Tidal channel development at the Oesterdam sand nourishment

Research Report

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Abstract

The Eastern Scheldt in the South Western delta of The Netherlands suffers from a sand deficit (Zanten & Adriaanse, 2008). This causes erosion of tidal flats and this leads consequently to a smaller habitat for wading birds and safety issues (Zanten & Adriaanse, 2008). The government organization responsible for water safety (Rijkswaterstaat) has carried out a sand nourishment at the foot of the Oesterdam (De Vriend et al, 2014). The placement of the sand nourishment causes changes in hydrodynamic conditions of the area. Discharge of the tidal flat at low water is blocked by the sand nourishment and therefore a tidal channel is shaped. As this tidal channel becomes wider, deeper and longer, it erodes the newly placed sand nourishment and tidal flat. It is of great interest to Rijkswaterstaat to monitor this development. (Centre of expertise delta technology, 2015). This research describes the development of the tidal channel of the last 17 months. Morphological parameters as channel length, sinuosity, pattern, stream flow gradient and cross-sectional area are used to state that during the initial phase, the tidal channel evolves the most. In the following 11 months, the development moves to a stable situation. The dynamic equilibrium between area of the channel and the discharge is not yet achieved. Erosion is still going on but it is expected to become stable over one year.

Recap

The Eastern Scheldt suffers from a sand deficit caused by anthropogenic structures that protect the hinterland from flooding. As a consequence the tidal flats erode which leafs less time for migratory birds to find their food in this Natura 2000 area. Next to environmental concerns also safety is at stake as the flats attenuate the wave action.

The Dutch government responsible for water safety (Rijkswaterstaat) placed a sand nourishment in front of the Oesterdam in order to cope with this two issues. The sand nourishment creates a barrier for the discharge of seawater from the tidal flat during the ebb phase. This results in a tidal channel of 655 meters in a period of 17 months. As the tidal channel erodes its banks and bed to discharge the water, it transports the newly placed sand into the Eastern Scheldt.

In this report the development of the tidal channel is researched from a morphological point of view. At the time the sand nourishment was placed, the dimensions of the tidal channel were not suitable for the discharge. Over time the tidal channel increases in length, width and depth and changes its pattern. It will stop eroding its way when it finds its equilibrium state.

The morphological parameters used in this report are channel length, channel pattern, migration rate, sinuosity, stream flow gradient and cross-sectional area.

The channel length increases by head ward erosion and with the magnitude of the meanders. The outer bend of the meanders erode the most and this leads to the migration of this meanders. It is noted that the meander that migrates Eastward has a higher migration rate as it is less difficult to erode the tidal flat (shallow and fine sand) than the sand nourishment. Over time, the migration rate of all meanders decrease. All meanders migrate downstream.

The development of the channel length, channel pattern and migration rate indicates that the channel is moving from an initial phase, with a lot of changes, to a more stable situation. In contrast, sinuosity as well as stream flow gradient point out that the tidal channel was always in a more or less stable state.

The cross-sectional area illustrates that in the initial phase, the area increased a lot, but the last nine months it stabilized. This last observation cannot be stated for the cross-sectional area of the delta. The increase of the area in the delta in het last period is presumably is not influenced exclusively by the tidal channel.

Over all it could be noticed that the tidal channel is moving towards its equilibrium state regarding different morphological parameters. The dimensions and pattern of the channel become more or less stable which means that less sand is eroded and transported to the Eastern Scheldt.

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1. Introduction

Background

The Eastern Scheldt in the South Western delta of The Netherlands suffers from a sand deficit caused by a misbalance between erosion and sedimentation (Zanten & Adriaanse, 2008). Tidal flats are slowly disappearing due to erosion by wave action and a lack of incoming sediment. These tidal flats are of great importance for the survival of migratory birds. The Eastern Scheldt is a Natura 2000 area. The disappearance of the tidal flats will lead to a decrease in ecological quality and quantity in the area. Next to environmental concerns also safety is at stake as the flats attenuate the wave action (Zanten & Adriaanse, 2008).

A sand nourishment of 350. 000 m³ was created in November 2013 at the Oesterdam (Centre of expertise delta technology, 2015). The objective is to increase the life span of the revetments of the Oesterdam with 25 years so maintenance costs will be reduced (De Vriend et al, 2014). An adjacent goal is to prevent the tidal flat at the Oesterdam from drowning. Furthermore artificial oyster reefs where placed to decrease erosion of the sand nourishment.
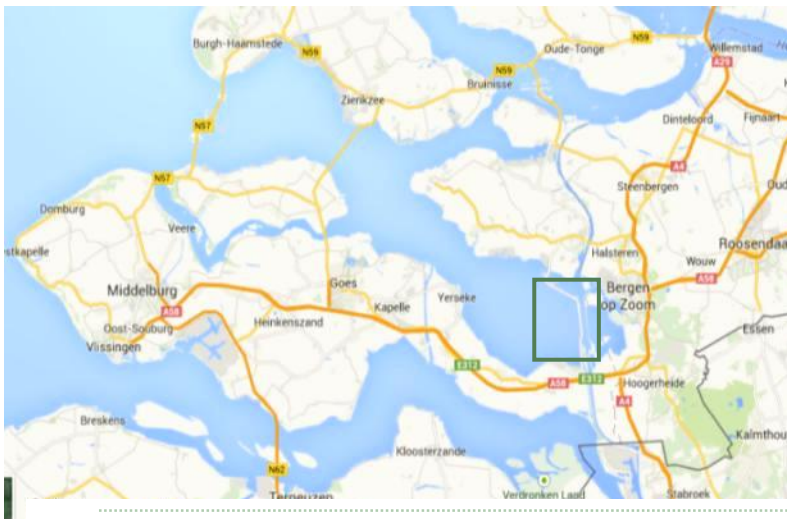
While monitoring the geomorphology of sand nourishment of the Oesterdam, a channel developed. The discharge of seawater from the tidal flat during the ebb phase, resulted in a channel of 655 meters in a period of 17 months. (Centre of expertise delta technology, 2015).

Fig 1: Overview of the South Western Delta of The Netherlands. The green square indicates the location of the Oesterdam.(Source: (Google.maps, 2015)

Area description

The Oesterdam is located in the South-West of the Netherlands. It is the barrier between the Eastern Scheldt and the Scheldt-Rhine channel. The sand nourishment has a length of 2 kilometers and is 0.5 m to 2 m high. This obstacle changes the hydrodynamic conditions in the area and reduces the impact of waves and currents. Furthermore it causes the tidal flat to remain longer dry. Additionally other habitats are created as the tidal flat consists of more fine sediment (125-250 μm) and the grain size of the sand nourishment is 250-300 μm (Centre of expertise delta technology, 2015).

The pattern of the tidal channel is formed by the discharge of seawater from the tidal flat during the ebb phase. Are there other hydraulic forces (waves, tides, currents, seasonal differences and moon phases) involved besides stream power in shaping the tidal channel as there?

Waves are created by the wind. The wind has a maximum speed of 0.2 m/s – 0.4m/s. The dominant wind direction is Southwest. Except for the delta of the tidal channel, waves have no influence on the channel itself

as the latter is located behind the sand nourishment. Energetic waves are not able to erode the channel. They might even cause the opposite effect as they strike off sediment that will aggregate the tidal channel. During winter time, storms cause high waves that could cause more sand deposit in the channel.

However the tidal channel is highly influenced by the tides. Spring tide and neap tide affect the shape of the tidal channel trivially. The bank full discharge [1]of the tidal channel stays relatively the same under those conditions.

Problem definition

One of the objectives of the sand nourishment was to create an supplementary buffer for the Oesterdam (for safety reasons). This ebb-dominated channel transports water and sediment from the tidal flat to the area North of the sand nourishment. It is important to research if the erosion at the sand nourishment and tidal flat continues. Rijkswaterstaat wants to know how long this eroding process will continue. When will the area of the tidal channel be in balance with the discharge and find its dynamic equilibrium?

Research question

This research centrally focuses in on understanding the development of morphological parameters of the tidal channel. Prognosis will be made on the further expansion of the channel. This leads to the main research question:

How did the tidal channel at the Oesterdam develop from November 2013 until April 2015 and did the channel reach an equilibrium state?

In order to be able to answer this question, the following sub-questions are considered by means of a literature review:

- What is the development over time of the cross-sectional area at bank full discharge?
- What is the development over time of the channel length?
- What is the development over time of the meandering /sinuosity/pattern in the tidal channel?
- What is the development over time of the stream flow gradient of the tidal channel?.

[1] Bank full discharge: Maximum discharge that a river or channel is capable of carrying without flooding.
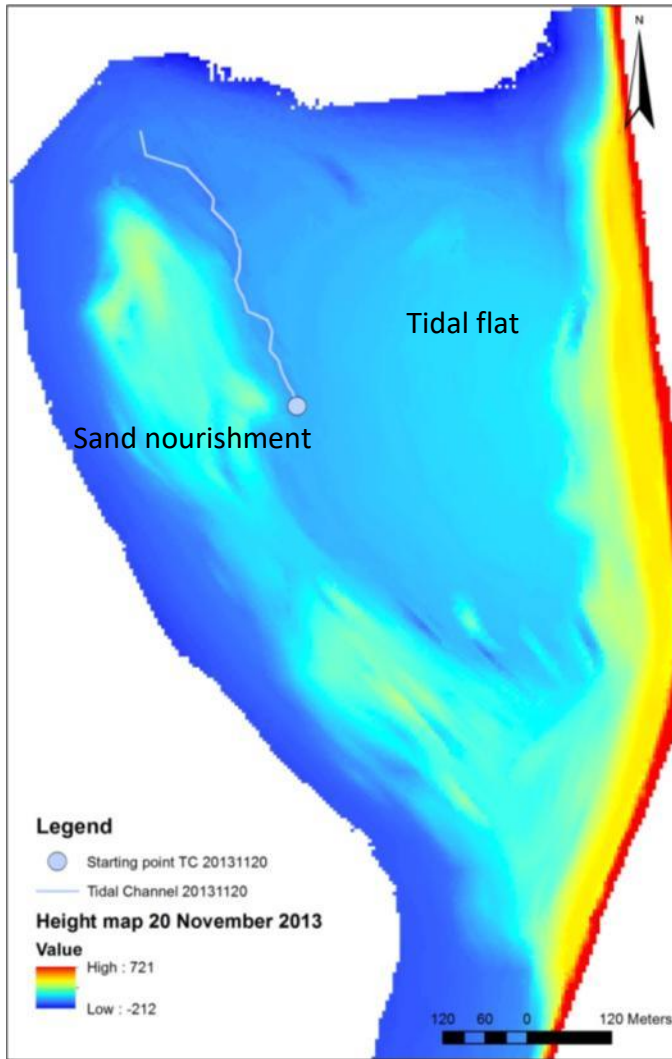
Fig 2: Overview of research area. Left the sand nourishment and at its toe the tidal channel, recorded at November 20th 2013. The Blue dot indicates the starting point of the stream flow at that moment. Right the tidal flat which water drains during ebb-tide to the tidal channel.

Demarcation

This descriptive research will not discuss the erosion rate of the sand nourishment, nor that of the tidal flat. Neither will it explain where the sediment is deposited. No hydrological calculations will be done. The aim of this research is to understand how the system functions from a morphological point of view and examine if the equilibrium state is already found.

Outline

First of all, this report provides the theoretical framework to the analysis executed in chapter two, which defines river morphology in general and equilibrium state. Than it moves on to different morphological parameters that will be studied in this research. Chapter three offers an overview of the method used to process the available Arc GIS maps into helpful data. Chapter four and five continue with the central problem analysis, first by discussing the results and second by making links between related morphological parameters as well as literature. The research concludes by answering the research question and if possible some predictions will be made to estimate how long it will take before the system has reached its equilibrium state.

2. Theoretical framework:

River Morphology

General

"A river is a complex phenomena that is shaped by a three-dimensional, time dependent water movement that interacts with soil characteristics of the bed and bank" (Jansen, 1994). Rivers and channels are shaped by various variables. Variables like gradient, soil type and grain size are commonly stable but other parameters alter throughout the year (discharge and velocity) since they are influenced by seasons (Berendsen, 1992).

The downstream part of a river is generally characterized by gentle gradients of the stream flow, wide river beds and large discharges (Jansen, 1994). The flow velocity is expected to be less as a consequence of a reduced gradient and increasing stream flow area.

Streams can erode, transport and deposit materials along the length of the river. Literature describes the depositing of grains as progressive sorting (Berendsen, 1992). This means that the average grains size decreases downstream in a longitudinal direction. Coarser grains are deposited more upstream and fine sediments are found more at the lower part of the river. In addition sediment is also spread progressively in lateral direction. This will be further clarified when meander is discussed.

Classification

Scientists tried to predict the pattern of rivers by paying attention to different variables. Four different patterns were specified: straight, meander, braided and anastomozing channels (Makaske, 2001).

Fig 3: Classification of rivers: braided, meander, straight and anastomozing. The sinuosity, which will be explained further on , is expressed by P ind. (Makaske, 2001)
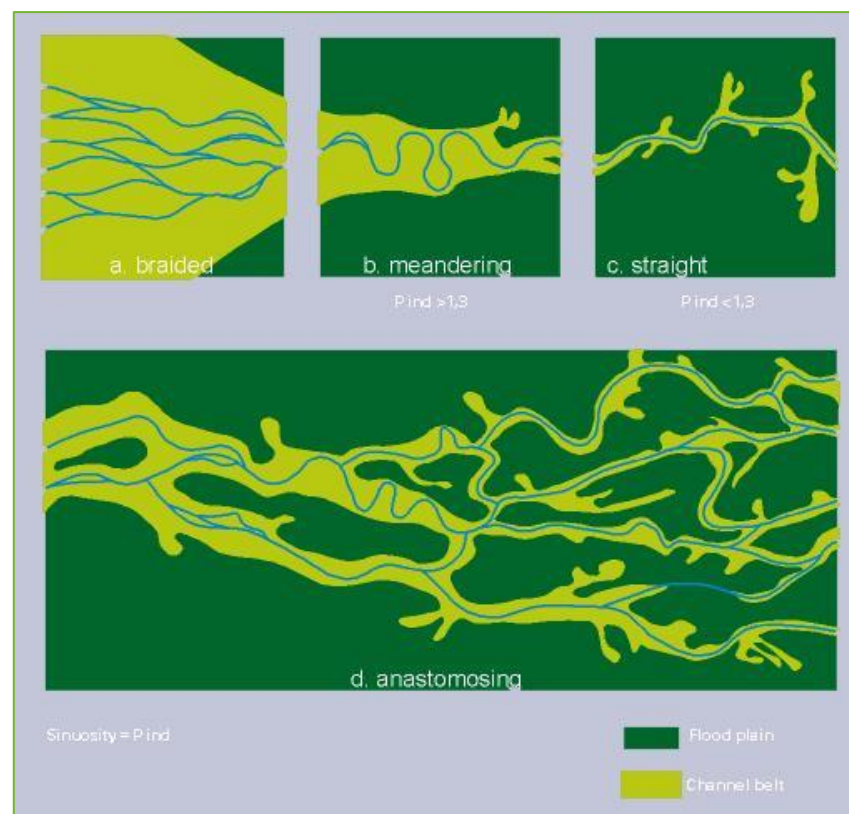
a) Braided: Sediment islands are formed in rivers with a high level of sediment transport. They are present in areas with high fluctuations in discharge which leads to an instable thalweg[2].
b) Meander: The swaying movement of the thalweg makes profound turns. There is a decrease of grain size from the inner bend in a lateral direction. The outer bend of the river is deep.
c) Straight: The banks are build up by less erodible material or the current is not powerful enough to erode it. The thalweg makes a swaying movement without steep turns.
d) Anastomozing: Channels separate and connect again. The thalweg varies.

To quantify these classifications, scientists came up with different equations throughout time. In 1957 Leopold and Wolman introduced the ratio of the channel slope versus the bank full discharge (Berendsen, 1992). This ratio was later on disregarded as the used parameters were not independent. Other important criteria as grain size, width, depth, density of the sediment and stream power were not taken into account (Jansen, 1994). Up till now, no conclusive quantitative definition is found to determine the pattern of a river.

Beside the quantitative approach, the qualitative approach tries to describe different features of the four river categories. As the two most important categories for this research are meander and straight river, these will be discussed more in detail.

Meander channels are common in nature. As ocean currents also have a meandering pattern, it could point out that this is the normal behavior of a fluid in motion. In addition literature describes the shape of a river according to the hypothesis that stream flows aim to find their way downward using as less energy as possible (Summerfield, 1991). As the river tries to find its way through the landscape, it starts to form bends. These curves make the length of the river course longer and less steep. Still a critical gradient has to be exceeded otherwise the stream flow will not be powerful enough. By contrast steep gradients with high velocity induce straight or braided water courses (Summerfield, 1991).
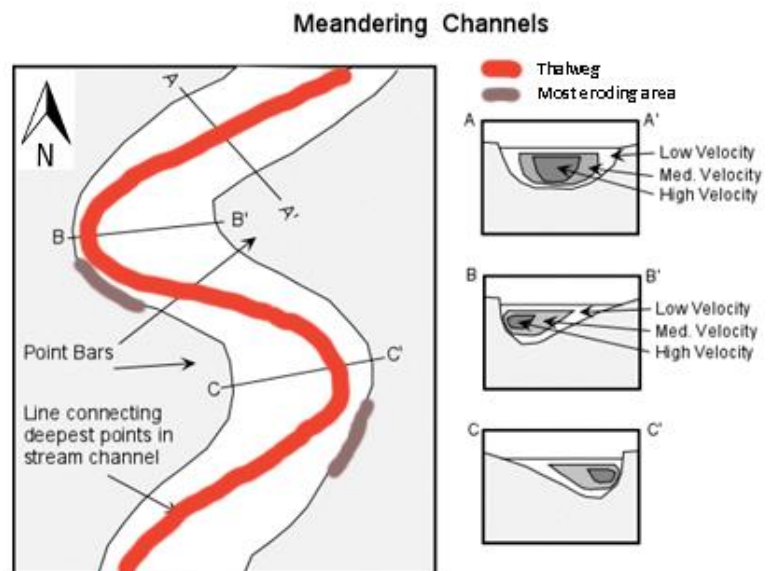
Fig 4: The outer bend of a meander erodes the most. At the inner bend a collection of fine sediment can be found (point bar). The sediment is gradual sorted starting with the fine sand at the point bar that becomes more coarse towards the outer bend. The meander will migrate downstream (South) as the second half of the outer bend (brown color) erodes the most. (Arizona State University, n.d.)

Meandering Channels

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[2] Thalweg: Line that connects the areas with the highest velocity in the River.

The bends of a meander have asymmetric cross sections. The highest velocity is concentrated at the outer bend where the sediment erodes and the channel will become deeper. Moreover the sediment deposits at the inner bend and forms a point bar. Figure 4 shows a cross section of bends in a meander where the lateral gradual sorting of sediment is plotted (Summerfield, 1991).

The second half of the outer bend, just beyond the maximum curvature, (Figure 4) erodes the most as the velocity is highest at that location. As a result, the meander has the tendency to move over time more downstream in rivers or in an ebb-dominant system (Berendsen, 1992).

Between two bends of the stream flow, the thalweg shifts first to the centre of the river and when it reaches a new bend, it will swing to the outer bend again (Berendsen, 1992). This typical jump of the thalweg from the outer bends to the center and back is also visible in a more or less straight part of rivers. This part of the river is shallow and the profile is more symmetric.

Dynamic equilibrium

Streams and channels always develop to a equilibrium state. The stream power which is a function of the discharge and the velocity has to be in balance with the shape and the size of the channel (Summerfield, 1991). It is clear that when the area is too large for the discharge, the stream power is be less and the stream bed will aggregate.

If on the contrary the energy is increasing, which is related to higher discharge and velocity, the bed and banks of the stream flow will erode. To establish its equilibrium state, the stream power will create wider and deeper meanders. In addition head ward erosion will generate a longer channel. (Berendsen, 1992). Stream power of the flowing water should be in balance with the channels bed and banks.

When a stream flow is altered by humans or by any other cause, it will start to find a new equilibrium. The initial phases of the process towards a balanced situation will occur fast and with a larger magnitude in comparison with the process phases later on. The more different the new condition is from its previous one, the faster and larger the changes are in the beginning.

Morphological parameters

To understand better the hydrological and geomorphological processes in a watershed, different morphological parameters can be used. This research focuses on the evolution of the shape of the tidal channel itself (Pareta & Pareta, 2012). The development of the tidal channel will be described by six different parameters.

- *Channel length*

The length of a river is predetermined by its source and mouth. The stream flow can become longer as it starts meandering or when it alters its route caused by tectonic, climatic or anthropogenic activities (Summerfield, 1991). In the case of the tidal channel the water of the tidal flat drains to the channel. This generates a concentrated current in the tidal channel. As a consequence the channel is becoming increasingly larger as head ward erosion[3] occurs.

- *Channel pattern*

A stable pattern of a channel is shaped over a period of time. It changes in response to changing variables (Summerfield, 1991). Over time the channel will make more profound meanders. Furthermore will those meanders migrate downstream. The migration of the meanders will occur in the initial phase more intense and eventually the eroding of the banks en bed of the channel will stabilize. At that point it can be stated that the channel has reached its dynamic equilibrium. This means that the large changes of the first period, are not representative for the development of a long standing new pattern. (Berendsen, 1992).

- *Migration rate of meanders*

In the initial phase meanders will develop a more profound migration East and Westward. As the pattern of the tidal channel will evolve to a more stable condition, the magnitude of the bends will gradually decrease. In time meanders will migrate downstream towards the delta.

The migration rate of meanders is expressed in the migration of the channel, in meters, related to its corresponding period.

$$migration\ rate = \frac{\text{location T2} - \text{location T1}}{\text{period of days}}$$

- *Sinuosity*

Sinuosity is the parameter that describes the irregularity of the channel course (Summerfield, 1991). The definition of sinuosity according to Berendsen (1992) is the ratio of the distance between two points following the thalweg of the stream flow and the distance between the same two points on a straight line (valley length measured along the valley axis) (Figure 5).

$$sinuosity = \frac{\text{length of stream flow}}{\text{valley lenght}}$$

The result is a number without a dimension. Literature describes rivers and channels with numbers exceeding 1.5 as meander. A straight river with a swaying stream flow is defined by sinuosity smaller than 1.3 or in case of a perfect straight concrete channels with 1 (Berendsen, 1992).

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[3] Head ward erosion: The lengthening of a river's course, by erosion back towards its source. (Oxford University Press, 2015)
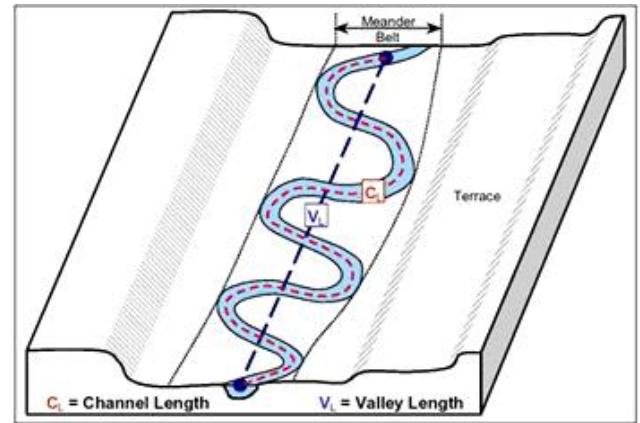
- *Stream flow gradient*

The stream flow gradient describes the longitudinal profile of the river. The most rivers have a concave profile which means that the gradient decreases downstream (Berendsen, 1992). Upstream the gradient is steep and causes high stream power and downstream near the mouth the gradient is shallow and the transported sediment will deposit (Summerfield, 1991).

$$i = \frac{\Delta z}{\Delta L}$$

$\Delta z = height\ difference\ between\ upstream\ and\ downstream$

$\Delta L = distance\ between\ upstream\ and\ downstream\ along\ the\ thalweg$

The parameters sinuosity and stream flow gradient are interrelated. If the height difference stays the same but the river meanders more, the length will increase and as a consequence the stream flow gradient will decrease. Only if het sinuosity stabilizes, and the height differences is in balance, will the stream flow gradient find its dynamic equilibrium.
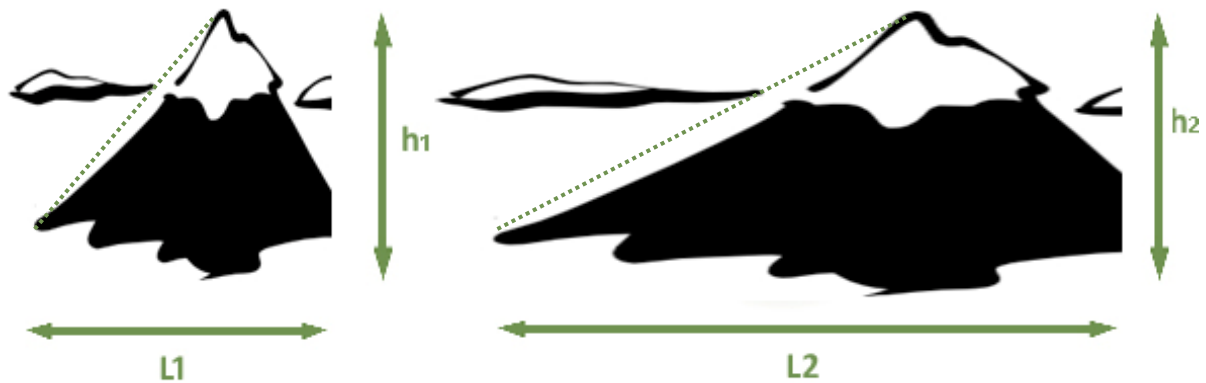

Fig 6: Visualizes the relation between sinuosity and stream flow gradient. If the height stays stable (h1=h2) but the length of the stream flow increases (L1<L2) as it meanders further, the gradient will decrease (dashed line).

- *Cross sectional area*

The width and depth of the area are brought together by calculating the cross-sectional area of the tidal channel. For the upper water level, bank full discharge is used. Literature describes bank full discharge as good measurement of the area as the stream flow has the most impact on bed and banks at that moment (Jansen, 1994).

As can be seen in figure 7, the banks of the tidal channel not only migrate, but erode as well. This means that the cross-sectional area is increasing. Nevertheless the upper water level of bank full discharge (green line) is fixed and does not change over time so the complete influence area of the tidal channel can be calculated. It is acceptable to state that the channel is full at a depth of -82cm NAP (green line) for both periods (T2 and T4).
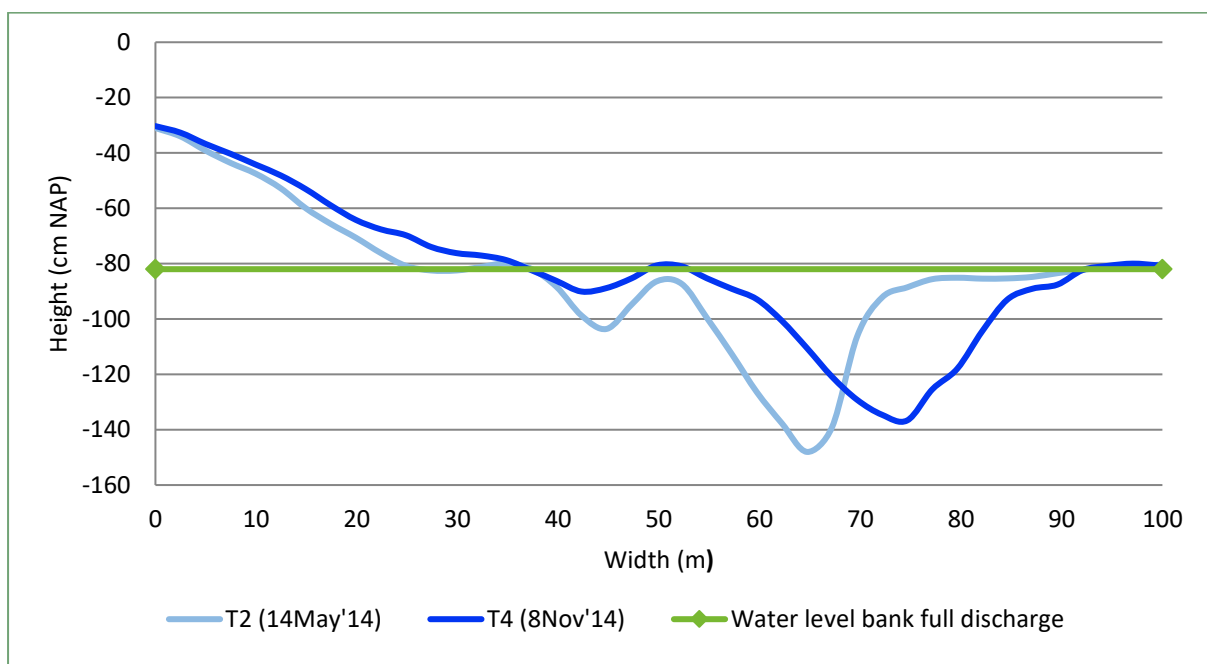

Fig 7: Area alters over time as the tidal channel erodes. In this figure the tidal channel of one location in different periods is plotted: May 14th 2014 and November 8th 2014.

3. Method and material:

Data collection

On average every three months height maps of the Oesterdam Nourishment were measured with a RTK-DGPS (accucracy is ± 3 cm), commissioned by Rijkswaterdataat Zee en Delta. The x,y,z data is collected on East – West transects, the spacing between the transects 50 meters and the spacing between de measurement points is 10m.

This research makes use of raster files (grid size: 2,5m x 2,5m) based on the RTK-dGPS measurements. To create raster files Digiipol (RIKZ, 1997) method is used.

The maps used for this research:

Code	date	extra information
T -1	27/03/2013	Before sand nourishment
T0	20/11/2013	
T1	18/02/2014	
T2	13/05/2014	
T3	14/08/2014	
T4	8/11/2014	
T5	3/04/2015	

Table 1: Different maps created by Rijkswaterstaat used to map the development of the tidal channel.

Data processing

Two software programs (Arc Gis 10.1 and Excel) were used to process the data of the maps.

Various morphological parameters

For morphological parameters as channel length, sinuosity and stream flow gradient, a source had to be defined. The minimum height difference between the channel bed and levee was arbitrary set at minimum 0.1 m.

By using the information button of Arc GIS (reveals the height with an accuracy of 0.01m), the thalweg of the tidal channel was drawn from starting point till delta.

Channel length

The length of the tidal channel along the thalweg is determined by the distance from starting point till delta with an accuracy of 1m. The thalweg is chosen because even though the source and mouth of the tidal channel may become stable over time, if the meanders enlarges, the length will increase.

Migration rate of meanders

The migration rate of meanders is calculated by converting the xyz coordinates from the outer bends 'A' (appendix figure 30) and 'B' (figure 8) from Arc Gis to excel. The incision of the water level in the outer bank has been determined with an accuracy of 0.1m.

The location where the water level of -0.9 m NAP in the tidal channel incises the outer bank of the meander on the 20th November 2013, is stated as a starting point. The distance between sequential incisions of the outer bank are placed in relation to the intermediate time (green numbers in fig 8)
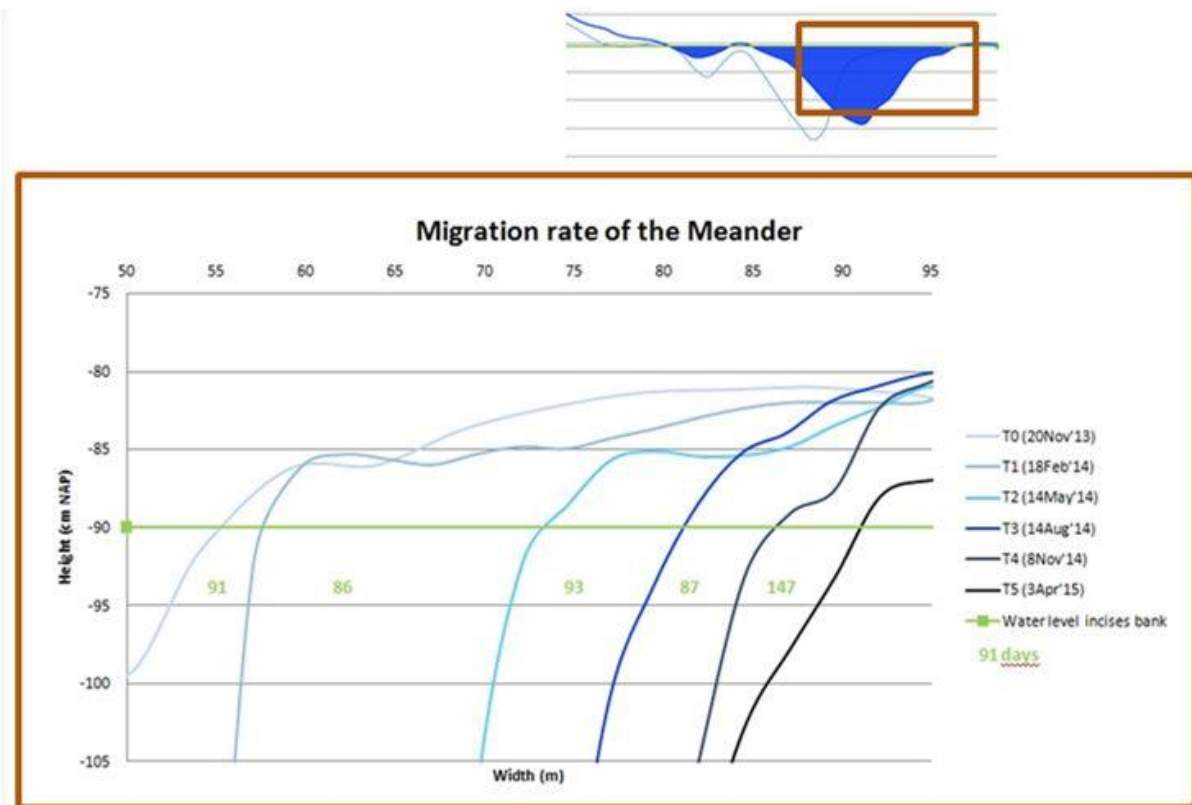

Fig 8: Migration rate of the outer bend (Eastside) of meander 'B' is recorded at the point where the water level at -0,9m NAP incises the bank.
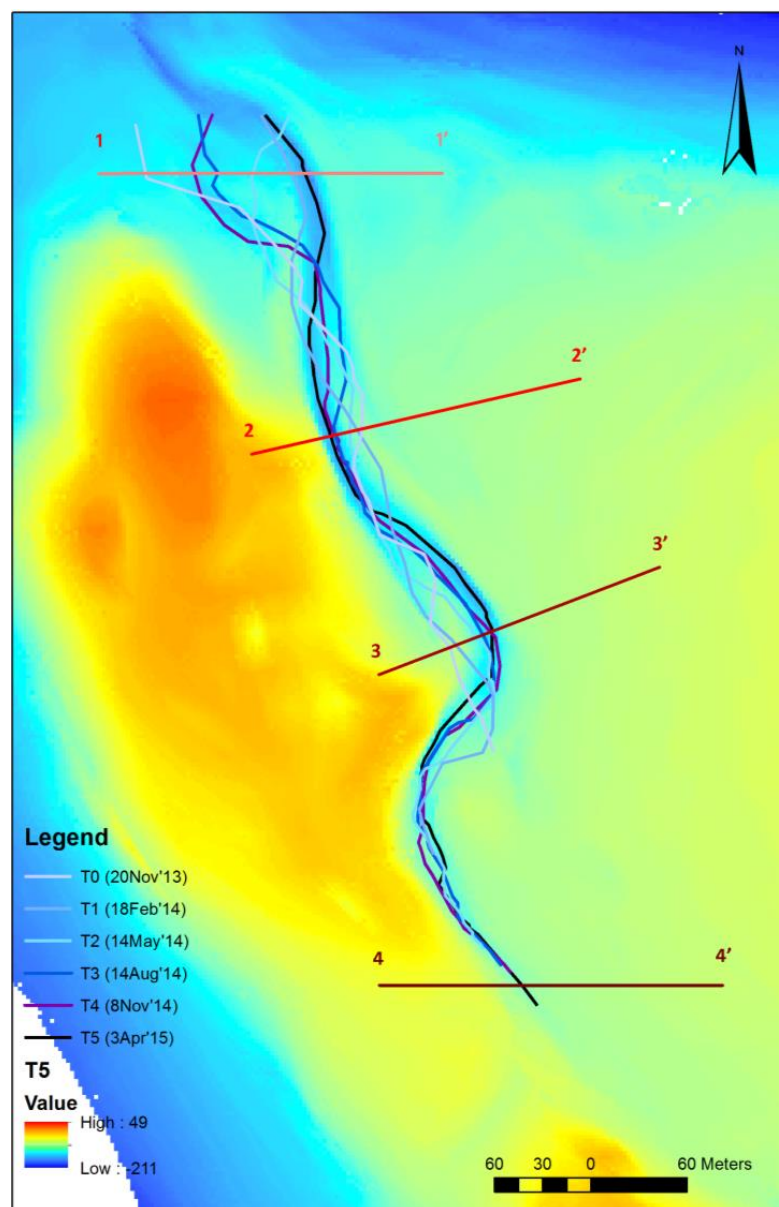
Stream flow gradient

To raise the accuracy, an average of 260 measuring points are taken to calculate the gradient (appendix figure 31) along the thalweg of the tidal channel over time. A trend line was abstracted from the longitudinal profile of the thalweg. This trend line reveals an equation **y=ax + b** where '**a**' expresses the slope (Douwes & Grasmeijer, 2009).

Cross-sectional area.

To visualize the development of the cross-sectional area of the tidal channel, at four different locations spread over the length of the channel, cross sections were taken perpendicular to the stream flow. The water level is set at bank full discharge. This means that the width and depth of the tidal channel are measured at the moment the channel is completely filled, without flooding.

To decrease the margin of error, a two step approach is used. First the bank full discharge was decided at cross-section three. At an elevation of -0.82m NAP, the carrying capacity of the tidal channel is at its maximum. In a second step the bank full discharge of cross sections one and two are calculated by using the average gradient of the stream flow, is 0.00077.

Fig 9: Overview of four cross sections taken of the tidal channel.

Cross section one is located 333 m Northwards (downstream) in relation to cross-section three. With a stream flow gradient of 0.00077, the height difference should be 25.6 cm. The Water level of cross-section one is set at -107 cm NAP.

$$\Delta L * i = \Delta Z => 333m * 0.00077 = 0.256\text{m}$$

$$Water\ level\ of\ cross-sectional\ area\ 1\ = -0.82\ -0.25m = -1.07m$$

This method, using the average stream flow gradient, cannot be applied for cross section four. The calculated bank full discharge level exceeds the influence area of the tidal channel. Arbitrary the bank full discharge level is set at -0.81m NAP.
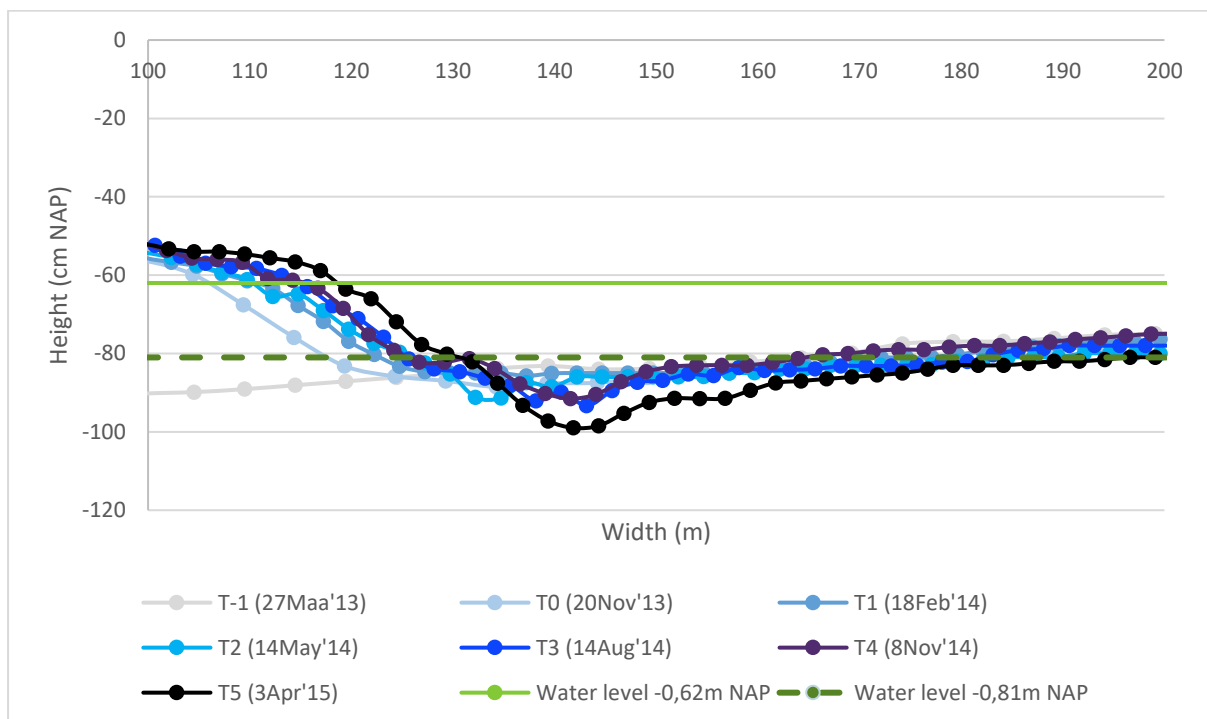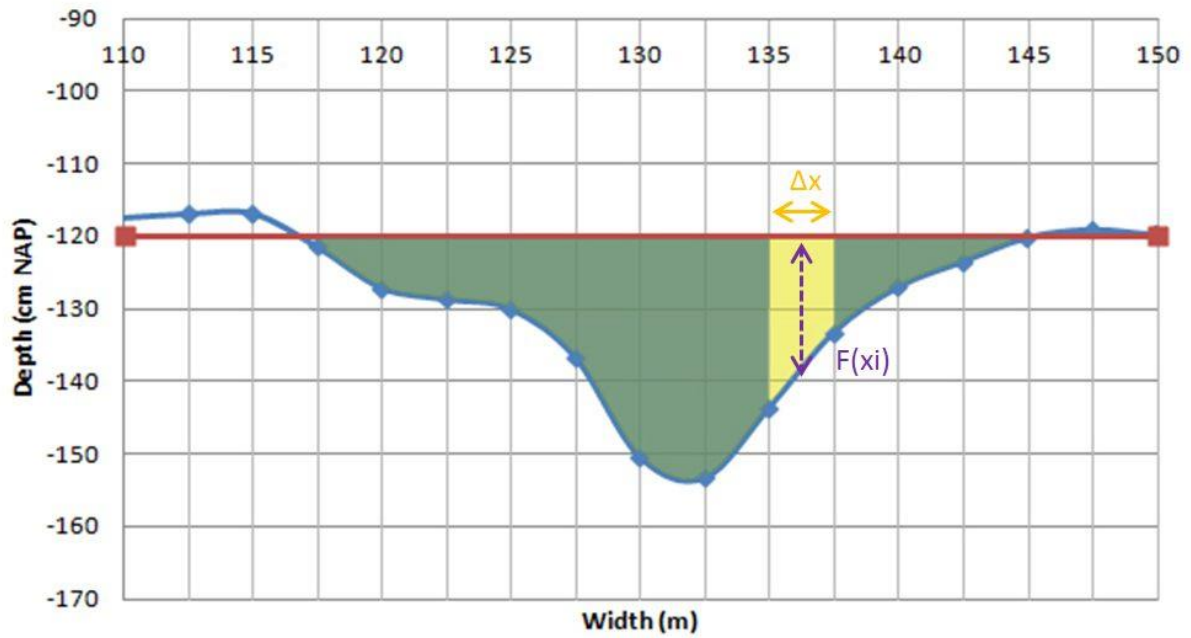

Fig 10: Cross section 4 –'4: The solid green line represents bank full discharge at - 0,62m NAP. Arbitrary is chosen for water level -0,81m NAP expressed by the dashed dark green line.

The cross-sectional area can be calculated by using the following formula.

$$A \cong \sum_{i=1}^{n} f(xi) * \Delta x$$

Fig 11: The cross-sectional area is the sum of the trapezium areas (yellow) having a width of 2,5m (Δx).

4. Results

In this chapter the processed data will be presented.

Channel length

The length of the tidal channel along the thalweg increases over time. In November 2013 (placement of sand nourishment), the drained water was collected in a tidal channel of 498m. In the first six months, the length increased 76%. Later on the differences became smaller. Comparing the last two measurements, the length of the tidal channel has even decreased.
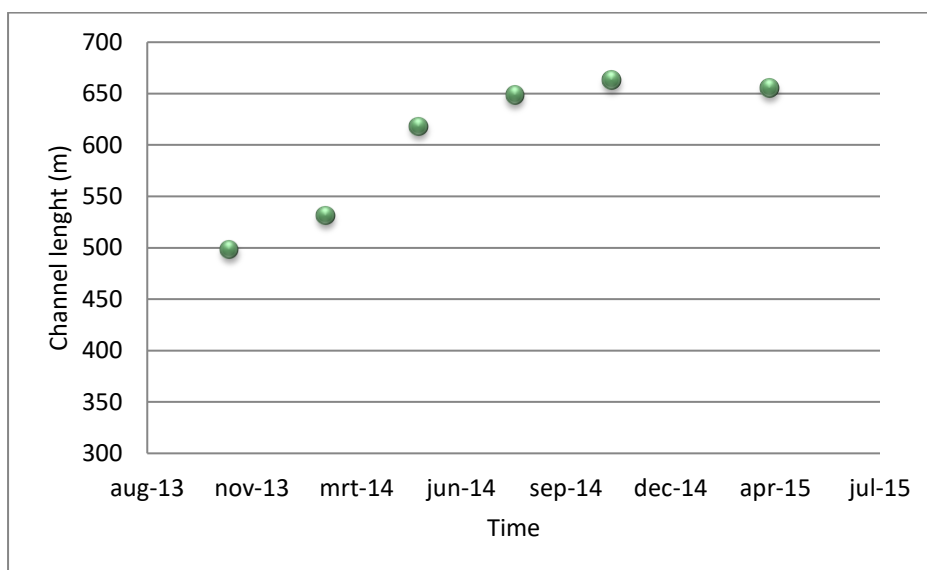

Fig12: Development of the tidal channels length over time.

Figure 13 illustrates that the tidal channel at 20th November 2013 (T0) drains relatively straight to the delta. But the more time passes by, the more the channel starts making curves. The last measurement (T5) makes the largest turns. Meander 'B' has a more profound outer bend than 'A'. The outer bend of 'B' incises in the tidal flat at the Eastside and 'A' migrates Westward in the direction of the sand nourishment. Another interesting feature is the migration at the delta.
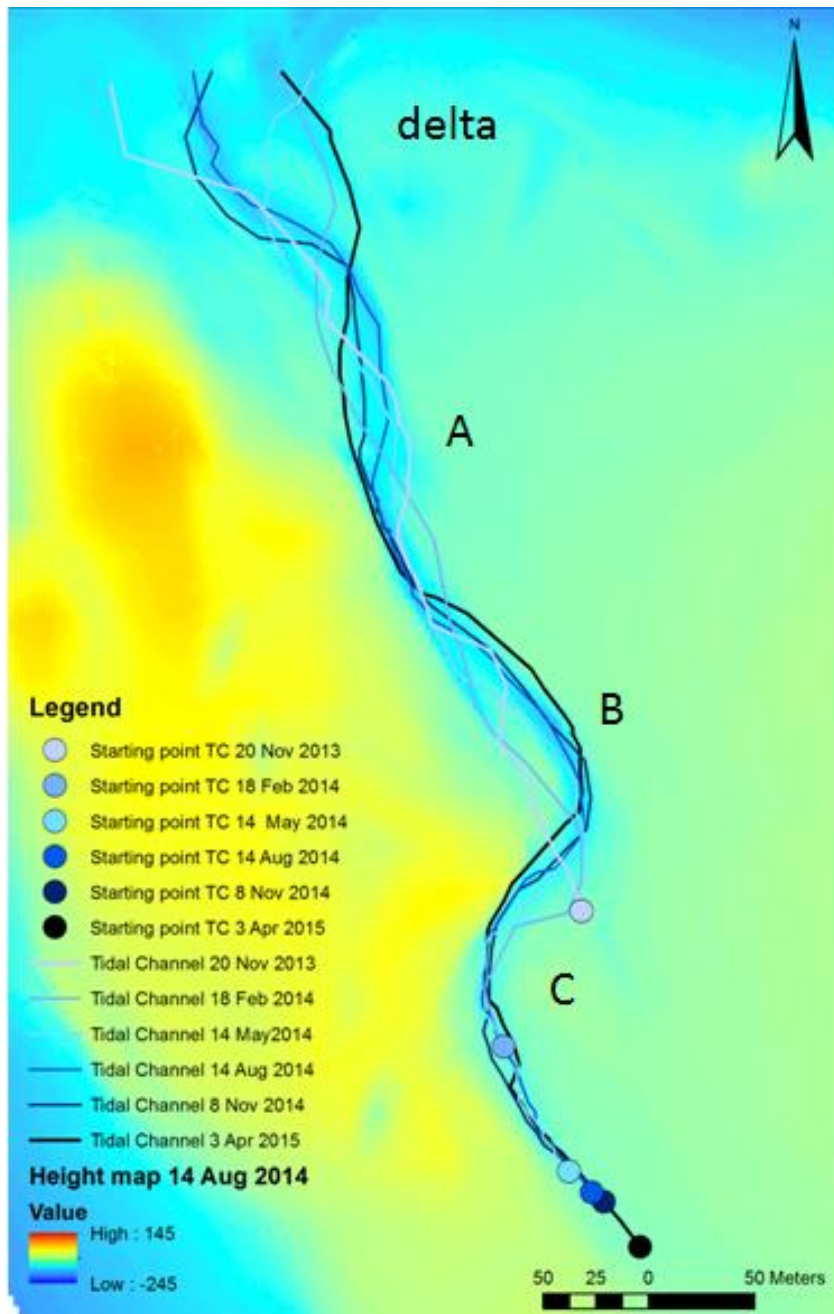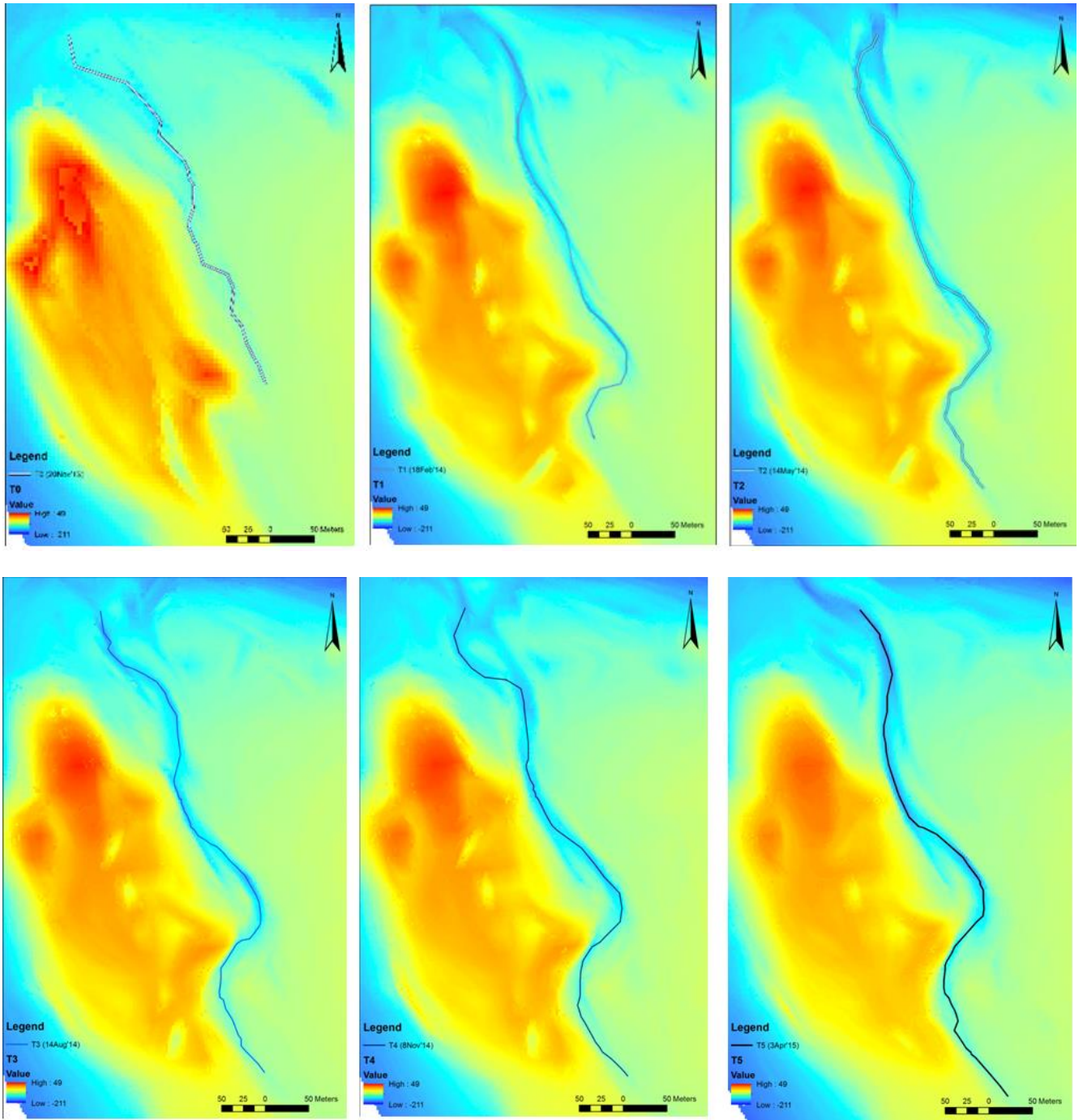

Fig13: Development of the pattern of the tidal channel over time. 'A' and 'B' indicate the migrating meanders. Meander 'C' migrates little.

Fig 14:Overview of the pattern through time, arranged from left to right and top to bottom.

The tidal channel is migrating in both directions over time in the delta area as illustrated by figure 15. The tidal channel that formed straight after the placement of the sand nourishment is indicated by T0 (light blue) and T5 (black) represents the last measurement of April 2015. Mostly tidal channels migrate in one direction. As the sand nourishment does not extend this far, waves presumably have a larger impact on this area. The storm season in the Netherlands is registered from the first of October until the 15th of April. The tidal channels migrates during storm season to the East. However during summer period it migrates back to the West. The first year the tidal channel covered a larger distance from West to East (distance A) than the second year, expressed in distances B in fig15.
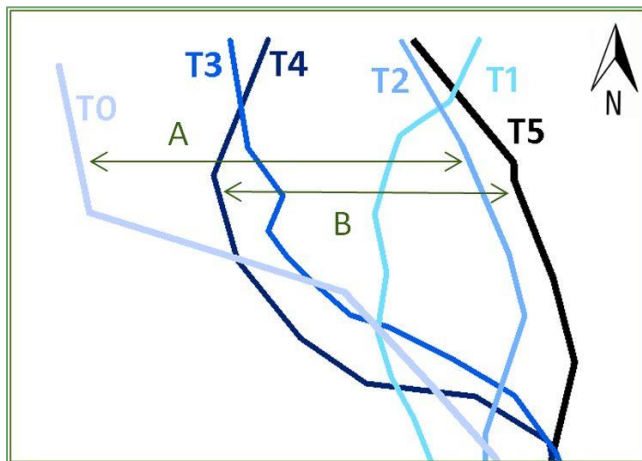

Fig 15 Pattern of the delta of the tidal channel. The numbers express the chronological sequence of the measurements where T0 is November 2013 and T5 is April 2015. The arrows indicate the shift of the channel during the winter period. 'A' stands for winter period 2013 – 2014 and 'B' the winter period of 2014 – 2015. For more detailed information of the legend, look to figure 13.

The tidal channel shows a more elaborate meandering pattern over time (fig16). The latest measurement T5 (April 2015 in black) of meander 'B' covers the most outer bend to the East. But the largest covered distance by migration routes are made in the initial phase. Tidal channel T2 till T5 are located closer to each other than channels T0 till T2. This means that the tidal channel has migrated the last 11 months approximately the same distance as it did the first 6 months.

The meander also migrates downstream. The second half of the outer bend is eroded by the high velocity. As a consequence the meander of the tidal channel moves North.

Fig 16: Pattern of the most pronounced meander of the tidal channel ('B'). The numbers express the chronological sequence of the measurements where T0 is November 2013 and T5 is April 2015. For more detailed information of the legend, look to figure 13.
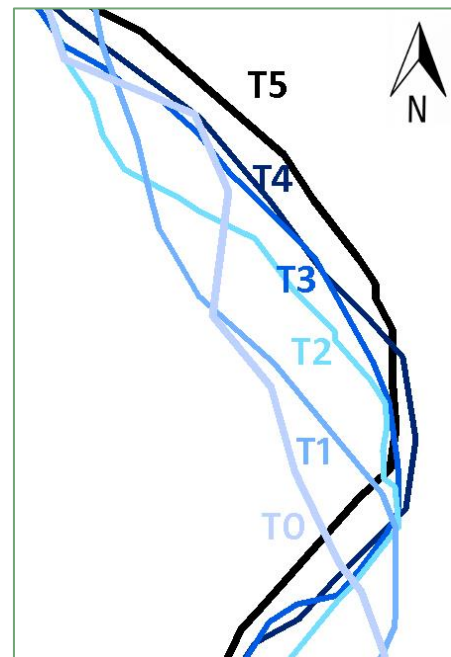
Migration rate of meanders

Meander 'B'

Meander 'B' migrates the most in the initial phase. Since May 2014 did the tidal channel shift 17.90 m to the East. Based on the measurements of the last 11 months, meander 'B' has an average migration rate of 1.77m/month. Over a period of 17 months meander 'B' migrated 35.7.m.
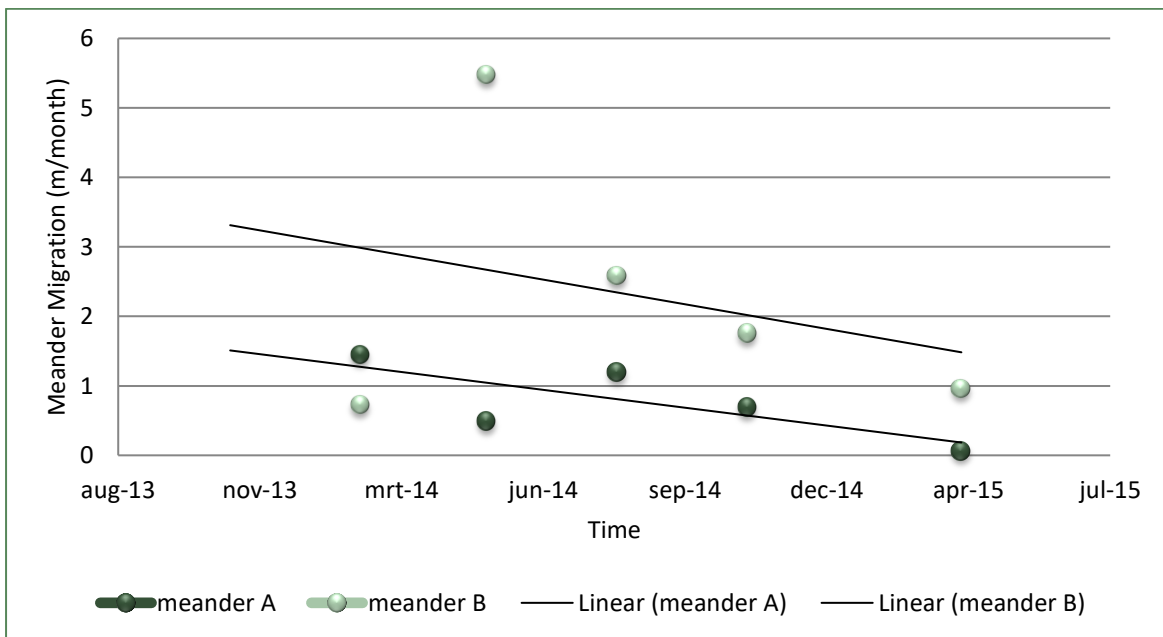

Fig 17: Migration of the outer bend of meander 'B' Eastbound over time and Westbound over time for meander 'A'.

Meander 'A'

Meander 'A' migrates the whole period in a rather constant way. No large fluctuations occur. Still the same trend in the migration of both meanders is perceptible regarding the last seven months. There takes a gradual decrease of the migration place in relation its time.

Based on the measurements of the entire period, meander 'A' has an average migration rate of 0.78m/month. In addition migrated meander 'A' only 0.65m/month on average the last 11 months. Over the last 147 days, the meander migrated 0.3m.

Sinuosity

The sinuosity is more or less constant over the entire period from November 2013 until April 2015. It rises maximum with 3.5% but decreases later on with the same amount. The trend line of figure 19 expresses this constant with a slope of $6 * 10^{-5}$. As the tidal channel may meander more, the valley length increases proportional. This means that time has little effect on the sinuosity. The average sinuosity is 1.138.
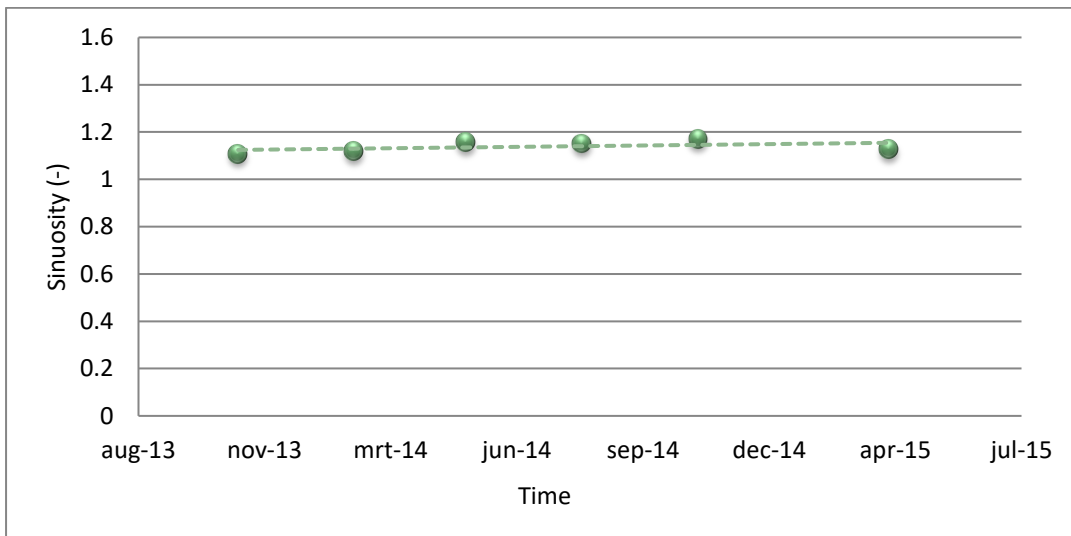
Fig 18: Sinuosity of the tidal channel over time.

Stream flow gradient

The average stream flow gradient (i) of the thalweg of the tidal channel overt time is 0.00077.

time	Stream flow gradient
Month	-
nov/13	0,000684
dec/13	
jan/14	
feb/14	0,000944
mrt/14	
apr/14	
mei/14	0,000747
jun/14	
jul/14	
aug/14	0,000732
sep/14	
okt/14	
nov/14	0,000642
dec/14	
jan/15	
feb/15	
mrt/15	
apr/15	0,000905

Table 2: Overview of the calculated stream flow gradient over time.
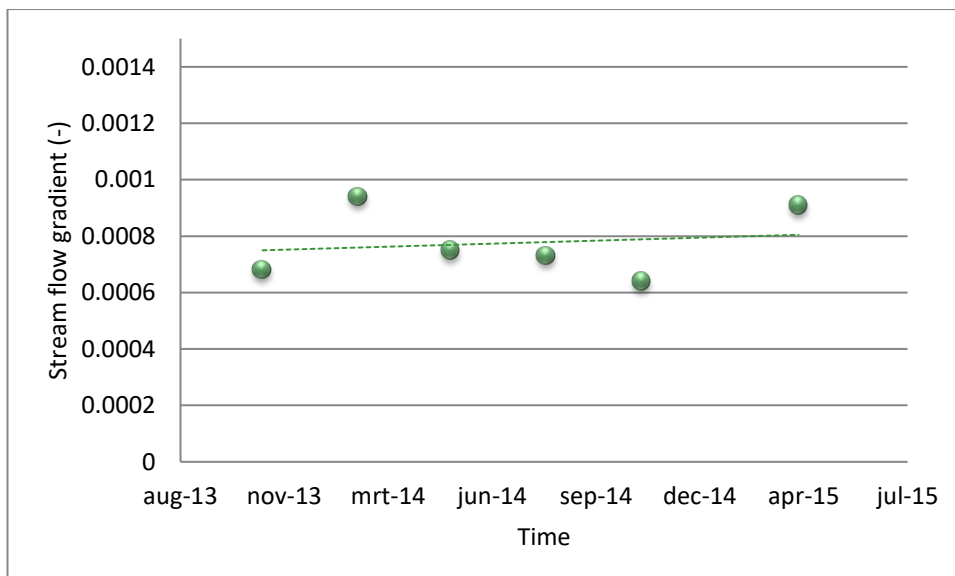

Fig 19: Development of the stream flow gradient over time.

Fig 19 illustrates the stable gradient of the stream flow. Only measurements of February 2014 and April 2015 fluctuate. All the other gradients have values between 0.00064 and 0.00075.

Cross-sectional area

Cross section 1 – '1

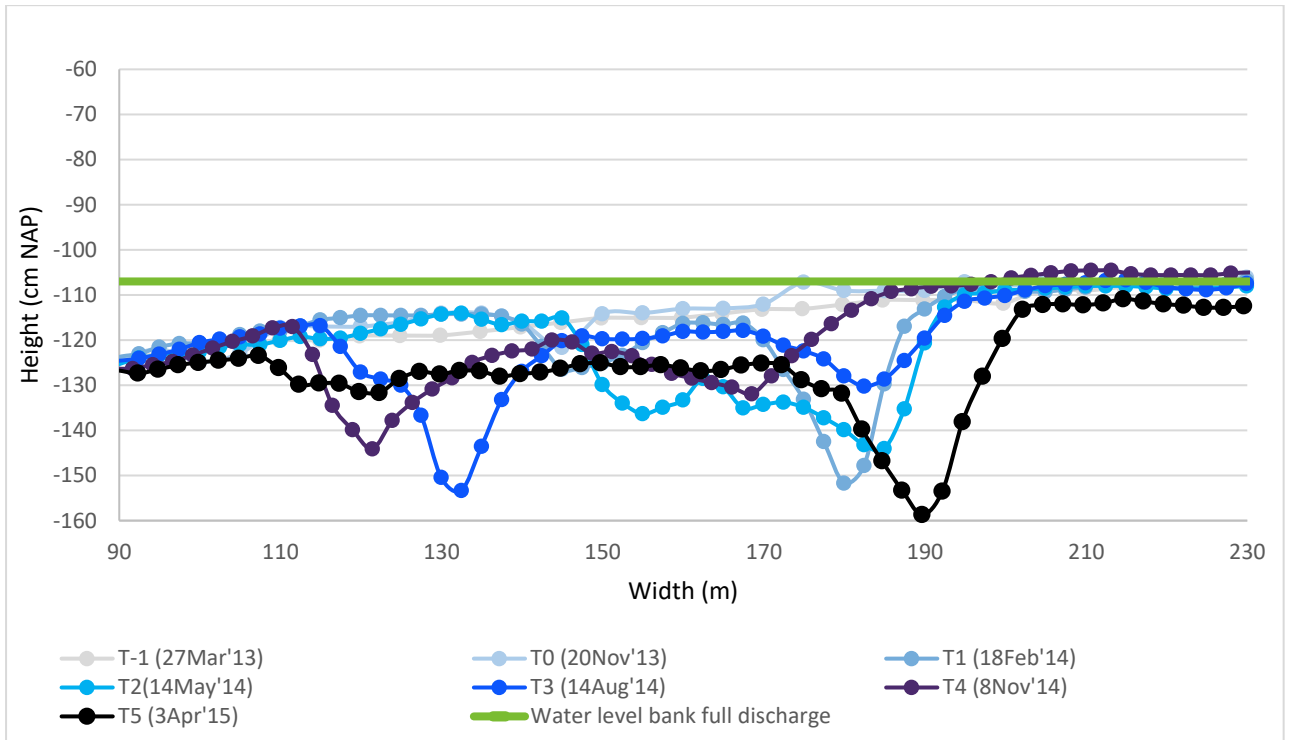

Fig 20: Cross section 1 –'1; T0 (light blue) indicates the first measurement after the sand nourishment. The green line represents the water level when the tidal channel is completely filled (bank full discharge).

By setting the Water level at -107 cm NAP, more or less the complete area at the left (Westside) of the channel is included as the sand nourishment does not extent that far. It is important to take only into account the area that is influenced by the channel. For all six tidal channels, the width (wetted perimeter) was separately determined though the water level of -107 cm NAP was maintained.
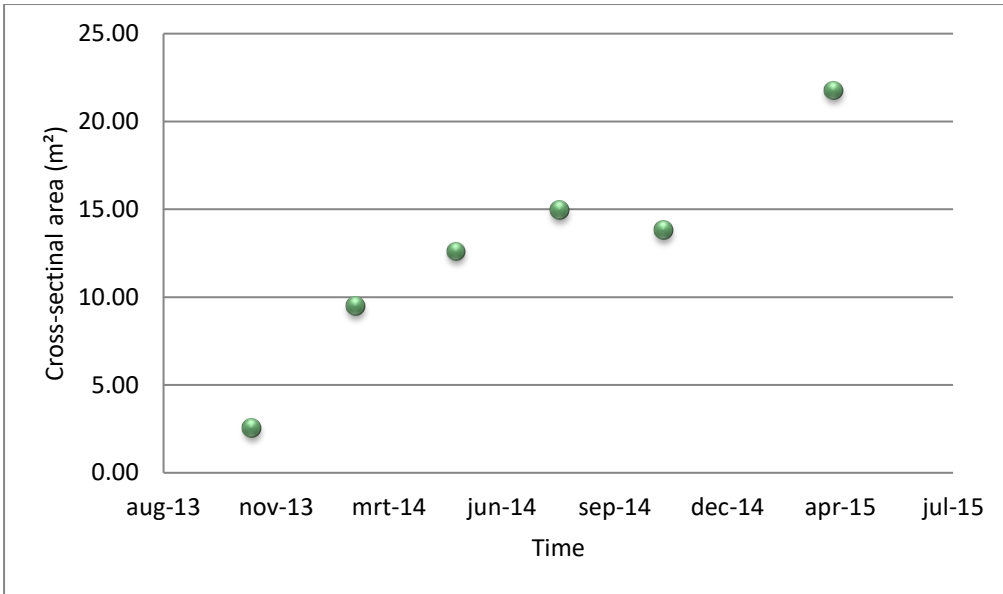
In the initial phase the area increases, intermediate period is stable but the latter fluctuates.

Cross-section 2 – 2'

The biggest rise of cross-sectional area is noted in the initial phase, later on it stabilizes but the last measurement fluctuates, though not so profound as the previous one.

Fig 22: Development of cross-sectional area over time at cross section 2 – '2.
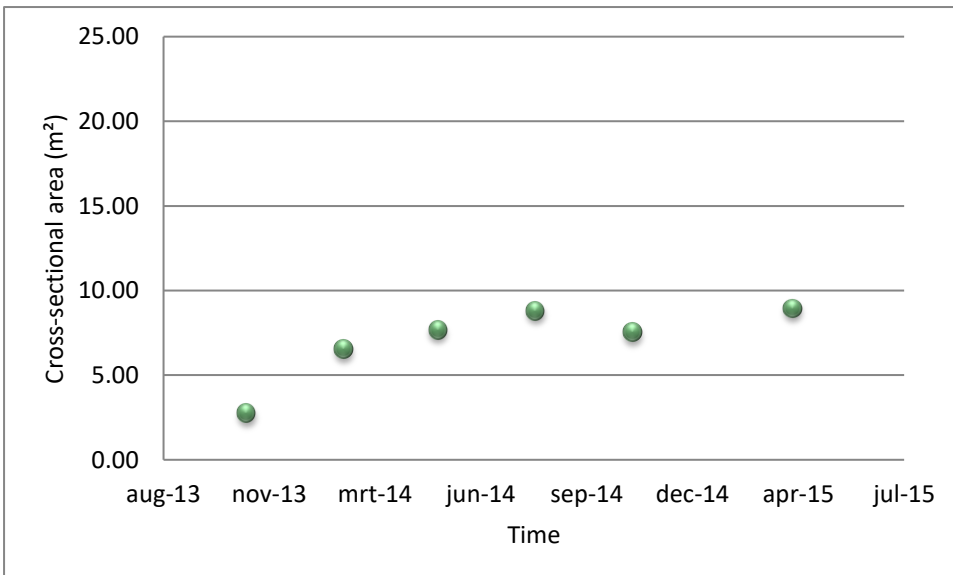
Cross section 3 – '3

Figure 23 shows the same development of the cross-sectional area as cross section 2. In the initial phase, the area of the channel increases fast. In an intermediate phase the channel stabilizes but the last measurement of April 2015 indicates a small increase of the area of the tidal channel
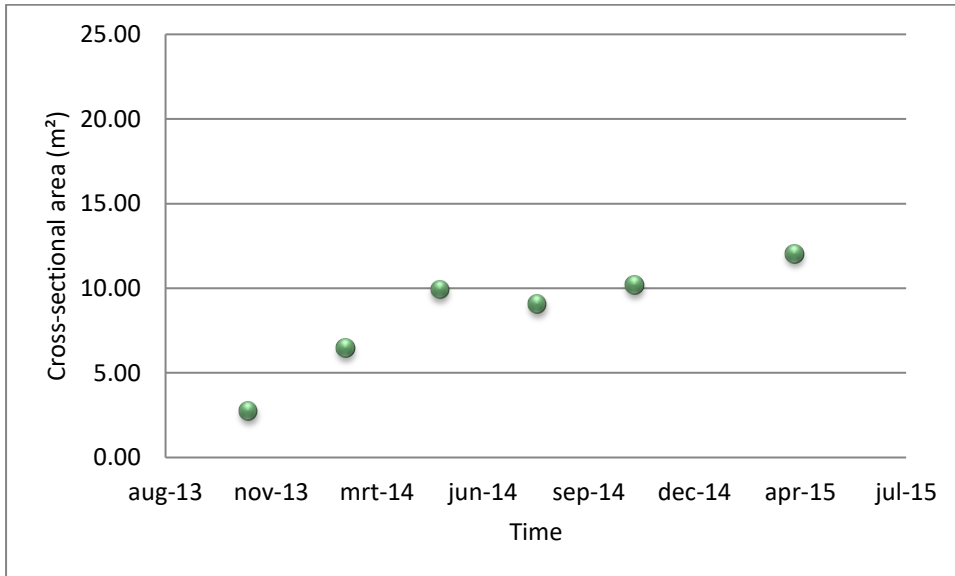
Fig 23: Development of cross sectional area over time at cross section 3 – '3.

Cross section 4 – '4

Cross section 4 is located at an average starting point of the tidal channel. Over time there are small changes visible with a constant increase. This graph shows not the same trend as previous ones, with a more modest increase and less variation between the periods.
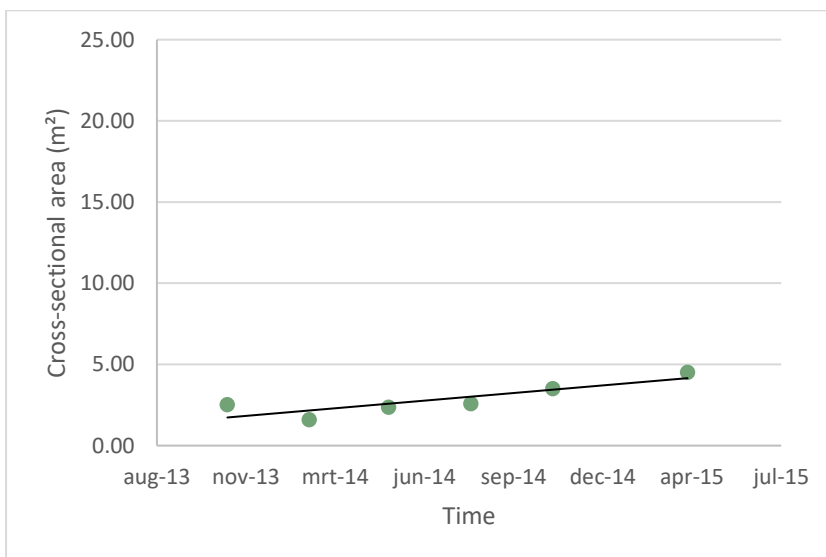
Fig 29: Development of cross-sectional area over time at cross section 4 – '4.

time	Cross - sectional area 1	Cross - sectional area 2	Cross – sectional area 3	Cross – sectional area 4	Average
month	m²	m²	m²	m²	m²
nov/13	2,52	2,73	2,72	2,53	2,62
dec/13					
jan/14					
feb/14	9,47	6,52	6,45	1,59	6,01
mrt/14					
apr/14					
mei/14	12,58	7,68	9,91	2,37	8,13
jun/14					
jul/14					
aug/14	14,95	8,80	9,06	2,58	8,85
sep/14					
okt/14					
nov/14	13,80	7,52	10,17	3,51	8,75
dec/14					
jan/15					
feb/15					
mrt/15					
apr/15	21,74	8,93	12,01	4,51	11,80

Table 3: Overview of the calculated cross-sectional areas of cross-sections 1 till 4 over time.

5. Discussion

In the discussion results are interpreted and linked to previous studies or literature. The aim is to understand the morphological system and to point out whether these results make sense. In a second chapter the limitations of this research will be discussed.

Channel length

The length of the tidal channel increases because of head ward erosion and the meandering shape of the tidal channel. The tidal channel enlarged with 157m in total over a period of 17 months (504 days). In the initial phase, the channel grew rapidly (76% in 6 months) but stabilized later on. The head ward erosion will probably continue for a while as the soil of the tidal flat and sand nourishment consists of fine sand. This means that it will erode easily. Still this head ward erosion will stop when the stream power of the discharge water is insufficient to erode the tidal channel upstream.

Meander

In the initial phase, the tidal channel had no profound bends but that changed over time. 17 months after the placement of the sand nourishment, three different meanders and a delta are visible (Fig 13). The tidal channel in the delta migrates during the winter season from West to East and in the summer period back. It is not clear if this is caused by the energetic waves during the storm season. The delta is not protected by the sand nourishment and maybe influenced by the waves or other natural forces besides the tidal channel.

Of the three meanders, meander 'B' migrates the most. The curve meanders Eastward, incises into the tidal flat and has more or less a symmetric form(appendix figure 33). Meander 'A' has the deepest area as it has difficulties with creating a wider area. The migration of the meander is complicated by the sand nourishment. It demands a higher stream energy to erode the coarser sand nourishment in comparison to the shallow tidal flat. Meander 'C' does not migrate that much Westward and its area changes insignificantly. The volume of water concentrated upstream has insufficient stream power to erode the West bank of the tidal channel. On top it is more difficult to erode the sand nourishment than the tidal flat (fine sediment and shallow slope).

Meanders 'A', 'B' and 'C' all migrate in downstream direction. This confirms that the tidal channel is ebb-dominated. The meanders amplitude stabilizes as illustrated by the relative constant sinuosity.

Over a period of 17 months meander 'A' moved 11.8m and meander 'B' 35.7.m. 50% of the migration of both meanders occurred in the initial phase, from November 2013 till May 2014 (fig 17). The average migration per month of the last 11 months for meander 'A' is 0.78m and for meander 'B' 1.77m. Meanders 'A' and 'B' are moving away from each other but presently at a much lower rate than in the initial phase. The movement of meander 'C' is at this moment negligible as the stream power of the drained water is not influential enough.

The sinuosity expresses the relation between the length of the thalweg of the tidal channel and the valley length. The average sinuosity of the stream flow is 1.14. Berendsen (1992) states that meandering rivers have a sinuosity of 1.5 or more (fig 3). Straight channels have a number smaller than 1.3. The tidal channel is according to this definition a straight channel.

Sinuosity is interrelated to the stream flow gradient. The average stream flow gradient was 0.00077. This means that the height difference changes in proportion to the enlarging meanders.

Area

Cross sections 2 and 3 show the same pattern (fig 22-23). The area increases the most in the initial phase, respectively 86% and 82%. Afterwards the size of the area stabilizes. Cross section 1 (delta) describes the same pattern except for the last measurement in April 2015 that is significantly higher than the others. This is because the top of the left bank (Westside) eroded (fig 20). This is probably not caused exclusively by the tidal channel but as a consequence does the stream flow have a larger floodplain in the delta. Cross section 4 stays relative stable as not much water is discharge at that location which causes less erosion.

Limitations

This research focuses exclusively on the morphological description of the development of the stream flow. No data was used to compare this evolution with hydrological calculations. Stream power causes the erosion or sedimentation of the tidal channel. Stream power is expressed in W/m² and takes into account the density, acceleration of gravity, discharge and the stream flow gradient (Summerfield, 1991).

$$\omega = \rho * g * Q * i$$

Next to velocity and discharge, other variables as grain size are not taken into account. It was not researched if the sand from the tidal flat would be more cohesive than that of the sand nourishment.

Exclusively height maps created by Rijkswaterstaat were used for this research. No fieldwork was carried out because a lack of time. It would have been nice to check the data of the maps with field data obtained by own dGPS measurements. However a trend in the development of the tidal channel can be deduced and linked to literature.

6. Conclusion

The purpose of this research was to understand the development of the tidal channel from a morphological point of view. Different morphological parameters were used to obtain knowledge that answers the research question:

How did the tidal channel at the Oesterdam develop from November 2013 until April 2015 and did the channel reach an equilibrium state?

Different morphological parameters were studied to answers the following subquestions.

- What is the development over time of the cross-sectional area at bank full discharge?

  The largest changes occurred in the initial phase. The cross-sectional areas moved later on to a relatively stable situation. Only the last measurement (April 2015) at cross-section 1 –1' revealed a new rise. It is not clear whether this increase is exclusively influenced by the tidal channel, so new measurements should put this increase more in perspective. Cross-section 2 and 3 illustrate that the cross-sectional area is becoming stable over time.

- What is the development over time of the channel length?

  It was observed that in the initial phase (first 6 months), the length of the channel increased with 76%. The tidal channel meandered and created profound turns. This as well as the head ward erosion caused the increase of the length. The last 11 months, the tidal channel enlarged only with 37m (24%).

- What is the development over time of the meandering /sinuosity/pattern in the tidal channel?

  The sinuosity which expresses the relation between the thalweg of the tidal channel and the valley channel is relatively stable. This means that the total length of the channel increased in proportion to the magnifying of its meanders. The outer bends of the meander migrated East- or Westward, still this occurred at a lower rate in the last 11 months. It was also clear that meanders 'A','B' and 'C' migrate downstream.

- What is the development over time of the stream flow gradient of the tidal channel?.

  Research suggests that stream flow gradient is relatively stable over time. The average stream flow gradient was 0.00077. It can be stated that the height difference changed in proportion to the magnifying meanders.

To conclude can be stated that the tidal channel changed the most during the first six months. The new situation that was created by placing a sand nourishment is developing toward an equilibrium state in respect to the tidal channel. The dimensions and pattern of the channel become more or less stable which means that less sand is eroded and transported to the Eastern Scheldt. It could be predicted that the system will find its

balance between discharge and volume in one year taking into account the variables of length, pattern and cross-sectional area.

This study could be confirmed by a hydrological study where calculation could be carried out on velocity and discharge. Now Rijkswaterstaat knows that the erosion rate will decrease and stabilize, it is interesting to know where the sediment is deposited. Furthermore research could be done on which areas the tidal channel eroded the most: tidal flat or sand nourishment.

7. Appendix

Figures & Tables:

time	Stream Flow Lenght
month	*m*
nov/13	498
dec/13	
jan/14	
feb/14	531
mrt/14	
apr/14	
mei/14	618
jun/14	
jul/14	
aug/14	648
sep/14	
okt/14	
nov/14	663
dec/14	
jan/15	
feb/15	
mrt/15	
apr/15	655

Table 4: Development of the tidal channels length over time.

time	Thalweg L	Valley L	Sinuosity	increasing sinuosity
month	*m*	*m*		*%*
nov/13	498	450	1,11	
dec/13				
jan/14				
feb/14	531	474	1,12	1,20
mrt/14				
apr/14				
mei/14	618	535	1,16	3,25
jun/14				
jul/14				
aug/14	648	563	1,15	-0,46
sep/14				
okt/14				
nov/14	663	567	1,17	1,68
dec/14				
jan/15				
feb/15				
mrt/15				
apr/15	655	582	1,13	-3,81

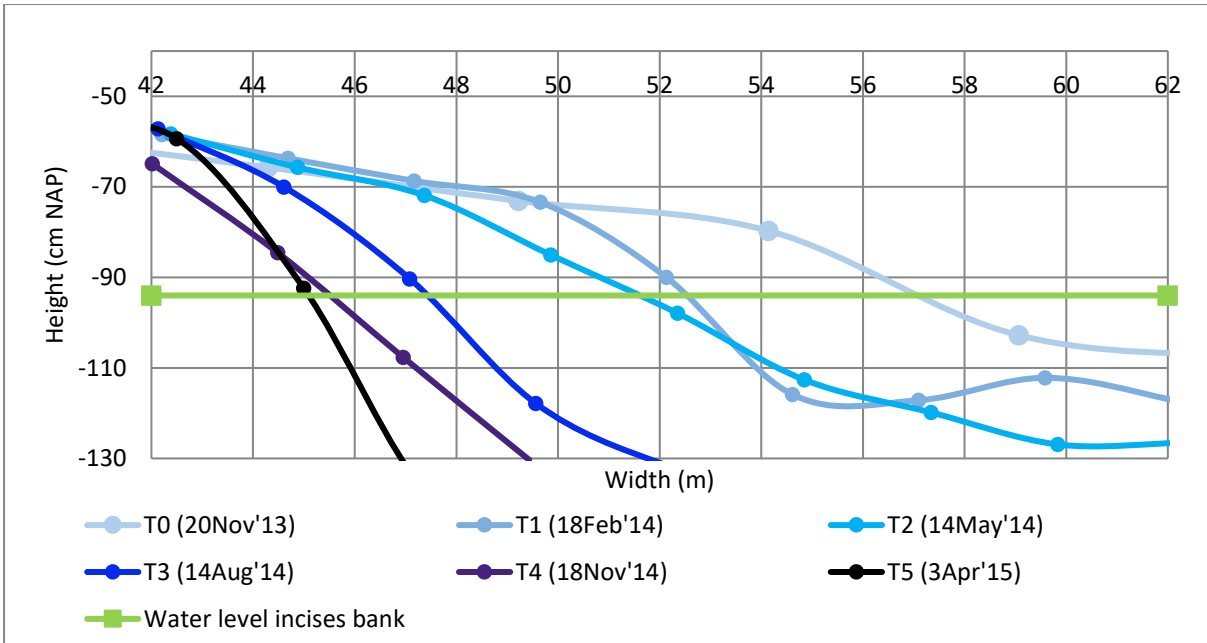Table 5: Development of the tidal channels sinuosity over time.

Fig 30: Migration rate of the outer bend (Westside) of meander 'A' is recorded at the point where the water level at -0,9m NAP incises the bank.
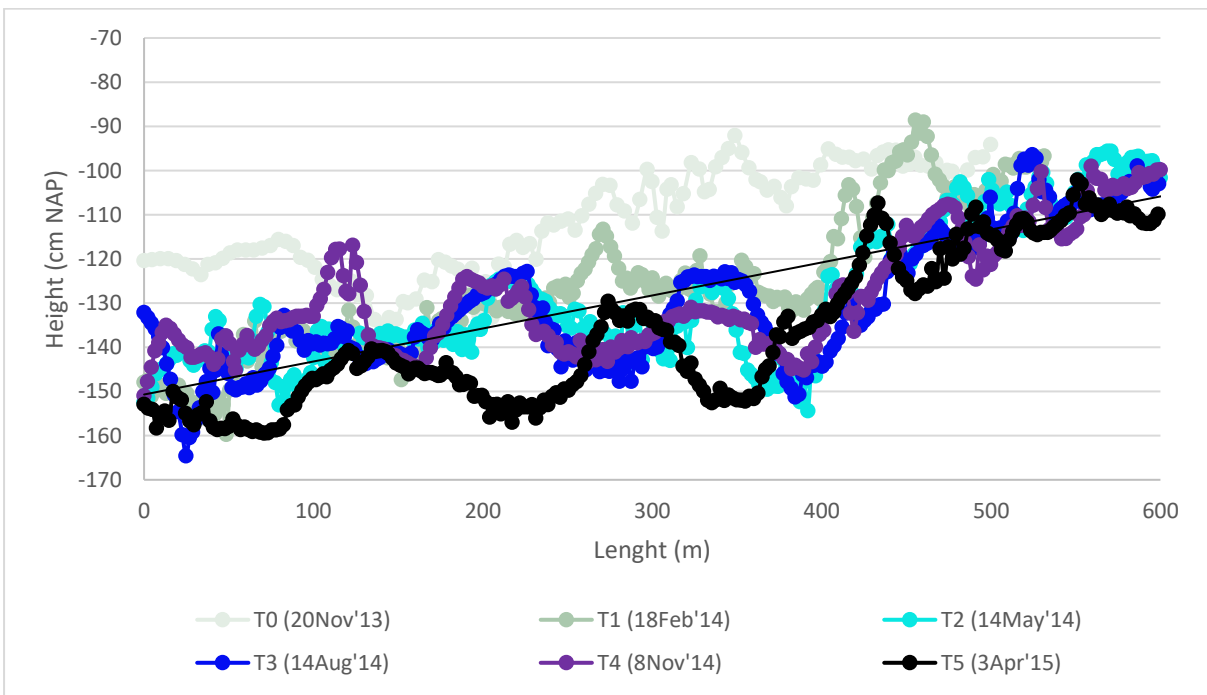

Fig 31: Stream flow gradient is determined by the trend line of the thalweg of the different periods of the tidal channel. The trend line of the measurement of 14 may 2014 is plotted as it has the same value as the average of the tidal channel over time.
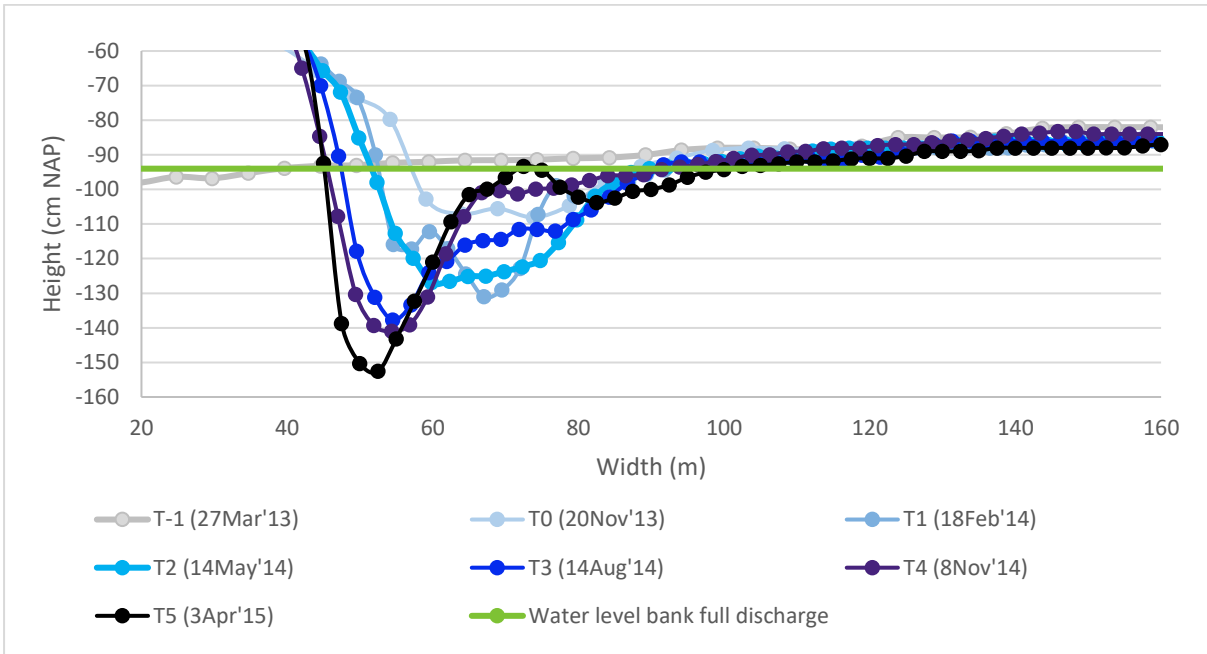
Fig 32: Cross section 2 –'2: T0 indicates the first measurement after the sand nourishment. The gray line symbolizes the level of the tidal flat before the placement of the sand nourishment. The green line represents the water level when the tidal channel is completely filled.
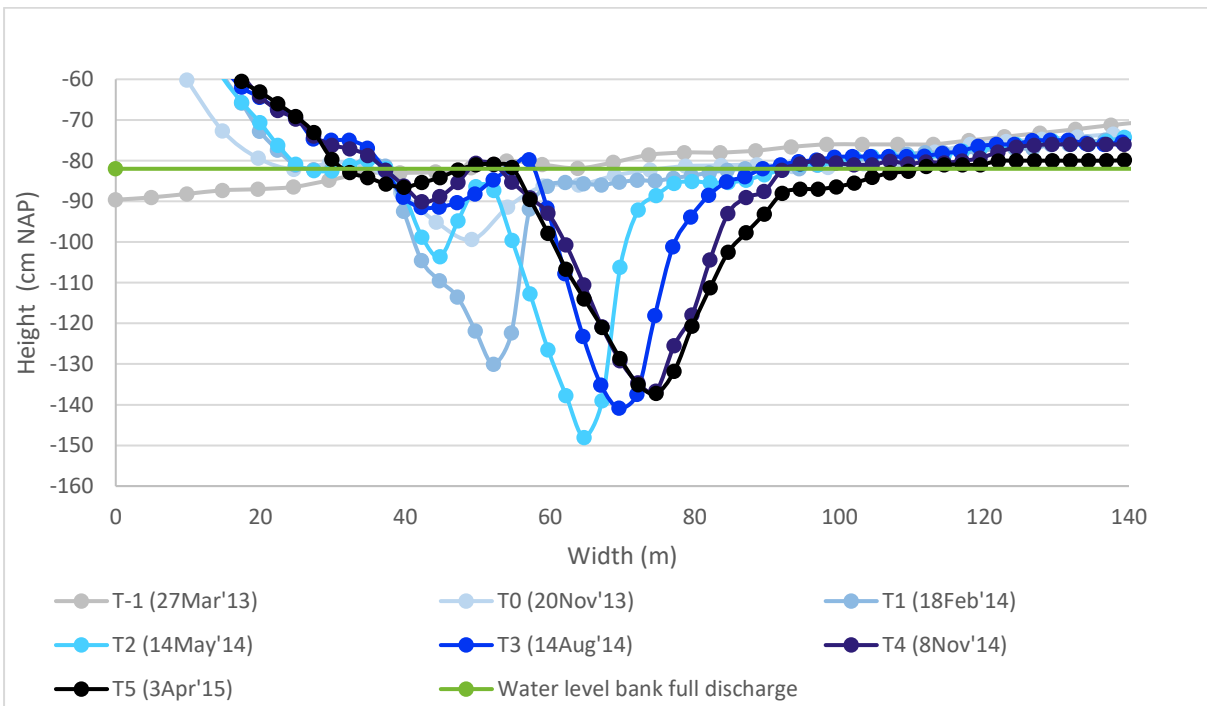

Fig 33: Overview of the development of the cross-sectional area at cross section 3 –'3 over time.

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