the origin and development of channel bifurcations and flood chutes are assessed. The two and three dimensional model have several settings in common, which are presented in Section 4.1.1. Differences in 2DH and 3D model configurations are thereafter described in a separate paragraph.

4.1.1. GENERAL MODEL SET-UP

A comprehensive Delft3D model has been developed for the Dutch Wadden Sea in the PACE-project. The aim of the PACE-project is to model the sediment fluxes in the Wadden Sea, to find out whether the import of sediment to the system is enough to keep up with local sea level rise (NIOZ [49]). To examine the sediment fluxes, a nested model has been set-up for simulations over three domains, see Figure 4.3. The first domain consists of an equidistant grid with a resolution of 200 m. The second domain has a grid resolution of 67 m and covers eastern part of the Dutch Wadden Sea, including the Ameland and Pinkegat inlets. The third domain is applied in this report and beholds the basin area south of Ameland. Its grid size is a factor 3 smaller (22 m) than the one of the second domain and the eastern boundary is located at the tidal watershed. The grid size was chosen by considering the computational time and the cell size needed to distinguish relevant processes in the channels (Herman et al. [2]).

![Figure 4.3](image.png)

Figure 4.3: The computational domain used for the hydrodynamic modeling. Left: the first domain in gray and the second domain in blue. Right: the second domain in gray and the third domain in blue; figures obtained from Herman et al. [2].

The Vaklodingen-data are used to construct the bathymetry maps of the most recent measurements (see section 3.1). Therefore, the bathymetry of the years 1993, 1999, and 2011 are used in the simulation. Especially for the analysis of the sedimentation problems in the Kikkertgat, Rijkswaterstaat provided the recent measurements of the 2016 bathymetry. This year was also converted to the 22 x 22 m grid and was applicable for this modeling study. For the first domain in the nested model, a sea surface height (SSH) and vertically integrated currents were imposed at the open boundaries and a closed boundary was prescribed in the east. In the first domain, and subsequently in the second domain, the SSH was calculated with an interval of 10 minutes (Verlaan and Heemink [50]). From the results of these simulations, the boundary conditions for the third domain were found. These consist of vertically integrated velocities and SSH, and are described in Section 4.1.2. Besides the velocities and SSH, also wind friction and freshwater discharge were included in the model. Because only currents are examined, wind friction and freshwater discharge have been excluded in the 2DH and 3D simulations presented here.

The simulation time-step is chosen based on the Courant number, $|\sigma|$, which is defined by the ratio between the step in space and time. It is found that a time-step of 6 seconds suffices to provide numerical stability of the model. Delft3D provides several options to include bottom roughness, which are primarily a function of the sediment properties. In the simulations presented here, the Manning bottom roughness formula is applied with a typical $u$- and $v$-value of 0.02 [s/m$^{1/3}$]. For an overview of the settings described here and the default model settings, a reference is made to Appendices C.1 and C.2.
Observation points have been introduced in the study area to observe the (secondary) flow development along the channel. They have been placed manually in the center of a grid cell, at the location that showed the largest depth. Furthermore, they have been placed on an interval of 3 to 5 grid cells, and several have been placed on the tidal flats (see Appendix C.4) and these results can be examined in another study.

4.1.2. Simulation Specific Set-Up

2DH model  The two dimensional horizontal (i.e. depth-averaged) model simulations provide information about the depth averaged flow velocities and the secondary flow intensity. The calculation method of the secondary flow intensity is described below by equation 4.1. The main input parameter for the model is a time series of the water level, which is presented in Figure 4.4.

Figure 4.4: The water levels that have been used for the 2DH and 3D simulations. The two upper graphs show the water level signals for both input time-series. A normal tide is determined and presented by the gray box, which is presented in the lower figures. The water level signal is retrieved from the most western observation point in the Kikkertgat.

At the western boundary of the numerical domain, the SSH and vertically integrated velocities are imposed. These variables originate from the second numerical domain (Figure 4.3). In Figure 4.4 the oscillation of the tidal water level can be observed clearly. Because these water levels are observed in the most western observation point of the Kik, the tidal elevation signals do not present a clear spring and neap tidal cycle. From the upper graphs, one tidal cycle that represents an average tidal range is chosen. This tidal range is used for the elaboration of the results and is depicted in the lower figures. Furthermore, the 2016 graphs are obtained with SSH data from 2016 and the simulations for 1993, 1999 and 2011 are performed with water level data from 2009.
In the two-dimensional Delft3D calculations, an option is implemented that can calculate the secondary flow intensity, \( I \), from the depth averaged velocity. The amount of influence of the secondary flow intensity on the calculations of the momentum equations can be included in the model by a factor \( \beta_c \). A factor of \( \beta_c = 1 \) is chosen, which means that the depth-averaged flow is influenced by the secondary flow [42]. The intensity is described by a term representing the centrifugal force (\( I_{be} \)) and a factor taking into account the effect of Coriolis (\( I_{ce} \)).

\[
I = I_{be} + I_{ce} \quad (4.1)
\]

where

\[
I_{be} = \frac{d + \zeta}{R} |\vec{R}| \quad (4.2)
\]
\[
I_{ce} = \frac{f}{2} \frac{d + \zeta}{2} \quad (4.3)
\]

Compared to the channel dimensions the magnitude of the secondary flow is expected to be small. It could however have a net effect to the sediment transport. For a better visualization of the magnitudes, an estimation of the secondary flow magnitude is calculated. Characteristic values for the radius, \( R \approx 350 \) m and the main flow velocity, \( |\vec{u}| \approx 1 \) m/s, are applied to the force balance of equation 2.2. The result is a water level difference \( \partial \zeta \) in the transversal direction of 0.29 mm. Also by applying characteristic values to the secondary flow intensity equations (eq. 4.1), a rather low flow intensity is found:

\[
I_{be} \approx \frac{2.5}{350} \approx 0.007 \ [m/s] \quad (4.4)
\]
\[
I_{ce} \approx 10^{-4} \frac{2.5}{2} \approx 0.000125 \ [m/s] \quad (4.5)
\]
\[
I \approx 0.007 + 0.000125 \approx 0.0071 \ [m/s] \quad (4.6)
\]

Even though the intensity will be small, it could have a net effect to the sediment transport. It should be noted that in between the channel tops the radius of curvature is much larger, meaning that the intensity will be dominated by the Coriolis term (eq. 4.5). Even though the Coriolis term is dominating, it is questionable whether it will lead to a relevant secondary flow velocity.

3D model  The 3D model is set-up for an average tidal range and two tidal cycles are simulated as can be seen in Figure 4.5. The model generates output every 10 minutes. The second tidal cycle is used for analysis in 2016 and the highest velocities in the first tidal cycle are used in the other years. The results are analyzed for the same tidal cycle as in the 2DH model.

![Water level at obs Kik1, 2016 (3D)](image1)

![Water level at obs Kik1, 2011 (3D)](image2)

Figure 4.5: The two tidal cycles that have been applied in the three-dimensional model simulations. For reference, the tidal range that is used in the 2DH analysis is included in this figure.

The main difference between the 3D and 2DH model set-up is the inclusion of 20 layers in the vertical \( k = 20 \). The layer thickness is defined as a percentage of the total water depth and at the bottom a finer grid spacing is applied than near the surface, see Appendix C.3. Also, some background vertical eddy viscosity of 0.001 m²/s is included to account for some vertical mixing.
The secondary flow velocities are determined according to the principles presented in Section 2.4. The procedure of secondary flow extraction from the modeling output is described as a series of steps which are clarified in Figure 4.6:

- Multiply the horizontal flow velocity components with the layer thickness, \( p_k \) [%], to correct (c in the subscript) for the influence of the vector in the vertical:

\[
x_{c,k} = p_k \cdot x_k \\
y_{c,k} = p_k \cdot y_k
\]  

(4.7)

- The horizontal velocity components \( x_{c,k} \) and \( y_{c,k} \), form the main flow matrix:

\[
\mathbf{u} = \begin{pmatrix}
  x_{c,1} & y_{c,1} \\
  \vdots & \vdots \\
  x_{c,k=n} & y_{c,k=n}
\end{pmatrix}
\]  

(4.8)

- The depth averaged flow velocity formed by the horizontal flow components is calculated as:

\[
\bar{x} = \frac{1}{n} \sum_{k=1}^{n} x_{c,k} \\
\bar{y} = \frac{1}{n} \sum_{k=1}^{n} y_{c,k}
\]  

(4.9)

- Jansen [43] defined the secondary flow as the component of the horizontal flow velocity perpendicular to the main flow (i.e. average flow). In Figure 4.6 this definition is presented by applying vectors to describe the flow components. The difference between the angle of the main flow magnitude and the flow magnitude per layer is determined first:

\[
|\bar{u}| = \sqrt{\bar{x}^2 + \bar{y}^2} \\
|u_k| = \sqrt{x_{c,k}^2 + y_{c,k}^2}
\]  

(4.10)

- The angles of the flow components and the difference are:

\[
\alpha_{u_k} = \arctan \left( \frac{y_{c,k}}{x_{c,k}} \right) \\
\alpha_{\pi} = \arctan \left( \frac{\bar{y}}{\bar{x}} \right) \\
\beta_k = \alpha_{u_k} - \alpha_{\pi}
\]  

(4.11)
• The secondary flow velocity per layer then yields:

\[ u_{sf,k} = \sin(\beta) \cdot |u_k| \] (4.12)

• To validate the computations, the sum of the secondary flow over the vertical are supposed to equal zero. This is confirmed for the channels evaluated in this study. The secondary flow velocity used in the analysis of the results is defined as the average secondary flow in the lower part of the water column:

\[
\text{Secondary flow} = \frac{\int_{z=0}^{z=h} \pi_{sf} \, dz}{z_{u_{sf}=0} - h}
\] (4.13)

**Concluding** With the calculated depth averaged and secondary flow velocities, several figures are created. In 2DH, overview plots (like Figure 4.1) are created for the depth averaged- and secondary flow velocity. These overview plots present the moment in time at which peak velocities occurred in the 1st observation point of the Kik. In 3D, only the depth averaged velocity is presented in these overview plots. The observation points at the channel centerline are presented in the overview plots, and the velocity variations during peak ebb and flood currents are presented in a separate figure. These figures show one peak-ebb and one peak-flood velocity per observation point, which has been determined by calculating the maximum flow velocity during the same tidal cycle per observation point separately. In this way, every result presented in these graphs present the maximum (secondary) flow velocity during a tidal cycle. The secondary flow along the channel was calculated per observation point separately and at the same moment in time at which the peak depth average velocity was found.
4.2. RESULTS DEPTH AVERAGED FLOW VELOCITIES

The depth averaged velocity is simulated to determine which channel sections are ebb or flood dominated. How this changes for different bathymetries (i.e. years) provides insight in the relation between the geographical developments and flow velocities. Figures 4.7a and b present a representative depth averaged velocity for an ebb and flood situation. The colors in the figure represent the velocity magnitude and the vectors are implemented to indicate the direction of the flow. The figure shows that the ebb currents mainly proceed through the ebb-channels and that the tidal flat runoff occurs predominantly towards the west. Flood currents proceed over the flats and through the channel, but the velocities in the channel remain larger than over the flats. Here it is also seen that the tidal flat runoff is deflected to a more eastward orientation. The funnel shaped channel top that was described in Section 3.5 accelerates the flow east of the channel top during flood. Whereas during ebb currents this acceleration is observed at both sides of the eastern top, the western bend does show a shift in peak flow velocity. North of the western channel top, a tidal flat region is found which appears to be deeper than other tidal flat areas. This deepening could be formed by the ebb flow that strives to flow westwards, instead of towards the nearest ebb channel. This development looks similar to the flood chute development in Figure 4.1.

Due to the submersion of the tidal flats during flood, a difference is expected in the bi-directional flow velocities in the channels. By calculating the difference between flood and ebb flow velocities, the dominant flow direction is derived. It describes the potential for sediment transport and therefore the flow velocities along the channels are examined in graphs c and d. The results in these graphs are based on the maximum ebb and flood currents, which are calculated for each observation point separately and in the same tidal period that is used in graphs a and b. The ebb and flood currents in graph c show a similar trend along the channel. However, as was expected, the ebb currents in the channel are stronger than flood currents. Ebb and flood dominance is presented in graph c by the green and orange markers as the difference between flood and ebb velocity. In graph d this difference is shown for the four years examined and it is observed that the flood dominance at \( x = 700 \text{ m} \) increases in 1993 to 2011, but becomes ebb dominant between 2011 and 2016. The flood dominance shifts along the channel as a result of a difference in starting location of the channel and bend growth. Finally, the channel is almost completely ebb dominant in 2016. This means that sediment inside the channel is more likely to be exported from the channel.

The four lower graphs present the depth averaged velocity results for the NSp and consist of a similar set-up as the Kik graphs. Graphs e and f are created at the same moment in time as the graphs a and b. The tidal flats have not ran dry yet, which may complicates the comparison between Kik and NSp. At the location of the 3\textsuperscript{rd} red marker, a high local velocity is found. This velocity peak is the result of a bed level gradient at this location, which is observed in the bathymetry maps (Appendix A). During flood this velocity peak is less profound due to the higher water level that increased the cross-sectional flow area and thereby influences the flow velocity (see eq. 1.1). Apart from this local inconsistency, the vectors show that at the channel top the velocities are generally higher than in the ebb channels. During flood, the velocities are also highest at the channel top and water proceeds through the flood chute. Graphs g and h show a mix between ebb and flood dominance. In time (graph h), the magnitude of the ebb dominance becomes larger, while this remains about the same during flood. At the channel top (left of 4\textsuperscript{th} red marker) flood currents are dominant and the cross-overs before and after the top are ebb dominant. This validates that the flood chutes are formed by the flood currents.

Concluding At both the Kik and NSp the largest velocities are found at the channel top. There, the ebb-flood difference is smallest and the flood currents are dominant. The flow acceleration around the channel top proceeds in the flood chute during flood and in the cross-over during ebb. This results in a local channel widening before and after the channel top. As the meander evolves, the ebb currents become stronger and the flood dominance is reduced. In the Kik the flood dominance even disappeared almost completely.

When the other channels are evaluated (figures in Appendix D), it is observed that the ZSp shows similar trends as the NSp with respect to the ebb- and flood dominance in the cross-overs and the channel tops. It also is seen that, as the channel becomes more variable (see Section 3.4), the difference between ebb and flood currents reduces as well. The ZKik, however, presents a completely opposite development. The ZKik-West shifted from ebb dominance in 1993 to predominantly flood dominant in 2011 and 2016. Around Holwerd, the channel becomes ebb dominated again, after which (to the east) similar trends as in the NSp and ZSp are observed. In the developing NKik, the shallower sections are flood dominated and the deeper beginning of the channel is mainly defined by the ebb currents.
4.2 Results Depth Averaged Flow Velocities

Figure 4.7: Several graphs representing the depth averaged velocity (D.a.v.) in the Kik and NSp. Graphs a, b, e and f are overview plots in which the vectors and colors indicate the flow velocity. Graphs c and g present the d.a.v. along the channel for one year and graphs d and h present the difference between flood and ebb for the four years that are simulated.
4.3. MEANDERING DEVELOPMENT

The hypothesis that was presented in Figure 3.19 stated that by the development of a flood chute the catchment area of the ebb channel would reduce. Furthermore it was hypothesized that if the ebb channel is being dredged, the local tidal watershed (in between the flood chute and ebb channel) would migrate northward and reduce the development of the flood chute. By observing the peak depth averaged velocities, and the flood chute development at the NSp and the Kik/ZKik-West, these hypotheses are tested.

In Figure 4.8, an overview is given of the ebb currents in the area in front of Holwerd. Also the development of the flood chute in the first bend of the NSp is shown in the upper graphs. In these graphs it is observed that the flood chute development in the NSp is characterized by a northward movement. By this migration, the flood chute obtains a more west-east orientation. Comparing the graphs of 1999 and 2016, it is clearly observed that in the latter the ebb channel has reconnected to the flood channel. Calmer flow conditions are found in the area between the channels resulting in a channel separation. A very interesting third observation is the development of the flow velocities in this calmer area. The evolution of the chute seems to stagnate and the flood currents are now directed more towards the ebb channel, which deepens. In the graphs of 2011 and 2016 an increase in flow velocities at the former cross-over occurs. East of this velocity increase, a splitting procedure as presented by Van Veen [22] is initiated (see also Figure 2.4a).

Contradicting the developments of the NSp flood chute, the local tidal watershed in between NKik and ZKik-West migrated southward. At the same moment, the NKik channel evolves and the flow velocities at a in Figure 4.8 and in the ebb channel (ZKik-West) reduce. These observations support the hypothesis that the location and migration of the local tidal watershed provides information about the development of the currents in the channels. When the channel centerline development in Figure 3.3 is re-examined, it is observed that the Kik had a more straight orientation before 1993. As the meander developed, a similar behavior to the NSp (2016) is observed. The development of a new channel (NKik) or a flood chute reduces the tidal prism of the ebb channel (ZKik-West), resulting in lower flow velocities and thereby sedimentation is enhanced. Whether the NKik develops due to the watershed migration or due to developments in the Kik is not evaluated in detail here.

Besides these observations, a similar development takes place northwest of the NKik (see also Figure 4.11). Also in the first bend of the ZSp the channel migrated westward after this phenomenon occurred. In case of the NSp, similar features as in the ZKik-West may occur if the ebb channel migrates westward. On the other hand, if the channel splitting in the east of the NSp graph (2016) develops and it starts migrating northward, the hypothesis of the channel initiation from splitting is supported. Monitoring these areas would provide more information about the importance of this phenomenon in the development of the tidal meanders. Furthermore, it would provide insight in how the ZKik-West would have developed without dredging of the channel.
4.3. Meandering Development

Figure 4.8: The two upper graphs present the flood chute at the first bend of the NSp during flood conditions. In these graphs the separation of the ebb and flood channel, and the reattachment of the ebb channel to the flood channel is presented. The lower graphs present the depth averaged velocity (D.a.v.) for the area in front of Holwerd during flood conditions. With these graphs, the migration of the local tidal watershed is evaluated.
4.4. SECONDARY FLOW RESULTS
Secondary flow can introduce a net effect on the sediment transport in the transversal channel direction (see Section 2.4.2). In order to estimate its influence to the channel development, the secondary flow is evaluated in this Section. Similar to the depth averaged velocity in Section 4.2, the secondary flow velocities in the Kik and NSp are presented and the results of the other channels are described in Section 4.4.3.

4.4.1. KIKKERTGAT RESULTS
Graphs a and b of Figure 4.9 are created for the same moment in time as Figure 4.7 a and b, and the vectors represent the same depth averaged currents. Three cross-over locations can be distinguished of which the first and the third remain at the same location during ebb and flood. The second cross-over location varies between ebb and flood. During ebb, it is located in between the channel tops and during flood it shifts eastward. The spatial variation (i.e. the AoI) between the two is approximately 400 m. This eastward shift can be explained in two ways. The first is that the bathymetry influences the propagation of the currents in the channels. The second is that the tidal flat runoff deflects the currents in the channel and thereby influences the secondary flow development. In Section 4.4.3 this second explanation is evaluated in more detail for all channels.

The influence of the channel dimensions on the currents is supported by the findings in graph c. This 2DH graph shows clearly that the flow increases in the channel bends and that at a cross-over, its direction changes. A shift is observed between ebb and flood which is in accordance to the observations in graphs a and b. The 3D graph shows similar trends as in 2DH with relation to the maximum around the channel tops and a minimum at the cross-overs. However, the shift at the AoI is not observed. The secondary flow velocities are higher in the first bend and lower in the second bend. This difference can be explained by the tidal range which is slightly larger in 3D than in 2DH, as was presented in Figure 4.4. This results in a larger depth averaged velocity during ebb, which is also observed in graphs 4.9e and f. Similarly, the flood currents are found to be smaller in 3D which explains the reduction of the secondary flow in the eastern bend. The increased flood velocities in the western bend can be devoted to the uncalibrated roughness in the model. If a larger roughness or vertical eddy viscosity would be applied, this may improve the comparability between the simulations. Another explanation could be that the flood chute somehow introduces an increase in current velocities in only the upper or lower part of the water column. This however, cannot be observed in the depth averaged situation.
Figure 4.9: Secondary flow (S.f.) results for the Kikkerigat channel. The two upper graphs present a top view of the secondary flow, and for reference the depth averaged velocities are included by means of black vectors. The secondary flow velocities are presented by the colorbar. The middle graphs present the secondary flow results along the channels in the 2DH and 3D simulations. In the lower two graphs the depth averaged velocity (D.a.v.) is added to explain differences between 2DH and 3D. The red markers in the upper figures correspond to the black markers in the lower figures.
4.4.2. Noorder Spruit Results

The NSp consists of a developed first channel bend (see Section 3.3.3) and it is included in the analysis for the comparison with channels that are influenced by dredging. The secondary flow in the upper graphs show that the beginning of the channel is largely influenced by the ZSp. In graphs c and d, a more irregular secondary flow pattern is observed, which is consistent with graphs a and b. The peak in the middle is the result of a large bed level gradient which is already described for Figure 4.7e and f. At the location of this peak velocity, the secondary flow (ebb) is significantly larger than during flood. Furthermore it is observed that the secondary flow east of the channel top (3rd red marker) is lower during flood, bringing forward the influence of the flood chute. In 3D, a similar irregular result is found at this location and at x = 4000 m the flood peaks and right after that the ebb peaks indicate a channel splitting, which was also observed in Section 4.3. Further, graphs e and f show that the flood velocities are very similar to the ones in 2DH. On the other hand, the ebb velocities are stronger in 3D. This results in a larger ebb secondary flow and the difference is most likely due to the small differences in SSH. Still, the velocities and trends are comparable for the 2DH and 3D situations.

In contrast to the Kik results, the cross-over locations are less profound in the NSp. However, a similar eastward shift is found in graphs a and b. The left (western) Aoi shifted approximately 50 m and the right (eastern) one approx. 250 m. Although the first channel bend is considered as developed, like in the Kik (see Chapter 3), the Aoi is much smaller. By examining the depth averaged velocity vectors, it is observed that the tidal flat discharge orientation is parallel to the channel. At the Kik this was more perpendicular to the channel and therefore a relationship is expected to exist between the Aoi and the orientation of the currents on the tidal flats.

Conclusions Secondary Flow Kik and NSp

Similarities between the NSp and Kik are found in the eastward shift of the cross-over. However, the shift at the Aoi is much smaller in the NSp than in the Kik. In the 3D graphs the shift at the cross-over is hardly detectable, but around a channel top it is observed. The non-detection of the shift at the cross-overs in 3D may be a result of the negligibly small secondary flow velocities at that location. Small deviations in secondary flow between 2DH and 3D are appointed to deviations in the SSH and to the not calibrated bottom roughness in the 3D simulations.
Figure 4.10: Secondary flow (S.f.) results for the Noorder Spruit channel. The two upper graphs present a top view of the secondary flow, and for reference the depth averaged velocities are included by means of black vectors. The secondary flow velocities are presented by the colorbar. The middle graphs present the secondary flow results along the channels in the 2DH and 3D simulations. In the lower two graphs the depth averaged velocity (D.a.v.) is added to explain differences between 2DH and 3D. The red markers in the upper figures correspond to the black markers in the lower figures.
At the Kik cross-over the possibility of flow deflection by tidal flat runoff was hypothesized. Furthermore, at the NSp cross-over, the hypothesis of the relationship between Aoi and tidal flat flow direction was proposed. By observing the overview plots of the other channels, these processes appear to occur at multiple locations. Figure 4.11a and b presents an overview of the secondary flow intensity in the entire study area. Similar to before, the vectors represent the depth averaged velocity direction and magnitude. Several locations are now highlighted that support these hypotheses.

The first channel to look at is the ZSp in graphs c and d. The ZSp ebb currents south of the second bend are flowing westward as they enter the channel. The cross-over during ebb is located more to the west, while during flood the opposite occurs and the cross-over location shifts eastward. The same observation can be made at ZKik-East and the NKik in graphs e and f. However, at the NKik the channel section over which water can enter the channel (the Aoi) is small and therefore the shift is less profound than in the Kik. The large bends in the Kik have a larger Aoi and there a larger shift is observed. East of the eastern Kik bend (see graphs e and f) this phenomenon is not observed, but at this Aoi the secondary flow intensity seems to reduce. This is observed in the color difference between the ebb and flood situation. This reduction, in combination with the stable cross-over location, could be explained by the dredging activities in the ZKik-West where the flood currents became more dominant over time. Furthermore, the non-developing flood chute between the start of ZKik-West and the end of the Kik could also be substantiated by this theory. During flood the secondary flow pushes the currents to this chute. As the Kik is predominantly ebb dominant and the ZKik-West more flood dominant, sediments are more likely deposited in the ZKik-West. Thereby, sediment is deposited on the flood chute, restricting its development. By dredging the ebb channel of the ZKik-West, these flood currents are redirected from the chute to the ebb channel causing sedimentation of the channel.

If the tidal flat runoff-theory holds, its influence on the secondary flow and thereby sediment transport is most relevant to larger meanders with a clear tidal flat–channel configuration. From observations in the NSp, it can be argued that the angle under which the currents on the flats enter the channel is important in the amount of secondary flow deflection. The secondary flow deflection described for the NSp in Section 4.4.2 also seems to relate to the Aoi. The relatively short tidal period, results in little time to recover from this deflection. With smaller bends and hence a smaller Aoi, the cross-over location changes every tide at approximately the same location. So if the bends evolve, the distance between channel tops increases and the Aoi becomes longer. The currents in the channel can then be influenced more by tidal flat runoff. However, its influence is then dependent on the orientation of the currents on the flats with respect to the channel orientation. The indication that this occurs is presented in the figures, but these findings are only based on 2DH results. In the 3D secondary flow figures this deflection is not observed, or only in minor detail. The deflection of the secondary flow therefore require further research.

Concluding 2DH secondary flow results indicate a relationship between the Aoi, the direction of the tidal flat runoff with respect to the channel orientation, and the deflection of the secondary flow in the channel. Larger meanders, with tidal flat runoff entering the channel perpendicularly seem to deflect the secondary flow. This can influence the sediment transport locally and enforce the bend migration. Because in the 3D secondary flow results the deflection was difficult to distinguish, further research should be performed to validate these findings.
4.4. Secondary Flow Results

Figure 4.11: Secondary flow (S.f.) overview plots of the entire study area are presented in graphs a and b. The middle graphs represent the secondary flow in the ZSp and the lower graphs the Nkik and ZKik. The vectors in the graphs present the depth averaged flow velocities and, similar to previous figures, the circular markers correspond to the observation points along the channel. The colorbar below the figure indicates the magnitude of the velocities presented in the graphs.
4.5. Conclusions

By modeling the hydrodynamics, the relation between the currents and the meandering development is tested. From the Chapter Tidal Channel Classification, the focus of the modeling study was narrowed down to the evaluation of the initiation and development of tidal meanders. In Section 3.5, Other Characteristics, hypotheses were proposed regarding this initiation and development. By answering the following subquestions, it is aimed to determine the influence of the depth averaged- and secondary flow velocities on the development of a tidal meander.

b.1 How does the depth averaged flow relate to the changing channel dimensions?
Flow accelerates around (funnel shaped) channel tops. Around a channel top, flood dominance prevails and at the cross-overs ebb currents dominate. This is observed in both natural and non-natural meanders (Kik and NSp). The flow acceleration around the channel top proceeds in the flood chute during flood and in the cross-over during ebb. This results in a local channel widening before and after the channel top. As meanders evolve, ebb dominance becomes stronger and in case of the Kik, flood dominance disappeared almost completely. On the contrary, the dredged ZKik-West presents a development towards a predominantly flood dominated channel. Towards the tidal watershed, ebb and flood currents become of the same order and fluctuations between ebb- and flood dominance are found. Where this occurs, the channel geometry becomes more variable and stable bifurcations are not observed anymore.

b.2 How does the secondary flow relate to the changing channel dimensions?
Secondary flow is derived from the depth averaged velocity, and therefore the secondary flow velocity profile along the channel corresponds to that of the depth averaged velocity. As was expected, smaller meanders correspond to a lower secondary flow velocity. The secondary flow in the Kik and NSp have been assessed and in both channels a shift of the cross-over location is observed. The cross-over is located more to the east than during ebb. However, the shift at the Aoi is much smaller in the NSp than in the Kik. In the 3D results, this shift at the cross-over is much smaller than in 2DH, but at the channel tops it is observed. Differences between 2DH and 3D are devoted to the small deviation in SSH imposed at the boundary. Finally, a correlation is hypothesized between the distance between channel tops, the shift and the orientation of the currents on the tidal flats with respect to the channel orientation.

b.3 How are the tidal currents related to channel bifurcations?
Channel bifurcations occur at the cross-overs and at the channel tops (i.e. flood chutes). The channel tops are found to be flood dominant, hence flood chutes can develop. This reduces the local flood current propagation in the adjacent ebb channel, which is subject to sediment deposition. As the flood chute develops, it obtains a more west-east orientation. While the flat between the flood chute and ebb channel develops, currents are deflected by the flat towards the ebb channel. This subsequently deepens, obtains larger ebb current velocities and tends to migrate westward. Observations in the development of the currents and topography in the NSp, ZSp, Kik/NKik and ZKik-West support this procedure. The dredging of the ZKik-West is therefore held responsible for the redirection of the flood currents into the dredged channel, resulting in the disappearance of the flood chute. The development of the flood chute is expected to have evolved into a new, shorter (ZKik-West) channel. This reduces its storage volume and increases the velocities that could have reduced the sedimentation in the channel.
The system of channels is analyzed and the differences between natural meanders and meanders influenced by human interventions are presented. Furthermore, the depth averaged- and secondary flow velocities are modeled to determine the relation between flow velocities and the channel development. In order to obtain these results, assumptions have been made and the data was assumed to be reliable. This Chapter discusses the reliability of the results and the applicability of the methods in three sections. First, a discussion on the accuracy and limitations in this research are elaborated in section 5.1. In Section 5.2 an evaluation is made by comparing the results with findings from other studies. The results are compared to findings in different environments, like rivers or salt marshes and it is discussed to what extent comparisons can be made. Then, in Section 5.3 the relevance of this study is presented, in which the discoveries of the research are highlighted. This Chapter will conclude with a discussion whether the methods presented in this thesis are applicable to other basins.

5.1. ASSUMPTIONS AND APPROACH
The influence of the assumptions proposed in the methods, and how this affects the results is described in this Section. Similar to the previous chapters, the influence of the local conditions (data and boundary conditions) is evaluated first. Subsequently, the assumptions and approaches applied in the analyses of the channel dimensions is elaborated from the Macro-scale to the Micro-Scale. This Section concludes with discussing the approach and methods applied in the Chapter Numerical Modeling.

5.1.1. LIMITATIONS DATA RESOLUTION
The used bathymetries for the tidal channel classification and the hydrodynamic modeling consist of Vaklodingen-data, with a 20 x 20 m grid size for most of the years. Inconsistencies in the data resulted in a reduced accuracy of the extracted channel network. In the determination of the channel width and bed level this difficulty came forward. With hydrodynamic modeling, the ADI-effect (see Deltares [42]) had to be prevented. This means that at least three grid cells should be present along the width of the channel. Because the channel sections of interest have a width of at least 100 m, the application of grid refinement was not necessary (Note: this width comprises a width estimated by visual inspection, so this is not the width determined in Chapter 3). However, towards the tidal watershed, the channel dimensions are less distinct and for the evaluation of these channels, grid refinement is advised.

Furthermore, the ebb- and flood dominance was calculated along the channel at the location of the observation points. These were introduced at the cell centers of the cells with the largest depth. The amount of grid cells over the channel width, the irregular bathymetry, and the exact location of the observation points in the channel can lead to a deviation in the observed (secondary) ebb- and flood flow velocities. Towards the end of the channel the bed level increases and the ebb- and flood currents become of a similar order. Because of the relative course spatial resolution, it is difficult to prove that this forms an indication for a stable bifurcation or flood chute.
5.1.2. Tidal Channel Classification

Channel Extraction Models

The accuracy of the extracted channel network is determined by the data resolution and the imposed gray-scale threshold value. For uniformity, one threshold value is chosen that applies to all years with bathymetry data. However, as Table 3.2 presented, the data consisted of different spatial resolutions and applying different threshold values may therefore result in more accurate results. Furthermore, the model only produces a channel network by connecting data points at sections where 10 dots can be connected. Reducing this value results in less accurate channel detection and an increase results in the failure to detect channel sections. Also, if the gray-scale threshold value is adjusted, the amount of connected dots could be adjusted as well. Although the results were quite accurate, imposing a threshold value as a percentage of the gray-scale range is expected to produce better results. Furthermore, the relation between the connected dots and the threshold value could be optimized if even more accurate results are required.

In order to derive the channel dimensions automatically, only one channel branch was analyzed per year (see Appendix B.6). Towards the tidal watershed, the channels split-up more irregularly and the width and bed level of one channel may not be representative for that location. However, if all branches would have been evaluated, the summation of the branch widths or depths could lead to more insights in the smaller channel developments.

The application of QGis forms a relatively simple and open source approach to the recognition of the channel centerline. Because the models make use of the gradient of the surface elevation, its accuracy is much higher in environments with larger gradients. It has been developed for detecting river networks on a larger spatial scale. So to improve the accuracy and applicability for tidal environments even more, a different aspect than the bed level gradient could be implemented in the model. Therefore, the method of Fagherazzi et al. [40] will improve the accuracy of the smaller channel detection. Especially the location of the channel start and end will become more accurate by this method.

Large-scale developments

By focusing on the tertiary channels, the influences of the basin-scale developments are not taken into account. Developments at the Ameland inlet may largely influence the developments in the tertiary channels. If the channel orientation changes there, the discharge towards the study area changes. Equation 1.1 described that a lower discharge relates to lower flow velocities and thereby sedimentation in the channels is enhanced. When west of the studied channels the geometry changes, it may have a larger influence on the developments than a small local change like the establishment of a new flood chute. Because this region has been discussed in a lesser extent, the inclusion of large-scale effects that may influence the geometric changes are subject to further research.

Analysis of the Channel Dimensions

The channel dimensions that are assessed for the description of the meandering evolution are the length, width and bed level. To begin with, the length is calculated from a smoothed channel centerline. Although Gaussian smoothing is performed to remove the irregularities from the channel centerline, some inaccuracies remain present that complicate the curvature calculation. Fagherazzi et al. [51] described that "the extraction of the curvature from planforms is inherently difficult". For the curvature calculation in salt marshes cubic spline and/or spline interpolation was applied, after which a low-pass filter was used to reduce the high frequency oscillations. The optimal filter consisted of a fifth-order polynomial applied to a 15-point window. As the Gaussian filter in this report uses a 4-point window, it can be assumed that by increasing this window more accurate results will be obtained. Then, by calculating the first derivative of the smoothed centerline it also becomes easier to determine the channel tops automatically. Fagherazzi et al. [51] suggested that the skewness in the channel can also provide information about the ebb- or flood-dominance in the basin. The minor adjustment of the smoothing window would provide more information about the wavelength, sinuosity and the skewness of the tidal channels, quickly improving the classification of the channels. On the other hand, smoothing with a larger window also smooths out typical centerline features around channel tops. Further research should be performed to examine the relation between the skewness of the channel geometry to the ebb- or flood-dominance in the Ameland basin.
The channel width and bed level are calculated from cross-sections that are imposed with an equidistant interval along the channel. At first, the hypsometric curve was calculated for each cross-section. However, the irregular bottom profile and bar formation in the channel resulted in several jumps in the curve. Because each cross-section has different dimensions (hence: flow areas), it was found difficult to determine automatically which jump should be seen as the location where the width is determined. Therefore, a different procedure was proposed in which a threshold value of 50 m (just over 2 grid cells) indicated the location where the width had to be determined from the width profile, $B(z)$. The bed level is calculated as the average bed level in the section where the width is determined. As a result of this arbitrary method, the flow area could not be calculated with the width and bed level, and the width-to-depth ratio becomes less comparable to the ones found in literature. This is unfortunate, because D’Alpaos et al. [52] concluded that the relation between tidal prisms and cross-sectional areas within a tidal landscape is a valuable morphological tool for describing long-term morphodynamics. These methods are not considered as wrong, but to improve the comparability of the results with respect to other studies, it is recommended to revise the application of the hypsometric curve per cross-section.

Concluding, the methods used to calculate the channel width, bed level and length is slightly different from those presented in other studies. However, these methods are not necessarily inferior, because of the presence of flood chutes and variable bottom topography. Also, the channel length should then be determined by the characteristics per meandering wavelength. Even though the extracted channel length was subject to inaccuracies, it did provide information about the channel evolution in the past decades that made it possible to evaluate the channel developments.

**Flood Chutes**

The influence of a flood chute on the width and bed level at a channel top is small. However, around a channel top the flood chutes made it more difficult to determine the width and bed level, because of the more irregular bottom profile at those locations. Furthermore, the network extraction model focuses on the ebb channels, whereas the evolution of the flood channels are found to be important in the development of a meander. Oost [46] described that the system of channels had roughly the same layout throughout the past 200 – 500 years. This means that the meanders in the Ameland basin show a cyclic pattern of formation and disappearance over time. Flood chutes are therefore not influencing the changes on a basin scale, but for the meandering fairway channels it can play an important role as well. Van Veen [22] describes that a water in a flood chute cannot flow into the ebb channel because of the created bar at the end of the flood chute (it forms a barrier). However, the western Kik flood chute developed in such a way that water is flowing over this bar. This does not imply that an ebb chute is formed, but it implies that the Kikkertgat meanders will return towards a more straight orientation in time. The modeling study revealed the importance of the flood chutes in the meandering development, and therefore the geometric development of the flood chutes should be evaluated in a future study.

**5.1.3. HYDRODYNAMIC MODELING**

The boundary conditions in the modeling study have been limited to the inclusion of the sea surface height (SSH) on the western boundary, and depth averaged currents on the eastern boundary (only in 2DH). Wind-, wave- and stratification influences on the flow velocities are excluded from this study to ease the comparison between the 2DH and 3D results. In a future study, it is advised to implement the other forcings as well to improve the accuracy of the model prediction. Especially the wind appears to form an important factor to the development of the currents. Duran-Matute et al. [16] emphasized that the effect of the wind on the water movement is particularly noticed with storm conditions. Hughes [37] stated furthermore that due to the bi-directional tidal flows, the time during which erosion thresholds are exceeded, are limited. More significant changes to the bottom topography are therefore expected during extreme events. In this study, the trends in flow velocities could be evaluated with the normal tidal range. When the aim is to model the morphological response of the system to the hydrodynamics, a spring tidal range and other (extreme) conditions should be implemented in the model.

Trends in flow velocities have become visible by the use of peak velocities. Flood peak-velocities do not necessarily occur when the tidal flats are submerged. The ebb- or flood dominance is therefore more determined by the flow development in the channel, which is determined by the channel geometry. Regarding the secondary flow, it is calculated under the assumption that the flow at the channel banks equals zero. When water flows onto the tidal flats, or when it is discharged towards the channel, this assumption is not valid anymore. Then the horizontal velocity term in momentum equations 2.17 and 2.18 is not excluded, resulting in...
in a more difficult calculation of the secondary flow velocity. Besides this, the circulatory motion is determined based on the information at the observation point. As the cross-sectional bottom profile is variable, different secondary flow magnitudes can be expected at different locations in the cross-section.

When the depth averaged velocities between 2DH and 3D are compared, similar trends in the results are observed. Some deviations are present which can be appointed to differences in the water level that is used to simulate the currents (see Section 4.1). The secondary flow results, however, showed some differences between 2DH and 3D. The secondary flow in 2DH is calculated based on the depth averaged velocity and the curvature of the channel. The same principles are used in 3D, but there the gradients in the vertical may also play a role. Deviations in the bottom profile can locally increase the horizontal velocities, leading to differences with respect to 2DH. This error is aimed to be reduced by calculating the peak secondary flow in 3D at the moment that the depth averaged velocity showed the highest velocity at the 10th layer in the vertical. Although more vertical layers are taken into account in 3D, the vertical mixing parameter and bed roughness are not calibrated. Therefore, it is possible to distinguish trends and magnitudes of the secondary flow, but the model needs to be calibrated and validated to determine which of the two simulations is more accurate. The depth averaged velocity is very similar in 2DH and 3D and secondary flow is also sufficiently presented in 2DH. In order to make predictions about changes in the system, modeling in 2DH therefore proves to be sufficient to simulate the currents in the Ameland basin.

5.2. Interpretation of the Results

Tidal meanders have different characteristics and within different tidal systems these characteristics vary as well. Channel dimensions have been analyzed in for example the Venice Lagoon (e.g. [32], [41] and [35]). Arcachon Lagoon [53] and Leopold and Wolman [24] evaluated channel dimensions and behavior for riverine environments. Furthermore, the development in channel dimensions has been described for estuaries, like the Eastern Scheldt (Jeuken [19]). However, this Section evaluates the results only with findings in the Wadden Sea basin, rivers and other unvegetated tidal environments where the fresh water influences are inferior to influences of the tide.

To begin with, the absolute and arc-channel length are determined to describe the meandering extent of the channels. Because the sinuosity is already considered in Section 5.1, another aspect related to channel length is mentioned here. In general, the bed level shows an exponential decreasing trend towards the tidal watershed. However, around a channel top, flood chute or bifurcation this decreasing trend is temporarily interrupted. De Vriend and Struiksma [30] described a channel length needed for the flow to adapt to irregularities in the bottom profile of a river. When this relation is applied to the tidal channels, it is found that the flow adaptation length is approximately (see also eq. 2.3):

$$\lambda_w = \frac{h}{2C_f} = \frac{h}{2 \cdot g/C^2} = \frac{3}{2 \cdot (9.81/60^2)} = 550 \ [m]$$

Assuming that this relation holds for tidal meanders as well, it is found that a bifurcation occurs before the flow adaptation length has been reached. So when the distance between channel tops increases, the bed level is expected to adapt to a larger extent before the next channel top is reached. In this regard Cleveringa and Oost [21] found that the length between two bifurcations decreases logarithmically. By roughly estimating the lengths in Figures 3.6 (bed level) and 3.5 (width) it is found that the non-natural channels ZKik-West and Kik do not share this logarithmic relation anymore. As the other channels appear to follow this logarithmic relation, the channel behavior is explained by the dredging activities. However, the relation between flow adaptation length and bifurcations, flood chutes and (funnel shaped) channel tops could be examined in a future study to provide a relation between occurring processes. However, channel skewness is found to relate to be able to predict the ebb or flood dominance. Also, the bed level did not recover from a cross-over in the developed, variable meanders below certain depths. How these three findings compare to the flow patterns therefore form an interesting topic for further research.

Secondly, the width and depth are determined along the channels. In salt marshes in the Venice Lagoon, width-to-depth ratios were found to be in the order of $\beta = 5 - 7$ [32]. In the same lagoon, tidal flats presented a ratio of $8 < \beta < 50$, corresponding to river-like patterns ($8 < \beta < 48$). In Figure 5.1, the results of Marani et al. [32] are presented by the black markers and the average width and depth of the tertiary channels in the Ameland basin are presented by the red triangular markers. The largest difference between the
study areas is found in the depth. The lower depth in the Ameland basin leads to a width-to-depth ratios of approximately $50 < \beta < 130$. Different methods are applied to calculate the depth (see Marani et al. [32], p. 7), but in the end the average depth is determined in both studies and this can not lead to such large differences. Furthermore, the determination of the channel width also proves to be difficult. Marani et al. [32] derived a double exponential relation for the dimensionless channel width for salt marshes, which proved to show accurate results.

$$\bar{B} = B_0 \frac{L_B}{L_s} \left[ 1 - \exp\left(-\frac{L_s}{L_B}\right) \right] \exp\left(-\frac{s_i}{L_B}\right)$$

(5.2)

However, the splitting of ebb- and flood channels (see Figure 2.4) around cross-overs in the Ameland basin is not mentioned in the derivation of this equation. This feature makes it more difficult to determine the width and thereby also $L_B$; the length over which the width decreases by a factor of $e$.

Thirdly, bifurcations and flood chutes in the study area are assessed. Irregularities in width and depth indicated the onset of one of these processes to occur. One of the principles that was brought forward in Dey [27] and Leopold and Wolman [24] regarding the initiation of meandering was the presence of irregularities in the flow profile. As a result of the data resolution this cannot be proven, but the width and depth variations found form a characteristic for channel splitting.

Simple features like the width and bed level can be determined in lagoons, estuaries, salt marshes, creeks, etc. A different combination of variables is present in each tidal environment, which makes it difficult to find robust relationships that describe the channel development. Because of the presence of for example flood chutes and a tidal watershed, the studied channels in the Ameland basin are therefore not truly comparable to salt marshes, creeks, etc. As will be described in Section 5.3, the results can and should be evaluated with other Wadden Sea basins, because of the similarities in e.g. tidal watersheds and the presence of tidal inlet-basin structure.

![Width versus Depth](image)

Figure 5.1: The width versus depth for a number of tidal channel sections in the lagoon of Venice and the examined tertiary channels in the Ameland basin. The data from the black markers originate from Marani et al. [32] and the red triangular markers from the averaged width and depth per channel, per year in the Ameland basin. Although the average width and depth are calculated different for the black and red markers, the clear difference between the systems comes forward.
5.3. STUDY APPLICATIONS
The combination of classifying the channels based on their dimensions and to the development of the hydrodynamics, a link is formed between the behavior and the physics driving the changes. In Table 3.1 it was brought forward that many factors and channel dimensions can influence the meandering channel evolution. This thesis examined several factors from this table and concluded they are relevant or require further research (see also Section 5.1). For other locations influenced by the tide (salt marshes, creeks, etc.) studies have been performed to these influencing factors, while for the tidal flats in the Dutch Wadden Sea no recent studies have been performed. This thesis also provides insights in the meandering development for shallow, tide-dominated areas with intertidal flats and flood chutes. The study area consists of very specific boundaries which may influence the comparability with other basins in the Dutch Wadden Sea. However, the result that the bed level is of large influence on the meandering stage can be projected at every other location in the Wadden Sea basin.

The automatic extraction of the channel network shows that analyses can be performed fast and accurate by the use of the open source computer program QGis. The onset of a channel bifurcation or flood chute is described by irregularities in the width and depth profiles along the channel. With new topographic measurements, the QGis models could be applied to determine whether a channel is about to develop a flood chute. As this is related to sedimentation of the ebb channel, it could be used in the dredging strategy of the fairway channels.

Similarly, the methods can be applied to other basins in the Wadden Sea by merging the Vaklodingen-data per basin. Smoothing of the channel centerline is then a necessary procedure, because the extracted network orthogonally follows the pixels. The quality of the data and the threshold parameters used in the model are influencing the accuracy. This accuracy should therefore be examined in more detail and a threshold value of the detected depth (the gray-scale) consisting of a percentage of the color spectra range is desired (see also Section 5.1). Although the methods in QGis are developed for terrains with larger gradients in elevation, its applicability to terrains with small gradients in bottom topography is presented in this thesis and it works well.

Although the methods can be applied to other basins, the results may deviate as a result of the different basin dimensions. The flood chutes developed in a west-east orientation, which is a specific feature for the tertiary channels in the Ameland basin. Where the distance between the barrier island and the main land increases, the tidal propagation direction may be different and as this seems to correspond with the flood chute orientation, this is expected to change as well. Another aspect that was not elaborated in this thesis is the ratio tidal range to water depth, which is much larger near the tidal watershed than at the tidal inlet. Figure 5.2 presents this principle and a more variable geometry is expected when this ratio becomes larger. This distance could form a large-scale dependency explaining the channel behavior, based on the location in the basin.

By assessing the hydrodynamics, the effects of the depth averaged- and secondary flow on the meandering development are estimated. The secondary flow has not been examined before in tidal channels. During an ebb or flood period, the velocities in the channels have to develop. The secondary flow velocities presented in Section 4.4 represent peak velocities and because these are already very small, its influence on alternating the main flow is expected to be limited as well. Because the depth averaged velocity is easier to calculate and because its magnitude is larger, this is expected to be the main influence on sediment transport.

This thesis furthermore describes a new principle of flood chute development, which is not yet specifically acknowledged in literature. The principle of the flood chute development is that the channel starts to meander and "shoots-out" over the tidal flat once the bends become too large (see Van Veen [22]). The splitting of an ebb tidal channel is also described by Van Veen [22] (Figure 2.4). From several decades of bathymetry data a combination of these two principles, a new principle is composed; the bifurcated flood chute. This "new" principle links the initiation to the development of a chute and is thereby new to what has already been described in literature. The evolution of the bifurcation at a cross-over that develops into a flood chute is somehow related to the basin geometry. From a quick look to the bathymetry maps of other Wadden Sea basins, the three meandering stages defined in Section 3.4 are applicable to other basins as well. However, when the channel depth is larger, the meanders are soon classified as developed. Furthermore, one of the criteria in the meandering stages is the presence of flood chutes. For larger channels it is often more difficult to distinguish whether the splitting feature is classified as bifurcating or as a flood chute. Still, when the network extraction is performed following the criteria described in this thesis, the longest continuous channel section
is derived. All other sections can be described as flood chutes or bifurcations. On the other hand, it should be noted that when the split-off channel has significant dimensions, and it shows meandering features, it should be taken into account in the analysis as well. Concluding, the methods in the network extraction can be applied to other basins, but when the split-off channel shows features comparable to developed or developed, variable meanders, it cannot be ruled out of the analysis.

The best reference material for the examined channels in the Ameland basin is found in channels with a more or less parallel orientation to the barrier island and closer to the tidal watershed. In the Dutch Wadden Sea, the channels behind Vlieland, Terschelling and Schiermonnikoog show the most consistent features with the Ameland basin. Also, the islands Juist, Norderney, Langeoog, Spiekeroog and Wangerooge in the German Wadden Sea show parallel channels to the islands and these channels could be analyzed well following the meandering channel classification methods. There, the tidal watershed behind the island is also located more to the east. West-east currents are expected at those locations, resulting in flood chute developments. These locations could be evaluated to validate the trends in depth averaged- and secondary flow velocities along the channels.
CONCLUSIONS AND RECOMMENDATIONS

6.1. CONCLUSIONS

The exponential growth in dredged volume and the migrating meanders in the fairway in front of Holwerd formed the initial motivation for this thesis (see Figure 6.1). The meanders in the fairway have developed to a greater extent than other meanders in the Ameland basin and this formed the main focus for this research. To obtain a better understanding of the meandering channels in this area, the goal was to explain the difference in evolution between non-natural (influenced by dredging) and natural tidal meanders. To achieve this goal, the channels have been classified based on their locations and dimensions. Because the developments are dependent on the scale that is considered, the channels are classified by substantiating three different scales; Macro, Meso and Micro. To link the evolution of the channel dimensions to the physics that drive the changes, the hydrodynamics are modeled with Delft3D. The focus of the modeling study is on the processes related to the initiation and development of tidal meanders. Secondary flow is described in literature as one of the possible mechanism for meandering initiation. Although its magnitude is small, it is expected to have a net effect on the sediment transport. The larger influence on meandering is formed by the depth averaged velocities and therefore these two hydrodynamic features are evaluated.

Figure 6.1: Two figures representing the problem definition of this thesis. The left figure presents the problem of sedimentation in the channel and the right figure presents the meandering development of the channels that increased the length of the fairway.
In the analysis of the tidal channel dimensions, the channel width, bed level and length are evaluated to answer the following research question:

**What are the trends in the development of tidal channels that characterize natural meandering behavior in the Ameland basin?**

The natural meanders evaluated in this thesis contain flood chutes, which can be detected by an irregularity in the width- and bed level-profile along the channel. By assessing the channel centerline developments in the Macro-scale analysis, the evolving meandering channels were distinguished from the more geographically fixed channels. The smaller channels near the tidal watershed showed the largest meandering development. An increasing trend is found in the (arc-) length for all channels until 1990. Thereafter, a decreasing trend is observed at all channels, except for the NKik which kept on growing (for channel names see Figure 3.1). The Meso-scale analysis presents a general trend of decreasing channel widths and increasing bed levels between 1989 and 2016. Along the channels, the bed level increases towards the location of the tidal watershed and the increase can be described best by an exponential trend. The channel width reduction dominates over the bed level increase and therefore it can be concluded that the channels became more distinguished from the tidal flats in time. By examining the dimensions at a smaller scale (Micro-scale), it is observed that around a cross-over the channel is wider and shallower than at a channel top. The channel top is described by a bed level reduction of factor 2 and a reduced width compared to around the top. This results in a funnel shaped geometry that can be observed in more detail when the meanders develop. Flood chutes are found not to be of influence on the channel top dimensions. Furthermore, flood chutes migrate simultaneously with the channel top and strive for a west-east orientation.

Comparing the dimensions of non-natural and natural channels, it is observed that the meandering extent (average sinuosity) is approximately 10% larger for the non-natural channels. This sinuosity also increases in the natural channels (e.g. in the NSp), but they develop to a lesser extent. By dredging the ZKik-West, the irregularities in width and bed level are flattened out and flood chutes or bifurcations - the natural meandering features - did not develop. Combining all these observations, the geographic development of a tidal meander in the study area can be described by distinguishing three meandering stages:

- **Developed meander (Kik):** This is a meander with a clear sinusoidal shape and with flood chutes. In this stage, the depth at a cross-over is approximately two times smaller than at the location of a channel top. The temporal averaged maximum channel depth between the seaward channel top, the cross-over and the landward channel top has a ratio 1 : 0.5 : 0.75. The width is smaller at the channel tops compared to the rest of the channel.

- **Developed, variable meander (NSp, ZSp):** This stage is defined by a clear sinusoidal channel shape, flood chutes and a variable ebb-channel location towards the end of a channel. Characteristic for this stage is a lower correlation between width and bed level, and the temporal averaged maximum channel depth between the seaward channel top, the cross-over and the landward channel top has a ratio 1 : 0.6 : 0.6 for the NSp and 1 : 0.8 : 0.8 for the ZSp.

- **Undeveloped meander (NKik):** Small and straight channels like the NKik develop into longer channels with initial meanders. This stage is defined by little meandering features and the absence of flood chutes. In this stage, a rather constant width and bed level are observed.

The results regarding the development of the width, bed level and flood chutes indicate that there is a correlation with respect to the initiation and development of a meandering channel. The dynamics that drive the changes in the basin can indicate why the non-natural and natural meanders develop in this way. Therefore the following research question was proposed:

**What trends in the depth averaged- and secondary flow velocities can be distinguished that could influence the development of a tidal meander?**

It is found that flow accelerates around the (funnel shaped) channel tops, where flood dominance prevails and flood chutes (are able to) develop. During ebb, a similar acceleration occurs towards the cross-over and there ebb dominance is found. Growing meanders correspond to a shift towards ebb dominance in both natural and non-natural channels. However, the dredged ZKik-West presents a development towards flood dominance.
Besides the shoot-out principle of Van Veen [22], several flood chutes seem to have originated from a channel splitting at the cross-over. It was hypothesized that the shallower area between the channel tops is more susceptible to changes in the flow and hence changes in topography. The section where the orientation of the secondary flow reverses (the cross-over), is located at a different location during ebb and flood. In both the Kik and the NSp, an eastward shift of the cross-over location is observed. Whether the shift corresponds to the migration of the channel, or that it strengthens the potential for channel splitting is not proven. However, an indication is found that a correlation exists between the distance between channel tops and the cross-over location shift. The distance between the tops increases with developing meanders, enabling a larger area over which the direction of the secondary flow can change. Furthermore, the orientation of the currents over the tidal flats seems to be correlated to the angle under which they flow into the channel.

Regarding the development of channel bends, a series of processes is found that describe the meandering channel evolution around a flood chute. The explanation for this relation is presented by the proportionality between the tidal prism, the flow area and the flow velocities. The increase in the flow area at the location where a flood chute develops reduces the flow velocities and enhances the sedimentation in the channels. Due to the flood dominance around the channel top, sedimentation mainly occurs in the ebb channel adjacent to the flood chute. After a flood chute is established, and it obtained a more west-east orientation, the flood currents over the tidal flat in between the ebb and flood channel are deflected towards the ebb channel. The thereby increased current velocities in the ebb channel result in increasing bends and a westward migration of the ebb channel. This deflection of the flood currents is observed at multiple locations. At the ZKik-West a similar process occurred before the dredging activities started. The natural process of filling in the ebb channel was counteracted by the dredging. The dredged channel redirected the flood currents away from the flood chute and towards the ebb channel. By forming a flood chute, the channel strives to reduce its length and obtain a new morphological equilibrium.

Whereas the channel length and flow area are maintained by dredging, a stronger reduction of the flow velocities and hence, sedimentation in the ebb channel is enhanced. In general, the examined channels showed a width reduction that dominates over the bed level increase. When the channel length is increased, the storage volume in the channel increases and thereby the velocities decrease. The flood chute development at the beginning of the ZKik-West indicated that the channel was developing a new, shorter channel to reduce its tidal prism. By maintaining the width, bed level and channel length constant, the lower flow velocities cannot be balanced by reducing the channel dimensions, resulting in enhancing sedimentation in the dredged channel. Furthermore, dredging activities fix the location of the ZKik-West, maintaining the connection with the Kik. The eastern Kik-bend developed to a greater extent because both ebb and flood currents remained to proceed through the ZKik-West. In a natural way, a flood chute would have developed at the channel top, which reduced the development of the ebb channel in time. By dredging, the flow through the ebb channel was maintained and the flood chute at the eastern Kik channel top never really developed. Therefore it is concluded that a natural tidal meander in the Ameland basin is distinguished by developing bends which are restricted by the existence of flood chutes.
6.2. Recommendations

In the discussion (Chapter 5) several recommendations were brought forward regarding the accuracy of the results. The accuracy of the results is mainly influenced by the data resolution. The used Vaklodingen-data provide enough precision to analyze the larger channels near the tidal inlet and the channel sections evaluated in this report. The channels around the tidal inlet are not included in the research, while they could provide valuable information regarding the small-scale developments in the study area. Large changes near the inlet could reduce the water discharge to the studied area and explain the general reduction of channel width and bed levels. For the smaller, shallower channels, the data resolution is too low to present reliable channel dimensions and flow velocities. It is therefore recommended to include the channel developments near the tidal inlet and to obtain measurements with a higher resolution to evaluate the dimensions of the smaller channels.

The definition of the key-parameters width, bed level and length are not straightforward and depend on subjective choices. Compared to other studies (e.g. Zeff [38] and Marani et al. [32]), slightly different definitions are used which reduces the comparability between studies. Therefore the influence of flood chutes on the width, bed level and length trends compared to other study areas is difficult to determine. It is therefore recommended to develop more objective procedures to determine these parameters.

Smoothing of the channel centerline should be improved for the automatic determination of the channel tops. With the locations of the channel tops, the analysis can be based on the wave-like pattern which excludes the influence of the beginning and end of the channel. This small improvement would furthermore provide more information about the wavelength, sinuosity, (radius of) curvature and skewness of the tidal channel centerline. The evolution of the channel length and orientation is also related to the location of the tidal watershed. Degrading tertiary channels can be the result of a westward moving watershed. However, in order to examine whether this is the case, the methods applied in this thesis should also be applied for the channels originating from the Pinkegat inlet.

How a flood chute influences the meandering development is described by a series of processes. The processes flood chute formation, ebb channel degeneration, and the reattachment of the ebb channel to the flood channel are observed at multiple locations in the basin. They could form an indication of how the ZKik-West would have developed without dredging activities. Also, the required time for these developments would provide knowledge about the rate at which the channel sections that are influenced by flood chutes migrate. By recognizing these processes, the dredging strategy can be adapted to maintain the most natural meandering extent in the fairway channels as possible. For that purpose, monitoring and studying the developments around flood chutes is recommended.

Van Veen [22] argued that the wind can have an important influence to the strength of the tidal currents. This is supported in the study of Duran-Matute et al. [16] where it is described that especially strong (storm) winds from the south to southwest have a marked effect on the currents in the Wadden Sea basin. It is expected that the magnitude of the currents during storm events have an increased potential to transport sediments and to change the lay-out of the tidal channels. To estimate the effect of storms on the evolution of tidal channels, a longer period should be modeled and the effect of wind should be implemented in the model.
BIBLIOGRAPHY


List of Figures

1.1 The Dutch Wadden Sea with the names of the islands. TX = Texel, VL = Vlieland, TS = Terschelling, AM = Ameland and SC = Schiermonnikoog. Source: http://www.waddenpost.nl/nl/afkortingen, geographical map: RWS [6] and Google Earth. ........................................... 1
1.2 The rapid growth of the volume of dredged material, source: Rijkswaterstaat, original figure: Cleveringa [10]. ......................................................... 2
1.3 Overview of the amphidromic points in the North Sea. The co-tidal lines indicate the times of high water (Kvale [12]). ......................................................... 3
1.4 Map of the Ameland basin, including the location of the fairway and tidal watersheds. Source of bathymetry map: RWS [6] ........................................... 4
1.5 The meandering evolution of the Kikkertgat in the period 1993 – 2016. ......................... 5
1.6 Flow chart that represents the approach of and the converging procedure of the channel classification analysis. Blue indicates data analysis and red indicates numerical modeling. ..... 6
2.1 Schematization of the origin of the circulatory motion in a channel bend, Figure obtained from Bosboom and Stive [18] ......................................................... 9
2.2 Idealized planform for a meandering channel section. This figure presents the definitions of the channel dimensions that are used throughout the report. Figure obtained from Dey [27]. .... 11
2.3 A presentation of the definitions bifurcation, flood chute, channel top (CT) and cross-over, which are used throughout the report. The two branches of a bifurcation show meandering features. For flood chutes the largest body of water is still discharged through the channel. .......... 12
2.4 Three different bar formations are presented. Channel splitting according to Van Veen [22] is presented in graph a. Source figure: Leuven et al. [34] ........................................... 13
2.5 Overview of the definitions of the water level ($\zeta$), depth ($d$) and the total depth ($h$) that are used in the shallow water equations. ........................................... 16
2.6 The secondary flow is directed to the outer bend in the upper part of the water column and towards the inner bend in the lower part of the water column. The polar coordinate system is presented in this figure and the figure is obtained from Jansen [43]. ............... 17
2.7 Schematization of the secondary flow in the transversal flow direction. Figure obtained from de Vriend et al. [44] ................................................................. 18
3.1 Channel names used in this research .......................................................... 21
3.2 An overview of the determination of the width (B) and bed level (D), $L_{arc}$ and $L_{abs}$ .... 22
3.3 The development of the channel centerlines for all channels in the Ameland basin .......... 26
3.4 The absolute- and arc- channel lengths over time ......................................... 27
3.5 The width development along the channels for the years 1989, 1999, 2011 and 2016 .... 29
3.6 The bed level development along the channels for the years 1989, 1999, 2011 and 2016 .... 31
3.7 The evolution of the radius of curvature in the Kik-channel .............................. 32
3.8 Percentual changes of the arc-length ($L$), width (B), bed level (D) and volume ($V$). Each point in this figure represents a value averaged over the entire channel and yearly averaged. .......... 33
3.9 Highlight of the characteristic width and bed level development around a channel top .... 35
3.10 The width and bed level development at the Kik channel tops .......................... 36
3.11 The width and bed level development at the NSp channel tops .......................... 37
3.12 The width and bed level development at the ZSp channel tops .......................... 38
3.13 The cross-sectional development at channel tops and cross-overs of the Kik ............. 39
3.14 The cross-sectional development at channel tops and cross-overs of the NSp ............ 40
3.15 The cross-sectional development at channel tops and cross-overs of the ZSp ............ 41
3.16 Histogram of the ratios describing the temporal averaged maximum channel depth at the considered cross-sections ........................................... 42
3.17 Overview of the meandering stages ........................................................... 44
3.18 Contour plot of the bathymetry at the transition from the Kik to the ZKik-West .......... 45
3.19 Schematization of the reduced catchment area as a result of a flood chute development .... 45
3.20 Schematic overview flood chute development from cross-over channel splitting ............. 47
4.1 Overview plot of the depth averaged velocities during ebb and flood ........................ 49
4.2 The two locations that will be examined by the hydrodynamic model ....................... 51
4.3 The computational domain used for the hydrodynamic modeling ............................ 52
4.4 The water level boundary conditions that have been used for the 2DH and 3D simulations .. 53
4.5 The two tidal cycles that have been applied in the three-dimensional model simulations. For reference, the tidal range that is used in the 2DH analysis is included in this figure .............. 54
4.6 Schematization of the method used to calculate the secondary flow in 3D simulations .... 55
4.7 Several graphs representing the depth averaged velocity in the Kik and NSp .................. 59
4.8 The migration of the local tidal watershed and the development of the ebb and flood channels . 61
4.9 Secondary flow results for the Kikkertgat channel ................................................. 63
4.10 Secondary flow results for the Noorder Spruit channel ........................................... 65
4.11 Secondary flow results for the entire study area, ZSp and the area in front of Holwerd .......... 67
5.1 The width versus depth for a number of tidal channel sections in the lagoon of Venice and the examined tertiary channels in the Ameland basin. The data from the black markers originate from Marani et al. [32] and the red triangular markers from the averaged width and depth per channel, per year in the Ameland basin. Although the average width and depth are calculated different for the black and red markers, the clear difference between the systems comes forward. 73
5.2 Schematized overview of a channel cross section near the tidal inlet and near the tidal watershed. The influence of the parameter tidal range, $H$, is relatively much larger in the smaller channels. 75
6.1 Two figures representing the problem definition of this thesis. The left figure presents the problem of sedimentation in the channel and the right figure presents the meandering development of the channels that increased the length of the fairway. ..................... 77
B.1 An example of the automatically generated channel network together with an overview of the outlier removal procedure ........................................................... 102
B.2 The residual channel centerline is presented by the red line and the blue line presents the centerline after smoothing ................................................................. 102
B.3 Hypsometric curve of the Ameland basin ................................................................. 103
B.4 The curvatures, $\kappa$, along the channel ................................................................. 104
B.5 Bottom slope development along the channels ......................................................... 105
B.6 The width and depth development at the Kik channel tops ....................................... 106
B.7 The width and depth development at the NSp channel tops ....................................... 107
B.8 Overview of the meandering stages ................................................................. 108
B.9 The probability density distribution of the bed levels in the Kikkertgat channel ............ 109
B.10 The probability density distribution of the bed levels in the NKik ................................ 110
B.11 The probability density distribution of the bed levels in the NSp .............................. 110
B.12 The probability density distribution of the bed levels in the ZKik-East ....................... 111
B.13 The probability density distribution of the bed levels in the ZKik-West ....................... 111
B.14 The probability density distribution of the bed levels in the ZSp .............................. 112
C.1 An overview of all the observation points that are defined in the model ...................... 116
D.1 The observation points along the channels that have been used in the evaluation of the developments along the channel ................................................................. 118
D.2 The difference (flood-ebb) in 2DH peak velocities along the channel ......................... 119
D.3 The difference (flood-ebb) in 3D peak velocities along the channel ............................ 120
D.4 Overview of the depth averaged- and secondary flow velocities along the channel in the Kikkertgat for the year 2016 ................................................................. 121
D.5 Overview of the depth averaged- and secondary flow velocities along the channel in the Kikkertgat for the year 2011 ................................................................. 121
D.6  Overview of the depth averaged- and secondary flow velocities along the channel in the Noorder Spruit for the year 2016. ................................................................. 122
D.7  Overview of the depth averaged- and secondary flow velocities along the channel in the Noorder Spruit for the year 2011. ................................................................. 122
D.8  Overview of the depth averaged- and secondary flow velocities along the channel in the Zuider Spruit for the year 2016. ................................................................. 123
D.9  Overview of the depth averaged- and secondary flow velocities along the channel in the Zuider Spruit for the year 2011. ................................................................. 123
D.10 Overview of the depth averaged- and secondary flow velocities along the channel in the Noorder Kikkertgat for the year 2016. ................................................................. 124
D.11 Overview of the depth averaged- and secondary flow velocities along the channel in the Noorder Kikkertgat for the year 2011. ................................................................. 124
D.12 Overview of the depth averaged- and secondary flow velocities along the channel in the Zuider Kikkertgat for the year 2016. ................................................................. 125
D.13 Overview of the depth averaged- and secondary flow velocities along the channel in the Zuider Kikkertgat for the year 2011. ................................................................. 125
List of Tables

3.1 Overview of tidal channel properties and forcings that can be found in the Wadden Sea. It represents the large amount of factors that can influence the tidal channel evolution. 19

3.2 Overview of the years and the spatial resolution of the used bathymetry maps. 20

3.3 Channels that are used in the dimensional analysis. Years presented in italics are used in the analysis, but do show errors in the data that may influence the results. 25

C.1 The model set-up which is similar for all two-dimensional model simulations. 114

C.2 The model set-up, unique settings for each year that has been modeled in 2DH. The observation points in this table are included to indicate that the observation point-file used is different for every year. 114

C.3 The model set-up which is similar for all three-dimensional model simulations. 115

C.4 The model set-up, unique settings for each year that has been modeled in 3D. The observation points in this table are included to indicate that the observation point-file used is different for every year. 115

C.5 The specification of the vertical layers applied in the three-dimensional model. Layer 1 is located at the water surface and layer 20 near the bed. 115
# Nomenclature

## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>MWL</td>
<td>Mean Water level</td>
</tr>
<tr>
<td>NAP</td>
<td>Nieuw Amsterdams Peil; Dutch reference water level</td>
</tr>
<tr>
<td>MG</td>
<td>Molengat channel</td>
</tr>
<tr>
<td>DG</td>
<td>Dantziggt channel</td>
</tr>
<tr>
<td>ZDG</td>
<td>Zuider (Southern) Dantziggt channel</td>
</tr>
<tr>
<td>ZWD</td>
<td>Zuid-West (South-Western) Dantziggt channel</td>
</tr>
<tr>
<td>Kik</td>
<td>Kikkertgat channel</td>
</tr>
<tr>
<td>NKik</td>
<td>Noorder (Northern) Kikkertgat channel</td>
</tr>
<tr>
<td>ZKik</td>
<td>Zuider (Southern) Kikkertgat channel</td>
</tr>
<tr>
<td>Sp</td>
<td>Spruit channel</td>
</tr>
<tr>
<td>NSp</td>
<td>Noorder (Northern) Spruit channel</td>
</tr>
<tr>
<td>ZSp</td>
<td>Zuider (Southern) Spruit channel</td>
</tr>
</tbody>
</table>
## List of Symbols

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Units</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>( a_m )</td>
<td>m</td>
<td>meandering amplitude</td>
</tr>
<tr>
<td>( A )</td>
<td>( m^2 )</td>
<td>(wetted) cross-sectional area</td>
</tr>
<tr>
<td>( \beta_c )</td>
<td>–</td>
<td>coefficient to account for secondary flow in the momentum equations in the 2DH hydrodynamical modeling</td>
</tr>
<tr>
<td>( b )</td>
<td>–</td>
<td>correction factor for the channel volume</td>
</tr>
<tr>
<td>( B )</td>
<td>m</td>
<td>channel width</td>
</tr>
<tr>
<td>( C )</td>
<td>( m^{1/2}/s )</td>
<td>Chézy roughness coefficient</td>
</tr>
<tr>
<td>( d )</td>
<td>m</td>
<td>water depth below the reference plane ( z = 0 )</td>
</tr>
<tr>
<td>( d_{50} )</td>
<td>( \mu m )</td>
<td>median grain size diameter</td>
</tr>
<tr>
<td>( D )</td>
<td>m</td>
<td>depth</td>
</tr>
<tr>
<td>( f )</td>
<td>( 1/s )</td>
<td>Coriolis parameter (inertial frequency)</td>
</tr>
<tr>
<td>( g )</td>
<td>( m/s^2 )</td>
<td>gravitational acceleration</td>
</tr>
<tr>
<td>( h )</td>
<td>m</td>
<td>water depth</td>
</tr>
<tr>
<td>( i )</td>
<td>( m/m )</td>
<td>bottom slope</td>
</tr>
<tr>
<td>( I )</td>
<td>( m/s )</td>
<td>secondary flow intensity</td>
</tr>
<tr>
<td>( I_{be} )</td>
<td>( m/s )</td>
<td>equilibrium intensity of spiral motion due to curvature of stream lines</td>
</tr>
<tr>
<td>( I_{ce} )</td>
<td>( m/s )</td>
<td>equilibrium intensity of spiral motion due to Coriolis</td>
</tr>
<tr>
<td>( I_n )</td>
<td>–</td>
<td>points of inflection</td>
</tr>
<tr>
<td>( \kappa )</td>
<td>( 1/m )</td>
<td>curvature</td>
</tr>
<tr>
<td>( k_s )</td>
<td>m</td>
<td>Nikuradse roughness coefficient</td>
</tr>
<tr>
<td>( \lambda_m )</td>
<td>m</td>
<td>channel wave length</td>
</tr>
<tr>
<td>( L_{abs} )</td>
<td>m</td>
<td>absolute channel length</td>
</tr>
<tr>
<td>( L_{arc} )</td>
<td>m</td>
<td>arc channel length</td>
</tr>
<tr>
<td>( m )</td>
<td>kg</td>
<td>mass</td>
</tr>
<tr>
<td>( n )</td>
<td>( m^{-1/3} )</td>
<td>Manning’s coefficient</td>
</tr>
<tr>
<td>( \pi )</td>
<td>–</td>
<td>( \pi )</td>
</tr>
<tr>
<td>( \phi )</td>
<td>deg</td>
<td>latitude co-ordinate in spherical co-ordinates</td>
</tr>
<tr>
<td>( p )</td>
<td>( m^3 )</td>
<td>tidal prism</td>
</tr>
<tr>
<td>( Q )</td>
<td>( m^3/s )</td>
<td>discharge</td>
</tr>
<tr>
<td>( \rho )</td>
<td>( kg/m^3 )</td>
<td>water density</td>
</tr>
<tr>
<td>( R )</td>
<td>m</td>
<td>channel bend radius</td>
</tr>
<tr>
<td>( R )</td>
<td>–</td>
<td>Rossby number</td>
</tr>
<tr>
<td>( \sigma )</td>
<td>–</td>
<td>standard deviation</td>
</tr>
<tr>
<td>( \sigma^2 )</td>
<td>–</td>
<td>variance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Courant number</td>
</tr>
<tr>
<td>( S )</td>
<td>–</td>
<td>sinuosity</td>
</tr>
<tr>
<td>( \theta_0 )</td>
<td>deg</td>
<td>maximum deflection angle at a cross-over</td>
</tr>
<tr>
<td>( t )</td>
<td>s</td>
<td>time</td>
</tr>
<tr>
<td>( T )</td>
<td>s</td>
<td>tidal period</td>
</tr>
<tr>
<td>( u )</td>
<td>( m/s )</td>
<td>flow velocity component in the ( x )-direction</td>
</tr>
<tr>
<td>( \bar{u} )</td>
<td>( m/s )</td>
<td>depth averaged velocity</td>
</tr>
<tr>
<td>( \nu_T )</td>
<td>( m^2/s )</td>
<td>diffusivity</td>
</tr>
<tr>
<td>( v )</td>
<td>( m/s )</td>
<td>flow velocity component in the ( y )-direction</td>
</tr>
<tr>
<td>( V )</td>
<td>( m^3 )</td>
<td>tidal volume</td>
</tr>
<tr>
<td>( \omega_e )</td>
<td>rad/s</td>
<td>angular frequency of the Earth's rotation</td>
</tr>
<tr>
<td>( w )</td>
<td>( m/s )</td>
<td>flow velocity component in the ( z )-direction</td>
</tr>
<tr>
<td>( x )</td>
<td>m</td>
<td>( x )-coordinate</td>
</tr>
<tr>
<td>( y )</td>
<td>m</td>
<td>( y )-coordinate</td>
</tr>
<tr>
<td>( \zeta )</td>
<td>m</td>
<td>free surface elevation above reference plane (at ( z = 0 ))</td>
</tr>
<tr>
<td>( z )</td>
<td>m</td>
<td>vertical, ( z )-coordinate</td>
</tr>
</tbody>
</table>
This appendix presents the bathymetry maps that are used in the assessment of the tidal channel dimensions. The maps are formed by merging several Vaklodingen-data, provided by Rijkswaterstaat [6]. Furthermore, the smoothed centerline that has been obtained by applying the QGis models, is added to the figures. This provides an overview of the centerline locations and can reveal some errors observed in the analysis of the channel dimensions. The size of the maps differs per year, as long as the channels of interest are included in the dataset.
Bathymetry 2011

Bathymetry 2005
Bathymetry 1989

Bathymetry 1981
In this appendix, background information, mathematical elaborations and results are presented that support the elaborations in the main report. Appendices B.1 and B.2 support the thesis introduction. Appendices B.3 to B.7 and B.11 support the methodology of the channel classification, and the dimensions that were examined but were not included in the main text are presented in appendices B.8 to B.10.
B.1. MORPHOLOGICAL SCALES
De Vriend [23] proposed four different scales on which a morphological features of tidal channels can be approximated. The scales are proposed for an estuarine environment, but are applicable to the Wadden Sea as well.

1. Mega-scale features: The entire estuary and its adjacent coast including the shoreface.
2. Macro-scale features: Alternating and interacting ebb- and flood-channels and shoals, on an aggregated scale; e.g. the inlet gorge and the ebb-tidal delta.
4. Micro-scale features: Smallest morphological phenomena; ripples and dunes formed on the bed.

The approach of the tidal channel classification in this thesis is based on this subdivision in scales.

B.2. SAILING TIME FERRIES
The ferries that sail between Holwerd and Nes could reach a maximum speed of 20 km/h. The effective sailing time under good circumstances is 45 minutes and the estimated sailing distance is 11.5 km (Veerbootinfo.nl [54]). This results in an average sailing speed of:

\[
\frac{11.5}{45} \cdot 60 = 15.33 \text{ km/h} \quad (B.1)
\]

When the navigation channel length increases with 500 meters, the delay becomes:

\[
\left( \frac{15.33}{0.5} \right)^{-1} \cdot 60 = 1.96 \text{ minutes} \quad (B.2)
\]

\[
1.96 \cdot 2 = 3.9 \text{ minutes} \quad (B.3)
\]

These calculation is made under the assumption that the navigability of the fairway does not change and that the ferry sails with a constant (average) speed towards its destination.

B.3. CORIOLIS
The Coriolis acceleration (or Coriolis force per unit mass) to the right of the velocity \( V \) reads:

\[
a_c = f \cdot V = 2 \omega_e \sin \varphi \cdot V \quad (B.4)
\]

where \( a_c \) is the Coriolis acceleration, \( f \) is the Coriolis parameter, \( \omega_e \) is the angular velocity of the earth \((\approx 7.29 \cdot 10^{-5} \text{ rad/s})\), \( V \) is the current velocity and \( \varphi \) is the latitude which is positive in the Northern Hemisphere and negative in the Southern Hemisphere.

Whether the Coriolis deflection is significant relative to inertia can be determined by the Rossby number, which is given by:

\[
R = \frac{V}{|f|L} \quad (B.5)
\]

where \( L \) is the length scale of the motion. For Rossby numbers of order 1 and smaller Coriolis deflection is important, which is for instance the case for large-scale motions such as tides. At mid-latitudes (say \( \varphi = 45^\circ \)), we have \( f \approx \pm 10^{-4} \text{ rad/s} \). However, in practice, for numerical models covering not too large areas the parameter \( f \) can be assumed to be a constant. At the Ameland inlet, the length scales are in the order of 10 kilometers. Hence, the denominator will become in the order of 1 and therefore Coriolis will only become of importance for flow velocities lower than 1 to 1.5 m/s.
**B.4. CURVATURE DERIVATION**

The radius of curvature is calculated as follows:

\[ R \equiv \frac{1}{|\kappa|} \quad (B.6) \]

\( \kappa \) is the curvature and can be calculated with equation B.7. At a given point on a curve, \( R \) is the radius of the osculating circle.

\[ \kappa = \frac{d\phi}{ds} \quad (B.7) \]

\[ \phi = \arctan \left( \frac{dy}{dx} \right) \quad (B.8) \]

\[ d\phi = \phi_{m+1} - \phi_m \quad (B.9) \]

\[ s = \sqrt{(dx)^2 + (dy)^2} \quad (B.10) \]

\[ ds = s_{m+1} - s_m \quad (B.11) \]

where \( \phi \) is the tangential angle, \( s \) is the arc length and \( m \) represents a step in space. By combining the equations above, the equation for the radius of curvature is:

\[ R = \frac{1}{|d\phi|} \quad (B.12) \]

**B.5. SINUOSITY**

The degree of meandering can be described by sinuosity [27]. Sinuosity is described by the ratio of the centerline length to wavelength of a meander. When this ratio is higher than 1.5, then the channel is classified as meandering. To give a reference, a straight channel has sinuosity < 1.1. In river environments, sinuosity is described as a function of the riverbed slope and the bankfull discharge. Bankfull discharge is the discharge at which the active channel, so not the flood plain, is filled. Sinuosity can be used as a threshold value for the change between a meandering and braiding pattern [24]:

1. The simplest equation that indicate that the threshold bed slope above which a river could exhibit a braided form increases with a decrease in bankfull discharge.

\[ S_0 = 0.012 \cdot Q_{bf}^{-0.44} \quad (B.13) \]

2. Lane (1957) proposed a slightly different criterion for the threshold of meandering from a straight river and braiding from a meandering river by using mean annual discharge \( Q \) as:

\[ S_0 = 7 \cdot 10^{-4} Q^{-0.25} \quad S_0 = 0.004 \cdot Q^{-0.25} \quad (B.14) \]

The above equations are in metric units being applicable for sand-bed streams. Note that the bed slopes for these two thresholds (meandering and braiding) differ by a factor of approximately 6.

3. Henderson (1976) and Ferguson (1987) identified the importance of participation of sediment size \( d_{50} \) along with mean annual discharge \( Q \) in defining the threshold:

\[ S_0 = 2 \cdot 10^{-4} d_{50}^{1.15} Q^{-0.44} \quad S_0 = 4.9 \cdot 10^{-3} d_{50}^{0.52} Q^{-0.21} \quad (B.15) \]

where \( d_{50} \) is in mm and \( Q \) in m\(^3\) s\(^{-1}\).
B.6. **Outlier Removal Procedure**

The removal procedure of the channel network outliers consists of several steps. After reducing the total basin area to the individual channel sections, the output of the QGis models contained outliers as presented here. The second figure presents the channel network after cleansing the data. There, the model output and the smoothed channel centerline are shown in order to show the model accuracy.

![Diagram of channel network with steps for outlier removal]

- **1. Remove outliers**
- **2. Remove points with depth > -1 m+NAP**
- **3. Choose one channel branch**
- **4. Connect to other channel**

Figure B.1: An example of the automatically generated channel network together with an overview of the outlier removal procedure.

![Diagram of residual channel centerline]

Figure B.2: The residual channel centerline is presented by the red line and the blue line presents the centerline after smoothing.
Figure B.3: Hypsometries of the cumulative area inside the Ameland basin for various years between 1926 and 2006 using fixed and actual boundaries. By the use of this figure, a channel threshold value of $-100 \text{ cm+NAP}$ is chosen. Figure obtained from Van Geer et al. [55].
B.8. Curvature plot

Figure B.4: The curvatures, $\kappa$, along the channel. The black triangular markers designate the approximate locations of a bifurcation or flood chute. Note further that the starting point of the channel for subplots 3 and 5 was set at 600 m in order to exclude the presentation of errors that occurred at the beginning of these channels.
B.9. Bottom Slope

With the cross-sectional depth an approximation of the bed slope along the channel is determined. The slope is calculated by evaluating the change in depth to the arc length of the channel:

$$i = \frac{d_n - d_0}{L_{arc}}$$  \hspace{1cm} (B.16)

where $i$ is the slope in $(m \cdot m^{-1})$, $d_n$ is the average depth of the $n$-th cross-section and $d_0$ is the average depth of the first cross-section. For channels that do not extent into other channels, e.g. NSp or ZDG, a value of $-1$ m+NAP was chosen for $d_n$.

Figure B.5: Bottom slope development along the channels. The black triangular markers designate the approximate locations of a bifurcation or flood chute. The high frequency oscillations in the graphs form the reason why this channel dimension was not included in the analysis.
B.10. MICRO-SCALE RESULTS

Figures B.6 and B.7 are equal to Figures 3.10 and 3.11, except that in this appendix all years are included in the graphs presenting the width and the bed level. In Chapter 3, years 1989 and 1999 were excluded to highlight the trends that can be observed along the channels.

Figure B.6: The development of the width and the depth at the Kik channel tops. The 1st bend is the channel top on the left (west) and the 2nd bend is the top on the right (east). In the two lower graphs only years 2011 and 2016 are presented. The location where the channel is subdivided into two bends is highlighted by a black marker and the approximated location of the flood chute is shown by a red marker.
Figure B.7: The development of the width and the depth at the NSp channel tops. The 1\textsuperscript{st} bend is the channel top on the left (west) and the 2\textsuperscript{nd} bend is the top on the right (east). In the two lower graphs only years 2011 and 2016 are presented. The location where the channel is subdivided into two bends is highlighted by a black marker and the approximated location of the flood chute is shown by a red marker.
Figure B.8: Overview of the meandering stages and where they are defined. Most channels are classified in the same stage throughout time, except for ZKik-West, which contained features of channel splitting in 1989.
The figures in this appendix present the probability density function of the bed level measured along the channel. The bed level is determined at each cross-section that was defined. These graphs are used to determine whether the number of cross-sections could be reduced. A reduction in amount of cross-sections would reduce the time needed for the calculation of the channel dimensions. In the end, no distinct distribution was found and therefore the total set of cross-sections have been used in the calculation of the dimensions.

Figure B.9: The probability density distribution of the bed levels in the Kikkertgat channel.
Figure B.10: The probability density distribution of the bed levels in the NKk.

Figure B.11: The probability density distribution of the bed levels in the NSp.
Figure B.12: The probability density distribution of the bed levels in the ZKik-East.

Figure B.13: The probability density distribution of the bed levels in the ZKik-West.
Figure B.14: The probability density distribution of the bed levels in the ZSp.
The model set-up and the other aspects corresponding to the hydrodynamic modeling are presented in this appendix.

**C.1. TIME-STEP AND THRESHOLD DEPTH CALCULATION**

The simulation time-step is chosen based on the Courant number, $|\sigma|$, which is defined by the ratio between the step in space and time:

$$|\sigma| = \frac{|u| \Delta t}{\Delta x} \leq 1 \quad (C.1)$$

For numerical stability of the model, the Courant number should be smaller or equal to one. In Figure 4.1, the peak velocities did not exceed approximately 1 m/s. Combined with a grid size of 22 x 22 m and a time-step of 6 seconds, the Courant number yields $|\sigma| \approx 0.27 \leq 1$, which suffices the $|\sigma|$-condition.

As a rule of thumb, the threshold depth can be calculated from (Source: Delft3D-Flow, User Manual [42]):

$$\delta \geq \frac{2\pi \cdot |1|}{74500} \geq 8.4 \cdot 10^{-5} \quad (C.3)$$

where $\delta$ is the threshold depth, $a$ is a characteristic tidal amplitude and $N$ is the number of time steps per tidal period. Because $\delta$ is very small, a value of $\delta = 0.05$ m is chosen. The last sheet of water on top of a tidal flat is not taken into account. This is not an issue, because these currents are very small and do not form the main focus of this modeling practice.
C.2. TWO-DIMENSIONAL MODEL

The model set-up for the 2DH model is described in Section 4.1. Because the parameter settings are using default values most of the time, they are not included in the chapter. A complete set of the model set-up in 2DH is presented here.

Table C.1: The model set-up which is similar for all two-dimensional model simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-ordinate system</td>
<td>Spherical</td>
<td></td>
</tr>
<tr>
<td>Grid points in M-direction</td>
<td>626</td>
<td></td>
</tr>
<tr>
<td>Grid points in N-direction</td>
<td>614</td>
<td></td>
</tr>
<tr>
<td>Number of layers</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Timestep</td>
<td>0.1</td>
<td>min</td>
</tr>
<tr>
<td>Grid cell size</td>
<td>22</td>
<td>m</td>
</tr>
<tr>
<td>Open boundary east</td>
<td>Current (timeseries)</td>
<td></td>
</tr>
<tr>
<td>Initial water level</td>
<td>0</td>
<td>m</td>
</tr>
<tr>
<td>Initial secondary flow</td>
<td>0</td>
<td>m/s</td>
</tr>
<tr>
<td>$\rho_{\text{water}}$</td>
<td>1025</td>
<td>kg/m$^3$</td>
</tr>
<tr>
<td>$\beta_c$</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Roughness formula</td>
<td>Manning</td>
<td></td>
</tr>
<tr>
<td>Roughness</td>
<td>Uniform</td>
<td></td>
</tr>
<tr>
<td>Wall roughness, slip condition</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>Horizontal eddy viscosity</td>
<td>1</td>
<td>m$^2$/s</td>
</tr>
<tr>
<td>Horizontal eddy diffusivity</td>
<td>10</td>
<td>m$^2$/s</td>
</tr>
</tbody>
</table>

Table C.2: The model set-up, unique settings for each year that has been modeled in 2DH. The observation points in this table are included to indicate that the observation point-file used is different for every year.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2016</th>
<th>2011</th>
<th>1999</th>
<th>1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference date</td>
<td>01/01/2016</td>
<td>01/01/2008</td>
<td>01/01/2008</td>
<td>01/01/2008</td>
</tr>
<tr>
<td>Simulation start date</td>
<td>20/03/2016</td>
<td>16/02/2009</td>
<td>16/02/2009</td>
<td>16/02/2009</td>
</tr>
<tr>
<td>Simulation start time</td>
<td>00:00:00</td>
<td>00:00:00</td>
<td>00:00:00</td>
<td>00:00:00</td>
</tr>
<tr>
<td>Simulation end date</td>
<td>22/03/2016</td>
<td>18/02/2009</td>
<td>18/02/2009</td>
<td>18/02/2009</td>
</tr>
<tr>
<td>Simulation end time</td>
<td>00:00:00</td>
<td>00:00:00</td>
<td>00:00:00</td>
<td>00:00:00</td>
</tr>
<tr>
<td>Observation points</td>
<td>obs$_{2016}$</td>
<td>obs$_{2011}$</td>
<td>obs$_{1999}$</td>
<td>obs$_{1993}$</td>
</tr>
</tbody>
</table>
C.3. THREE-DIMENSIONAL MODEL

The model set-up for the 3D model is described in Section 4.1. Because the parameter settings are using default values most of the time, they are not included in the chapter. A complete set of the model set-up in 3D is presented here.

Table C.3: The model set-up which is similar for all three-dimensional model simulations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co-ordinate system</td>
<td>Spherical</td>
<td></td>
</tr>
<tr>
<td>Grid points in M-direction</td>
<td>626</td>
<td></td>
</tr>
<tr>
<td>Grid points in N-direction</td>
<td>614</td>
<td></td>
</tr>
<tr>
<td>Number of layers</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Timestep</td>
<td>0.1</td>
<td>min</td>
</tr>
<tr>
<td>Grid cell size</td>
<td>22</td>
<td>m</td>
</tr>
<tr>
<td>Open boundary</td>
<td>Fully reflective</td>
<td></td>
</tr>
<tr>
<td>Reflection parameter α</td>
<td>0</td>
<td>s</td>
</tr>
<tr>
<td>ρ_water</td>
<td>1025</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Roughness formula</td>
<td>Manning</td>
<td></td>
</tr>
<tr>
<td>Roughness</td>
<td>Uniform</td>
<td></td>
</tr>
<tr>
<td>Wall roughness, slip condition</td>
<td>Free</td>
<td></td>
</tr>
<tr>
<td>Horizontal eddy viscosity</td>
<td>1</td>
<td>m²/s</td>
</tr>
<tr>
<td>Vertical eddy viscosity</td>
<td>0.001</td>
<td>m²/s</td>
</tr>
<tr>
<td>Model for 3D turbulence k-ε</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Advection scheme for momentum</td>
<td>Cyclic</td>
<td></td>
</tr>
</tbody>
</table>

Table C.4: The model set-up, unique settings for each year that has been modeled in 3D. The observation points in this table are included to indicate that the observation point-file used is different for every year.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2016</th>
<th>2011</th>
<th>1999</th>
<th>1993</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference date</td>
<td>01/01/2016</td>
<td>01/01/2008</td>
<td>01/01/2008</td>
<td>01/01/2008</td>
</tr>
<tr>
<td>Simulation start date</td>
<td>20/03/2016</td>
<td>16/02/2009</td>
<td>16/02/2009</td>
<td>16/02/2009</td>
</tr>
<tr>
<td>Simulation start time</td>
<td>08:10:00</td>
<td>01:10:00</td>
<td>01:10:00</td>
<td>01:10:00</td>
</tr>
<tr>
<td>Simulation end date</td>
<td>21/03/2016</td>
<td>17/02/2009</td>
<td>17/02/2009</td>
<td>17/02/2009</td>
</tr>
<tr>
<td>Simulation end time</td>
<td>08:50:00</td>
<td>01:40:00</td>
<td>01:40:00</td>
<td>01:40:00</td>
</tr>
<tr>
<td>Observation points</td>
<td>obs_2016</td>
<td>obs_2011</td>
<td>obs_1999</td>
<td>obs_1993</td>
</tr>
</tbody>
</table>

The vertical grid consists of 20 layers, which are defined as a percentage of the water depth. The layers are distributed non-linearly, to allow for more resolution near the bed where the bed shear stress is calculated.

Table C.5: The specification of the vertical layers applied in the three-dimensional model. Layer 1 is located at the water surface and layer 20 near the bed.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Size [%]</th>
<th>Layer</th>
<th>Size [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>11</td>
<td>3.8</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
<td>12</td>
<td>3.8</td>
</tr>
<tr>
<td>3</td>
<td>9.3</td>
<td>13</td>
<td>2.7</td>
</tr>
<tr>
<td>4</td>
<td>9.3</td>
<td>14</td>
<td>2.7</td>
</tr>
<tr>
<td>5</td>
<td>8.8</td>
<td>15</td>
<td>2.0</td>
</tr>
<tr>
<td>6</td>
<td>8.8</td>
<td>16</td>
<td>2.0</td>
</tr>
<tr>
<td>7</td>
<td>6.4</td>
<td>17</td>
<td>1.4</td>
</tr>
<tr>
<td>8</td>
<td>6.4</td>
<td>18</td>
<td>1.4</td>
</tr>
<tr>
<td>9</td>
<td>4.6</td>
<td>19</td>
<td>1.0</td>
</tr>
<tr>
<td>10</td>
<td>4.6</td>
<td>20</td>
<td>1.0</td>
</tr>
</tbody>
</table>
C.4. LOCATION OBSERVATION POINTS

Besides the observation points that have been introduced along the channel centerlines, they were also introduced around the channels. These points have not been examined in this report, but the model output at the location of these points can be used in future studies. They are especially interesting for the examination of the development and direction of the currents over the tidal flat.

Figure C.1: An overview of all the observation points that are defined in the model. For the analysis in this report only the observation points along the ebb channel are used. For the other points, the results are saved and can be used for future studies.
Numerical Modeling Results

On the following pages all graphs of the two dimensional model simulations are presented. First an overview is given of the location of the channel observation points which are used in the analysis. In Figure D.2 the difference plots of the peak depth averaged flow velocities are presented. From this figure, the ebb or flood dominance can be distinguished for all assessed channels for the years 2016, 2011, 1999 and 1993. This difference can also be observed in the figures on the preceding pages. There, the peak ebb and flood (secondary) flow velocities are plotted in a graph.
**D.1. Observation Points along the Channels**

Figure D.1: The observation points along the channels that have been used in the evaluation of the developments along the channel. For reference with other figures, every tenth point has a marker with a different color.
Figure D.2: The difference (flood-ebb) in 2DH peak velocities along the channel. If the points are located above the line $y = 0$, then the flood currents are stronger, i.e. flood dominance. Vice versa, the ebb currents are dominant. Every tenth point has a squared marker.
D.3. Difference Plots 3D

Figure D.3: The difference (flood-ebb) in 3D peak velocities along the channel. If the points are located above the line $y = 0$, then the flood currents are stronger, i.e. flood dominance. Vice versa, the ebb currents are dominant. Every tenth point has a squared marker.
D.4. **Kikkertgat**

![Figure D.4: Overview of the depth averaged- and secondary flow velocities along the channel in the Kikkertgat for the year 2016.](image)

![Figure D.5: Overview of the depth averaged- and secondary flow velocities along the channel in the Kikkertgat for the year 2011.](image)

Figure D.4: Overview of the depth averaged- and secondary flow velocities along the channel in the Kikkertgat for the year 2016.

Figure D.5: Overview of the depth averaged- and secondary flow velocities along the channel in the Kikkertgat for the year 2011.
D.5. NOORDER SPRUIT

Figure D.6: Overview of the depth averaged- and secondary flow velocities along the channel in the Noorder Spruit for the year 2016.

Figure D.7: Overview of the depth averaged- and secondary flow velocities along the channel in the Noorder Spruit for the year 2011.
D.6. Zuider Spruit

Figure D.8: Overview of the depth averaged- and secondary flow velocities along the channel in the Zuider Spruit for the year 2016.

Figure D.9: Overview of the depth averaged- and secondary flow velocities along the channel in the Zuider Spruit for the year 2011.
D.7. Noorder Kikkertgat

Figure D.10: Overview of the depth averaged- and secondary flow velocities along the channel in the Noorder Kikkertgat for the year 2016.

Figure D.11: Overview of the depth averaged- and secondary flow velocities along the channel in the Noorder Kikkertgat for the year 2011.
D.8. ZUIDER KIKKERTGAT

Figure D.12: Overview of the depth averaged- and secondary flow velocities along the channel in the Zuider Kikkertgat for the year 2016.

Figure D.13: Overview of the depth averaged- and secondary flow velocities along the channel in the Zuider Kikkertgat for the year 2011.