Ups-and-downs of tidal systems: formation and development of ebb- and flood tidal channels and bars.

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Abstract

Ever since Van Veen (1950) described the different tidal channels in the Western Scheld, people have known of their existence. Ebb and flood use different tidal channels in an estuary, and form certain patterns to lead these different tides through. The exact process that forms these ebb-flood tidal channel pairs remains a mystery however. Previously it was not possible for scientists to investigate this formation with something different than modelling, but with the introduction of the 'tilting flume' it has become possible to imitate tidal behaviour on an experimental scale. This study has been done to try to find the factors determining the formation of tidal channels and whether they form an equilibrium or not.

Figure 1: Sketches of flanking (left) and forking tidal channel systems (right). Van Veen (1950)

To mimic the tides in an experimental setup, a basin on a moving axis was used. By means of an extracting pole on one side of the basin it could tilt in a controlled way. The basin is filled with 4 cm layer of sediment (either sand or plastic) and two 'seas' on both ends of the basin. These ends also have the recharge and discharge of water into the basin, so that when the basin tilts to one side, it will be recharged from the other. This way a more or less constant water level is insured. Tidal amplitude and duration can be altered to investigate the effect of these tidal characteristics on the formation of tidal channels. In the layer of sediment an initial channel of varying width and depth is dug to channel the water through. Furthermore, this channel can be altered with a soft or hard perturbation.

Figure 2 shows an example of a typical tidal experiment. Contrary to the sketches of Van Veen (1950) (figure 1) no clear singular patterns are seen. Experiments often displayed complex patterns with channels influencing the formation of others through the whole length of the estuary, something that is not unheard of in nature (Dalrymple and Rhodes, 1995). Particle tracking experiments did show though that tides preferred certain channels, where ebb chose different channels than flood. This already happened at the start of the experiments, where one tidal flow would create bars that obstruct and lead the other tide into other channels. Perturbing a channel may force a system to form channels, but the most natural ones form only when tidal amplitudes and initial width/depth ratios are right. Trying to predict the formation of well-developed channels proved to be a failure though. Shear stress and tidal amplitude play a large role in the formation of developed systems, but both too large and too small magnitudes of the factors can prevent channels from forming.

Figure 2: End state of a tidal experiment done in sand.

-Tidal amplitude is the most important factor in both the formation as the destruction of tidal channels.
-Tidal bars form like river bars, only with different tides taking different channels.
-Flanking and forking systems do not stand for certain characteristics: both systems can develop and disappear during the development of the estuary.
-Prediction of the amount of channel formation still is something that need more research.

Summary

This thesis investigates the progress of tidal channel formation and its continuing development. The patterns seen in estuaries resemble the patterns of braided rivers, and this study tries to find the comparisons between the two processes, despite their different environments. This study is performed by using an experiment setup to mimic tides in a flume. 50 experiments have been done, all with varying tidal amplitudes and initial conditions, with both sand and plastic grains as sediment.

It is hard to find general hard laws that define the formation of channels in an estuary. The process of bar formation is quite uniform, and in the initial phase of the experiment formation of bars often follows the same trends. However, perturbation of the flow and tidal amplitudes can have large effects on the formation of bars. Perturbation is often important to initiate the sediment motion, and after that initial motion the tidal amplitude often defines the growth rate of bars. Whether the whole process of channel development will persist for the duration of the experiment also is dependent of the tidal amplitude. There seems to be an optimal sediment mobility however. When sediment mobility becomes too large, the estuary will only widen rapidly until the whole experiment floods.

Experiments are also compared with both other tidal experiments and river experiments. From this results that tidal channels need to be more mobile than braided rivers to form the same patterns. A theory about the formation of channels is also made. This theory describes the formation of one single ebb-flood channel pair. It also explains that different channel pair types can exist under the same circumstances.

Acknowledgements

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An extra word of thanks for the men from the technical support within the Department of Physical Geography: Henk Markies, Chris Roosendaal and Marcel van Maarseveen. Without them there would be no pictures to show in this report, if there even were results to report at all.

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1. Introduction

Estuaries are an important part in the process of discharging water and sediment to the sea. These locations form the mouth of a river when it reaches the sea, and this unique location between river and sea leads to situations that cannot be seen in other geographical systems around the world. The most typical feature of estuaries is the fact that both river discharge and tides are influencing the morphology of the estuaries. This leads to phenomena that look like structures that can be found in rivers, but differ with their counterparts in a way that still cannot be explained.

One of those phenomena is the formation of tidal channels. In estuaries, it often is the case that ebb and flood, being flows with opposite directions, use different channels to discharge their water. Opposite to rivers, where all channels, either active or inactive, are formed by the same flow. This phenomenon has been described first in 1950, but since then no satisfying research has been done after the exact formation of these channels. This means to following question still lingers: Why do estuaries develop channels separate channels for ebb and flood?

For long it was hard – if not impossible – to do good experiments to investigate tidal environments. Both wave and river activity could be mimicked in experiments, and results from those actually look quite natural. Tides were hard to simulate in experiments though. There are some modelling studies after the development of tidal systems, but no physical experiments worked decently. Only raising and lowering the water level of an experiment ultimately lead to estuaries in equilibrium – something that has never been seen in nature. Until prof. dr. Kleinhans introduced the tilting flume. With this tides can be simulated by means of tilting a basin over an axis, both creating a gradient on the bed and changing the water level. This proved to be sufficient for systems to form, and therefore this will be used to investigate the formation of tidal channels.

Not much is known about tidal environments, but research of them is very important. Natural estuaries – being at the transition zone between river and sea – often are the location of world's largest harbors. However, since natural processes always continue to go on, it is very costly to keep the estuary fit for shipping. If the natural processes going on in tidal environments are better understood, one could maybe benefit from nature instead of dredging the whole estuary. For example, if we could learn under which circumstances channels are more stable or silt less fast, we could use that information to alter the dredging schemes, an adjustment that could save millions on a yearly basis. Furthermore, this would also have a positive ecological impact, because dredging has a large impact on the natural processes. 'Keeping things natural' would therefore benefit the development of the natural habitat in an estuary. This thesis aims to contribute to the better understanding of tidal systems, in order to make it possible to implement these kinds of changes as described.

Definition

Estuarine research is a fairly new concept in comparison with research to rivers or coasts. The formation and behavior of channels in an estuarine system has been studied before (Dronkers, 1986; Stefanon et al., 2009; Jeuken and Wang, 2010, among others). Only a few studies investigated the formation of patterns within a channel though (Hibma et al, 2004; Schuttelaars and de Swart, 2000). Even less research has been done to the so-called tidal channels. These tidal channel pairs were at first reported by Van Veen (1950), but since then the questions about how and why these channels formed have never been answered. Other research investigated the formation of bars in an estuarine channel (Dalrymple and Rhodes, 1995), but the channel behavior remained unknown.

Ebb- and flood tidal channels exist all around the world, as can be seen in figure 1.2. Different tidal- and river characteristics form different tidal patterns, but all channels more or less behave in the same way. In most estuaries, one channel takes the lead role and has the largest dimensions in the estuary. This is mainly the ebb-tidal channel, profiting from the extra river discharge. This means that the flood tidal channel forms the smaller opposite-flowing channels, like the chute bars in rivers (figure 1.4A), only in the opposite direction of the main flow.

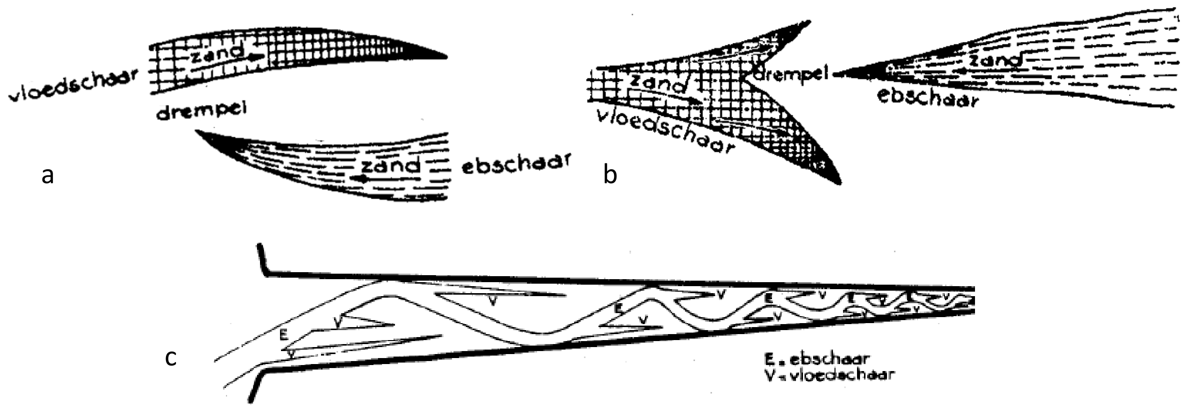

Figure 1.1: Evading tidal channels. (Vloedschaar = flood tidal channel, zand = sand, drempel = sill, ebschaar = ebb tidal channel). Water flows in the same direction as the sand indicated in the figure. a) flanking channels, b) forking channels, c) continuing main channel. Van Veen (1950).

It is unclear how the channels exactly formed, but it has long been known what they look like. One pair of ebb- and flood-tidal channels exists of two channels that are formed by their associated tide. Ebb-channels are formed during ebb, and flood-channels during flood, but at the same time one channel influences the behavior of the other channel. (van Veen, 1950). The two channels belong to the same system, but have different directions. This is due to the fact that the channels form under different tides. As it happens, ebb tidal channels control the flow of the water during the ebb tide, while flood tidal channels do this during flood. The two channels are not always parallel to each other over their whole length. The estuary is sometimes just filled up with several different channels that alternate at the sides of the estuary, and only the ends of the channels flank each other. As long as the channels are separated by sills and shoals, we still may speak of an ebb- and flood tidal system. An ebb- and flood-tidal channel pair looks like patterns that can also be found in meandering or braided rivers (figure 1.3). The main difference between the river- and tidal patterns is that in braided rivers, all channels and shoals are formed by a unidirectional flow. This patterns differs from the tidal patterns, where shoals seem to be raised between channels that are formed by flows with an opposite direction.

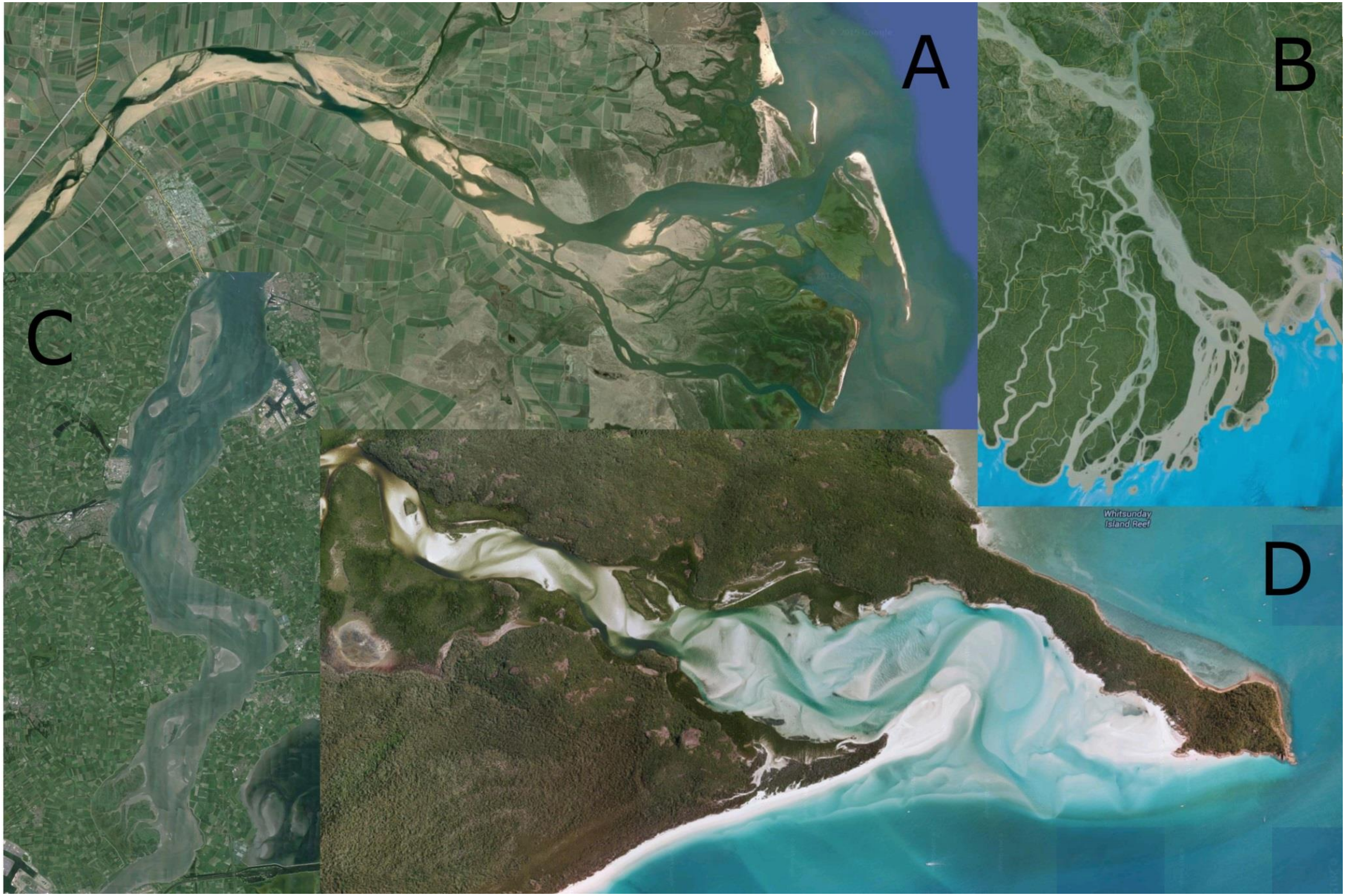

Figure 1.2: Natural estuaries around the world. A) Burdekin River, Australia, B) Padma River, Bangladesh, C) Rio Amazone, Brasil, D) Whitehaven beach, Australia.

The tidal channels are not endless, since the tides are not endless either. The channel will become shallower where the flow velocities lessen until the channels end. At this location a sill is formed. This sill often marks the boundary between the tidal channel and the (main) channel it would flow into. That channel could be the tidal channel in the other direction, in which case we speak of flanking tidal channels (figure 1.1a). Another version of the system is the forking channels system. In this version the sill of one channel is located in the opposite channel, forcing it to bifurcate around the sill(figure 1.1b).

The last of the tidal system is a variant of the forking ebb-flood channel pair, but with one main channel that looks like a meandering river (figure 1.1b. Real meandering is not always the case, and the channel often is maintained by means of dredging. This continuing channel is the main channel of either the ebb- or flood flow, and the other tide can cut off the point bars in the form of chutes (figure 1.3). Often the channel is dominated by the ebb tide, since ebb tends to concentrate its flow in the channels. However, when flood flow is substantially stronger than ebb, the channel can also be formed by the incoming tide. The next paragraph will investigate the comparison between rivers and estuaries further.

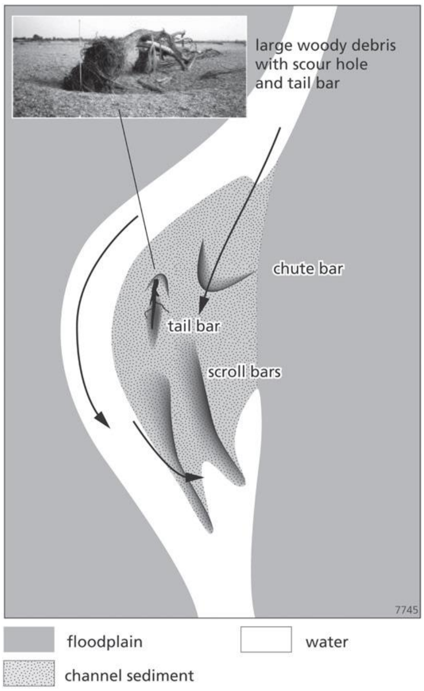

Figure 1.3: Meandering main channel patterns. A) in rivers. Kleinhans and van den Berg (2011) B) in estuaries. Van Veen (1950).

Of rivers and bars

It is unclear why ebb- and flood tidal channels form, but since the channels look a lot like river patterns, it is expected that they behave with the same rules. An important difference exists between rivers and estuaries: In rivers, bifurcations tend to become unstable after a while, as flow will mainly concentrate itself in one channel, abandoning the other. That abandoned channel will fill up completely, and the remaining channel will eventually form a new bifurcation, starting the process of abandoning anew. Another possibility is that the bifurcation is highly out of equilibrium, with one channel a lot larger than the other. This results in a bifurcation where all sediment transport will go through that channel (Kleinhans et al., 2008; Bolla Pittaluga et al, 2003). The only exception to this phenomena is a river that is non-resonant (Bertoldi and Tubino, 2007). In these types of channels, disturbances in the flow will not have any effect, as the flow is not strong enough to alter the channel in any way. At the moment it is not clear if bars in estuaries will disappear though, as channels remain on the same location for longer times in estuaries. Whether this is due to lower flow velocities or changing flow directions, and if tidal bifurcations are stable at all is not known at the moment.

In rivers, Kleinhans and van den Berg (2011) found that stream power is an important factor determining the formation of river bars, where stream power is defined with the following equation:

$$\omega_{pv} = \frac{\rho g Q S_v}{W_r} \qquad \text{where} \qquad W_r = \alpha\sqrt{Q} \qquad \text{eq. 1, 2}$$

and ω_{pv} is potential stream power, ρ is sediment density in kg/m^3, Q is discharge in m^3/sec, S_v is the valley slope in m/m, W_r is reference channel width (van den Berg, 1995) and α is a constant between 3 and 5 (Kleinhans and van den Berg, 2010). Figure 1.4 shows the distribution of river patterns based on this stream power. Not all rivers fall in their predicted stability fields, but the general trends are clearly visible. This raises the question whether it could be possible for tidal systems to fall in this diagram too, since comparing figure 1.1c and 1.3 with a visual comparison, the patterns in these estuaries do not differ very much from river patterns.

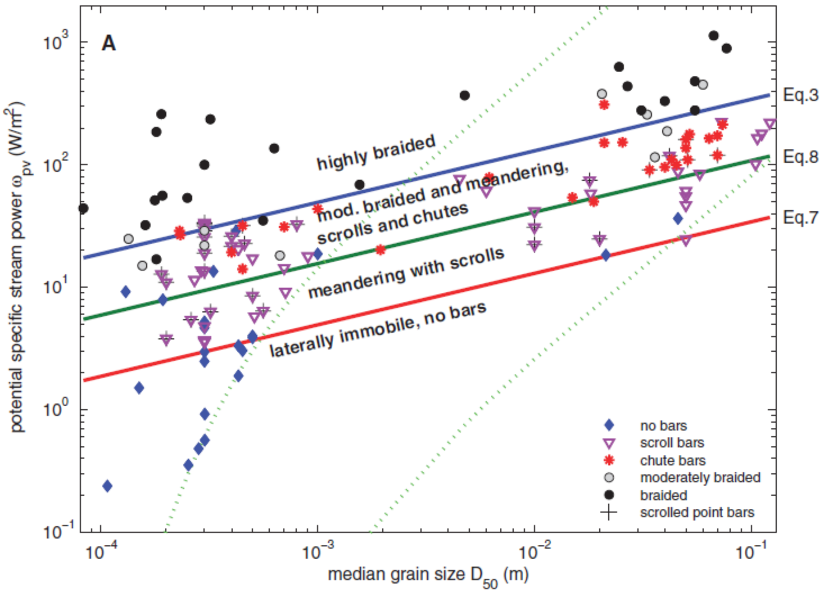

Figure 1.4: Pattern prediction of rivers based on their stream power. Kleinhans and van den Berg (2011).

This comparison between rivers and estuaries can also be found in current modelling studies, like the ones of Hibma et al. (2003) or Schramkowski et al. (2002) for example. These modelling studies point out that the bar-and-channel system found in estuaries works on the whole width of the estuary, as Hibma et al. (2003) showed in her model. In her model an initial flat estuary developed itself under the influence of alternating water flow directions into a system with alternating bars and channels. Both authors also seem to hint that the formation of channels has to do with the concentration of the ebb and flood flow in separate channels, but do not explain why different flow directions concentrate itself in the different channels. However, the models prove that the estuary should be seen as one complete system, with channels the result of processes within. Van Veen (1950) shows that the initial form of the estuary explains the formation of tidal channel pairs. His report theorizes that an initial bend in the estuary causes ebb and flood to concentrate on different parts of the estuary, creating each their own channels (figure 1.5). This would mean that tidal channels would not form in initially straight estuaries though.

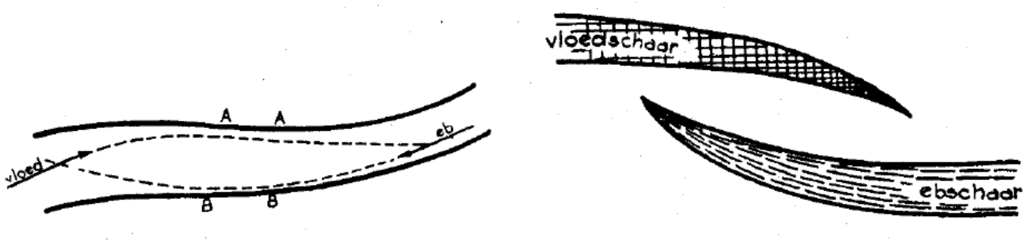

Figure 1.5: Formation of tidal channels due to the form of the initial estuary. Van Veen, 1950.

Federica and Paola (2003) found that the stability of a bifurcation in a braided river is dependent on the Shields number that works on the river. When the Shields number exceeds 0.15, bifurcations become stable, while they 'switch' their location when stresses are lower than 0.15. Kleinhans et al. (2012) state however that the stability is also dependent on the width/depth ratio. They found that when the Shields number exceeds 0.01w/d, bifurcations could become stable. Seminara and Tubino (2001) found in their work that noncohesive sediment in the bed was important for the formation of bars in the middle of an estuary. Bars in a channel form when the aspect ratio exceeds a certain threshold value. This aspect ratio is not an exact value for estuaries, contrary to rivers. They also found that due to the oscillatory flow in an estuary, bars would not move except for small movements due to the asymmetry of the tides (Tambroni et al., 2005). Both reports also found that bars would grow to wavelengths that are about three times the width of the channel. As to when channels are stable, Seminara and Tubino (2001) found that when their bars had a length of a few times the width of the channel, bars would become very active and thus never reach an equilibrium. This seems differ in other research, since Wang and Winterwerp (2001) found that even when channels were brought out of equilibrium by deepening or shallowing them with 10%, channels would go back to their equilibrium state. Jeuken and Wang confirmed this, but also stated that this 10% is an indicative amount, and not enough historical data is available to fully prove this. The results of Seminara and Tubino (2001) complement the theories based on real estuaries (Dalrymple and Rhodes, 1995), which state that bars in tidal environments are formed and determined by the channel width in an estuary. Interestingly, these authors state that there is no real difference between tidal dunes and bars but for the dimensions of the bodies. This would imply that the bifurcations between ebb and flood channels form when dunes grow so much in size that they become obstructions to the stream in the estuary. This seems to be a reasonable theory, because this is what is found in river bifurcations too.

Formation of bars

It is hard to clarify the difference between bars and dunes in a tidal environment (Dalrymple and Rhodes, 1995; Tambroni et al., 2005). Dalrymple and Rhodes (1995) believe that bars in a tidal environment just grew out of dunes when given enough time to develop. This implies that if the duration of one tide was long enough to make the flow start forming ripples, this flow would eventually form ebb- and flood tidal channels of its own. Even if one of the two tides would not be able to form bars of its own. The dunes, when becoming bars, would eventually block the flow though, forcing it to relocate its bed, hereby explaining channel development. This is more or less what Stefanon et al. (2009) found. They did experiments with changing wave numbers in estuaries, and they found that a higher flow depth would create more bed forms and less well defined channels. With other words, channels did not get the chance to develop much, because the amount of developing bed forms continually forced the channels to relocate themselves. Stefanon et al. (2009) did do estuary-scale experiments though, instead of focusing on one channel. Since the focus of the experiments was on the formation of the whole estuary, bars inside the channels were less important, therefore could act differently in other situations. Another important point is that the systems in the experiments of Stefanon et al. (2009) ended up into a static equilibrium phase. Ultimately the in- and outgoing water did not have enough transport capacity, because the channels broadened and therefore flow velocities decreased. At this moment the basin stopped developing itself, but it is not clear if under 'normal' circumstances the systems inside the channels would stop developing too. Cohesiveness of the sediment also plays a role though. Kleinhans et al. (2015) found out that the 'threshold channel' concept of Parker (1978) also holds true for tidal experiments. This concept explains the phenomenon where a channel with no cohesive banks constantly widen over time. As this creates quite an amount of sediment and space in the channel, the channel will form bars on its bed, but these bars will remain mostly immobile. The widening will continue until the moment that shear stress at the boundaries becomes lower than the stress on the bed of the river. In experiments with light-weight sediment, the moment where the shear stress at the banks becomes too low may not happen before the channel has become too wide though, and this could mean that during the experiment no bars will form in the estuary at all.

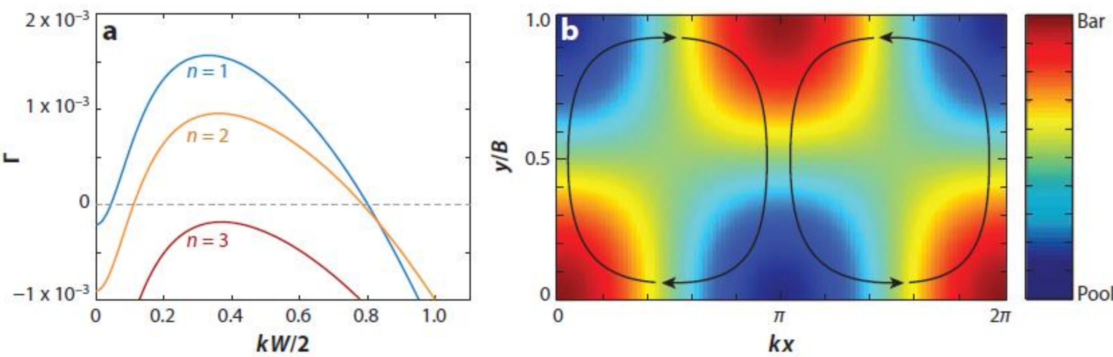

Figure 1.6: a) Dimensionless growth rate of bars Γ versus wave-number k and channel width W. b) bottom pattern for mode n=1 in a. The solid black lines show the tidal residual circulation. De Swart and Zimmerman (2009).

Whether bars can develop large enough to influence the flow in the estuary all has to do with the wave number of the incoming tide (de Swart and Zimmerman, 2009). Apparently, if the width/depth ratio of an estuary exceeds a certain value, bars can form. How fast their development goes is dependent on the wave number, and the amount of bars in the channel, defined by the mode number n (figure 1.6b shows the bars and troughs for a mode with number 1). Figure 1.6a shows that when the mode increases, the growth rate decreases or even becomes negative.

Schramkowski et al. (2002,2004) also found out that the growth rate of bars depend on the mode and wave number of the tides. The mode of the estuary alters the effect of the wave number on the growth of bars, but over all a dimensionless wave number of 2.5 – 3 resulted in the largest growth rates (figure 1.7). Important is to note that an increasing bar mode would increase the growth of the bars, as opposed to the results of de Swart and Zimmerman (2009). The trend that growth decreases when the wave number increases does compare well between the two studies though. The modelling results of Hibma et al. (2004a) do support the results of Schramkowski (2004) though. Stefanon et al. (2009) also found corresponding results, because they found that the development of channels decreases when wave numbers rise above 3. Whether bar growth increases or decreases for higher nodes therefore remains to be seen.

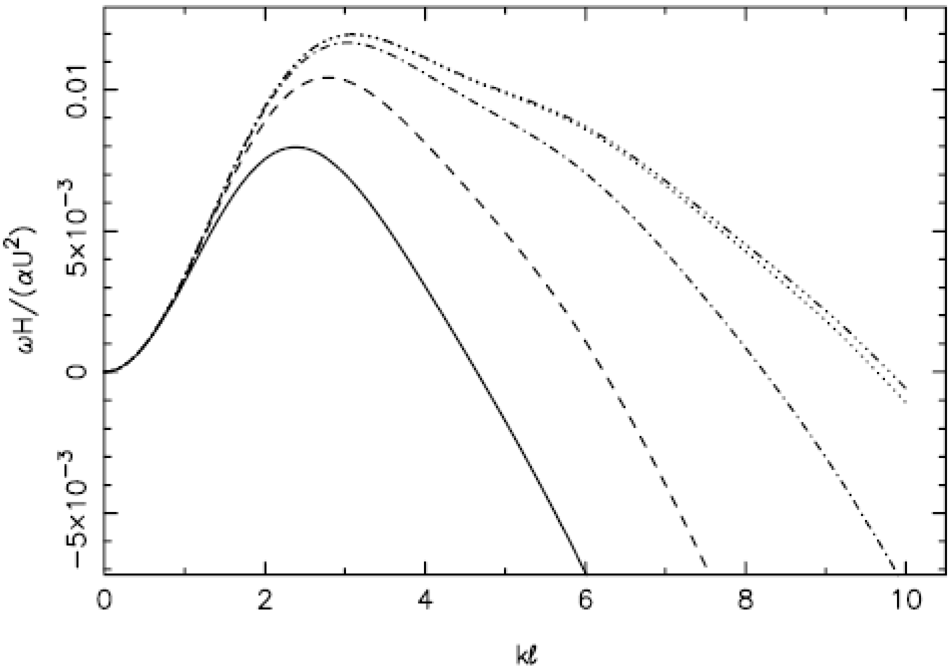

Figure 1.7: Dimensionless growth rate versus longitudinal wave number k for mode n=1 (solid), n=5 (dashed), n=20 (dot-dashed), n=100 (dotted) and n = 100000 (triple-dot-dashed). Schramkowski et al (2002).

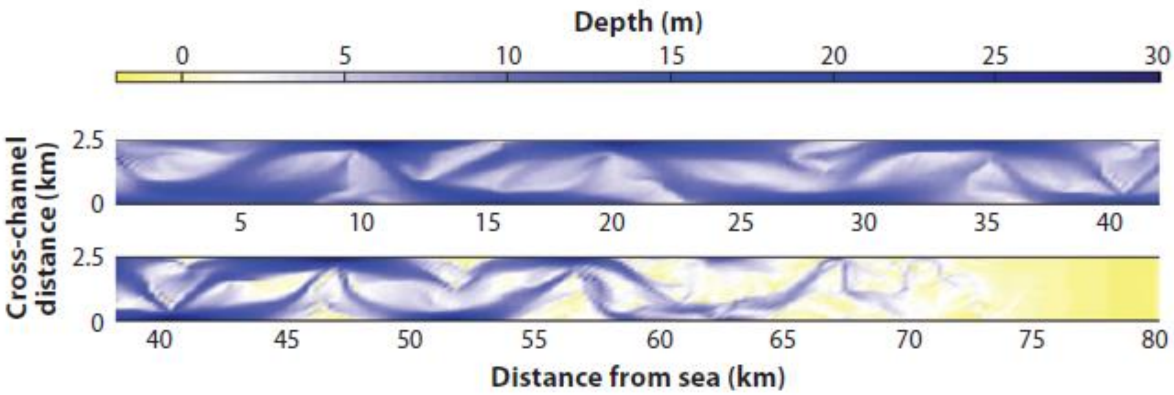

Figure 1.8: Development of channels in a modelrun done by Hibma et al. (2003).

Formation of bars has also been found in models. Seminara and Tubino (2001) and Hibma et al. (2003,2004b) all had working models on a flat initial estuary. Problem with these models is that it is not clear how and where ebb and flood work in the estuary. When we look at figure 1.6, after the model results of de Swart and Zimmerman (2009) from the model of Seminara and Tubino, we see a clear difference between bars and troughs, and the residual flow that distributes the sediment along the estuary. Only Hibma et al. (2003) has created a model that plots the development of channels in an estuary (figure 1.8). It is clearly visible that different parts of the estuary have a different dominant tide, therefore the results look more natural than those of Seminara and Tubino (2001). It remains a model however, and therefore dependent on the settings that were set by its maker, settings that do not have to hold true for natural systems. Hibma et al. (2003) also found out that formation of bars possibly is caused by the positive feedback between current and sediment. Small perturbations can grow into better developed bed forms when exposed to a flow. When flows start to concentrate on their own channels, the bed forms will only be exposed to one current direction and can grow even larger, until bars form. The model did not go on after the bars and channels were fully developed though, so it is not clear what would happen with the tidal channel systems. At this moment, scenarios have been stopped before one could prove if the channel systems would develop after their formation.

2. Hypotheses

Previous research partly explains the development of bars in tidal channels, but the question remains how ebb- and flood tidal channels exactly form. The following hypotheses are made up to try answering this question:

Asymmetry between the tides could be the reason behind the behavior of bars in a tidal channel. An estuary that has reached its equilibrium width/depth ratio will have parts in its channel with more and less flow. Bars will start to form on the locations with less flow, which results in less sediment movement on the bars. The locations with low flow will exist due to small perturbations on the bed of the estuary. This does not explain the natural formation of bars though, nor does it explain why a bar would form in the middle of the channel: Stresses are larger at the sides of the channel, so the lowest transport would happen there. A possible explanation could be that during one tide, flow – and thus transport – will increase on the bed, leaving a small dune on the bed when flow is decreasing again when the tide ends. During the other tide, water will flow slightly slower over that dune, and will find or create channels to lead the water through during the motion of water in the other direction.

Another question is why a certain kind of bar pattern would form, and possibly the difference in dominance of one tide defines the type of ebb- and flood-tidal channel system. If both ebb and flood are equally dominant, the estuary has to form a system where both tides can form equally large channels. This means flanking channels will form, as both tides can use their own channel in this system. When one tide becomes more dominant than the other, the estuary will form forking patterns though. One tide, the most important one, will take the route with the least resistance, which will be straight through the estuary. This means the other tide will have to form its channels around this main channel.

Tidal systems are thought not to be in an equilibrium. Previous research shows that bars can develop from perturbations on an initially flat bed. The concentration of flow leads to better formation of bars, and existing bars can more easily be altered with a more concentrated flow. This will lead to continuing the alteration of existing bars and the formation of new ones. Following this theory, it will be highly unlikely that estuaries will end up in equilibrium. Tidal asymmetry will also affect the bar pattern: basically, the tide with the higher amplitude or duration will dominate the system, dominating the transport direction of the bars and the formation of a main uninterrupted channel. The asymmetry of the process will also determine whether the system is in equilibrium or not. In an estuary where the influence of both tides is more or less the same, channels in both directions will form and interact with each other, but prevent each other from outgrowing the other channel. This would result in a dynamic equilibrium, where channels and bars keep moving but do not develop past a certain state. Some asymmetry in the tides will result in a surplus of transport in one direction, followed by the movement of the bar, and changing of the locations of the channels. Basically, the more asymmetric the tides become, *the more it will look like a river*. Rivers do seldom form stable bifurcations, and therefore it is thought that tidal asymmetry will (partly) determine the stability of a tidal system.

3. Methods

This thesis aims to find the relation between several characteristics of an estuary and the dimensions of the tidal channels that form inside. To this end, and experimental setup of an estuary was made. This small-scale setup made it possible to perform quick, 24-hour long experiments in which an estuary could develop. Development started in an initially straight channel, with at both ends of the flume an equally large sea. This way ebb and flood had more or less the same volume of water going through the channel. Some experiments had an initial perturbation in its channel, being either hard or soft. Hard perturbations remain present for the total duration of the experiment, while soft perturbations only affected the flow in the first couple of cycles (normally not more than 10). During the experiment, every couple of cycles photographs are taken from the topography in the basin. This way the development of the different channels in the experiment can be investigated after the experiment. Based on these photos it is possible to determine if tidal channels form under the given boundary conditions, and how they will develop.

Description of the experimental setting

The experiments described in this thesis are all done in a rectangular basin that imitates the tides, but on a smaller scale. This basin has a length of 3.60 meter, a width of 1.20 meter and a depth of 0.25 meter, of which only a small part is used. The basin has two inlets, one on each end of the basin, through which both water can flow in and flow out. The inlets connect with a main sump tank, from which water is pumped into the inlets. (figure 3.1).

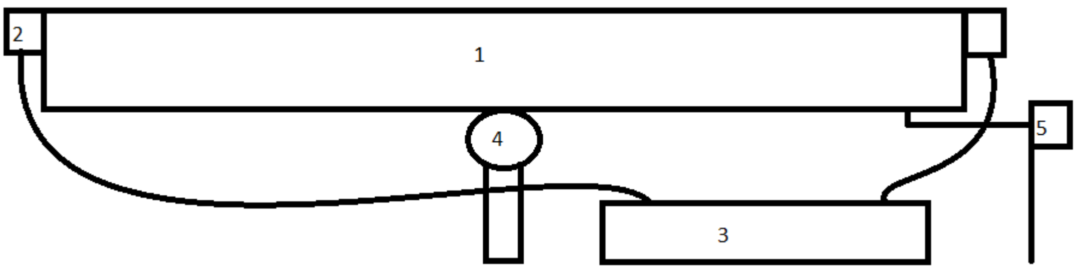

Figure 3.1: Sketch of the basin, with 1: the basin itself, 2: the inlets of the flume, 3: the sump tank, 4: the axis on which the basin tilts and 5: the device that controls the tilting.

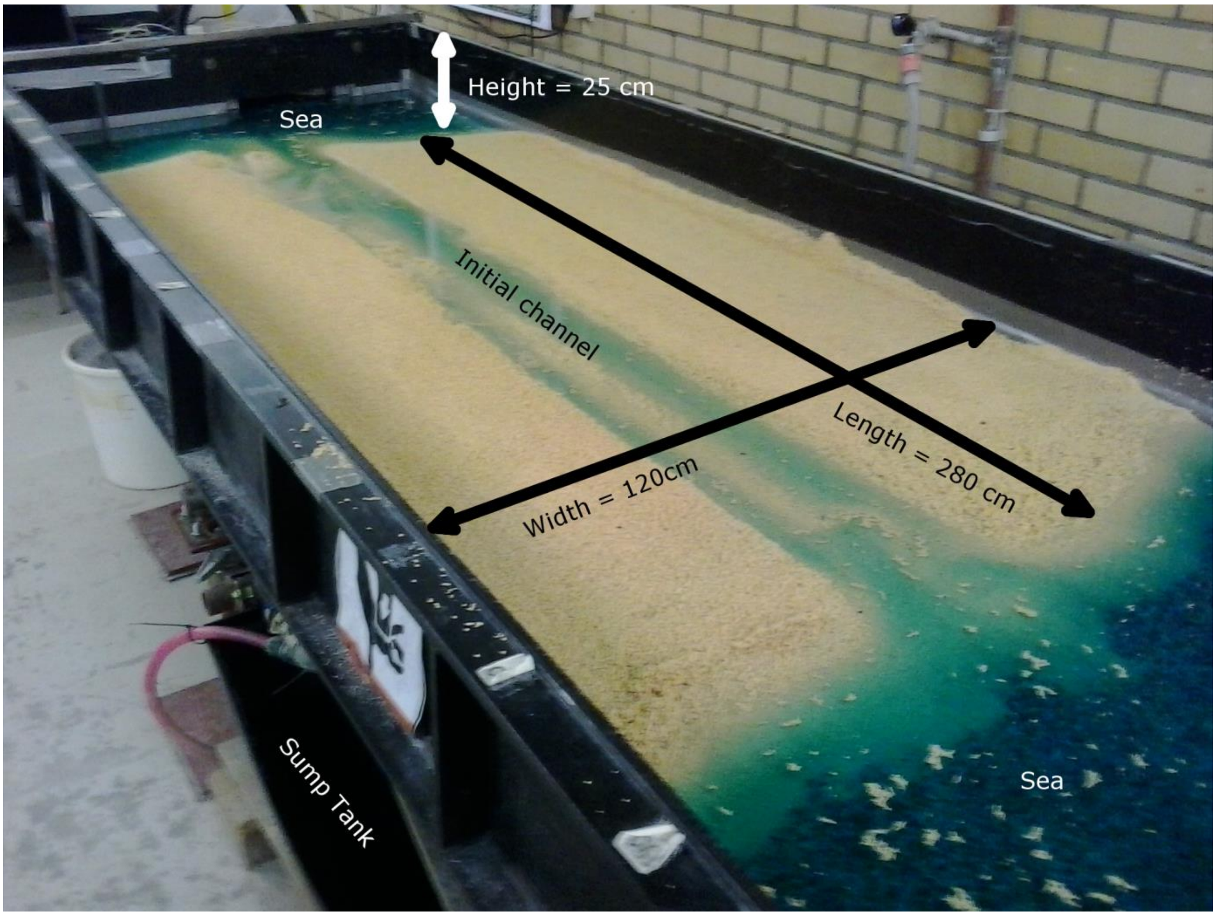

Figure 3.2: setup of the experimental basin.

The height of both drains can also be controlled. By changing the height, the water level in the basin can be controlled. Normally the height of both drains is the same, thus creating a constant head in the basin. Draining the water in the basin is also done by the lowering of the drains in the small storage. In the same storages water is pumped from the main storage. The pump pumps with a constant discharge, but the amount of water that flows into the storages can be controlled by means of three taps: one for each of the inlets, and one that drains back to the main storage.

The tilting of the basin was performed by a vertical threaded pole driven by a stepping motor on one end of the basin. The whole setup rested on one axis installed under the middle of the basin, and was tilted by pushing and pulling the pole. By pushing it, the pole would extend and the whole basin will tilt over its axis to the side without the device. When pulled the basin would tilt to the side with the device. Tides could be produced by continuously pulling and pushing the pole by an amount that could be set in the device. Amplitudes could be set to the tenth mm precise, but based on a reference level that was only on the mm precise.

It was also possible to create asymmetric tides by creating a difference between the upward and downward amplitude. Besides the amplitude, tidal characteristics could also be changed by changing the duration of the tide. This was done by changing the velocity by which the device tilted the flume. The velocity of this pole can be set to micrometers per second, but has a default velocity of 0.5 meter per second. Furthermore, to create a more natural tidal course, a delay could be set at high water and low water, to lengthen the duration of that period. This resulted in a tidal movement of the flume as shown in figure 3.3.

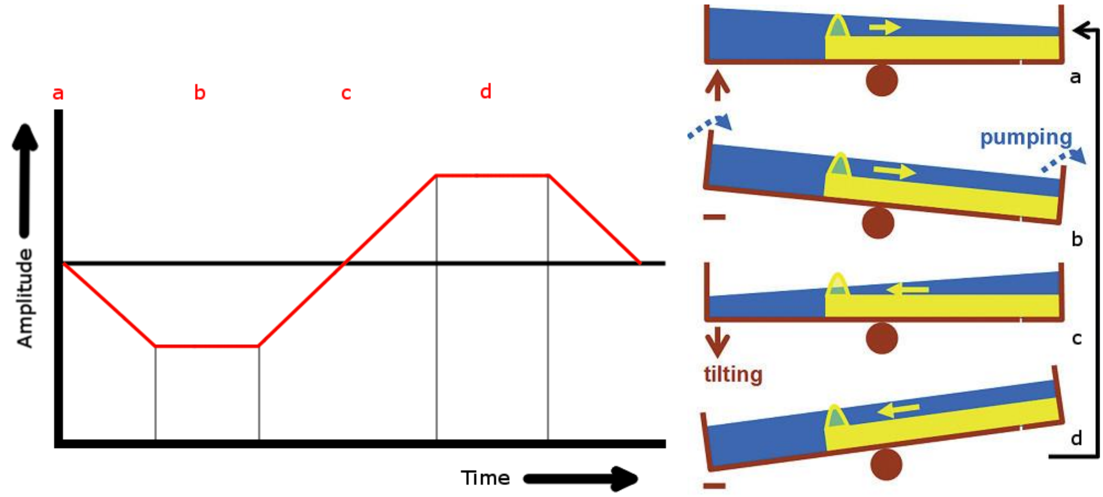

Figure 3.3: Tilting pattern of the flume. Positions a and c show the moment the flume goes through its center. Positions b and d show the flume at its highest and lowest tilt respectively. At b and d, the tilting pauses for a moment. Right schematic from Kleinhans et al. (2014)

For this thesis, it was important that the initial conditions of the estuary in the basin can be changed. External conditions could be changed by changing the tide and water level with the tools of the basin itself. To keep every scenario the same, it was important that not only the sea level, but also the sea volume stayed the same. During one tide, all the water from the sea would try to flow through the channel, so the same scenario would have different results if the sea volume differs between scenarios. There is no tool to keep the sea line constant, but every 20 cm the length from the middle was marked. In the scenarios explained in this report, the standard location of the sea-land boundary was at 1.4 meters from the middle – for both sides of the basin.

Sediment transport can be triggered by putting a perturbation in the water. The perturbation used in this research consists of a dam, being it either a hard or a soft one. The hard dam is an iron sheet of 2 cm wide and 38 cm long. To create some roughness, the sheet was covered by roofing felt. A soft perturbation was made out of a small amount of sediment spread in a line over the middle of the channel, with a length of 40 cm and a width of approximately 5 cm. Since the depth of the channel differed between scenarios, it was not possible to define an actual volume of sediment that makes up the dam. This did not become a problem though, as the dam was always eroded away within a couple of tidal cycles and distributed along the channel. Differences in the amount of sediment that made up the perturbation did not affect that phenomenon, nor the speed at which it happened. It enhanced the formation of new bars a little, as the sediment from the perturbation was directly available.

For this research two kinds of sediment were used. Most experiments were run with light-weight polymers this sediment has a density that is a little higher than water (with a density of 1042 kg/m^3). This meant that the grain size could be larger than sand grains, while still be able to be transported by a channel with a couple of cm depth. Polymers made it possible to create sediment transport, while maintaining normal flow velocities in the basin. The other sediment, normal river sand, is a lot heavier (with a density of 2650 kg/m^3), and this meant that flow velocities in the channel had to be a lot higher to create normal sediment transport (where all particles can move, and not only the smallest, lightest particles). The grainsize distribution is shown in figure 3.4.

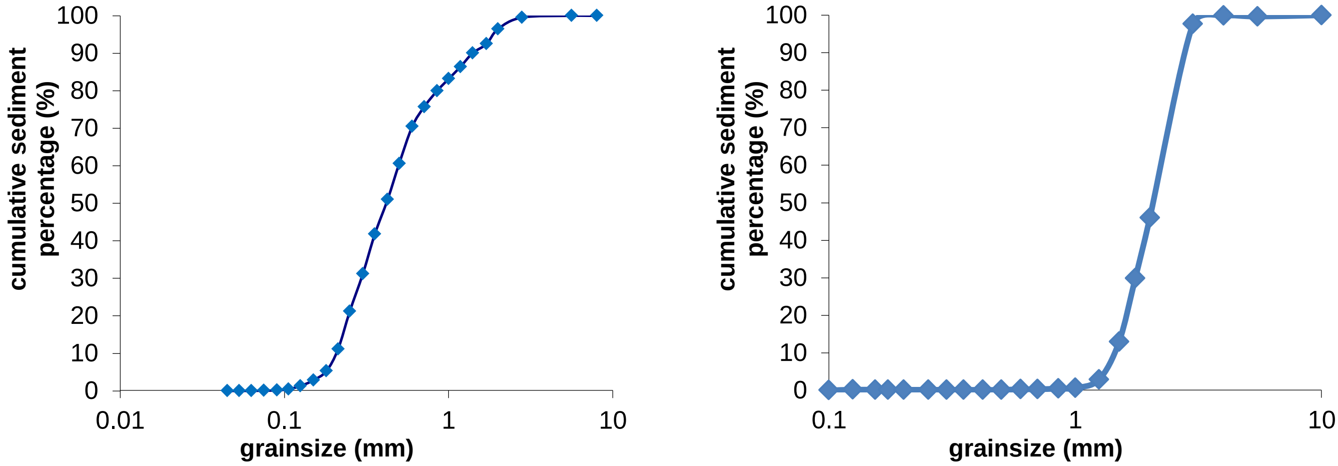

Figure 3.4: Sieve curves for a) river sand. D10= 0.21 mm; D50= 0.42 mm; D90= 1.40 mm, and b) polymer plastic. D10= 1.03 mm; D50= 2.1 mm; D90= 2.8 mm

Scenarios

For every scenario, a different combination of tidal and estuarine conditions was made. Alternations of the same estuarine settings were made with different tidal conditions. Most of the time this meant the tidal amplitudes were made higher or lower, but sometimes the tide was made asymmetric as well. This way results could be compared with each other to see how important the ebb or flood itself were in the formation of tidal channels. Mainly, there are three tidal scenarios: low, medium and high, with respective amplitudes of 2.7 mm, 3.0 mm and 3.3 mm for plastic and 20 mm, 22.5 mm and 25 mm for sand. The medium scenario was most of the times the best, since there would be enough transport but processes would not go too fast in the channel. On the other hand, if processes went too fast in a medium scenario, no high scenario would be done with the same settings, as processes would only go faster that way. An experiment with lower amplitudes would be done to see if amplitude really was the limiting factor in the formation of channels under those circumstances.

Experiments done with an initial narrow channel are experiments where the channel was dug by using the slider with the initial scoop to dig out the sediment. This resulted in a channel with a base depth of 2.1 cm and a width of approximately 15 cm. Additionally the channel could be deepened with a small shovel that increases the depth to 2.7 cm. For these scenarios tidal amplitudes at the boundaries were the medium and high amplitudes. Since the channel is too narrow to place any perturbation, either hard or soft, experiments with perturbations were scarcely done.

Experiments	**Sediment type**	**Initial configuration**
1-8,27,31,32	Polymer plastic	Narrow channel
9-12,15-17,26,28	Polymer plastic	Wide channel, symmetric tide
13,14,18-25,29,30	Polymer plastic	Wide channel, asymmetric tide
33-50	River sand	Wide and narrow channel

Table 1: Experiment characteristics

Experiments with a wide channel had their initial channel widened with a wider shovel after the slider is used to flatten the bed. Since this shovel had a lower depth then the initial channel, it automatically lowered the depth of initial channel. This resulted in a channel with a depth of 1.6 cm and a width of approximately 20 cm. For some experiments this bed was deepened to create a deeper channel, but this was done with a filling knife and therefore not very accurate. The resulting depth of the channel then became 2.2 cm. For the wide experiments low, medium and high amplitudes were used. The high amplitude often was too high for these experiments, resulting in very fast transport that would reach the ends of the basin quite fast, so therefore lower amplitudes were more often used.

Experiments with asymmetric tides were prepared in the same way as the experiments with symmetric tides. The only difference was that for these experiments the up- and down amplitude of the basin differed. The asymmetry experiments were not exactly regarded as a separate set though. This explains the higher amount of experiments with a perturbation. When it was found out how effective a soft perturbation was in the development of channels, these perturbations were more often used in the later experiments. Since most asymmetric experiments came after this discovery, the amount of asymmetric experiments with a perturbation is slightly larger.

For the experiments with sand no distinction was made between symmetric and asymmetric experiments, as the polymer experiments already showed that no different patterns formed when the tides were asymmetric. Table 4 shows the initial conditions of the experiments done in sand. After experiment 38 the bed of the estuary was sieved. Experiments after number 38 have a lot less coarse grains on the bottom, so bed armoring did not stop the transport of sediment in later experiments. This possibly caused the higher amount of experiments with sediment movement in later sand experiments.

Measurement methods

Besides controlling the movement of the basin, the tilting device could also be used to automatically send triggers to make photographs of the basin. Every adjustable number of tidal cycles the device would send this trigger to capture the situation. For the experiments with plastic sediment every 4 cycles a picture was made when the flume tilted through its mean level. For sand experiments the number of cycles per picture was increased to 8. Capturing the situation was done with three Canon™ cameras that each made a photo of one section of the basin. Since photographs have a certain curvature, the photos were first flattened out, after which they were combined to one displaying the whole basin.

The height of the bed and bars was measured with a so-called Zsnapper. This device measured the height of a certain surface by projecting certain light patterns on the basin and measuring the reflection of that light. The data the snapper gathered existed of point clouds consisting of points with an x, y and z location. These points could be used to create a height model of the basin with the help of a Matlab code. Since light reflects poorly on a water surface, these heights could only be measured at the end of an experiment, when the whole system was drained. To find the water depth during the experiments the pictures from the cameras were used. After a scenario, the photographs made by the three cameras are saved and analyzed. The water in the basin is colored blue to make it better visible on the photos, and this has the added benefit that the depth of channels could be related to the color depth intensity. This way cross-sectional areas of the channel could also be made, by coupling the blue scale with its location on the basin. By evaluation of the changing of these cross-sections the formation and disappearance of bars and channels were studied, including width to depth ratios and other characteristics of the channel, like the volume of the initial bar at the start of an experiment.

In some experiments, a separate camera was used, which zoomed in on a specific area to make a movie. Since the lightweight sediment had a density that does not differ much from the water density, several particles kept floating on the surface due to surface tension. These floating particles could be tracked with the camera, and from it the flow velocity could be measured. This was done by measuring the time it took for a particle to travel a certain distance during several phases of the tidal cycle (but mainly the phases with the highest flow velocities). For the experiments that did not use the high-res camera for particle tracking, the estimated flow velocity was calculated with the following formula:

*MSL at inlet (m) * tilt from MSL (m) * tilt speed (mm/s) / 3 * 1.000.000 = estimate flow velocity (m/s)* eq 3

This formula does not give the exact flow velocities, but when compared to the measured values they do seem to be reasonable.

Exp.	Width (cm)	Depth (cm)	Amp up (mm)	Amp down (mm)	Delay (sec)	Pert	Purpose
1	15	2.1	2.9	2.9	3	n	Start movement
2	15	2.1	3	3	3	n	Start movement
3	15	2.1	3.3	3.3	3	h	Perturbation effect
4	15	2.7	3.3	3.3	3	n	Depth effect
5	15	2.7	3.3	3.3	3	h	Depth + Perturbation
6	15	2.7	3.3	3	3	n	Asymmetry effect
7	15	2.7	3	3.3	3	n	Control exp.
8	15	2.7	3.3	3.3	3	s	Effect soft pert.
9	20	1.6	3.3	3.3	3	n	Control exp.
10	20	1.6	2.7	2.7	3	n	Low amplitude
11	20	1.6	3	3	3	h	Perturbation effects
12	20	2.2	3	3	3	n	Width and depth
13	20,0	1.6	2,7	3,0	3,0	n	Asymmetry effects
14	20,0	1.6	3,0	3,3	3,0	n	Higher amplitude
15	20	1.6	3	3	3	h	Skewed pert. effects
16	20	2.2	3	3	3	n	Depth effects
17	20	1.6	2.7	2.7	3	?	Pre-meandering
18	20.0	1.6	2.7	3.0	3.0	s	Soft perturbation
19	20.0	1.6	2.7	3.0	3.0	h	Hard perturbation
20	20.0	1.6	2.7	3.0	3.0	s	Soft perturbation
21	20.0	1.6	3.0	3.3	3.0	s	Control exp.
22	20.0	1.6	3.0	3.3	3.0	h	Control exp.
23	20.0	2.2	3.0	3.3	3.0	s	Higher depth
24	20.0	1.6	3.0	3.3	3.0	s	Soft perturbation
25	20.0	1.6	3.0	3.3	3.0	s	Higher amplitude
26	20	1.6	3.0	3.0	3.0	s	Soft pert. effects
27	15	2.7	3.3	3.0	3.0	n	Asymmetry effect
28	20	2.2	3.0	3.0	3.0	n	Depth effects
29	20.0	1.6	2.7	3.0	3.0	s	Soft pert.
30	20.0	1.6	2.7	3.3	3.0	s	Increased amp difference
31	15	2.7	3.0	3.3	3.0	n	Control exp.
32	15	2.1	3.3	3.3	3.0	s	Soft pert. in shallow ch.

Table 3: Initial characteristics of the light-weight plastic sediment experiments. Amp up and amp down are the amplitudes of the tilting at the location of the control panel. Pert is the kind of perturbation used in the experiments, where [n] is no perturbation, [s] is a soft perturbation and [h] is a hard perturbation. *Continued on next page.* *[?] is the experiment where an initial meandering channel was created. The blue experiments are the experiments with an initially narrow initial channel. The orange experiments are the symmetric, initially deep experiments and the green experiments are the asymmetric, initially deep experiments.*

Exp.	Width (cm)	Depth (cm)	Amp up (mm)	Amp down (mm)	Delay (sec)	Pert	Purpose
33	20	1.5	20	20	4	s	Movement testing
34	20	1.5	25	25	4	s	Movement testing
35	20*	1.5	22.5	22.5	4	2	Alternate movement testing
36	22.3	1.5	15	15	4	l	Alternate movement testing
37	22.3	1.5	22.5	22.5	4	l	Alternate movement testing
38	22.3	1.5	30	30	4	l	Alternate movement testing
39	20	1.5	15	15	4	s	Movement testing
40	8	1.5	22.5	22.5	4	n	Sieved sediment
41	8	1.5	20	20	4	n	Amplitude effects
42	20	1.5	22.5	22.5	4	n	Amplitude, width effects
43	20	1.5	25	25	4	n	Amplitude effects
44	20	1.5	25	25	4	s	Soft perturbation
45	20	1.5	25	25	4	h	Hard perturbation
46	20	2.6	22.5	22.5	4	n	Deep channel
47	20	1.5	22.5	22.5	4	n	Control
48	20	1.5	25	25	4	s	Control
49	20	1.5	22.5	22.5	4	n	Control
50	20	1.5	27.5	27.5	4	n	Control

Table 4: Initial characteristics of river sand sediment experiments. Amp up and amp down are the amplitudes of the tilting at the location of the control panel. Pert is the kind of perturbation used in the experiments, where [n] is no perturbation, [s] is a soft perturbation and [h] is a hard perturbation. [2] is the experiment with 2 initial channels.

4. Results

Description Plastic Experiment 8

This experiment was done with the polymer plastic. The tide was symmetric in this experiment, with high and low water amplitudes of 3.3 mm and a water change velocity of 50 mm per minute. Delay during high water and low water was 3 seconds, so one tidal cycle takes 14 seconds. The initial setup of the experiment was a channel with a width of ~10 cm and a depth of 2.7 cm. Also, a 40 cm long, 2 cm wide bar was built in the middle of the channel, parallel to the flow direction in the channel (this perturbation was already gone after 5 cycles and thus is not visible on the picture).

Figure 4.6 shows the development in the basin after the start of the experiment. The initial bar diffused over the width of the initial channel in the first 200 cycles, which triggered widening by bank erosion on both sides. This shallower part of the channel tends to be incised by the channel coming from the left end of the basin. At the same time, the channel at the right side of the channel widens, albeit not as much as the part with the perturbation. This widening of the channel at the free-end continues until the end of the experiment. However, at the left side of the perturbation, the channel deepens somewhat. At this moment the middle of the estuary existed of a bar that was incised by the main channels from both sides through the middle, while two smaller, disjointed channels encircled the bar on both sides. These channels were not fully connected, and they widened the channel at this location. The process of widening of the channel continued for the whole duration of the experiment. This widening of the channel created space for more bars and channels to form. Channels slowly started to develop further. There was only one main channel in the beginning of the experiment, but the number of developed channels slowly increased after this moment. Together with the increase of channels, the distinction of different tidal channels also started. The end of a these channels often deposited a mouth bar that had its steep edge on the side the dominant flow was directed to. Furthermore, the system as a whole changed its tidal dominance multiple times during the experiment. Ebb and flood took turns in dominating the largest channels, a process that started slowly, but happened more often when bars and channels became better developed. At cycle 400 the incisions at both sides of the of the bar slightly curved to the right, and a third channel was formed in between them. Only this middle channel connected both ends of the basin. The other two channels just came up to an end. This structure continued to exist, only the middle channel took over from the right-end channel and became the main flood channel. The left end channel remained ebb-tidal. Both channels continued to grow, protruding further in the bar, eventually dominating the whole system.

Dominance of the system alternated between the ebb- and flood tidal channel. In this case, dominance is defined as being the largest channel. At the cycle 800, the upper side channel was dominant, as it was larger and a lot deeper in the middle of the widening, while the ebb-channel shallowed early. This dominance of the flood channel continued, and the ebb channel more or less disappeared. This clear dominance started to disappear at cycle 1400 though. At this point, the ebb channel had a small bifurcation at the upward side of the system while the flood channel bifurcated in the direction of the downward side of the system (at the beginning of the experiment, this was the other way around). The middle channel, which acted as the main channel of the system, did not have any tidal dominance at that point though. This stage did not exist long though, as can be seen in cycle 1600. There it can be seen that the middle channel was taken over by the ebb tidal flow to the right, and the flood tide had created a new barb at the upward side of the system. The ebb-tidal system also developed the channel at the ruler-side of the channel further, and this channel was also eroding the bank of the river. The channel coursed almost straight into the land, suddenly coming to a halt at the end, where it had to make a sharp bend to connect back to the main channel. This bend did not make for a good connection with the main channel though, so the water flowing into the channel was pushed up, since it could not flow further through the channel. This made the water flow over the bar that divided this channel from the flood tidal channel that was forming in the meantime. The further development of this flood channel at the same time terminated the formation of th ebb tidal channel, as in cycle 1800 it can be seen that the flood-tidal channel cut of the opening of the channel. The ebb-tidal channel did not cease to exist though, it only ceased to develop. At this point the dominance of the ebb tide became vague, as the main ebb tidal channel also became less ebb-dominated. This could be seen by the relocation of the mouth bar that formed at the bend of the ebb channel, that bended itself more into the direction of the flood flow. Therefore the channel seemed to be used equally by both ebb and flood. The channel was still dominated by the ebb tide, but flood slowly became more dominant too, as can be seen at the threshold that forms at the left end of the channel. Flood became even more dominant, and this is best seen in the 2000th cycle, where the directionality of the channel changed to the flood tide. At the same time the abandoned upward side ebb channel had developed at the cost of the previous main flood channel. This channel now seemed to be abandoned. Dominance of the largest channel had changed two times in 2000 cycles, though.

The main channel did not exist for long after that all, as at the 2400th cycle it had almost completely disappeared, save for a small part that became ebb-tidal. This seemed to have to do with bar formation of the other flood-tidal channel. This channel, visible in cycle 2200 as being smaller yet deeper at the point where the estuary widened on the right side, deposited its sediment near the opening to the ‘main’ flood tidal channel, blocking it from further inflow. Since the ebb flow was still active in this channel, its dominance in the channel increased, but it was not large enough to stop the flood tidal channel from pushing it back. This flood channel started to silt at cycle 2400 though. There were two ebb-tidal channels at that moment, and those were both better developed than the flood-channel, which did not protrude further than half the widening of the channel. All those tidal channels ceased to exist though, and a period without developed tidal channels began. There was one weakly developed flood-tidal channel at the upward side of the channel and an ebb-tidal channel at the downward side, but those were small and shallow. Only straight bars parallel to the channel were formed. This situation often was the end situation of other experiments, but this time the system escaped this system after 400 cycles, as at that moment, in the 3000th cycle, a new flood-tidal channel formed. At the same time, an inlet for an ebb-tidal channel was formed, but the channel that should follow this inlet cannot be seen. The channels that were formed were not as deep as the ones that formed early in the experiment, yet they still were well defined. It was clear where there was a water flow, and where sediment was deposited, in contrast to the phase in the 2600th cycle. On the other hand, most channels at this stage of development were not clear ebb- or flood tidal, and the same is true for the next and last displayed cycle. Channels are better visible in this stage than in previous stages, but channels still did not have a distinct function, and seemed to be used equally by both tides. At this point the experiment was stopped, as not much changes were going on, and the estuary reached almost one of the sides of the basin.

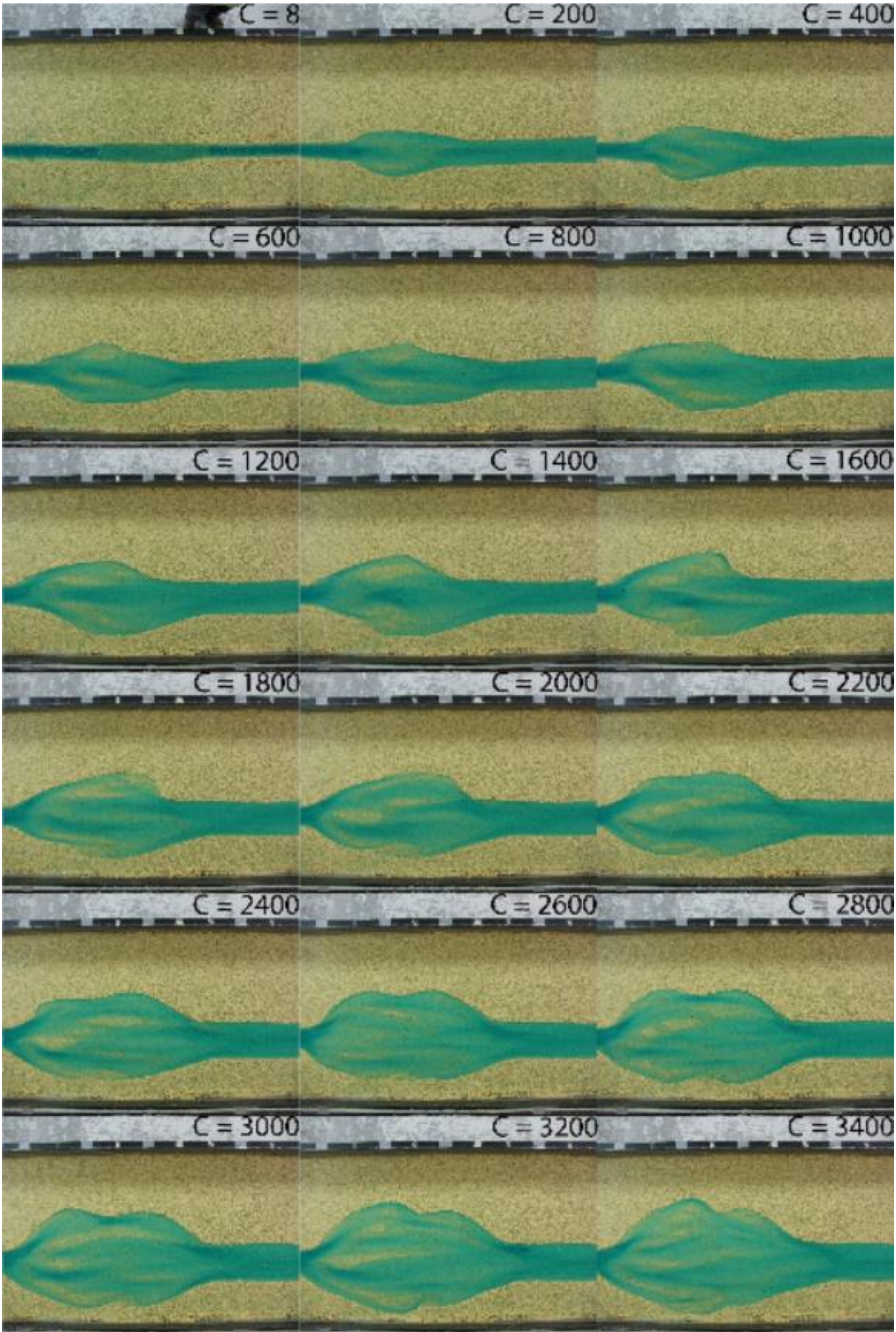

Figure 4.1: Development of polymer experiment 8

Description of Sand Experiment 43

This experiment was done in sand. Since the first tidal experiments with sand resulted in bottom armoring, this was one of the first experiments with a channel with sieved sand. The initial channel had a width of 20 cm and a depth of 1.6 cm. The tide was symmetric with an amplitude of 22.5 mm and a tilting velocity of 60 mm min^{-1}. Delay during high and low water was 4 seconds, so a total tidal cycle takes 98 seconds. Figure 4.2 shows the development of the estuary, showing every 80^{th} cycle.

In contrast to the plastic experiment, no initial perturbation was applied in the initial channel. This did not prevent the system from creating one though. On its own, the system formed a bar in the middle of the channel, and similar to the plastic experiment it created a channel that tried to cut through the middle of the bar while near the banks of the estuary channels tried to encircle the bar. These channels were not fully connected with the main inflowing channels of the estuary though. Contrary to the plastic experiments, the bar in the channel did not remain fixed on one position. Over the whole length of the estuary the channel started to widen. At the same time some bars, mostly connected with each other, started to form everywhere in the middle of the channel. On most locations the bar was disconnected from the bank with a small channel though. For the rest of the experiment, this main bar in the middle of the channel was reworked by the tides. Please note though, that in contrast to the plastic experiment no dominant tide was visible in the experiment. Every channel had its own main flow direction, but for the whole system it was not clear whether ebb or flood was more dominant. What could be seen though, is that in the beginning of the experiment the upper side of the channel was ebb-dominated. For the downward side it was not really clear if flood was more important. However, there seemed to be more flood-directed channels in the downward part. Later in the experiment this all disappeared. The downward channels became less active, while the upper channels started to discharge both tides. As such, no dominant features were really visible.

The first photo was clear, showing a straight shallow channel. The next cycle is already a lot different though. At the left end of the estuary only a little relocation of sediment was seen, with a small lobe of sand at the downward side of the channel. The opposite was true for the right end of the basin. There the lobe of sand was really formed by a channel. Another channel at the downward side of the estuary had deepened itself below the initial bottom depth. This channel was around 50 cm long and flowed out on a bar in the middle of the estuary that was encircled by two channels at both sides of the estuary. These two estuaries were not as developed as the channel at the mouth of the estuary, but it was clear that these channels were the main water transporting channels in this part of the estuary, and this combination of one and two channels could be the start of a forking system.

The next step did show something else though. What first looked like a system with one-and-two channels had become a system where two channels encircle each other, as one channel comes from the left end and flows in the direction of the upper side of the estuary while another channel comes from the right end of the basin and flows to the downward side of the estuary. Both channels became more shallow in the direction they are flowing, creating a clear bar in the middle of the estuary, between the two channels. Both channels also connected with the two channels at the sides of the middle of the estuary, where one large bar was located. The channel coming from the right end was located at the downward side of the estuary, slowly widening itself and becoming shallower, forming a lobe that had its end at 40 cm from the end of the estuary. This lobe also had a counter-channel, but this channel ended at the main bar in the middle.

Most of these described channels became less clear in the next step. The flanking channels at the right end of the basin were gone, and the large bar in the middle was extended to this end. The main channel at the downward side still existed though, but its curves became better developed. The counter-channel was shorter than in the previous time step though and it had a very irregular depth. The upper side channel also had become narrower and was not as long as it was in earlier cycles. This did not change in the next time step. Only the counter-channel at the left end developed a more regular depth (possibly due to armoring), while the main downward side channel formed all kinds of ripples. At the same time something that could be classified as a chute bar in the middle of the large bar formed. In the 328th cycle this chute was a little messy, because it was built from two channels coming from both ends, but ultimately the channel distinguished itself, and in the 488th cycle this chute clearly flowed from the left end, only to vanish again in the 568th cycle.

This closing of the chute could be connected with the reopening of the main upper side channel, since this channel at the right end of the basin deepened again. In the 648th cycle this channel even grew more, as it both widened and deepened at this side of the basin. At the bottom the formation of small bedforms could also be seen. Meanwhile a flanking pattern formed in the downward channel. It was not very clear because the downward channel had an abundance of ripples at the bottom, but in the middle of the channel a small bar was formed that was flanked by the left end channel on the downward side, and the right end channel on the upper side. This bar remained for the rest of the experiment, but later in the experiment – starting already at the 648th cycle but becoming clearer and multiple in the 968th cycle – it became larger.

In the 648th cycle the flanking chutes near the left end had nearly disappeared. Instead the channel coming from the left end flowed into the upper side channel. It did not flow straight though, as the bedforms at the bottom here indicated a more sinuous flow. In the next step the system near the mouth on the left side was flanking again in the active channel, but it was not clear whether this was caused by the bedforms or some other factor. It seemed that the upper side channel was both used by ebb- and flood-flow, as on both ends the channel had formed a flanking system with a channel coming from sea and one from the land. Both the flanks coming from the sea had their location at the downward side of the system. Besides the two bars at the end of the channel, there were also two small bars in the channel itself. These bars were made of fine sand encircled by channels. Of these two channels the main channel had a bottom armoring of fine stones while the smaller channel had sand as its bottom sediment. These bars existed only for one time step, after which the bars evened out while the small channels filled up. There was still water flowing here though, and this was clearly visible by the small chutes on the bar. In between the two bars there was sediment movement too, which can be seen by the small scour that was formed. In the 808th cycle this scour had disappeared again, but the chute from the left end was protruding further from the sea. This chute was flanked by a new chute on the downward side of this one, starting at the location of the old small bar. The protruding chute disappeared at the next time step, and the incision created by the counteracting chute still remained, eventually resulting in a scour hole.

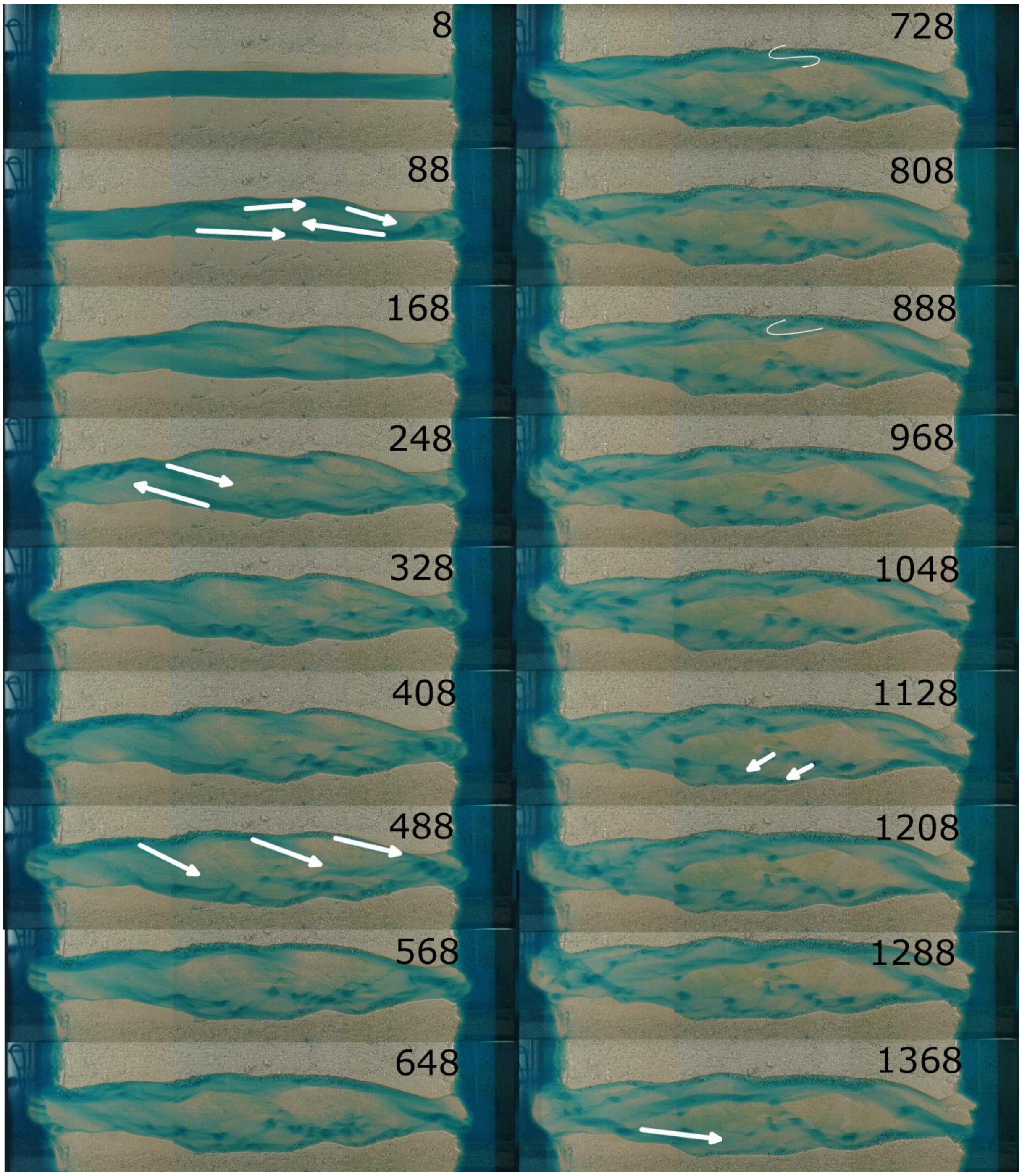

Figure 4.2: Development of experiment 43. Arrows show channel directions, lines show bar patterns.

By this time the sediment mobility had reduced to the threshold for general motion. As the protruding chute at the left end retracted, it left only a small channel, and the rest of the channel started forming ripples. After that the morphology became rather static. The upper side channel had become a lot shorter due to the protruding chute, and the remainder flowed into the better developed counteracting chute. Only the flanking channels at the right end of the estuary remained, but even these flanks disappeared near the end of the experiment. For the rest of the experiment there did not change much in the cycles 1048 to 1208. At the 1288th cycle there started to be some sediment movement again though: First, the flanking channels at the right end of the basin disappeared as the channel from the sea started to take over. At the same time the upper side channel developed its left end again and the channel there became clearer and formed a nice lobe at its end. Overall, it seemed that flow from the right end started to take over, as all large deposits were directed at the left end. This changed again at the 1368th cycle. At that moment the downward side channel lost half of its 'scour-ripples' and a real channel started to form again, this time in the direction of the upper side. Shortly after this the experiment was stopped, as at the time it was believed that the channel armoring at the borders of the estuary would stop the further development of structures in the estuary. In retrospect this is a pity, because this experiment showed one of the few cases where a channel would reactive itself after being dominated by scour holes.

Comparison of the experiments with polymer plastics

For this research two types of sediment were used, of which the plastic granules were one type. Boundary conditions between these sediments were quite different, and therefore will be treated differently. This chapter will describe the results of the experiments done with the plastic sediment. Each type of experiment will be treated on its own, where the experiments are classified as narrow channel, wide channel with symmetric tides and wide channel with asymmetric tides.

Experiments with a narrow initial channel

Experiments that started with a narrow channel are listed in table 1. Also, figures 4.3, 4.4 and 4.6 show the 3200th cycle of each experiment, or the last cycle if the experiment ended earlier. Most experiments with a narrow initial channel also had their channel deepened, because transport was quite low in a narrow, shallow channel. For the same reason no tidal amplitude of 2.7 mm was used, as that amplitude was too low for sediment movement.

There are three processes that could happen when an experiment is initiated, of which the first process is nothing. This can be seen in the first couple of experiments. Examples are the first two experiments that show that a small initial channel limits the formation of bar patterns (figure 4.3). Amplitudes in the experiments were 3.0 mm, and nothing happened even after a few hundred cycles. Both experiments were more or less the same, only the initial channel in the second experiment was moved towards the water inlets of the basin. This was done to prevent that the curvature of the flow to reach the channel would affect the formation of patterns in the estuary. It could be seen that the location of the channel did not alter the formation of bars, and after experiment 2 the initial channel was always located more to the downward side. The following experiments did not improve the formation of bars though. Both the hard perturbation in experiment 3 and the deepened channel in experiment 4 did not affect the formation of patterns. The channel in experiment 4 did go to a new equilibrium though, where the channel both widened and became more shallow, but still this did not induce the formation of bars or channels. Sediment was transported to reach this new phase, but not by means of bars and channels. Experiment 27 also resulted in minimal channel development, with only a little widening of the channel at the right side of the basin.

The second thing that could happen in an experiment, is the formation of simple channels in the experiment. These channels remain small, and never develop further into self-perturbing systems. Sediment mobility in these experiments is large enough to initially relocate the sediment. However, when the main channels have been formed, flow only concentrates itself there and further development ceases. An example of such an experiment was experiment 5. In this experiment the combination of a deepened channel and a hard perturbation led to the irregular widening of the channel. It was clear that one tidal direction caused more motion in this process, and no well-developed channels formed. There still were some patterns visible however. The same development was visible in experiments 6 and 31. Experiment 6 did not end up in something spectacular, only a widening of the channel at the free end of the basin, and experiment 31 developed some deeper parts as well as bars, but without channel systems.

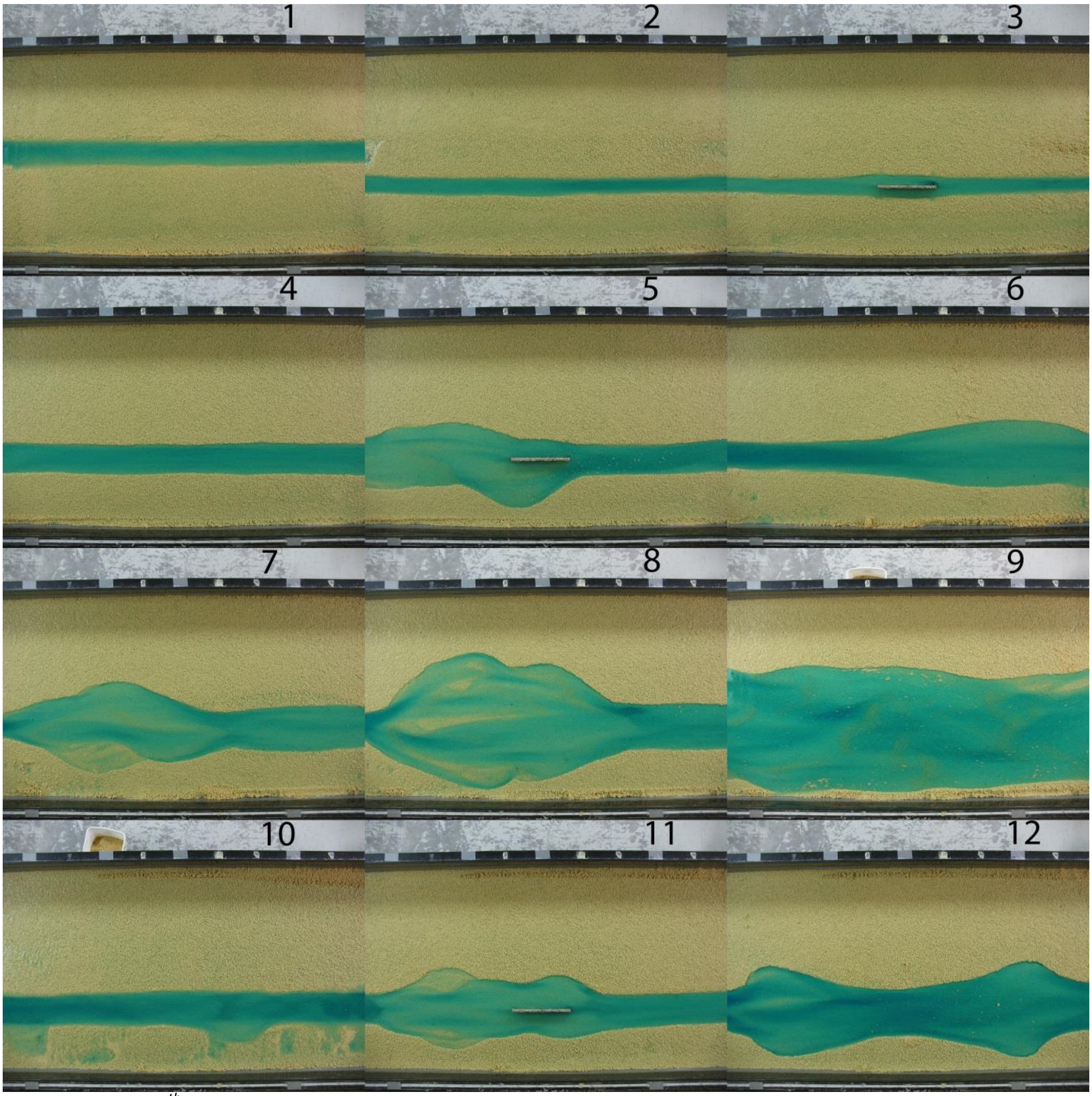

Figure 4.3: 3200th of experiments 1-12

The last, and most preferred outcome of an experiment was the formation of well-developed, self-perturbing ebb- and flood tidal channel pairs. Experiment 7 showed the first bar and channel pattern development. If looked at carefully, the channel coming from the left end of the basin slightly curved to make room for the channel coming from the middle. At the same time the channel coming from the right end bifurcated at the other side of the wide part. From this channel the main branch slowly shallowed while the small branch flowed into the main channel at the wider part of the estuary. The channels were not developed enough to classify those as flanking channels, but it still implies that it was possible to get the right patterns in the basin. Experiment 8 was good example of these patterns. This experiment showed multiple channels, deepening in different directions and building bars. This experiment is already described with much detail in the previous chapter though.

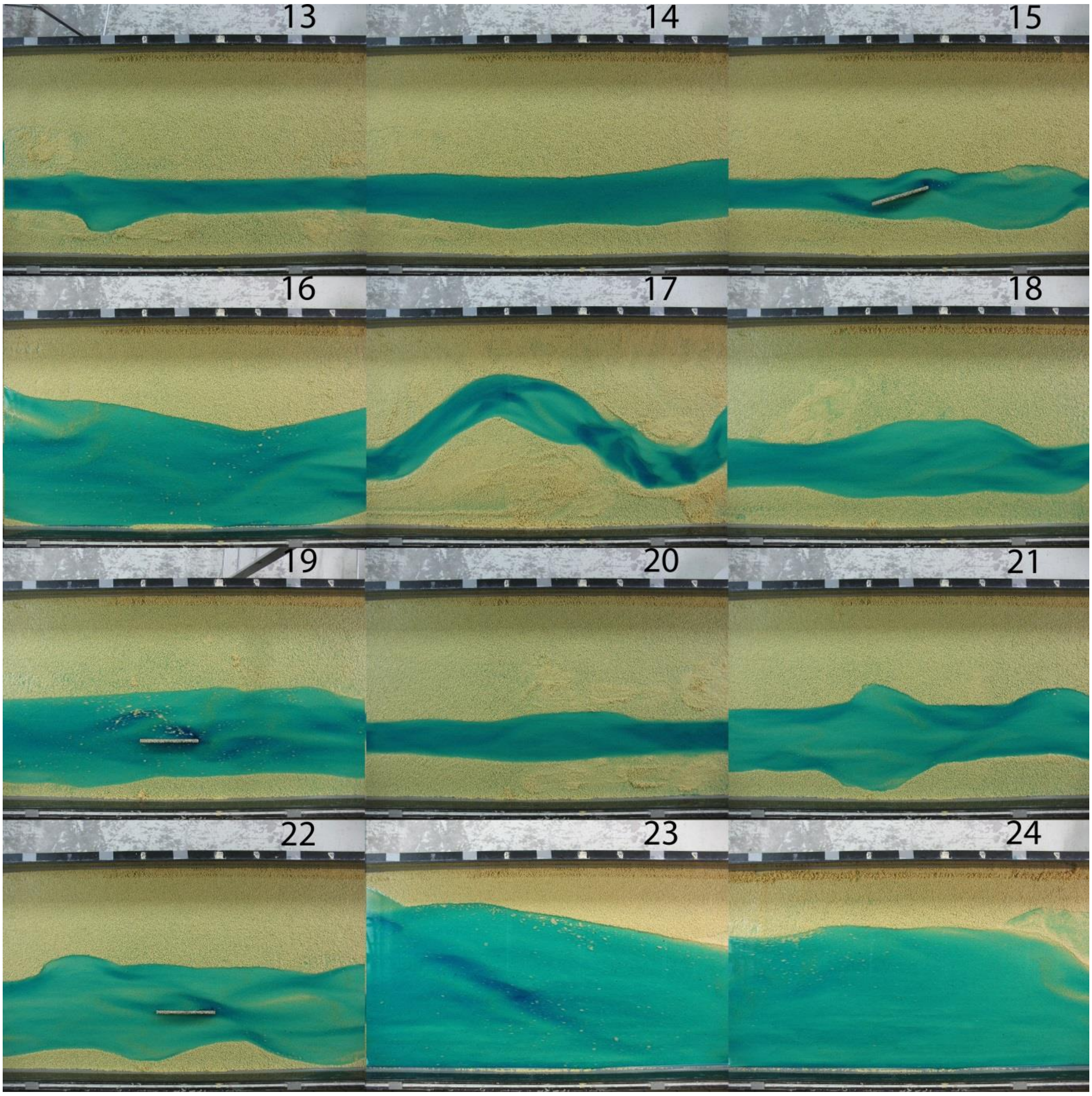

Figure 4.4: Experiments 13-24

Wide channel with symmetric tides.

The experiments done with a wide channel and symmetric tides are shown in table 2. Overall, experiments with a wider channel had more mobile sediment than the experiments with a narrow initial channel. The experiments with a shallow channel had a lower initial depth than the initial depth of shallow narrow channels, which caused an increase in bottom friction. Channel deepening already started at the beginning of the experiments though, so the initial depth did not affect channel development. The transition between movement and no movement is very narrow, as can be seen in experiments 9 and 10. The first experiment done with a wide channel also had an amplitude of 3.3 mm. Contrary to the narrow channel experiments, the channel in experiment 9 expanded very rapidly and had to be stopped already, at its 800th cycle. Transport clearly went too fast in this experiment: there are some deeper parts in the channel, but no clear formation of geomorphology had happened, and basically during one tide the bed of the whole channel came into motion. Experiments 16 and 28 performed the same, with fast widening of the channel without developed channels. Experiment 10, with lower amplitude, showed opposite results: there were some deeper and shallower parts in the channel here, but still no real formation of channels could be seen. Sediment transport was low in this experiment, as even the banks of the estuary could not be eroded. These first experiments clearly showed the importance of the tidal amplitude on the formation of channels and bars. No experiments had been done with an amplitude of 3.0 mm without extra depth or dam, but there were some asymmetric experiments that had been done with 3.0 mm as one of the amplitudes. These experiments are described in the next paragraph.

Figure 4.5: Forking channel pairs at both ends of experiment 12.

Examples of experiments with a wide channel were experiments 11 and 12. Both experiments were done with a tidal amplitude of 3.0 mm. Experiment 11 had a hard dam placed in the middle of the estuary though, and experiment 12 had its channel deepened to a depth of 2.2 cm. Both experiments showed a more regulated change in the development of the estuary. Experiment 11 did display some short channels. Furthermore processes of erosion and deposition had been going on at the banks of the estuary, where bars had developed to new banks. The opposite was true in experiment 15. The skewed perturbation did not have much effect on the formation of bars and channels in the estuary, and channels remained underdeveloped except for the scour near the dam itself. The experiment also showed that even if the tidal amplitudes were the same, the system could develop more to one a side of the basin. Why this happened is not clear, but the effect on the formation of tidal channels seems small. A better development of channels and bars can be seen in experiment 12. Here, deposition of sediment had only taken place at 60 cm from the middle on both ends of the estuary. In the middle of the estuary the channel still widened and deepened, but it was not as wide as other places in the estuary, resulting in a shape that resembled a pair of glasses. In the wider parts of the estuary, formation of channels could be seen. At the tilting end of the basin, the channels in the wider part resembled a forking channel pair (figure 4.5). Two channels coming from the sea ‘embraced’ one channel coming from the land. This pattern was, albeit less clear, also visible on the other side of the estuary. On this side the channel had more curvature though, which indicates that this was not the final form of the estuary. It did look like the flow to the left was more important in this experiment, as could be seen at the deeper and better developed channels at the left side of the basin, even though the tides were more or less equal to each other.

Only the last experiment, 32, and experiment 26 formed clear channels. Both experiments had some channels that curved and flanked, but at the same time both experiments did not show any clear relations between those channels. The channels were formed, but they did not form one system where ebb and flood each use their own channels.

Wide channel with asymmetric tides

For most asymmetric experiments, the channel at the end of the experiment did not differ a lot from the experiments with a symmetric tide. For example, experiments 13 and 14 formed a channel that was asymmetric in both directions of the basin. At the same time asymmetry in the estuary was also seen in other experiments, like experiment 15, even though it had a symmetric tide. The resulting channel did not develop any ebb- and flood tidal channels though. The same was true for experiment 20. It seemed that in a asymmetric experiment only one of the tides was determinative for the development of the estuary. This meant that when the two amplitudes differ, only one would form the estuary as it would in a symmetric experiment, and the other tide would just follow with that. In experiment 20, the 2.7 mm ebb amplitude defines the form the estuary would take (which is low movement and almost no morphology, just like the symmetric 2.7 mm experiments) and even though the flood tide was higher, it was not enough to induce more transport in the estuary.

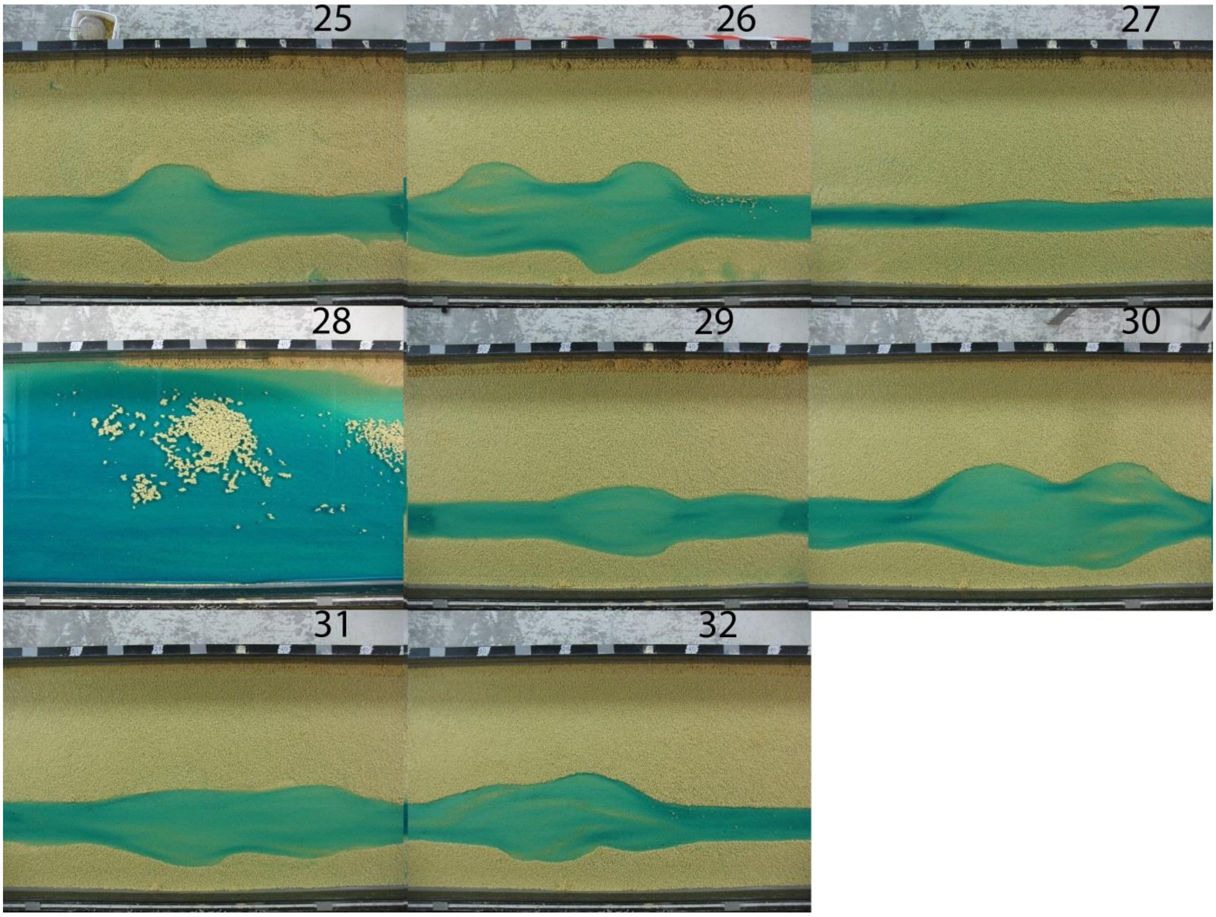

Figure 4.6: Experiments 25-32

Experiment 18 developed a quite small estuary that still had a few short bifurcating channels, and experiment 19 developed even more channels. The widening in this experiment went too fast though, so the formation of the channels did not happen very naturally. Other examples of this type of channel development are experiments 21, 22 and 30. In experiment 21 the estuary looked like something a 3.0 mm tide could form would it be a symmetric experiment. In this case the 3.3 mm flood tide again was not enough to start very fast transport and flood the basin, something that could be seen in 3.3 mm symmetric tidal experiments. Experiment 21 developed some nice channels though, but no real tidal channels. The channels looked like they could make part of a forking pattern, but since there was no middle channel they did not have any channel to fork around. Experiment 22 looked like experiment 21, but now the hard perturbation made the channel locations in the estuary only more random.

Asymmetric tides also could not prevent the problems that arose in symmetric experiments. For example, experiments 23 and 24 had excessive flooding again, and experiment 25 and 27 had no motion at all.

Comparison of the experiments with sand (figure 4.7 and 4.8)

The first three experiments done with sand, numbers 33, 34 and 35 still had a lot of coarse grains on the bed. That, and the fact new ideal amplitudes had to be found for the sand, made the experiments immovable. Experiment 35 did show some ebb and flood dominance in its channels though: the wall-side channel had a blocking delta at the right side and the free-side channel had a delta at the left side, but this had more to do with the wrong experimental composition than with tide-dominance.

For the next three experiments, 36 to 38, something different was tried. Two channels were built parallel to each other, with a thin dam that extended over the whole basin. Since the dam was easily erode away, there was enough sediment for the water to relocate, and the first patterns could be found, with a small ebb-dominant flanking system at the left of experiment 36. Experiment 37 shows a semi flanking system at the left side and another underdeveloped flanking system more to the right. Experiment 38 shows two channels, but it is clear that the free-side channel has different chutes shooting over the bar in the middle of the channel. Bed armoring is still a problem here though.

As soon as the particles with a diameter larger than 2 mm were removed from the system by sieving, sediment really came in motion. Experiments 39 and 41 showed the ripples that could be formed when the large particles were removed. This formation of ripples seems to prevent the formation of channels – or the ripples form when no channels can be formed. No (tidal) channels could be seen in these experiments though. Experiment 40, on the other hand, has a lot of channels, even some that could be classified as tidal ones. For example, in the utmost left part of the picture two channels that flank each other, slowly shoaling, can be seen. Other channels also look like they are mainly used by one tide, but they do not make part of a larger system.

All experiments performed after number 41 developed estuaries that looked the same. Experiment 42 developed a flanking system, but it was not clear for all channels which tide was the most dominant. Since both main channels were fully armored and thus not moving a lot, the flanking systems that flowed directly out of these channels seemed to be dominated by the flow from these channels. That meant flow to the right for the downward channel and flow to the left for the upward channel. The other channels were remnants of previously dominant channels, with the main hole in the middle of the estuary a remnant of a left-flowing channel. Experiment 43 would be described in detail in the next paragraph. Experiment 44 had less distinct channels in the picture, but since the estuary had not reached an equilibrium it probably just was a stage that would change again. It seemed as if the deep ripples are influencing the formation of channels, but in this experiment the ripples were continually moving, never fixing the locations of the channels.

Experiment 45 was the first experiment in sand with a hard perturbation, but this did not alter the development of channels much, contrary to the experiments done with polymer plastic. This experiment developed some kind of forking system on the left side of the basin. One channel from the left was embraced by two channels from the right. The free-side channel was better developed in this case, but a wall-side channel was still present, maybe due to the hard perturbation that forced the bifurcation of flow from the right (on the left this is not needed, as flow from the main channel just fanned out after the channel has completely shoaled).

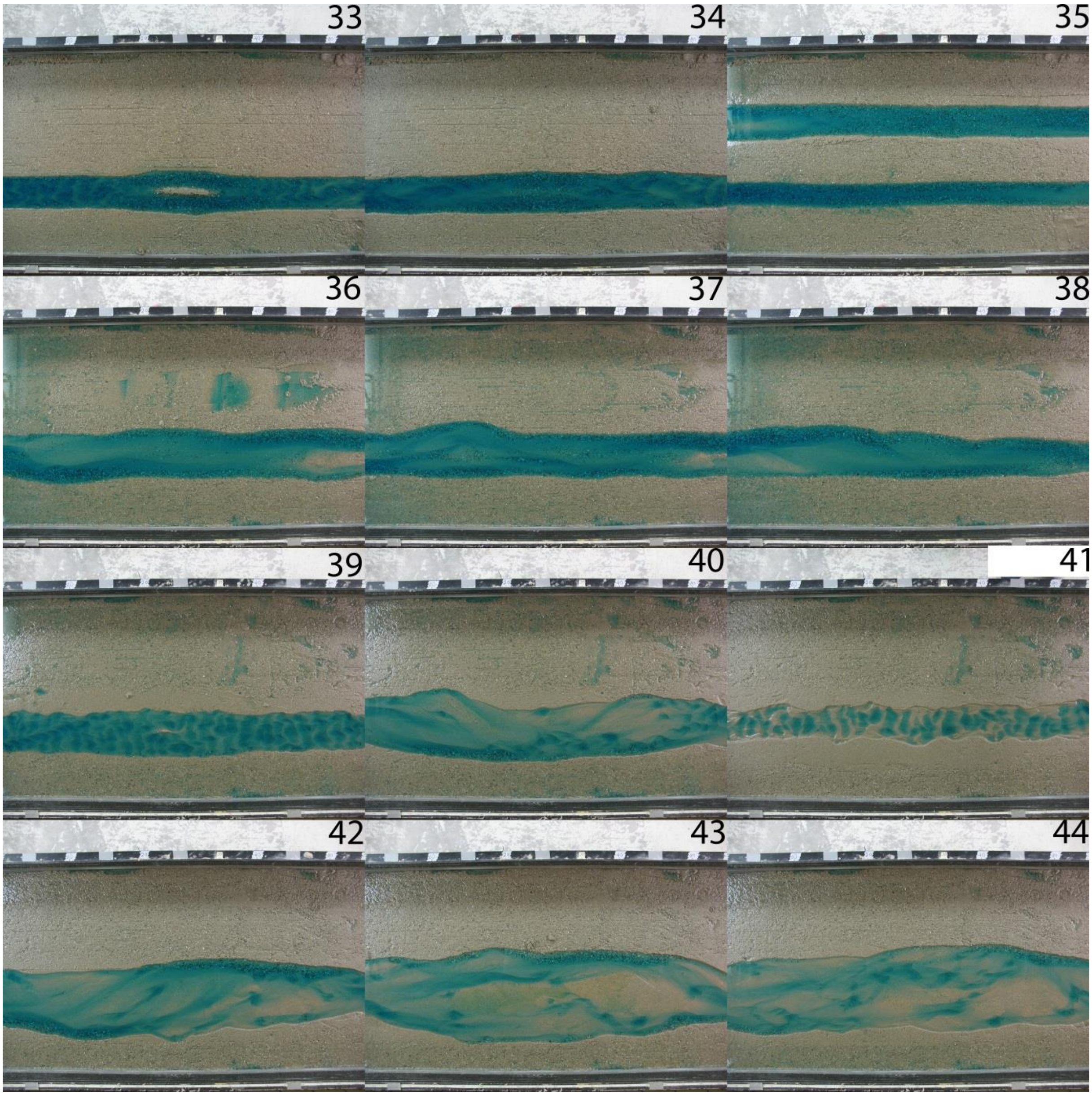

Figure 4.7: Experiments 33-44

Experiment 46 had a less well-developed system, with bed armoring at the free end of the basin and ripples at the tilt-side. In between, no real channel are visible, but still some deeper parts can be seen that are flowing in opposite directions. There are no clear patterns visible though. The same is more or less true for experiment 47. Here the main channel more or less meanders through the whole estuary, beginning at the free end curving toward the free end for 60 cm after which it curves to the wall-side after which it flows out at the tilting end. The channel is less deep than in experiment 46 and has longer ripples, making it less clear, but as the bars in this experiment are higher it still is the deepest part. At the tilting end there seems to be a bifurcation without a clear direction, but for the rest no clear tidal morphology can be found.

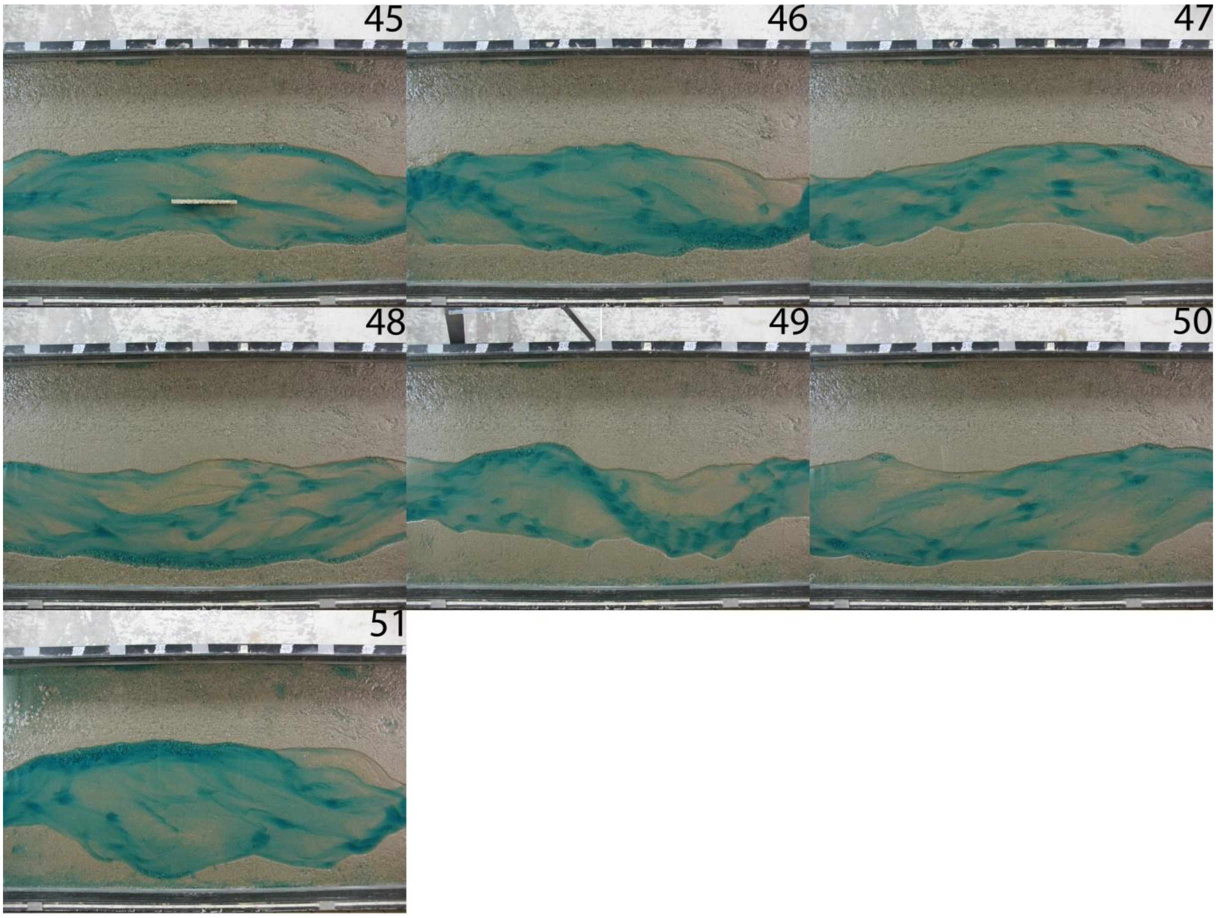

Figure 4.8: Experiments 45-51

This was completely different in experiment 48. Channels in this experiment were chaotic, continually forming chutes and bifurcations, and these smaller channels made part of bigger ones. In general, there was one channel coming from the right, flowing towards the wall-side. This channel encircled a bar together with another channel coming from the left. This channel originated from a shallow part at the left that bifurcated into this channel and another short channel that shoaled on the bar that lied against the free-side bank of the basin. Both bars had their own chutes, mainly shoaling towards the left. The chutes also flanked, as the main channels are used by both the ebb- and flood-flow, and these chutes encircled the bar they shared with this main channel.

Those channels with chutes were not seen in experiment 49. Only two bars had been formed in this experiment, and those lied against the both side banks of the estuary. There was only one channel, and this channel described a perfect meander through the estuary. It kind of looked like experiment 47, only the channel was a lot more distinct. In experiment 50 no distinct channels were formed. Following the curves seen in the bed, the right-flowing water was slightly curving to the free side of the estuary, while the flow to the left curved to the wall. This resulted in one more or less clear bar in the middle of the estuary, encircled by the right-going flow on the wall-side and free end and by the left-going flow on the free side and tilting end. The other deposits were results of previous bars and deserted channels that formed during the development of the estuary. Note that at this point the main development has already passed.

Development of the channels

This chapter investigates the effect of different initial conditions to the formation of tidal channels in the experiments. The results are shown in figure 4.9 and 4.10. The experiments are distributed over three types of channel formation, which are determined visually. The classification 'no channel formation' means that even if sediment was transported, no channels developed during the experiment. An example of this can be seen in experiment 24, where transport went too fast for the system to form any geomorphology. 'Little channel formation' means that the experiment formed small tidal systems, like a single ebb/flood-channel pair. Somewhere during the experiment the basin shows sediment transport that formed channels and bars. Note that it is possible for the experiment to show a different morphology in the final phase and still get this classification. Due to the threshold channel effect, the formation of bars ultimately would be prevented. However, sometimes experiments would look quite natural even though this threshold phenomenon was happening. When systems are classified with large channel formation it means that the system forms clear, well-developed channels during the experiment. This means that often channels keep moving and developing for the whole duration of the experiment. An example of this classification is experiment 8, which has a lot of formation and erosion of bars and channels during the experiment, and a large part of those were well developed.

Polymer experiments

The type of channel formation sorted by their initial conditions is shown in figure 4.9. Figure 4.9A shows the type of channel formation for different kinds of perturbations. Most experiments were executed without an initial perturbation, and most of these experiments had low amplitudes. This combination of initial settings could explain the high amount of experiments without channel formation in a channel without perturbation. The most developed channels formed in experiments with a soft perturbation in the initial setting. This is possibly caused by the fact that the dam itself only momentarily disturbs the flow at a certain location. When the dam was eroded the sediment from the dam relocated itself over the estuary where it would form new bed forms that disturbed the flow. A hard perturbation kept disturbing the flow at one point. This made it possible for the channels induced by this perturbation to develop very well, but it also meant that they could not change their location as the dam kept disturbing the same place continually. This explains the relatively large amount of experiments with little channel formation, while the part with well-developed systems is smaller.

Figure 4.9B shows the distribution of the geomorphology for different tidal amplitudes. It clearly shows that the best developed channels form when the mean tidal amplitudes were between 2.85 and 3.15 mm (the 'middle' tidal amplitudes). The high tide experiments also had a relatively high number of developed channels, but since less experiments have been done with these amplitudes it looks like they performed worse. The asymmetric experiments were all classified as experiments with 'middle' amplitudes, which explains the large number of this type of experiments. Low amplitudes did not create any developed channels. They still are able to form some small systems and standalone channels though. This proves that tidal systems need substantial tidal amplitudes to form.

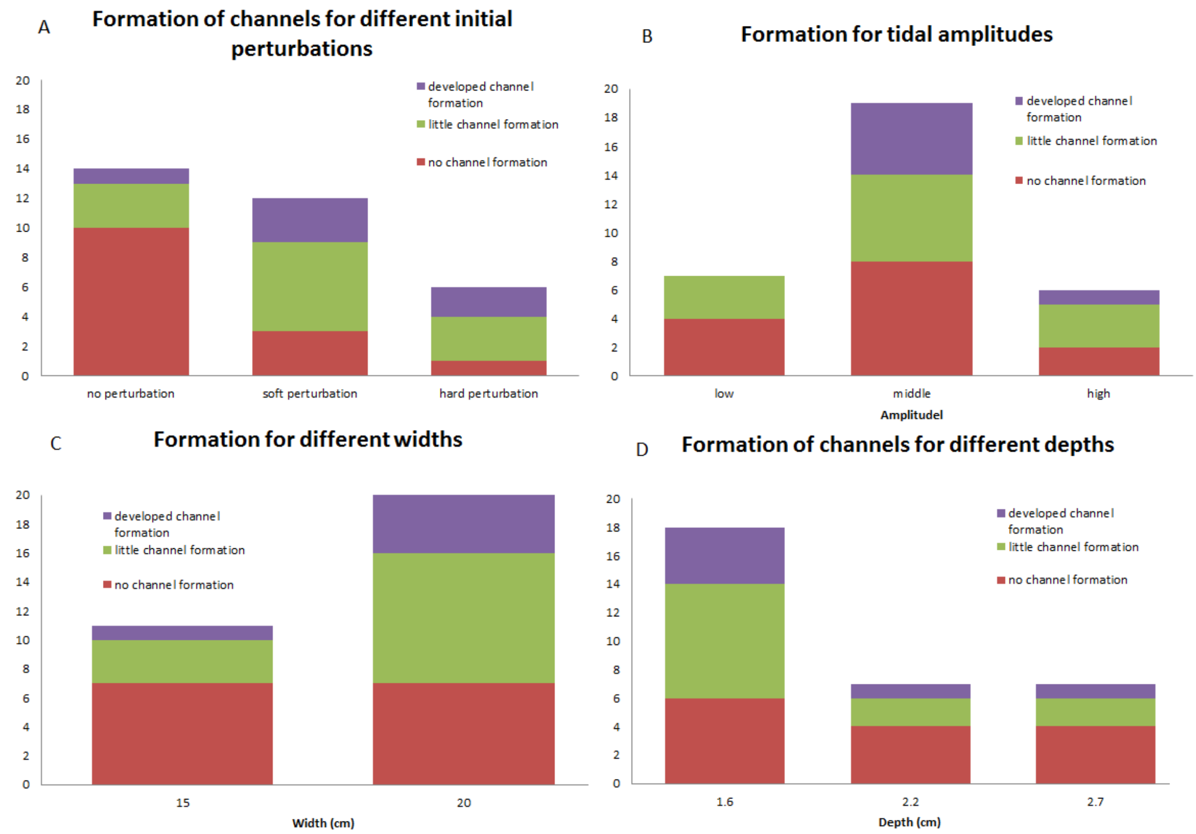

Figure 4.9: Number of experiments done with polymer plastic showing a certain kind of channel development based on different initial conditions.

The comparison between channel formation and initial width in the experiments is shown in figure 4.9C. Again, a larger number of experiments has been done with an initially wide channel. Furthermore, more wide experiments had 'channel-inducing' elements like larger tidal amplitudes or a soft perturbation in the channel. There were more experiments with some form of geomorphology in the experiments with a wider channel. The final form of these experiments did not differ much from experiments with channel formation in an initially narrow channel however. This means width does not seem a very limiting factor in the formation of tidal channels. Only if the initial width is limiting the amount of sediment transport it will stop the development of geomorphology.

Figure 4.9D shows the effect of the initial depth on the formation of channels. This histogram shows that for the lowest depth the most geomorphology will form, despite the fact that a higher depth would have more transport. This is caused by the fact that by far the most experiments had this depth as an initial setting though. Relative to the amount of experiments done with a certain depth, experiments with an initial depth of 2.2 cm also had a large amount of channel formation. Still, the figure clearly shows that depth does not have to be the incriminating factor in channel development.

Sand experiments

The number of experiments with developed channels is larger for experiments with sand than for experiments with plastic, as is shown in figure 4.10. This is partially caused by the fact that the behavior of the channels and the flume was better understood. This meant that less experiments were executed with initial conditions that would not create channels anyway (like amplitudes that were set too high/low)

In figure 4.10A the effect of a perturbation on the formation of channels is shown. Contrary to the experiments done with polymer plastics, in the sand experiments the perturbation plays a smaller role. In the polymer experiments the perturbation often was needed to activate the flow to form channels, but for sand this was not needed. It even proved to be true that when the system would not form any channels, disturbing it with a perturbation was not enough to create channels anyway. It seems that for sand, small differences in depth in the channel are already disturbing enough for the flow to concentrate itself on certain parts, something that would happen in nature too.

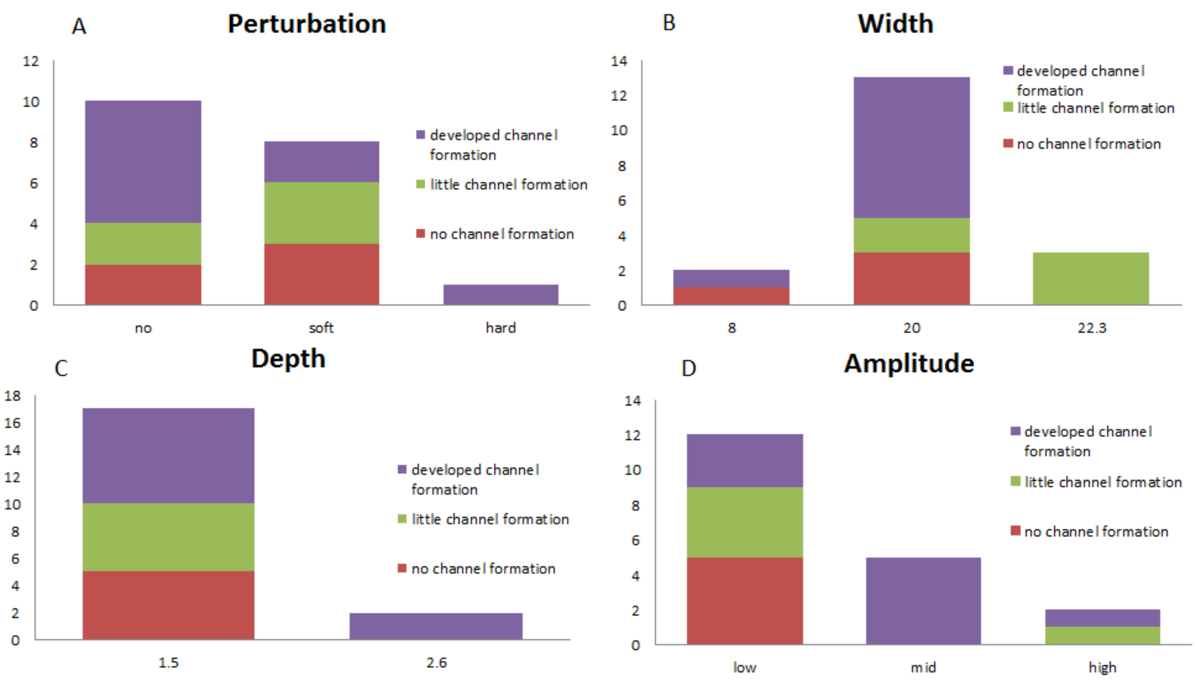

Figure 4.10: Number of experiments in sand showing a certain kind of channel development based on different initial conditions.

The effect of initial channel depth on the formation of channels is shown in figure 4.10B, but there are too few experiments done in deep initial channels to say something about its effects. Final stages in experiments with initially deep channels looked exactly like experiments with shallow channels and no channel formation. Based on these results, later experiments did not have any increased depth, as this extra depth was assumed to be unimportant. The same is true for the width of the channels in figure 4.10C. When it was clear that the width did not have a large effect on the formation and transport of bed forms, only the standard width of 20 cm was used. This explains the low number of experiments with an increased depth of smaller width.

The effects of the amplitude on the formation of channels were also investigated and shown in figure 4.10, and like the plastic experiments the middle amplitude shows the most developed channel patterns. This represents the experiments with an amplitude of 25 mm. Lower amplitudes often result in no movement at all, or in the formation of ripples in the channels that prevent the formation of channels. These ripples also form in the experiments with higher amplitudes, but here the experiment 'overcomes' the ripples and starts forming bars anyway. For low amplitudes, the ripples often are a final phase, and when the whole channel has been filled with these no transport will occur, except for the tops of the ripples changing direction every tidal cycle. Larger amplitudes can lead to the formation of channels too, but the water can become too critical in those experiments, which prevents the formation of the bed forms that are wanted.

Relations between mobility and development

Sand experiments

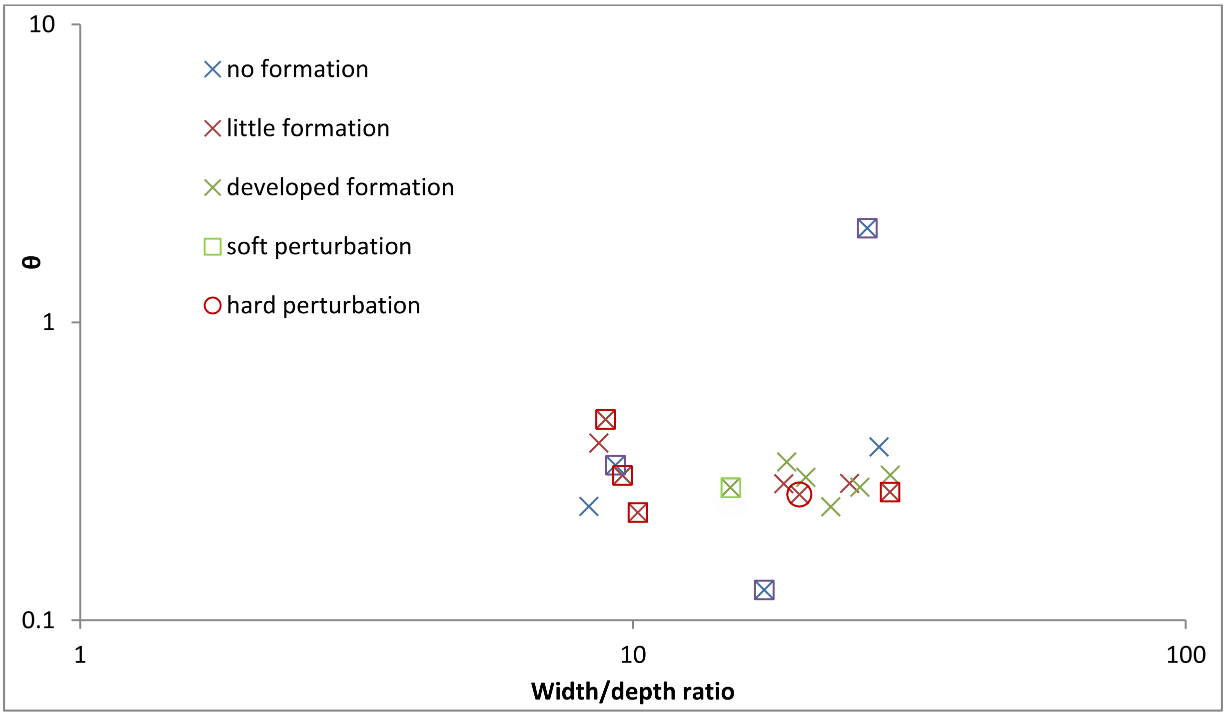

Figure 4.11: Formation of channels based on the dimensionless shear stress and the width/depth ratio in the middle of the estuary at the end of the experiment.

Mobility and the initial width/depth ratio of the experiments are barely related to the formation of tidal systems in an estuary. Figure 4.11 makes this clear: independent of the mobility of the sediment (the Shields number, as calculated with the tidal amplitude in the experiments) experiments would develop no channel formation. The most developed tidal systems were formed in systems where the width/depth ratio was not too large. Furthermore, the most developed systems were formed in estuaries where the width/depth ratio was in the range of 20-50. Estuaries with only little formation of channels existed in a wider range of width/depth ratios, not excluding the range with developed channels though. Experiments without channel formation plotted in experiments with the highest and lowest Shields numbers. This is not strange, as low mobility of sediment prevented the sediment from moving, while high mobility resulted in sediment that was too mobile to form bars and channels within the estuary.

Almost all experiments without an initial perturbation had large- or no channel formation, and for these experiments mobility was the determining factor if channels would form. Only with a sufficiently large mobility channels would start to form in these estuaries. Volume was also a determining factor. Please note that in figure 4.11, channels with a small width/depth ratio also had smaller cross-sections. Since less water would flow through a small channel, the sediment had to be more mobile to make transport happen. Therefore better developed channels only formed when the shear stress was larger in a small channel.

Polymer experiments

For the polymer experiments, which can be seen in figure 4.12, there was even less consistency in the distribution of experiments. The experiments without channel formation are plotted all over the figure. The figure shows how unimportant the conditions of the experiments were when polymer plastic sediment is used. The low density of the sediment in combination with the coarse grain size made it really easy for the flow to bring sediment into motion, regardless of the width or depth of the channel. Of course, when the tidal amplitude was lower, the sediment would not move as much, especially in small channels. This does not mean that no well-developed channels could form though. The mobility of the sediment and the formation of developed estuaries were related, but not very strict. When the sediment mobility became too large, no patterns would form at all. The channel would just widen very rapidly until the sediment in the ebb delta started to choke the inlet of the basin, after which the estuary will not develop any further. Only long zones of deeper and shallower parts stretched along the length of the estuary, but no patterns could be seen between those zones. Therefore too much mobility did not create good tidal systems. Sometimes the addition of a perturbation could induce the formation of small channels where an unperturbed system would develop no channels of any kind, but these small channels never grew in a well-developed system. The exchange from a soft perturbation to a hard one did not help the system either. In fact, a hard perturbation only made less developed channels. Since the perturbation stayed at the same place for the duration of the experiment, the estuary was constantly perturbed in the same way. This meant that only one, fixed channel system would follow this perturbation. Since a soft perturbation only temporarily disturbed a part of the channel, this part could start to perturb other parts of the estuary when the sediment of the perturbation was eroded. This would continue for the whole duration of the experiment, since the reversal of the flow direction prevented a lot of sediment from leaving the channel. A hard perturbation would only perturb one part of the estuary, and the farther from the perturbation, the lesser its effects would be, so only a small part was perturbed and would stay that way.

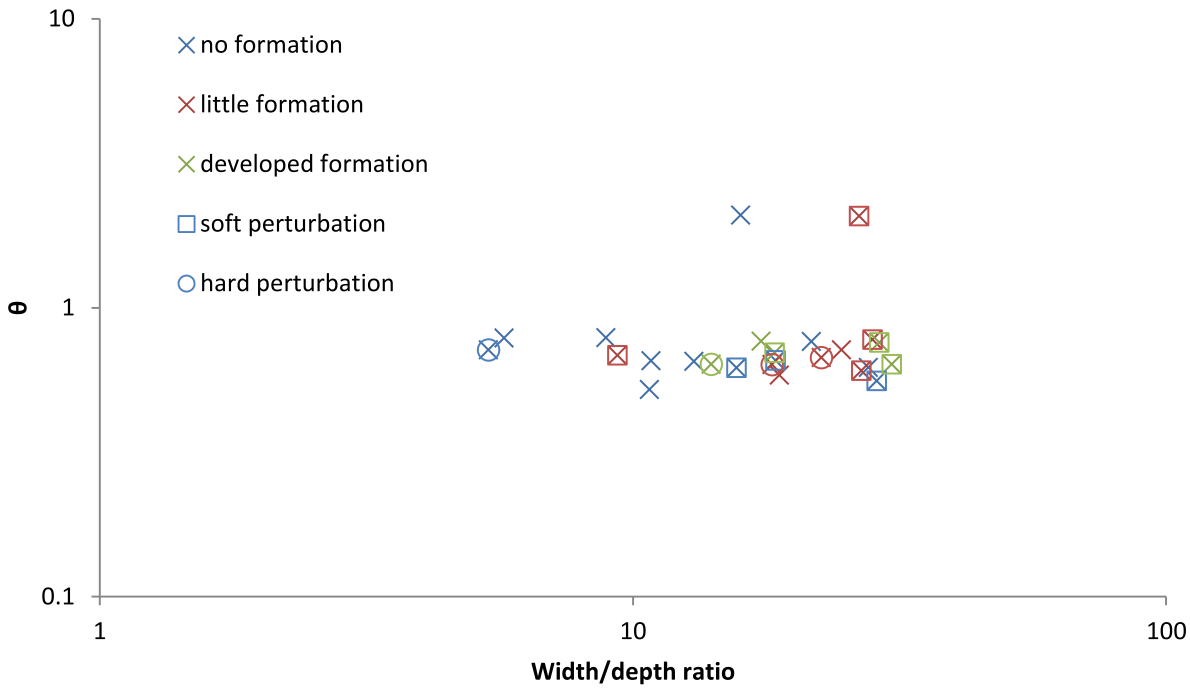

Figure 4.12: Formation of channels in polymer experiments based on dimensionless shear stress and the initial width/depth ratio of the channels.

Velocity measurements and flow patterns

This paragraph describes the concentration of different directional flows on different locations during the experiment. Streamlines and their velocities are based on visual particle tracking of floating particles in short movies of the basin.

system	ebb velocity (m/s)	flood velocity (m/s)
A1	0.30	-0.29
A2	0.21	-0.31
B	0.21	-0.26
C	0.32	-0.31
D	0.27	-0.27

Tabel 5: flow velocities (m/s) for the tidal systems in the basin

In the beginning of the experiment (timestep 19 in figure 4.14) there was no clear separation between ebb and flood tidal channels, as both flows used the same channels during their cycle. There are some parts that were used by only one flow, but this mainly had to do with the inlet of the estuary. As can be seen in the depth model in timestep 19 figure 4.13, flow from the right was blocked from the largest part of the inlet by the ebb-delta that had formed during the other tide. As such, water could only enter the basin by one channel that cut through the delta. When this channel ended, the flow bifurcated and concentrated itself in two channels. One at the downward part of the estuary and one more through the middle of the estuary. These flows basically continue this way to the end of the basin, but only the middle flow started to use the channel from the other tide near the end of the basin instead of continuing its own course. For the flow from the left the same principle of a one-channel origin applied. After that, the channel bifurcated too, but this time into the downward side channel that was also used by the other flow, and a channel on the upper side of the channel. This upward channel had a threshold in the middle that prevented the flow from the other tide and thus was only usable by the flow from the left. This meant that at the end of the channel, the main channel in the ebb-delta was embraced by these two flows on the sides.

During the next particle tracking moment, the basin had already widened substantially. No clear tidal channels were visible, and this also had its effects on the flow. Flow from the right mainly concentrated itself on the upper side of the basin, having flow in other parts of the basin but being too low to affect the morphology there. The threshold that first prevented from flood flow to enter this channel is not active anymore though, as flow from the left now originates from the downward side of the basin (again due to the ebb delta blocking the rest of the basin). This flow did not concentrate itself in one channel, instead it bifurcated into one channel that crossed the basin and one channel that followed the wall side of the basin. This last channel was not as deep as the upward channel and it had formed some bars and chutes that bifurcated the flow, but these channels come together each time. The scour holes at the end of the basin created some deeper parts in another fork of the channel but the water still preferred to follow the smaller, narrower channel that flowed straight to the end of the basin. The basin-crossing channel eventually flowed into the large upper channel and continued to follow it. Flow from the right was clearly more concentrated on one part of the basin and this also clarifies the next moment.

For the third tracking moment, nothing happened for the flow from the right, as it still followed the upper channel. This channel had developed more at this moment though. Especially on the tilting end of the basin the channel deepened more. Flow from the left moved more to the middle of the basin though. It bifurcated again into one channel that flowed in the main upper channel, and another channel that more or less flowed through the middle of the estuary. The channel shallowed and disappeared into another channel (this time with a scour hole at its beginning) and the flow itself bifurcated again where one part followed this new channel and the other made a strange curve around a small bar in the basin to follow a small channel that formed from the scour holes described in the previous tracking moment.

The last tracking moment still had the flow from the right following the main channel at the upward side, but some smaller flows also used the channels that came from the left. The flow from the left had its origin changed again to the downward side of the basin. There still was a basin-crossing channel that had slightly changed its location but it was at that moment better developed than its predecessors. The rest of the flow from the right just went straight on, not following old channel that followed the levee, but crossing the estuary slightly more to the center. Before the end it bifurcated again to flow in both channels that were used by the flow during the last two tracking moments.

The velocities measured, even when there are no clear tidal systems in a part of the basin, show that ebb and flood flow will concentrate itself on different parts of the estuary. These velocities were not measured for every experiment, but they still show that certain patterns were induced by different flows. The best examples are found in timestep 19 of figure 4.14, where the clear flanking systems had their own dominant flow. Note that there was almost no flood flow in an ebb-dominated channel until the flood channel shallowed and disappeared, and the flow spreaded itself over the bars surrounding the channels until it found the nearest ebb channel.

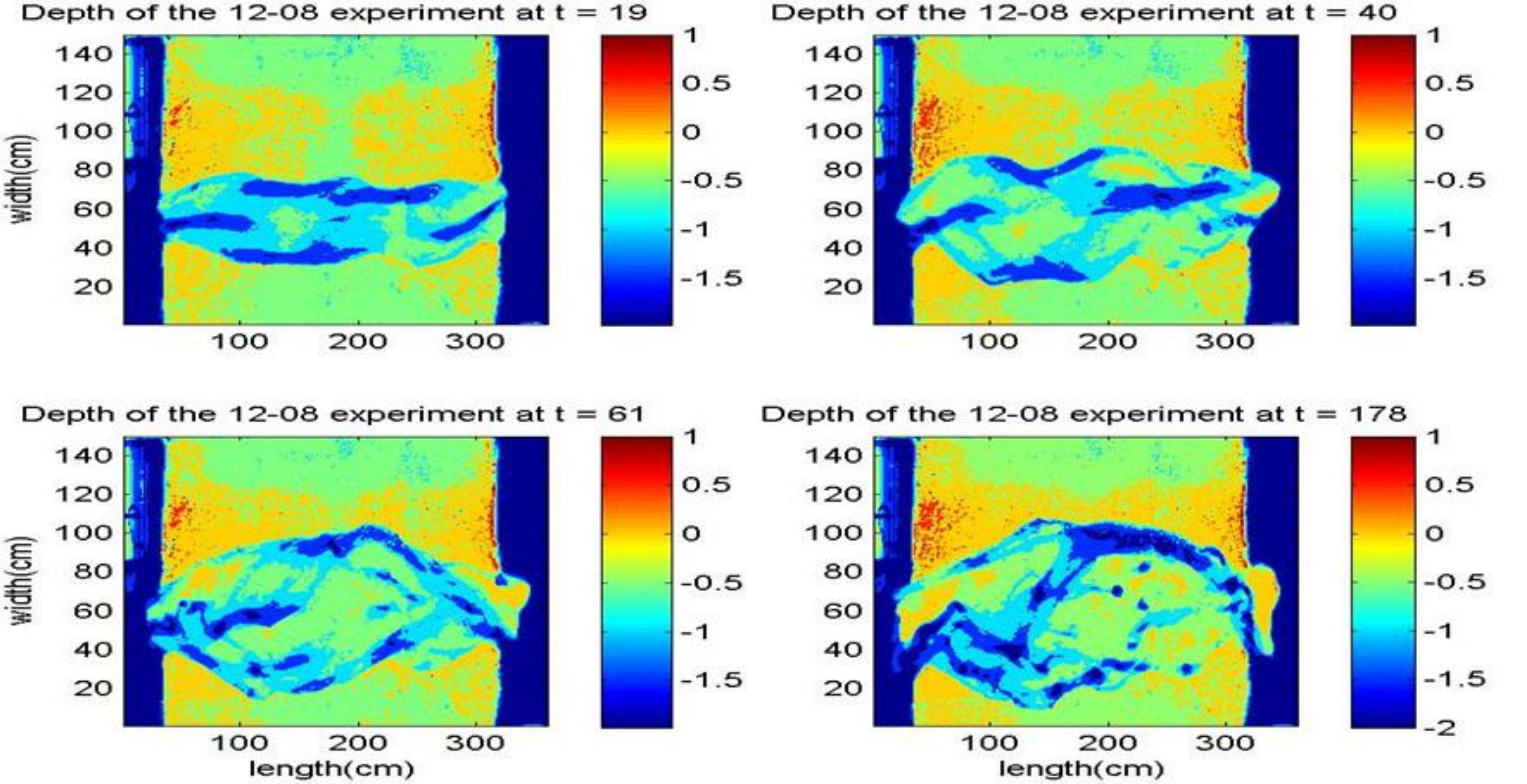

Figure 4.13: Depth models (in cm) of several cycles in the velocity measurement experiment.

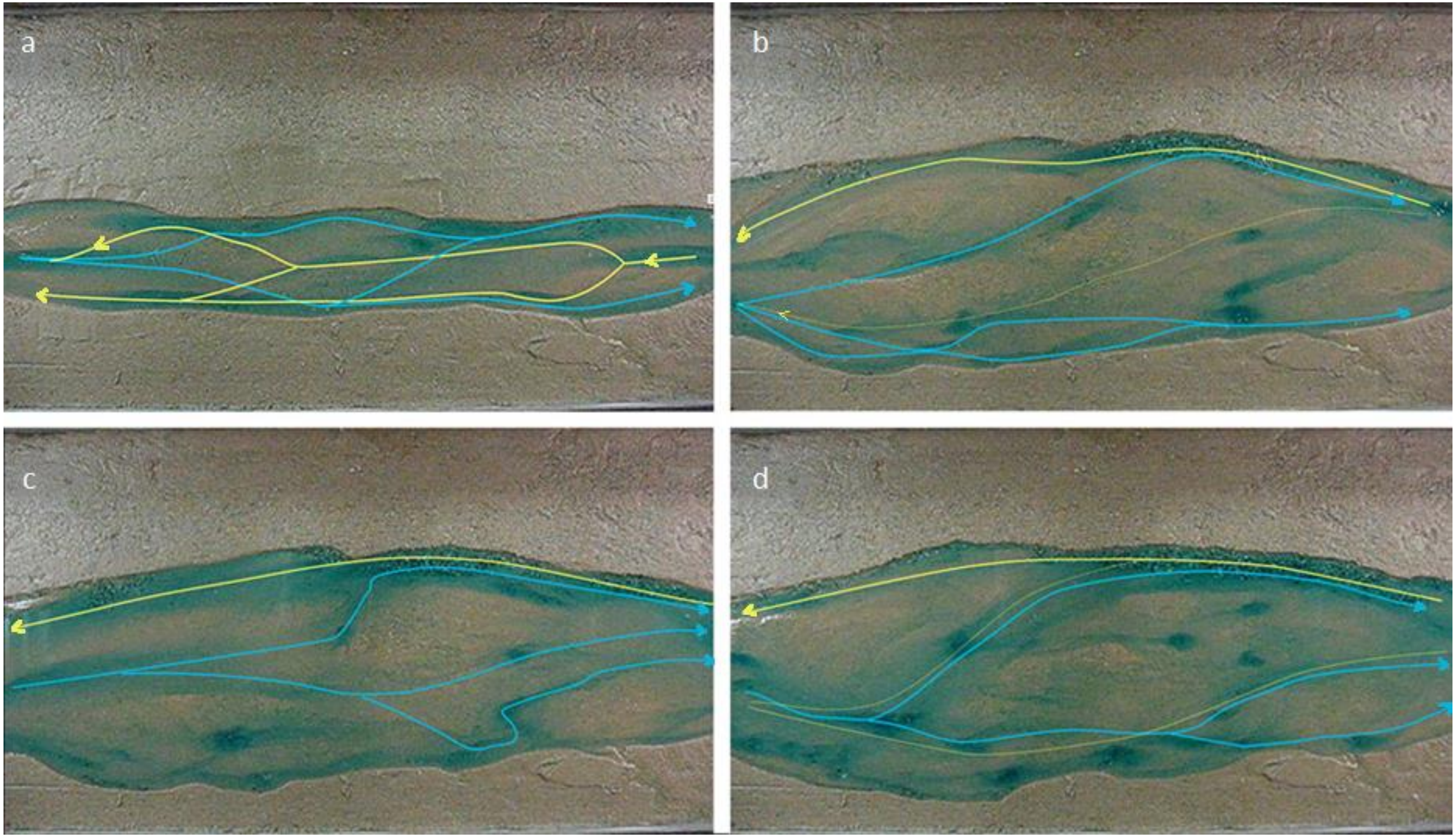

Figure 4.14: Flow patterns for right-going 'ebb' (blue) and left-going 'flood' (yellow) water flow in the velocity measurement experiment.

For the experiments without particle tracking, the flow velocity was estimated with equation 3. This resulted in the flow velocities displayed in appendix A. With these flow velocities, it was also possible to calculate the streampower in the experiments. The value for constant α used to calculate the reference width W_r with, was 4.7 for the sand experiments, and 3.0 for the plastic experiments. Also, instead of the bankfull discharge, the normal discharge, calculated with the mean velocity, width and depth was used. Results from these calculation will be discussed in the next chapter.

Occurrence of channel types

Together with the degree of channel formation in the experiments was also the type of tidal channel classified during a couple of experiments. Figure 4.15 shows the occurrence of each channel type during those experiments. For the duration of most experiments, mainly either no channels or flanking channels exist in the estuary. However, there seems to be a small trend visible between sediment mobility and the amount of forking channels during an experiment. Most experiments with a small sediment mobility display little forking channels. When the mobility increases, so does the amount of forking channels in an experiment. This partly comes due to the environment in which the forking channels exist. These channels mainly form as a phase between two systems. When the estuary starts forming channels, these channels often start out as forking. When these forking channels further develop, they become flanking channels,. These channels are more stable, and thus occur more often in the experiments. Still, when the flanking channels are relocating themselves again, a forking system can develop again, only to be alternated for flanking channels again. Thus, when mobility is larger, the channels relocate themselves more often, and the forking 'in-between phases' occur more often. This phenomena is further illustrated in the following chapter.

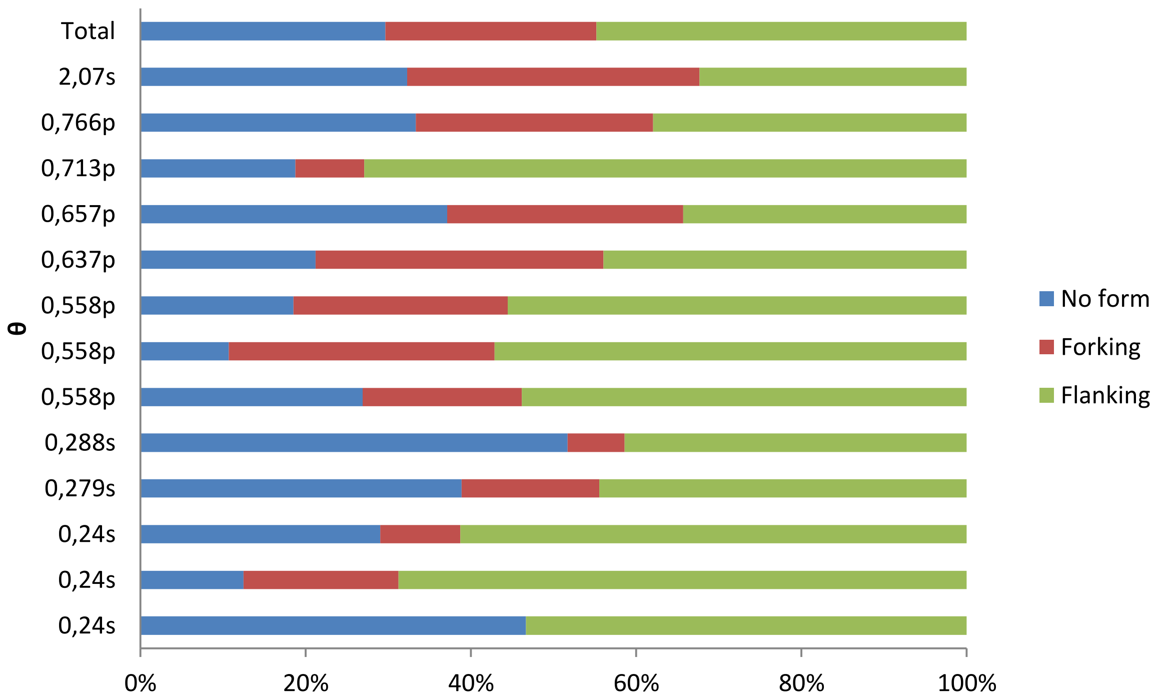

Figure 4.15: Occurrence of different channel types for experiments with a certain Shields number. The letter behind the Shields number defines the sediment type used in the experiment, where s = sand and p = polymer plastic.

Width and volume development

The total volume of water in the estuary varies due to the widening and deepening of the channels. This variation is calculated for four experiments, and figure 4.16 clearly shows the difference between development of sand and plastic experiments. The plastic experiment (figure 4.16D) clearly shows a continually growing system. The fastest widening happens in the first 50 cycles of the experiment, but even after that the channel still continues to widen. This was normal for the plastic experiments, as the banks of the estuary were built up from the same loose material as the rest of the basin, and thus could be eroded very easily. For the experiments done in sand, this phenomena did not always occur. The example that looks most like the plastic experiment clearly is the normal-amplitude sand experiment (figure 4.16C), where the initial widening of the channel occurs very rapidly during the first 500 cycles. Note however, that the duration of this widening was times longer than in the plastic experiment. The rest of the experiment also did not show continuous growth of the basin. There was a small trend that showed an increase in the volume of the channels, and it started and ended with a decrease in the total volume. The end volume of the experiment also did not differ much from the total volume after the initial growth of the system. Thus the variation of the volume after initial growth was caused by the relocation of channels and bars in the estuary instead of the total growth of the system. Also note that the total change of volume in the system is about 2.5 liter in the sandy experiment, while the volume in the plastic experiment increased with 0.9 cm^3, or 9 liter.

The other sand experiments did not show any kind of continuing trend in the change of the volume. Figure 4.16A showed a rise in the volume of the estuary in the last 600 cycles, but before that the system had a more or less constant volume and it started with a rapid decrease of the volume in the first 150 cycles. This decrease had to do with the filling up of the channels in the beginning of the experiment, as those were too deep. The estuary itself did widen, as can be seen in figure 4.14, but the active channel remained small, so a large part of the estuary existed of bars that rose above the water surface, thus did not add to the volume. The same was true for the experiment of figure 4.16B that started with 300 cycles of fluctuating volume but no actual increase or decrease. The 400 cycles after that the volume increased with 1 liter, after which it decreased until the end of the experiment.

The increase in the volume of the channels can also be seen in the development of the width, as shown in figure 4.17. However, width and volume do not completely follow the same trend. Figure 4.17A is the best example of this phenomenon. While the volume of this experiment first decreased with 10 per cent of its original value, the width of the channel did increase tremendously in its first 400 cycles. After that, the widening of the channel slowly came to a halt, but the volume kept increasing, slowly but steadily. The other experiments had their width develop with more or less the same trend as their volume. The experiment from 4.17B also had a small decrease of its width in the beginning of its run, and the only difference with the width development was the stabilization of the width at the second half of the experiment, while the volume during that time was decreasing.

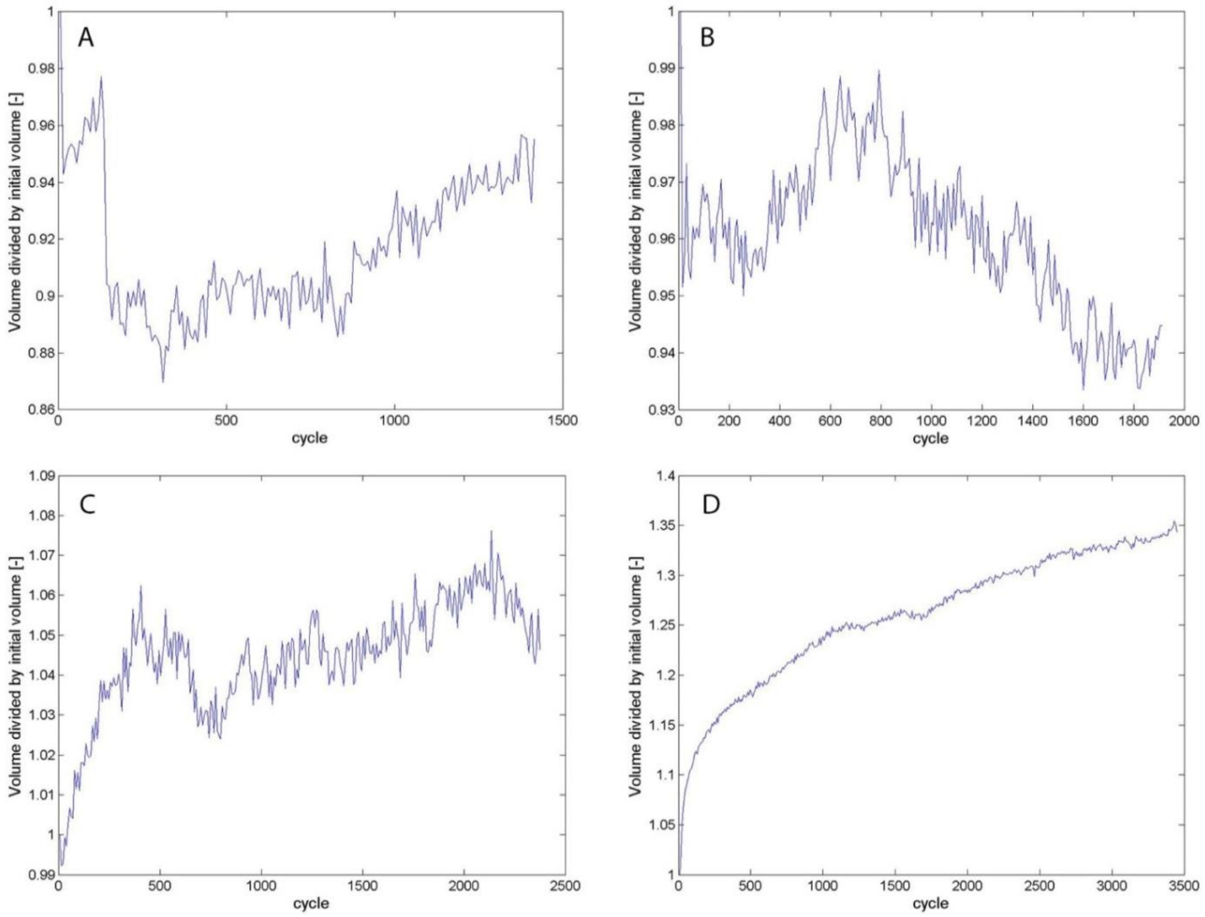

Figure 4.16: variation in the relative volume of water in the channels for four different experiments. A) sand experiment, B) a normal-amplitude sand experiment C) a high-amplitude sand experiment D) the symmetric high amplitude polymer experiment

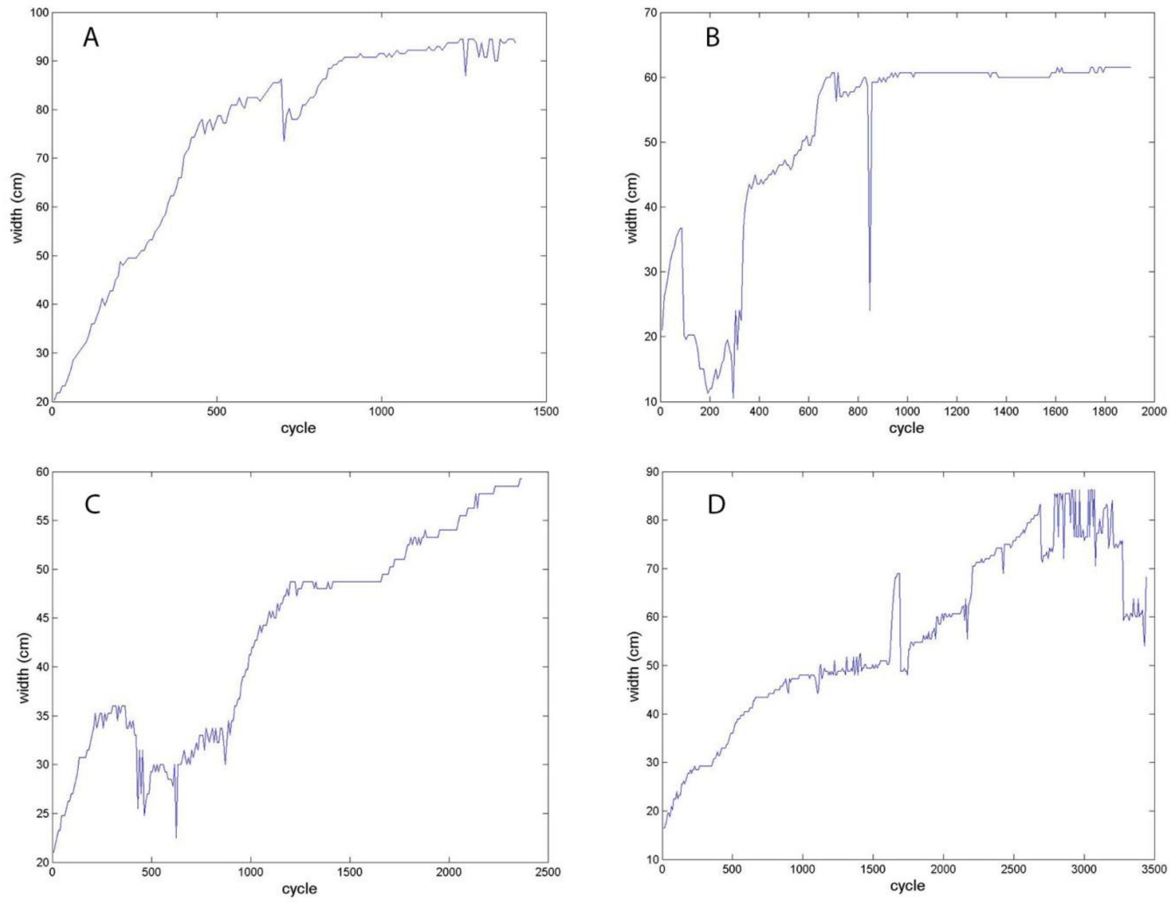

Figure 4.17: Development of the width of the channel in the middle of the basin for the same experiments as figure 4.16. A) velocity measurement sand experiment, B) a normal-amplitude sand experiment C) a high-amplitude sand experiment D) the symmetric high amplitude polymer experiment.

5. Discussion

How do multiple channels in a tide-dominated system form?

Van Veen (1950) accurately described the appearance of tidal channels, but he offered no description how these system developed. This chapter describes the formation of these ebb/flood channel pairs, on the basis of the visual observation of the experiments.

The estuarine reach starts as a straight channel with one perturbation (figure 5.1A). This perturbation is displayed in the figure 5.1 as a bar, but it also can be caused by a disequilibrium in the width/depth ratio of the river. When the width of the channel is out of equilibrium, the threshold channel concept will start. This way sediment is continually added to the system by the caving of the banks. Sediment in the channel will be spread over the total width of the channel, as shown by figure 5.1B, and the river will widen at the location of the perturbation as a reaction on the perturbation. The perturbation now lies completely under the water surface, but it still acts as an obstruction as flow will still concentrate in the deeper parts of the channel.

Now the alteration of the bar starts. One of the two tidal flows will concentrate itself in the deeper channels (figure 5.1C). This affects the direction in which sediment from the bar will be deposited. This sediment will be deposited at the end of the two deeper parts encircling the bar in the middle, thereby obstructing the channel from that side and narrowing the channel at the end of the deeper parts. This obstruction affects the flow of water when the tide turns: water from the opposite flow will less likely concentrate itself in the channels, therefore water from the straight channel will just flow straight over the bar due to the inertia of the body of water. Doing this, a channel that cuts right through the bar will be eroded.

In a one-channel system, the rightward-directed flow (figure 5.1C) apparently cannot keep up two channels simultaneously, so one of the two will be deserted (figure 5.1D, see also figure 4.6 of experiment 8). This leaves space for the left-directed channel to move further away from the left-over right-directed channel, meanwhile filling up the space left by the abandoned channel. When this channel has moved more to the side, the right-directed channel can also come more to the middle of the channel, as the water still wants to flow straight. This can be seen in figure 5.1E and even further in figure 5.1F. What also can be seen is that one of the channels, in this case the right-directed one, is growing in size. Due to the curvature of the channel, sediment is deposited in front of the left-directed channel, thus obstructing part of the opening. During the opposite tide, this means less water will enter the channel and thus flow over the bar instead, limiting the concentration of flow in the channel, which will therefore decrease in size. This process is comparable with the desertion of a channel at the bifurcation of a river, since also at that location a channel with less flow will eventually fill up with sediment (Kleinhans et al., 2012).

In theory, the channel could also be deserted when the right direction did not curve at all. However, when this would happen, the channel would still develop small bars at its sides as well as at its end. When the channel size increases, these bars would increase with it, as a larger channel is also wider and deeper, and the sediment that this channel generates would end up in the sidebars. Eventually the bars are wide enough to start obstructing the other channel, resulting with the same effect.

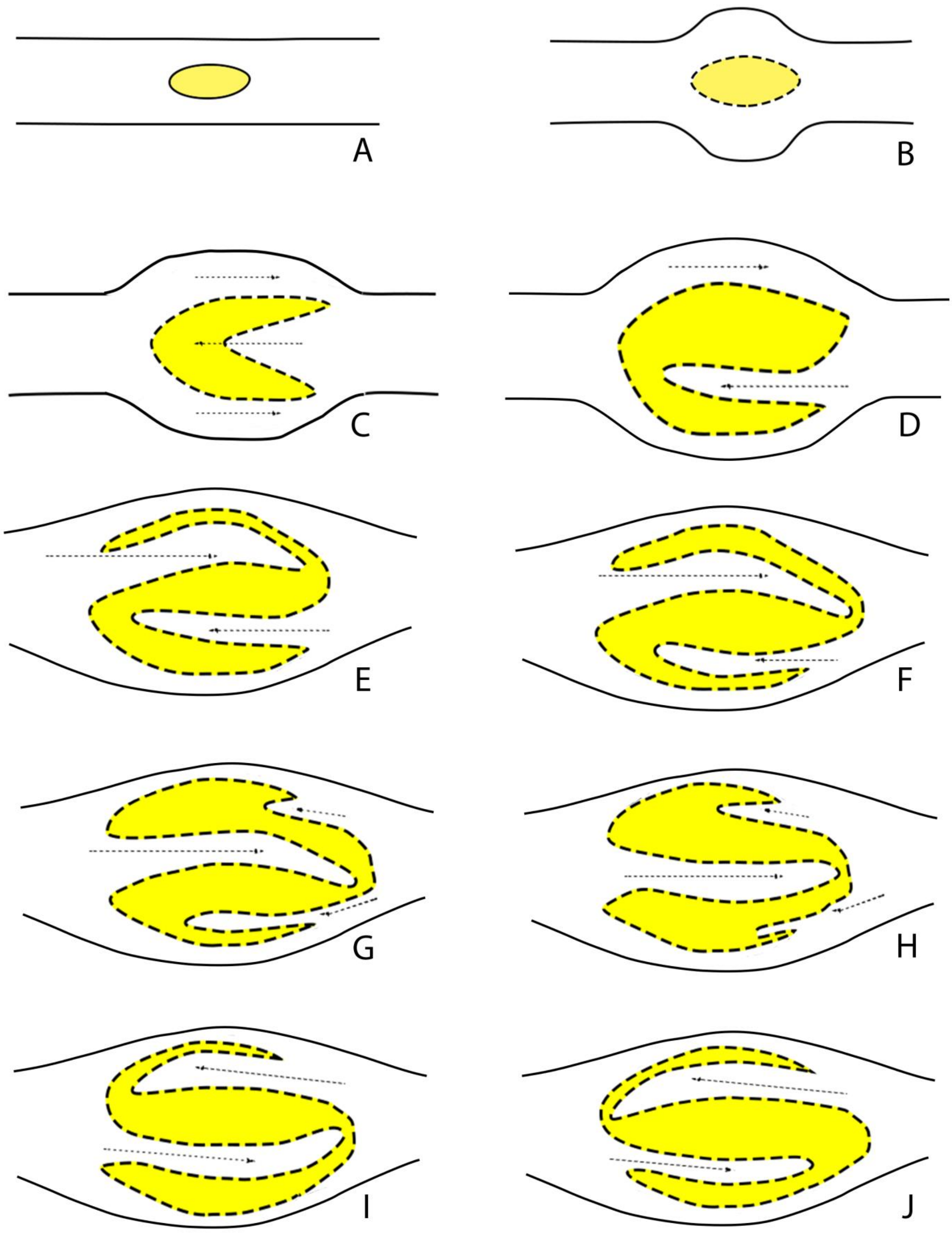

Figure 5.1: Schematic development of flanking and forking channels

The main left-directed channel becomes smaller, but the same amount of water still has to move through the channel. This water will flow more over the bar than through its channel, but since the right-directed channel has moved more to the middle of the estuary, this results in the start of a concentration of flow near the other bank of the estuary (figure 5.1G). A small channel will start there, not enough to directly cut through the bar, but enough for water to distribute itself across the two smaller channels, and through this new channel water can more easily flow into the well-developed right-directed channel. Since that results in less friction for the flow, more water will concentrate itself in this small channel.

Since the right-directed channel will only continue to block the old left-directed channel, this new channel will start to grow in size. Eventually the old channel will completely be gone (figure 5.1I). This development of this new channel will only 'push' the right-directed channel more to the side of the estuary, but since the water still tries to flow through the middle, the deepest part of the estuary, it will have a curvature in the other direction. The further development of this channel will be eroded by the flow of the left-directed channel, and thus both channels now reach the same dimensions again, until one of the channels takes over and starts blocking the other channel (figure 5.1J).

Comparison with Cobequid Bay

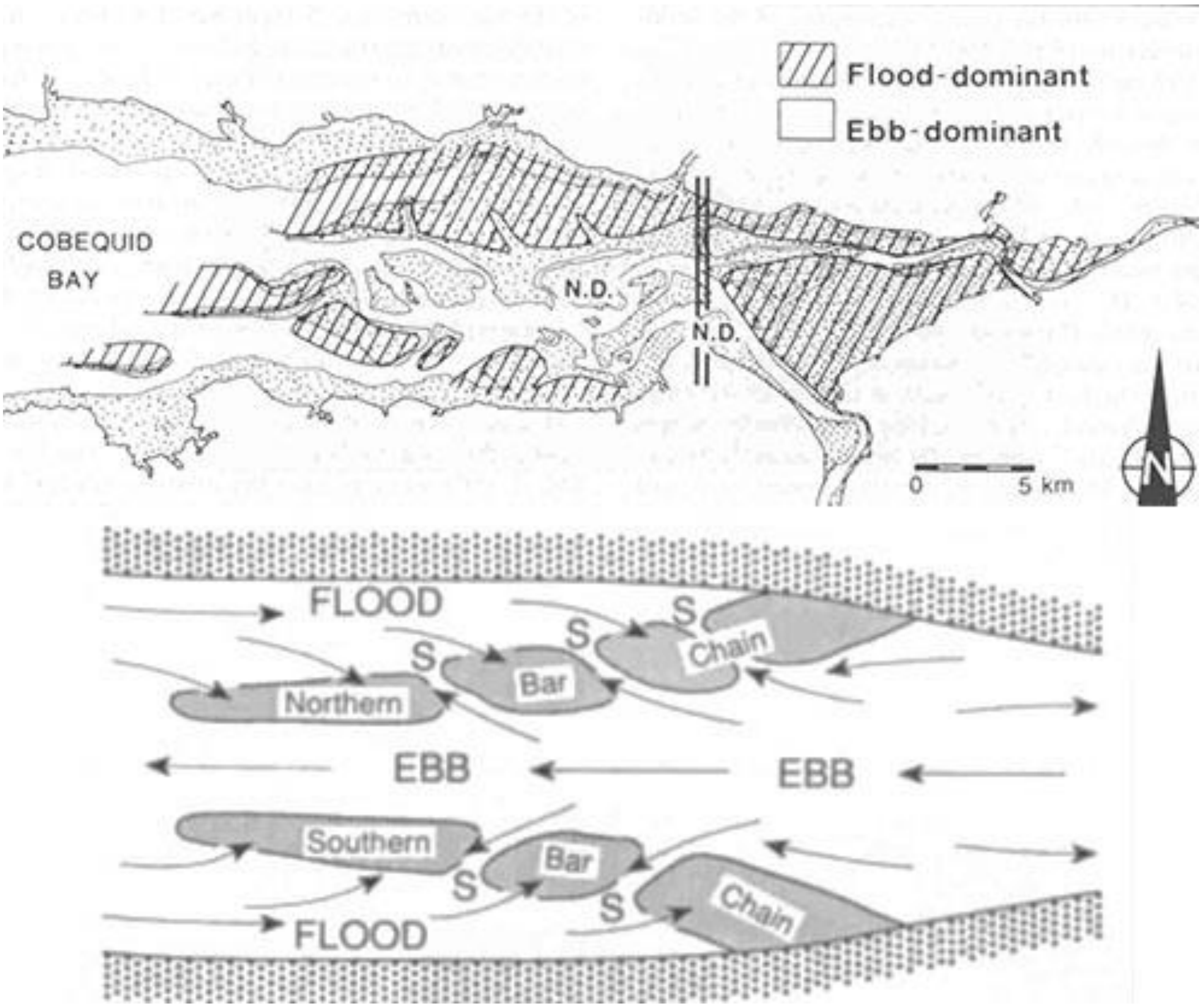

Figure 5.2: Cobequid Bay and the schematic illustration of the sand bar complex. Dalrymple, 1990

This process is the basic formation of ebb and flood tidal channels. In the experiments, often ebb-flood channel pairs formed at the same time, and one channel would be active in two systems. This means that the development in natural estuaries could be a lot more complicated than described here, as the same process is happening at multiple locations, with different durations. However, that natural estuaries do not have to be complicated shows figure 5.2. This is a schematic illustration of the sand bar complex in the Cobequid Bay as found by Dalrymple et al. (1990). The schematic illustration looks quite like the figures displayed in figure 5.1C, G and H, but then better developed. The flood channels protrude further into the basin than in the schematics, and there are some extra channels in the bars that divide ebb and flood channel. This phenomenon is not unique for natural situations though. One difference between figure 5.2 and the experiments is the way the flood flow is interpreted. Dalrymple displays the flood flow as flowing over the bars, while the ebb flow cuts channels through the bar chain. The experiments showed however that the flood flow cuts through the bar system. Figure 5.3 shows one of the situations in the experiments where this kind of phenomenon also occurred. As can be seen in the figure, even though the continuing channel follows the bank of the estuary, in the middle the channels forks into another channel that cuts through the bar. This is due to the fact that the narrowing channel cannot drain all the water that flows in the channel at the beginning, thus the water level around this point is pushed up, overflowing the bar and eventually cutting a channel. Note the deposition of sediment at the end of the channel: this sediment is clearly deposited by the flow coming from this embracing channel. This is different than the interpretation Dalrymple gave to these channels. In the Cobequid Bay, the overshoot channels are used by the channel that lies in the middle of the estuary instead of the embracing channels near the banks of the estuary. Water from that channel just flows over the bars instead of cutting through them. This process could be explained by the method used for the experiments. In the experiments done in the tilting flume there is no difference between the water levels of the different tides. There were differences between the duration of the tides, but this had no effect on the water level during the tides. Since the channels in the middle of the estuary often were deeper due to being older and better developed, these channels could drain more water than the channels that were pressed into the sides of the estuary. Therefore water will be pushed up earlier, and these overshoot channels are formed, while flow going through the middle can drain through this channel until the moment the bars are flooded and water can flow over these obstructions. This is what happened in the Cobequid bay, as water levels rise higher during flood, making it possible for the water to flow over the bars while during ebb the water level will fall, forcing the water to concentrate itself in the channels. This water has to cut through the bars when the sole channel proves to be too small to drain all the water. It remains difficult to believe that the flood flow would prefer to flow over the bar instead of cutting through it. Modelling research of Schuurman et al. (2013) showed that in braided rivers comparable phenomena formed. Continuous 'attacking' of the bars resulted in new channels cut through the bars.

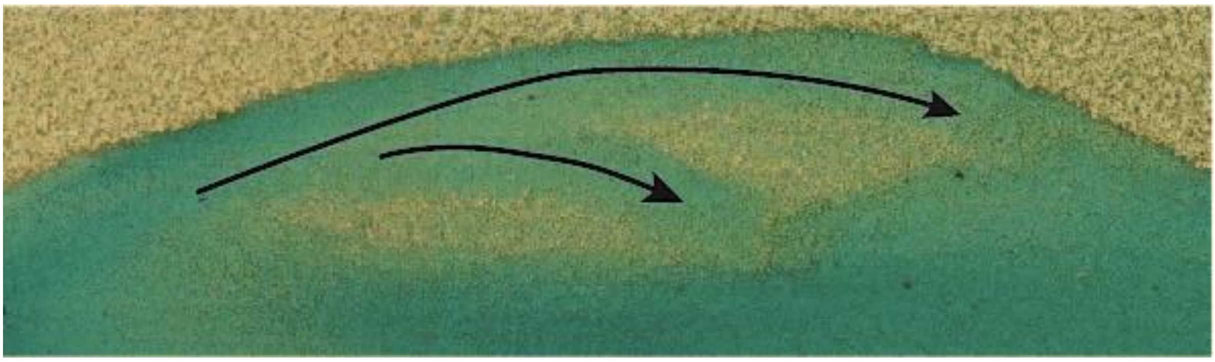

Figure 5.3: Overshoot channels in the high-amplitude polymer experiment

Another reason for the fact that the middle flow cuts through the bars (figure 5.3) could be that the ebb tide is dominant in the overshoot channels, which holds true for the Cobequid bay. This way the ebb flow could deposit its channel deposits at the end of its channel. Flood flow then would be prevented to enter the channel and attack the bar itself instead. In most of the experiments there is no dominant tide, as both the up- and down-tilting of the basin happen at the same speed and amplitude. Sometimes the duration of the tides would differ, but still this did not alter the kind of channels that were formed.

Comparison with Van Veen

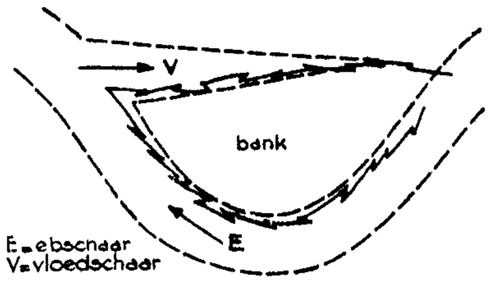

Figure 5.4: Schemetic view of ebb and flood tidal channels in an estuary (in Dutch: bank = bar). Van Veen (1950)

Figure 5.4 shows the schematic view of a tidal system in the Western Scheld according to Van Veen (1950). This figure resembles the sketches in figure 5.1D, F and J. The main difference between his interpretation and the one described in this research, is that Van Veen interprets this situation as the last phase in the development of tidal channels. This thesis however describes this phase in the experiments only as a part of a continually changing system. The same is true for the forking channels displayed in figures 5.1G and H, as these show that, under the right circumstances, a forking channel system only reforms into something else over time. This reformation also has to do with the fact that the banks of the estuary are not cohesive, and as such the estuary can keep widening until the sides of the flume have been reached. Furthermore, the experiments do not have any form of sediment input. That could cause the bars to be more mobile, because the sediment could obstruct the flow of water, but at the same time also create more stable bars. This would cause water to concentrate itself more in better developed channels.

Of course, multiple tidal channels can exist simultaneously in one estuary, and together they will create a more complex system. The experimental estuaries do not behave very differently from the reality, nor from other experiments that were done to investigate braided rivers (figure 5.5). This also had to do with the flow velocities that were active in the experiments. Velocities measured in the tidal experiments were in the same range as the experiments with braided patterns. The bars also look quite natural when compared to the investigation of Dalrymple and Rhodes (1995): Bars are randomly spread across the width of the estuary and channels vary in width to cut through these higher parts of the estuary. Not only that, but ebb and flood dominant channels exist everywhere in the estuary, not always following the patterns described at the beginning of the chapter. The systems of Van Veen do compare more to the single bars that were found in the lower mobile experiments (where only one or two bars were formed), but this example compares to the more mobile experiments where transport is larger and bars influence the development of each other.

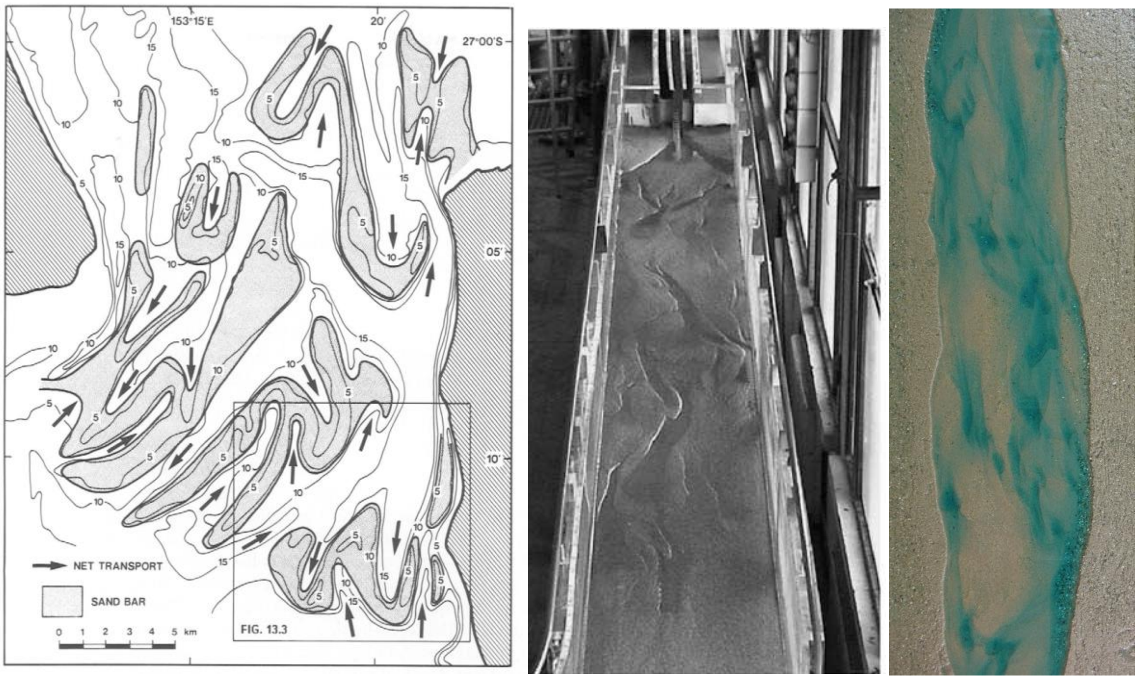

Figure 5.5: Left: Bar patterns at the entrance of Moreton Bay, Australia. Dalrymple and Rhodes (1995). Middle: Result of a braided river experiment by Federici and Paola (2003). Right: One of the tidal experiments done in sand.

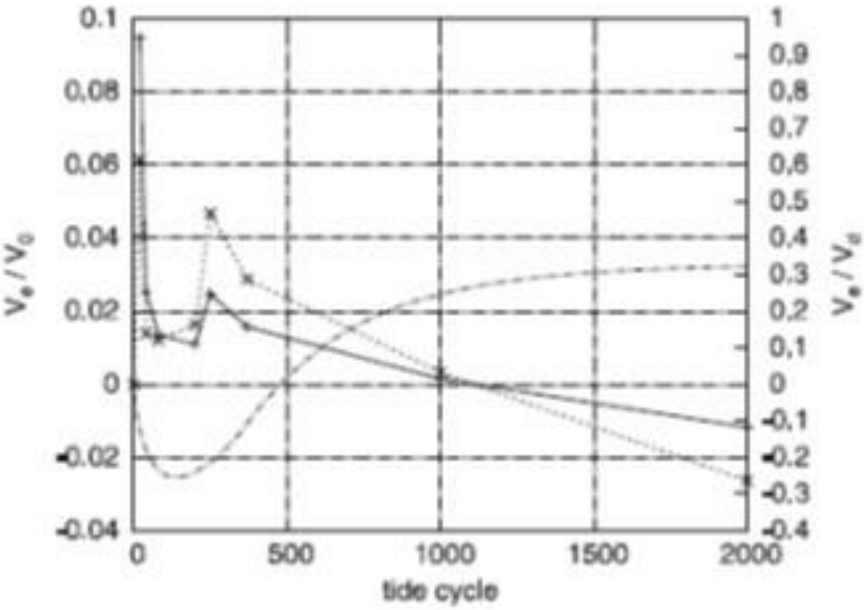

Figure 5.6: Volume of sediment exchanged between the channel and the storage basin V_e scaled by the initial volume of the channel V0 (dotted) and scaled by the volume of sediment deposited in the landward end of the channel (solid). V_e/V0-ratio by Lanzoni and Seminara (2002) is also shown (dash-dotted). Tambroni (2005)

Figure 5.6 shows the exchange between sediment in the channel and in the storage in the experiments of Tambroni et al. (2005) and Lanzoni and Seminara (2002). It begins with a rapid decrease in the supply of sediment to the channel. After 50 cycles the supply rate slowly decreases until the channel slowly starts to feed sediment to the adjacent basin. The same happens for the area upstream of the channel (where tide is less important). This development implies that at first, the initial channel is too large for the flow and has to take sediment from the basin to fill up. When the right amount of sediment in the channel has been reached, supply decreases and the channel starts to relocate sediment instead of taking sediment from the sides. Eventually the estuary reaches a state from where it can start to grow again, and sediment from the sea is put into the basin. It is sediment from the sea, because at the upstream channel the supply of sediment from the basin also has turned around, so it is not the river that supplies the sediment in the sides of the estuary. This development compares well with the development of the estuary in the sand experiment shown in figures 4.13 and 4.14. In this experiment the volume of the estuary decreased in the beginning. After that the estuary widened, and several channels started to form, but at the same time the rest of the estuary filled up partially, resulting in a net decrease of the volume. After this initial decrease, the volume remained more or less constant for 700 cycles, after which it started to increase. Of course, this experiment was done without a source of sediment input which could have altered the development of the estuary. At the same time, the channel in the experiments of Tambroni et al. (2005) had a fixed width, so that also influenced the estuary. Also, the trend of the experiment done by Lanzoni and Seminara shows a development that is comparable with the high-amplitude sand experiment from figure 4.16C. This experiment also has an increase in the volume of the estuary in the beginning, but after that it mainly starts recycling its own sediment and the total volume of the estuary decreases again.

The results were found during small-scale experiments, but they represent the natural processes quite well. This means that, while the estuary is developing, a constant formation of channels and bars is active as in the process displayed in figure 5.1. In this research, especially in the experiments with polymer sediment particles, the relocation of channels and bars stopped when the widening of the estuary came to a halt. It seems that low flow characteristics and the shortage of sediment supply are more important for this 'equilibrium state' than the process of bar and channel formation though, because often there were no real patterns visible in such a stable state. This research was mainly focused on the effects of tidal characteristics and initial settings of the estuary, but from what can be seen here, it seems sediment availability also plays an important role in the formation of tidal systems.

What are the effects of (tidal differences in) flow velocity, tide duration, tidal water level, amplitude, width and depth of the system on the formation of bars/channels?

There is no visible effect of asymmetry on the formation of bars and channels in the experiments. In experiments with asymmetric tidal amplitudes, it is one tide that 'determines' how the bars will form in the estuary. The other tide, either having a higher or lower amplitude, will just 'follow' this pattern and act like it has the same amplitude as the dominant tide. It is hard to compare this to nature, as the process of forming channels still is not understood well enough to see the direct influence of the amplitude without the effects of river influence and dimensions of the basin.

Furthermore, tide duration and water level were characteristics of the estuary that were hard to alter in the experiments. Increasing the water level would often flood the entire basin, which was especially dangerous for the polymer experiments, as the high mobility of the sediment would cause the floodplains to be eroded away before the channel had a chance to influence those locations. Lowering the water level did not alter the basin much, on the other hand, as flow would still be concentrating itself in the initial channel. It is thought that if the mean water level affected the experiments, this originates from the difference in the volume of the seas at both sides of the basin, because those volumes could variate differently for different water levels. However, since the seas never had the exact same volume, it is hard to deduce the role of the water level on channel mobility. Tide duration has a lesser effect on the sediment, but more on the water flow itself. Decreasing the duration of the tides, especially in the sand experiments, caused the formation of a wave in the estuary. At the moment the tides turned, the flow of water was preceded by wave. This type of wave is not natural for most estuaries and it is unclear what the effects of this wave are on the basin, therefore the wave height was kept as low as possible. This means, however, that all the water in the basin is flushed through the system before the end of the tide. There was no circulation of water inside these experiments, so increasing the duration of the tides is superfluous, as the effect of circulation never occurs in the first place. The theory that water circulation affects the formation of bars and channels therefore is not possible to prove within this investigation.

Comparison based on characteristics

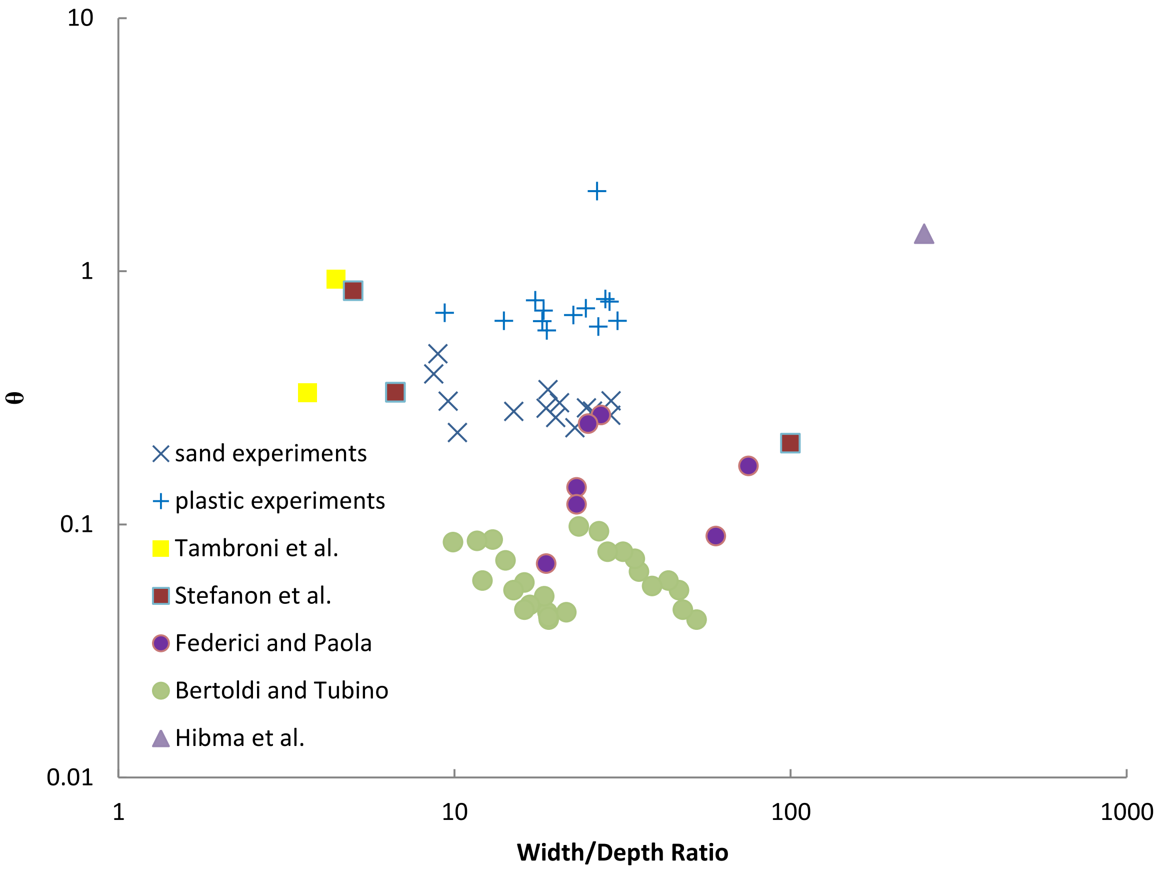

Figure 5.7: Comparison between the experiments in the tilting basin and experiments by others, and natural estuaries.

The comparison between the experiments and results from others is shown in figure 5.7. All results are based on received from experiments, models and real estuaries, except for the results from Federici and Paola (2003), and Bertoldi and Tubino (2007), which come from braided river experiments. Furthermore, only the experiments that resulted in channel formation are displayed in this figure. It is clearly visible that the results received in the experiments fall between all the results from other experiments.

The braided river experiments were done under different circumstances than the tidal environment that was set up in the tilting flume. This resulted in a lower Shields number, but the width/depth ratio is more or less the same. Still, the patterns that formed in both sets of experiments look alike, so one could expect that both processes –braided bar formation and tidal bar formation – would relate to each other in some way. The difference in Shields number could be explained by the short duration of the tides in the experiments: the sediment had to be very mobile to come into motion in the short time water flow had reached its highest velocity. For rivers this is not the case. A new investigation with a longer duration of the tides could probably give more insight in this problem.

The modelling result of Hibma et al. (2004) is also shown in the graph of figure 5.7, and its most prominent aspect is the high width/depth ratio used in the model. However, the tidal system formed in the model of Hibma et al. was better developed than just a channel and a bar, with real forking ebb- and flood tidal barbs. The mobility of the sediment in the model is only slightly larger than the mobility in the experiments. This means that the lower mobility of the braided rivers really seems to be river-related.

The other tidal experiments also spread across the diagram. The research of Stefanon et al. (2009) did not focus on the formation of tidal channels in an estuary, instead they focused more on the formation of the estuary itself. Therefore no tidal channels were created in the experimental setup. There should be any formation of tidal channels in one experiment though, because the results of Stefanon do have the same mobility as the other tidal experiments. The opposite is true for the results of Tambroni et al. (2005). These experiments focused on the simulation of channels in a tidal environment and succeeded. The width/depth ratio of these experiments are even lower than those of Stefanon, but also have the same range of sediment mobility. Even though mobility and width/depth ratio of the experiments of Tambroni et al. and Stefanon et al. do not differ much, the results of the experiments do. Clearly the width and depth of an estuary does not have a large impact on the formation of tidal channels. This connection was thought to exist during the experiments (a deeper channel will induce more sediment transport, therefore more bars and channels will form), but this diagram proves otherwise.

The mobility also shows us how important the tidal amplitude is. If the channel's width-to-depth ratio is not in equilibrium for the active tidal amplitude, channels will start to form. If channels are too small a soft perturbation can help in starting the formation of channels. However, as long as the tidal amplitude is too low, only simple channels will form. To get a system that keeps perturbing itself – and thus keeps forming new channels and relocating old ones – tidal amplitudes have to be sufficiently large. This does not mean that larger tidal amplitudes will always form better developed channels and bars. The rule 'slow but steady' also applies to tidal systems: as long as tidal amplitudes are sufficiently large, channels will form. At the moment they become too large, channels will develop too fast. This means that no clear bars will form. Instead of the bars becoming obstacles for the flow, guiding both directional flows into their own channels, the sediment will be transported constantly. Normally, more sediment on a certain location leads to lower transport, since the lower depth automatically induces lower velocities at that location (Kleinhans et al., 2012). When the amplitude becomes too large, this does not matter though. Even on the shallower parts the flow velocity will be large enough for sediment to come into motion. This probably would not be a problem if there was some kind of sediment input. However, in the case of our experiments there were two seas on both sides of the estuary that basically just were large sediment collectors, while there was no form of sediment input. This means that all moving sediment would end up in the ebb tidal delta before it could form any bars. This phenomenon could be the reason why there are no clear trends in the bar formation diagram, as experiments with a large mobility still could be classified as underdeveloped channels. Whether this phenomenon also is applicable to natural estuaries is not clear, as those estuaries have a natural supply of sediment. Also, natural estuaries have a more or less fixed tidal amplitude, so it is hard to say what would happen would the tidal amplitude suddenly increase. Tidal amplitude is a critical factor in the formation of tidal channels, but to what extend still needs to be investigated.

Relating the experiments to the bar pattern prediction model of Kleinhans and van den Berg (2011) (figure 1.4) also did not result in good results. The streampower in the experiments simply is too low to be predicted well in the diagram. This could have multiple causes. The first one is the chosen value for the constant to calculate the reference width W_r. For experiments with sand, this value was chosen to be 4.7, just like Kleinhans and van den Berg (2011) used for their sandy rivers. For experiments with polymer sediment, this value was chosen to be 3.0, just like gravel rivers. This value was chosen because of the large grains in the river, which compared better to the grain size of gravel in real rivers. Van den Berg (1995) showed in his paper that there are more values for α that could be used to calculate the reference width. Their effects remain small however: even when the value of the constant was reduced with a factor 10 (to 0.3) the streampower was not affected a lot, and rivers would still be predicted to have no pattern. Only when the constant was reduced with a factor 1000 (to 0.003) experiments were predicted to be braided rivers. This is not true either however, because not all experiments would produce bars. For these experiments the diagram would give an overestimation of the mode the estuaries would fall into. This overestimation could also be caused by the fact that streampower is also calculated from the bankfull discharge of the river. For experiments, this value is very small simply because the dimensions of the channel are a factor 1000 smaller than the smallest rivers. Of course the small value of Q is partly compensated by the small value of W_r, but not enough to create reasonable streampower values. Possibly streampower needs to be calculated in a different way for estuaries, because the valley slope is a lot less important than tidal amplitudes. Since ebb and flood have different amplitudse, the valley slope should be changed to make up for that. Maybe the low value of the streampower would also be affected by this change.

What are the differences in the circumstances of tidal environments that decide what kind of tidal system forms, being it flanking, forking or something completely different?

Contrary to the belief of Van Veen (1950), who described that flanking and forking channels were two distinct features in a tidal environment, the experiments in the flume showed that both patterns are representative for certain kind of environment. In the experiments both kinds of patterns even could be representative in the basin at the same time. This means that the occurrence of flanking and forking channels is quite systematic: what the experiments showed was that the basin initially tends to form forking channels. Even when a soft perturbation is installed in the estuary, one tide will eventually take a (short) dominance over a part of the channel and shallow the channel in his direction. The other tide then only can flow around that obstruction, since that is the path with the least resistance. This system corresponds with the results of Tambroni et al. (2005) and Seminara and Tubino (2001), who state that bars start from an instability in the bed of the estuary. This formation of bars is similar to the formation of bars in rivers, which makes it more strange that the activity of bars does not correspond with research of Kleinhans and Van den Berg (2011). Since the patterns formed display everything from no activity to braided patterns, one would expect that the results plot over the whole length of the diagram, but all results plot in the area where no formation of bars was predicted.

For the flanking systems it is the other way around: these patterns are found in later phases of the experiments. Since forking systems have one dominant channel in the middle and two recessive channels on the side, it is not in equilibrium in an estuary where both tides have an equal magnitude. For flanking systems both channels are able to form equally large channels, and thus are more in equilibrium than the flanking system. That we barely see flanking systems in equilibrium is because the channels can continue to grow during the experiments, since sediment is not cohesive. At a certain moment one channel will cut off the other, forcing it into a bifurcation. However, since the beginning of the channel often still is quite well developed, the bifurcation will experience more flow than at the start of the experiment, so the point where one of the channels will be abandoned will happen faster. At this point, the system will be more or less flanking again. This shorter development from forking to flanking probably is the reason why later in the experiment more flanking systems occur.

It is not clear for how far this formation is entirely natural though, as in this case ebb and flood are more or less of the same value, and both are flowing straight into the estuary. Since both tidal amplitudes are of an equal height in the experiments, when one tide creates a bar the other tide will directly build further from it. The formation and movement of bars is not something that occurs due to a certain net mean current that results from a difference between the two tides (Garotta and Bolla Pittaluga, 2004, in Tambroni et al., 2005).

Future Research

In my experiments, the focus of the scenarios was on the difference between tidal amplitude and initial width and depth. Discharge in and out of the basin was kept constant, and the volume of the seas at both sides of the estuary was considered unimportant. As Leuven (2014) in his thesis showed though, discharge of a river is quite important in the development of a tidal environment. This thesis also shows some resemblance between river and estuarine bars. Therefore it could be possible that the formation of the bars and channels could differ if there was some kind of river discharge. This could be done by introducing river discharge on one side of the basin (basically changing the discharge between both sides of the basin), or the volume of the seas could be altered. During high water, the concerned sea will try to be completely drained. Altering the volume of the seas will change this volume of water , making the flow through the channel more dependent on the direct supply of water from the pump. Problems with this approach will be that the ebb delta will reach the end of the basin earlier, so experiments will have shorter runs before sediment will be spilled. This shorter duration may prove to be too short for experiments to overcome their first bar/channel formation. This definitely is something that needs to be looked into more though.

As was found out in the experiments, hard perturbations lead to simple channel patterns, as the estuary keeps being perturbed on the same location, and only those first perturbed channels will form, without developing or relocating themselves along the estuary. This was an unwanted effect in this research, but maybe it could be an interesting implementation in natural estuaries. In natural estuaries, especially ones where shipping is active, the constant supply of sediment leads to a lot of dredging every year. Future research could try to find out the exact effects of such a hard perturbation, and whether it could be used to fix channels in estuaries to encourage the deepening of the channel and therefore lower dredging, an operation that could save hundreds of millions on yearly basis. The big question of course is, if even with sediment input the hard perturbation would maintain its fixed channels. For that sediment input also has to be implemented in laboratory experiments. I do not know at the moment how any form of sediment supply could be coupled with the experiments, as a whole new cycle of sediment supply and discharge has to be implemented in the experiments. When it is possible though, the effect of sediment supply – in combination with perturbations – could result in some very interesting experiments.

This discussion stated this earlier, but the importance of sediment plays an underestimated role in the formation of channels. How this exactly works is not clear though. In my experiments the banks of the river were non-cohesive, which lead to the constant widening of the channel. The sediment from these banks then would be distributed along the estuary to form bars eventually. It is not clear what would have happened if extra sediment would have been added to these experiments. I predict that with more sediment obstructing the flow, channels will only widen more as descripted by figure 5.1, and channels will form even more braided channels. However, if the banks of the channels would be fixed in combination with sediment supply, I do not know what would happen. Changing the input of sediment in such an experimental setting could be very interesting.

More research has to be done after the relation between mobility and bar formation. I think this thesis showed that there are some relations between the two, but also that the shear stress of a channel can hold both the formation and destruction of channels. It would only seem logical that there is some kind of upper boundary that defines whether transport happens too fast to form decent channel systems. This boundary is not found in this research (mainly due to a shortage of experiments) but when more results from small-scale experiments become available it could be possible to investigate this further in future research.

6. Conclusions

This study proved again that tilting an experimental flume is a good way to investigate tidal patterns. Final phases of experiments often showed ebb- and flood tidal channels that compared well to natural tidal barbs in estuaries. Experiments done with sand displayed even better results than experiments performed with polymer sediment, which was thought to be better scaled to the experiments than normal sand.

The process of tidal channel and –bar formation does not differ much from the formation of bars in rivers. Near the end of one tidal cycle, sediment in motion will settle and form small obstructions for the opposite flow. The opposite flow then has to bifurcate around these obstructions, automatically concentrating itself in other parts of the channel. The sediment stirred by this counter flow also settles in places that obstruct the first flow, only forcing it more in the channels it created first. This way the channels will grow around one or two bars.

The main factor contributing to the formation of developing channels is the tidal amplitude. As long as the tidal amplitude is high enough, sediment particles are set into motion and form the aforementioned obstructions. At lower amplitudes perturbed channels are often able to form simple, local channels and bars, as long as the amplitude is too low. At higher amplitudes it does not matter if a perturbation is installed, as channels and bars will always form. Only hard perturbations can alter this process, as those fix channels on specific locations. The amplitudes should not be too large either though. If the mobility of the sediment becomes too large, formation of channels will go too fast, and channels will be destroyed before they have become stable. Initial width and depth also play a role in the formation of channels. Stable channels with a small cross section and a width to depth ratio in equilibrium will not come into motion easily.

Given enough time and/or sediment, tidal channels never form an equilibrium phase. The channels are always encircling each other, and one channel will block the another when it grows too far and starts obstructing the other channel. This also means that there is no real 'final phase' in an estuary. Flanking and forking channel systems will constantly alternate and succeed each other. This also means that there is no 'typical' environment that forms specifically flanking or forking channel pairs. Forking systems often form in the initial phase of the experiments, but it does not exclude them from forming in later phases of the experiment.

Appendix A: Velocity and streampower tables

Plastic	v (m/s)	Q (m^3/s)	Wr (m)	ω (W/m^2)
1	0.04	1.22E-04	0.033	0.06
2	0.04	1.26E-04	0.034	0.06
3	0.04	1.39E-04	0.035	0.07
4	0.04	1.78E-04	0.040	0.08
5	0.04	1.78E-04	0.040	0.08
6	0.04	1.78E-04	0.040	0.08
7	0.04	1.62E-04	0.038	0.07
8	0.04	1.78E-04	0.040	0.08
9	0.04	1.41E-04	0.036	0.07
10	0.04	1.15E-04	0.032	0.05
11	0.04	1.28E-04	0.034	0.06
12	0.04	1.76E-04	0.040	0.08
13	0.04	1.15E-04	0.032	0.05
14	0.04	1.28E-04	0.034	0.06
15	0.04	1.28E-04	0.034	0.06
16	0.04	1.76E-04	0.040	0.08
17	0.04	1.15E-04	0.032	0.05
18	0.04	1.15E-04	0.032	0.05
19	0.04	1.15E-04	0.032	0.05
20	0.04	1.15E-04	0.032	0.05
21	0.04	1.28E-04	0.034	0.06
22	0.04	1.28E-04	0.034	0.06
23	0.04	1.76E-04	0.040	0.08
24	0.04	1.28E-04	0.034	0.06
25	0.04	1.28E-04	0.034	0.06
26	0.04	1.28E-04	0.034	0.06
27	0.04	1.78E-04	0.040	0.08
28	0.04	1.76E-04	0.040	0.08
29	0.04	1.15E-04	0.032	0.05
30	0.04	1.15E-04	0.032	0.05
31	0.04	1.62E-04	0.038	0.07
32	0.04	1.06E-04	0.031	0.06

Table A.1: Velocity, and the resulting streampower for each plastic experiment. The α used to calculate the reference width is 3.0.

Sand	v (m/s)	Q (m^3/s)	Wr (m)	ω (W/m^2)
33	0.13	4.00E-04	0.09	0.61
34	0.13	4.00E-04	0.09	0.61
35	0.13	4.00E-04	0.09	0.61
36	0.20	6.69E-04	0.12	1.19
37	0.30	1.00E-03	0.15	2.19
38	0.40	1.34E-03	0.17	3.37
39	0.20	6.00E-04	0.12	1.13
40	0.30	3.60E-04	0.09	1.31
41	0.27	3.20E-04	0.08	1.10
42	0.30	9.00E-04	0.14	2.07
43	0.33	1.00E-03	0.15	2.43
44	0.33	1.00E-03	0.15	2.43
45	0.33	1.00E-03	0.15	2.43
46	0.30	1.56E-03	0.19	2.73
47	0.30	9.00E-04	0.14	2.07
48	0.33	1.00E-03	0.15	2.43
49	0.30	9.00E-04	0.14	2.07
50	0.37	1.10E-03	0.16	2.80

Table A.2: Velocity, and the resulting streampower for each plastic experiment.

Appendix B: Delft3D simulations

Aside from copying an estuary in a scale experiment, a computer model was also made. For this, the program Delft3D was used. This program is able to create models that compute the sediment transport due to water flow with the currently known formulae. In this case the model was not used to imitate a real estuary, but just to imitate the scale experiments that were created in the lab. This meant that, for the model to use the same values as the experiments, a certain 'upscaling' had to take place, which was actually very nice since this meant that the model could use normal sediment grain sizes to work with, as those also exist in a normal estuary.

Settings

In the model runs, the size of the basin was about two hundred times larger than the size of the basin in the lab experiments, coming to a length of 720 meters and a width of 35 meters. The initial channel depth was varying between 0.6 meter and 2 meter below the mean sea level and the floodplains were lying at 0.3 to 1 meter above this mean water surface.

The tidal amplitude was not 200 times larger than the amplitude in the lab. Making a tidal wave with an amplitude of 0.6 meter would flood the floodplains during flood, while the water depth in the channel would be only 40 cm during ebb, resulting in supercritical flow, something the model does not play nicely with. Thus, the typical amplitude is 30 cm, 10 times larger than the laboratory experiments. Scenarios where the amplitude was 50% or 150% of this value were used too, but please note that the heights and depths of the basin were changed in these cases too. An amplitude of 30 cm leads to good flow velocities in the channel though, around 1 meter per second, so this value seems to be all right. The speed of the tide is set at 90 degrees per hour, so one tidal cycle takes 4 hours.

On both sides of the basin an open boundary is set, where the water level can change, but these boundaries are set out of a phase of 180 degrees, so that when it is low water at one side, it is high water at the other, just like the experiments. This creates a gradient in the water level that induces the flow of water, rather than tilt the whole basin to create a gradient on the basin itself, but this should be enough to create flow. Experiments are performed both with and without a sea, which is a body of water with twice the depth of the channel, occupying the whole width of the basin with a length of 5 grid cells. When a sea is used, it lies at both sides of the basin, just like in the experiments.

Two types of scenarios were run: water level-forced scenarios and flow velocity-forced scenarios. The main initial conditions were the same between those scenarios, but there was one main difference: water level-forced scenarios existed of experiments with forced fluctuating water levels at both sides of the grid. Flow velocity-forced scenarios had forced flow velocities, leading to different water levels, instead. In these scenarios one boundary would have an influx of water, while at the other side an outward flow would be defined. The change of inflow and outflow then would change with a harmonic motion. In theory, this led to the same results in the experimental settings, as flow velocities were chosen such that the water level at the border would change at the same pace as a water level-forced experiment would do. This difference in forcing would affect the behavior of the model itself though, so different results in the model output could be expected. The different scenarios are shown in table B.1 and B.2. For the experiments that had flow-defined boundaries no sea was defined at the boundaries. After a while the sea was added to some of these scenarios, and of course the defined flow velocity at the boundaries would decrease (so if the sea was 10 times as deep and 3 times as wide, the flow velocity at the boundary would be 30 times lower).

D (m)	Amplitude (m)
0.6	0.3
0.3	0.3
1	0.3
0.6	0.15
0.3	0.15
1	0.15
0.6	0.45
0.3	0.45
1	0.45

D	Velocity (m/s)
0.6	1
0.3	1
1	1
0.6	0.5
0.3	0.5
1	0.5
0.6	2
0.3	2
1	2

Tables B.1 and B.2: Combinations of initial settings for the Delft3D model scenarios.

The process

At first, the changing of the water level seemed enough to get the desired channels. Sediment transport was clearly visible and it behaved naturally. The model had one peculiarity though: near one of the open boundaries, sediment would endlessly erode, providing enough sediment for the whole basin. As the initial sediment thickness was set at 100 meter (to prevent getting errors for reaching the hard bottom of the basin) this meant that this one cell could produce an amount of 2500 m^3 of sediment, while the rest of the channel would silt up.

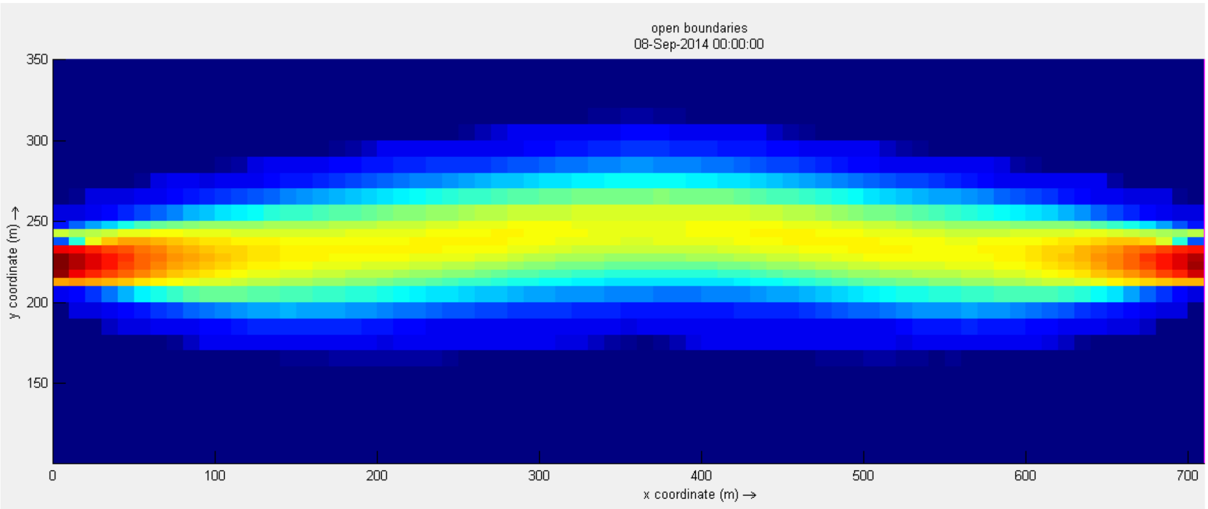

Figure B.1: Formation of a small bend in the estuary. Note the large scour at both boundaries of the grid.

Another phenomena seen is the formation of 'a pair of glasses' (figure B.2). In the channel there would start to form to parts where the channel really widened. In between those parts, in the middle of the basin, the channel would remain narrow though. In this part, and at the edges of the channel, the channel would deepen, while at the glasses the channel would become shallower. This state would often remain for a very long time, slowly eroding the bridge in the middle, until that was eroded away and the channel could widen over the whole width of the basin. This phenomena resulted often in a situation where the whole basin would slowly silt up, and the model would create an error as the water level increase may not be more than 5% of the current water level – something that would happen when the whole system is only a couple of centimeters deep.

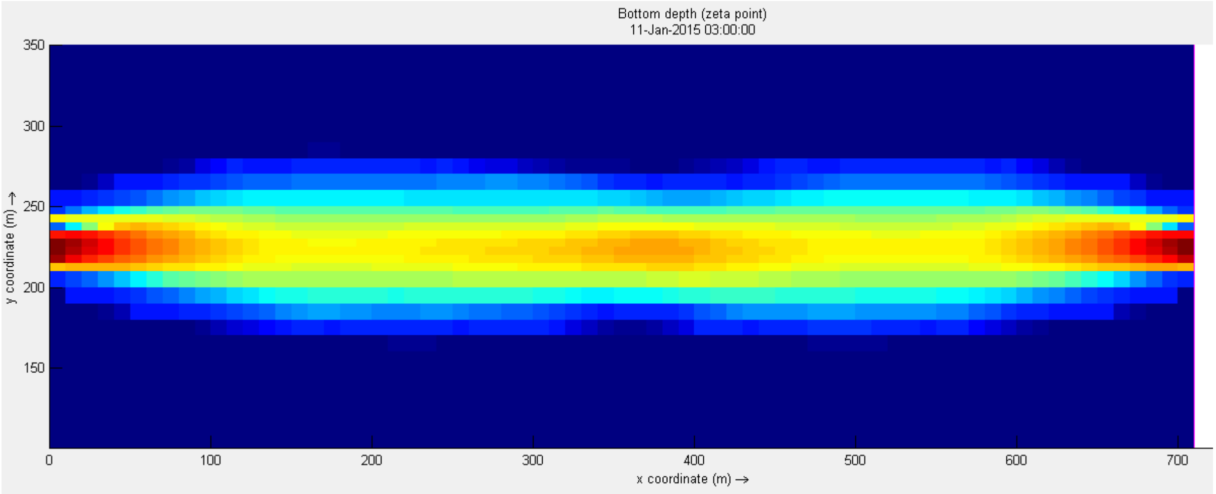

Figure B.2: Formation of a pattern that looks like a pair of glasses: the channels remains small at the boundaries and the middle, while deepening the channel there. The rest of the channel widens, forming a pattern that looks like the pattern displayed in figure 4.5

To prevent this phenomena, the open boundaries were changed from water level boundaries to flow velocity boundaries. This way, instead of changing the water level on the boundary, the flow velocity through the boundary changes. The typical velocity amplitude used was 0.5 meter per second, to keep things safe, but scenarios with 50% and 200% of this value have also been run. The duration of one tidal cycle still is four hours, and the boundaries are still 180 degrees out of phase. The idea behind this change of the boundaries is that when input on one side and output on the other are the same, water in the whole channel will have to flow through the whole length of the channel.

There is just one flaw with the implementation of velocity boundaries in the basin though: the water level in the basin slowly rose. How this works precisely is not known, but the current theory describing this phenomenon is as follows :

On the side where the water is flowing in, the water level is naturally pushed up. Since the flow velocity that is set on the boundary is flowing through the whole surface that is delimited by the basin boundaries and the water level, the amount of water that is flowing in rises with this rise in the water level. With other words, the flow velocity on the boundary was determined to get a total water inflow that would be the same as the inflow that was created by the changing of the water level. This value is not the same, however, as the inflow during flood continues to rise as the water level is not fixed. The same is true for the ebb-side of the basin. When there is outflow on a boundary, the water level there will fall, and the total amount of water that goes through the boundary will fall with it. You could say the model is too smart for its own good, for this change in water level was an effect that was not accounted for. The effects of this phenomenon are that the total inflow of water rises, while the outflow of water falls, resulting in a net inflow of water, and since the tides in the basin are ebb and flood *at the same time*, there is no moment for the water to flow out of the basin. The water level in the basin will keep rising until the floodplains are flooded and the whole basin just one big sea.

To prevent this phenomenon, instead of velocity boundaries discharge boundaries were set. These boundaries should not be dependent on the water level at the boundary, as they would just spread their discharge over the whole surface of the boundary. This is not true though. It seems that the discharge boundaries use discharge per square unit, and increasing the total surface would increase this discharge to. At this moment both velocity and discharge boundaries thus do not seem to work properly, as the defined channel is flooded in no time.

Discussion and conclusion

Hibma et al. (2003a, 2003b, 2004) showed that it is possible to mimic estuaries in a model. This small study showed however that the simple yet unrealistic scenario that was built here is not effective. Possibly the small scale of the experiments was the limiting factor here, as the model of Hibma et al. had a grid that extended for a couple of kilometers. The calculation time that is needed to run such a model is way too long for the scope of this study. Furthermore, it does not seem logical that the scale is the limiting factor here. The experiments in the main research showed us that tidal channels can form on all scales. A length of 700 meters therefore should be more than enough to at least show one channel pair.

The program Delft3D in theory is a good program to compute geomorphology in channels, but the setup used in our scenarios is too unnatural to work with in this program. Either the program makes some computational errors that create very deep scour in some cells, or the system just floods so fast the biblical flood seems no more than a cold shower. It is too bad, as modelling the system would create data a lot faster than the experiments would do, but this way nothing can be done about it.

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