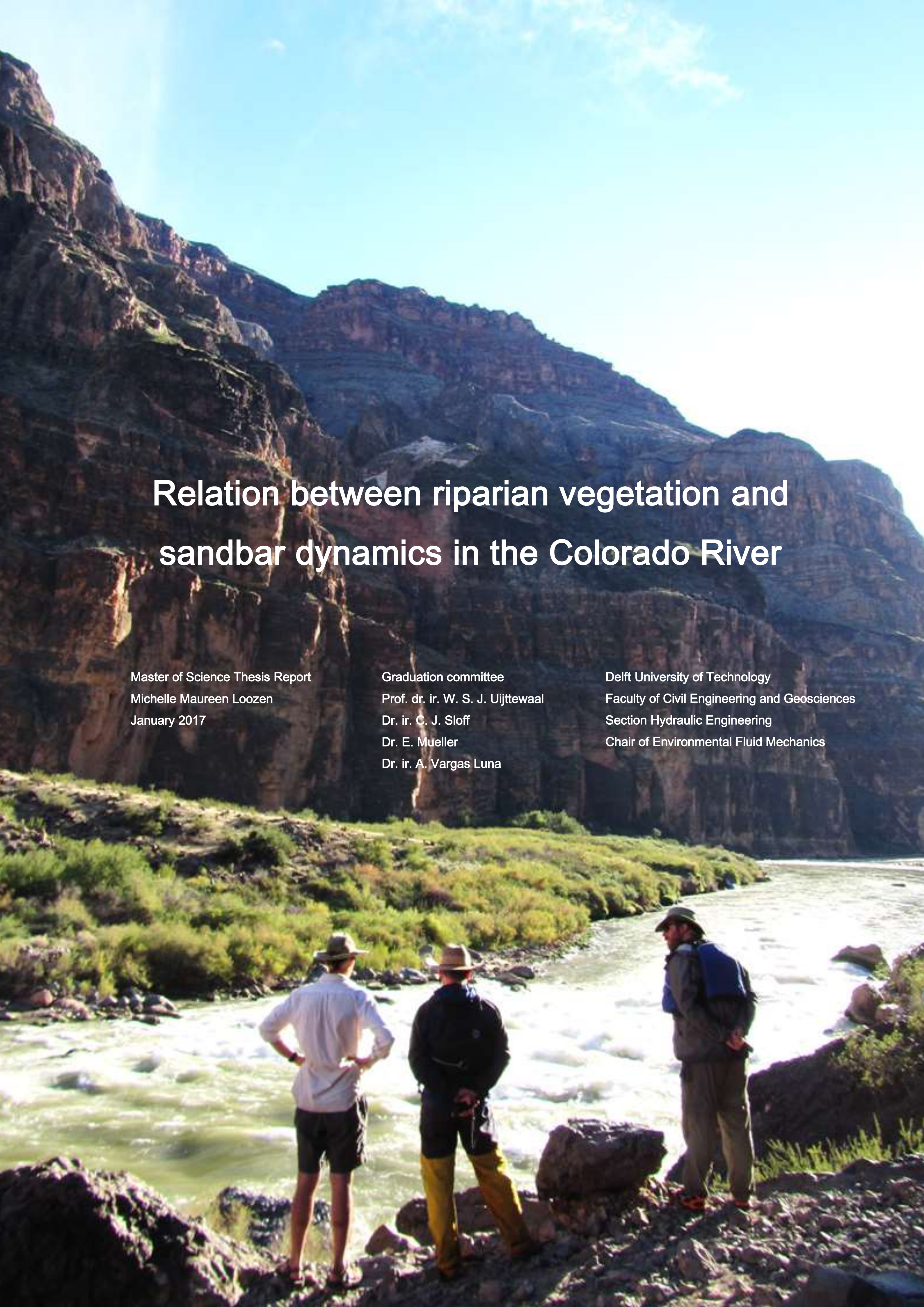

Relation between riparian vegetation and sandbar dynamics in the Colorado River

Master of Science Thesis Report
Michelle Maureen Loozen
January 2017

Graduation committee
Prof. dr. ir. W. S. J. Uijttewaal
Dr. ir. C. J. Sloff
Dr. E. Mueller
Dr. ir. A. Vargas Luna

Delft University of Technology
Faculty of Civil Engineering and Geosciences
Section Hydraulic Engineering
Chair of Environmental Fluid Mechanics

PREFACE

This thesis report is the final step in fulfilling the Master of Science degree in Hydraulic Engineering at Delft University of Technology, faculty of Civil Engineering and Geosciences. The research is done in cooperation with Deltares and USGS Grand Canyon Monitoring and Research Center.

I would like to thank the graduation committee for their comments, advice and support. Prof. dr. ir. W. S. J. Uijttewaal who always freely made time for me and advised me on the approach of this thesis, Dr. ir. C. J. Sloff for enabling the research and the contacts he made for me with USGS, Dr. E. Mueller for his thorough feedback and the huge contribution to the knowledge and finally Dr. ir. A. Vargas Luna for his creative input and suggestions. I also thank Paul Grams for the welcoming stay in Flagstaff and his support and inspiration during the field trip. Lastly I would like to thank my family and Andreas who played an important role in the finalization of my thesis. They were invaluable to me, without their help and support I still had to go a long way.

To the reader, thank you for showing interest in my study.

Michelle Loozen

Delft, January 2017

ABSTRACT

The Colorado River with a total length of 2330 km is located in the Southwest of North America, originating from the Rocky Mountains and flowing into the Gulf of California. In 1963 the Glen Canyon Dam was built to generate hydropower. The construction of the dam caused several significant changes in the river system. One of these changes is the expansion of the riparian vegetation. Because of its magnitude and importance as a natural water carrier, the Colorado River has been studied extensively for decades. One can argue that the sandbars in the Colorado River are well mapped and its dynamics are well understood. Additionally, the species of riparian vegetation, the location of growth as well as the dimension of vegetation changes are extensively mapped. However, the influence of the aforementioned riparian vegetation expansion on the sandbar dynamics is poorly understood. It is crucial to shed light on this correlation as the dynamics of the system indicate the course of action and determine the possible activities in the area. The main research objective is to gain better understanding on the correlation between vegetation expansion and sandbar dynamics. Two different methods are used to explain the phenomenon; an analysis of data concerning vegetation and geo-morphology is performed and also a detailed hydraulic and geo-morphodynamic model is created.

Seven locations in the Colorado River are selected for the data analysis in the period between 2002 and 2013. Of each location different features are visualized and linked including the geo-morphology of the sandbar and the adjacent channel, the geometry and hydraulics of the channel and finally the vegetation coverage on the sandbars. As a result of this data analysis a clear relation was found between flood cycles and changes in sandbar volume. Moreover, a clear relation between change in sandbar volume and changes in vegetation coverage was observed. Lastly, a clear relation between the location of vegetation and the bed level changes was found. At the end of this section several methods in order to improve the analytical results are mentioned.

The sandbar selected for modelling purposes is a reattachment bar, overgrown with a significant amount of vegetation which has expanded remarkably over the years. The flow module of the DELFT3D suite is used. The Baptist model assumptions are used for the representation of vegetation. The parameters determined in the Baptist model are derived from field measurements on arrowweed. The model investigation of the influence of vegetation on the sandbar dynamics is restricted to the flow pattern. Based on the flow pattern an explanation is given for the expected bed level changes. The main flow features that are affected by the expansion of the riparian vegetation are, among others, the characteristic of the primary and secondary eddy, the deflection on the main stream, the location on the reattachment point and the velocity of the flow in the vegetated areas. Inarguably, the above mentioned changes heavily alter the geomorphology of the system. These changes in geomorphology, on its turn, are likely to influence vegetation succession and even the hydraulics. This lastly mentioned feedback, however, has not been thoroughly investigated in this research. Finally, several methods in order to improve satisfying the flow pattern and in order to reduce the discrepancy of the bed level changes are mentioned.

Overall it can be stated that vegetation certainly contributes to the stability of sandbars and that it clearly contributes to their growth. Hydraulic forces, which are strongly related to the width of the channel, determine the magnitude of sediment transport fluxes. Sandbars which develop in narrow channels stay low in elevation and are dynamic; this generally obstructs the natural succession of vegetation. Sandbars which develop in wide channels become high in elevation and become stable; this promotes vegetation growth. If vegetation expands on low, dynamic parts of the sandbars the growth of vegetation is likely to promote stabilization and vertical accretion, creating a feedback towards a higher elevation and more stable sandbar. When this occurs the expected long term result is a river system with a significant part of the sandbars becoming high in elevation, less dynamic and vegetated. However continued monitoring of the system is necessary to determine what the exact vegetation extent over time will be.

The iconic feature of the Colorado River during the pre-flood period, namely the open dynamic sandbar system, is currently replaced by a more vegetated river system with less open sand. On the one hand, vegetation provides riparian habitat for a variety of species. At the same time it decreases the open sand area available for recreational activities. The final decision upon the fate of vegetation should be taken after weighting the relative importance between scenarios and future planning. A suggestion to improve the overall study is to take into account other aspects that determine the ability of vegetation to expand such as the availability of groundwater, the daily exposure to sunlight, the fertility of the soil and the activity of the local species. If the effect of these parameters gets integrated in the interdependency between sandbar and vegetation dynamics then the result will give a solid picture of the natural system and the current beneficial results of this research will be further strengthened.

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1 INTRODUCTION

1.1 PROBLEM DEFINITION

The Colorado River is one of the longest rivers of North America with a total length of 2330 km, located in the Southwest of the continent, originating from the Rocky Mountains and flowing into the Gulf of California. Melis et al. (2011) [1] states that the Colorado River, especially the part in which the Grand Canyon is located, is one of the most studied rivers in the world in 1963 the Glen Canyon Dam, with a height of 200 m, was built to generate hydropower. The mean annual peak flow has been reduced by 65% and the annual and daily flow variability increased considerably. Furthermore, the dam took away upriver sediment contributions. Recent measurements by Topping et al. (2000) [2] proved that the sediment load is less than 20% of the original yield.

This new flow and sediment regime modified the river morphology and still contributes to modifications in the river system; sandbars erode more significantly and changes in vegetation coverage and growth are observed. Research by Sankey et al.(2015) [3] confirms a net increase in vegetated areas in the Colorado River since the completion of the dam. At lower elevated areas of the river expansion of vegetation can be observed consequent to the increase in the base flow. At higher elevated areas the riparian vegetation gets intermittent and decreases. Changes in vegetation influence the hydraulics, geo-morphodynamics as well as sediment transport and vice versa. Little is known about this mutual influence.

Fig. 1-1: Location Colorado River

1.2 RESEARCH QUESTIONS

The relation between vegetation, geo-morphodynamics and hydraulics is investigated in an attempt to gain insight of the influence of vegetation on the sandbars dynamics. We pose the following research questions:

I. Does vegetation contribute to stabilization of the sandbar and potentially also contribute to its growth?
II. What explains the difference in vegetation degree across the various sandbars?
III. What is the influence of vegetation expansion on the flow pattern on and around the sandbar and consequently on the geo-morphological changes?
IV. What will be the expected long term lay out of the Colorado River system when no measures on vegetation are taken?

1.3 APPROACH

Different steps are taken to gain insight of the role of vegetation on the changes and development of the sandbars in the Colorado River. A scheme of these steps and their relation is shown in figure 1-2. First, literature regarding the Colorado River system and the influence of vegetation on the hydraulics and geo-morphodynamics was reviewed. The aim was to gain insight into the several processes in the Colorado River system, to study the influence of vegetation on morphological river processes in general and to understand the local influence of vegetation on the hydraulics and morphology. Second, a field survey was executed, to get both a first impression of the occurring processes and their interdependency and to collect data for the modelling of hydro- and morphological processes. Third, an analysis of already existing data concerning vegetation and geo-morphology of seven sandbars was performed. This analysis focuses on different features of the sandbars: degree and change of vegetation coverage, width of upstream rapid and adjacent channel, range of water level, depth of submersion, volume and shape of sandbars, and change of bed level. Fourth, a detailed hydrodynamic and geo-morphodynamic model was created for a specific sandbar to assess the influence of vegetation on flow pattern and on bed level changes during a flood event. The results of data and model analysis are combined to an overall conclusion.

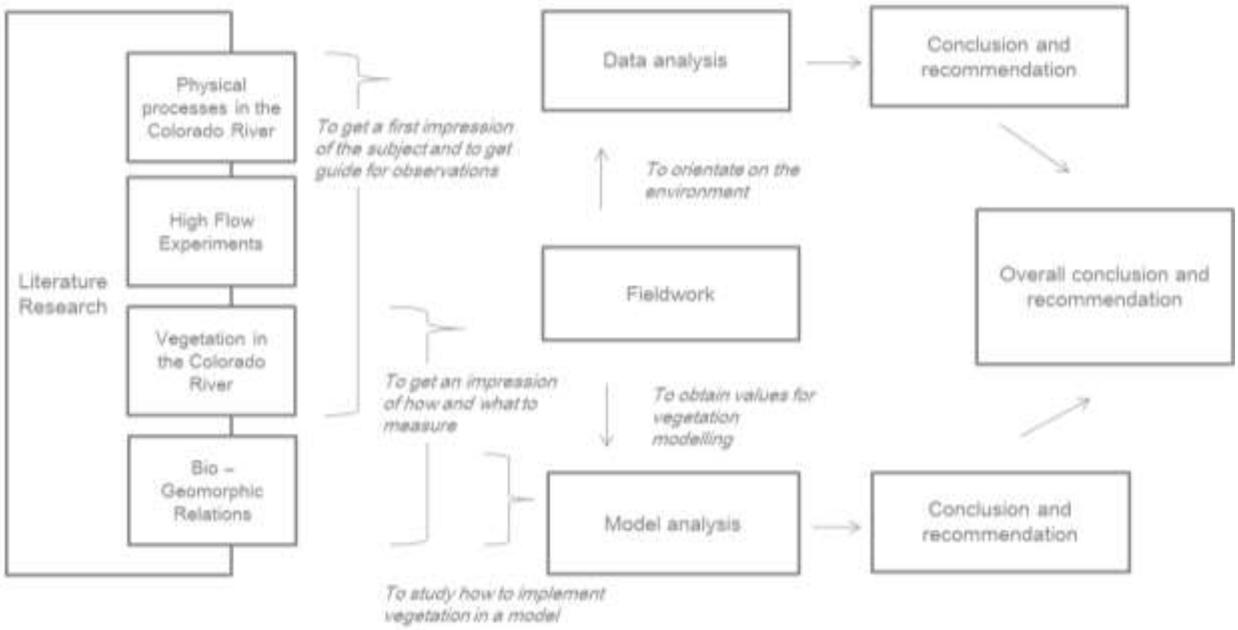


Fig 1-2: Scheme of the approach of the research

2 DESCRIPTION OF THE RIVER SYSTEM AND GOVERNING PROCESSES

2.1 PHYSICAL PROCESSES IN THE COLORADO RIVER

The Colorado River flows through various types of bedrock layers. Due to differences in the hardness of the rock in various stretches the river, considerable variations in channel dimension, channel slope and valley-width can be observed. Soft rock areas, for example, are more easily eroded, leading to wider channels and less constrictions.

The Colorado River has lots of tributaries, each delivering large amounts of fine and coarse sediments. Fine sediments entering the main river are mostly kept into suspension. Coarse sediments get accumulated and create constrictions (figure 2-1). Downstream from the constrictions the channel-width increases abruptly. This abrupt increase results in separation of the main flow which provokes circulations. These circulations create the so-called recirculation currents in the area between the main stream and the river bank (recirculation area). The point where the main flow starts to separate is referred to as the separation point (figure 2-2). At the downstream end of the recirculation area, the main flow reaches the bank perpendicularly. This location is called the reattachment point (figure 2-2).The boundary between main flow and recirculation area, the eddy fence is a vertically orientated plane, separating the recirculation current from the main flow. The pattern of the recirculation currents is mostly consistent, consisting of one primary eddy and some secondary eddies. In the recirculation area, the primary eddy fills the downstream part while one or more secondary eddies fill the upstream part. These secondary eddies are not presented in figure 2-2. The size and shape of the recirculation currents are likely to depend not only on the features of the zone of flow expansion and the features of the rapid (narrow, deep rapids cause elongated recirculation areas), but also on the discharge volumes. Schmidt (1990) [4] studied the features of the circulation currents in the Colorado River. At low discharges, the recirculation currents are one-celled eddies that fill the entire recirculation area. At high discharge, secondary eddies develop upstream of the primary eddy, causing upstream migration of the separation point and downstream migration of the reattachment point.

The constriction and therefore the flow patterns and behaviour of the recirculation areas, determines the location and size of sandbars. Sandbars develop in areas where the flow velocity is low causing a low sediment transport capacity. Flow velocities are low near the separation points, at the reattachment points, in the centre of the primary eddy and on the eddy fence. Sandbars formed at the upstream end of the recirculation area are called separation bars and sandbars formed downstream of the primary eddy are known as reattachment bars. Observations at low discharges reveal that reattachment deposits and eddy centre deposits build up one continuous sandbar (figure 2-1).

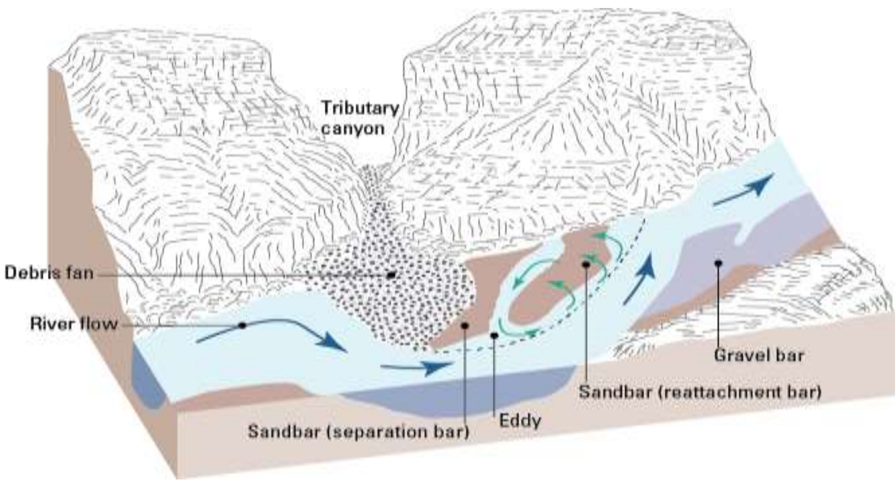


Fig. 2-1: Recirculation area and reattachment sandbar and separation sandbar (Hazel Jr et al. 2010) [5]

Separation bars and reattachment bars are common throughout the Colorado River, mostly at locations where the reach is wide. According to Schmidt (1990) [4], 399 recirculation areas can be identified within 197 km downstream from Lees Ferry. Separation bars occurred in 47% of the recirculation areas and reattachment bars occurred in 71 % of these areas. In narrow reaches (width less than 75 m), separation bars occurred in 23% and reattachment bars in 31% of the recirculation areas. In the wider reaches separation bars occurred in 24%, and reattachment bars in 40% of the recirculation areas. Allegedly the width of the reach is a predominant factor for the occurrence of reattachment bars. Separation bars are composed of finer sands than reattachment bars. This distribution is consistent with the flow patterns, and indicates that sediment moves from the main stream to the reattachment bar and subsequently to the separation bar.

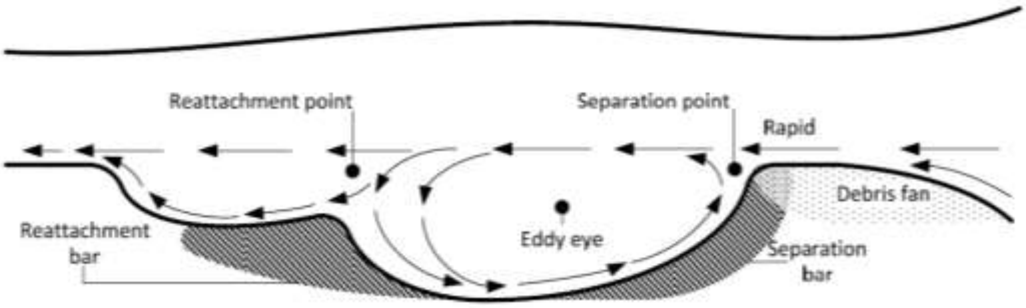


Fig. 2-2: Top view of a recirculation area (Hazel Jr et al., 2010) [5]

2.2 VEGETATION IN THE COLORADO RIVER

Many different species of riparian vegetation are found in and around the Colorado River. A distinction can be made between grass classes, shrub classes and tree classes (figure 2-3). According to a study of Ralston et al. (2008) [6], shrub type vegetation accounted for the most abundant type of vegetation in the Colorado River. A study by Sankey et al. (2015) [3] confirmed a net increase in vegetated areas since the construction of the Glen Canyon dam. The magnitude and timing of the changes in vegetation seem to be depending on the discharge of the river. They showed that vegetation expansion is related to the inundation frequency. The vegetation expansion at the lower areas of the sandbars is greater during periods with lower peak flow and higher base flows; the vegetation expansion at higher areas of the sandbars is related to the precipitation patterns and decreases during droughts. Short pulses of high flow, i.e. during the High Flood Experiments, seem to not disrupt vegetation growth.

Grass class

Shrubs class

Tree class

Fig. 2-3: Different vegetation classes in the Colorado River

2.3 HIGH FLOW EXPERIMENTS

In 1963 the Glen Canyon Dam was built to generate hydropower. As a result of the construction of the Glen Canyon dam, not only the discharge (figure 2-4), but also the inflow of sediment has significantly decreased. The sediments originating from tributaries upstream have been trapped behind the dam and deposited in Lake Powell. Topping et al. (2000) [2] stated that before the construction of the dam, annually approximately 23 million metric ton of sediment flow through the river. After its construction, the total amount of sediment was less than a fifth of this. These changes in discharge and sediment inflow volumes influence the development of sandbars, their locations and the volumes of sandbars. O'Brien and Pederson (2008) [7] showed that in 2008 19% of the sandbars had been severely eroded due to the construction of the dam.

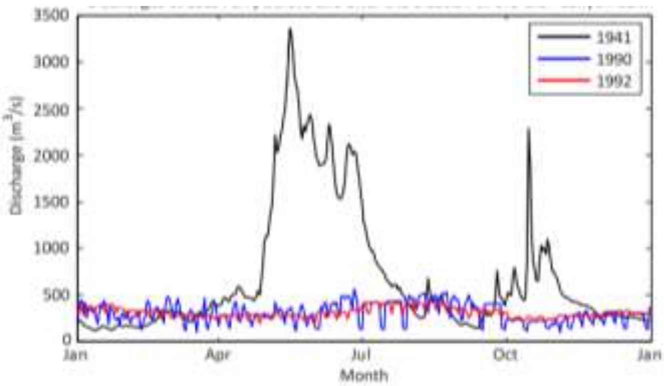


Fig. 2-4: Discharge in the Colorado River at Lees Ferry, before and after the construction of the Glen Canyon dam (Nieuwboer, 2012) [8] . Before the construction, during spring, high amounts of melt water flowed through the Colorado River (black line). After the construction, the discharge regimes changed enormously. The peak flow during spring decreased significantly in magnitude and duration. Furthermore, consequent to differences in hydropower demands, the discharge largely fluctuated between day and night, with a water level varying from 2 to 4 metres (blue line). In 1991 the fluctuations in discharge were lessened upon advice of the U.S. Department of the Interior, to ensure the safety of people fishing and boating the river (red line)

Sandbars play an important role in the ecosystem of the Colorado River and have been therefore thoroughly studied. The study by Rubin et al. (2002) [9] demonstrated that vegetation on sandbars attracts different kinds of fauna and creates locations with stagnant water, which forms a favourable habitat for native fish. In the Colorado River region, sandbars are also used as campsites by tourists. There have been on-going efforts to rebuild sandbars by mimicking the natural, seasonal pre-dam discharges. This is done by releasing high discharge volumes during a short period of time, the so called 'High Flow Experiments' (HFE) which started in 1996. The subsequent floods are shown in figure 2-5. In the beginning floods were limited releases, nowadays, floods are released once every 2/3 years depending on sediment inputs from tributaries.

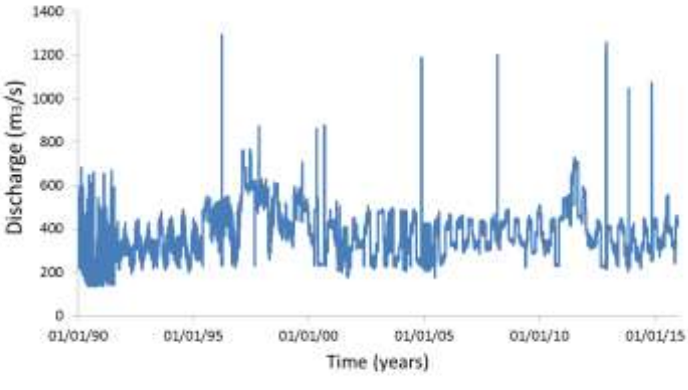


Fig. 2-5: Discharge at Lees Ferry from 1990 – 2015

The High Flow Experiments influence the volume of the sandbars in the Colorado River. The volume of the sandbars is determined by several factors. First, the amount of pre-flood sediments available in the river system determines the volume of the sandbar. This depends on the time of the year. Rubin et al. (2002) [9] state that the highest amount of sediment is delivered in the Colorado river (by the tributaries) in the end of summer. The sediments on the bottom of the river are stirred up and transported by the flood. These sediments settle in areas where the flow velocity and hence the sediment transport capacity is low. Therefore, the amount of pre-flood sediments determines the amounts of sediments deposited at the sandbars. Besides that, the volume of the sandbars is determined by the duration of the flood. Because of the high concentration of suspended sediment in the first phase of a flood, deposition mainly takes place in the beginning of the flood. Floods with a long duration result in low concentrations of suspended sediment. This leads to reduced sediment deposition and in some cases even erosion of the sandbars. Schmidt et al. (1999) [10] demonstrated that during the seven days HFE in 1996, deposition mainly occurred in the first two days of the flood, whereas erosion occurred in the last days of the flood. Throughout the HFE in 2004 that lasted less than 3 days sandbars enlarged more significantly in size compared to the flood in 1996, which can mainly be attributed to the duration of the flood. Additionally, the volume of the sandbar is determined by its location. During the HFE in 2004, only sandbars located in the upper part of the river system enlarged, while sandbars located in the lower part of the river reduced in size, thus indicating that most of the sediment already had been settled. Ultimately, the volume of the sandbars is determined by the daily fluctuations during low water conditions. The higher the fluctuations are, the bigger are the erosion rates.

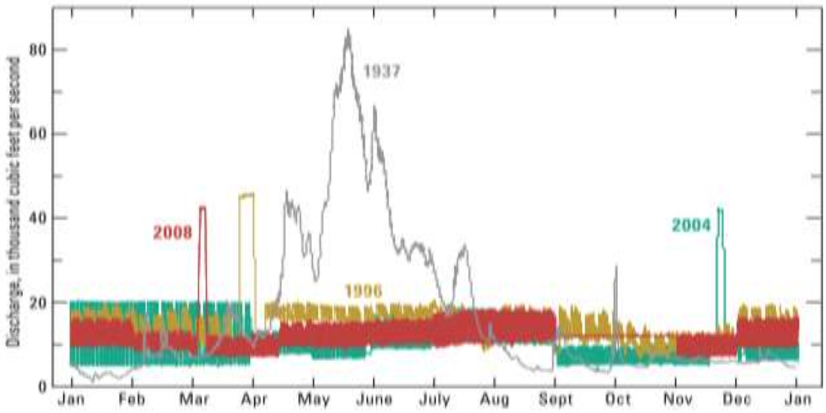


Fig. 2-6: The pre-dam flood discharge in 1937 and the discharges during High Flow Experiments in 1996, 2004 and 2008 in the Colorado River at Lees Ferry (www.gcmrc.gov).

2.4 BIO-GEOMORPHIC RELATIONS

Birkeland et al. (1996) [11] stated that the distribution of riparian vegetation in relation to channel morphology is poorly understood in canyon rivers. The channel morphology in canyon rivers is characterized by fluvial sediment deposits in the channel rather than flood plains. The study focuses on riparian vegetation and sandbar characteristics in two reaches of the lower Little Colorado River canyon in Arizona. One reach has a short regulated flow from the watershed (regulated study reach) and the other reach has a long natural base flow from a spring (natural study reach). Both reaches have been colonized by riparian vegetation which influences the geo-morphic features of the river channels. Birkeland et al. (1996) [11] sampled 18 sandbars. They showed that vegetation frequency and density are significantly greater in the natural study reach. However, sandbar morphology variables do not differ between the reaches, despite a significantly narrower and deeper channel caused by the regulated flow. Hydraulic calculations of flood depths and correlations between bar and vegetation variables indicate reach-specific bio-geomorphic relationships. In the regulated study reach, higher bars are less affected by flood inundation, support older vegetation, and could be a more favourable ground for vegetation. In the wider natural study reach, bars are lower and more expansive and vegetation patterns relate more to bar size. Also in this type of reach, riparian vegetation is most common on the largest sandbars. Overall, this study suggests that; (1) riparian vegetation variation relates to base flow, (2) sandbar formation relates to high discharge events, and (3) riparian vegetation patterns respond to, rather than influence, sandbar form.

Manners et al. (2014) [12] investigated the geo-morphic and vegetation history of the Yampa River in Western Colorado, in order to identify the key mechanism under which vegetation alters fluvial processes leading to a narrower channel. This study identified a distinct similarity in timing and magnitude of vegetation encroachment and channel change, with a lag in the channel response, thus suggesting vegetation as the driving force. Within a decade of establishment, the vegetation effectively trapped sediment and, as a result, caused floodplain construction. The expansion of vegetation coverage over time also reduced the occurrence of floodplain stripping. The vegetation succession was driven by both hydrologic and hydraulic variables, and the majority of the vegetation established in the lower zones of the sandbars. Therefore, the vegetation regularly interacts with the flow and sediment transport field. Changes in flow regime directly impacted vegetation and changes in vegetation cover influencing fluvial processes. Today the rate of channel change and vegetation succession is small. Vegetation expansion and related floodplain construction are believed to have led to narrower channels pushed the Yampa River into a new state of equilibrium.

A schematic representation of the interrelation between hydrodynamics, morphology, sediment transport and vegetation, based on the study of Tsujimoto (1999) [13] , is shown in figure 2-7. In short, the interrelation can be described as follows. Hydrodynamics are affected by the morphology of the bed (1). Hydrodynamics are also affected by vegetation (2). More specifically, vegetation increases the hydraulic resistance (determined by parameters such as plant density, diameter, height and flexibility) which alters the flow field as demonstrated by Baptist et al. (2007) [14] and Zong et al. (2010) [15]. Hydrodynamics leads to sediment transport (3), which causes changes in bed morphology (4). Changes in bed morphology as well as changes in hydrodynamics affect vegetation (i.e. vegetation expansion) (5,6). Bed morphology affects sediment transport (7). Vegetation itself can also affect bed morphology (9). More specifically, vegetation increases the strength of the river banks by reinforcing soil. Vegetation also affects sediment transport (10). Overall, it can be concluded that this interrelated system is complicated and multi-factorial, thus cause and effect are often hard to distinguish.

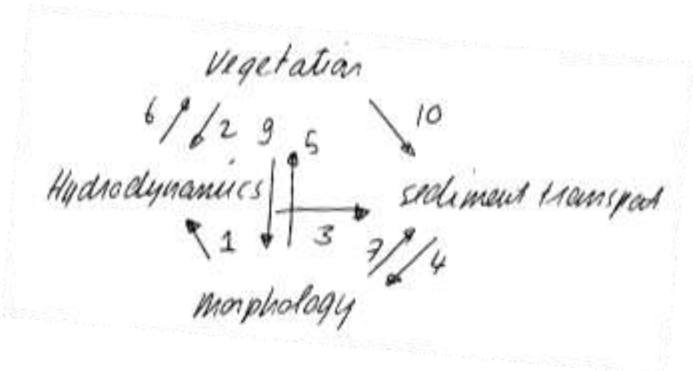


Fig. 2-7: The interrelating system, based on the diagram by [13]

The influence of vegetation on a fully developed sandbar was investigated in a research by Rominger et al. (2010) [16]. This study was performed on a point bar in the meander of a constructed stream. Significant changes in flow structure and bed topography were observed. The study showed that the addition of vegetation on the sandbar reduced the depth average velocity over the bar, and increased the velocity in the open region. Additionally there were indications that the secondary circulation increased in strength, but became confined to the deepest section of the channel. The changes in flow led to consequent changes in sandbar shape. Sediment deposition was observed in the region of the bar closest to the inner bank while erosion and the removal of plants by scouring occurred at the interface between the vegetated bar and the open channel.

The flow and deposition pattern in and around a patch of vegetation was investigated by Zong et al. (2010) [15] and shown in figure 2-8. This laboratory study describes the flow and deposition pattern in and around vegetation located at the wall of a channel. The velocity field measured in and around the patch by acoustic Doppler velocimetry revealed three distinct zones. In the first zone, the leading edge of the patch, the flow in line with the patch decelerates and the bulk of the flow is diverted towards the open channel (figure 2-8). In the second zone, the vegetated patch itself, the velocity is uniform across the width and the length of the patch. In the third zone, the interface between patch and open channel, a shear layer is formed causing turbulence. The pattern of disposition in these three zones differs. In the first zone, net deposition increases in the stream wise direction, as the local velocity reduces. In the second zone, the deposition decreases towards the downstream end of the path, as the concertation in the water column reduces. The deposition pattern across the patch width is nearly uniform. This indicates that the turbulence created in the third zone has no significant influence on the sediment deposition.

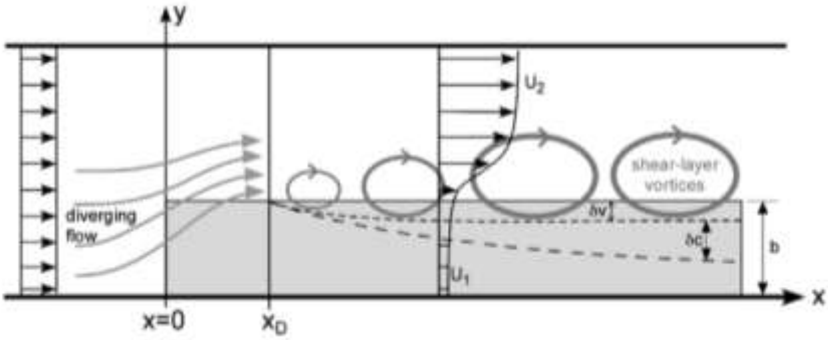


Fig. 2-8: A conceptual picture of the flow field in and around a finite patch of vegetation by Zong et al. (2010) [15]. The position X_D indicates the end of the diverging flow, the shear layer penetrates a distance δv into the patch of vegetation, b is the width of the patch of vegetation.

Hu et al. (2012)[17] reported that vegetation exerts a drag force on the water particles. They stated that vegetation can be schematized as (an amount of) cylinders and the drag force can be defined as:

$$F(z) = \frac{1}{2}\rho_0 C_D(z)a(z)\left|u(z)\right|u(z)$$

Where ρ_0 is the water density, u(z) the horizontal flow velocity at height z, a(z) the frontal area and CD(z) the drag coefficient. The drag coefficient is a dimensionless quantity, related to skin friction and shape of the stem cylinder. The frontal area a (z) is the number of stems cylinder per unit area (n) times the average stem cylinder diameter (D), at a specific height (z).

Baptist et al. (2005) [18] related vegetation dimensions to bed roughness and composed equations in which vegetation is valued by means of bed roughness. These equations are used in this research to implement vegetation in the Delft3D-FLOW model. Baptist schematizes vegetation as a set of rigid cylinders having a height (k), density (m), stems diameter (D) and drag coefficient (Cd). Baptist differentiates the shear stress in a bed shear stress (τb) and the shear stress due to the vegetation (τv). The total bed shear stress (τt), is the sum of both.

$$\tau_t = \rho g h i = \tau_b + \tau_v$$

$$\tau_b = \frac{\rho g}{C_b^2} u_v^2$$

$$\tau_v = \frac{1}{2}\rho C_D m D h u_v^2$$

Where:

ρ = water density (kg/m^3)

g = gravitational acceleration (m/s^2)

u_v (k) = velocity inside the vegetation related to the height of the vegetation (m/s)

C_b = Chézy coefficient of the alluvial bed (m^{½}/s)

C_D = drag coefficient of the vegetation structure (-)

m = frontal area (1/m^2)

D = diameter of cylinders (m)

h = water depth (m)

i = slope of water surface (-)

Furthermore makes Baptist makes a distinction between partially and fully submerged vegetation. The velocity profile through this vegetation is divided in two zones: a zone of uniform flow inside the vegetated part and a zone with a logarithmic velocity profile above the vegetation. Bed load transport is a function of the bed shear stress (τ_b). The bed shear stress is related to the near bed velocity and the Chézy value. Vegetation reduces the flow velocity near the bed which results in a reduction of the bed load transport. The degree of submersion determines the near bed velocity, which on its turn is depending on the degree of submersion.

Nepf (2012) [19] investigated the influence of vegetation on the vertical velocity profile. In absence of vegetation, the vertical flow velocity profile is logarithmic, highest near the surface and almost zero near the bottom. In presence of vegetation, the velocity profile changes. Through and above submerged vegetation, they identified four zones: (1) The zone closest to the bed, where the velocity is significantly influenced by the roughness of the bed. The velocity is almost zero. (2) The zone in between vegetation, sufficiently away from the bed and from the top of the vegetation. Within this layer the velocity is assumed to be uniform. (3) The zone near the top of the vegetation, where a transitional velocity profile is created, connecting the uniform velocity inside the vegetation and the logarithmic profile above it. The difference in velocity creates a shear zone which can generate turbulence. This turbulence can penetrate into the vegetation to a certain extent, which depends on the features of the vegetation. (4) The zone on top of the vegetation, where a logarithmic profile is observed, similar to the flow velocity profile in absence of vegetation. The exact shape of the above mentioned velocity profiles depends on several features of the vegetation, such as density and height and flexibility. The height of the vegetation decreases proportionally to its flexibility. In figure 2-9 different shapes of the vertical flow velocity profile and turbulence are related with different densities.

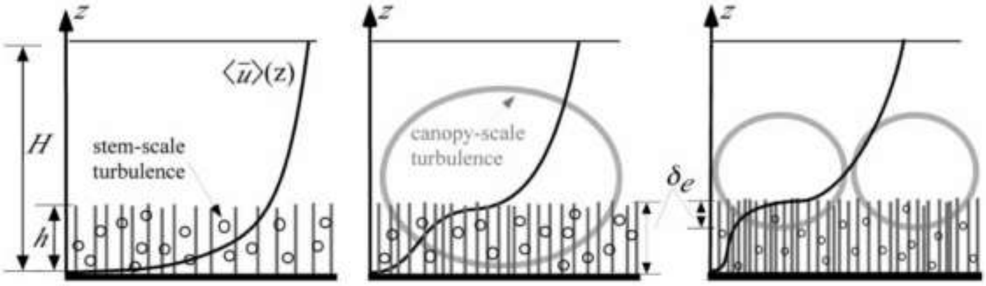


Fig. 2-9: The vertical flow velocity profile through submerged vegetation with increasing density. The vegetation height is h, the water depth is H, the turbulence penetration depth is δe. (Nepf et al. (2012)

Sediment transport is influenced by the presence of vegetation. Changes in flow velocity change the amount of sediment transport. Regarding sediment transport a distinction can be made between bed load transport, suspended load transport and transport of wash load. The amount of sediment transport depends on the size, shape and fall velocity of the grains. The amount of transport also depends on the density, chemical composition and amount of pores of the sediment in the bed. Bed load transport is defined as the transport of bed material by rolling and sliding, and is related to the bed shear stress caused by the flow velocity. When the bed shear stress (τ_b) exceeds a critical limit for the initiation of motion, sediment gets mobilized. Suspended load transport is the transport of grains in the water column. It depends on the amount of sediment in suspension and the flow velocity. The suspended concentration depends on the upward and downward transport mechanisms near the bottom (De Vriend et al., 2011, [20]). Wash load transport involves very fine suspended sediment that may never touch the bed and is usually assumed to "wash through" the system. Vegetation reduces the velocity near the bed, which reduces the bed shear stress, which then reduces the bed load transport. Upstream of the vegetated patch the flow is untouched; therefore the amount of sediment inflow into the vegetated areas is relatively high. This results in a difference between in -and outflow of sediments, increasing sedimentation in the vegetated areas. The transport of suspended sediment is also influenced by vegetation. Vegetation reduces the transport velocity near the bed, which enables sediments to settle. Furthermore acts vegetation as an object in water; sediment particles colliding with vegetation reduce in velocity and therefore their ability to settle increases. Additionally, due to the changes in the vertical flow velocity profile, the sediment concentration profile changes (figure 2-10). As a result of vegetation, the suspended sediment concentration is lower near the bed compared to the concentration profile with reduced or no vegetation. A reduction of the 'near bed' concentration reduces the amount of sediment to settle. Finally, vegetation creates a shear layer at the vegetation interface, which creates enhanced turbulence. This causes vertical transport, counteracting sediment settlement. The sum of these above mentioned processes results in either the increase or decrease of the suspended sediment settlement in the vegetated areas.

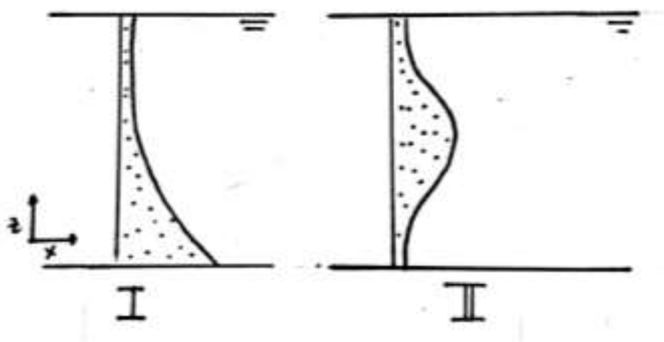


Fig. 2-10: A sketch of the suspended sediment-concentration profile (I) without vegetation. (II) influenced by vegetation.

2.5 RESEARCH IN THE CONTEXT OF THE LITERATURE REVIEW

A significant amount of research on different scales has been executed on the influence of vegetation on the hydraulics and geo-morphodynamics in river systems. Despite the enormous amount of data derived from fieldwork, experiments, measurements, modelling and analyses, an overview of the cumulative impact of vegetation is a difficult objective to attain. This is not only the result of studies carried out at different spatial and temporal scales (e.g. the stem of vegetation versus reaches of rivers, short term changes versus long term changes), but is linked also to the complex and variable shape of vegetation and the enormous variety of vegetation. Nevertheless it is clearly stated in the existing literature that vegetation has a significant influence on the fluvial processes of a river system. These researches are used to declare the observed phenomenon in this study.

Because of its magnitude and importance, the Colorado River has been measured and studied extensively for decades. The construction of the Glen Canyon dam has caused significant changes in the river system. One of these changes is the expansion of the riparian vegetation. The environmental impact of the Glen Canyon dam as well as the growth of vegetation in the riparian zone have been investigated so far. The species of riparian vegetation, the places where they grow as well as the moments and the dimension of change are well mapped. However, the influence of the expansion of vegetation on the dynamics of the is not yet adequately researched. This poorly understood correlation is the subject of this thesis. This research aimed to provide an insight in the impact of vegetation expansion on the sandbar dynamics in the Colorado River.

To make the research tangible several simplifications are made. Only reattachment bars are taken into account, furthermore is only arrowweed is used as species of interest, moreover are only sandbars taken into account in a stretch from the Glen canyon dam till 200 mile downstream are and finally only depth-average flow velocities are taken into account.

3 GEO-MORPHOLOGICAL AND VEGETATION DATA-ANALYSIS

The aim of this chapter is to assess the role of vegetation on the geo-morphological features of sandbars by means of available data. Firstly, sandbars suitable for further research are selected. Secondly, information about geo-morphology, geometry, hydraulics and vegetation coverage of the selected sandbars is collected and presented. Thirdly, the relation between vegetation coverage and geo-morphology of the sandbar is investigated and the mechanism behind vegetation expansion and sandbar growth is explained. At the end of the chapter conclusions are drawn and are recommendations are given.

3.1 METHOD

3.1.1 Sandbar selection

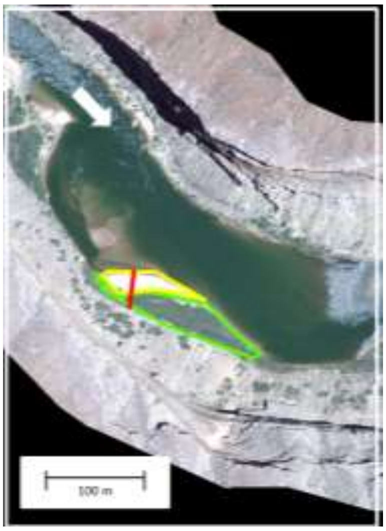
More than 40 sandbars in the Colorado River are surveyed by the USGS. A list of all these sandbars is depicted in Appendix A. Seven of these sandbars are selected for further research. In this selection process, three criteria are applied.

- The sandbar has to be a reattachment bar, i.e. a bar in the middle of two constrictions. In total, 27 sandbars fulfilled this criterion.
- The sandbar has to be sufficiently surveyed during the period 2002 – 2013. In total, 15 of the 27 sandbars fulfilled this criterion.
- Sandbars with different types of vegetation coverage has to be represented: scarcely, intermediate and densely vegetated. The rate of coverage is estimated and calculated by means of aerial photos of 2009.

In total 7 sandbars are selected for investigation. Two scarsely vegetated (0-20% of the sandbar covered with vegetation), three intermediate vegetated (30 – 80% of the sandbar covered with vegetation) and two densely vegetated (80 – 100% of the sandbar covered with vegetation). The location of the seven selected sandbars is indicated in figure 3-1. In figure 3-2 the aerial photos of all the investigated sandbars are displayed.

Fig. 3-1: Colorado River and location of investigated sandbars. The names assigned to the sandbars correspond to their distance in miles from Lees Ferry (0 miles), a place approximately 15 mile downstream of the Glen Canyon dam. The miles are calculated along the centre of the channel.

Sandbar 30.7 (0% vegetated)



Sandbar 41.1 (40% vegetated)

Sandbar 44.5 mile (50% vegetated)

Sandbar 51 (90% vegetated)

Sandbar 55.9 (90% vegetated)

Sandbar 65.1 (20% vegetated)

Sandbar 119.4 (80% vegetated)

Fig. 3-2: Aerial photos of the investigated sandbars from 2009. The photos are derived from the database of the USGS; each photo has a similar scale. In the figure is depicted the part of the sandbar above the average base flow level in the river, which is 226m^3/s. The vegetated and un-vegetated parts of the surface are indicated by means of polygons: the vegetated parts of the sandbar in green and the un-vegetated parts in yellow. The bank ward border of the polygons is taken at the maximum water line of the 2008 flood. The direction of the flow is indicated with the arrow and the location of the cross section is the red line.

3.1.2 Features of the investigated sandbars

Of each sandbar and its surroundings different features have been investigated: (1) the geo-morphology of the sandbar and the adjacent channel, (2) the geometry and hydraulics of the channel (3) the vegetation coverage on the sandbars. The selection of these features as subjects of investigation was based on the study by Tsuijmoto (1999)[13], who researched these themes (and their relation) in a river system.

Concerning the geo-morphological features of the sandbar the surface changes in volume, shape and bed level are assessed.

- According to USGS, the sandbar surface is the area of the bar above the average base flow in the river (226 m^3/s) and the sandbar volume is the portion above the average base flow. Both, surface and volume, are assessed during the entire study period. The changes in volume define the erosion and deposition volumes. The deposition volume during a flood event is the difference of the sandbar volume just after a flood and the sandbar volume just before a flood. The erosion volume in the post flood period is the difference between the volume just after the previous flood and the sandbar volume just before the new flood.
- The shape of the sandbar and its change is displayed by means of cross sections at three moments in the research period. The cross section approach in this thesis involves a cut across the sandbar at the reattachment point (red lines in figure 3-2), which is the most dynamic section of the sandbar. This is where the highest amounts of deposition during a flood event are to be observed (Schmidt (1990)) [4] The bank ward border of the cross section is indicated by the maximum water line of the flood in 2008. There is a difference in the interval between flood and cross section moment at the three occasions of investigation, as illustrated in the timeline in figure 3-4. Because floods are the main driving force of the morphologic changes of a sandbar and therefore also of the changes in the cross section of sandbars these different intervals might hamper a true comparison of the changes in shape of the sandbar. A further assumption considers the cross section as representative for the whole sandbar in this study, which might not reflect reality because it is measured at only one location effectively. When analysing the results, these limitations have to be considered.
- The change in bed level, which includes the sandbar, the eddy and the adjacent channel, is the difference between pre-flood and post-flood bed level. Only the bed level changes due to the 2008 flood are assessed.

Concerning the geometry the width of the channel adjacent to the sandbar and at the rapid are assessed. Both are determined by means of aerial photos, on which the discharge is equal to 226 m^3/s. (1) The channel width at the location of the sandbar includes sandbar and channel and is measured at the middle of the sandbar. (2) The channel width at the location of the rapid is measured at the most constricted point.

Concerning the hydraulics the water level range and the submerging depth are assessed.(1) The water level range is the difference between high and low water and is calculated by subtracting the base flow level (226 m^3/s) from the level during a flood event (1200 m^3/s). (2) The submerging depth is the height of the water column on top of the sandbar during a flood event. It is calculated by subtracting the average cross section elevation from the 2008 flood water level. In this research the flood in 2008 is chosen as the 'standard' flood because in terms of discharge the three floods are relatively similar.

Measurements on the vegetation are performed during a field trip. The most suitable species for measuring appeared to be Pluchera Sericea, commonly known as arrowweed. Several characteristics gave reason to choose this species. It is one of the most abundant present species on the banks of the Colorado River and Buck Farm (the modelled sandbar) is considerably overgrown with it. It grows close to the waterfront, which is a location of main interest because of its exposure to hydraulic forces. It is suitable for measurement because of its accessible characteristics, namely straightforward shrubs, mainly one single stem and a small amount of canopy and branches. Features that might affect the hydraulics and geo-morphodynamics were subject of measurement during the fieldtrip. Figure 3-3 gives an impression. The vegetation has been investigated on an area scale (degree of coverage) and a plant scale (different features of the vegetation). The degree of the vegetation coverage on the selected sandbars is indicated by a polygon drawn on the aerial photos. Features of the vegetation that might affect the hydraulics and geo-morphodynamics are measured. The measured features are the following: (1) The stem height; measured by means of a ruler from the top to bottom. (2) The stem diameter; measured with a tape at 0.1 m above ground level. (3) The degree of canopy; estimated by means of frontal photos. (4) The flexibility of the stem: the force necessary for 0.1 m deflection is measured with a force meter attached 0.1 m above ground level. (5) The number of stems per shrub is counted. (6) The number of shrubs per square meter is recorded.

Number of shrubs per square meter | Degree of canopy per stem | Numbers of stems per shrub

Fig. 3-3: Impression of some measurements on vegetation during the fieldtrip.

3.1.3 Time considerations

The investigation period of this research runs from 2002-2013. This is the period in which the sandbars were surveyed in most detail and of which most of the data of interest was available. Ideally, the features of each sandbar are measured not only at fixed moments each year, but also at fixed intervals of time between each other. The data, however, is limited to certain moments during the investigated period. Measurements of vegetation coverage are available at three moments in the selected investigation period: May 2002, May 2009 and May 2013. Because the vegetation coverage on the sandbar is the main focus of this research, these moments are used as guidance for the assessment of other features. In the event that data and measurements on other features were not available on these dates, measurements at moments as close in time as possible were used. This causes a different time span in-between the measurements. For instance, the time span in-between the measurements of vegetation in 2009 and the previous flood is 12 months and in 2014, 6 months. The timeline in figure 3-4 gives a view of the different times where data was available and thus obtained.

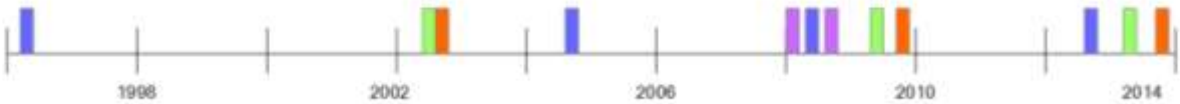


Fig. 3-4: Timeline of the gathered data. Floods events (bleu); Apr 1996, Nov 2004, Mar 2008 and Nov 2012; Vegetation coverage (green); May 2002, May 2009 and May 2013 Cross sections (orange); May 2002, Oct 2009, Sept 2013; Bed level (purple); Feb 2008 and Apr 2008.

3.1.4 Accuracy of the used data

To draw conclusions on the (inter)relation between different data, the data has to be reliable and accurate. Table 3-1 shows the collected data and a prudent estimate of their accuracy. As indicated before, some data is derived from the enormous database of USGS, some is based on aerial photography measurements, while some data is field measurements collected during the field trip in September 2015.

Theme	Features	Accuracy (%)	Justification
Geo-morphology	Sandbar surface	± 1.5	Accuracy estimated by USGS
	Sandbar volume	± 1.5	Accuracy estimated by USGS
	Sandbar shape	± 1.5	Accuracy estimated by USGS
	Bed level changes	± 12.5	Accuracy estimated by USGS
Geometry	Channel width rapid	± 10	Distances on aerial photos
	Channel width main basin	± 10	Distances on aerial photos,
Hydraulics	Water level range	± 1	Accuracy estimated by USGS
	Submersion depth	± 15	Obtained by a sum of several assumptions, therefore the accuracy is low.
Vegetation	Degree vegetation coverage	± 10	Polygons drawn on aerial photos
	Stem height	± 2	Measurements in the field, the measurements are precisely.
	Stem diameter	± 5	Measurements in the field, accuracy questionable due to small diameter of the stems
	Degree of canopy	± 20	Measurements in the field; accuracy questionable due to difficulty to quantify the amount of canopy
	Flexibility	± 10	Measurements in the field: accuracy questionable due to complicated measurement method.
	Number of stems	± 10	Measurements in the field: accuracy questionable due to difficulty to identify number of stems per shrub caused by the density of the shrub.
	Number of shrubs	± 2	Measurements in the field: number of shrubs could be clearly identified.

Table 3-1: the collected data and a estimate of their accuracy

3.2 RESULTS - RAW DATA

In this paragraph the geo-morphology of the investigated sandbars, the hydraulics and geometry of the river stretch, the absolute vegetation coverage and finally the detailed dimensions of the vegetation on the selected sandbars are described.

3.2.1 Geo-morphology of the investigated sandbars

The geo-morphology of the different sandbars and the adjacent river system is described on the basis of sandbar volume and the cross section. Although closely related, these features will be discussed separately.

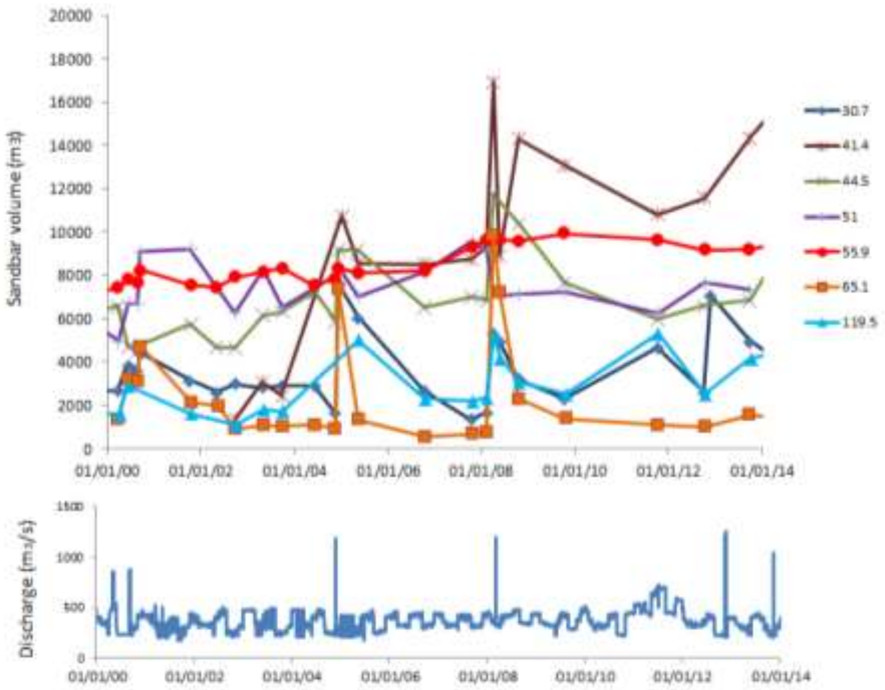


Fig. 3-5: Sandbar volumes and discharge, the moments of measurement are indicated with dots

	Flood cycle 2002 – 2008		Flood cylce 2008- 2013		2002 – 2013
Sandbar (mile)	Increase in Volume (m^3)	Decrease in volume (m^3)	Increase in volume (m^3)	Decrease in volume (m^3)	Total Increase in volume (m^3)
30.7	5981	5908	3657	2733	910
41.4	8255	1952	7593	6138	13026
44.5	3214	2284	4837	5728	2171
51	1946	1681	1130	1127	1083
55.9	817	200	0	0	1757
65.1	6427	6790	9289	8869	- 395
119.5	3301	2617	2841	2713	3038

Table 3-2: Values of the volume changes of the investigated sandbars

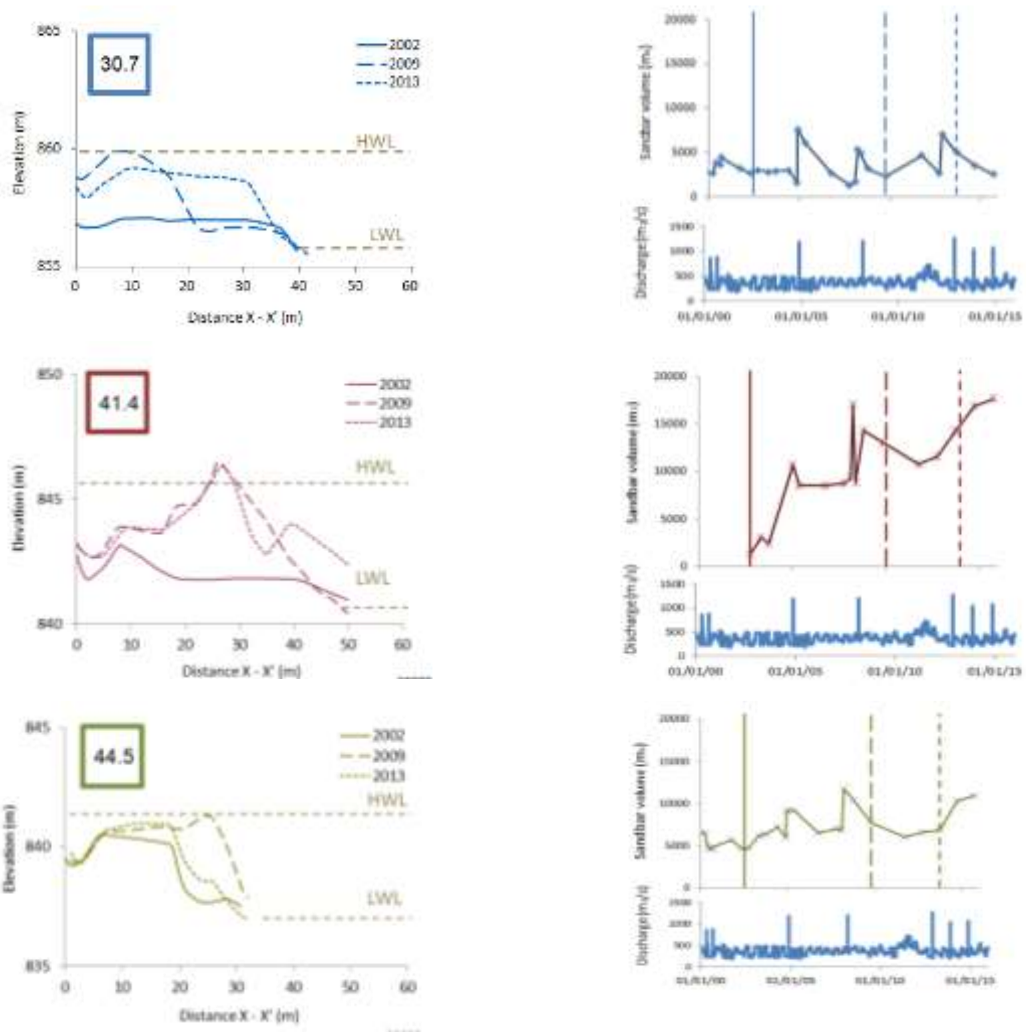
The graphs in figure 3-5 display the changes in volume of the investigated sandbars during the study period. As these changes are directly related to the discharge of the river, the discharge graph is added. In table 3-2 the erosion and deposition volumes on the different sandbars during two floods cycles are shown (2002 - 2008 and 2008-2013). From the graph and table the following observations can be summarised:

- Every sandbar enlarges significantly in volume during each flood. This enlargement in volume differs per flood and varies widely among the sandbars. As explained in chapter 2, during a flood event enormous amounts of sand are transported from upstream and deposited at low velocity areas, creating or nourishing sandbars.
- After each flood most sandbars show a marked decrease in volume, the effect of erosion. The exact cause of sediment detachment is still a matter of debate. According to researchers in 1970, erosion is caused by the daily fluctuations of water

caused by the production process of hydroelectric power (Melis, 2011) [1] . Later, researchers concluded that sandbar erosion occurred when the amount of suspended sediment was low and the flow regime changed (Melis, 2011) [1].

- At the majority of the sandbars, the erosion rate starts with a steep gradient followed by a rate with a milder gradient. The volumes that are fast to erode are assumed to be the depositions located at places exposed to the mean flow during base flow. The slow eroding volumes are probably sand volumes deposited at more sheltered locations.
- The long term development of a sandbar depends on the difference in deposited and eroded volume. Consequent to these differences some sandbars, for example sandbar 41.1, expand in the long term and some sandbars, for example 65.1, return to the pre-flood volume after each event, resulting to a stable volume over time.
- Some sandbars, however, show a deviant pattern than the expected pattern. Some sandbars seem to increase in volume even before a flood (for example 119.5 and 51 before the 2004 flood). This is attributed to a lack of data at some specific pre-flood moments.

Based on the volume pattern and the data indicated in the table roughly three types of sandbars can be distinguished. (1) Sandbars which fluctuate remarkably in volume, showing a substantial enlargement as result of each flood and a substantial decrease in volume after each flood. These sandbars (sandbar 30.7 and 65.1) are small and eventually remain small in volume during the entire study period as their volume replenishes to the pre-flood volume. (2) Sandbars which slightly fluctuate in volume, these sandbars (sandbar 55.9 and to a lesser extent sandbar 51) are high in volume and remain high in volume during the entire study period. (3) Sandbars, which enlargement during the study periods a stepwise enlargement (sandbar 41.1 and 119.5). Sandbar 44.5 is apparently a mix of these three types.



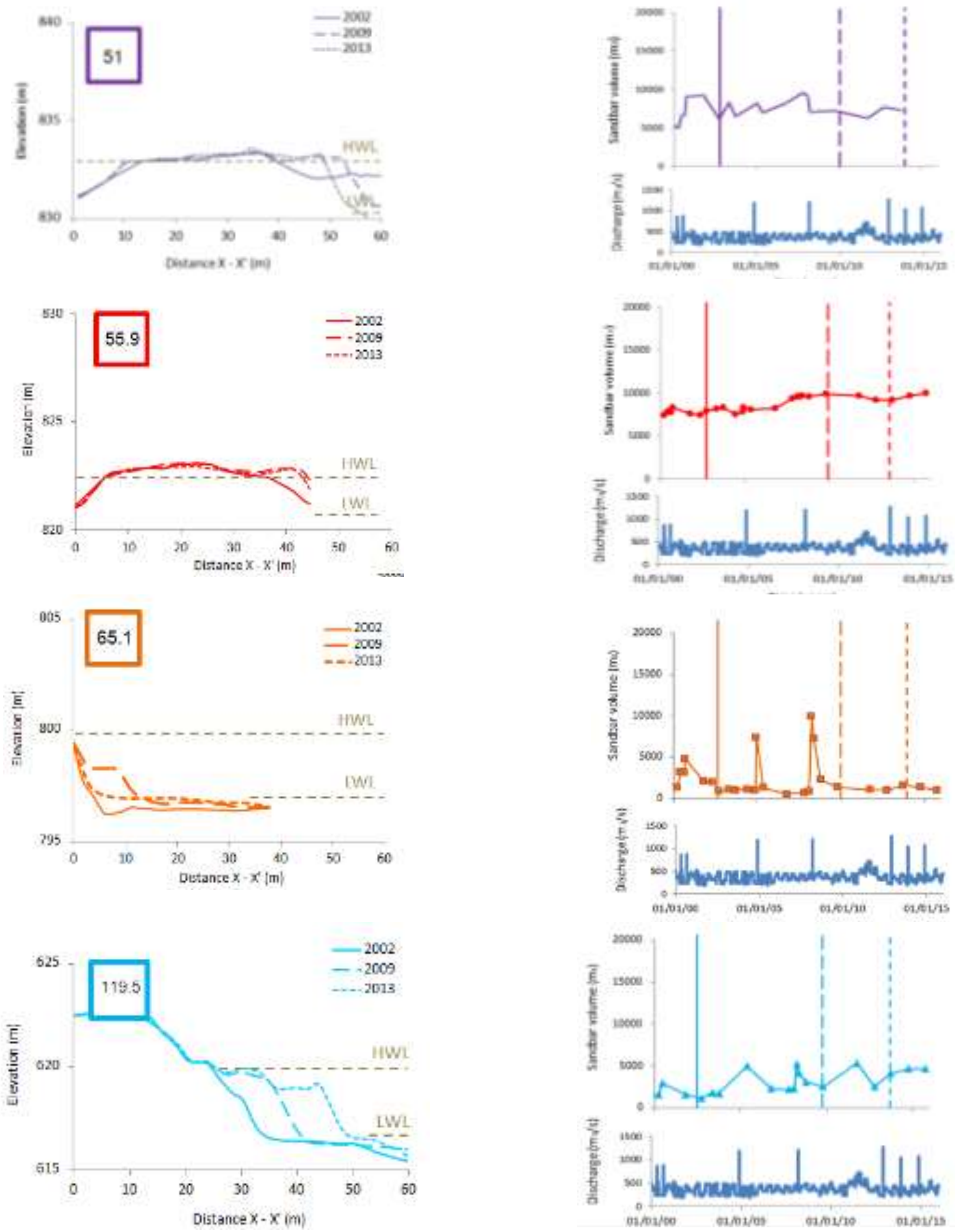


Fig. 3-6: Investigated sandbars (left) cross section at three different times; (right) sandbar volume and discharge. The different lines in the cross section graphs indicate the subsequent moments of measurement. In each cross section the riverbank is on the left and the channel on the right. The horizontal lines indicate the water level during a flood event (HWL) and base flow (LWL). The volume graph added to gain insight into the amount of accretion or erosion over time. The vertical lines indicate the moments at which the cross sections are taken. The discharge curve is added to indicate the moments of flood which determine the volume changes.

To gain insight into the location of accretion and erosion, the sandbars are pictured by means of subsequent cross sections. The cross-sections, the water level, the sandbar volume and the discharge of the investigated sandbars are depicted in figure 3-6. It is remarkable that, in 2002 all the sandbars are relatively low in volume and low in elevation. This is the result of the long floodless previous period (±6 years). The following observations of the different sandbar are made. Sandbar 30.7 and 65.1 has been submerged during each flood and the same accounts for sandbar 41.4 with the exception of its highest middle point. Sandbar 44.5 has been slightly submerged during each flood. The middle part of sandbar 51 remains above the water level during each flood event and the sandbar shows a similar erosion pattern to sandbar 44.5. The largest part of sandbar 55.9 has not been submerged during the floods, except from the channel ward and bank ward side. The shape changes of 55.9 follow the same pattern of the respective changes for sandbar 51, in a smaller magnitude. Last, the channel side of sandbar 119.5 has been submerged during each flood with no remarkable sediment detachment traces.

Based on this cross section plots, it can be stated that the submersion depth during a flood event plays an important role in the amount and location of accretion or erosion. Sandbars which are highly submerged during a flood event seem to fluctuate largely in volume, such as sandbar 30.7, 41.4, 44.5 and 65.1. In sandbars 30.7 and 41.4, the changes in shape mainly occur in the middle of the sandbar, in sandbar 44.5 the changes in shape mainly occur at the channel ward side and in sandbar 65.1 at the bank ward side. Sandbars which are hardly or not submerged during a flood event, such as sandbar 51 and 55.9, seem to fluctuate hardly in volume. If changes occur, they mainly occur at the channel side. These findings are in agreement with the study of Birekland et al. (1996) [11], who states that high sandbars are stable because they are less affected by floods and low sandbars are volatile because they are more affected by floods.

To prove this hypothesis the submersion depth on the studied sandbars is plotted against the increase in elevation during two intervals. The result is shown in figure 3-7. A slight positive correlation between submersion depth and sandbar size is to be seen. This correlation could be potentially explained by the distinct shape of the cross sections. More specifically, an increase of 1m of sandbar 41.4 will indicates something different than an increase of 1m of for example sandbar 119.5. It should also be noted that whether a sandbar enlarges or erodes is a result of a combination of several factors including the geometry of the channel, the distance from the dam, the submersion depth and presumably the amount of vegetation coverage. These factors are closely related to each other.

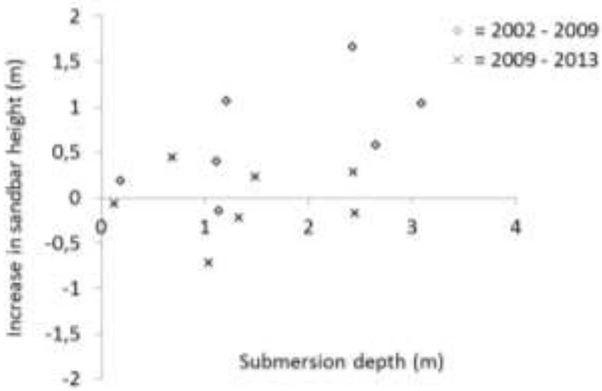


Fig. 3-7: Average submersion depth versus the increase in sandbar elevation during two intervals

3.2.2 Hydraulics and geometry of the adjacent channel

Insight into the hydraulics of the river enables us to understand further relations regarding sandbar morphodynamics and vegetation. In table 3-3 the width of the channel, the width of the upstream rapid from the investigated sandbars and the water level range near the sandbars is indicated. In figures 3-8 to 3-11 the relations between these parameters are depicted.

Sandbar (mile)	Rapid width (m)	Channel width (m)	Water level range (m)
30.7	50	120	4.9
41.4	70	150	4.3
44.5	60	140	4.1
51	80	180	3.4
55.9	80	160	2.5
65.1	75	120	2.8
119.5	60	140	4.6

Table 3-3: The hydraulic geometry near the investigated sandbars

Based on the relations depicted in figure 3-8 to 3-11 the following conclusions can be drawn:

- In figure 3-8 is visible that sandbars which are in high volume are located in channels with a large width. The channel width downstream of the rapid influences the flow pattern on and around the sandbar. A wide channel seems to create a favourable hydraulic environment for the development of sandbars. This is confirmed by Schmidt (1990) [4] who states that sandbars are most commonly found at locations where the channel is wide.

- In figure 3-9 the upstream rapid width is plotted against the length of the recirculation zones. In figure 3-10, the upstream rapid width is plotted against the sandbar volume. It is expected that the rapid width influences the velocity of the flow leaving the rapid. For example, Schmidt (1990) [4] investigated the flow in the recirculation area. The speed of the flow leaving the rapid influences the speed and surface of the downstream directed flow and therefore the size of the recirculation area. In his research it is stated that widening of the rapid results in an increased surface area of the downstream directed flow and a decrease of the width of the recirculation area. Also a study by Izbach and Khaldre (1970) showed that the length of the recirculation area depends on the width and the depth of the rapid; the narrower and shallower the rapid, the longer the recirculation area. In contrary to what is mentioned in literature, no clear relation exists between these parameters. It seems that several other factors, such as for example the depth of a rapid or the width of the channel have more influence on the size of the recirculation eddy and therefore the sandbar size.
- In figure 3-11, the relation between water level range and the sandbar volume is plotted. The water level range, in combination with the height of the sandbar, determines the submersion depth. Melis (2011) [1] states that the dimensions of the rapid downstream from the sandbar determine the water level range. A narrow and shallow downstream rapid causes a higher water level upstream because the flow is ponded by the rapid. This ponded flow can extend several miles upstream. The steepness and roughness of the channel also influence the water level range. A moderate range is expected in channels with a steep gradient and a smooth river bed; a large range is expected in channels with a mild gradient and a rough river bed. In contrary to literature, no clear relation is observed between water level range and sandbar volume. As explained before, several other determining factors such as width of the channel or depth of the rapid are expected to have more influence on the hydraulics and thus on sandbar size.

We propose that the width of the channel determines the volume of the sandbar; in wider channels sandbars with larger volumes are found. However, in contrary to the observations, between the width of the upstream rapid and sandbar volume, no direct relation can be demonstrated and the same goes for the link between the water level range and the sandbar volume.

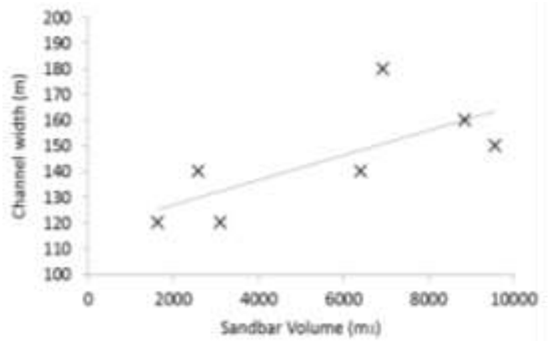


Fig. 3-8: Relation channel width (m) and the sandbar volume (m^3)

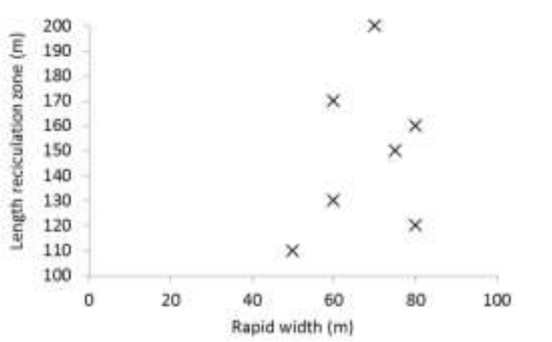


Fig 3-9: The length of the recirculation zone (m) plotted versus the rapid width (m)

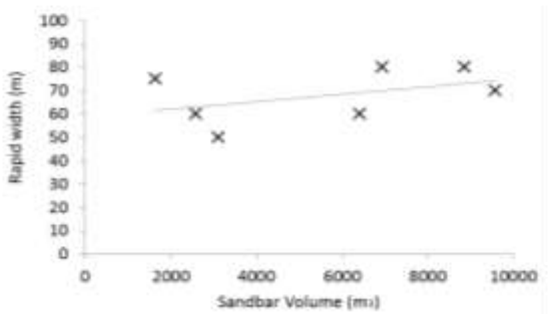


Fig 3-10: Relation between rapid width (m) and sandbar volume (m^3)

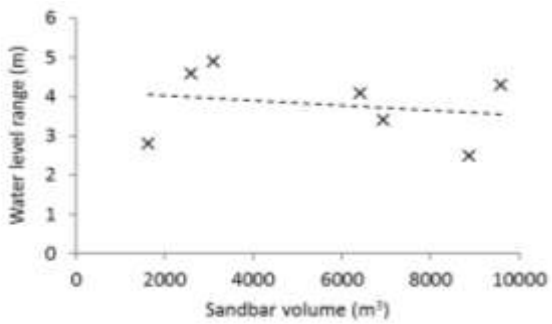


Fig 3-11: Relation between water level range (m) and sandbar volume (m^3)

3.2.3 Vegetation on the investigated sandbars

To indicate the amount of vegetation on the sandbars, a distinction is made between absolute and relative vegetation coverage. Figure 3-12 depicts the absolute vegetation coverage on each sandbar at three moments in the research period. The initial absolute vegetation coverage (2002) differs per sandbar. During the first period (till 2009) the absolute vegetation coverage increased on five of the seven sandbars and during the second period (till 2013) only on one sandbar. In this second period the absolute vegetation coverage reduced on four of the seven sandbars and stayed equal in two. The relative vegetation coverage of each sandbar is indicated in table 3-4. Three types of sandbars can be distinguished: (1) Sandbars which are highly vegetated and which stay highly vegetated during the research period (sandbar 51, 55.9 and 119.5). (2) Sandbars which are scarcely vegetated and remain so during the research period (sandbar 30.7 and 65.1). (3) Sandbars on which the vegetation coverage or the sandbar volume is changing throughout the time (sandbar 41.4 and 44.5).

The investigated sandbars differ in terms of absolute and relative vegetation coverage and in its change over time. A large number of factors can affect the vegetation coverage and its expansion rate. Changes in vegetation coverage can occur abruptly or at a slower pace. In general, it can be said that abrupt changes are caused by different factors, for example: fires, winds, gullying or extreme flood events. Changes at a slower pace may be caused by environmental factors, like temperature, light, water and nutrient levels and genetic factors of vegetation such as, species-specific growth factors. The changes in relative vegetation coverage can be the result of a change in absolute coverage as well as a change in sandbar surface.

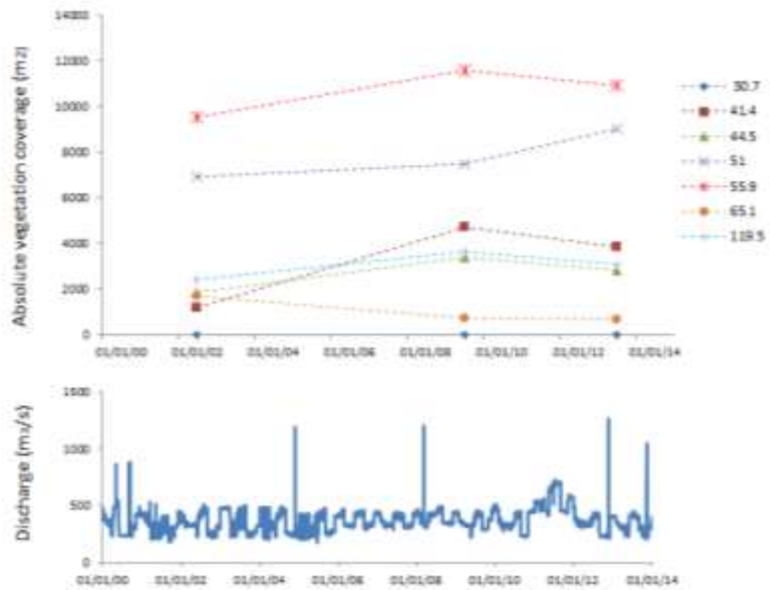


Fig. 3-12: The absolute vegetation coverage of the investigated sandbars at three moments in time

Sandbar	**Relative vegetation converge [-]**			
(mile)	May 2002 (T1)	May 2009 (T2)	May 2013 (T3)	Average of T1 - T3
30.7	0	0	0	0
41.4	0,1	0,35	0,28	0,24
44.5	0,2	0,45	0,36	0,33
51	0,72	0,82	0,95	0,83
55.9	0,86	0,89	0,96	0,93
65.1	0,28	0,18	0,24	0,27
119.5	0,84	0,86	0,87	0,85

Table 3-4: Relative vegetation coverage

The results of the vegetation measurements are shown in figure 3-13 and 3-14 and table 3-5.

- The graph in figure 3-13 represents the stem height plotted against the stem diameter. An average height of 1.6 m (h_a) corresponds to a mean diameter of 9.25 mm (D_a). A logarithmic relation exists between the stem diameter and stem height of arrowweed. The R^2 value is high which indicates a strong logarithmic relation between height and diameter of the stems. This logarithmic relation implies that the stem first grows in height and in diameter. After a while it keeps on growing in diameter but less in height. This implies that the stem becomes stiffer over time. This can be a mechanism of the plant to remain upright when frequently inundated.
- The graph in figure 3-14 represents the force for a deflection of 0.1 m plotted against the stem diameter. The lower the deflection force the higher appears the flexibility of the stem. The average force for a deflection of 0.1 m is 0.42 kg (F_a). When the plants are still young, the deflection force and diameter are linearly related. At a later stage, with an increasing diameter, the relation deviates from linear. This is caused by changes in features when vegetation increases in age. The characteristics of the older stems are influenced by the age of the stem and the environment around the vegetation. Moreover, when limited water is available in the environment, stems are expected to become less flexible. The cross indication close to the x-as indicates a stem with a large diameter and a negligible flexibility, it represents a broken stem.
- The results of the measurements on stems per shrub and the number of shrubs occurring per square meter are presented in table 4-2. Sxx / σ indicate the ratio between the average of stems to shrubs and the standard deviation. More specifically, deviation from the median is larger for higher values. The average number of stems per shrub is almost similar for each height range. This indicates that a negligible amount of stems start growing at a later stage. The number of shrubs per square meter differs only slightly with an increase of the height. Higher (and therefore assuming wider) shrubs seem to impede or even eliminate other shrubs. This might explain the decrease in amount of shrubs with the increase of the height.

Overall, a logarithmic relation exists between the stem diameter and stem height of arrowweed, which implies that effectively the stem grows mainly in diameter. A linear relation exists between the stem diameter and the stem flexibility. The number of stems per shrub remains constant during the plant's lifetime. The number of shrubs per square meter deviates and depends on the age of the shrub. Older (and thus wider) shrubs seem to impede or even eliminate other shrubs.

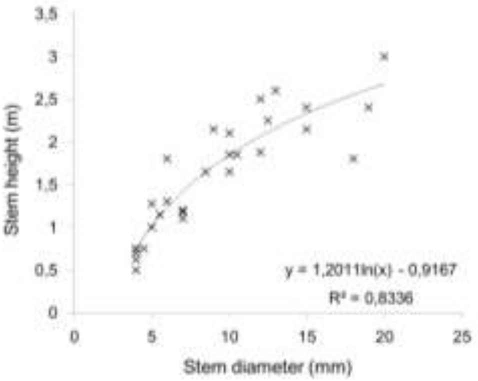


Fig. 3-13: Stem height plotted versus stem diameter
N = 30, h_a = 1,6 m, D_a = 9,25 mm

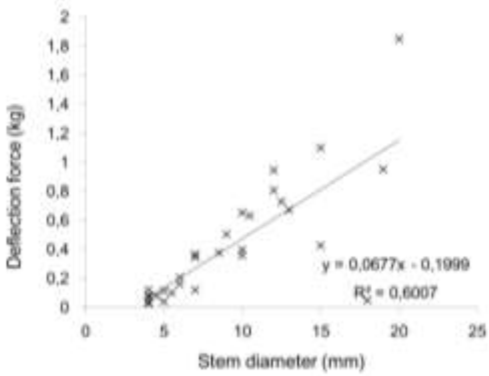


Fig. 3-14: Deflection force plotted versus stem diameter
N = 30, F_d = 0.42 kg, D_a = 9,25 mm

Stems per shrub				
Height range	Number of measurements (N)	Average number of stems (St_a)	Standard deviation (σ)	St_a /σ
0.1 – 0.9	10	11	3.7	0.34
1.0 – 1.9	10	12	3.3	0.27
2.0 – 2.9	10	10	3.5	0.35
All heights		11		
Shrubs per square meter				
Height range	Number of measurements (N)	Average number of shrubs (Sh_a)	Standard deviation (σ)	Sh_a /σ
0.1 – 0.9	4	7	0.7	0.1
1.0 – 1.9	4	9	1	0.11
2.0 – 2.9	4	3	1.4	2.14
All heights		6.33		

Table 3-5: Results of the measurements on shrub and square meter

3.3 RESULTS - RELATIONS BETWEEN RAW DATA

3.3.1 Relation between sandbar surface/volume and vegetation coverage

In this paragraph the mutual dependency between surface area, sandbar volume and absolute vegetation coverage is revealed. These features not only differ on each sandbar but also change during flood cycles.

- In figure 3-15, the sandbar surface is plotted versus the absolute vegetation coverage at three moments. The black dotted line indicates that the vegetation coverage is equal to the sandbar surface, which means that the sandbar is completely vegetated. Based on the coloured dots, different types of sandbars can be identified. (1) Sandbars 55.9 and 51: are sandbars with a large sandbar surface and which are densely vegetated and remain that way during the research period. (2) Sandbars 30.7 and 65.1: are sandbars with a moderate surface area, which are scarcely vegetated and remain so during the research period. (3) Sandbar 41.4: is a sandbar with an increasing surface and expanding vegetation coverage. (4) Sandbar 119.5: is a sandbar with a moderate surface, which is densely vegetated during the study period and shows slight changes in sandbar surface and vegetation coverage. Sandbar 44.5 shows a deviant pattern and cannot be compared with any of the other sandbars. The surface of sandbar 44.5 decreases slightly in the beginning and subsequently increases, while vegetation on sandbar 44.5 slightly increases at first and subsequently decreases.
- In figure 3-16 the rate of sandbar surface increase is plotted against the expansion rate of absolute vegetation during two periods; period I (May 2002 to May 2009) and period II (May 2009 to May 2013). If the vegetation expansion was increasing at the same pace with the sandbar surface growth, the crosses would be on and around the dotted line. Based on this, rather small amount of, data no clear or direct relation can be observed. This indicates that vegetation expands not directly in pace with the increase in sandbar surface. This outcome is not in accordance with the findings of several researchers. According to Birkeland et al. (1996) [11] , vegetation patterns respond to changes in sandbars surface, the larger the available sandbar surface is, the faster the vegetation will expand.
- In figure 3-17, the sandbar volume is plotted versus the absolute vegetation coverage at three moments. It has to be kept in mind that a 3D measurement is compared with a 2D measurement. Different types of sandbars can be identified. Four sandbars (41.4, 51, 55.9 and 119.5) increase in volume and show vegetation expansion to a greater or lesser extent during the entire study period. In sandbar 51 the sandbar enlargement is less significant than the vegetation expansion. Sandbar 30.7, a bare sandbar, shows only an enlargement. Sandbar 65.1, shows a decrease in both volume and vegetation coverage. From the remaining sandbars, sandbar 44.5 shows a deviant pattern and cannot be compared with the rest (see above).
- In figure 3-18, the change in sandbar volume is plotted versus the change in absolute vegetation coverage, during two periods; period I (May 2002 to May 2009) and period II (May 2009 to May 2013). On most sandbars, an enlargement of the sandbar is coupled with expansion of vegetation. This relation is more pronounced compared to the relation between sandbar surface area and vegetation coverage (figure 3-12). It can be therefore assumed that the elevation of the sandbar is an important factor determining the succession of vegetation compared to the surface. This is confirmed by Brikeland et al. (1996) [11]. According to the study, high sandbars are less affected by flood inundation, they support vegetation and create a stable habitat for vegetation, while low sandbars are more expansive and vegetation patterns relate to the sandbar size.

Overall we can conclude that the change in sandbar surface is not at the same pace with the change in vegetation coverage. However, on most sandbars, an enlargement of the sandbar is coupled with an expansion of vegetation. Since this relation is more profound, the elevation of the sandbar seems to play an important role in vegetation expansion. Based on this data, it cannot be determined whether vegetation is the cause or the result of sandbar growth. More factors than just changes in sandbar features also play a significant role in the expansion or reduction of vegetation however are not examined extensively in this study. Indicatively, Wind can cause an abrupt enlargement of the sandbar on the one hand but may bury parts of vegetation on the other. Furthermore, the location of the sandbar in the canyon may play a role because of its influence on the hours of sunlight exposure. Also hydraulic features play a role in the vegetation succession. Sankey et al. (2015) [3] stated that the vegetation expansion in the Colorado River seems to be coincidental with the inundation frequency. When the inundation frequency exceeds a specific value, 5% of the time, the vegetation expansion reduces.

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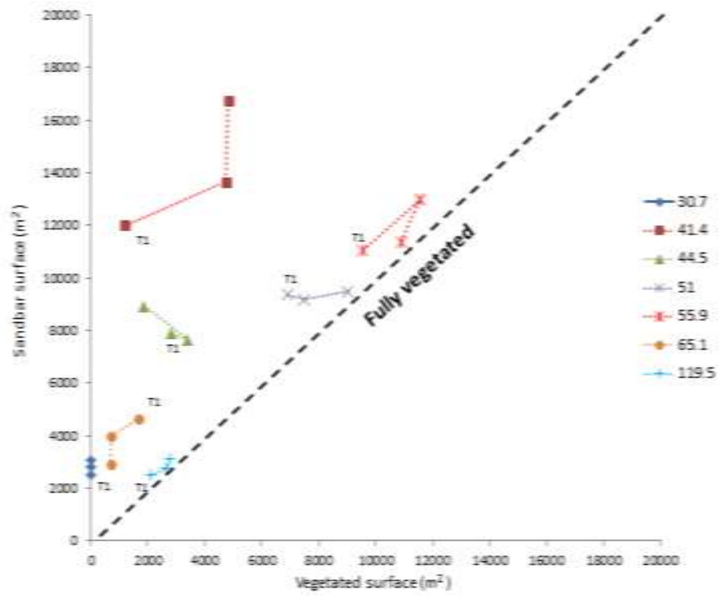


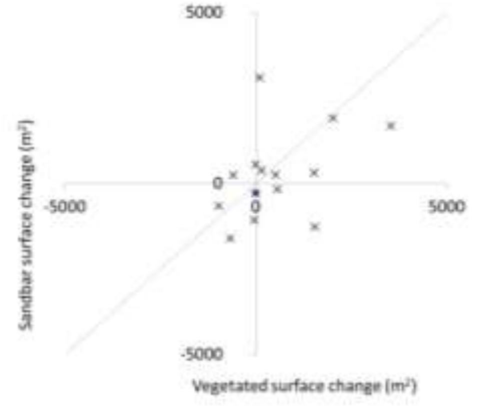
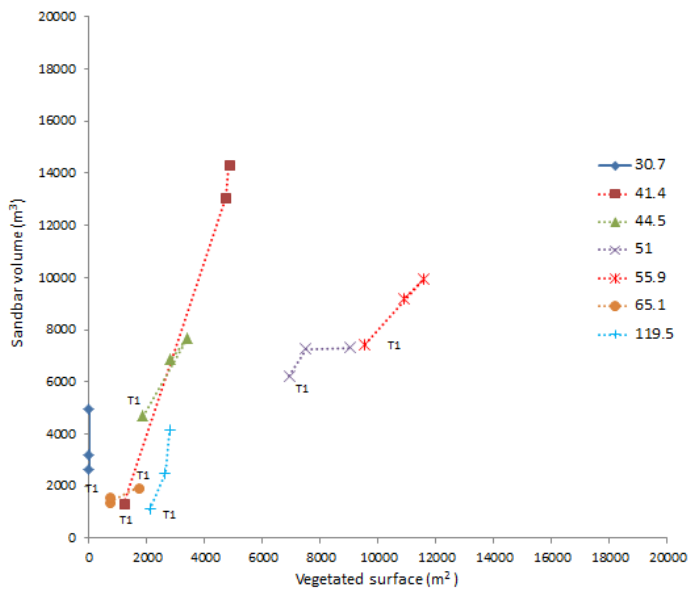


Fig. 3-15: Sandbar surface versus vegetated sandbar surface at three moments: 2002, 2009 and 2013. T1 represents 2002.

Fig. 3-16: Change in sandbar surface (m^2) plotted versus change in vegetation surface (m^2)



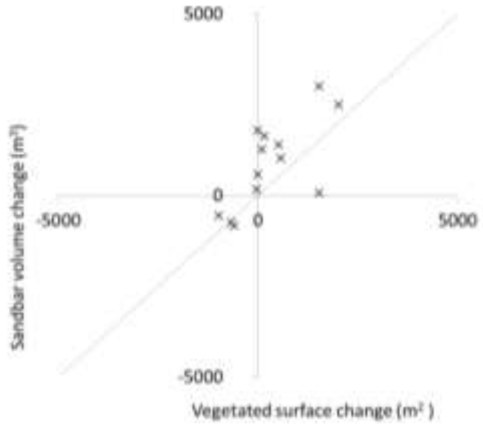


Fig. 3-17: Sandbar volume (m^3) versus vegetated sandbar surface (m^2) at three moments: 2002 (T_1)), 2009 and 2013.

Remark: Graph 44.5 (green) inclines towards 2009 and declines towards 2013

Fig. 3-18: Sandbar volume change (m^3) plotted against vegetation surface change (m^2)

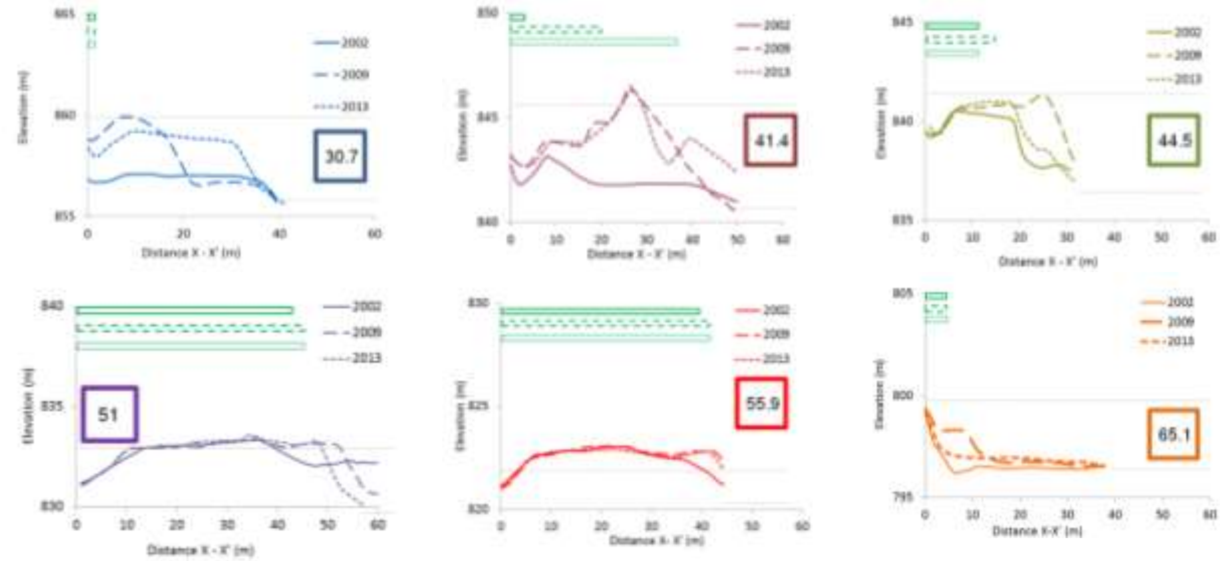
3.3.2 Relation between sandbar shape, submersion depth and vegetation coverage

In the present paragraph the relation between vegetation coverage and sandbar shape is investigated. As discussed in paragraph 3.2.1 changes in shape of the researched sandbars are related to the submersion depth. The submersion depth determines the amount and location of sandbar change. In figure 3-19 the cross sections as well as the vegetation coverage of the investigated sandbars are indicated. In figure 3-20 the relative vegetation coverage is plotted against the submersion depth.

- Based on figure 3-19, three types of sandbars can be identified: scarcely vegetated (sandbars 30.7 and 65.1), densely vegetated (sandbars 44.5, 51 and 55.9) and sandbars with expanding vegetation (sandbars 41.4 and 119.5). (a) Scarcely vegetated sandbars are significantly submerged during a flood event. As explained in paragraph 3.2.2, they are, due to this submersion, variable in shape and volume which makes them unfavourable for vegetation to encroach, expand and finally even succeed. (b) Densely vegetated sandbars are hardly submerged during a flood event. As explained in paragraph 3.2.2, they seem to fluctuate hardly in volume. In general they are stable in volume and shape, which makes them favourable for vegetation to encroach, expand and even succeed. (c) In the remaining sandbars, sandbar 41.4 and 119.5, both the volume increases and the vegetated surface increases. Sandbar 41.4 grows in vertical direction. Sand deposited during the 2008 flood seems to be blown towards the middle of the sandbar, thus creating a high and sheltered area. This might be favourable for vegetation to encroach, expand and even succeed. Sandbar 119.5 grows in the direction of the channel, which might be the result of the expansion of vegetation. The volumes deposited on the channel ward side during subsequent floods seem to be overgrown by vegetation, resulting in a relatively stable and permanent sandbar.

- Figure 3-20 shows that a smaller submersion depth corresponds with a high amount of relative vegetation coverage and vice versa.

We can conclude that the submerging depth, which is correlated to the height of the sandbar, plays an important role in the ability of vegetation to settle, expand or succeed. Sandbars that are hardly (or not) submerged during flood events seem to fluctuate minimally in volume and are favourable for vegetation establishment. Sandbars that are highly submerged during a flood event seem to fluctuate largely in volume and are therefore unfavourable for vegetation succession. Some sandbars show a growth in volume as well as in vegetation coverage. It seems that vegetation expansion can be either the reason for sandbar growth, provoking an enlargement mainly on the channel ward side, or can be the result of sandbar growth, provoking an enlargement mainly on the top of the sandbar.



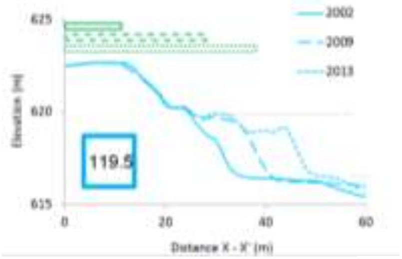


Fig 3-19: Cross sections and vegetation coverage at three moments, May 2002, 2009 and 2013. The vegetation coverage is shown by means of green bars. The length of the bar indicates the extent of vegetation at the cross section site, which is the cut across the sandbar located at the reattachment point. It has to be noted that the values concerning the sandbar shape, sandbar elevation and vegetation coverage are measured at only this single location and are considered to be representative for the whole sandbar.

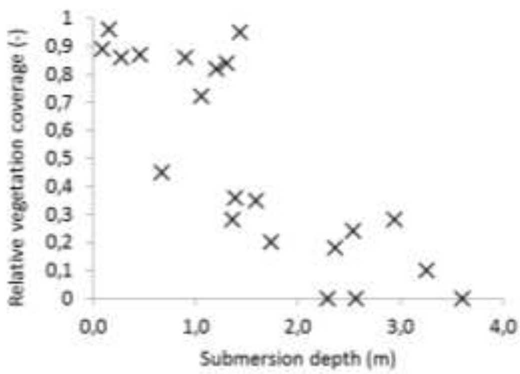
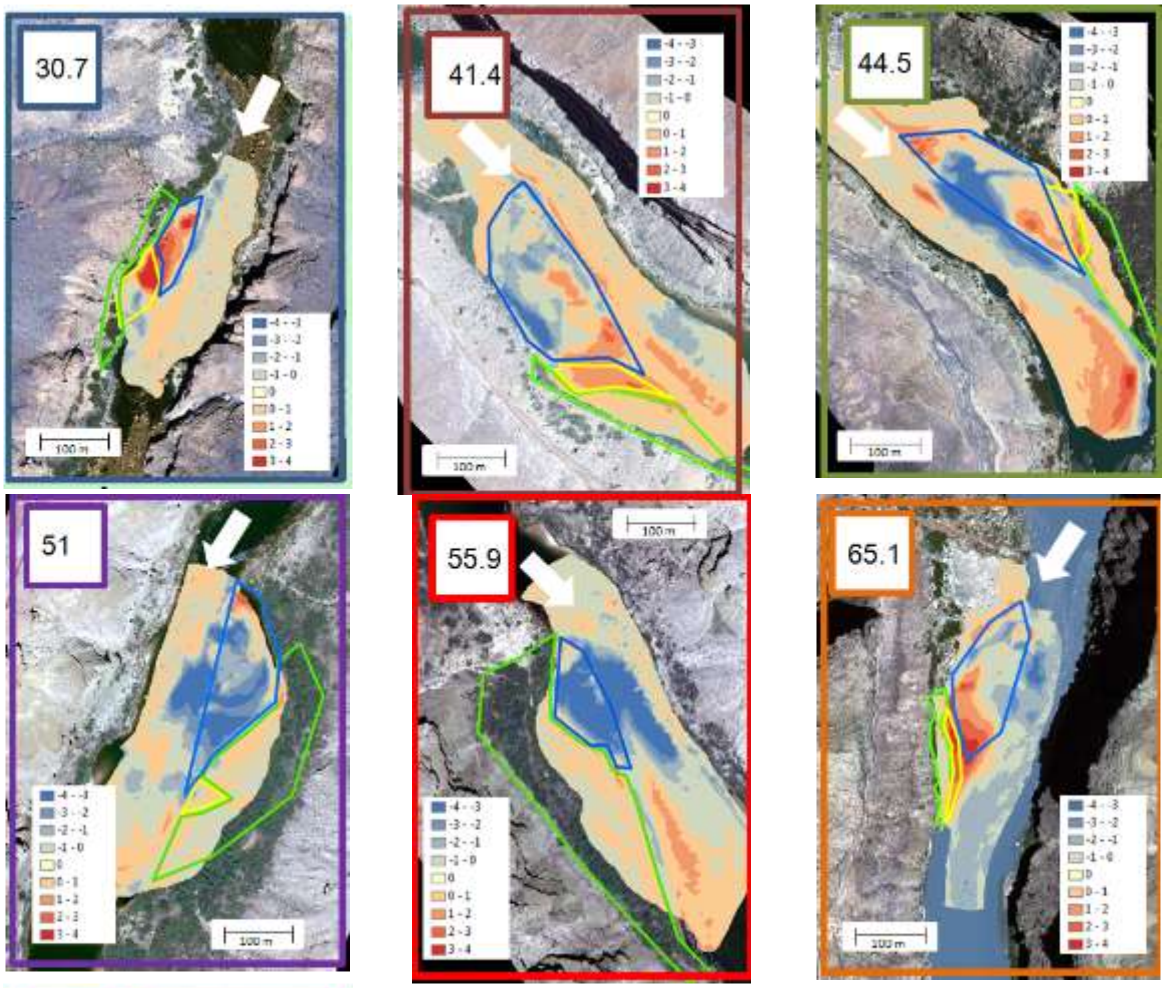


Fig 3-20. Relative vegetation coverage (-) related to submersion depth (m)

3.3.3 Relation between bed level change and vegetation coverage

In this paragraph, the bed level changes on and around the investigated sandbars in different areas are described and discussed. Three areas are identified: a vegetated area on the sandbar, a non-vegetated area on the sandbar and an area adjacent to the sandbar where the flow recirculates during base flow. The main focus of this analysis is on the processes taking place in the vegetated area. Figure 3-21 show the change in bed level during the flood in 2008 on and around each of the investigated sandbars.



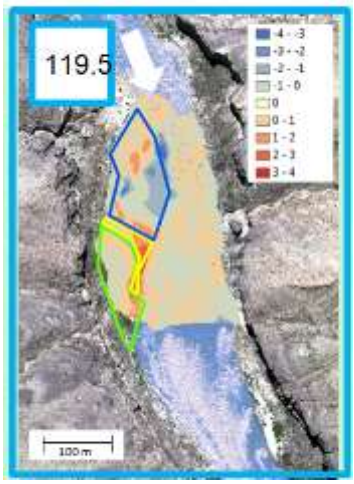


Fig. 3-21: Maps indicating the bed level change consequent to the flood in 2008. Colours are used to indicate the change in bed level: red indicates an increase in bed level whereas blue indicates a decrease in bed level. The vegetated areas are indicated with a green polygon, the bare areas with a yellow polygon and the recirculation areas with a blue polygon. In some cases the vegetated area permeates the bank, therefore it is not always assessed as a whole. This however has no further consequences to the analysis.

Bed level change in the vegetated areas

Two main observations are made concerning the bed level change during the flood event in the vegetated areas.

A first observation is that, compared to the surrounding areas only minor changes (-1m to +1m) in the bed level are observed on all the investigated sandbars. These minor changes indicate that the bed level of the vegetated area on the sandbar remains relatively stable during a flood event. Different explanations can be given. A first explanation is that vegetation only succeeds on elevated areas and therefore is hardly submerged during a flood event. As a result of the low submersion depth no or limited bed load transport takes place. A second explanation is that, vegetation on the river-vegetation interface blocks the flow towards and inside the vegetated area, which prevents supply and transport of sediments. This blocking effect of vegetation is confirmed by the observation that deposition is visible at the river-vegetation interface of the vegetated areas. Vegetation blocks the flow, which decelerates the flow. This causes suspended sediments to settle. The flow reaching the interface still contains high amounts of suspended sediment, resulting in large amounts of deposited volumes. A third explanation is that the roots of vegetation can potentially reduce or even prevent abrupt sediment detachment during flood events and therefore contribute to the stability of the system. Several studies confirm the effect of roots against sediment detachment during low water scenarios, however no flood events where incorporated in the analysis. Manners et al. (2014) [12] show that in those cases vegetation reduces erosion by restraining sand particles. It is likely that these processes occur simultaneously, leading to a durable area with minor changes in the bed level during flood events.

A second observation is that the bed level of the vegetated patches within the vegetated area slightly increased, whereas the bed level of the bare zones within the vegetated area reduces to some extent. This is especially noticeable for sandbars 51 and 55.9 when comparing figure 3-2 with figure 3-21. We see that the vegetation pattern corresponds to the deposition pattern. This phenomenon can be explained as follows. The presence of vegetation influences the suspended load transport. The suspended load transport in the Colorado River is of primary importance because the water contains high amounts of sediments during flood events. As explained before, vegetation reduces the flow velocity, causing sedimentation. Vegetation can also act as a body in the water; therefore sediment particles collide with vegetation units. This also reduces the particles' velocity and leads to sedimentation. As described by Nepf (2012) [19], the amount of sedimentation is determined by the size of the vegetated patch. A large vegetated patch causes a strong deceleration of the flow and therefore significant sedimentation. Also the species and age (dimensions) of the vegetation itself determine the amount of settlement. With dense and stiff vegetation and an increased canopy of leaves, flow is decelerated resulting in increased sedimentation (Nepf, 2012) [19]. However several processes can counteract sedimentation, although not significantly. Vegetation changes the shape of the vertical flow velocity profile, leading to lower concentrations of suspended sediment at the riverbed, which reduces sedimentation. Additionally, vegetation causes turbulence, which stimulates upward transport and therefore reduces the amount of deposition. This turbulence is the result of the difference in velocity between the decelerated flow inside the vegetation and the outer flow, creating a shear layer on top of the vegetation. The sum of these processes result in either an increase or decrease of the suspended sediment settlement along the vegetated areas. The presence of vegetation influences the bed load transport as well. As described by Nepf (2012) [19], vegetation reduces the flow velocity near the bed, resulting in a reduction of the bed shear stress. This, in turn, causes a reduction of the bed load transport. The bed load transport in the vegetated patches is, therefore, reduced compared to the bed load transport in the zones before the vegetated patches. This difference in transport load causes an inflow of sediment in the vegetated patches. The reduced outflow from the vegetated patch then enters the sandy zone. This accelerates the flow causing higher bed load transport rates and sediment detachment. Therefore, the bed level in bare zones within the vegetated area lowers. The sum of influence of vegetation on the suspended load transport as well on the bed load transport results in either an increase or decrease of the bed.

Bed level change in the bare areas

Concerning the bed level change in the unvegetated areas one main observation can be made. At all the investigated sandbars the bed level in the bare areas has significantly increased (2-3 m) compared to the surrounding areas. This increase in bed level extends towards the recirculation areas. The bare areas seem to be situated at locations where the flow approaches the sandbar perpendicular, more specifically the reattachment point. Schmidth (1990) [4] state that the highest amounts of depositions are located near the reattachment point. The reattachment point is the most dynamic section of the sandbar. This dynamic character seems to create an unfavourable environment for vegetation to settle and for sandbars to expand. In addition, seems the pre-flood elevation of the area to play an important role in the amount of deposited sediment during the flood. The bare areas that are lowest in elevation seem to increase significantly in elevation during the flood (demonstrated for sandbars 30.7 and 65.1).

Bed level change in the recirculation areas

Regarding the bed level change in the recirculation area adjacent to the investigated sandbars three main patterns can be identified. These are basically the sandbar categories as explained in paragraph 3.2.2; scarsely, moderately and heavily vegetated. (1) The entire recirculation area shows a significant decrease in bed level due to the flood (sandbar 51 and 55.9). (2) A large part of the recirculation area shows a significant increase in bed level following the flood (sandbar 30.7 and 61.5). (3) The recirculation area shows a combination of the above described patterns, namely a decrease in bed level in the return channels and in the area between the eddy and the main channel and an increase in bed level near the reattachment point and near the eye of the recirculation area (sandbar 41.4, 44.5 and 119.5). Several explanations can be given for this difference in bed level change in the recirculation area adjacent to the investigated sandbars.

Firstly, the different widths of the channels in which the investigated sandbars are located. The channel width influences the hydraulic forces and therefore the sedimentation in the recirculation zone during low water conditions. Under these conditions, the hydraulic forces within a wide channel are weak and therefore large amounts of sediment can settle in the recirculation zones. During a flood event, these large amounts of deposited sediments can easily be eroded, introducing a significant reduction to the bed level in the recirculation zone. This is observed adjacent to sandbar 51 and 55.9, which are located in relatively wide channels. The opposite applies to narrow channels that generate strong hydraulic forces during low water times and therefore limited pre-flood sedimentation in the recirculation area.

Secondly, the differences in elevation and therefore the vegetation coverage across the sandbar. The elevation of the sandbar influences the amount of vegetation on it and both factors determine the degree of flow that is blocked during the flood. This determines the discharge, as well as the flow velocity in the recirculation areas and is therefore a main regulator of the bed level. Sandbars that are high in elevation and densely vegetated prevent the recirculation area from extending over the sandbar. High flow velocities are generated when high discharges enter a constricted recirculation area. High flow velocities promote erosion in the recirculation area. Scarcely vegetated, low-lying sandbars allow the recirculation area to extend over the sandbar. The wide recirculation area results in relatively low flow velocities, accelerating sedimentation. The hypothesis, that the recirculation zone of elevated and densely vegetated sandbars are small in size and therefore characterised by strong flow velocities while the opposite applies to the recirculation areas of low, bare sandbars, can be only partly confirmed by the model study in chapter 4. So I think the wider reaches always have lower velocities – that allows sediment to accumulate on the bed and scour away, but inhibits high-elevation bar deposition especially when combined with a large vegetated bar filling up the eddy. In this study only the vegetation coverage is taken into account and not the sandbar elevation. The model shows that the recirculation zone adjacent to a bare sandbar is naturally large in size, but is also governed by remarkably high flow velocities. Moderate flow velocities are to be observed at the recirculation zone of a vegetated sandbar, despite what would be expected at a moderate area like this. This indicates that the major part of the flow during high water conditions flows directly downstream through the main channel and not into the recirculation area. It is expected that the shape of the sandbar and the location of vegetation on the sandbar determine whether the flow is driven into the recirculation zone or downstream.

Lastly, the different widths of the rapids upstream from the investigated sandbars. As demonstrated by Schmidt (1990) [4], the dimensions of the rapid determine the size of the recirculation zone and therefore the flow velocity within this. It is mentioned that wide rapids result in large surfaces of the main stream and, hence, short recirculation areas. A significant discharge volume driven into a short recirculation zone develops high flow velocities, which causes sediment detachment. However a clear correlation between rapid width and recirculation zone size is not identified in this study.

Duration of the flood period

Clearly, the duration of the flood has a significant influence on the bed level change and therefore (directly or indirectly) the vegetation coverage. However, it not further taken into account the mechanism is shortly mentioned. The peak of suspended sediment concentration is at the beginning of the flood period. The study by Wright and Kaplinski (2011) [21] showed that the concentration of suspended sediment decreases linearly throughout this period. At the end of a flood period, the concentrations of suspended sediment are negligible. Different studies (Schmidt et al.,1993 [10] and Wright and Kaplinski, 2010 [21]) show a profound relation between the concentration of suspended sediment and sedimentation. Logically, high amounts of suspended sediment concentrations lead to high deposition volumes. So, the majority of deposition takes place at the beginning of a flood period. Towards the end of the flood period, the erosion will be higher than the deposition. Naturally, the duration of the flood has a direct impact on the volume changes of sandbars. The duration of the flood not only influences the sandbar volume and therefor the ability of vegetation to succeed, but it also directly affects vegetation. Several studies confirm this and show that the duration of the flood effects plants. Vervuren et al. (2003) [22] showed that the longer the vegetation is flooded, the more it is damaged. Since the floods in the Colorado River only lasts for three days, high deposition volumes are observed. Due to the short high water period, the vegetation is not expected to be directly damaged.

3.3.4 The development of vegetated and bare sandbars

In the paragraph an attempt to elucidate the mechanism behind the development of the different sandbar types is made. This is considerably complicated as the factors determining the sandbar morphology are strongly linked to each other. The width of the channel in which the sandbar is located appears to play an important role in the development of the sandbar itself and hence in the vegetation expansion. This mechanism will be illustrated by comparing sandbars located in narrow and wide channels. The changes in (geo) morphology and vegetation during three subsequent flood cycles are described and illustrated schematically.

The Glen Canyon Dam was built in 1990. After a 6 year period without floods, the first post-dam flood was released in 1996. As a result of the long floodless period, large amounts of sediment were in taken into suspension. During the flood, large amounts of sediment were deposited at several locations along the river channel, creating sandbars or underpinning existing sandbars. Due to several floods in the following two decades, some sandbars increased in volume while others decreased, while a number of sandbars remained constant in size. Eventually three types of sandbars could be identified with respect to vegetation coverage; scarcely vegetated sandbars, densely vegetated sandbars and sandbars with expanding vegetation coverage. Each sandbar type is characterized by a number of different features as shown in table 3-4.

- Small and scarcely vegetated sandbars are generally located in relatively narrow channels. During flood events, these sandbars are highly submerged, leading to large deposition volumes of suspended matter.
- Large and densely vegetated sandbars are generally located in relatively wide channels. During flood events, these sandbars are hardly submerged, inciting to the production of insignificant deposition volumes of sediments.
- Sandbars on which vegetation substantially expands seem to enlarge with time. However, no relation is to be identified between channel width and submersion depth for this type of sandbars.

Characteristics; (average during 3 flood cycles)	Scarcely vegetated sandbar	Densely vegetated sandbar	Sandbar with expanding vegetation
Channel width	120 m	160 – 180 m	140 -150 m
Sandbar volume	1000 m3 – 4000 m3	6000 m3 – 9000 m3	2500 m3 – 9500 m3
Change in sandbar volume	-1000 m3 – 1000 m3	1000 m3 – 2000 m3	3000 m3 - 14000 m3
Submersion depth	2.6 m – 2.8 m	0.2 m – 0.8 m	0.9 m – 2.1 m
Deposition volumes	4000 m3 – 8000 m3	0 m3 – 2000 m3	3000 m3 – 8000 m3

Table 3-4 Characteristics of the different sandbars

The behaviour of scarcely vegetated sandbars

In narrow channels, the hydraulic forces are strong; as a result, the flow velocities on and around the sandbar as well as in the recirculation areas are also high. In low water conditions, these strong forces lead to fast sediment detachment rates of sandbar surface area. For this reason, soon after the flood in 1996, the sandbars located in narrow channels declined in volume and elevation. During the subsequent floods, these sandbars were highly submerged, leading to the deposition of large amounts of sediment, which then eroded as result of the strong post-flood hydraulic forces. At the end of the flood cycle, no increase in sandbar volume could be observed. This pattern is considered to be repeated during every subsequent flood cycle, resulting in low and dynamic sandbars (large erosion fluxes and sedimentation volumes). The dynamics and changeability seem to hamper the natural succession of vegetation. During low water conditions, the sandbars gradually erode which may damage all newly grown vegetation. Then, at the time of flood events, the large amounts of deposited sand further hinder vegetation growth or even destroy it. The above mentioned process is schematically shown in figure 3-22 and possibly explains why sandbars 30.7 and 65.1 are small in volume, varied in shape and scarcely vegetated.

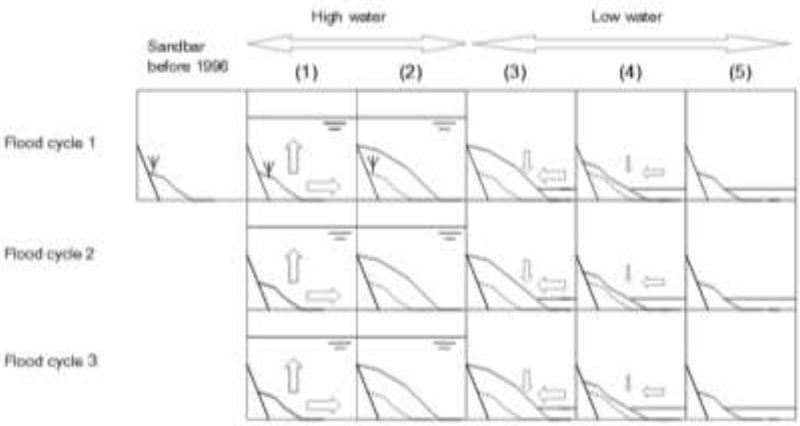


Fig 3-22. A conceptual cross section of the behaviour of a scarcely vegetated sandbar located in a small channel during 3 flood cycles. The arrows indicate the direction and magnitude of sandbar growth.

Flood cycle 1: (1) and (2) Significant sandbar enlargement due to the high submersion depth during the 1996 flood (3) Fast erosion of the sandbar due to the strong hydraulic forces (4) Continues erosion leading to an shrinking of the sandbar: environment unfavorable for vegetation succession (5) The final sandbar size is equal to its initial pre-flood size but without vegetation.

Flood cycle 2, 3 and subsequent flood cycles: Repetition of cycle 1

The behaviour of densely vegetated sandbars

In wide channels the main stream as well as the recirculation zones are less constrained compared to narrow channels creating moderate hydraulic forces during both low and high water levels. Due to the moderate hydraulic forces at low water conditions the erosion rates are low and sediment transport is reduced. For this reason, after the flood in 1996, this type of sandbars remained fairly large and highly elevated. Such elevated sandbars promote vegetation encroachment. During each subsequent flood cycle, the volume of these sandbars slightly increased, causing a lower submersion depth. This lowering, combined with the blocking effect of vegetation, reduced the supply and transport of sediments which reduced the amount of sediment mobilization from the sandbars during flood events; moderate volumes were deposited, either on top of the sandbars or at the channel bank. This eventually led to an amplified sandbar. Sedimentation during low water conditions led to a gradual constriction of the channel, this resulted in stronger hydraulic forces and hence increased erosion. During the subsequent flood cycles, erosion and deposition took place in a lower degree at the channel side of the sandbar. Allegedly, a dynamic balance was restored and the system was stabilized. This, as illustrated in figure 3-23, gives an indication why sandbars 51 and 55.9 are large, stable, and densely vegetated.

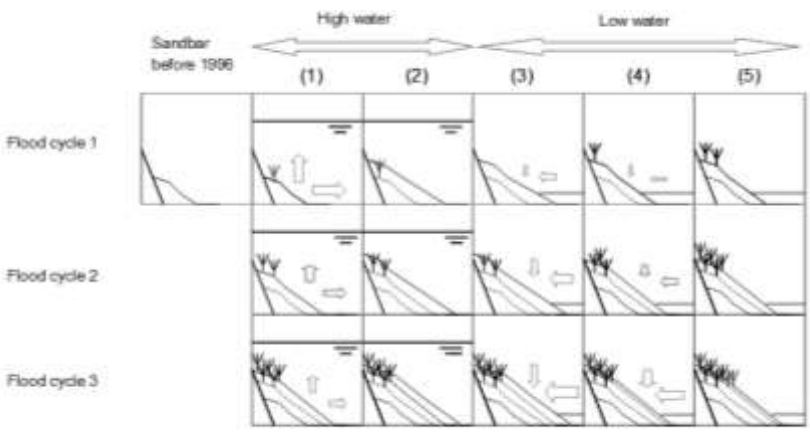


Fig 3-23; A conceptual cross section of a densely vegetated sandbar located in a wide channel during 3 flood cycles.

The arrows indicate the direction and size of sandbar growth. The columns indicate the different stages during the flood cycles.

Flood cycle 1: The 1996 flood (1) and (2) Significant sandbar enlargement. (3) Slow erosion of the sandbar due to the moderate hydraulic forces (4) Stable and elevated sandbar, a favourable environment for vegetation to encroach (5) The final sandbar is larger in size than its initial pre-flood one and slightly vegetated.

Flood cycle 2: (1) and (2) The sandbar is relatively large in volume, slightly vegetated and high in elevation, resulting in a relatively small submersion depth. This combined with the blocking effect of vegetation reduces the rate of accretion of the sandbar during a flood event. (3) Consequent to the sandbar enlargement, the channel is more constricted compared to cycle 1, leading to stronger hydraulic forces and therefore an increase in erosion rate. On the other hand, the present vegetation, decelerates this erosion process. (4) A stable and elevated sandbar being a favourable environment for vegetation expansion and succession. (5) A sandbar larger in size and more vegetated than the pre-flood one.

Flood cycle 3 and subsequent cycles: Repetition of the processes described above, eventually leading to equal deposited and eroded volumes and thus creating a stable vegetated sandbar which is constant in volume.

Behaviour of sandbars with expanding vegetation

On some sandbars vegetation seems to be mainly the result of sandbar growth. The sand deposited during the flood creates sheltered areas that are optimal breeding grounds for vegetation. This possibly explains why sandbar 41.4 is expanding and flourishing over time. On the contrary, for other sandbars it is vegetation that seems to be causing them to expand. The sediment deposited at the channel banks during flood events seem to become overgrown by vegetation. Whether or not vegetation is able to grow towards the newly enlarged sandbar area depends on a number of factors, including the type of vegetation, the location of the sandbar (determining the hours of daily exposure to sunlight) and the fertility of the soil/sand. During low water periods, the roots of vegetation contributed to the stability of the sandbar by reducing or even fully hindering erosion in some cases. This resulted in a relatively stable sandbar system where vegetation could expand and succeed. During the next flood event, the enhanced vegetation stimulated transport of sediments from the sandbar towards the channel by catching a significant fraction of the sediment. Over the course of the subsequent cycles and as result of the continuous constriction of the channel by the sandbar, erosion and deposition rates were eventually leading to a steady state system. Figure 3-24 shows this phenomenon which justifies why sandbar 119.5 is steadily accreting and why its vegetation coverage is expanding.

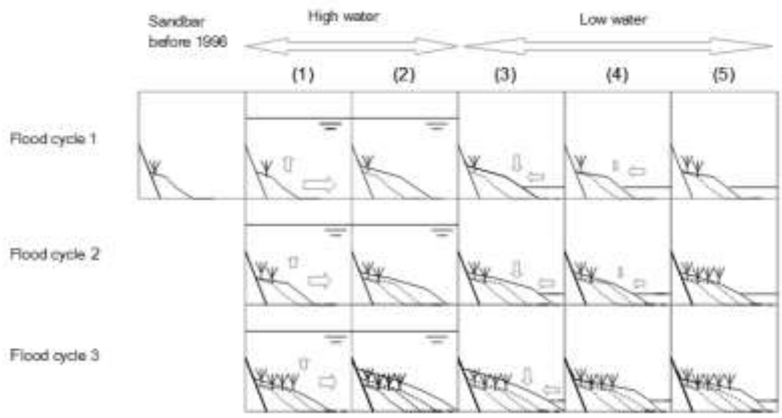


Fig 3-24: A conceptual cross section of the behaviour of a sandbar which enlarges and in vegetation coverage during 3 flood cycles. The arrows indicate the direction and size of sandbar growth. The columns indicate the different stages during the flood cycles.

Cycle 1: (1) and (2) Significant channel ward accretion (3) and (4) At the channel ward side, vegetation expansion and slight erosion. The final sandbar has enlarged towards the channel, has expanded vegetation coverage and is larger in volume compared to its initial pre-flood volume. (5) The final sandbar is larger in size (mainly at the channel side) than its initial pre-flood one and slightly vegetated.

Cycle 2 and subsequent cycles: Repetition of the processes described above, eventually leading to a vegetated sandbar accreted towards the channel.

In an attempt to tackle the mechanisms regulating the formation of the various sandbar types as listed above we are lead to the logical conclusion that the overall development of a sandbar is the outcome of more than one factor. For better understanding of the system, the interdependency between hydraulic forces, the width of the channel, vegetation expansion and submersion depth should be thoroughly studied.

3.4 CONCLUSIONS AND RECOMMENDATIONS REGARDING THE DATA ANALYSIS

3.4.1 Conclusions

Regarding the long term dynamics of the sandbar the following could be concluded; (1) a clear relation between flood cycles and changes in sandbar volume exists. During flood events, sandbars are nourished, while during base flow, sandbars erode. The long term growth of a sandbar is dependent on the difference between the deposited and eroded volumes during the flood cycles. (2) A clear relation exists between change in sandbar volume and the change in vegetation coverage. Since no clear relation can be observed between change in sandbar surface area and the change in vegetation coverage, it is assumed that the elevation of the sandbar plays an important role in the ability of vegetation to expand. This importance is confirmed by the observation that highly elevated sandbars that endure submersion are densely vegetated, whereas lower laying sandbars that get highly submerged during flood, are scarcely vegetated.

Regarding the short term dynamics of the sandbar, during one flood event, the following could be concluded; (1) in the vegetated areas of the sandbars the bed level remains relatively stable compared to the surrounding areas. This can be explained by the fact that vegetation grows on areas that are high in elevation and are therefore hardly submerged during floods, resulting in limited sediment transport. Moreover, it can be explained by the fact that vegetation blocks the flow towards the vegetated area, reducing the discharge, and thus depleting sediment transport into the vegetated zone. Lastly, the roots of vegetation can be a cause of the stable bed because the roots can prevent further erosion. (2) The bed level of the vegetated patches of sandbars slightly increases, whereas the bed level of the non-vegetated patches within the vegetated areas of sandbars slightly shrinks. This happens due to the fact that vegetation lessens the rate of bed sediment transport. In addition, sediment particles colliding with vegetation promote sedimentation. This mechanism is confirmed by the observation that sedimentation mainly takes place at the water-vegetation interface.

3.4.2 Recommendations

Based on the data analysis, interesting observations regarding the relation between sandbar geo-morphology and vegetation coverage were made and a number of conclusions were drawn. However, the data analysis could be improved by the following adjustments. Firstly, the period studied in this thesis is from 2002 to 2013, however the period before 2002 should be taken into account. Because major changes in sandbar morphology occurred during the first post-dam flood in 1996 this period is of utmost importance. Due to the lack of data for all sites concerning vegetation in the period before 2002, this period was not taken into account. Secondly, seven sandbars have been investigated. The question is whether these sandbars compile a representative sample for an overall geo-morphological/vegetation analysis. Ideally, more sandbars should be investigated, enabling more reliable conclusions to be drawn. Thirdly, the geo-morphological development of the sandbar is well presented in this study by linking data on the sandbar volume, surface and cross section at three moments in the 10-year study period. The time period between the measurements and the previous flood (the post flood period), however, differs. Indicatively, in 2002 the post flood period was 6 years, in 2009 this period was 19 months and in 2013 this period was 10 month. These differences are a limitation since floods are the main driving force for changes in sandbar morphology. In future research, a consistent post-flood period is recommended to improve understanding. Fourthly, data required for the assessment of vegetation coverage was often not available or not detailed enough. Vegetation was measured at three moments during the study period, with a time interval of at least three years in between. Since vegetation changes day by day, a more frequent assessment of the vegetation coverage (e.g. once every month) could improve the results. Fifthly, the assessment of vegetation coverage was based on the aerial photos, which is fairly inaccurate. In the present thesis, the density of the vegetation and species have not been taken into consideration because this data was not available. It is plausible that these factors also play an important role and should be taken into account in future research. Lastly, the hydraulics on and around sandbars were estimated, based on Q-H relations and channel dimensions. Detailed information concerning the hydraulics (e.g. the velocities in the rapid, recirculation zone, on the sandbar and in the mainstream) have not been taken into account due to the lack of measurements however they will improve detailed understanding.

4 DETAILED ANALYSIS OF THE MODELLED HYDRAULICS AND GEO-MORPHODYNAMICS ON AND AROUND THE BUCK FARM SANDBAR

This chapter contains descriptions of the hydraulics and morphodynamics during a flood on and around a specific sandbar in the Colorado River by the use of a numerical model. The aim is to investigate the influence of vegetation on the depth average velocity and bed level change during a flood. First, the selection of the sandbar suitable for further investigation is justified. In addition, a numerical model is set up and calibrated. Moreover, the vegetation input values are explained. Subsequently, the model results are described, compared with the field data and discussed. Finally, the results are presented and recommendations are made.

4.1 SANDBAR IDENTIFICATION

The sandbar selected to be modelled is Buck Farm (sandbar 41.4), one of the investigated sandbars discussed in chapter 3. The selection is based on the following features;

- The sandbar has to be a reattachment bar, bordered by two distinct recirculation zones.
- The sandbar has to be overgrown with a significant amount of vegetation, preferably consisting of arrowweed, as this is the measured vegetation.
- The sandbar must show a remarkable expansion of vegetation over the years, so that the investigation of potential correlation between vegetation expansion and sandbar growth is meaningful.

Fig. 4-1: Buck Farm sandbar and environment in 2002: the reattachment bar (yellow) and two recirculation zones (blue) and the vegetation map

4.2 NUMERICAL MODEL

The topics are modelled. The hydraulics are modelled, intending to show the horizontal depth average flow velocities and their directions. Besides, the morphodynamics are modelled to show the changes in bed level consequent to a flood.

4.2.1 Description of the model

The flow module of the DELFT3D suite is used. DELFT3D-FLOW can solve the unsteady shallow-water equations in three dimensions. The system of equations consists of horizontal and vertical momentum equations. The horizontal momentum equations are the continuity equation and the transport equation. In case of depth average modelling, the vertical momentum equation is reduced to the hydrostatic pressure relation as vertical accelerations are assumed to be small compared to gravitational accelerations. The morphology modules in DELFT3D-FLOW account for bed-load and suspended-load transport of cohesive and non-cohesive sediment and for the exchange of sediment between bed and water column. Bed-load transport is computed using an empirical transport formula and suspended load is calculated using the advection-diffusion equation.

4.2.2 Set up of the model

In a model a balance has to be found between complexity (great modelling effort) and simplicity (less representative). Table 4-1 shows the input parameters and their allocated values. The last column is a summary of the justification for the selected values. These values are extensively explained in Appendix B.

Topic	Parameter	Value	Unit	Remarks
Dimension		2D		Baptist's formulations which are used to represent vegetation makes calculations in 2D
Spatial scale	Modelled area	1200 x 120	m	Included are one pool and two rapids
	Grid	100 x 30	cells	Longitudinal grid lines follow the stream, cross sectional grid lines reach from bank to bank
	Cells	12 x 4	m	The size of the cells appeared to be relatively large
Temporal scale	Period	03-03'08 -12-03'08		This includes 9 days; three days of low water conditions, three days of high water conditions and finally three days of low water conditions. To avoid spin-up errors, the period before and after the flood, being the focus of modelling, is rather long.
	Time step	0.1	s	This time step was chosen to be small, to provoke a courant number below 10, this ensures a stable computation.
Bed topography				Approximately 40% is based on measurements by the USGS, the remaining part is estimated by means of interpolation.
	Rapids depth	0,5	m	The depth of the bed in the rapids is estimated by assuming a critical flow in the rapids. Critical flows have Froude numbers equal to 1.
	Remaining not measured bed			Estimated by means of interpolation.
Initial conditions	Water level	+ 841.1	m (AMSL)	The initial water level is chosen as close as possible to the water level at the upstream boundary to reduce initial fluctuations.
	Bed roughness	50	$m^{½}/s$	The initial bed roughness, calculated by means of the Chézy formula and is assumed to be uniform over the whole stretch. This may not be in line with reality. The roughness value in rocky areas in rapids and main stream is higher than the sandy areas in the hydraulically quiet zones.
	Bed thickness	0 and 3	m	At the sandbar area a thickness layer of 3 meters is applied, the depth is based on the maximum measured erosion; at the remaining locations 0m thickness is applied.
	Bed grain size	0.312	mm	The median grain size is derived from physical samples derived from the measurement station at 30 mile.

Boundary conditions	**Upstream boundary**			**The values of discharges and suspended sediment volumes are derived from measurement station at 30 mile.**
	- Low water discharge	226.53	m^3/s	The flood expands from 226.53 m^3/s to a peak discharge of 1206.6 m^3/s
	- High water discharge	1206.6	m^3/s	The flood expands from 226.53 m^3/s to a peak discharge of 1206.6 m^3/s
	- Suspended sediment size	0.135	mm	The average measured grain size (D_{50}) of the suspended sand during the flood period is taken. Suspended sediments can be divided in fine (clay) and coarse sediments (sand). The concentration suspended clay is significantly lower than the concentration suspended sand. Therefore only the suspended sand concentration is implemented.
	- Volume of suspended sediment	graph shown in appendix B		At low flow, a negligible amount of suspended sediment is present in the water. During a high flow, a significant increase in suspended sediment occurs, which again gradually decreases during the subsequent high flow period. The modelled concentration of the suspended sediment is stepwise deceasing during the high water period.
	Downstream boundary			A water level, calculated by means of QH- relations, is set as downstream boundary.
	- high water level	+ 845	m (AMSL)	
	- low water level	+ 841	m (AMSL)	
Sediment transport formula		Van Rijn		The sediment transport formula by van Rijn (1984) makes an explicit distinction between bed load and suspended load transport. The sediment transport in the Colorado River is a sum of both types, therefore van Rijn's formula is assumed to be appropriate.
	Calibration coefficient	1.5		The calibration coefficient indicates the importance of the suspended load transport compared to the bed load transport. The value of 1.5 is taken because the processes in the river are expected to be dominated by suspended sediment transport. This is confirmed by Schmidt (1990) [4] who stated that the reattachment sandbar comprises of sediments similar in size to the suspended sediments.
	Reference level	0.01		Bed layer thickness
	Fall velocity	-	m/s	This parameter depends on the grain size and it is calculated by the model.
Turbulence		HLES		Turbulence is taken into account by applying horizontal large eddy simulation (HLES). However, HLES only resolves large scale turbulent eddies. Small scale turbulent eddies are not considered. Large scale eddies contain the greatest part of the turbulent energy and the dynamics of large scale motions are of main importance in the river situation, which might justify the omission of the influence of the small scale turbulences.
Vegetation	Height	1.6	m	Justified in paragraph 4.2.3
	Density	0.75	-	Justified in paragraph 4.2.3
	Vegetation drag	1	-	Justified in paragraph 4.2.3

Table 4-1: Characteristics, allocated values and short justification of the parameters used in the model

4.2.3 Vegetation model input values

This paragraph gives a description of the way measurements on vegetation have been transferred to parameter settings in the model. Besides, the shortcomings of the implementation of variable parameters of vegetation in a numerical model are given. It has to be mentioned that the measurements performed on vegetation were far more extensive than necessary for model input values, this because of unfamiliarity with the way of representing vegetation in a numerical model.

To implement vegetation in DELFT3D-FLOW different vegetation models can be used. The performance of existing vegetation models has been analysed by Vargas- Luna et al. (2014) [23]. In their study the assessment of flow resistance for different vegetation types under several degrees of submergence was considered. It was concluded that the Baptist (2005) [18] model would allegedly provide results which agree best with measurements of both artificial and real vegetation. Therefore in this study the Baptist (2005) [18] model is used to implement vegetation. An additional clarification of the equations and assumptions used by Baptist are explained in paragraph 2.4 and more extensively explained in Appendix C.

In the Baptist model the following parameters have to be determined: vegetation height (k), frontal area (m), vegetation drag coefficient (C_d) and bare bed roughness (C_b). Moreover the grid cells in which vegetation is assumed to be present, have to be specified. In table 4-2 the used values are identified and justified.

Parameter	Value	Justification
Vegetation height (k)	1.6 (m)	The average stem height derived from the measurements
Frontal area (m)	0.75 (-)	The frontal area indicated as the number of stems per square meter (n) times the diameter of the stems (D) at a specific height. The number of stems per square meter (n) is calculated by the average number of stems multiplied by the average number of shrubs (n = 11* 6.3 = 69.3 [-]). This results in a frontal area of 0.65 (n * D = 69.3 * 0.00925 = 0.65 [m]). The density of the canopy is not included in this value, although canopy is present and is expected to be of importance for the density of vegetation. To account for the canopy part, the value of the frontal coverage is increased by 0.1.
Vegetation drag (C_d)	1 (-)	Regarding the stem skin friction and shape of arrowweed no measurements have been executed. The drag coefficient can be considered to be constant. (Baptist)
Bed roughness (C_b)	40 ($m^{½}/s$)	The bed roughness is assumed to be uniform and calculated by mean of the Chézy equation.
Grid cells	Figure 4-2	The recent vegetated area in the grid is identified by means of aerial photos. To investigate the influence of expanding vegetation, a second version is made in which vegetation is added at a randomly chosen larger area. The areas are indicated in figure 4-2.

Table 4-2: Summary of input values Baptist

Fig. 4-2: Location of vegetation at scale (left) vegetation at larger scale (right)

The modelled vegetation type is arrowweed. Arrowweed is complex in shape, little uniformity exists both on a small and on a larger scale. Indicatively, this type of vegetation shows differences in height, in diameter of stems, in amount and flexibility of stems, in the amount of canopy foliage etc. Furthermore, arrowweed is not evenly distributed and is changeable in space and time. By Baptist vegetation is schematized as a set of rigid cylinders equal in height and diameter which are distributed equally over the space of a grid cell. The size of the grid cell is 12 by 3 meter. The values are assumed to be equal in all parts in a grid cell. Therefore some noteworthy differences in modelled vegetation and natural arrowweed are noted.

- Arrowweed typically grows in shrubs. In the model, arrowweed is supposed to consist of stems equally distributed over the grid cell.
- The stem of arrowweed decreases in diameter with an increase of height, in the model the stem diameter is a constant.
- The height of arrowweed differs considerably, in the model the height is the same for every branch.

- Arrowweed is very flexible, especially when the plant is young, in the model, vegetation is schematized as ridged cylinders.
- The canopy of arrowweed can be significant in volume, especially for older vegetation, in the model vegetation is schematized as cylinders.

Overall, a significant difference exists between the modelled and the natural arrowweed. Therefore will the model results regarding the influence of on the hydraulics and morphology not exactly match the reality of nature. The shortcomings of the model should be taken into account for future studies and decision making approaches.

4.2.4 Calibration and sensitivity analysis

With regard to the hydraulics, initially, the model results did not match the measured data. Therefore the flow features are calibrated. The Chézy value was adjusted to match the modelled water level. Moreover, the reflection factor downstream was adjusted to reduce the numerical reflection wave downstream. The calibration is extensively explained in Appendix D. The finally used values are listed below:

Parameter	Value	Unit
Chézy	40	$m^{½}/s$
Reflection parameter	100	

Table 4-3: Adjusted values after calibration

The measured and modelled magnitudes of the bed level changes are shown in figure 4-3. The figure reveals several similarities and contrasts between the measured and modelled bed level changes. The development of a return channel (I) and sedimentation on the sandbar (II) were simulated correctly. The high amounts of deposition over the entire stretch (III), the appearance of erosion holes along the border of the sandbar in the main channel (IV) and the large amount of sedimentation in the lateral separation zone at the upstream end of the eddy (V) did not match real facts.

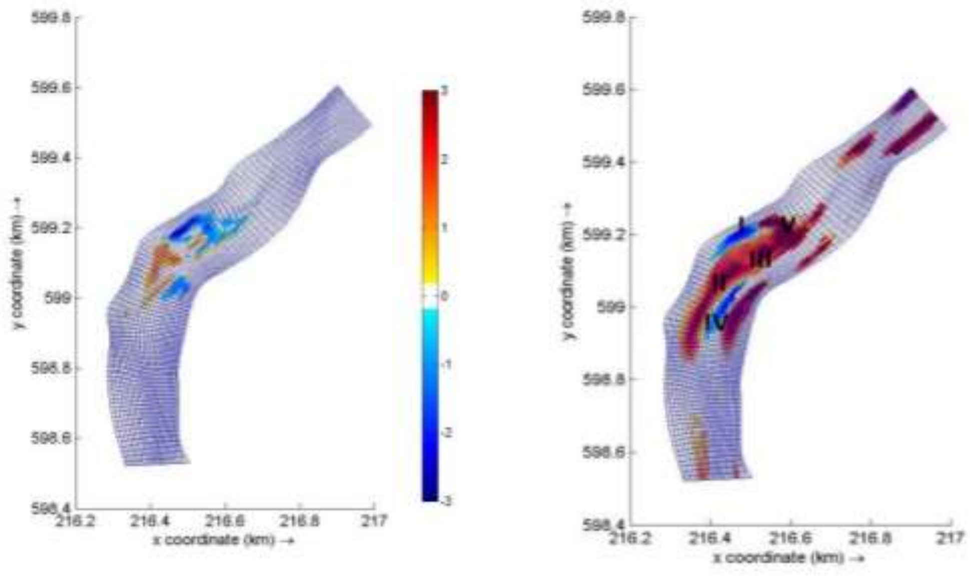


Fig. 4-3: Measured (left) and modelled (right) bed level changes during the flood in 2008

In order to correct both the high amount of sedimentation over the entire stretch and the deviating bed level change pattern, the sensitivity of several parameters is investigated. In Appendix E the results are shown and extensively explained. The key observations in a nutshell are as follows:

- The deposited sediment volume seems to be sensitive for the volume of the inflow sediment. The exact amount of inflow sediment is unknown. Adaption of the volume of the inflow sediment reveals that the lower the volume of sediment inflow, the lower the deposited volume in the entire study area. Deposition mainly takes places close to the reattachment point.
- The deposited volume appears to be independent on the sediment grain size of the inflow sediment. Adaption of the grain size of the inflow sediment mainly alters the location of deposition: the smaller the grain size the more deposition takes place at the bank ward side of the sandbar. Possibly, smaller grains stay longer in suspension and do not settle at the first location with low hydraulics.

- By changing the bed thickness the bed level pattern is influenced. The deviant erosion at the interface between sandbar and main channel reduces. The bed thickness has been changed from uniform to gradual increasing towards the river bank. This because the Colorado River is a bedrock river and sediment is expected to settle in larger amounts near the river bank than near the main channel.
- Adaption of the grain size of the bed reveals that suspension occurs easier when the sediment grain size is smaller, leading to reduced bed level changes.

After numerous attempts to apply adapted values, the modelled bed level changes still deviates significantly form the measured bed level changes. Further optimisation of the model has not been executed, however the following adaptions are recommended;

- In this model study only the Van Rijn formula is used. Other formula's (e.g. Engelund & Hansen) take other processes into account, which may lead to more realistic outcomes.
- In this model study is only calculated in 2D. Calculation in 2D uses a depth average, while calculation in 3D takes processes in different layers into account, which corresponds more with a realistic outcome. Logan et al. (2010) [24] models an eddy sandbar in the Colorado River. This study shows a significant improvement of morphodynamic outcomes when calculating in 3D.
- In this model study parts of the initial modelled bed topography differed significantly from the measured bed topography. This seemed to be caused by the size of the grids. Several attempts were made to correct this, without remarkable success. In future model studies it is advised to use smaller grid cells in order to improve the initial bed topography.

4.3 MODEL RESULTS AND DISCUSSION

Because of the difficulty of properly modelling morphology, the investigation of the influence of vegetation on sandbar dynamics is restricted to focus on the flow pattern only. In this paragraph the hydraulics in the different scenarios of the modelled results are compared with findings from the literature. In addition, the modelled hydraulics are linked to measured bed level changes and the influence of the vegetation growth on the bed level change is discussed.

4.3.1 Flow structures on and around the Buck Farm sandbar

Depth average flow velocities at low and high flow

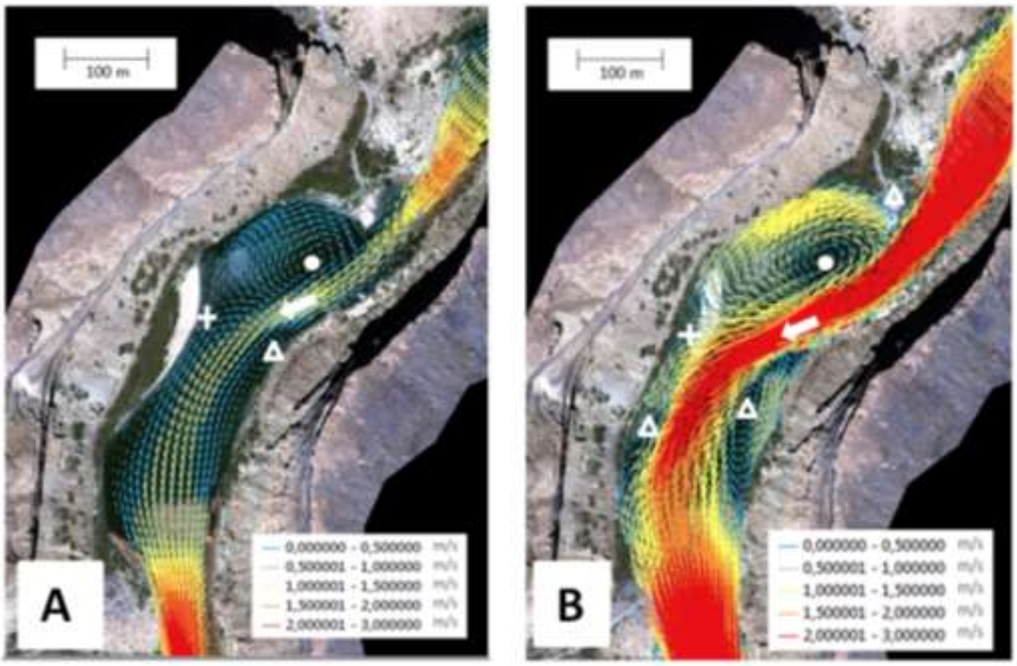


Fig. 4-4 Depth average flow velocity at low flow (A) and at high flow (B)

With respect to the depth average flow velocities at low and high flow (figure 4-4) the following observations can be made. At both low and high flow a primary recirculation eddy, with clockwise rotation, appears downstream from the constriction. The downstream directed flow is deflected towards the outer bank (white arrow), which is more prominent at high flow. With increasing discharge rates the surface area of this downstream directed flow increases and the shape of the recirculation eddy changes. The recirculation eddy extends downstream thus overflowing the sandbar, the recirculation eye (white dot) remains at the same location, and the reattachment point (white cross) shifts towards the bank and slightly downstream. In addition, the depth average flow velocities in the recirculation eddy increase by a factor of 2 and three 'separation' eddies with counter clockwise rotation arise (white triangles); one just upstream from the primary recirculation eddy, a second just downstream of the sandbar and a third one at the location where the main stream deflects towards the outer bank. The latter is also visible at low flow, however, significantly smaller in dimension and velocity.

Schmidt (1990) [4] investigated recirculation flow patterns in the Grand Canyon based on field measurements and observations. The results of his study largely correspond to our model results. An increase of the discharge caused widening of the constriction, movement of the separation point towards the shore and lengthening of the recirculation eddy which generated an increase in the surface area of the downstream directed flow. Our model results are in line with these observations. It was also demonstrated, that the steeper the canyon walls the longer but narrower the recirculation eddy. This decrease in width of the primary recirculation eddy cannot be observed in our model. This might be brought about by the mild slope of the riverbank, which enables a lateral extension of the recirculation eddy. At high discharges, Schmidt measured; a velocity in the primary eddy of less than 1 m/s, a velocity of almost zero near the separation and reattachment point and an absolute velocity in the recirculation zone significantly less than in the main channel. This only partly agrees with the outcome of this research. The velocity in the recirculation eddy stays under 1.5 m/s and the velocity in the main stream is always higher than 1.5 m/s.

Wright and Kaplinski (2011) [21] also studied the flow structures and sandbar dynamics in the Grand Canyon. They described the development of recirculation eddies downstream from constrictions, the shape of which changed substantially during high flow cases. At high flow, the recirculation eddy became more narrow and longer as the recirculation eye and reattachment point moved downstream and towards the bank. This is partly confirmed by our model; indeed, the eddy becomes longer and the reattachment point moves downstream, however, the recirculation eddy extends slightly laterally and the eye moves very slightly downstream. (This could be related to the deflection of the main stream mentioned at the end of this paragraph.) As explained before, the lateral extension might be caused by a difference in slope of the riverbank and by deviating dimensions and shape of the rapid and channel stretch. Wright and Kaplinski (2011) [21] also showed a substantial increase of the flow velocities in the recirculation eddy (a factor of 2.5) and the development of a separation eddy upstream from the primary eddy. In our model, the velocity in the eddy increases to a lesser extent (a factor 2) and several other secondary eddies develop.

Overall an increase in discharge loads leads to the movement of the separation point in the direction of the shore, an increase of the surface area of the downstream directed flow, a shoreward and slightly downstream movement of the reattachment point, a lengthening of the primary recirculation eddy with an increase of its flow velocity by a factor 2 and finally the development of a secondary eddy upstream from the primary eddy. These model results are globally in line with the observations and measurements of the above-mentioned studies. In the field studies, however, no widening but a narrowing of the primary eddy has been observed and no development of secondary eddies downstream. It has to be kept in mind that the research has not been executed on this particular sandbar. So there could be a difference in the geometry of the investigated and modelled riverbank, like the slope of the riverbank and the curvature of the reach. Whereas the development of the two downstream secondary recirculation eddies might be the result of the angle in the channel, causing a significant deflection of the main flow.

Depth average flow velocities at high flow with and without vegetation

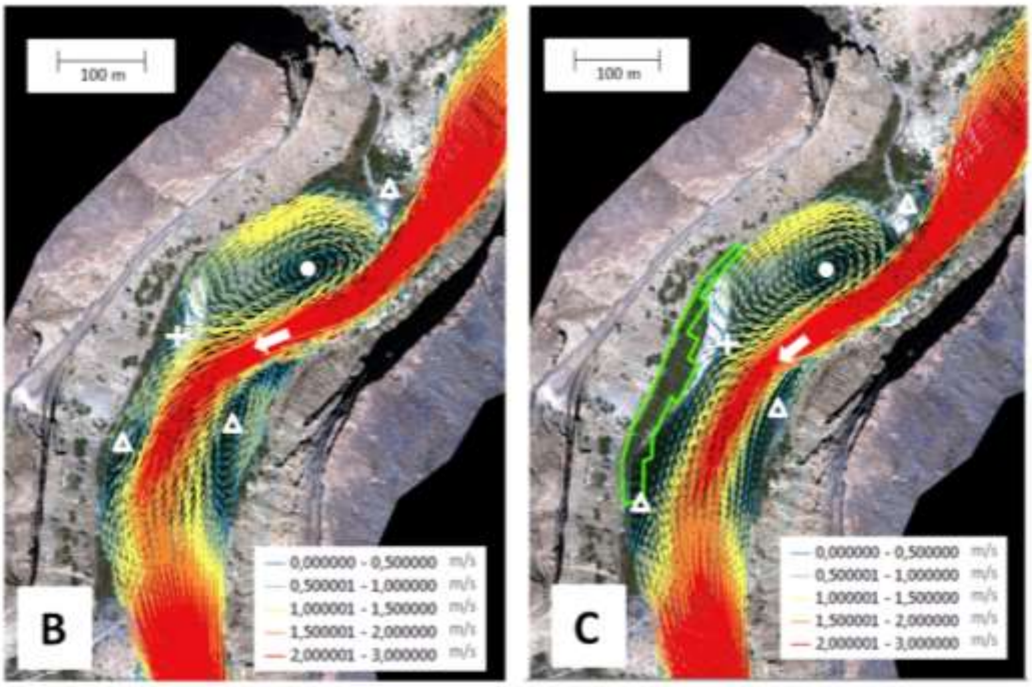


Fig. 4-5: Depth average flow velocity at high flow without vegetation (B) and with vegetation at a natural location (C)

When comparing the flow patterns at high flow with and without vegetation (figure 4-5) the following observations can be made. When vegetation is present, the downstream directed flow (white arrow) is less deflected, appears to get blocked by the sandbar and its surface area is decreased. This will lead to a narrowing and shortening of the recirculation eddy. The recirculation eye (white dot) remains at the same location. The reattachment point (white cross) moves towards the channel and slightly upstream while the flow velocities in the recirculation eddy slightly decrease. The 'separation' eddies with counter clockwise rotation (white triangles) decrease in size and they reduce in velocity. In the vegetated area, flow velocity reduces by a factor of 2, while the flow pattern remains the same; an upstream and downstream directed flow starting from the reattachment point. These velocities are too small to be clearly depicted from the figure.

The influences of vegetation on the detailed flow patterns have been the subject of several studies. Unfortunately, none of these have been executed on the recirculation currents in the Colorado River. Rominger et al. (2010) [16] investigated the influence of vegetation on a fully developed sandbar. By adding vegetation to the sandbar surface the depth average velocity over the bar reduced, consistent with the findings of our model and the velocity in the open region increased (not visible in our model). A slight increase of the velocity in the channel might be overlooked by the wide velocity range; the red colour depicts 2.0 – 3.0 m/s, in our model. Zong et al. (2010) [15] described the flow and deposition pattern on and around a vegetated patch "located at the wall of a channel" based on the results of a laboratory study. Regarding the flow pattern they revealed three distinct zones. In the first zone, the leading edge of the patch, they found that the flow in line with the patch decelerated and the major part of the flow diverted towards the open channel. In our model the flow approaching the vegetated patch decelerates at the reattachment point and diverts towards the recirculation area and towards the main channel. In the second zone, the vegetated patch itself, they found the velocity to be significantly reduced and uniform across the width and the length of the patch. In our model the velocity in the patch, although significantly reduced, is not uniform. This may be explained by the density of the vegetation or by the slope of the Buck Farm sandbar, which is rather steep, as demonstrated in chapter 3. In the third zone, the interface between patch and open channel, they described that a shear layer is formed, creating turbulence. In our model no turbulence is evident. This is the result of the use of a depth average modelling method, which doesn't take into account small turbulent scales.

Overall, vegetation significantly decelerates and diverts the flow. This is observed in both literature and modelling. These deceleration and diversion phenomena result in a less deflected and more constricted downstream directed flow, the reattachment point's movement to the channel, a narrower and shorter recirculation eddy with lower flow velocities, 'separation' eddies which decrease in size and velocity and a significant reduction of the flow velocity in the vegetated areas.

Depth average flow velocities at high flow with vegetation and with extended vegetation

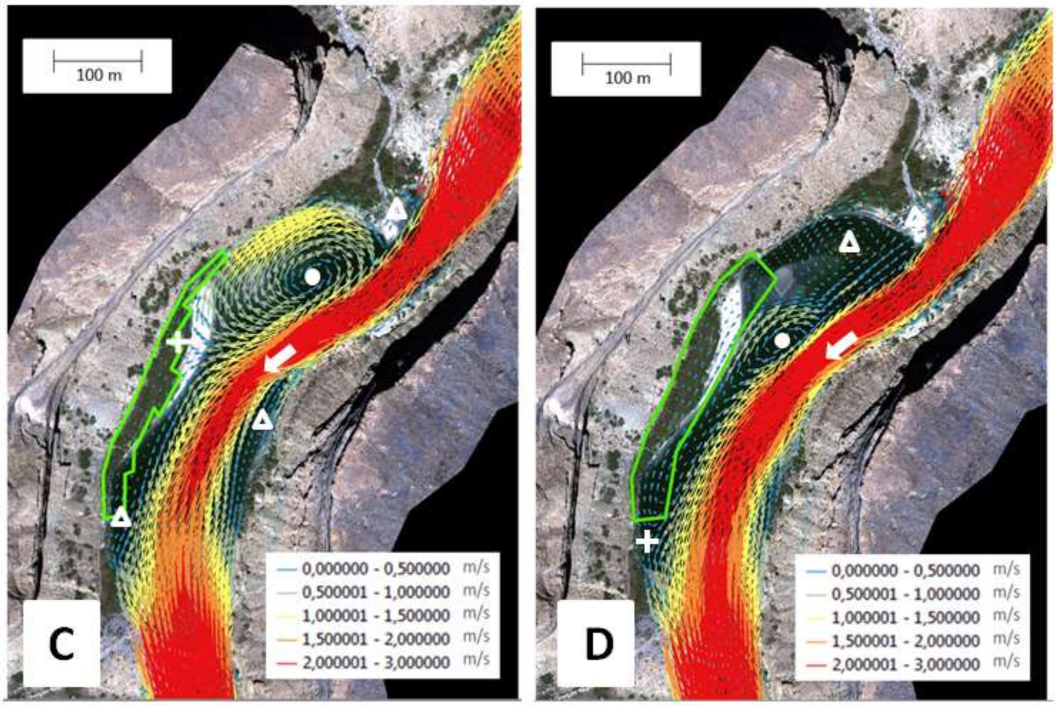


Fig. 4-6: Depth average flow velocity during high flow with vegetation at a natural location (C) and at an extensive location (D)

To get an impression of the influence of expanded vegetation on the depth average flow velocity and flow pattern, the vegetation in the model is added on an extensive scale. On and around a sandbar with extensive vegetation, the primary recirculation eddy with a clockwise rotation (white dot) moves downstream alongside the vegetated patch. The flow towards the recirculation area seems to be blocked by the vegetation and due to the lack of space, the primary eddy is driven into a compressed and "smeared" eddy. The velocities in this eddy are low, which indicates that the main part of the flow stays in the mainstream. The reattachment point (white cross) moves towards a location downstream from the vegetated sandbar where a wake circulation develops. From this location a part of the flow deflects upstream overflowing the vegetated sandbar. The velocity on the vegetated sandbar decreases towards the river bank, which might be attributed either to the elevation of the sandbar or to the density of the vegetation. A large secondary eddy with counter clockwise rotation arises upstream from the vegetated sandbar, which seems to be formed by two types of flow; the upstream flow originating from the reattachment point and an upstream flow originating from the recirculation eddy. The mainstream adjacent to the extensively vegetated sandbar is larger in surface, higher in velocity and less deflected towards the outer bank.

One can argue whether the modelled flow pattern on and around the extensive vegetated sandbar adequately represents reality. However, with extensive vegetation, one would expect a similar flow pattern as with realistic vegetation, though, slightly more pronounced. The following seems to be representative observations of the real life system: (1) The significant deceleration of the flow through vegetated areas. This deceleration of the flow by vegetation is confirmed in several studies. A study by Rominger et al. (2010) [16] shows a fast gradual lateral decrease of the velocity from 0.6 till 0 m/s in a densely vegetated area. So does the study by Zong et al. (2010) [15]; they mentioned a fast lateral decrease of 0.2 m/s till 0 m/s in dense vegetation. (2) The increase in flow velocity in the channel. The increase in flow velocity in the channel is confirmed by several researchers; Rominger et al. (2010) [16] stated that the addition of vegetation on a fully developed point bar increased the velocity in the open region and Manners et al. (2014) [12] stated that vegetation expansion leads to constricted and thus increased flows.

What seems not correspond with any field observations or flow patterns described in other studies is; (1) The location of the primary eddy and secondary eddies created next to the extensively vegetated sandbar. (2) The location of the reattachment point created next to the extensively vegetated sandbar. Field and model studies like the one from Wright and Kaplinski (2011) [21], Schmidt (1990) [4] and Sloff et al. (2010) [25] describe a clock wise rotating primary eddy just downstream from the constriction and a reattachment point located at one third of the sandbar. It has to be remarked that in none of these studies the presence of vegetation is taken into account at all.

The lack of congruency can be caused by several factors. (1) The unnatural shape of the vegetated area, a nearly squared polygon. In nature vegetation expands gradually, in smooth, natural forms and does not grow in strait edges. The strait shape might enlarge the blocking effect which prevents the flow from deflecting towards the recirculation area. This provokes the development of a recirculation eddy adjacent to instead of upstream from the vegetated sandbar. Additionally, these strait edges induce a wake circulation at the downstream corner of the patch, which is the source of an unrealistic upstream flow across the sandbar. (2) Another possible reason for the disparity between studies can be the schematization of the vegetation in the model, as it is plotted under the Baptist formulas. Baptist represents vegetation as rigid, artificially uniform and unvarying cylinders, while in reality vegetation is flexible and multiform. Flexible vegetation will bend and reduce the blocking effect of the flow while flooded. In addition, according to Baptist, vegetation is uniformly distributed across the grid cells while, in reality, vegetated shrubs alternate with bare areas. This alternation might reduce the blocking effect of vegetation.

Histogram of the depth average flow velocity in different cross sections with different vegetation coverage

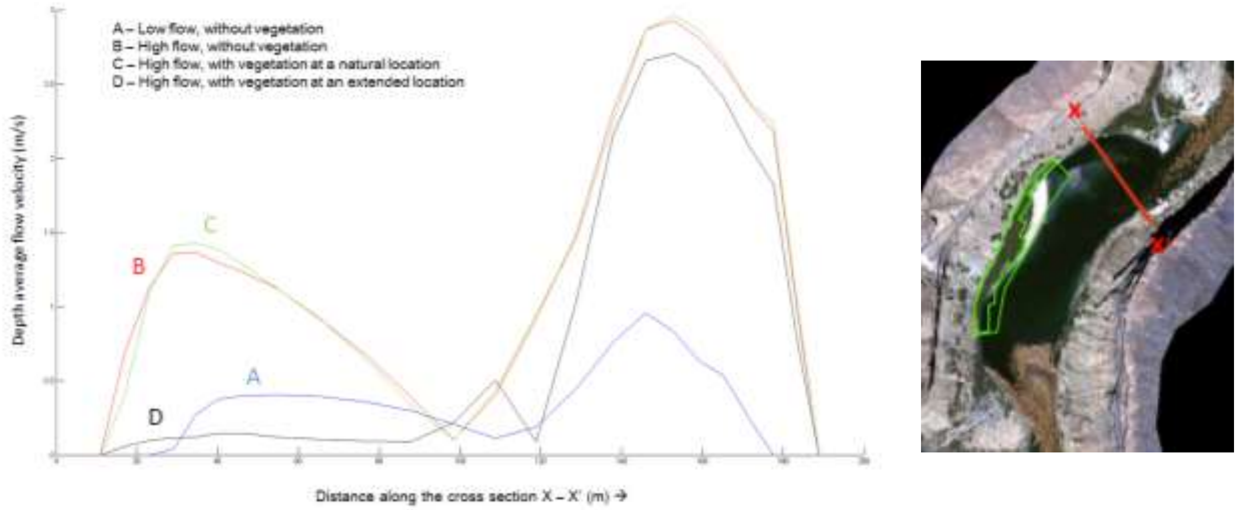


Fig. 4-7: Depth average velocity in cross section X – X'. The left side of the graph represents flow velocities in the recirculation eddy and the right side of the graph represents flow velocities in the main channel. The red line on the aerial photo indicates the location of the cross section.

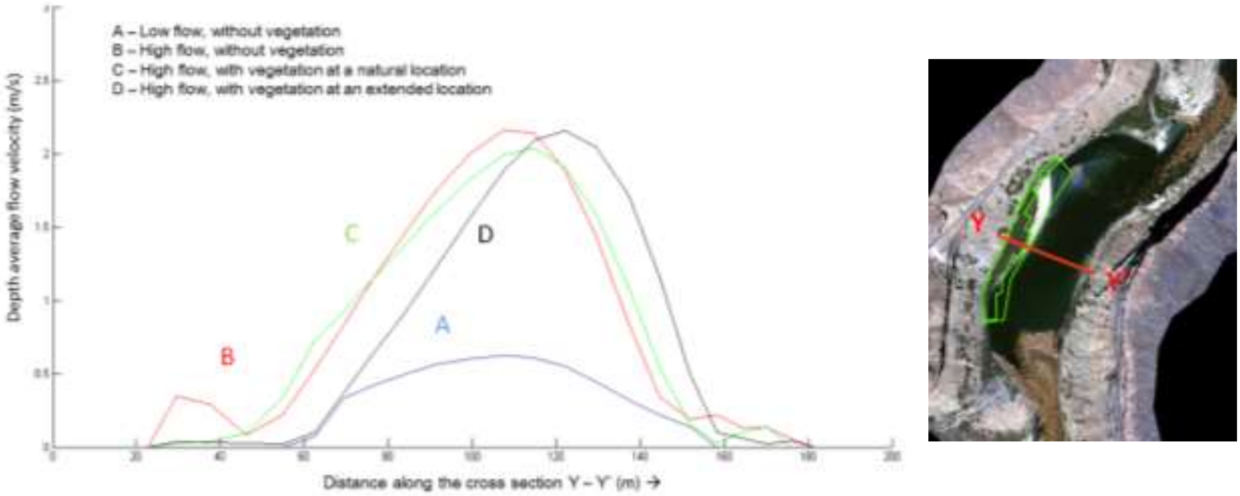


Fig 4-8: Depth average velocity in cross section Y – Y' The left side of the graph represents flow velocities in the recirculation eddy and the right side of the graph represents flow velocities in the main channel. The red line on the aerial photo indicates the location of the cross section.

To be able to make a more quantitative comparison of the depth average flow velocity on the different types of sandbars, the flow velocities at two different cross sections are depicted in figures 4-7 and 4-8. Based on figure 4-7 the following can be noted on the flow velocities in the main channel and the recirculation eddy;

- During low water without added vegetation (curve A) the maximum flow velocity in the main channel (±1 m/s) is twice as big compared to the flow velocity in the recirculation current (±0.5 m/s).
- During high water without added vegetation (curve B) the flow velocity in the main channel increases by a factor of 3 and its maximum shifts towards the inner bank (left). The flow in the recirculation current increases by a factor of 3 and its maximum shifts towards the outer bank (right).
- When vegetation is on natural background levels (curve C) the velocity in the eddy and main stream changes slightly compared to the velocities without vegetation the location of the maximum velocity slightly shifts to the right.
- When vegetation is more far-reaching (curve D) the flow velocity in the eddy is remarkably low (±0.2 m/s) while the velocity in the main stream decreases just slightly. The relatively high flow velocity (±0.5 m/s) at the interface between eddy and main stream is caused by an upstream directed flow indicated in figure 4-6.

As figure 4-8 shows the following can be seen on the flow velocities in the main channel and on the sandbar;

- During low water (curve A) the maximum velocity in the channel is ±0.5 m/s
- During high water times without vegetation (curve B) the velocity increases to a maximum of ±2.3 m/s. Next to the main stream (on the sandbar) a secondary circulation is created which results in relatively high return flow velocities (±0.3 m/s).

- When vegetation is at the natural scale (curve C) the secondary current on the sandbar seems to be supressed and the main stream is slightly more constricted.
- When vegetation is introduced at an extreme scale (curve D), the maximum velocity in the main channel is significantly shifted towards the inner bank (right) and the flow velocity on the sandbar reduces to almost zero.

Overall, the presence of vegetation causes a decrease in the flow velocity on the sandbar and in the eddy, however the velocity in the main stream is not remarkably affected by the presence of vegetation, despite expectation for the opposite. The location of the maximum velocity in the main channel is influenced by vegetation. More specifically its maximum is shifted towards the inner bank.

4.3.2 Bed level changes linked to flow structures on and around the vegetated Buck Farm sandbar

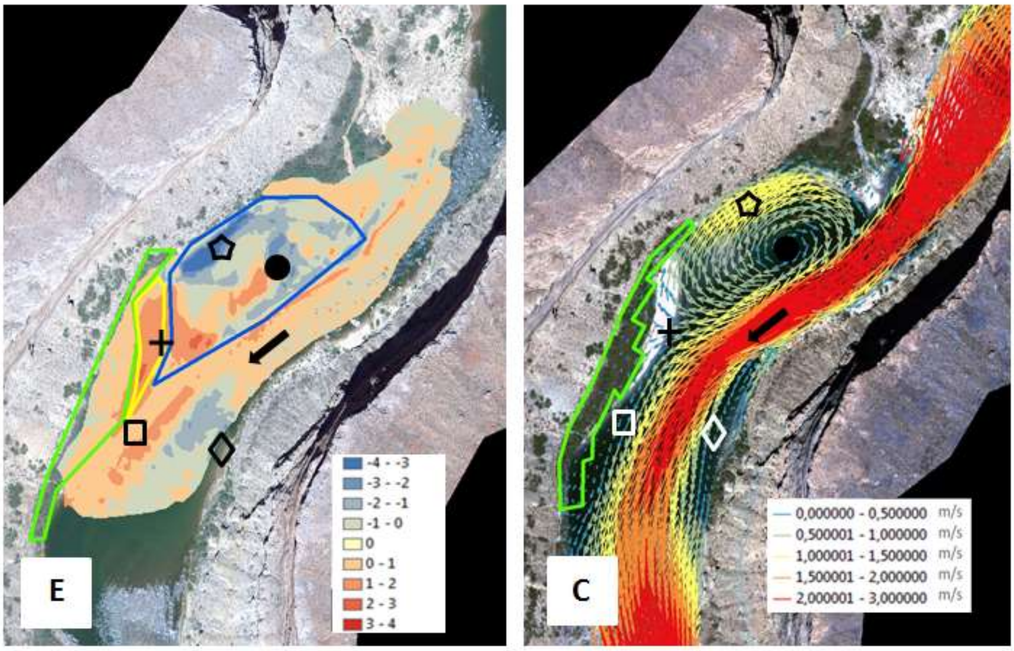


Fig. 4-9: Changes in bed level as result of high flow (E) depth average flow velocity during high flow (C)

Bed level changes as result of the 2008 flood are shown in figure 4-9 (E) and are used to assess the model results.
At locations where the flow velocity is low notable sedimentation can be observed; more specifically, near the reattachment point (cross), as well as just downstream from the eddy eye (dot), at the eddy fence and near the separation point. This relation is confirmed by Schmidt (1990) [4], he stated that sediments settle where flow velocities are low, at locations near the reattachment points, in the centre of the primary eddy, in the eddy fence and near the separation point. Conversely, at locations where the flow velocity is high and where bed sediment is present, erosion will take place. This explains the high erosion flux in the return channel (hexagon). Despite the high flow velocities in the main channel no remarkable erosion is observed apparently due to insignificant erodible bed material. The permanent high velocities in the channel hinder sediment to be stored during low water conditions. This is confirmed by Hazel Jr. et al. (2010)[5], this study states that due to a limited amount of available sediment at a discharge level below 226 m3/s little changes in bed level are visible. This relation between velocity and deposition does not apply to the elongated stretch of deposition in the main stream vegetation interface (square), where the flow velocities are high. This could be the result of an error in the modelled flow pattern. The modelled main stream is proposed to be strongly diverted towards the outer bank, which is also suggested by the erosion near the inner bank (diamond). Lesser diversion of the flow would lead to lower velocities at the interface which would explain the deposition. Alternatively, this deposition could be the effect of possible turbulence that was not accounted for in our model. Zong (2010) [15] attribute this deposition at the main stream vegetation interface to turbulence. The used modelling method, however, does not consider small turbulences. Overall, besides the assumed over-deflection of the main flow, the modelled flow pattern is found to be closely in line with the erosion-deposition pattern derived from USGS measurements.

4.3.3 Changes in erosion deposition due to vegetation growth

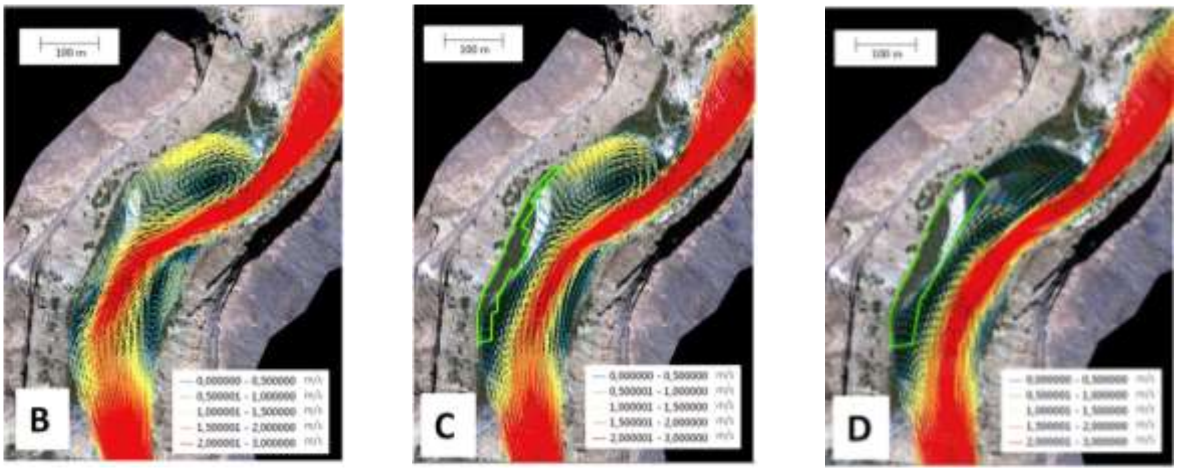


Fig. 4-10: Velocity and direction of the depth average flow in different situations. Green polygon indicates the vegetation.

Based on the modelled flow patterns (figure 4-10) an explanation is given on the influence of expanding vegetation on the bed level changes during flood events.

<u>Vegetated area on the sandbar</u>

The presence of vegetation determines the flow pattern across the sandbar which directly influences sediment transport and hence the erosion and deposition rates. A significant expansion of vegetation alters the flow pattern on the sandbar, predominantly leading to an upstream flow across the sandbar. As flow velocities stay small over time the sediment transport is expected to be moderate.

<u>Recirculation area</u>

A slight expansion of vegetation causes narrowing and shortening of the primary eddy and reduction of its flow velocity. Hence, the amount of captured sediment decreases resulting in less material available for deposition. A significant expansion of vegetation compresses and shifts the primary eddy downstream and decreases its velocity. Due to these changes, the previously developed recirculation area upstream of the sandbar turns into an area separated from the main currents and alters in a secondary eddy with very low velocities. This calm hydraulics combined with the lack of sediment supply from the main channel leads to a system with limited bed level changes.

<u>Reattachment point</u>

A slight expansion of vegetation promotes the movement of the reattachment point towards the channel, where it gets sandwiched between the extended vegetation and the main steam. The surface area for sedimentation decreases leading to a smaller amount of deposited sediment near the reattachment point. A significant expansion of vegetation causes a downstream movement of the reattachment point. This may lead to deposition downstream from the sandbar, which in the long run will lead to a downstream extension of the sandbar.

<u>Deflection of the main stream</u>

The expansion of vegetation reduces the deflection of the main steam and increases its velocity. As a result the this the areas adjacent to the outer bank become hydraulic more calm creating environments for sediment to settle, which may lead to gradual constriction of the channel. This is in line with observations by Manners et al: vegetation expansion is related to floodplain construction that is believed to lead to narrower channels and finally to a new state of equilibrium.

<u>Secondary eddies</u>

Around bare sandbars secondary eddies are most abundant. Because of their relatively large dimensions and relatively high velocities, they have the ideal features to trap sediment and therefore promote sedimentation. A photo of the scarcely vegetated Buck Farm sandbar from 1984 in Appendix F shows an elongated sandbar spreading over the outer bank and a small sandbar at the inner bank. These areas of deposition correspond with the locations of secondary eddies. A significant vegetation expansion causes secondary eddies to get compressed and sedimentation there is limited which eventually results in a shorter sandbar. No deposition is observed in the inner bank.

4.4 CONCLUSIONS AND RECOMMENDATIONS REGARDING THE MODEL STUDY

The sandbar selected for modelling is Buck Farm (mile 41.4) and arrowweed is chosen as the species for measuring because of its abundant presence, its location at the waterfront and its straightforward characteristics. Vegetation has been represented in two different formats, a natural and expanded coverage. The Baptist model assumptions are used for the representation of vegetation in the numerical model. The flow pattern appeared to be adequately simulated, unfortunately this did not apply for the calculation of bed level changes. Therefore we focused on the influence of vegetation on the flow pattern, the influence of vegetation on the bed level changes is only discussed.

4.4.1 Conclusions

Three different scenarios are modelled. In the first scenario the flow pattern at low and high flows on and around a sandbar were compared. An increase in discharge led to the movement of the separation point in the direction of the shore. Increases in the surface area of the main flow had as a result the shifting of the reattachment point towards the shore and slightly downstream. Moreover the increase in discharge led to an increase of the flow velocity of the primary recirculation eddy and the development of a secondary eddy upstream from the primary eddy. Various field studies verify these findings. Revealed in the model, but not directly observed in the field, is the widening of the primary eddy and the development of several secondary eddies. This disparity might be explained by the difference in the geometry of the studied (Wright and Kaplinski, 2011 [21]) and modelled river stretch.

In the second scenario, the flow patterns at high flow on and around a sandbar with and without vegetation were compared. When vegetation was added the following patterns altered: the main flow became less deflected by the bedrock wall, the main flow became more constricted, the reattachment point shifted towards the channel, the recirculation eddy became narrower and shorter with lower flow velocities and the 'separation' eddies decreased in size and velocity. As an overall statement we can say that in the vegetated areas the flow velocity reduced significantly, as expected. These findings are in line with the results of several studies, showing a significant deceleration and diversion of the flow in the presence of vegetation.

In the third scenario, the flow pattern at high flow on and around a sandbar with realistic vegetation was compared with the flow on and around a sandbar with extended vegetation. The model showed that in the presence of extended vegetation the deflection of the main flow was further diminished, the main flow became even more constricted and the primary recirculation eddy moved downstream alongside the vegetated area. The compressed primary recirculation eddy was characterized by low velocities. Additionally, a large secondary eddy arose upstream from the vegetated sandbar and the reattachment point moved downstream creating a wake circulation. There seem to be threshold where the primary recirculation eddy gets completely blocked by the vegetation and significantly alters the recirculation at high flow.

The modelled flow pattern on and around the sandbar with natural realistic vegetation was found to be closely in line with the bed level change measured by the USGS. More specifically, the model showed low flow velocities at location with notable sedimentation based on the measurements of the USGS. In addition, at locations were the modelled flow velocities are high and sufficient bed sediment is available (i.e. in the recirculation zone), erosion took place. Though insignificant bed level changes are experienced at locations were the modelled flow velocities are high yet no bed sediment is available (i.e. the main channel). Unfortunately, the relation between flow velocity and bed level change did not apply to the interface between the main stream and the vegetated area. In this area, an elongated stretch of deposition is visible despite the high modelled flow velocities. This discrepancy can be explained by an unrealistic deflection of the modelled main stream (too far towards the outer bank) or by turbulence, which is not simulated in the model.

4.4.2 Recommendations

The influence of the vegetation abundancy on the flow pattern in the Colorado River is represented satisfyingly in our model study. However some components in this research can be improved in the future.

In natural circumstances vegetation appears in gradual, smooth forms. In the model, however, the extended vegetation is implemented by means of straight edged polygon shapes, which has an effect on the representation of the flow pattern in the model. As a future reference on model development, it is recommended to strive for a vegetation schematization as realistic as possible. Given the time frame of this project the achieved simulation of vegetation coverage in simplified squared polygons is assessed as reliable. Moreover, arrowweed is simulated using the Baptist formulas, which represent vegetation as rigid, straight forward cylinders, while in reality vegetation is flexible and multiform. In addition, according to Baptist, vegetation is evenly spread across the grid cells whereas in reality vegetated shrubs alternate with non-vegetated areas. Either any flexibility of the plants or the alternation with bare areas could have diminished the blocking effect of vegetation. In future research it is recommended to investigate other vegetation formulations in order to get a more consolidated idea of the ruling mechanisms in the system, i.e. formulations that take into account the flexibility of the stems. However, until now, Baptist seems to be the most reliable. Additionally, it is recommended to reduce the size of the grid cells which enables a more accurate differentiation between characteristics of vegetated and bare patches.

The hydraulics on and around the sandbar are well modelled using Delft3D. Nevertheless some discrepancy in the modelling of the bed level changes is to be seen. This seems to be the result of incorrect input values due to incorrect assumptions or insufficient data. A sensitivity analysis was performed and the following adaptations are recommended; reduction of the inflow sediment volume, reduction of the grain size of inflow sediment and modification of the sediment thickness of the bed. In addition, calculations in 3D are recommended in order to reduce discrepancies. Generally, 3D analyses outcompete 2D calculations as they provide more detailed information, namely take into account processes which take place at different depths. Regarding the pre flood bed level, data from a series of locations was missing. The missing parts were added assuming a critical flow in the rapids or were calculated by means of interpolation. Due to the large size of the grid cells, the results of the interpolation showed some inaccuracy. To tackle this it is recommended to reduce the size of the grid cells.

Lastly, by means of the Delft3D software the influence of vegetation on the hydraulics in a river stretch can be illustrated in many ways and many factors can be assessed. In this research only the depth average flow velocities were taken into account. For future researches it is advised to investigate the effect of vegetation on different hydraulic factors, for example, evaluating the influence of vegetation on the downward secondary eddies by means of 3D calculations.

5 OVERALL CONCLUSIONS AND RECOMMENDATIONS

The answers on the research questions stated in chapter 1 are based on combining observations gained during the research process, literature review and the knowledge gained during the study civil engineering. This chapter concludes with recommendations on whether or not maintaining riparian vegetation and it gives suggestions on potential study subjects to improve the overall understanding of interdependency between vegetation expansion and sandbar dynamics.

5.1 CONCLUSIONS

Does vegetation contribute to stabilization of the sandbar and potentially also contribute to its growth?

Vegetation inarguably contributes to the stability of sandbars. That is demonstrated in different ways within this research. Firstly, the bed level changes during a flood event in vegetated areas are insignificant (figure 3-19). Moreover are the changes in morphology of the sandbar small at locations where vegetation is present, especially at the larger scale (figure 3-19). Lastly, in the long run, densely vegetated sandbars seem to be more stable than bare sandbars (figure 3-5). Vegetation clearly contributes to the growth of sandbars too. In this research this is demonstrated in different ways. First of all is on some sandbars the vegetation expansion proportional to the increase of the sandbar volume itself (figure 3-19). More specifically, vegetation seems to be the result of sandbar growth while in some cases the reverse phenomenon is to be observed. Mover exist a rather linear relation between sandbar volume change and change in the size of the vegetated area (figure 3-18).

What can be the cause for the difference in vegetation degree across the various sandbars?

The overall development of a sandbar with different degrees of vegetation is the result of more than one factor and the interdependency between them. Hydraulic forces, which are strongly related to the width of the channel, determine the magnitude of erosion fluxes and thus the sediment transport rates. The submersion depth during flood, which is logically related to the elevation of the sandbar, also determines the sediment transport rates. Sandbars which develop in narrow channels stay low in elevation (deposition fluxes equal erosion fluxes) and are dynamic (high sediment transport fluxes); these two factors obstruct the natural succession of vegetation (figure 3-22). Sandbars which develop in wide channels become high in elevation (the vegetated parts of the sandbar reach an elevation near the maximum flood stage and the deposition fluxes are larger than the erosion fluxes) and become stable (moderate sediment transport fluxes); these two factors promote vegetation growth (figure 3-23). Moreover, on such sandbars, vegetation acts as a sediment trapping agent and consequently supports sandbar growth. This controls the shape of the channel and which eventually narrows the channel which on its turn affects the hydraulic forces developed within. Eventually, equilibrium may be reached, in which case a sandbar may remain constant in volume and with a fixed vegetation coverage. Yet, it is not clear if sandbars are still adjusting to changes in the flow and sediment regime.

What is the influence of vegetation expansion on the flow pattern on and around the sandbar and consequently on the geo-morphological changes?

Based on the model study the following can be stated regarding the flow pattern on and around the vegetated sandbar (chapter 4). Vegetation blocks the flow which leads to insignificant bed level changes in the vegetated area itself. Moreover causes vegetation narrowing and shortening of the primary eddy and the reduction of the flow velocities developed within. Consequently, the amount of captured sediment decreases resulting in less material available for deposition. Furthermore, vegetation promotes the movement of the reattachment point towards the channel. The vegetated part of the bar thus decreases the area for potential sedimentation which likely reduces the amount of deposited sediment near the reattachment point. Moreover, vegetation reduces the deflection of the main stream and increases its flow velocity. In this way additional ground for sediment to settle becomes available near the edge of the vegetated bar, which may lead to further constriction of the channel. Finally, the deflection of flow and narrowing of the channel by vegetation compresses secondary eddies which may limit sedimentation at these locations. The aforementioned changes in the morphology of the sandbar are likely to influence vegetation succession itself. This feedback, however, has not been thoroughly investigated.

What will be the expected long term lay out of the Colorado River system when no measures on vegetation are taken?

As explained before, extensively vegetated sandbars in relatively wide channels will gradually increase in height to near the maximum flood level at which time their volume will likely stabilize. Consequently, during subsequent floods they will not get significantly inundated and therefore will only minimally contribute to the sediment exchange due to their enhanced elevation. This minimal sediment exchange between the eddy and main channel may result in more sediment availability in the remaining parts of the river system. Higher deposition rates during floods are likely in narrower stretches of the river where bars are more dynamic. If vegetation expands on parts of sandbars that are now dynamic and scarcely vegetated, the growth of vegetation will likely promote stabilization and vertical accretion, creating a feedback toward a higher elevation and more stable sandbar. The expected long term result is a river system with a significant part of the sandbars becoming high in elevation, less dynamic and vegetated. Continued monitoring is necessary to determine whether changes in vegetation extent on sandbars are stable, increasing, or decreasing through time.

5.2 RECOMMENDATIONS

The iconic feature of the Colorado River during the pre-flood period, namely the open dynamic sandbar system, is currently replaced by a more vegetated river system with less open sand. One geo-morphological characteristic of the post-dam period is the presence of stable, vegetated sandbars. A decision upon the fate of vegetation across the Colorado River has to be taken. On one hand, vegetation provides riparian habitat for a variety of species. On the other hand, vegetation decreases the open sand area available for recreation uses. If the restoration of the more historical dynamic sandbar system is desired, then two alternatives are theoretically available. (1) Significantly increase the dam releases in order to create strong currents that will remove the excessive vegetation on the sandbars, such as occurred during the 1980s floods. The advantage of this option is that it would scour vegetation from the entire river corridor with minimal mechanical removal. Unfortunately, low reservoir levels in Lake Powell preclude releases greater than the maximum controlled flood (1274 m^3/s). (2) Alternatively, eradication campaigns could be organised to mechanically uproot vegetation, which has been implemented along other parts of the Colorado River corridor. This is a more selective way of removing vegetation though likely more expensive than the flood management option. If a steady state system with stable sandbars is desired, the on-going flood regime should be maintained. The advantage of such a river system is that sand is stored up high and ecosystem services are promoted. More specifically, riparian vegetation is a great natural calibrator of the geo-morphology of the system and promotes the welfare of a variety of species, mainly fish and bird populations. The final decision should be taken upon weighting of the relative importance between scenarios and future planning.

A suggestion to improve the overall research is to take into account for several other aspects that determine the ability of vegetation to expand such as the availability of groundwater, the daily exposure to sunlight, the fertility of the soil and the activity of the local species. If the effect of these parameters on the expansion of vegetation across the sandbars gets integrated in the interdependency between sandbar and vegetation dynamics then the result will give a solid picture of the natural system and the existing good outcome of our research will get even more strengthened.

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APPENDICES

APPENDIX A - LIST OF MEASURED SANDBARS BY USGS

River mile	Name site	Reattachment bar whether or not	Vegetation coverage 2008	Investigated sandbars
2.5	Cathedral Wash	x	x	
8.1	Below Jackass			
8.9	9 mile	x	Scarcely	(not enough data)
16.6	Hot Na Na Wash			
22	Twenty Two Mile	x	Scarcely	(not the right location)
23.6	Lone Cedar			
29.5	Shinumuo Wash			
30.7	Sand pile	x	Scarcely	x
31.9	South Canyon			
33.3	Redwall Cavern	x	x	
35.1	Nautiloid	x	x	
41.4	Buckfarm	x	Intermediate	x
43.4	Anasazi Bridge			
44.6	Eminence	x	Intermediate	x
45	Willy taylor	x		
47.6	Lower Saddle	x	Intermediate	
50.2	Dinosaur	x		
51	Fiftyone Mile Camp	x	Densely	x
55.9	Kwagunt Marsh	x	Densely	x
56.6	Kwagunt Beach			
62.9	Crash Canyon	x	?	
65.2	Carbon	x	Intermediate	x
68.8	Tanner			
70.1	Basalt	x	x	
81.8	Grapevine			
84.6	Clear Creek	x	x	
87.6	Cremation			
91.8	91 mile			
93.8	Granite			
104.4	Upper 104 mile	x	x	
119.4	Big dune	x	Intermediate	x
122.7	122 Mile camp	x	x	
123.3	Upper forster	x	Intermediate	
137.7	Football field	x	x	
139.6	Fishtail			
145.8	Above Olo	x	x	
167.2	Lower National			
172.6	Below Mohawk	x	Intermediate	(not enough data)
183.3	Below Chevron	x	Intermediate	(not enough data)
194.6	Hualapai Acres	x	Densely	(not enough data)
202.3	202 mile	x	x	
213.3	Pumpkin springs			
220.1	Middle 220			
225.5	Above last chance	s	x	

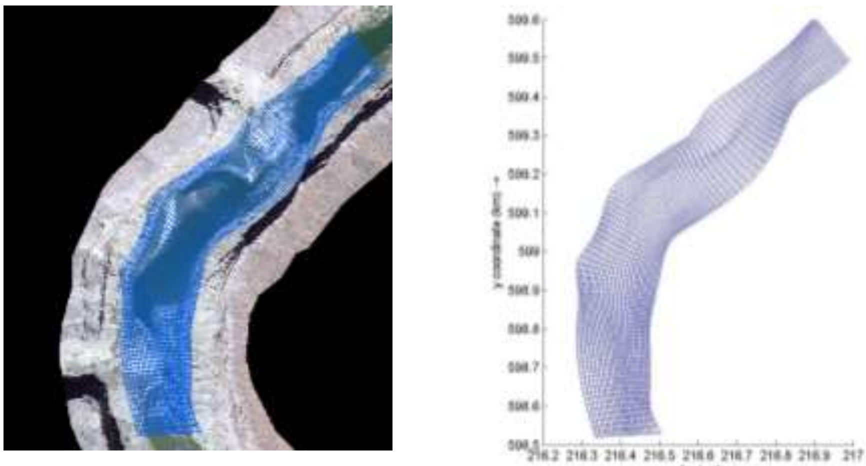
APPENDIX B - EXTENSIVE ELABORATION OF THE MODEL SET UP

Dimension

An important choice is the dimension of the model, 2DH (depth averaged) or 3D. In both dimensions the model uses the hydrostatic pressure assumption instead of the vertical momentum equation. This means that the vertical accelerations are assumed to be small compared with the gravitational acceleration. The model in 2DH uses the vertically depth averaged approach, a constant velocity profile over the depth instead of a real logarithmic velocity profile. In the 3D version differences in the vertical can be applied. A number of horizontal layers over the vertical allow vertical differences in the velocity to simulate the velocity profile.
Baptist’s formulations are well suited to represent vegetation in a model. Its formulations calculate in 2D. That’s the reason why chosen is to start with the 2DH model. Broadening to 3D is still possible and might improve the results by taking more processes into account, but it will increase complexity and modelling effort.

Spatial scale

The modelled area is a stretch of 1200 m by 120 meter and covers one pool and two rapids. The area chosen to model is somewhat larger than the area of interest to prevent errors, intruding from the boundaries and from interfering with the phenomena at the places of interest. On the other hand the area chosen to model may not be too large; this not only to avoid input errors from unimportant parts but also to save computation time. A coarse curvilinear grid of 100 x 30 grid cells of about 12 x 4 m is constructed. The longitudinal grid lines follow the stream of the river and the cross sectional gridlines reach from bank to bank. The cells in the area of interest are relatively large. This can be justified by the uniformity of vegetation. No differentiation in vegetation parameters per cell has to be added.



(Left) Modelled area includes a sandbar in the centre, two constrictions and a pool around the sandbar. (Right) Curvilinear grid, 100 by 30 cells, each 12 by 4 m

Temporal scale

The objective of the model is to investigate the processes happening during a flood event. The time period for modelling should meet two conditions: the occurring of a flood and the availability of sufficient data from that period. Chosen is to run the model from 03-03-2008 till 12-03-2008, 9 days, including three days of low water, three days of high water and finally three days of low water.
The time step for the model is calculated by means of the courant number (CFL):

$$CFL = u \frac{dt}{dx \text{ or } dy}$$

Where u the current velocity [m2/s], dt the computational time step [s], dx and dy the grid sizes in x and y direction [m]. By keeping the courant number below 10 the computation will be stable. A time step of 0.1 [s] is appropriate and used for the simulations: small enough to ensure stability and large enough to avoid long simulation times.

Initial conditions

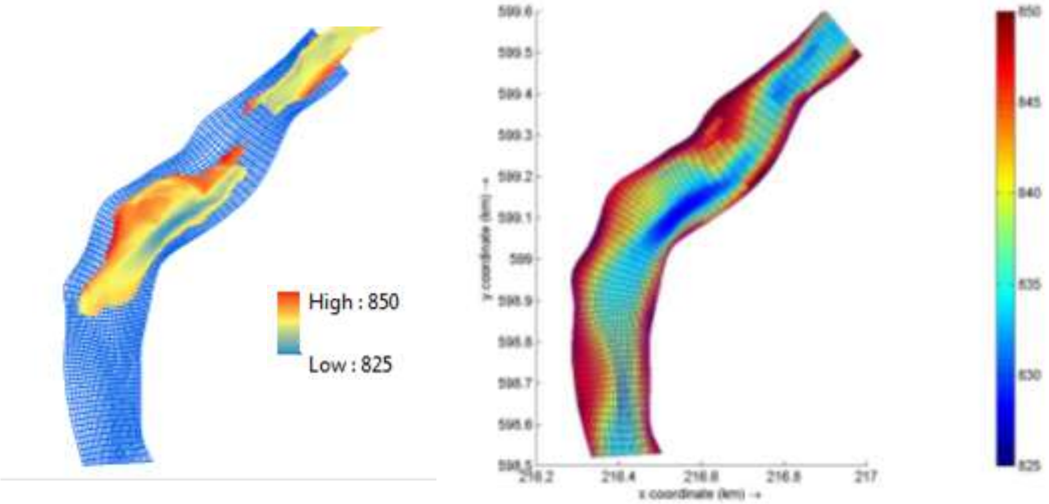
An initial condition is the input value to start the model. In this model initial values are given to water level, bed level, bed roughness and bed thickness. It has to be admitted that lots of assumptions and estimations are made; this has to be taken into consideration in the model results.

The initial water level has to be entered in the model. To reduce initial fluctuations the initial water level should be as close as possible to the boundary water level. Based on water level data this value is set as a constant over the whole stretch: 841.1 m above mean sea level.

Furthermore the initial bed topography has to be indicated. It includes shallow areas at rapids and deep (on to 15 meters) areas in the pools. The bed topography data is partly obtained from USGS. Data of the rapids and of some parts downstream of the sandbar are missing; they are estimated. The bed topography of the rapids is estimated by assuming a critical flow in the rapids. Critical flows have Froude numbers equal to 1 (eq. 5-2).

$$Fr_{critical} = \frac{u}{\sqrt{gh}} = 1$$

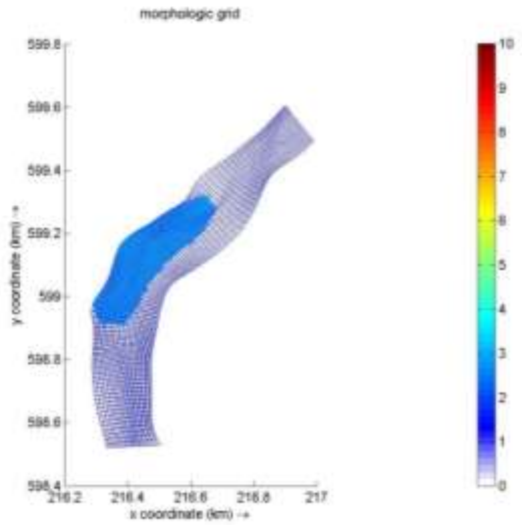
Where u is the velocity [m/s], g the gravitational acceleration [m/s^2], h the water depth [m]. The missing bed topography downstream from the sandbar is estimated by means of interpolation and checked by comparison with similar areas in other pools.



(Left) Bed topography (elevation above mean sea level) from data receive by USGS. (Right) Supplemented model bed topography (elevation above mean sea level)

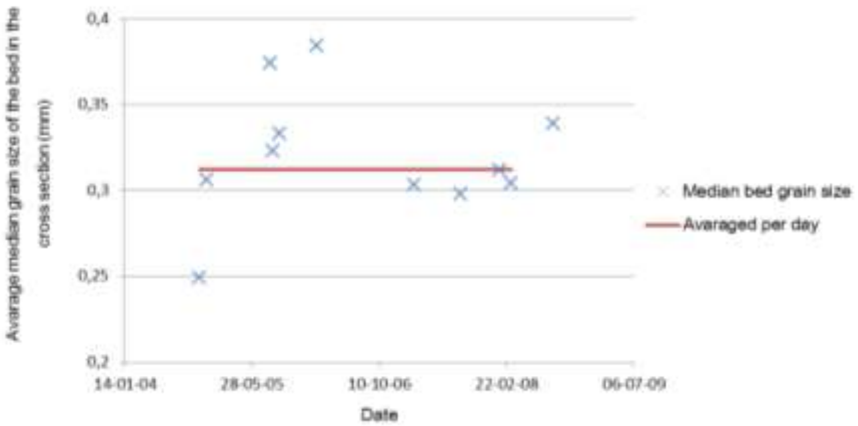
Another initial value that has to be entered is bed roughness. The rocky areas in rapids and main stream have a higher roughness value than the sandy areas in the hydrodynamics quiet zones. For simplification the initial bed roughness is assumed to be uniform over the whole stretch and is calculated by means of the Chézy formula. A Chézy value of 50 [m½/s] is calculated.

In the model a value of the thickness of the bed has to be allocated, indicating the thickness of the erodible and accretable part of the bed. Sediments in the channels are coarser and less movable compared to sediments at the sandbars. To simplify, only at the sandbar area, the location of interest, a thickness layer has been applied: 3 meter, the maximum measured erosion-accretion value. At the remaining locations a thickness layer of zero is applied.



Modelled initial bed thickness

As default values for wet bed density and dry bed density the values 2650 kg/m3 and 1600kg/m3 respectively, are applied.
As default value for grain size of the bed sand the median grain size derived from measurements of physical samples at 30 mile is applied: 0.312 mm.



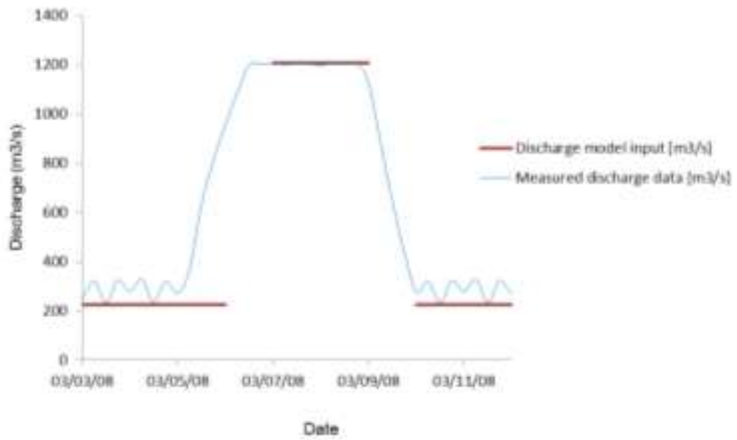
Median grain size of bed (data USGS) at 30 mile

Boundary conditions

The lateral boundaries, the left and right border are assumed to be closed. The longitudinal boundaries, the up and downstream border of the model, are open. At the upstream boundary a discharge and at the downstream boundary a water level is applied.

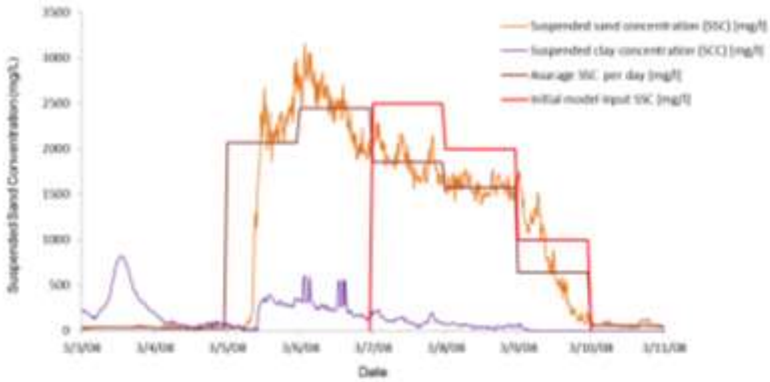
<u>Upstream conditions</u>

At the upstream boundary a discharge and a suspended sediment volume are imposed. At 30 mile (11 mile upstream from Buck Farm sandbar) the nearest GCMRC measurement station is located. Data from this station, measured by acoustic techniques and physical samples on frequent basis, are used as input data for discharge amounts and suspended sediment volumes.
The figure below shows the measured flood, which lasted approximately 3 days and swelled from an average discharge of approximately 250 m3/s to a peak discharge of 1200 m3/s. The values entered in the model are a low water discharge of 226.53 m3/s and a high water discharge of 1206.6 m3/s.



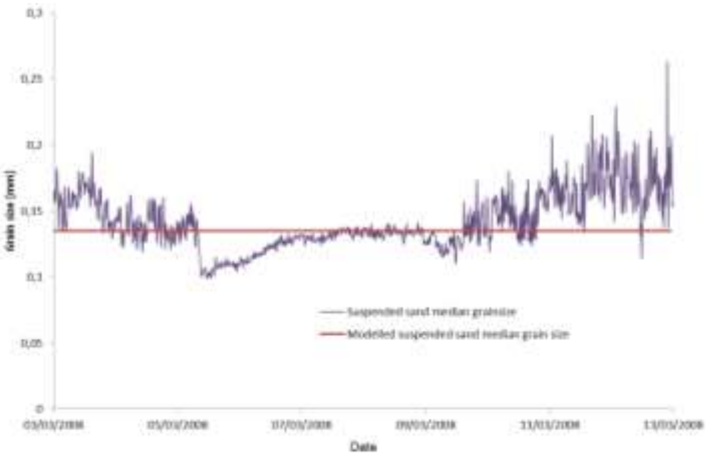
Upstream discharge, measured and modelled

Suspended sediments can be divided in fine sediments (clay) and coarse sediments (sand). The figure below shows the measured and modelled suspended sediment inflow volumes. The suspended clay concentration is significantly lower than the suspended sand concentration. In the light of simplification, only the suspended sand concentration is implemented in the model. Furthermore, the figure shows a negligible concentration suspended sand during low water and a significant increasing amount during high water, which gradually decreases during the flood period. The concentration of the suspended sediment entering the reach has a significant impact on the final topography.



Measured and modelled suspended concentration inflow volume

The figure below shows the grain size (D50) of the suspended sand during the flood. In the model the average size of 0.135 mm is taken during the whole flood period, the average of the measured median grain sizes.



Measured and modelled suspended sand median grain size

Downstream conditions

As downstream boundary a water level is imposed, calculated by means of Qh- relations [26]. These are available at locations just upstream (41.3 mile) and downstream (43.4 mile):

$$h = 839.6944 + 0.0059Q - 1.1409 \cdot 10^{-4} \cdot Q^2$$

$$h = 838.3170 + 0.0072Q - 1.9473 \cdot 10^{-6} \cdot Q^2$$

The water level at the downstream boundary (42 mile) is derived from the water level gradient calculated by means of the Qh relations, resulting in a water level of 841 m during low water and 845 m during high water.

Sediment transport formula

Many sediment transport equations exist, all with their own specific application area. They define sediment transport as a function of gravity, fluid characteristics, sediment characteristics and parameters describing the influence of the flow.

$$s = (g, \rho, v, \rho_s, D, \tau_b) \quad \text{[m3/s]}$$

In Delft3D most of the sediment formulas could be applied. The sediment transport formula by van Rijn (1984) makes an explicit distinction between bed load and suspended load transport. The sediment transport in the Colorado River is an addition of both types of load transport, so is decided to start with van Rijn's formula.

$$s = s_b + s_s \quad \text{[m3/s]}$$

Suspended sediment transport

The formula concerning the suspended load transport (s_s), the sediment transport in the water column, reads:

$$s_s = Fuhc_a \quad \text{[m3/s]}$$

Where u is the depth averaged velocity [m/s], h the water depth [m], F the dimensionless shape factor [-] and c_a the sediment concentration at the reference level a (distance measured from the bed). In Van Rijn's formula the sediment concentration at the reference level has significant effect on the outcomes. This sediment concentration at the reference level is defined as:

$$c_a = 0.015\,\alpha_{cal} \frac{D_{50}}{\xi_c} \frac{T^{1.5}}{D_*^{0.3}}$$

Where D* is the dimensionless parameter for the grain diameter [-], T a transport parameter derived from the bed shear stress, ξ_c the reference level [m], D_{50} the diameter of the grain size [mm] and α_{cal} a calibration coefficient. The dimensionless parameter for the grain size (D*) reads:

$$D_* = D_{50} \left(\frac{\Delta g}{v^2}\right)^{1/3}$$

The transport parameter T is a function of the critical bed shear stress for the start of motion according to Shields (τ_{bcr}) and combined with the bed shear stress related to the bed roughness and the velocity:

$$\tau_b = \frac{\rho_0 g u^2}{C^2}$$

Bed load transport

The formula considering the bed load transport (s_b), the sediment transported over the bed layer, reads:

$$s_b = \phi_b \sqrt{\Delta g D_{50}^3} \quad \text{[m3/s]}$$

Where ϕ_b is a parameter depending on the bed shear stress and the dimensionless parameter for the grain diameter, Δ the relative density [-], g the gravitational acceleration [m2/s] and D50 the grain size diameter [mm]. The parameter reads;

$$\phi_b = 0.1 \frac{T^{2.1}}{D_*^{0.3}}$$

Entered parameters

In Van Rijn's formula the following values have to be entered: calibration coefficient (α_{cal}),a parameter which influences the amount of suspended sediment transport is taken as 1.5, the reference level (ξ_c) is chosen to be 0.01 and the fall velocity (w_s [m/s]) is depending on the grain size and not necessarily to be entered and is taken as 0.013 [m/s]. The diameter of the suspended sediment of 0.135 (mm) results in a fall velocity of approximately 0.013 (m/s).

Turbulence

The majority of flows encountered in nature are turbulent flows. Due to its complexity it is hard to come up with a precise definition of turbulence. An attempt is made by Hinze [27] "Turbulent fluid motion is an irregular condition of flow in which the various quantities show a random variation with time and space coordinates, so that statistically distinct average values can be discerned" [27]**.** In the model the turbulence is taken into account by applying the horizontal large eddy simulation (HLES). The HLES only resolves large scale turbulent eddies. Small scale turbulent eddies are not considered. Because the large scale eddies contain the greatest part of the turbulent energy and the dynamics of large scale motions are of main importance in the river situation, the omission of the influence of the small scale turbulences can be justified.

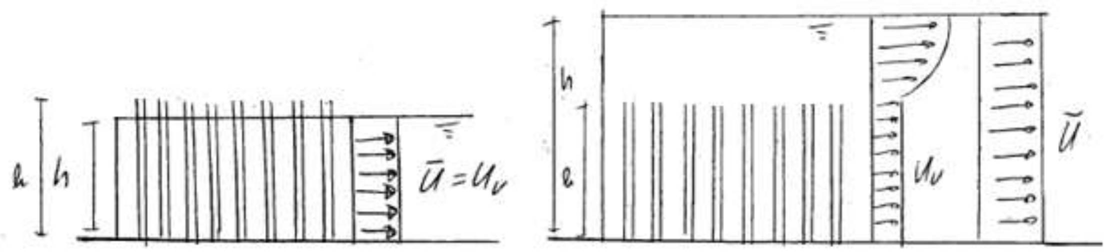
APPENDIX C -ASSUMPTIONS AND EQUATIONS BAPTIST MODEL

The numerical model that will be used in this thesis is the hydrodynamic and morphodynamic model Delft3D. To implement vegetation in the Delft3D model different methods can be used. Baptist et al. (2005; 2007) relates vegetation dimensions to bed roughness and composed an equation in which vegetation is valued by means of bed roughness. This method is used in this thesis and the assumptions and equations are explained below.

Baptist schematizes vegetation as a set of rigid cylinders having a height (k), density (m), stems diameter (D) and drag coefficient (C_d). The flow velocity through the plants is assumed to be uniform in the vertical. Baptist differentiated the shear stress in a bed shear stress (τ_b) and the shear stress due to the vegetation (τ_v). The total bed shear stress (τ_t), the sum of both is schematized equal to:

$$\tau_t = \rho g h i = \tau_b + \tau_v$$

Where ρ is the water density (kg/m^3), g the gravity acceleration (m/s^2), h the water depth (m) and i the slope of the water surface (-), Moreover makes Baptist a distinction between partially and fully submerged vegetation. In partially submerged vegetation the water height is lower than the height of plants. In fully submerged vegetation the water height is equal or higher than the plant height. The velocity profile through this vegetation is divided in two zones: a zone of uniform flow, u_v (m/s) inside the vegetated part and a zone with a logarithmic velocity profile u_u (m/s) above the vegetation.



Velocity profile in partially submerged vegetation and fully submerged vegetation (according to Baptist)

Bed load transport capacity is a function of the bed shear stress (τ_b). The bed shear stress is related to the near bed velocity and the Chézy value. The near bed velocity on its turn is depending on the degree of submersion. In partially as well as fully submerged vegetation the flow velocity near the bed is reduced this results in a reduction of the bed load transport. The Baptist formula calculates the roughness caused by vegetation; consequently it only takes into account bed load transport.

Partially-submerged vegetation

In partially-submerged vegetation, the flow velocity through the plants is equal to the reach averaged velocity. In this case the bed shear stress and the vegetation shear stress can be represented as:

$$\tau_b = \frac{\rho g}{C_b^2} u_v^2 = \frac{\rho g}{C_b^2} \bar{u}^2$$

$$\tau_v = \frac{1}{2} \rho C_D m D h u_v^2 = \frac{1}{2} \rho C_D m D h \bar{u}^2$$

Where ρ is the water density, g the gravitational acceleration, u_v the velocity near the bed, $\bar{u}$ the reach average velocity, C_b the Chézy coefficient of the alluvial bed, C_D the drag coefficient of the vegetation structure (-), m the number of cylinders per unit area (1/m^2) , D the diameter of cylinders (m) and h the water depth.

To indicate the resistance to the flow by the partly-submerged vegetation, the Chézy coefficient (C_{ps}) is represented as a function of various features of vegetation. This Chézy coefficient is calculated by combining eq 2.7 and 2.8 with the assumption that $\bar{u} = u_v$.

$$\bar{u} = u_v = C_r\sqrt{hi} = \sqrt{\frac{1}{\frac{1}{C_b^2} + \frac{C_D m h}{2g}}}\sqrt{hi}$$

Fully-submerged vegetation

In case of fully-submerged vegetation, it is assumed that the flow velocity is uniform between the plants (u_v) and has a logarithmic profile above the plants (u_u). The uniform flow between the vegetation can be represented by:

$$u_v = C_{fs1}\sqrt{hi} = \sqrt{\frac{1}{\frac{1}{C_b^2} + \frac{C_D m k}{2g}}}\sqrt{hi}$$

In contrary with above mentioned equation (eq 2.9), the water depth (h) is replaced by the plant height (k). These qualify the new flow velocity between the plants (u_v). Because k > h the flow velocity between fully submerged plants will be lower than the flow velocity in partially submerged plants.

To calculate the reach averaged velocity in fully submerged vegetation another Chézy value is used (C_{fs2}) and is represented in eq 2.11. In this equation, in case the highness of the water equals the highness of the vegetation (h = k), the first term on the right-hand side equals the representative roughness for partly-submerged vegetation and the second term will be 0.

$$\bar{u} = C_{fs2}\sqrt{hi} = \left(\sqrt{\frac{1}{\frac{1}{C_b^2} + \frac{C_D m k}{2g}}} + \frac{\sqrt{g}}{\kappa}\ln\left(\frac{h}{k}\right)\right)\sqrt{hi}$$

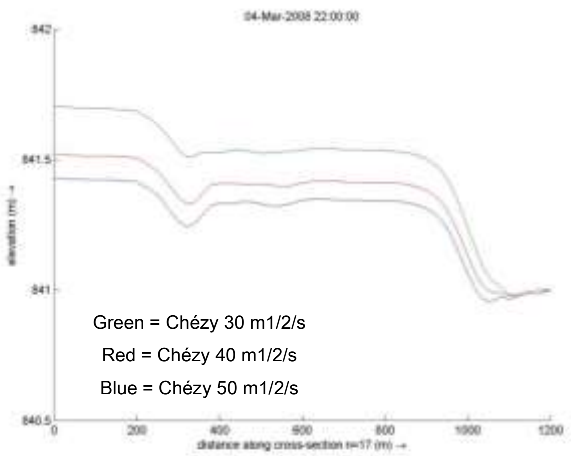
When comparing the Chézy coefficient for the depth average velocity for partially and fully submerged vegetation the Chézy coefficient of partially submerged vegetation (Cps) is smaller than the Chézy coefficient of fully submerged vegetation (Cfs2).
This supports that partially-submerged vegetation offers higher resistance to the depth average flow than fully submerged vegetation.

APPENDIX D - HYDRODYNAMIC CALIBRATION

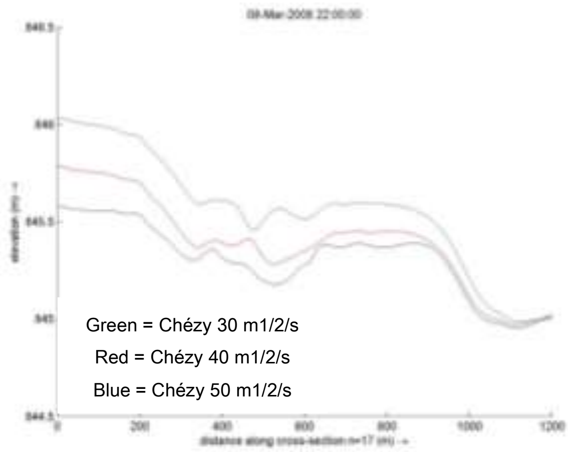
The first run intended to investigate the hydrodynamics had the following results: eddy and reattachment area were imaged in a correct way, but other features were not imaged in a realistic way. The water level is too low, deviant hydraulic features at the downstream end were present and the depth average velocity curve showed deviant oscillations. To reduce or even eliminate these errors several adaptations have been made.

Water level

The water level gradient is related to the bed roughness. The water level gradient is compared with literature data Schmidt n.d.) measured an average water level gradient of 0.0015, flattening in pool areas (0.0005) and steepening in rapids (0.01). In the model the water level gradient didn't match these data and had been modified by adjusting the bed roughness, the Chézy value. The figure below shows the different water levels as result of the input of different Chézy values. A Chézy value of 40 $m^{1/2}/s$ creates a water level gradient that matches the data best.



Water level during low water, 04 march 22:00

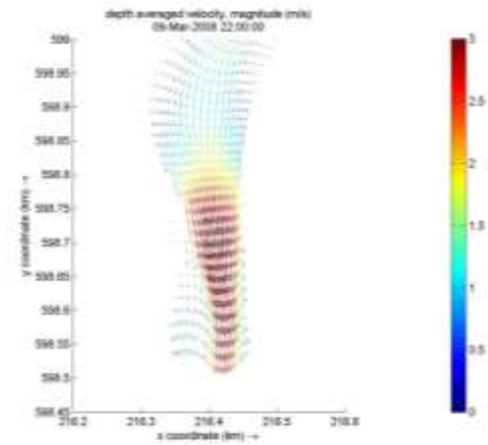


Water level during high water,

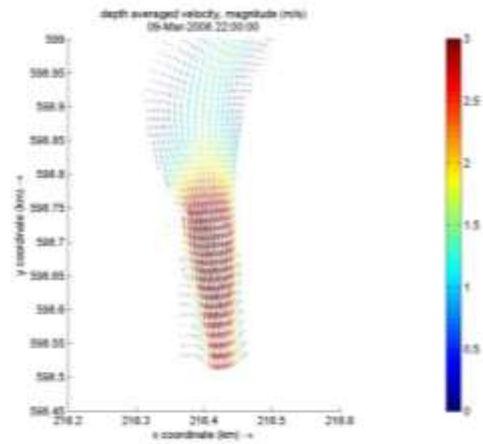
Identification Chézy coefficients

Water reflection

At the downstream end the model shows deviant hydraulics: especially during high flow: the water seems to be reflected, which provokes oscillations. This was encountered by changes of grid and bathymetry downstream and by adding a reflection parameter. The grid was more specifically adapted to the channel shape and the bed topography downstream was deepened. Furthermore a reflection parameter of 100 has been added.



Before adaption. Depth average velocity at the downstream boundary during flood. At the left side of the downstream boundary a reflected flow is visible.



After adaption: Depth average velocity at the downstream boundary during flood

Depth average velocity and direction at the downstream boundary

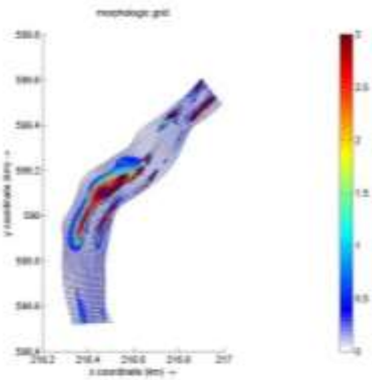
APPENDIX E - MORPHODYNAMIC SENSITIVITY ANALYSIS

Suspended inflow sediment

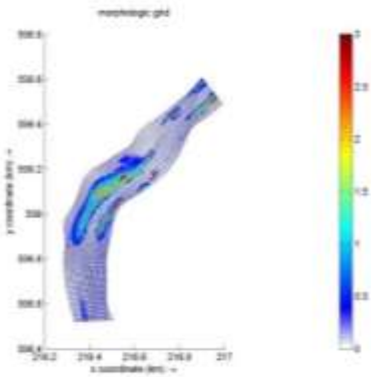
The influence of the inflow of suspended sediment is investigated by varying the inflow volume and the grain size.

Volume

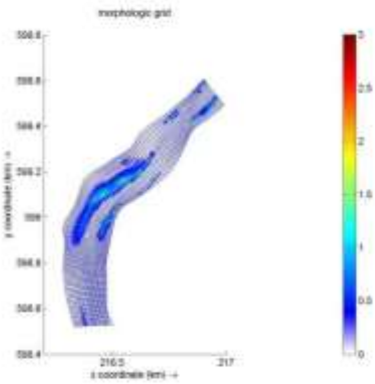
The inflow of suspended sediment is adapted on its inflow volume and on the sediment grain size.
The inflow and distribution of suspended sediment is shown below. Chosen is to continue with the reduced amount of suspended inflow sediment C.



A. Measured inflow volumes
T = 07-05 S = 2.5 kg/m3
T = 08- 05 S = 1.75 kg/m3
T = 09- 05 S = 1.0 kg/m3



B.Sedimentation pattern reduces inflow values
T = 07-05 S = 1.25 kg/m3
T = 08- 05 S = 0.875 kg/m3
T = 09- 05 S = 0.5 kg/m3

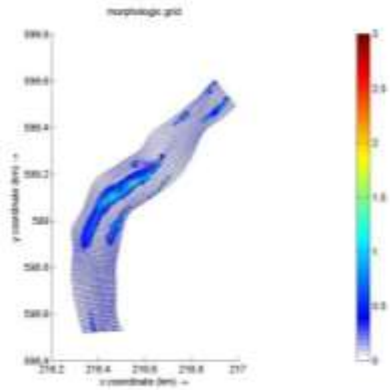


C.Sedimentation pattern reduced inflow values
T = 07-05 S = 0.75 kg/m3
T = 08- 05 S = 0.4375 kg/m3
T = 09- 05 S = 0.25 kg/m3

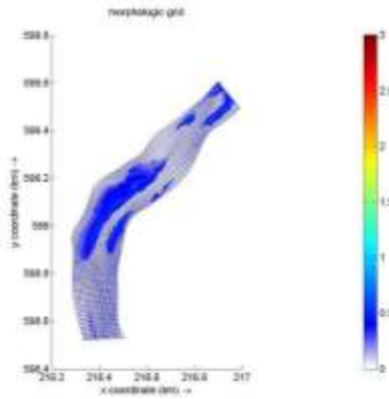
Sedimentation pattern inflow sediment when changing inflow volumes

Grain size

By reducing the size of the sediment particles less sediment will settle and besides the sediment will settle more spread out.



Dsus = 0.135 mm



Dsus = 0.065 mm

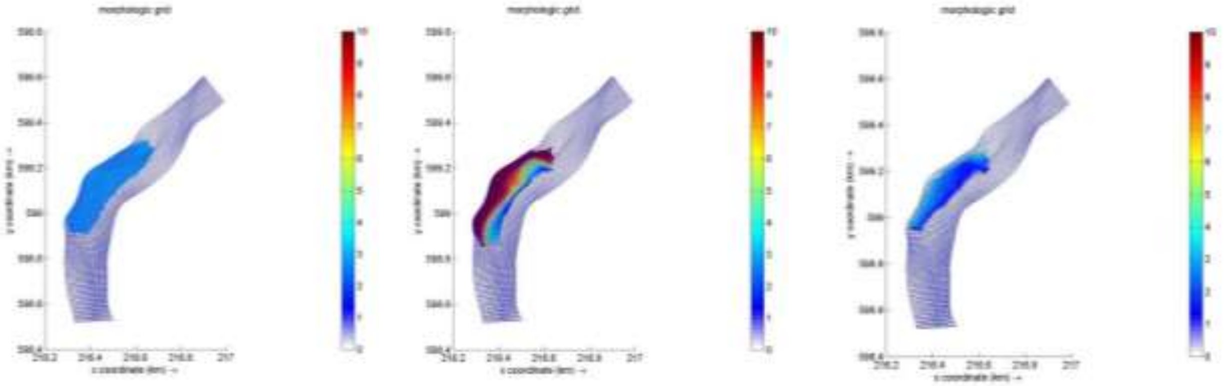
Change of sedimentation pattern by varying with sediment grain size

Initial bed sediment

The unrealistic high amount of sediment might be the result of the value of the initial bed sediment. To investigate the influence of the bed sediment varied is with the bed thickness and the grain size.

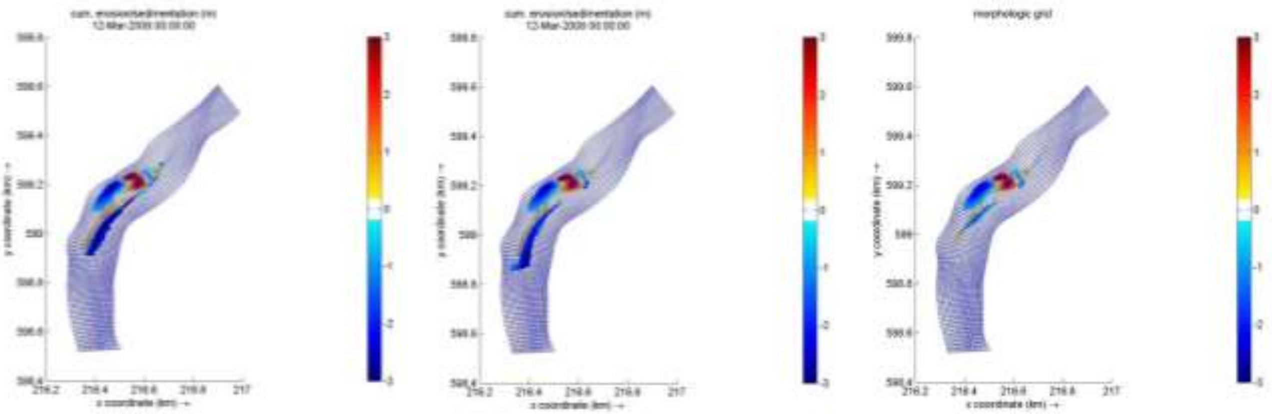
<u>Bed thickness</u>

The bed thickness is adapted, no sediment inflow is entered



Initial thickness layer | Gradual thickness layer, thick layer | Gradual thickness layer, thin layer

Thickness files

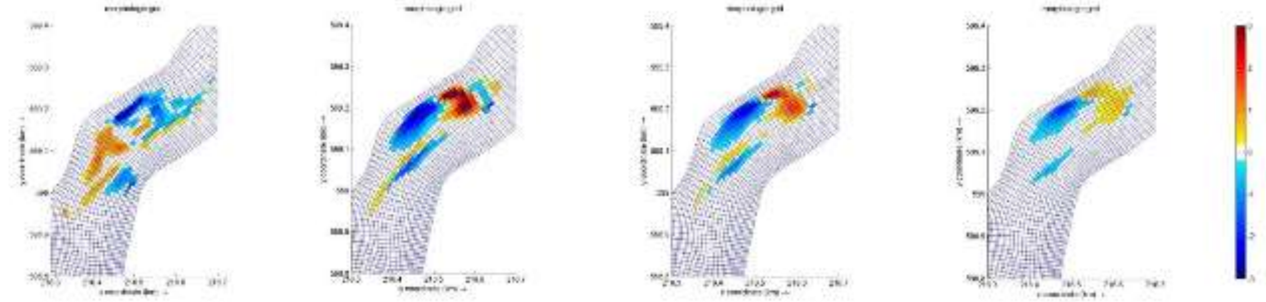


Erosion deposition -Initial thickness layer | Erosion deposition - Gradual thickness layer | Erosion deposition - Gradual thickness layer

Deposition-Erosion pattern

<u>Grain size bed</u>

The bed grain size appeared to be of influence on the large deposition amount at the upstream part of the eddy. A smaller grain size resulted in more realistic results. On locations where erosion should have been, still deposition was seen. The grain size 0.200 mm displayed the most realistic outcome. The figure below shows the remarkable decrease in amount of sedimentation and erosion by reducing the grain size.



A. Measured pattern | B.G0.320 | C.G0.200 | D.G0.130

Erosion- deposition pattern

APPENDIX F - AERIAL PHOTO BUCK FARM FROM 1984