Scroll bar formation in experimental meandering rivers

MSc Thesis Earth Sciences

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Date: 14-5-2013

Abstract

Even though scroll bars are often observed in meandering rivers, it is still not evident what exactly causes their formation. According to several studies on natural rivers, scroll bars only form when there are discharge variations and therefore pulses of outer bank erosion. Otherwise a flat point bar would develop as a continuous process. However, numerous flume experiments have reported on scroll bar formation while discharge is constant. Also, there are observations in natural rivers that sedimentation on the inner bank causes outer bank erosion. The objective of this research is to determine if erosion of the outer bank or variation in sediment supply is the leading process for the development of scroll bars. In order to study the development of scroll bars while controlling the boundary conditions, an experimental meandering river was created in a 3x11m flume. Eight cases were performed in developed bends, which included the addition of sediment pulses and removal of part of the outer bend. Sediment pulses were added in order to determine if variations in sediment supply from upstream causes individual scroll bars to form and whether inner bend accretion is the dominant process in bend migration. This was done in an already migrating bend and in a bend that did not migrate before the perturbation. Part of the outer bend was removed several times in order to determine if outer bend erosion is the dominant process leading to scroll bar formation and bend migration. This corresponds to discontinuous outer bank erosion in nature. Also, in one bend the outer bank was fixated, in order to see if scroll bars would still develop if there is no erosion of the outer bend . In nature this corresponds to a meander bend with a high bank strength. In all cases the accretion of the inner bend and the erosion of the outer bend were monitored and flow velocities were measured. Scroll bars were observed in all bends that migrated and were formed by multiple bedforms that were deposited by secondary currents. Channel width increased downstream of the apex of these bends, causing flow velocities to decrease. Therefore, scroll bars were formed at the downstream end of a bend. Forced sediment pulses did not cause individual scroll bars to develop and had no significant effect on flow velocities and outer bend erosion. In the bend that was fixated, eventually no sediment was deposited on the point bar anymore and therefore also no scroll bars formed. However, each removal of part of the outer bend caused flow velocities to decrease at the inner bend due to the increase in width, which caused a scroll bar to develop. Erosion of the outer bend is thus the leading process in scroll bar formation and channel width variations are essential to explain sediment deposition and meander bend migration. Further research can be done on scroll bars in relatively sharp bends where flow separation zones are present. Also, in several natural rivers relatively wide scroll bars are observed, which differ with the scroll bars in the experiment.

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1. Introduction

On the point bar of meandering rivers, scroll bars can be observed. A scroll bar is a ridge on the inside of a meander bend which parallels the curvature of the channel and is separated from the inner bank by a swale (Nanson 1980, Kleinhans and van den Berg, 2011). Over time, multiple successive scrolls can form on the point bar, creating a ridge-swale topography. In figure 1.1 an example of a meander bend with scroll bars in the Ob river (Russia) can be seen. Even though this feature is often observed at meandering rivers, it is still not evident what exactly causes the formations of discrete scroll bars rather than nearly level floodplain surfaces caused by gradual inner bank sedimentation and gradual outer bank retreat (Nanson, 1981). In this research, the focus is on scroll bar formation with the specific objective to determine if erosion of the outer bank or variation in sediment supply is the leading process for the development of scroll bars.

First, a literature review is presented to provide background information needed to understand the process of meander development, to describe the several theories that exist on the formation of scroll bars and to identify the subjects that need further research. With this knowledge, the objective and research questions are stated. Then, the current experiment will be described, followed by the results and conclusions.

Figure 1.1 – A meander bend of the Ob river, Russia. Scroll bars can be recognized, e.g. on the inside of the bend. Rather chaotic patterns of scroll bars are visible, which are a record of past meander migration.

2. Literature review

2.1 General morphology of a meandering river

The geometry of a meandering river can be described by several characteristics. The channel sinuosity is defined as the length of the channel divided by the length of the valley (Bridge, 2003). The definition of the bend wave length, radius of curvature and the wave amplitude are shown in figure 2.1.

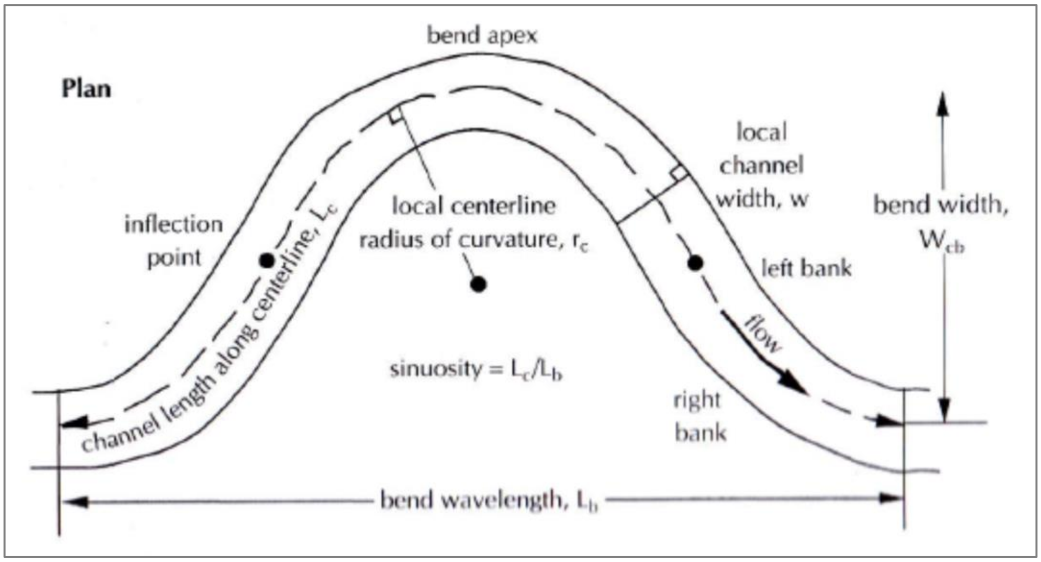

Figure 2.1 - A schematic drawing of a meander bend, indicating the definitions of geometrical parameters (Bridge, 2003).

In the inner bend of a meander, a point bar develops. A point bar is defined as an accretional body of sediment within the channel against the convex bank of a bend (Nanson, 1980). A point bar therefore extends from the deepest part of the channel to the starting point of accumulation (the left bank in figure 5). At the outer bend, a much steeper slope than at the inner bend develops, with a nearly vertical upper part of the bank (Hickin and Nanson, 1986).

At the point bar three types of bars can be found (Kleinhans and van den Berg, 2011). A tail bar is formed behind an obstruction of the flow, e.g. stranded trees, and are therefore not related to the general flow conditions. A scroll bar is, as mentioned before, a ridge which parallels the curvature of the channel. It often points down-channel and extends for almost the entire length of the point bar. Successive scroll bars create a ridge-swale topography of the point bar (figure 2.2) and can be grouped in bundles, defined as groups of scroll bars which are oriented similarly. Chute bars form at the downstream end of a chute channel, which is formed during periods with relatively high stream power and crosses the point bar (Fielding and Alexander, 1996).

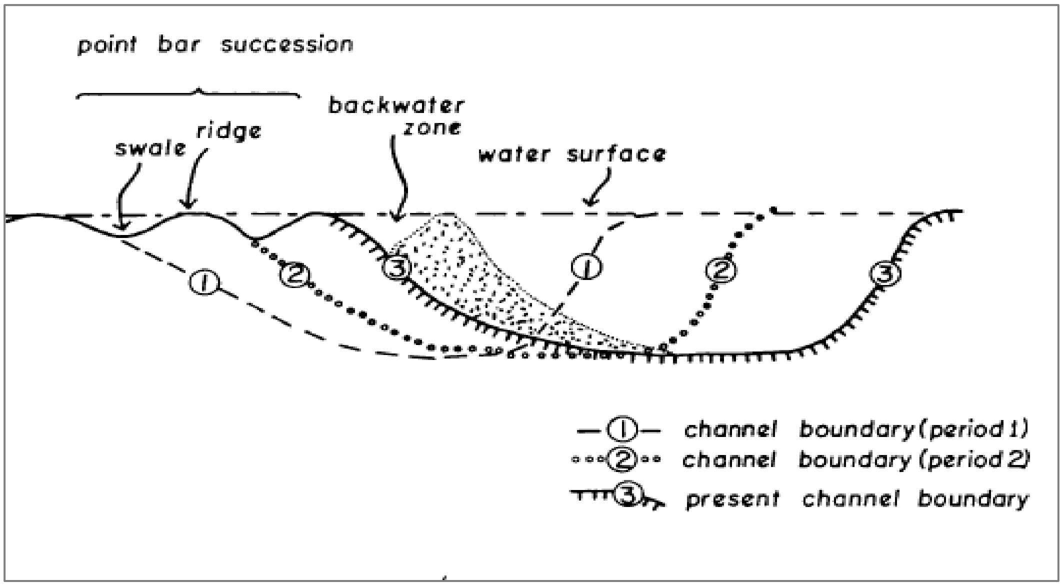

Figure 2.2 - A schematic representation of the succession of scroll bars on the inside of a river bend (left in this drawing), resulting in a ridge-swale topography (Hickin, 1974).

2.2 Development of a meandering pattern

2.2.1 Characteristics of different river patterns

River patterns can be divided in several categories, based on the formation of bars and the sinuosity of the channel segments (Bridge, 2003). Straight and meandering rivers consist of single channels with different sinuosity, while braided rivers consist of multiple parallel channels. Kleinhans and van den Berg (2011) emphasized that the channel pattern that develops depends on the formation of bars. Bars in meander bends are forced to their positions by the bends, in contrast to free bars that may migrate in braided rivers. The type of bars that develop depends on the channel width-depth ratio.

The stream power of a river is important in the formation of a channel pattern, as it represents the energy of the river to move sediment (Ferguson, 1987). The stream power (ω) is calculated as:

$$\omega = \frac{\rho g Q S}{w} \quad (1)$$

where ρ = density of the water [kg/m^3], g = gravitational acceleration [m/s^2], Q = river discharge [m^3/s], S = slope [m/m] and w = width of the river [m]. However, when trying to predict a channel pattern using stream power, these variables are too dependent on the already existing channel pattern; the slope of the river bed, the existing channel width and the bankfull discharge are characteristics of the existing channel, and therefore influence the channel pattern prediction. Therefore, Van den Berg (1995) defined a specific stream power which is independent of channel geometry, as it uses the mean annual flood discharge, the valley slope and a predicted width. Kleinhans and Van den Berg (2011) showed that the stream power of a river is correlated to the width-depth ratio and therefore the formation of bars.

Braided rivers are characterized by a higher stream power and a higher width-to-depth ratio than meandering rivers (Van den Berg, 1995).

Another important parameter influencing channel pattern is the sediment size, which determines the mobility of the bed. Van den Berg (1995) developed empirical discriminators between straight rivers and meandering rivers, and between meandering rivers and braided rivers based on the stream power and the median grain size of a river. These discriminators imply that at a given discharge sand-bed rivers braid at lower slopes than gravel-bed rivers do. Braiding rivers need higher slopes, because of the larger amount of channel erosion needed (Kleinhans, 2010).

Braided rivers have easily erodible banks, while meandering rivers have banks that are more cohesive. When a floodplain is formed at about the same rate as channel banks are eroded, meandering channels can be maintained. Therefore, meandering channels need more cohesive banks that can resist sufficient erosion, otherwise the channel would widen and become braided. The bank strength is determined by vegetation and the cohesiveness of the sediment (Kleinhans and van den Berg, 2011)

2.2.2 Incipient meandering

Lewin (1976) observed a reach of the coarse grained river Ystwyth in mid-Wales when a meandering pattern developed from an initial straight plane bed channel. First regularly spaced mid-channel bars developed, with two side channels. One channel dominated, while the other channel developed a chute bar. Eventually, these bars attached alternately to one bank. These alternating bars increased in length and height and migrated downstream. A larger tail of fine sediment developed on the lee side of the bars by deposition during lower water levels. Because of these alternate banks, the flow followed a sinuous path causing bank erosion at the opposite side of a bar. The channel therefore widened and the water level dropped, which causes the alternate banks to emerge. Bridge (2003) also observed the development of these alternate bars as described above (figure 2.3). At this stage of development, sediment is deposited on the banks on the inside of the developed bends, which causes the width to decrease and therefore the flow velocity to increase. This increase in flow velocity causes more erosion of the outside of the bends (Sundborg 1956, Pyrce and Ashmore 2005). As a result, channel sinuosity increases and a meandering planform develops. Ackers (1982) also described the onset of meandering, but in experiments. Similar processes where observed, but chute channels developed due to the low bank strength and eventually the planform became braided.

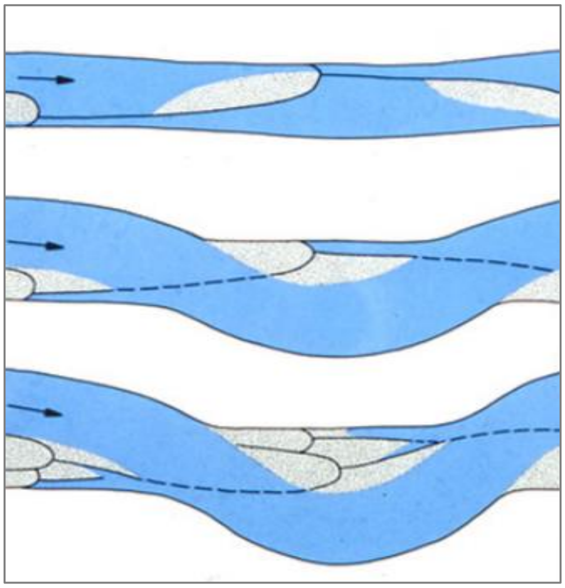

Figure 2.3 - Meander development as described by Bridge (2003). In the top sketch alternate bars in a straight channel are visible. The two panels below describe the evolution of alternate banks into point bars, by bank erosion and channel widening. Arrows indicate flow direction and dashed lines indicate topographic highs (riffles).

2.3 Influence of flow patterns on the morphology of a river bend

2.3.1 Flow patterns

When flow enters a meander bend it is directed to the outer bend, as momentum is conserved. This causes a centrifugal force, which is balanced by a rise in water level at the outer bend. This radial pressure gradient therefore causes a transverse water slope (Allen, 1970). The strength of the centrifugal force depends on flow velocity and on the ratio between the radius of the meander bend and the width. The following equation represents the balance between the centrifugal force and the pressure force (Allen, 1970):

$$\Delta z = \frac{u^2 w}{gr} \qquad (2)$$

where *Δz* = difference in water level between the inner bend and the outer bend [m], *u* = average flow velocity [m/s] and *r* = radius of the meander bend [m].

The centrifugal force increases with increasing water depth. At the bottom the flow velocity is low due to a high shear stress and the pressure force caused by the transverse water slope is therefore larger than the centrifugal force. As a result, an element of fluid near the bed will gradually curve inwards towards the convex bank. At the water level the reverse happens, as the centrifugal force is larger than the pressure force. The inward motion of the fluid near the bed and the outward motion of the fluid near the surface create a helical spiralling motion. The mean velocity and therefore the shear stress and stream power decrease from the outer to the inner bank (Allen, 1970; Blanckaert and de Vriend, 2003). Hey and Thorne (1975) also studied these secondary currents and concluded that the flow patterns are more complex and may consist of several counteracting cells. Next to the helical motion described above, another rotation cell can exist near the outer bend due to the interaction with the bank (figure 2.4). This is also described by Blanckaert and de Graf (2001).

When the ratio of the radius of the bend and the width of the river has reached a critical value and is therefore too sharp, flow separation takes place (Bagnold, 1960; Blanckaert, 2010). This means that the flow around the inner bend becomes unstable and breaks away from the boundary, leaving a zone of static or slightly circulatory water near the inner bend (Nanson, 1980). The flow separation therefore reduces the width of the main flow (figure 2.5).

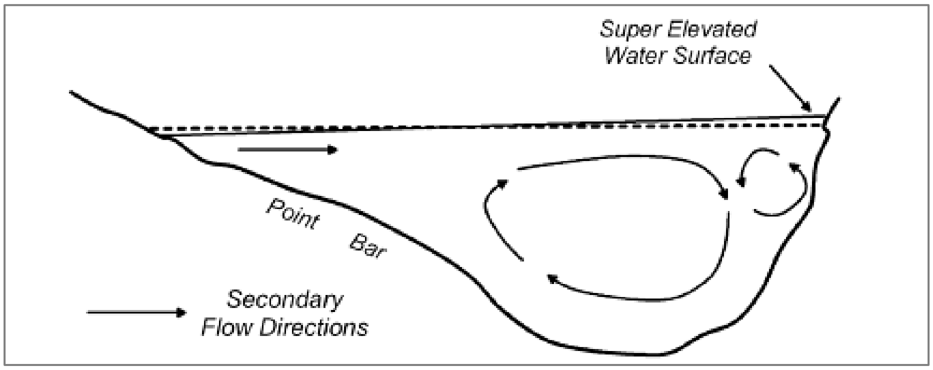

Figure 2.4 – Secondary flow directions in a cross-section of a meander bend, as described by Hey and Thorne (1975). Two counteracting cells are visible near the outer bend.

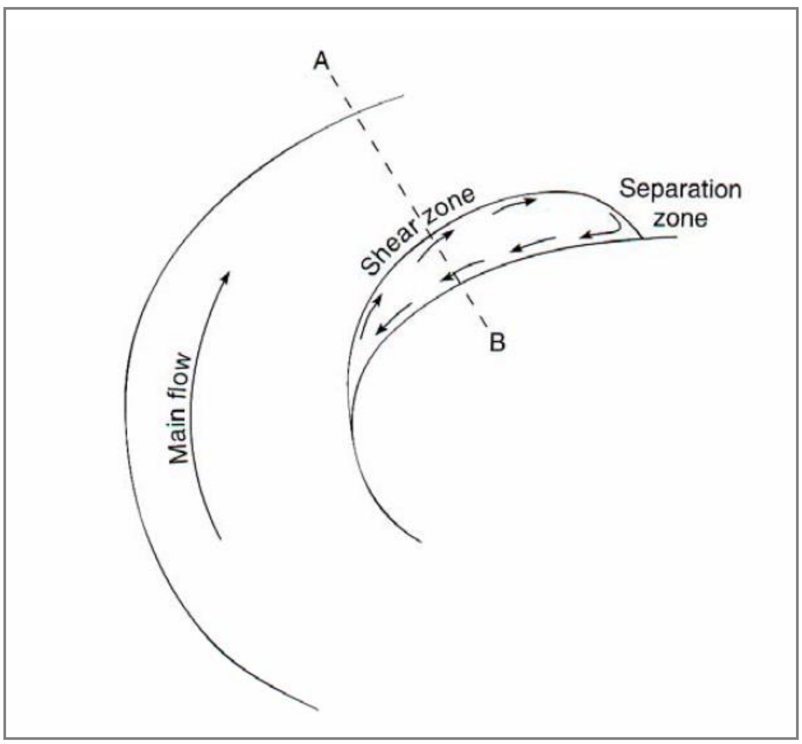

Figure 2.5 - Schematic representation of a flow separation zone near the inner bank of a river bend (Nanson, 1980).

2.3.2 Morphology of the river bed

In a meandering channel a characteristic morphology of pools and riffles can be found. Also, dunes and ripples are a normal feature on sandy river beds with high bed load transport (Sundborg, 1956). Pools are defined as the central part of the deep channel areas and riffles as shallow areas between pools (Hooke and Harvey, 1983). When there is a pronounced curvature increase, the flow tends to flow straight on and collides at an oblique angle with the outer bank . This causes vertical downwelling of the flow, which is subsequently inwardly directed near the bed. The development of the pool scour can be attributed to this process, as the sediment transport capacity is here locally higher than the sediment supply (Blanckaert, 2010). At successive bends the direction of rotation of the secondary currents is reversed, because of the opposite curvature of the bends. At the inflexion point between two bends there is therefore no secondary circulation, as old cells are dissipated and new ones are developed (Hey and Thorne, 1975). At this zone flow diverges and sediment is deposited as the main current moves from one bank to another (Church and Jones, 1982). The sediment that is deposited originates from the pools and forms the riffles. The riffle is often continuous with the point bar downstream, especially in rivers with low sinuosity (Pyrce and Ashmore, 2005). Luchi et al. (2012) observed that the maximum channel width is experienced close to inflection points and the minimum close to the bend apex where the pools are located. Blanckaert (2010) stated that in regions of pronounced curvature change, the cross-sectional area increases leading to a reduction in flow velocities.

According to Allen (1970) dunes will occur in the deeper part of the bend, while ripples will be present at the shallower parts due to the differences in amount of shear stress. Because the shear stress and stream power decrease from the outer to the inner bank, the height of the dunes can be expected to decrease radially inwards (Allen, 1970). Also, as the water near the river bed has a larger component towards the inner bend due to secondary currents, bedforms are observed to curve slightly inwards when moving through a river bend (Sundborg, 1956). According to Kisling-Møller (1993), the tendency of rotation of the bedforms towards the inner bend increases near the inner bank and down the bend. At the downstream end of the point bar, the rotation is at a maximum and the dune migration direction deviates from the main flow direction by about 60 degrees. Ashmore (1982) observed bed load sheets in rapidly evolving bends, with the same tendency to accrete to the point bar.

2.3.3 Transverse bed slope

Sediment that is carried as bed load transport is driven slightly towards the inner bend as a result of the inward motion of the secondary flow. Here, a point bar is build up in the inner bend as sediment is swept up the bar slope. The steepness of the point bar slope that is formed is determined by the strength of the secondary flow, because the downslope component of the particle weight is balanced with the upslope component of the fluid force caused by the secondary flow *(*Allen, 1970*)*. The slope therefore increases with increasing water surface slope and flow velocity, and decreases with increasing radius of the meander bend.

However, Struiksma et al. (1985) stated that not only the balance between the upslope drag force and the downslope gravitational force is important, but also non-local effects should be taken into account. The secondary flow patterns and the transverse bed slope do not appear instantaneously, but adapt asymptotically. The same holds for the downstream end of a bend. Therefore, the lateral bed slope is also influenced by a difference between the conditions upstream and those in the bend. Struiksma et al. (1985) therefore identified adaptation length scales of the flow and of the bed disturbance. When the adaptation length scale of the flow is smaller than the adaptation length of the bed, the flow has already adapted to an upstream perturbation while the bed has not. The flow then has to adapt again to the changing bed. In this case, a significant part of the transverse bed slope is caused by an overshoot effect induced by the redistribution of the water and sediment motion in the first part of the bend. When the reverse is the case, i.e. the adaptation length scale of the flow is longer than the adaptation length of the bed, a disturbance disappears in a short distance downstream and has less effect on the transverse bed slope downstream.

Hooke (1975) stated that the importance of secondary currents is not very important for the formation of a point bar. Flume experiments suggest that point bars are primarily formed due to inertial forces that transport sediment from the preceding outer bend. Secondary currents only modify the point bar when sediment is already deposited. However according to Nanson (1980) the theory of Hooke is not supported by observations in many rivers.

Because the transverse component of the flow velocity and therefore the shear stress decreases from the outer bank towards the inner bank, the mean particle size of the bed load material also decreases from the deepest part of the channel towards the inner bend *(*Allen, 1970). Variations in discharge cause finer material to be deposited on top of coarser sediment (Leopold & Wolman, 1960). According to Pyrce and Ashmore (2005) point bars consist of a coarser part upstream of the meander bend apex and become finer downstream.

2.3.4 Erosion of outer bank

The amount of erosion of the outer bend is a result of the strength of the helical flow and the resistance of the outer bank (Nanson and Hickin, 1986). As mentioned before, this resistance is determined by the vegetation and the cohesiveness of the bank material. Simon et al. (2000) also investigated the influence of pore-water pressure on the stability of the outer bank. According to Nanson and Hickin (1986) vegetation can only protect the upper part of the bank that is situated above the water level, causing the bank beneath the water level to be fully exposed to boundary shear. Hickin and Nanson (1975) stated that the main mechanism of erosion of the outer bend is undercutting of the bank at high discharge and subsequent slumping of blocks of sediment at lower water levels. These failed blocks can protect the bank temporarily against erosion, as the flow cannot attack the bank and must remove the failed material first (Simon et al., 2000).

2.4 Meander migration

2.4.1 Erosion-deposition balance

According to Leopold & Wolman (1960) the amount of bank erosion of the outer bend is in most cases approximately equal to the amount of deposition on the inner bank, as the sediment that is eroded has to balance the sediment that is deposited (Kleinhans, 2010). Therefore, the width and cross-sectional area remain about constant when migrating laterally. However, Nanson and Hickin (1983) stated that lateral migration is discontinuous and therefore the width varies around an equilibrium width. Lateral migration of a meander bend is discontinuous as there are discharge variations, but also the erosion of the concave banks does not have to be the same during comparable floods. The differences in migration rate on the short term can be a result of differences in bank strength, but also from differences in the stage of an erosion-deposition cycle described by Nanson and Hickin (1983); when a river bend experiences a flood, the concave bend can undergo severe erosion while the accretion of the point bar is much slower. Therefore the width of the river increases, causing the flow velocity and therefore the erosion of the concave bank to be lower at the next comparable flood. Meanwhile the lateral accretion of the point bar continues until the equilibrium width is reached again. The migration rate of a meander bend therefore depends on the rate that the point bar accretes and adjusts the width. This rate of accretion depends on the sediment supply and is for example influenced by the amount of erosion of the outer bank of a bend upstream.

2.4.2 Migration rate

Hickin and Nanson (1975) determined the rate of lateral migration by examining the spacing between successive scroll bars and the time interval between their formations. They stated that when the discharge or the slope of the water level increases, the rate of lateral migration also increases, due to the increase in stream power. The bank strength of the outer bend also influences the migration rate, as it affects the erosion of the outer bank.

The ratio between the radius of the bend and the main width of the channel is an important parameter, as this determines the strength of the secondary current. When a meander is formed, the ratio is generally larger than 5 and there is only a slight asymmetry of the velocity distribution towards the outer bank (Hickin, 1978). Secondary circulation is therefore weak and the rates of channel migration are very small due to relatively small shear stresses at the outer bend (Hickin, 1974). However, the channel does migrate and this causes the bend to sharpen. When the ratio therefore decreases, the flow experiences an increase in transverse acceleration and therefore also an increased transverse water slope and secondary circulation. The bend tightens and because of the increase in secondary flow the shear stress and therefore the erosion rates at the outer bank increase (Hickin, 1974). In the research of Hickin and Nanson (1975), the migration rate reaches a maximum when the ratio between the radius and the width approaches 3. This in turn implies that the migration rate decreases when the ratio becomes smaller than 3 which can be explained by the internal distortion resistance that increases when the secondary circulation becomes larger. When the ratio is near the value of 2, the bend is so sharp that the separation zone near the convex bank breaks down into eddies which increases the total resistance significantly (Bagnold, 1960; Hickin, 1974). Hickin (1978) did not find this, but stated that the maximum flow velocity shifted towards the inner bank at ratios smaller than 3. The declining shear stresses at the convex bank therefore cause the migration rate to become negligible. Deposition at the point bar also stops due to the increasing shear stress at the inner bend. Jackson (1976) found that natural meandering streams all have a ratio between the 1.5 and 4.3.

When the migration rate at the apex of the bend is very small due to the small radius to width ratio, elsewhere in the bend the channel will try to migrate to increase the radius of the bend (Hickin, 1974). Therefore most bends observed in nature have a ratio between the 2 and 3 (Leopold and Wolman, 1960, Hickin and Nanson, 1975). Also, adjacent meander bends influence the rate and direction of lateral erosion of each other. An increase in the radius of a bend often results in a decrease in radius of an adjacent bend (Hickin, 1974).

When the amplitude and sinuosity of a meander bend increases, the bed slope decreases. This can cause the formation of chute channels (Peakall et al., 2007). Flow through a chute channel can further reduce the sediment transport capacity in the meander bend, such that the flow is even more diverted into the chute (Grenfell et al, 2012). A chute channel can therefore disturb the lateral migration of a meander bend and can cause a new meander bend to develop (Sundborg, 1956).

2.5 Scroll bar formation

A scroll bar starts to form upstream of a meander bend against the inner bank and grows downstream parallel to the inner bank while simultaneously growing in height (Allen, 1970). As mentioned before, scroll bars are associated with meander bend migration. However, it is still not evident why scroll bars form instead of a plane point bar. Hickin (1974), Nanson (1980), and Nanson and Hickin (1983) conclude that scroll bars develop when the concave bank is eroded and the convex bank has to accrete in order to maintain the equilibrium width. Also, according to these studies they can only form when there are discharge variations and therefore pulses of outer bank erosion. When there is no significant difference in discharge, a flat point bar would develop as a continuous process. However, for example in the experiment of Pyrce and Ashmore (1995) scroll bars are observed while discharge is constant.

How scroll bars are first initiated is described in several theories. According to Nanson (1980) accretion of the point bar is done by new bars that are deposited by secondary currents. The process is described as; the sediment is deposited along the boundary between the flow separation zone and the main flow, where the shear stress and velocity is low and the sediment supply the highest. In the flow separation zone there is probably also some flow circulation that moves sediment towards the boundary, as Hey and Thorne (1975) occasionally observed a small circulation cell at the inside of the meander bend. Therefore a ridge is formed along the boundary between the main flow and the flow separation zone, which is separated from the point bar by a swale area. In figure 2.6 this theory is illustrated in a schematic cross-section of a meander bend. In the figure two scroll bars are visible which are indicated by ‘silt lens’, separated by a lower swale area. When the concave bank is eroded again at the next flood, a new ridge is formed stream ward of the previous deposited ridge. A sequence of sufficient erosion of the outer bend is needed, followed by deposition of the ridges by secondary currents on the inner bend.

Nanson (1980) also explains the preservation of the deposited ridges when new sediment is deposited during preceding floodings; the secondary currents on either side of the scroll bars show a tendency to converge downstream and towards the crest. Therefore, when fine sediment is deposited between the ridges during falling stage, it is redistributed towards the crest by secondary currents during the next flood. The ridge-swale topography is therefore preserved, even though there is a large amount of sediment deposited on top.

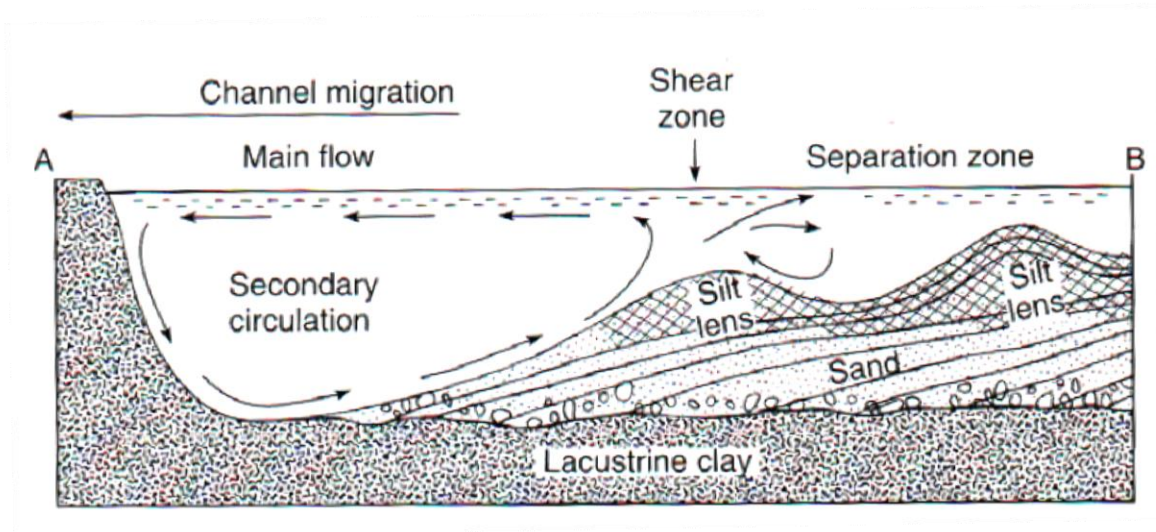

Figure 2.6 - A schematic representation of the location of scroll bar deposition ('silt lens' in this drawing), caused by the interaction between the secondary circulation cell and the separation zone (Nanson, 1980).

Nanson (1980) also suggested that a bimodal sediment distribution can result in the formation of scroll bars. Flow velocity declines towards the convex bend and therefore the coarser sediment is deposited some distance from the existing point bar, while the finer sediment is deposited closer to the point bar. In between no sediment is deposited, because of the discontinuity in the range of sediment sizes. Therefore, a ridge of coarser sediment is separated from the point bar by a swale area where no sediment is deposited.

Sundborg (1956), and Kleinhans and Van den Berg (2011) state that scroll bars are build up by transverse bars that migrate from the main channel towards the point bar. As the water near the river bed has a larger component towards the inner bend due to secondary currents, the bars also curve slightly inwards when moving through a river bend. Finally, they reach the scroll bar near the bank. According to Sundborg (1956) the reason that there is a lower swale area between the longitudinal bar and the adjoining bank, is that the flow velocity and therefore the shear stress is extremely low when approaching this lower area. Therefore, the movement of bed load across the longitudinal bar and the deposition on the other side of the bar cease when the bar has approached so close to the bank.

Other theories include vegetation. According to Hickin (1974) a ridge of sediment that is deposited at flood discharges is colonized by vegetation when it is exposed during lower water levels, and therefore the ridge is protected (figure 2.7). However scroll bars are also observed without vegetation and therefore this cannot be the only explanation of the formation of scroll bars. The same holds for the theory of scroll bar formation of Nanson (1981), which states that stranded trees can form scroll bars by trapping sediment and altering the flow pattern in a way that will cause a bar to grow and maintain a linear form. This bar type is what Kleinhans and van den Berg (2011) called tail bar.

Figure 2.7 – Field example of a meandering river with scroll bars which are colonized by vegetation at the inner bend.

2.6 Meandering rivers in experiments

2.6.1 Previous experiments

In the current research an experimental setting is used, because this will allow a better understanding of the observed processes by controlling the boundary and initial conditions, such as discharge and sediment input. However, dynamic meandering rivers are not easily created in an experiment. Friedkin (1945), Schumm and Khan (1972), Jin and Schumm (1987) and Smith et al.(1998) created meandering channels by using cohesive sediment, but failed to create a self-formed and dynamic system (Kleinhans et al., 2010). Kleinhans et al (2010) stated that it is necessary to have a cohesive bank such that the width-depth ratio is small enough to encourage the formation of alternate bars and to prevent chute cut-offs that lead to a braiding pattern. Van Dijk et al. (2012) and Van de Lageweg et al. (2012)used a transversely migrating upstream inlet point to simulate an upstream bend migrating into the reach of interest and thereby creating a self-formed dynamic meandering river. Van Dijk et al. (2012) focussed on the effects of adding silt to the upstream boundary. They concluded that sedimentation of fine cohesive material on the floodplain is a necessary condition to sustain meandering rivers as bank erosion rate and chute incision decreases.

2.6.2 Froude scaling

Beside the challenge to reproduce meandering rivers in experiments, scale issues are an important limitation of experiments. Traditionally, Froude scaling was applied to derive flow parameters (Kleinhans et al, 2010). According to this method the Reynolds number and the Froude number should be equal in the real situation and the scale model. The Reynolds number (Re) and the Froude number (Fr) are defined as:

$$\mathrm{Re} = \frac{hu}{\nu} \qquad (3)$$

$$\mathrm{Fr} = \frac{u}{\sqrt{gh}} \qquad (4)$$

where h = water depth [m] and v = viscosity [kg/(ms)]. With these formulas it can be derived that according to the Reynolds number the flow velocity depends on the inverse of the water depth, while according to the Froude number the flow velocity relates to the square root of the water depth. This means it is not possible to satisfy both conditions to obtain the same velocity scale (Kleinhans et al. 2010). According to Kleinhans et al. (2010) it is possible to relax these conditions, as long as the flow remains subcritical ($Fr < 1$) and turbulent ($Re > 2000$).

2.6.3 Sediment mobility

The sediment mobility is an important parameter that must be comparable between the experiment and reality. Sediment mobility is represented by the Shields parameter (ϑ):

$$\theta = \frac{\tau_b}{(\rho_s - \rho) g D_{50}} \qquad (5)$$

where τ_b = bed shear stress, ρ_s = sediment density, ρ = density of the water and D_{50} = median grain size. The Shields parameter depends on the median grain size, which means finer sediment has to be chosen in the experiment to scale with reality. However, this is not possible due to cohesive characteristics of clay. The cohesiveness of clay is far too strong for the lower shear stresses in experimental settings (Kleinhans et al., 2010). Therefore, coarser sediment has to be used and the mobility of the sediment is thus relatively less than in the real situation. It is often also less cohesive. Because of this, it is difficult to reproduce a realistic interaction between erosional and depositional processes in experiments.

2.6.4 Hydraulic roughness

Another reason to use coarser sediment is to secure that there are hydraulic rough conditions in the experiment. This means that the sediment has to be coarse enough to disturb the laminar sub-layer of the flow. This can be determined with the Reynolds particle number (Re^*), which has to be larger than 11.63:

$$\mathrm{Re}^* = \frac{\rho U_* D}{\mu} \qquad (6)$$

where U^* = shear velocity [m/s], D = grain size [m] and μ = dynamic viscosity [Ns/m^2].

For the grain size it is best to use the D90, because the coarser sediment is responsible for disturbing the laminar sublayer to create a hydraulic rough boundary (Kleinhans et al., 2010). When this condition is not satisfied there are hydraulic smooth conditions, which favour sheet flow instead of flow concentration. This causes scours and ripples, which do not scale with the flow conditions and therefore they do not scale with reality either. They thus provide an unrealistic morphology and are unwanted (Kleinhans et al., 2010).

2.6.5 Bar pattern

For developing a meandering river pattern in experiments, the channel width-depth ratio must be taken into account, as this determines the bar formation and therefore the river pattern. This is represented by the interaction parameter of Struiksma (*IP*), which predicts the type of bar present:

$$\mathrm{IP} = \frac{\lambda s}{\lambda w} \quad (7)$$

where λ_s = is the adaptation length of the bed and λ_w = the adaptation length of the flow (Stuiksma et al., 1985), represented by:

$$\lambda_w = \frac{C^2 h}{2g} \quad (8)$$

$$\lambda_s = \frac{h}{\pi^2}\left(\frac{w}{h}\right)^2 f(\theta) \quad (9)$$

where *C* = Chézy coefficient for hydraulic resistance [$m^{0.5}$/s] and $f(\vartheta)$ is represented by:

$$f(\theta) = 9\left(\frac{D50}{h}\right)^{0.3} \theta^{0.5} \quad (10)$$

As mentioned in section 2.2.3, if the water adaptation length is longer than the sediment adaptation length, perturbations are damped within a short distance downstream. This is therefore the case when the interaction parameter is smaller than 1 and this is called the overdamped regime. As the adaption lengths mostly depend on the width-depth ratio, this occurs in narrow and deep channels. For wider channels the adaptation length scale of the flow becomes smaller relative to the adaptation length of the bed and multiple bars may exist downstream of the perturbation (Kleinhans en Van den Berg, 2011). This is the underdamped regime. Underdamping causes an overdeepening of the pool in the outer bend and a steeper transverse bed slope in the inner bend just downstream of the entrance to the bend. In shallow channels excitation can occur; bars become unstable and grow in height downstream of the perturbation.

In experiments with meandering rivers, the river should be in the underdamped regime, as this stimulates the growth of meander bends instead of damping them out. The interaction parameter should be in the following range:

$$\frac{2}{n+1+2(2n-2)^{0.5}} < \mathrm{IP} < \frac{2}{n-3} \quad (11)$$

where n = the degree of nonlinearity of sediment transport versus depth-averaged flow velocity. For sand-bed rivers a value of n=4 should be used, while for gravel bed rivers a value of n=10 should be used, as gravel is closer to the threshold of motion and the nonlinearity of sediment transport is therefore larger (Kleinhans and Van den Berg, 2011). Since sediment size cannot be scaled and the mobility of the sediment is relatively less than in the real situation (section 2.6.3), experiments generally represent a gravel bed river. Therefore a value of n=10 should be used, while taken into account that the sediment mobility must be larger than the critical sediment mobility.

3. Objective, research questions and hypotheses

3.1 Objective and research questions

It remains unclear why individual scroll bars eventually stop growing and instead a new scroll bar starts to form. There seems to be a limitation for further building out a scroll bar, which could be caused by the sediment supply or the sediment transport capacity of the flow. The objective of this research is to determine if erosion of the outer bank or variation in sediment supply is the leading process for the development of scroll bars.

In a meander bend, the inward motion of the fluid near the bed and the outward motion of the fluid near the surface create a secondary flow. The mean flow velocity and therefore the shear stress and stream power decrease from the outer to the inner bank (Allen, 1970). When the ratio of the radius of the bend and the width of the river has reached a critical value and is therefore too sharp, flow separation takes place (Bagnold, 1960), leaving a zone of static or slightly circulatory water near the inner bend (Nanson, 1980). According to Nanson (1980) new scroll bars are deposited by the secondary currents, along this flow separation zone near the inner bend. However, other studies on scroll bars do not mention this flow separation zone. This leads to the first research question:

- What are the flow velocities in an experimental meandering river and what is the influence on morphology?

According to Leopold & Wolman (1960) the amount of bank erosion of the outer bend is in most cases approximately equal to the amount of deposition on the inner bank in a meandering river. Hickin (1974), Nanson (1980) and Nanson and Hickin (1983) state that when the outer bank is eroded and the inner bank has to accrete in order to maintain an equilibrium width. According to these studies the concave bend can undergo severe erosion while the accretion of the point bar is much slower. However, Sundborg (1956) and Pyrce and Ashmore (2005) observe that first sediment is deposited on the point bar, which causes more erosion of the outer bank.

- Is the erosion of the outer bend balanced by the rate of point bar formation and which is the leading process?

According to several studies scroll bars can only form when there are discharge variations and therefore pulses of outer bank erosion and an increase in accommodation space at the inner bend (e.g. Hickin, 1974; Nanson, 1980; Nanson and Hickin, 1983). When there is no significant difference in discharge, a flat point bar would develop as a continuous process. However, the observation that sedimentation on the inner bank causes outer bank erosion by Sundborg (1956) and Pyrce and Ashmore (2005) contradicts this. If scroll bars are formed by bedforms as stated by Sundborg (1956), this could also suggest that sediment input is important. Also, for example in the experiment of Pyrce and Ashmore (1995) scroll bars are observed while discharge is constant.

- Is it necessary to have variation in sediment transport capacity, i.e. discharge variation, or in sediment supply in order to form a new individual scroll bar?

Nanson (1980) stated that there is a possibility that scroll bars are formed by fine sand and silt derived from suspended load, while Sundborg (1956) observed that bed load transport is responsible for the formation of scroll bars.

- Are observed bedforms responsible for the formation of scroll bars and if so, is a scroll bar formed by multiple bedforms? Can bedforms trigger the formation of a new individual scroll bar?

Bundles of scroll bars can be distinguished at the point bar on a larger time scale and are not mentioned in literature. Scrolls seem to orient differently in a new bundle due to upstream changes in channel configuration.

- What process is responsible for the formation and direction of a new bundle of scroll bars? Is this related to upstream or downstream changes in channel pattern?

3.2 Hypotheses

Based on the literature, hypotheses can be formed which provide answers for the questions formulated in the previous section. These hypotheses will be tested in experiments, as will be described in chapter 4.

Hypothesis 1:
At the water surface the flow is directed to the outer bend, while at the bottom the flow will be directed slightly towards the inner bend. The mean velocity and therefore the shear stress will decrease from the outer to the inner bank (Allen, 1970; Blanckaert and de Vriend, 2003). The rate of erosion depends on the strength of this helical flow (Nanson and Hickin, 1986). The helical flow strength is determined by the sinouosity of the river. As the bend tightens, the secondary flow increases and therefore the erosion rates at the outer bank increase (Hickin, 1974).

Hypothesis 2:
When the outer bend is eroded, the width increases and therefore the flow velocity decreases. The transport capacity is therefore lower and this means there is less erosion at the outer bend and more deposition at the inner bend. The lateral accretion of the point bar continues until the equilibrium width is reached again (Nanson and Hickin,1983). The rate of point bar accretion should therefore be comparable with the rate of erosion of the outer bend, looking at a certain period of time.

Hypothesis 3:
When there is erosion of the outer bend, the channel widens and the point bar must accrete in order to reach the equilibrium width (Nanson and Hickin,1983). When the erosion of the outer bend occurs suddenly, it is possible that the flow patterns also shift quite suddenly. This will then causes the deposition of the sediment along the region of low sediment transport capacity to shift towards the channel and a separate ridge can form.

Hypothesis 4:

Since the experiment represents a bed load dominant gravel-bed river and will therefore not have a suspended sediment load, the accretion of the point bar will be caused by bed load transport. This could be in the form of bedforms or bedload sheets. At the bed the flow will be directed slightly towards the inner bend, causing the bed forms to also curve inwards until they reach the point bar. It is expected that bedforms do not trigger the formation of a new scroll bar, but that this is caused by changing flow conditions due to erosion of the outer bank. A scroll bar can therefore exist out of multiple bedforms.

Hypothesis 5:

Scrolls will orient differently due to upstream changes in channel configuration. When the amplitude and sinuosity of a meander bend increases, the bed slope decreases. This can cause the formation of chute channels (Peakall et al., 2007). Due to this change, the water will enter a bend downstream from another direction. The orientation of the scroll bar formation will also be changed due to the new channel configuration. This reorientation of scroll bars will results in new bundles of scrolls.

4. Methods

4.1 Experimental setup

The experiments were performed in the Eurotank flume of the University of Utrecht, which is 6m wide and 11m long. For the current experiment, a section of 3m by 11m was used (figure 4.1A). At the upstream end the water enters the flume with a controllable discharge, and a variable amount of sediment can be added to the flow. The inlet position of the water and sediment feeder can be varied, using a laterally migrating inlet (see figure 4.1B). At the downstream end an overlet is created, where the water is collected and recirculated. Above the flume a computer controlled camera and laser scanner is present, which can reach the entire flume.

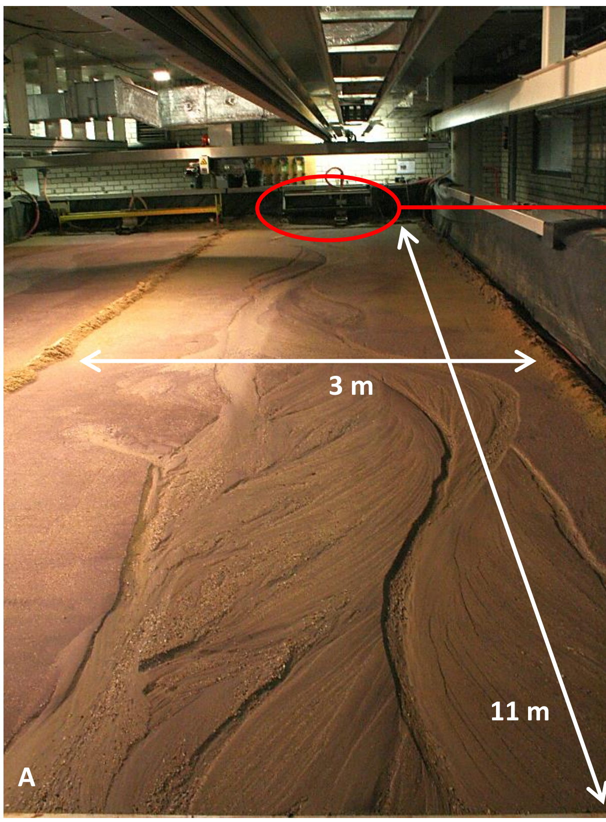

Figure 4.1 – (A) An overview of the flume used in the experiment. The water and sediment entered the flume at the upstream end through a lateral migrating inlet (B). The development of the experiment is monitored with an overhead camera and laser.

4.2 Boundary and initial conditions

The experiments were designed to represent a gravel-bed river with bed load transport. The initial and boundary conditions were based on scale rules mentioned in section 2.6 for the Froude number, Reynolds number, Reynolds particle number and interaction parameter. These have to remain between specific ranges. In table 4.1 these ranges are specified and in table 4.2 the initial and boundary conditions are summarized. The range of the interaction parameter was calculated using equation 11, with a n-value of 10, as the experiment represents a gravel-bed river. To create hydraulic rough conditions and stimulate channelization, poorly sorted sediment was used with a D10, D50 and D90 of 0.23 mm, 0.52 mm and 1.67 mm respectively (see figure 4.2). The Initial bed was 10 cm thick and had a gradient of 0.01 m/m in which a straight channel was carved (table 4.2). The discharge of the flow and the sediment feed was kept constant during the experiments at 1800 L/h and 0,25 L/h respectively. The sediment in the feeder was the same as the sediment in the flume, but without grains larger than 2mm to prevent damage to the feeder. The inlet position of the water and sediment was varied with a lateral migration rate of 0,01 m/hour, to mimic a bend that translates into the flume. When the inlet had migrated 0,30m with respect to the initial channel, the inlet migrated in the other direction. At the start of the experiment the inlet was positioned with an offset of 0,07 m with respect to the initial channel to stimulate the development of a meander bend. These initial conditions and setup of the flume were based on previous experiments of Van Dijk et al. (2012) and Van de Lageweg et al. (2012).

Table 4.1 - Scale rules of non-dimensional variables for hydraulic conditions, sediment transport conditions and morphological features, which have to remain between specific ranges during the experiments. The values are based on Van Dijk et al. (2012) and Van de Lageweg et al. (2012).

Non-dimensional variable	**Scale rule**	**Value Van Dijk et al. (2012)**
Froude number	Fr < 1	0.5-1.0
Reynolds number	Re > 2000	1700-3300
Shields number	$\theta > \theta_c$ (=0.04)	0.12
Reynolds particle number	>11.6	42
Interaction parameter	0.10<IP<0.29	0.12-0.47

Table 4.2 – Initial and boundary conditions of the experiment.

Initial condition	**Value**
D10	0.23 mm
D50	0.52 mm
D90	1.67 mm
Width initial channel	0.15 m
Depth initial channel	0.01 m
Slope	0.01 m/m
Boundary condition	**Value**
Discharge	1800 L/h
Sediment feed	0,25 L/h
Migration speed inlet	0,01 m/hour
Amplitude migrating inlet	0,3 m

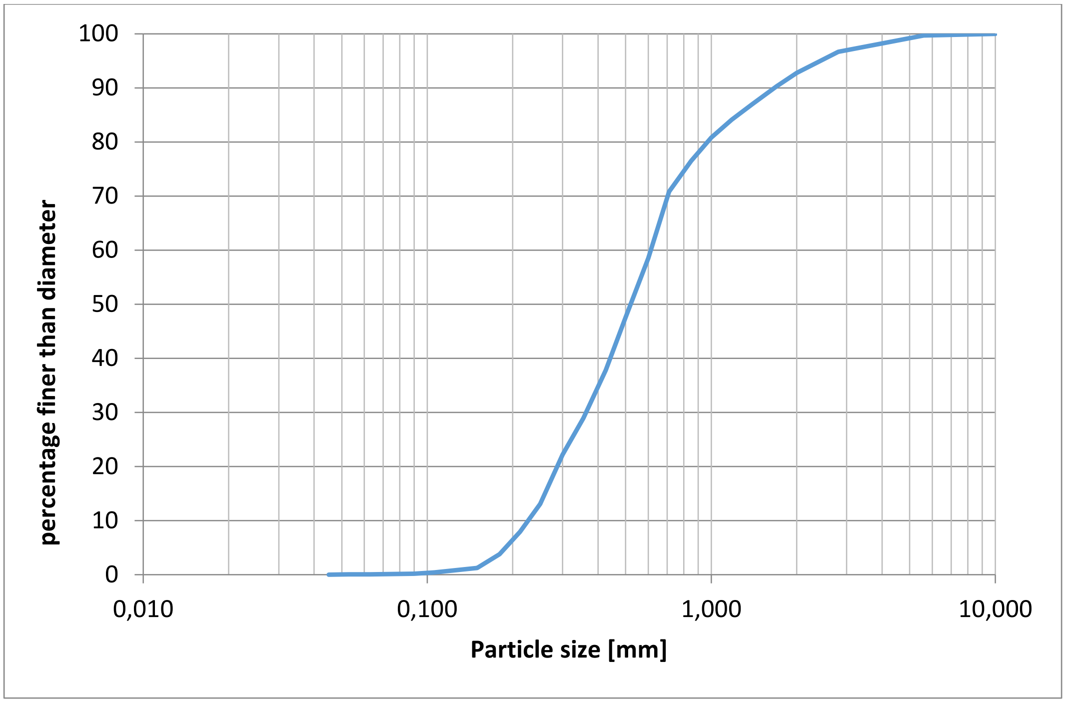

Figure 4.2 – Grain size distribution of the sediment used in the experiment, with a D10 of 0.23 mm, a D50 of 0,52 mm and a D90 of 1,67 mm.

4.3 Data collection

The development of the river pattern was monitored with Digital Elevation Models (DEM) using an automatic laser scanner (0.2 mm vertical resolution) and with photographs using an overhead camera (0.25mm resolution). These DEM's and photographs of the entire flume were made every two to six hours, depending on the amount of change in river pattern. Even though the general development of the river pattern was monitored, the focus of this research was on individual meander bends. Selected individual bends were photographed every 30 seconds using the overhead camera. These photographs were used to analyze developed bed forms, scroll bar formation and the displacement of the inner and outer bend. The displacement was quantified by plotting the coordinates of a bank against time using successive photographs in Matlab.

Flow velocities in these selected bends were measured using polystyrene spheres with a diameter of 4 mm that float on top of the water. Numerous photographs were taken of these spheres travelling through a specific bend with a fixed shutter speed of 0,10 seconds and with a known resolution of 0,25 mm. By measuring the length of the stripes showing up on the photographs, the flow velocities (*u*) of each sphere could be determined using the following formula:

$$u = (0.25*10^{-3}((x_2-x_1)^2+(y_2-y_1)^2)^{0.5}- 4*10^{-3})/0.10 \qquad (12)$$

where *x* and *y* are the coordinates of the beginning (*1*) and the end (*2*) of a stripe. These values were determined and processed using a MATLAB script. With these velocities of separate points in the bend, flow velocity profiles of specific sections were made.

4.4 Testing of hypothesis

In order to determine the dominant processes in scroll bar formation, individual bends that develop were selected for further research. Eight experiments were performed in five different bends, as summarized in table 4.3. In each case flow velocities were measured along the entire length of the bend. Also, the displacement of the inner and outer bend was determined. In table 4.3 these cases are summarized. Two bends, with and without developed scroll bars, were left undisturbed during measurements as control experiments, while in 6 cases perturbations were added.

Table 4.3 – An overview of the eight different cases that were performed in developed meander bends. The cases differ in the perturbations that are added and whether the bend has scroll bar formation on beforehand.

Case	Bend	Bend characteristics	Perturbation/experiment
1	2	no scroll bars, not migrating	control
2	3	scroll bars, migrating	control
3	1	scroll bars, migrating	sediment tracing
4	2	no scroll bars, not migrating	sediment pulses
5	4	scroll bars, migrating	sediment pulses
6	5	scroll bars, migrating	sediment pulses without flow over the point bar
7	5	scroll bars, migrating	outer bend removal
8	5	scroll bars, migrating	fixed outer bend, sediment pulses

4.4.1 Sediment tracing

In the first developed meander bend, colored particles in three different colors were added to the outer bend, in order to determine where eroded material from different parts of the outer bend would deposit. These three different colors were added to the beginning of the outer bend, downstream of the apex and the end of the outer bend (figure 4.3).

Figure 4.3 – At bend 1 colored particles were added to the outer bend in order to determine where eroded sediment deposits. The black arrow indicates flow direction.

4.4.2 Variations in sediment supply

In order to determine if variations in sediment supply from upstream causes individual scroll bars to form and whether inner bend accretion is the dominant process in bend migration, sediment pulses were added in four cases. In nature, these sediment pulses may correspond to upstream sediment input from cutoffs or major bank failure following a flood event. Sediment pulses were added upstream of the bend, with a volume of 200 ml. This volume was chosen by estimating the volume of an existing scroll bar. The time interval between subsequent pulses was determined by looking at the migration speed of the previous sediment pulse and varied between 15 and 30 minutes. The added sediment was colored, in order to follow the migration of the sediment. Subsequent pulses had a different color, in order to see if successive pulses cause individual scroll bars to form.

In case 4 and 5, sediment pulses were added to meander bends with and without scroll bar formation respectively. This was done to study the differences in the effect of the sediment pulses and to see if scroll bars could hereby start developing in the case without scroll bars. In case 6, again sediment pulses were added to a bend with scroll bar formation, but now dikes were created at the outer bend upstream, so there is no flow over the point bar and all of the discharge is flowing into the bend. Therefore no chute cutoff could occur.

4.4.3 Outer bank erosion

In order to determine if outer bend erosion is the dominant factor in scroll bar formation and bend migration, two cases were focusing on the outer bend. In case 7, part of the outer bend was removed four times along the entire length of the bend. In nature, this outer bank removal corresponds to discontinuous outer bank erosion. The aim of this case was to observe the response of the inner bend and to see if individual scroll bars form after each removal. In case 8 the outer bend was fixated using glue, in order to see if scroll bars would still develop if there is no erosion of the outer bend and if so, if they differed from other developed scroll bars in width and height. In nature this corresponds to a meander bend with a high bank strength, for example due to vegetation. After some time sediment pulses were added in this case, to stimulate inner bend accretion and scroll bar formation.

5 Results

5.1 River pattern development

The entire experiment lasted 160 hours, which corresponds to about 1.25 cycles of the migrating inlet. At the start of the experiment, immediately erosion took place at the beginning of the straight channel due to the offset of the inlet. At the other side of the channel sedimentation took place and a bar developed. The flow was hereby directed towards the other bank downstream and caused erosion and again sedimentation at the opposite side of the channel. This process continued and caused alternate bars to develop, which dampened out downstream. In the next three hours these small bends increased in amplitude and length. In general, the amplitude and length of the bends now increased in downstream direction (figure 5.2A). After 23 hours, the migrating inlet had reached its maximum amplitude of 0.3m and started to move back towards the center. This change caused a chute cut off in the first bend and the downstream part of the river returned to a straight channel (figure 5.2B). New bends with small amplitudes formed, but these were cut off relatively fast (figure 5.2C). Only when the inlet moved past the center, bends with larger amplitude could develop (figure 5.2D). After 83 hours the inlet reached it maximum amplitude at the other side, and this process started again. In figure 5.2E and 5.2F, the river pattern is visible in later stages. In some bends scroll bars with a different orientation than previously formed scroll bars were visible when the bend had suddenly changed due to a different inflow upstream. These older scroll bars were often separated from the current point bar by a small channel, caused by erosion of the older point bar (figure 5.1). Also, throughout the experiment remnants of deserted river bends were preserved, which influenced the course of the river later on due to height differences in the morphology.

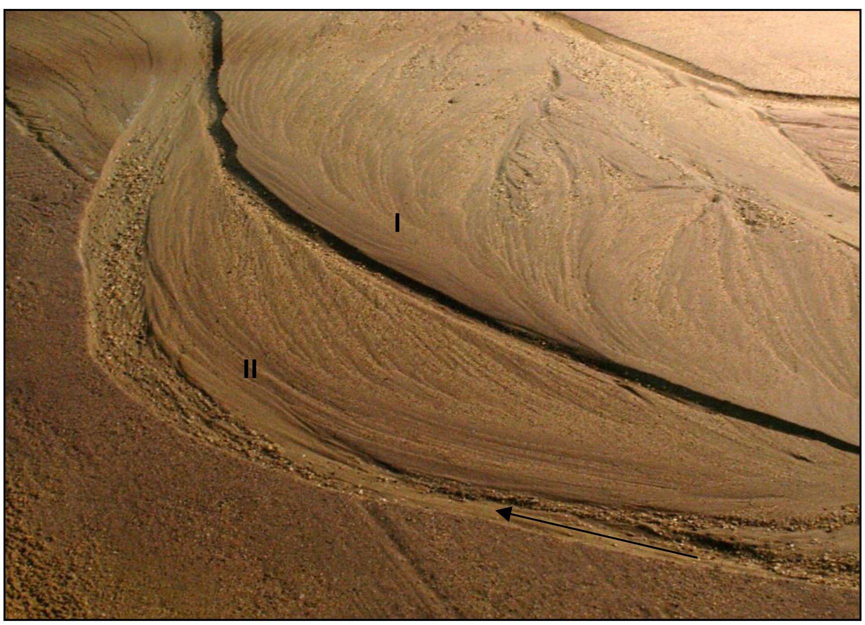

Figure 5.1 – A meander bend where recently formed scroll bars (II) have a different orientation than older scroll bars (I). The older scroll bars have a higher elevation and are separated from the newer point bar by a channel. The arrow indicates flow direction.

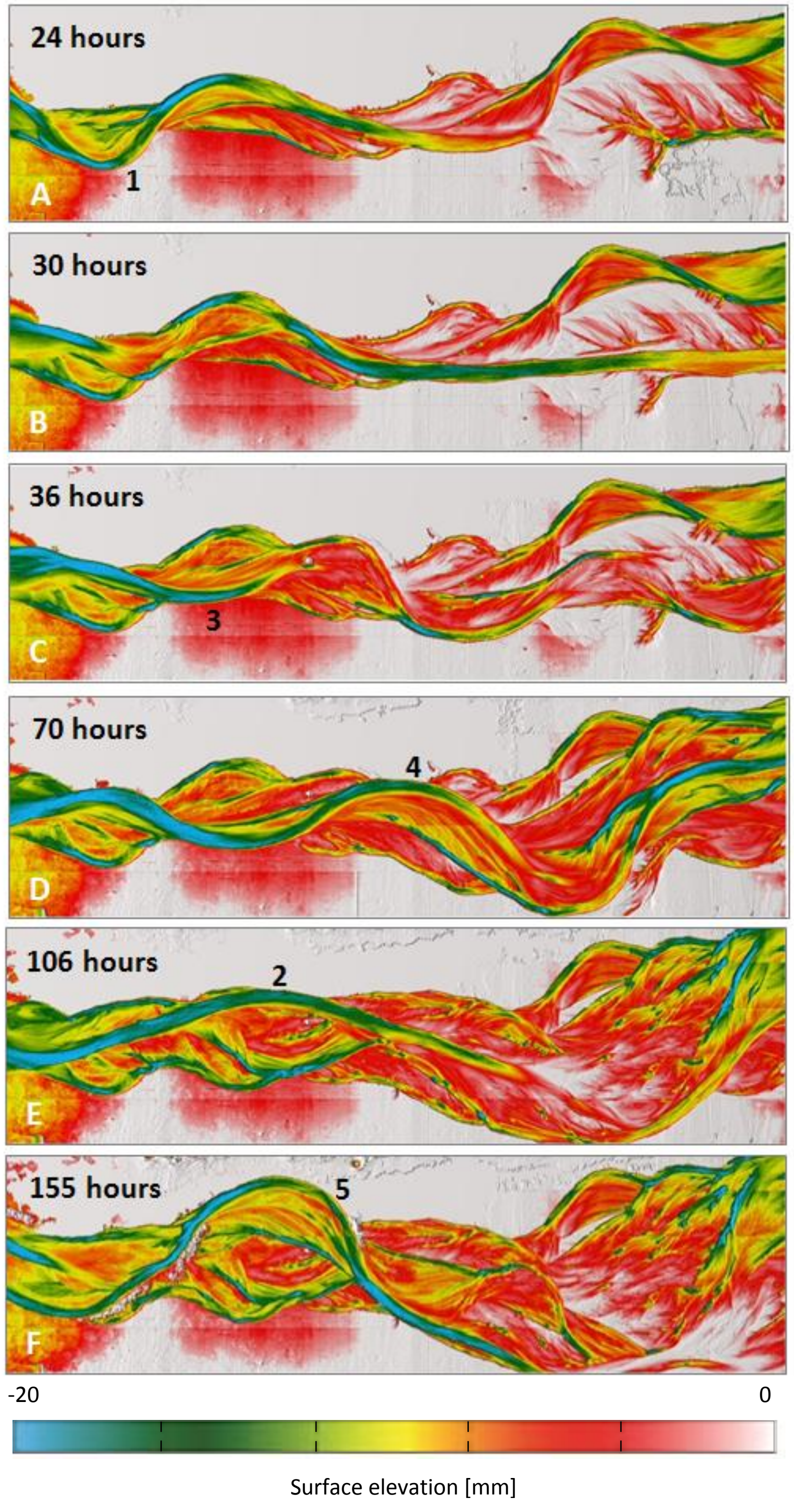

Figure 5.2 – Digital Elevation Models (DEM) of the river at several time steps, showing the evolution of the river pattern. The numbered bends are selected meander bends which are used for specific measurements (see table 4.3). Flow direction is from left to right.

5.2 Processes in undisturbed meander bends

5.2.1 Bend development

Bends started to develop by erosion of one side of the initial channel and the formation of a bar at the other side (figure 5.3A). A bar started as a lobe of sediment, with still a small channel between the bar and the bank of the initial channel (figure 5.3B). As visible in figure 5.3, bedforms in the shape of sediment sheets were visible, traveling along the bar and between the successive bars. The ridges of the sediment sheets that were visible (figure 5.3B) rotated when travelling along a bar, so that they were aligned more parallel to the curvature of the channel. When the amplitude of the small bends increased, the alternate bars built out and formed the point bars of a meander bend. Bedforms were also visible in more developed bends, travelling along the point bar (figure 5.4B). The sediment sheets consisted of relatively fine sediment, compared to the larger grains present in the channel. Sometimes bedforms could be observed in the entire cross-section of the channel (figure 5.4A) between successive meander bends. On a point bar, these sediment sheets rotated and travelled upslope. Deposition of several of the bedforms caused a scroll bar to form. Scroll bar formation was visible in all bends that actively migrated and was absent in bends that stopped migrating. Scroll bars formed parallel to the curvature of the channel and generally downstream of the apex, especially in bends with smaller radius. At a later stage, sediment was also deposited at the point bar head. In figure 5.5 an example is shown of a migrating bend with scroll bar formation. The point bar upstream of the apex consists of a flat surface, which continues into more pronounced scroll bars downstream.

A bend stopped migrating when a chute cut-off took place, which was the result of a changing flow direction at the bend upstream. A bend could also stop developing when there was no significant change in inflow direction from the bend upstream and the water could flow continuously into the bend downstream. An example is the second bend in figure 5.2D, which stopped developing between 55 hours and 70 hours. As is visible, the inflow direction did not change significantly and the channel continues into the next bend without variation in depth and width, compared to the same bend in 5.2C when it was still developing scroll bars. This only happened with bends that did not yet have a large amplitude and were located relatively close to the inlet. These bends could start developing again when the inflow from the upstream bend changed significantly.

5.2.2 Erosion and deposition patterns

In figure 5.6, the displacement of an actively migrating inner and outer bend (bend 3) is shown. The outer bend erosion and inner bend accretion show in general the same trend, but do not show a clear response to each other. Where the eroded material of the outer bend ended up depends on the location of erosion, as is shown in figure 5.7. Sediment that is eroded from the beginning of an outer bend travelled to the opposite point bar, while sediment that eroded from downstream of the apex travelled to the point bar in the next bend. Sediment that originated from the end of the outer bend was deposited nearby on the beginning of the next point bar. In the bend shown in figure 5.7, the yellow particles and the blue particles were first deposited. The green particles were eroded later on and deposited on top of the blue particles at the beginning of the next point bar. When comparing figure 5.7 with figure 5.3, it is visible that the blue part of the outer bank eroded the most.

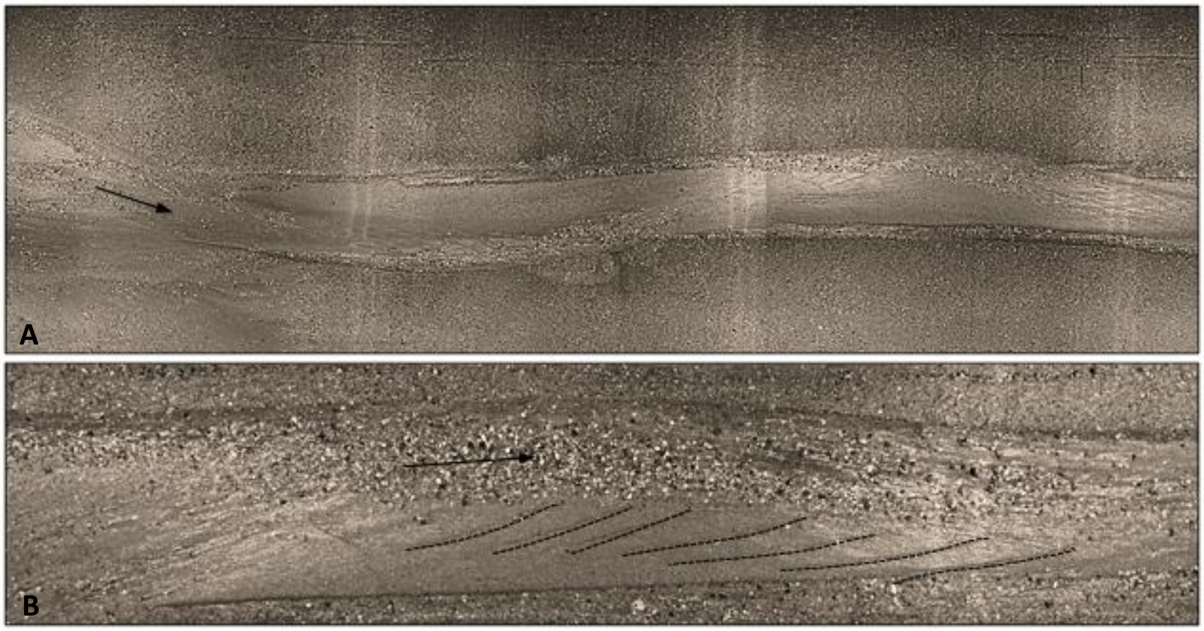

Figure 5.3 – Morphology of the river after 3 hours (A) with alternate bars present. Sheets of sediment are visible, traveling between the bars and on the bars (B). The arrows indicate flow direction and the dotted lines indicate the ridges of sediment sheets

Figure 5.4 – Bedforms in a channel between meander bends (A) and bedforms travelling along a point bar of a meander bend (B), indicated with the dotted lines. The bedforms consist of finer material compared to the coarser sediment in the remainder of the channel. The arrows indicate flow direction.

Figure 5.5 - A migrating bend with scroll bar formation, developing from A to C. The point bar at the upstream end of the bend, as indicated with the solid lines in (B), shows a flat surface, while after the apex scroll bars are formed, as indicated with the dotted lines in (B). The arrows indicate flow direction.

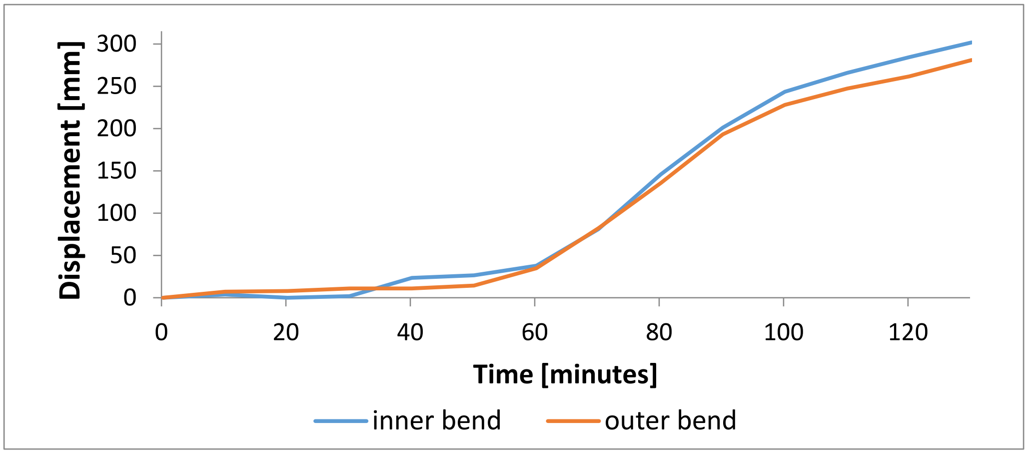

Figure 5.6 - Displacement of the inner and outer bend of bend 3 during 130 minutes. Outer bend erosion and inner bend accretion show in general the same trend.

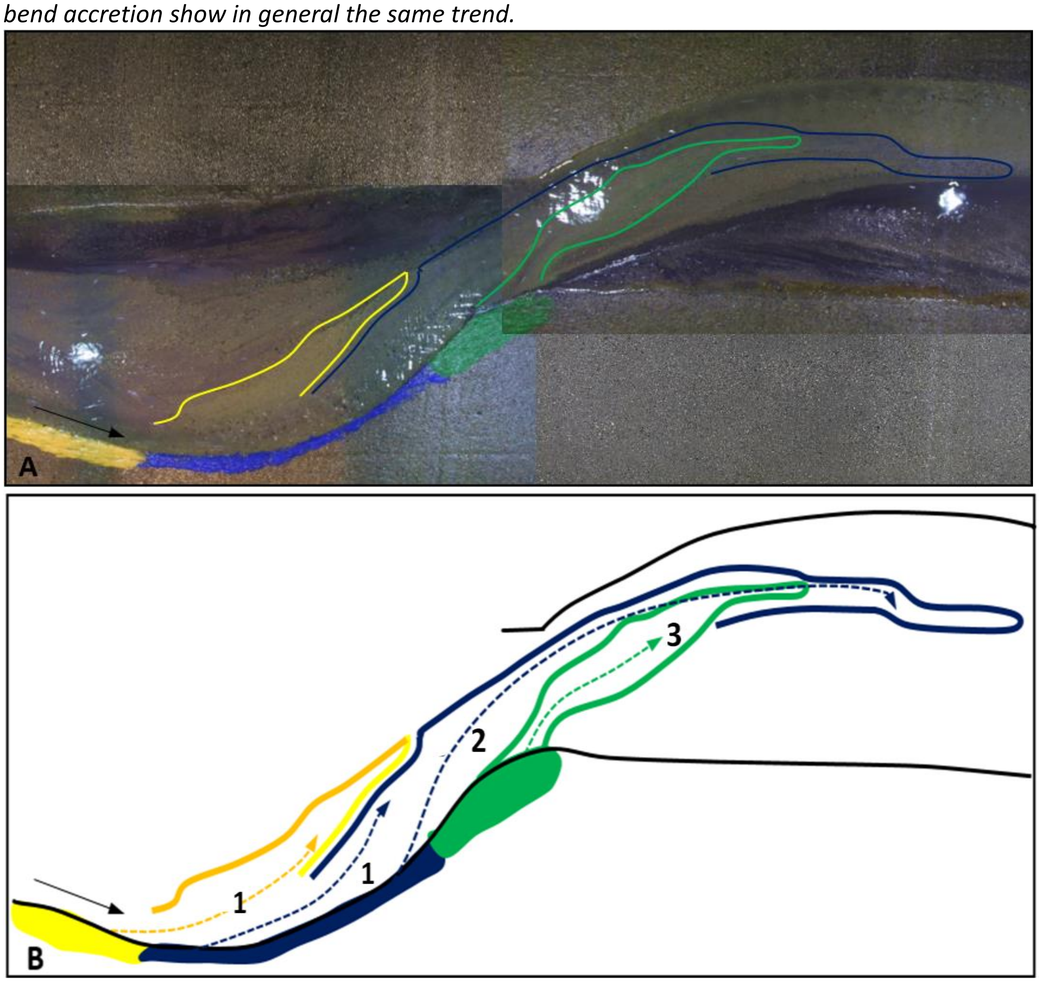

Figure 5.7 - Stitched photographs (A) and a sketch (B) of eroded sediment paths, as indicated by colored particles that were added to the outer bank in case 1. Sediment that is eroded from upstream of the apex travelled to the opposite point bar, while sediment that eroded from downstream of the apex travelled to the point bar in the next bend. The number in (B) indicate the order of erosion; First (1) the yellow and blue particles from upstream of the apex eroded and travelled to the opposite point bar, then (2) the blue particles from downstream of the apex travelled to the next point bar and finally (3) the green particles were eroded and deposited on top of the blue particles at the beginning of the next point bar.

5.2.3 Width and depth variations

Actively migrating meander bends with scroll bar formation had characteristic width variations along the bend. The channel width increased towards the end of the bend and was in general between 0.12 m and 0.2 m at the apex, and between 0.2 m and 0.3 m at the downstream end. Typically, the channel at the downstream end was 1.5 times as wide as the channel at the apex. In figure 5.8 an example of a typical bend is shown. In this figure it is clear that the depth of the channel was larger at the beginning of the bend and decreased towards the end when width increases (5.8B). In meander bends without scroll bar formation, the width and depth did not vary significantly.

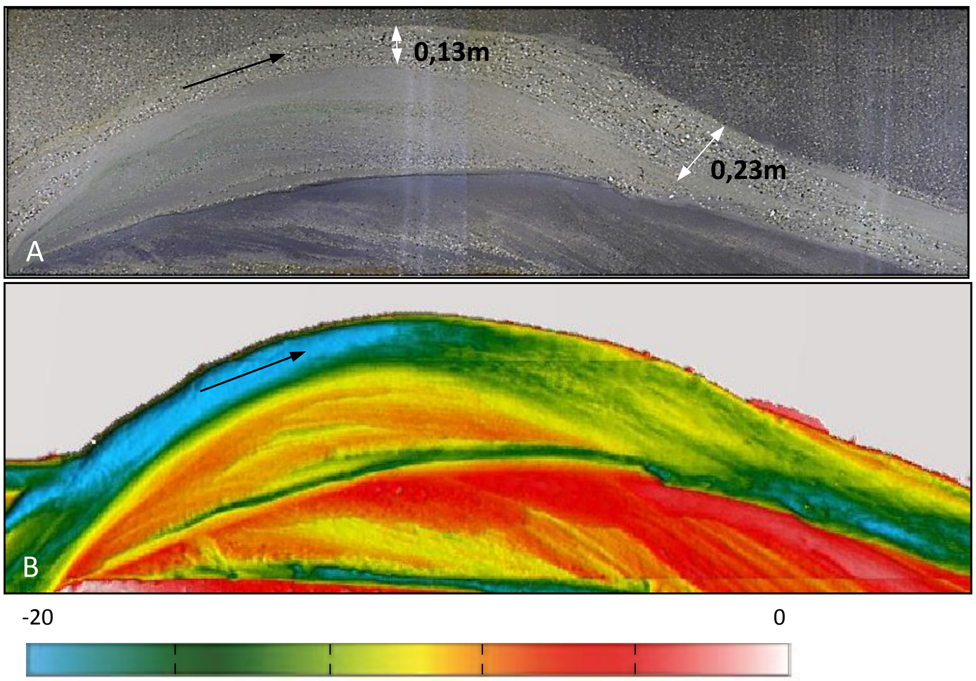

Figure 5.8 - (A) Width variation along a meander bend with scroll bar formation (second bend in 5.2A). As visible, the channel width is larger at the end of the channel (0,23m) than at the apex (0,13m). (B) Digital Elevation Map of the same meander bend, which shows that the depth decreases towards the end of the bend. The black arrows indicate flow direction.

5.2.4 Flow velocity

In bends with active scroll bar formation, flow velocities decrease from the apex towards the end of the bend (figure 5.9B), while flow velocities in a meander bend without scroll bars slightly increase and have values comparable with the beginning of the bend (figure 5.9A). In both bends the flow velocity decreases from the beginning towards the bend apex. At the beginning of both bends, flow velocities are lower at both sides of the channel compared to the middle of the channel. At the apex, flow velocities are highest at the outer bend and decrease towards the inner bend. However, this trend is more clearly visible at the bend with scroll bar formation. At the end of the bend this is still the case for the bend with scroll bar formation, but at the bend without scroll bar formation the flow velocity is now slightly higher at the other side of the channel.

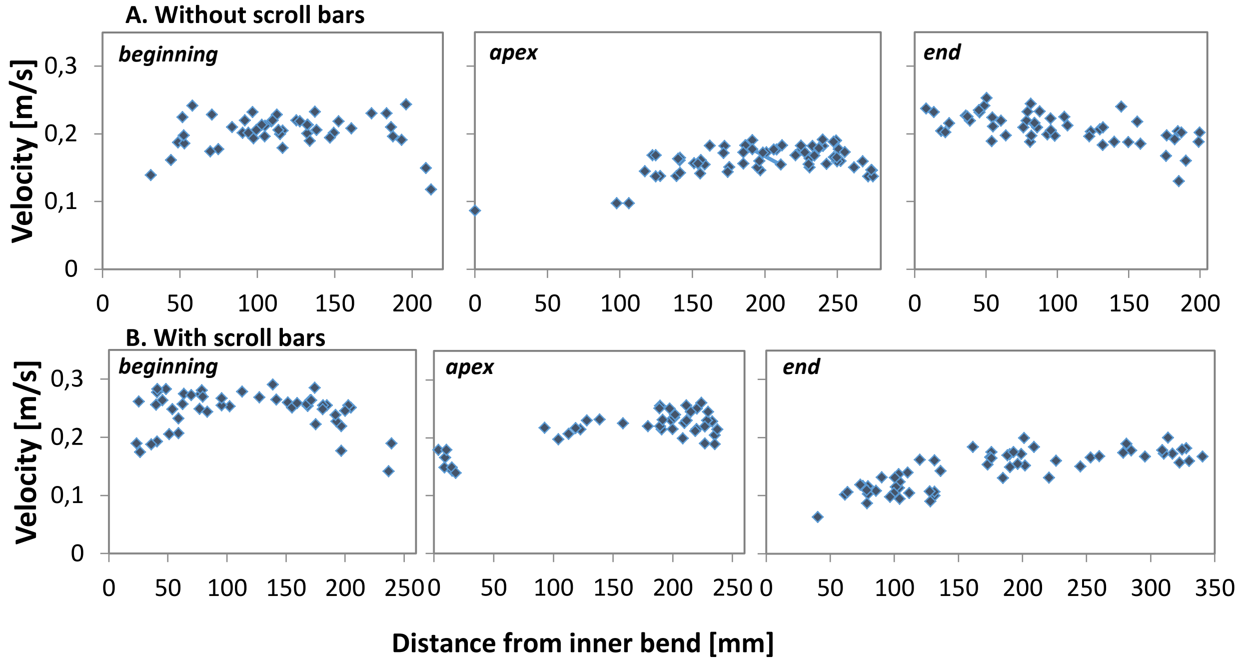

Figure 5.9 - Flow velocities in a meander bend without scroll bar formation (A) and with scroll bar formation (B). The first graph shows the flow velocities along a cross-section at the beginning of the bend, the second graphs at the apex and the third at the end of the bend. Flow velocities in bends with scroll bar formation decrease towards the end of the bend, while flow velocities in bends without scroll bars increase.

5.3 Perturbations to force scroll bar formation

5.3.1 Variation in sediment supply

For cases 5 and 6, sediment pulses were added to the beginning of an actively migrating bend (bend 4 and 5 respectively). A pulse roughly corresponded with the volume of an individual scroll bar each time. The majority of the added sediment travelled as a lobe along the entire point bar, but some particles were deposited on several ridges of existing scroll bars, relatively fast after the addition of the sediment pulse (figure 5.10A). However, a sediment pulse did not necessarily form a new scroll bar, but often migrated over the previous one (figure 5.10B). The sediment was thus deposited on the ridge of the already present scroll bar instead of leaving a new ridge. In figure 5.10C the morphology of the bend in case 5 is shown after five pulses and it is visible that only two new scroll bars have formed. These scroll bars have roughly the same spacing as the scroll bars that deposited before the addition of sediment pulses. The point bar in the bend in case 6 (fig 5.11) has significantly expanded, but consists of a flat surface before the apex and only some small ridges further downstream, which also did not form by individual sediment pulses. As visible in figure 5.17A and 5.17B, the outer bend did not react significantly to the added sediment pulses in both cases. Only when the point bar considerably expanded at case 6 after eighty minutes, the erosion of the outer bend increased slightly. In both cases, there is no attachment of individual sediment pulses recognisable in the displacement of the point bar over time. However, migration rates of both bends differ, as the displacement of the banks is larger at case 6 is than at case 5. Also, in case 5 the flow from upstream was eventually directed over the point bar, while at case 6 this was not possible due to the dikes upstream of the bend.

Bend flow velocities for case 5 are visible in figure 5.15A and show the same trend as the bend flow velocities for case 2 without sediment pulses. Although flow velocities are slightly higher at the end of the bend with sediment pulses. In the bend at case 6 (figure 5.15B), flow velocities are higher at the outer bend and the transverse water slope is steeper towards the inner bend than in the bend at case 5. Also, flow velocities at the beginning of the bend at case 5 are slightly higher at the inner bend than at the outer bend, while at case 6 there already is a transverse water slope directed to the inner bend.

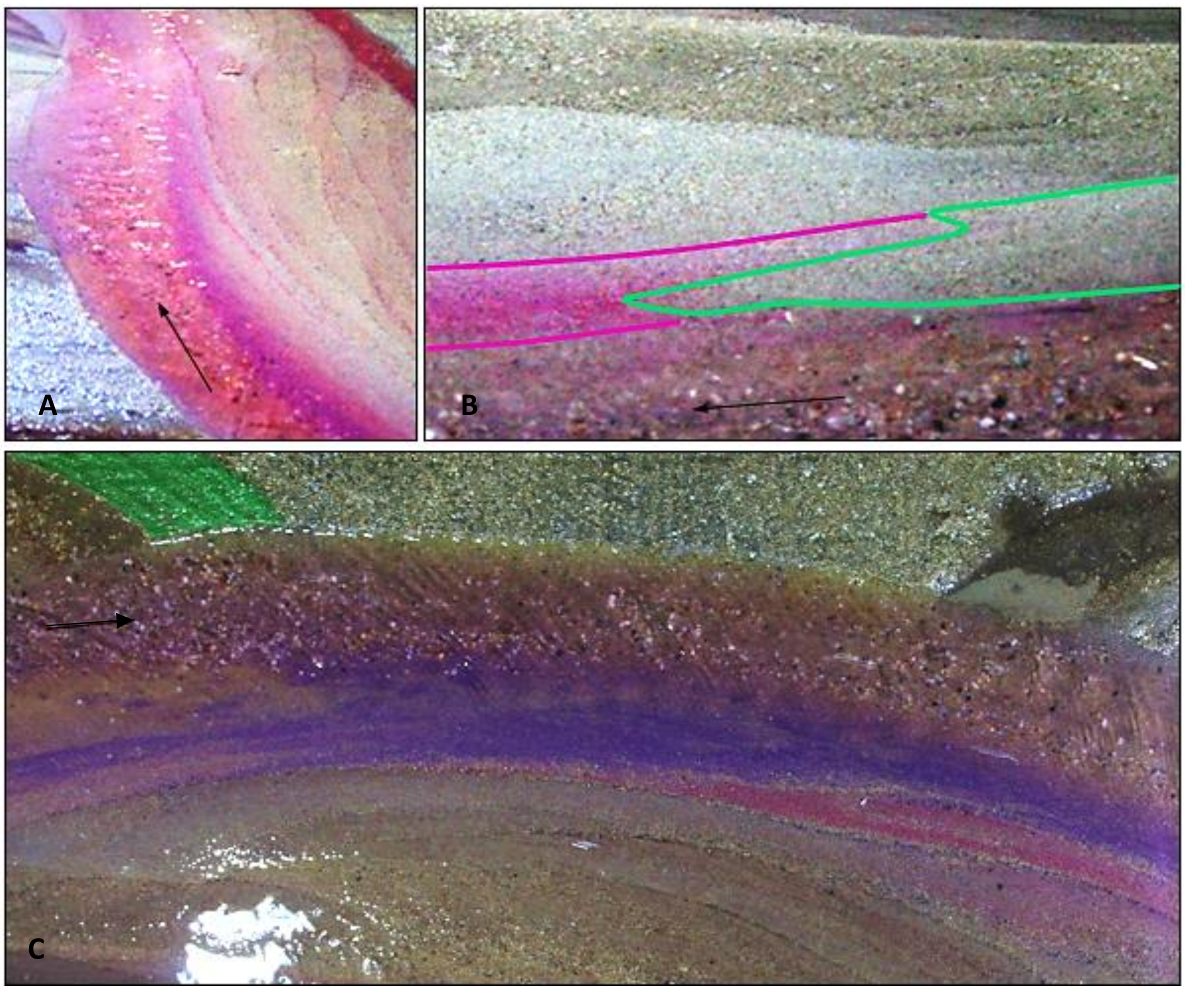

Figure 5.10 - An overview of case 5 with added sediment pulses. (A) The deposition of pink particles on previously formed ridges, just after the addition of a pink sediment pulse. The purple sediment originates from a sediment pulse added twenty minutes earlier. (B) The migration of a green sediment lobe over a previously deposited pink sediment pulse. (C) An overview of the morphology after five sediment pulses. The arrows indicate flow direction.

The addition of sediment pulses also had no effect on a bend that previously did not migrate significantly (case 4). The sediment pulses did not accrete on the point bar, as most of the sediment was transported further downstream instead of depositing. In figure 5.17C it is visible that there was some sedimentation at the point bar over time, but this was not more than 20 mm and always followed by erosion. At the end of the measurements the point bar had displaced only 10 mm and no colored sediment was visible anymore (figure 5.12B). This also indicates that the deposited sediment did not remain long on the point bar. The outer bend eroded 15 mm during 400 minutes, which is not significant compared to the previous described cases.

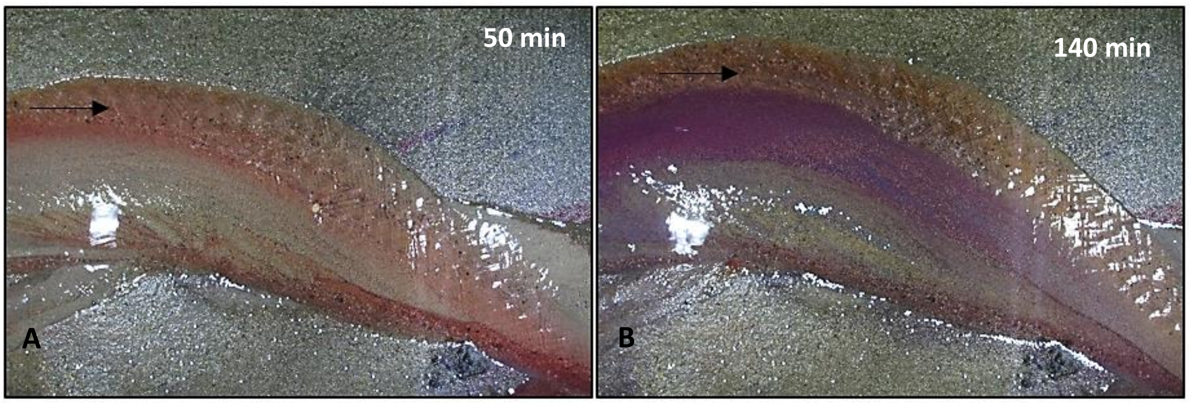

Figure 5.11 - Morphology of case 6 just after the first sediment pulse (A) and after the addition of four sediment pulses (B). As visible in (B), the point bar has expanded significantly due to the pulses, but no individual scroll bar was formed. The arrows indicate flow direction.

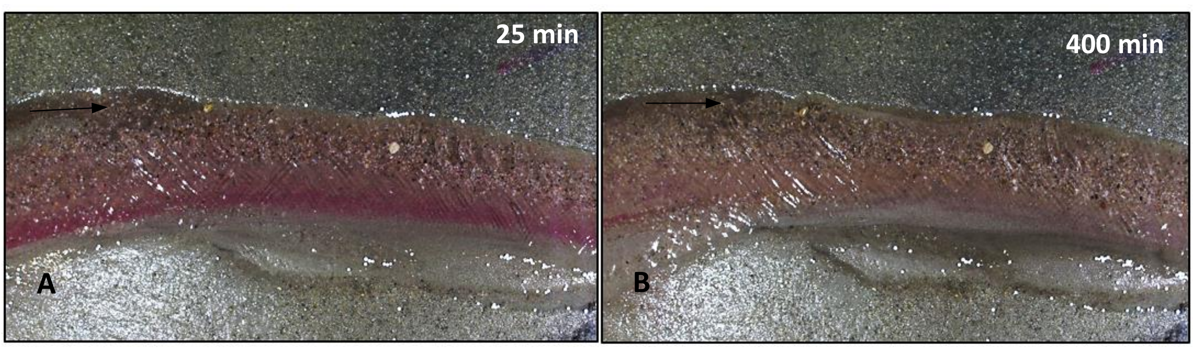

Figure 5.12 - Morphology of case 4 after the first sediment pulse (A) and at the end of the measurements (B). As visible, some colored sediment was deposited on the point bar, but did not remain there, as no colored sediment is present at the end of the measurements. The arrows indicate flow direction.

5.3.2 Fixed outer bend

For case 8, the outer bend of a migrating bend was fixed, so that it could not erode (figure 5.13A). In figure 5.17D the displacement of the outer and inner bend is shown during the measurements. First, the inner bend lost up to 30 mm of the point bar when it could not erode the outer bend anymore and stayed at that position after that. After the first sediment pulse, sediment was deposited along the point bar (figure 5.13B), causing the position of the inner bend to return to about the same as before the fixation of the bend. Sediment of the second pulse was partly deposited along the point bar on top of the sediment of the first pulse and partly in the channel further upstream (figure 5.13C). After the next pulses, the added sediment was deposited in the whole channel just after the location where it was added, causing it to block the flow. This caused flow over the point bar (fig 5.13D) and eventually a chute cut-off took place upstream.

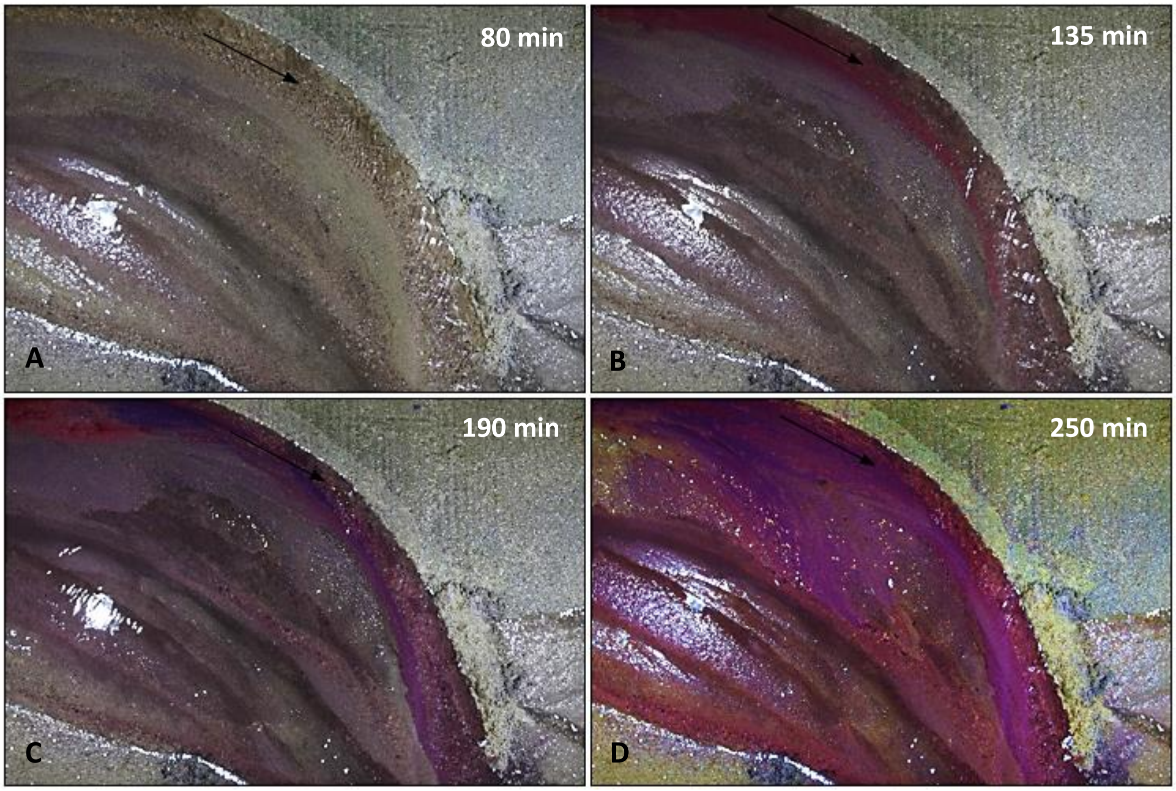

Figure 5.13 - Morphology during several stages of development at case 8. (A) The situation before the sediment pulses. (B) The morphology after the first sediment pulse, which is deposited along the point bar (pink sediment). (C) Part of the second pulse (purple) is deposited on top of the previous pulse and part is deposited in the channel more upstream of the bend. (D) After five pulses, the channel has filled up and part of the flow is directed over the point bar. The arrows indicate flow direction.

5.3.3 Removing part of the outer bend

For case 7, part of the outer bend was removed four times in order to determine the effect of outer bend erosion (figure 5.14). The width of the outer bend reach that was removed varied from about 30 mm to 60 mm, which correspond to about a tenth and a fifth of the channel width, respectively. The first two of these erosion events increased the channel width significantly whereas the third and fourth event had a smaller impact on channel width. Immediately after the removal, a lobe of sediment formed at the point bar, which resulted in a sudden inner bend displacement (figure 5.17E). This lobe travelled relatively fast from upstream along the point bar in downstream direction (figure 5.14B). Deposited sediment did not only originate from sediment that travelled along the point bar, but also from remnants of the outer bend reach that was removed. After this initial response, inner bend deposition continued but at a slower rate. However, inner bend deposition ceased when the channel approximated its initial channel width again. This process was observed at every outer bend erosion event. The time it took before the channel reached its initial channel width again varied between five and fifty minutes.

In figure 5.16 flow velocities are visible before and after erosion events 2 and 3. In figure 5.16A, flow velocities are lower near the outer bend than in the remainder of the channel. After the erosion event, flow velocities are highest where the outer bend used to be and decrease to the current outer bend. Before the next erosion event, the same trend is visible near the outer bend and there is also a clear decrease in flow velocities towards the inner bend. Flow velocities are higher at the outer bend after the erosion event and lower at the inner bend.

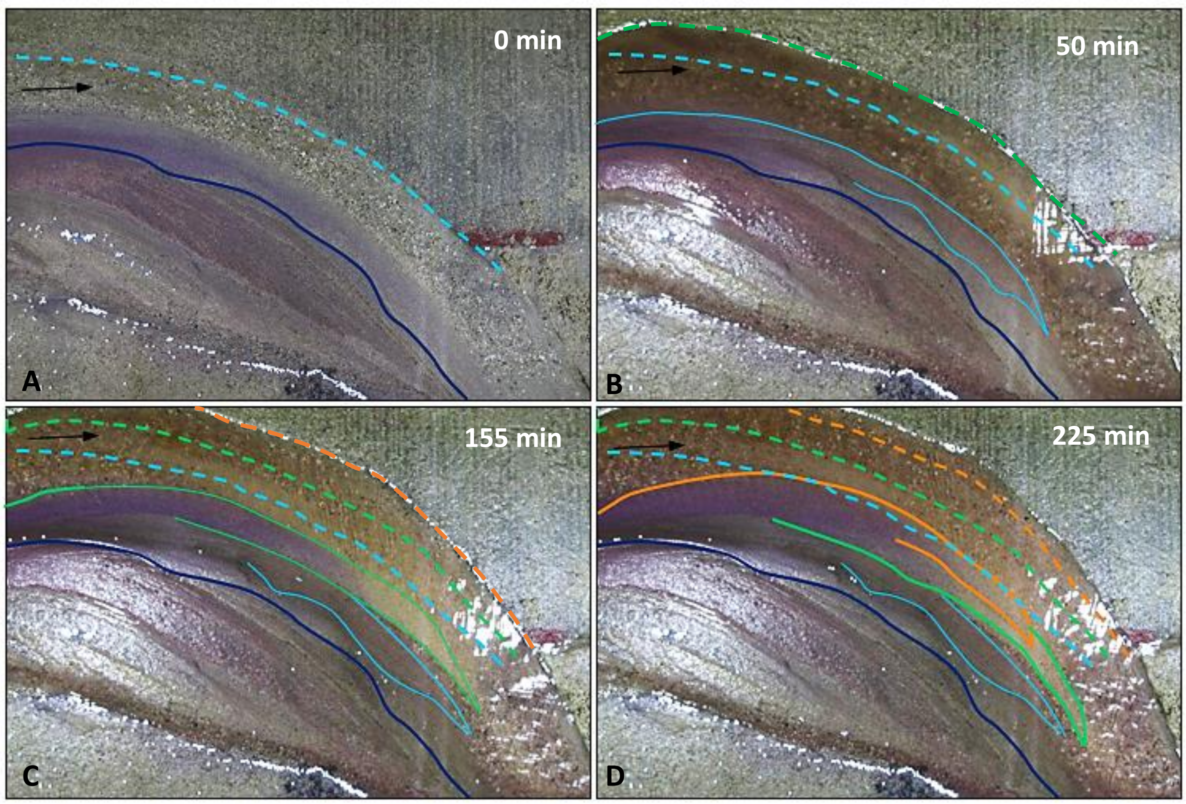

Figure 5.14 - Morphology at several times during case 7. (A) The situation before removal of the outer bend. The solid dark blue line indicates the last developed scroll bar and the dotted light blue line indicates the current position of the outer bend. (B) The morphology 50 minutes after the first erosion event. As visible, a scroll bar has developed (solid light blue line), after the area between the dotted light blue line (previously the outer bend) and the dotted green line (current outer bend) has been removed. (C) The morphology 30 minutes after the second erosion event, which shows that another scroll bar has formed (solid green line) after the removal of the sediment between the dotted green line and the dotted orange line (current outer bend). (D) The morphology 28 minutes after the third erosion event, with the scroll bar (solid orange line) that formed after the removal of the outer bend between the dotted green line and the dotted orange line (current outer bend). The arrows indicate flow direction.

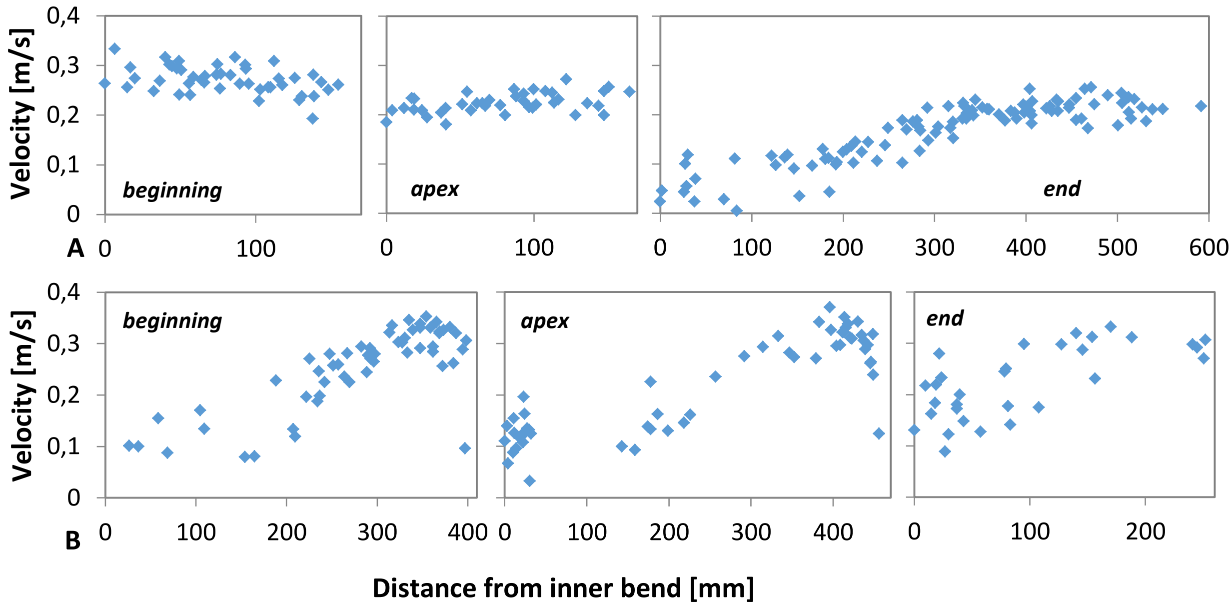

Figure 5.15 - Flow velocities for case 5 (A) and case 6 (B). The first graphs show the flow velocities along a cross-section at the beginning of the bend, the second graph at the apex and the third at the end of the bend. Flow velocities at case 5 show the same trend as the meander bend without sediment pulses, while flow velocities for case 6 show a larger difference between the inner and outer bend.

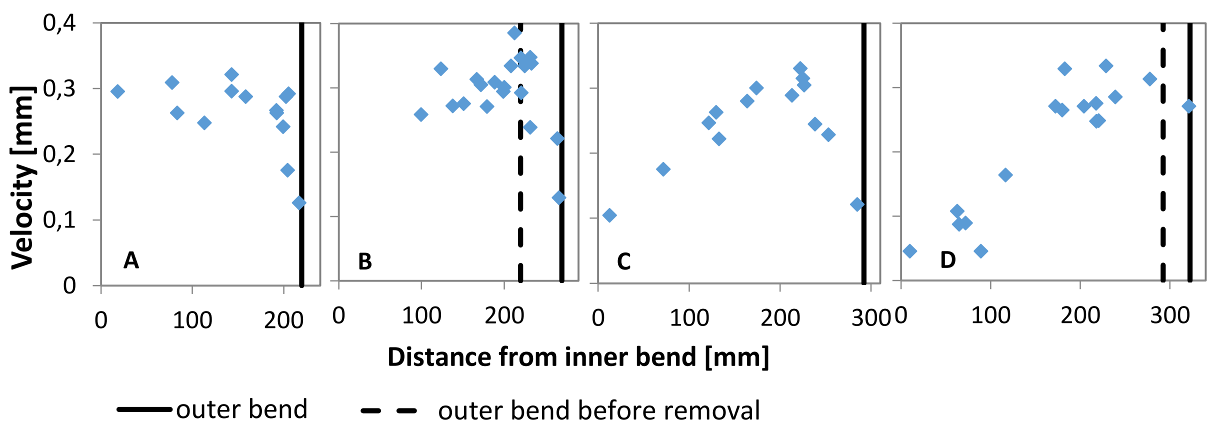

Figure 5.16 - Flow velocities for case 7. (A) Flow velocities before the second erosion event. (B) Flow velocities after the second erosion event. (C) Flow velocities before the third erosion event. (D) Flow velocities after the third erosion event. After erosion events, the region with the highest flow velocities shifted towards the new outer bank and flow velocities decreased at the inner bend.

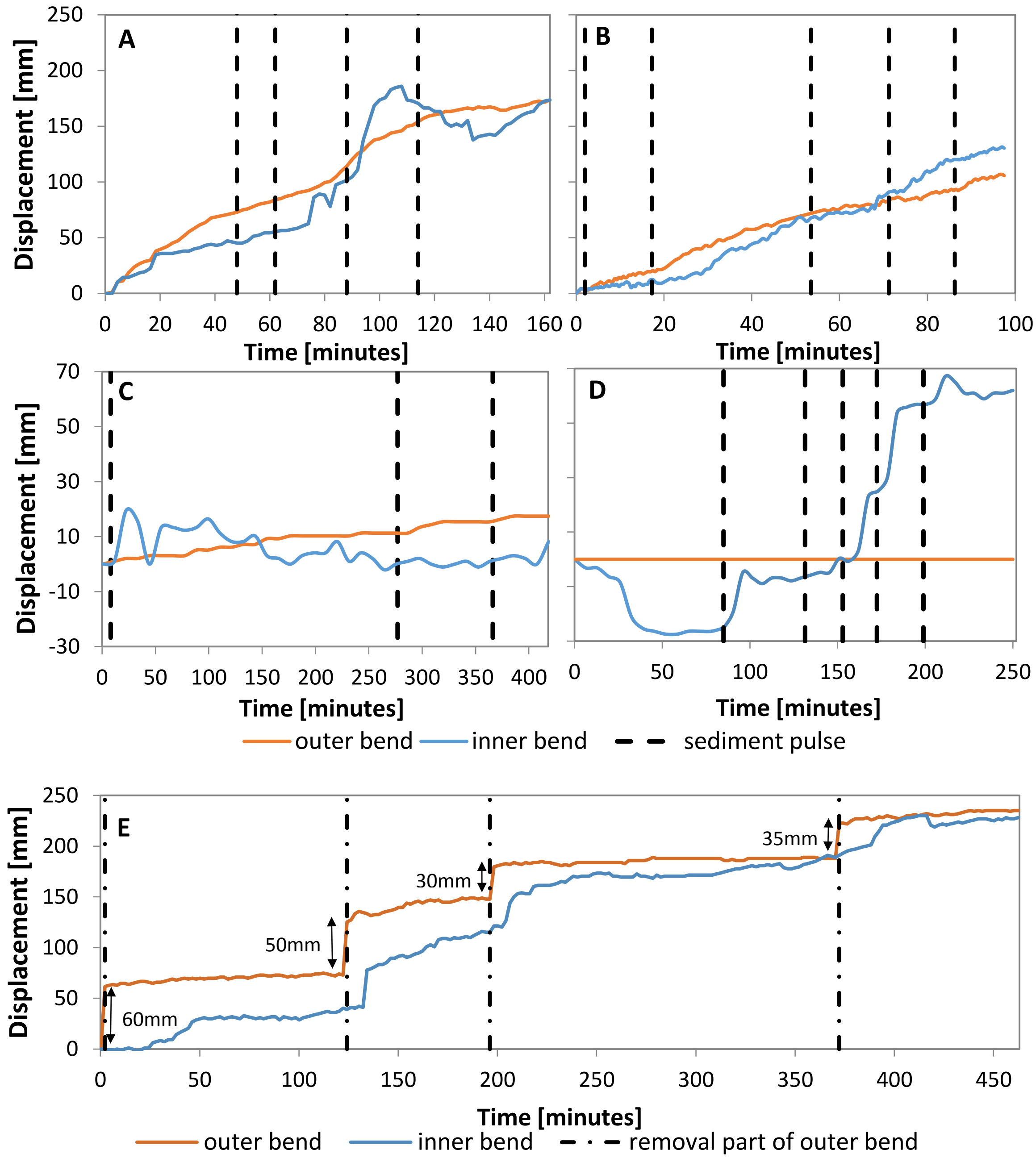

Figure 5.17 - Displacement of the inner and outer bend during the cases with perturbations. (A) The erosion of the outer bend in case 6 only slightly increased when the inner bend considerably expanded after the addition of three pulses (dotted lines). (B) No significant relation is visible between the sedimentation at the inner bend and the erosion of the outer bend in case 5. However, the total sedimentation is slightly higher than the total erosion after five sediment pulses. (C) There is no significant sedimentation at the inner bend and erosion of the outer bend during case 4 after three sediment pulses. (D) When the outer bend was fixed in case 8, the inner bend firstly eroded, but expanded after the addition of multiple sediment pulses. Eventually, the channel filled and a chute cutoff formed. (E) Displacement of the outer and inner bend for case 7. The outer bend was removed four times (dotted lines), which caused a significant response of the inner bend.

6 Discussion

In order to determine the mechanism of scroll bar formation, several cases were performed in an experimental meandering river. In table 6.1 the results of the eight different cases are summarized. In this section these results are discussed. First, the flow conditions in the experiment are compared to previously stated scale rules. Then, the development of the river pattern will be explained. After this, the flow patterns in a meander bend and its influence on sediment transport and morphology is discussed, followed by the findings of the cases where perturbations were added. Finally, recommendations for further research are given by comparing the findings of this experiment with observations in other experiments an in meandering rivers in nature.

Table 6.1 – An overview of the results of the eight different cases that were performed in developed meander bends. The cases differ in the perturbations that are added and whether the bend has scroll bar formation on beforehand.

Case	Bend characteristics	Summary experiment	Summary results
1	No scroll bars Not migrating	Control	• No width variation • Flow velocities are the same at beginning and end of the bend
2	Scroll bars Migrating	Control	• Width increases towards end of the bend • Flow velocities decrease towards end of the bend. • Displacement inner and outer bend show the same trend
3	Scroll bars Migrating	Sediment tracing	• Eroded sediment from upstream of the apex travelled to opposite point bar • Sediment from downstream of the apex travelled to the point bar downstream.
4	No scroll bars Not migrating	Sediment pulses	• No scroll bar formation • No reaction outer bend • Added sediment did not remain on point bar
5	Scroll bars migrating	Sediment pulses	• Sediment pulses did not cause individual scroll bars • No reaction outer bend • Same trend in flow velocities as in control case 3
6	Scroll bars Migrating	Sediment pulses No flow over the point bar	• Sediment pulses did not cause individual scroll bars • Small reaction outer bend after attachment of large sediment lobe • Larger flow velocities than at case 5 and larger flow velocity difference between outer and inner bend.
7	Scroll bars Migrating	Outer bend removal	• Reaction inner bend: a scroll bar formed after each erosion event • Accretion of the point bar until equilibrium width is reached again • Flow velocities are lower at the inner bend after an erosion event
8	Scroll bars Migrating	Fixed outer bend Sediment pulses	• Fixing outer bend resulted in point bar erosion • Initial channel width was restored with first sediment ulse • Flow was blocked by subsequent sediment pulses

6.1 Scaling

A dynamic experimental meandering river was successfully created, representing a gravel bed river. A difference between the setup of the experiment and the experiments of Van Dijk et al. (2012) and Van de Lageweg et al. (2012) is that no silica was added to the sediment feed. It is possible that meander bends would have developed further when silica would have been added, as this increases bank stability and therefore reduces chute cutoffs. Also, the sediment was coarser than in the experiments of Van Dijk et al. (2012) and Van de Lageweg et al. (2012). The discharge was therefore also higher, so that the stream power (eq. 1) was high enough to create the same pattern. Using the average channel depths (figure 5.2) and average flow velocities (figure 5.9) it is estimated if the conditions are in agreement with the scale rules mentioned in section 2.6 (table 6.2). Although the resulting values are only an estimate using average values, it is clear that the Froude number, Reynolds number and sediment transport capacity comply with the scale rules. The lower values for the Reynolds number and sediment transport are found at the end of a migrating meander bend, where the width increases and the depth decreases. Also, no scour holes are observed, which indicates that hydraulic rough conditions are present. Values of the interaction parameter are between 0.19 and 0.55, which means the river is in the underdamped regime or in the exited regime. Therefore, bends were stimulated to grow instead of dampening out.

Table 6.2- Scale rules of non-dimensional variables for hydraulic conditions, sediment transport conditions and morphological features compared with the current experiment and the experiment of Van Dijk et al. (2012) and Van de Lageweg et al. (2012).

Non-dimensional variable	**Scale rule**	**Value Van Dijk et al. (2012)**	**Value current experiment**
Froude number	$Fr < 1$	0.5-1.0	0.4-0.95
Reynolds number	$Re > 2000$	1700-3300	900-5000
Shields number	$\theta > \theta_c$ (=0.04)	0.12	0.07-0.12
Interaction parameter	$0.10<IP<0.29$	0.12-0.47	0.19-0.55

6.2 River pattern development

Erosion is the driving force in river pattern development in the current experiment. Due to the offset of the migrating inlet at the start of the experiment, the flow is directed to the other bank of the initial channel and erosion takes place. At the same time, sediment is deposited on the other side of the initial channel, because here flow velocities are too low to transport the sediment. Because the flow collides with the bank, the flow is redirected downstream towards the opposite bank and is thus following a slightly sinuous path. The erosion of the outer bank therefore causes sedimentation at the opposite side of the channel which forms the alternate bars. This differs from the observations by Lewin (1976), Bridge (2003) and Pyrce and Ashmore (2005), who observed that the flow starts to follow a sinuous path because of developed alternate bars in a straight channel, which then leads to erosion of the opposite bank. However, alternate bars did develop in a still straight section at the downstream end of the flume in the current experiment. This was probably still influenced by the flow that was directed towards the other bend and therefore lower flow velocities at the location where the alternate bar developed. The sinuous path of the flow decreased downstream and did not cause erosion anymore and therefore the alternate bars dampened out downstream.

The direction of the flow into a meander bend remains the cause of migration of the bend. When the migrating inlet moved to a larger amplitude, the inflow direction into the first bend was more directed to the outer bend, which stimulated erosion and also influenced the inflow direction into the next bend. This caused bends to develop with larger amplitudes. When the migrating inlet moved towards the center, the flow was directed more to the inner bend, which stimulated chute cut-offs to occur. When an upstream bend did not change significantly and therefore the inflow direction into the bend did not change, a bend with a relatively large radius could stop migrating as an equilibrium was found between the morphology and the flow conditions. These bends could start migrating again when there was a significant change in inflow direction from the upstream bend enabling erosion. This significant change of the inflow direction was visible in the orientation of the bundles of scroll bars that formed.

6.3 Control cases

6.3.1 Flow patterns in a meander bend

At the beginning of an undisturbed meander bend, flow velocities are highest in the middle of the channel, while at the apex flow velocities are highest at the outer bend. This is due to the centrifugal force, as described by e.g. Allen (1970) and Blanckaert and de Vriend (2003). The difference between the velocities at the outer and inner bend at the apex is highest in bends with a relatively small radius, as is visible when comparing case 5 and case 6 (figure 5.15). Since this flow velocity distribution is found at the surface, one can assume there is also a secondary current present and a current near the bed that will gradually curve inwards towards the inner bank (Blanckaert and de Vriend, 2003). The presence of a return flow along the bed towards the point bar is visible by the bedforms travelling along the point bar. First, the ridges of the bedforms are aligned almost perpendicular to the channel curvature, but after the apex they curve towards the point bar and travel upslope. This corresponds with the observations of Sundborg (1956) and Ashmore (1982). Calculations with the average values discussed in section 6.1 show that the average adaptation length of the flow is about 1.1 meters. This means that after 1.1 meters the flow has adapted for 63% by establishing a secondary flow.

According to Allen (1970), the mean particle size of the bed load material decreases from the deepest part of the channel towards the inner bend, as shear stress and thus the sediment transport capacity decreases. Therefore, in the current experiment the relatively fine material is transported along the point bar. There is no large difference in flow velocity present over a cross-section at the beginning of the bend and bedforms that consist of finer material are visible in the entire channel. Flow paths due to the secondary currents are also visible in the deposition patterns of the colored particles (figure 5.7). Eroded sediment from before the apex of the outer bend is transported by the secondary current towards the inner point bar, while sediment from downstream is carried with the main current towards the next point bar, where it deposited by the secondary current of that bend. The angle of the bed shear stress that is directed towards the inner bend can be determined by comparing the location of deposition with the location of erosion. This is about 24 degrees at the apex. This value can be compared to a theoretical value, computed with the equation of Struiksma et al. (1985) for the direction of bed shear stress (δ), using the measured velocity vectors at the apex:

$$\delta = \tan^{-1}\left(\frac{v}{u}\right) - \tan^{-1}\left(\frac{2\varepsilon}{\kappa^2}\frac{h}{R}\left(1 - \frac{\sqrt{g}}{\kappa C}\right)\right) \qquad (13)$$

Where v = velocity in transverse direction [m/s], ε = calibration coefficient and κ = Von Kármán constant. With this equation an average value of 14 degrees is found at the apex, which is thus lower than the observed angle. However there is a lot of scatter when using the measured velocity data in these calculations and angles towards 25 degrees are also present.

In the current experiment a pool formed upstream of the apex of a migrating meander bend. According to Hey and Thorne (1975) and Blanckaert (2010) the secondary flow causes the shear stress to be the largest at this location due to flow convergence. Downstream of this pool, the depth of the channel decreased and width increased. According to Church and Jones (1982), this is because flow diverges downstream of the pool and sediment is deposited as the main current moves from one bank towards the other. Although flow velocities decreased downstream of the apex of migrating meander bends in the current experiment, this shift of the main current from the outer bank towards the outer bank of the next bend was not visible here. This shift is visible in bends that did not migrated, but here no sediment deposited. Here, sediment input was in equilibrium with the sediment transport capacity of the flow.

6.3.2 Erosion and deposition patterns in a meander bend

The equilibrium width is preserved in the developed meander bends, as the amount of bank erosion of the outer bend is approximately equal to the amount of deposition on the inner bank. This corresponds with the observations of Leopold & Wolman (1960). Width increases downstream of the apex, which had a large impact on flow velocities and sediment deposition along the bend. Due to the increase in width, flow velocities decrease towards the end of the bend and therefore bedforms deposit on the downstream side of the point bar. Widening of the cross-section and corresponding decrease in flow velocities is also obseverved by Blanckaert (2010). Migration rate was highest in bends with a smaller radius, as a smaller radius causes the flow to collide with a larger force with the outer bank (Blanckaert, 2010). In bends that did not migrate, there was no erosion of the outer bend and therefore no channel widening towards the end of the bend. This resulted in an increase in flow velocities towards the end of the bend.

At every migrating bend scroll bars formed, because individual scroll bars are formed by erosion events at the outer bend. Sediment sheets travelling along the point bar deposit when shear stresses and therefore the sediment transport capacity of the flow reaches a critical point and the flow cannot transport the sediment further upslope. At this point a ridge is visible, which is the front of the deposited sediment sheets. When the outer bend erodes, this critical point moves more towards the channel and sediment can travel less far on the point bar. As a result, a new scroll bar ridge is formed. Scroll bars thus consist out of multiple deposited bedforms. They cannot form by suspended load, as the experiment represents a gravel bed river where no suspended load is present.

6.4 Test of hypotheses

6.4.1 Influence of sediment input on scroll bar formation

Scroll bars form by several bedforms that travel along the point bar and travel upslope due to the secondary current. It is not clear what drives the formation of individual scroll bars. It is unknown whether variations in sediment supply or discharge variations can explain the formation of individual scroll bars. The observation that scroll bars are formed by bedforms suggests that a variation in sediment supply is important in scroll bar formation. However, adding sediment pulses to the beginning of a meander bend did not cause individual scroll bars to form. The sediment passed through a bend or was deposited on top of an already existing scroll bar without forming a new ridge. Because there was no significant change in the rate of expansion of the point bar, flow patterns did not alter and therefore sediment pulses did not cause an increase in outer bend erosion. For example, in case 5 only two new scroll bars were recognizable after five sediment pulses and the erosion rate of the outer bend did not change. The spacing between the scroll bars remained the same as before the addition of the sediment pulses, as the pulses had no influence on scroll bar formation and the erosion rate of the outer bend remained the same. Similar results were visible in a bend that did not migrate beforehand. When adding sediment pulses, the added sediment passed through the bend, but did not deposit permanently. The sediment input was balanced by the sediment transport capacity of the flow. Therefore, it did not influence the outer bend erosion rate and the bend did not start to migrate.

Higher flow velocities were present at case 6, because all of the discharge had to flow through the bend. These higher velocities and the smaller radius of the bend caused a stronger secondary current (Allen, 1970). However, this did not make a difference compared to case 5, as no individual scroll bars formed due to individual sediment pulses. In this case there was a change in expansion rate of the point bar after three pulses and also some reaction of the outer bend erosion rate is visible after that, although this is very small. Here, the volume of the added sediment was too large and the flow could not carry all the sediment downstream. This was also visible when the outer bend was fixed and more sediment was added after the equilibrium width was reached.

6.4.2 influence of width variation on scroll bar formation

When part of the outer bend was removed, the width of the channel increased. This caused the flow velocity to decrease at the inner bend and therefore the flow could not transport all the sediment at the inner bend anymore. As a result, a new scroll bar formed and the original channel width is restored. This process is as described by Hickin (1974), Nanson (1980) and Nanson and Hickin (1983), who conclude that scroll bars are developed when the outer bank is eroded and the inner bank has to accrete in order to maintain the equilibrium width. In this study, the scroll bar started to form immediately at the beginning of the bend and travelled downstream, as the sediment arrives from upstream. According to Nanson and Hickin (1983) the concave bend can undergo severe erosion while the accretion of the point bar is much slower. In this case, the accretion rate of the point bar increased significantly after the removal of the outer bend, but is indeed somewhat slower than the instantaneous outer bend removal. The difference in accretion rate depends on how much sediment is available from upstream to form the scroll bar and does not depend on the width of the outer bend reach that is removed, which is also in accordance with the observations of Nanson and Hickin (1983). There is almost no erosion of the outer bank between two artificial erosion events. According to Nanson and Hickin (1983) this is because the stream power is too low due to the overwide channel and the equilibrium width should be reached again first.

The importance of the width of the channel is also visible when the outer bend is fixed. First, some erosion of the point bar takes place and the width increases. When sediment pulses are added, more sediment comes in than can be transported near the point bar and therefore the point bar accretes. This continues until the equilibrium width from before the bend was fixed is reached again and sediment supply is balanced by sediment transport capacity. As mentioned in the previous section, the following sediment pulses were not transported downstream and the channel was blocked.

From these cases it can be concluded that an increase in channel width and corresponding decrease in flow velocity at the inner bend causes the formation of individual scroll bars. Erosion of the outer bend thus leads the expansion of the point bar. Therefore, variations in the sediment transport capacity of the flow is more important than variation in sediment supply.

6.5 Further research

6.5.1 Separation zones in sharp bends

Further research is needed on the difference in scroll bar formation between relatively gently curved bends and relatively sharp bends. In the current experiment, relatively gently curved bends developed. Ferguson et al. (2003) and Nanson (2010) describe how flow separation zones exist in relatively sharp meander bends along the outer bend and along the inner bend. Flow around the inner bend becomes unstable and breaks away from the boundary near the most sharply curved point, leaving a zone of static or slightly circulatory water near the inner bend. These inner bank flow separation zones severely affect the sediment dynamics and here fine sediment can accumulate (Ferguson et al., 2003). According to Nanson (1980), scroll bars are deposited along the boundary of a flow separation zone at the inner bend, which displaces when the outer bend is eroded. Although the conclusion that scroll bar development depends on erosion of the outer bend corresponds with the current findings, this flow separation zone is not clearly observed in flow velocity patterns in the current research. Possibly, the bends in the current experiment are not sharp enough for flow separation to occur.

Teske (2013) did find evidence for the presence of flow separation zones in a similar experiment as in the current research. In his experiment vegetation was added to the developed meandering river, which resulted in less erosion of the outer bank. Some bends became sharper and here a sediment splay developed upstream of the bend apex, covering older deposits. Scrolls were formed in the lee of the sediment splay, downstream of the apex (figure 6.1). This could indicate that at the point where the sediment splay ends and the scroll bars begin, the flow breaks away from the boundary and a zone of low flow velocities is present downstream. At this zone scroll bars form out of fine material to fill up the space. When the outer bend erodes, this zone migrates in the direction of the channel and a new scroll bar is formed. This morphology is also visible in lesser extent in the relatively sharper bends in the current experiment (figure 6.1). Thus, when bends become sharper the separation zone seems to become more important in the formation and the location of scroll bars. At the experiment of Teske (2013) scroll bars were also formed at the outer bend downstream of the apex, possibly indicating the presence of an separation zone as is observed by Blanckaert and Graf (2001). In the experiment of Teske (2013) developed scroll bars were thicker than in the current experiment, which is possibly due to the lower migration rate of the outer bend due to a higher bank strength. More sediment that comes in from upstream has to deposit on top of an already present scroll bar, instead of forming a new scroll bar when the bend has migrated. The experiment of Teske (2013) also represents a gravel bed river with only bed load transport, which differs from the observed scroll bar formation in sharp bends by suspended sediment by Nanson (1980).

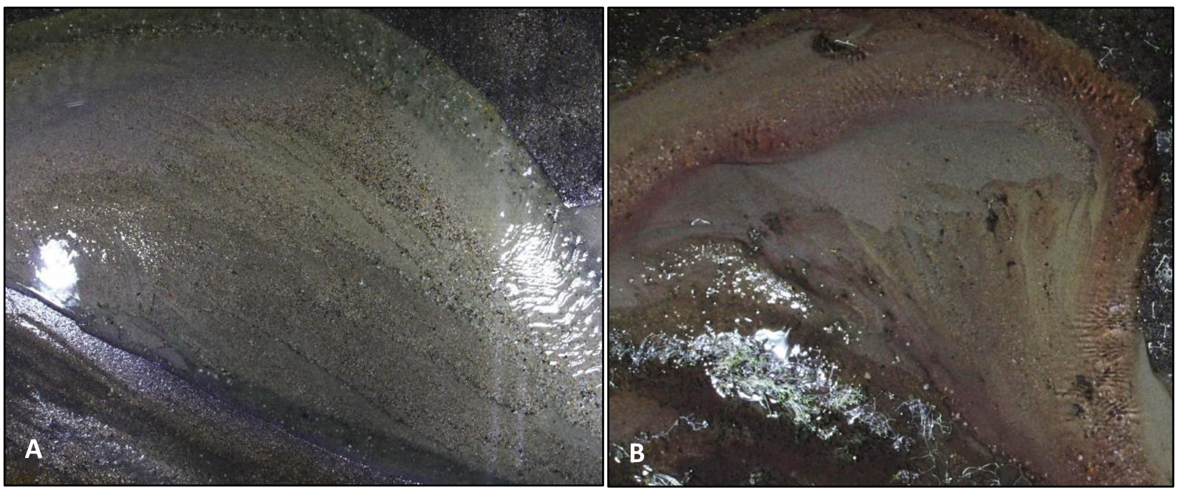

Figure 6.1 – The morphology in a relatively sharp bend in the current experiment (A) and a sharp bend in the experiment of Teske (2013)(B). Both bends have a sediment splay upstream of the apex and scroll bars forming downstream. Scroll bars in (B) are thicker and seem to consist out of finer material.

6.5.2 Scroll bar formation in nature

The development of scroll bars in an experimental river is explained by our research. The main mechanism responsible for the formation of scroll bars is outer bank erosion. As mentioned before, this is in agreement with observations in several natural rivers. However, scroll bars formed with constant discharge in the experiment, even though Hickin (1974), Nanson (1980) and Nanson and Hickin (1983) state that discharge variations are needed in their research of the Beatton river. This can be explained by the observation that in nature floods are likely to cause failure of the outer bend, thus leading to inner bend scroll ridge deposition.

Another observation in the current research is that bend migration is highly influenced by upstream changes in channel pattern, which is also observed in nature. An example is the development of the Rhine River close to the border between the Netherlands and Germany. A bifurcation developed at this location about 2500 years ago, resulting in an avulsion about 300 years ago (Kleinhans et al., 2011). The avulsion took place because one bifurcate silted up, while the other bifurcate widened. This process was stimulated by a decrease in the angle between the upstream channel and the enlarging bifurcate through bank erosion, while the angle with the aggrading bifurcate increased (Kleinhans et al., 2011). A map of the morphology after the avulsion is shown in figure 6.2A. The meander bend at the location where the avulsion took place migrated downstream (bend I), which caused a change in inflow direction into the next bend (bend II). This bend rapidly migrated northward between 1725 and 1745 as a result (Kleinhans et al., 2011). Due to this migration large scroll bars are visible in both bends. In figure 6.2B the morphology of bend II in 1772 is visible in more detail. The scroll bar in this bend is present at the apex, where the bend is migrating, and consists of sand and gravel. A zone where finer sand is deposited is present downstream, in the lee of the scroll bar. This is a flow separation zone as described in section 6.5.2.

The question that arises from the example of the Rhine River is how the scroll bars that are visible on the map in figure 6.2 are related to scroll bars in the current experiment. The scroll bars in the Rhine River are much wider compared to the channel width than the experimental scroll bars. In figure 6.3 another two examples of scroll bars in natural rivers are visible. The scroll bars in the Okavango river in Botswana (figure 6.3A) are comparable with the scroll bars in the current experiment, while in the Allier River in France relatively wide scroll bar are present (figure 6.3B). It is thus observed that the experimental scroll bars are comparable to scroll bars in nature, but there also seems to be another type of scroll bars. It remains unclear how these relatively large scroll bars relate to the findings in the current experiment. These scroll bars also formed due to migration of the outer bank, but regarding the findings of the current experiment this would mean a sudden migration of the outer bank with the same width as the scroll bar, or perhaps a very gradual migration of the outer bend. Both options seem unlikely. Comparing figure 6.3A and 6.3B, the existence of relatively wide scroll bars seems to coincide with a relatively sharp transition into the next bend. There are some characteristics of the experimental river and the Okavango River that differ with the Allier River. For example, The width to depth ratio and the streampower are much higher in the Allier River. To understand which variables are relevant and thus what is the difference between these two kinds of scroll bars, further research is needed.

Figure 6.2 – (A) An historical map of 1752 of the morphology of the Rhine near the border of the Netherlands and Germany after an avulsion took place. the meander bend at the location were the avulsion took place migrated downstream (bend I), which caused a change in inflow direction into the next bend (bend II). As a result, this bend rapidly migrated northward between 1725 and 1745. (B) A detailed map of bend 2 in 1772. A scroll bar formed due to the migration, which consists of sand and gravel. Downstream a zone where finer sand is deposited is present in the lee of the scroll bar (Kleinhans et al., 2011)

Figure 6.3 – (A) Scroll bars in the Okavango river in Botswana, which have a relatively small width compared to the channel width and are comparable with the scroll bars in the experiment. (B) Relatively wide scroll bars in the Allier river in France. (source: Google Earth)

7. Conclusions

Controlled flume experiments are used to identify the major processes in the formation of scroll bars. Results demonstrate that:

- Scroll bars are formed of multiple bedforms that deposit on the point bar by secondary currents.
- Outer bend erosion controls scroll bar formation. Outer bend erosion results in channel widening which decreases flow velocities and thus leads to deposition of scroll ridges along the inner bend point bar.
- Channel width variations are essential to explain sediment deposition, scroll bar formation and meander bend migration.
- Variations in sediment supply do not cause the formation of scroll bars and do not influence channel width. Therefore, sedimentation at the inner bank does not influences erosion of the outer bank.
- Upstream changes in morphology influence the flow direction into a meander bend and therefore control the erosion of the outer bend. Therefore, bundles of scroll bars have a different orientation due to upstream changes in channel pattern configuration.
- Scroll bars can form during constant discharge. This implies that discharge variations are not a necessary condition, although in nature floods are likely to cause outer bend erosion and thus lead to inner bend scroll ridge deposition.
- Further research can be done on the difference between scroll bar formation in gently curved bends and relatively sharp bends where flow separation zones are present.
- In several natural rivers relatively wide scroll bars are observed, which differ with the scroll bars in the experiment. It is yet unknown what causes this difference.

8. Acknowledgements

First I would like to thank my supervisors Maarten Kleinhans and Wietse van de Lageweg for their ideas and support in all stages of this thesis. The experiment was done in cooperation with Roy Teske, who I would like to thank for his help on the experiment and all the helpful discussions. The experiment would also not have been possible without Wout van Dijk and the technical staff: Henk Markies, Chris Roosendaal and Marcel van Maarseveen. KNAW assistant Eveline van der Deijl was a great help in setting up the experiment and Marjolein Baar helped to improve the writing style of the thesis.

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