Combined effects of mud and riparian vegetation on river morphology

MSc thesis Earth Surface and Water

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Preface

This thesis was written to fulfil the requirements to obtain my Master's degree in Earth Sciences at Utrecht University. The main aim is to be able to independently carry out scientific research applying acquired academic skills and combining advanced knowledge of multiple fields. This research was conducted between June 2016 and May 2017.

This research is part of the research on biomorphodynamics by the group of Maarten Kleinhans. The research provided me with the opportunity to work with the widely used state-of-the-art model Delft3D. Furthermore, it enabled me to focus more on the interesting role of biology in landscape formation.

I would like to thank my supervisors Maarten Kleinhans and Mijke van Oorschot for their enthusiastic guidance during the entire research process. I would like to thank Marcel van der Perk for his help in understanding and using his floodplain sedimentation model. I also would like to thank Maarten Zeylmans for providing me with a computer on which I could run my models from any location at any time. I thank Lisanne Braat and Wout van Dijk who gave useful advice regarding Delft3D modelling. Furthermore, many thanks to Arjan van Eijk for his thoughtful help with the fieldwork preparation. Special thanks to Ivar Lokhorst for the useful discussions and help during the fieldwork at the river Allier in France. I would also like to thank Erik van Onselen and Steven Weissher for their assistance during the fieldwork. Additionally, I thank Harke Douma for providing and discussing remote sensing data of the vegetation dynamics at the river Allier. Finally, I would like to thank my parents who reviewed my work and supported me during this research.

Abstract

Cohesive sediment (mud) and riparian vegetation interact with river morphodynamics and affect the formation of river patterns. Mud and vegetation are both associated with a shift from multichannel braided to single channel meandering patterns, because they (1) increase bank strength, (2) fill in abandoned channels and lows, limiting formation/reoccupation of multiple channels, and because (3) vegetation increases flow resistance in the floodplain, causing focus of flow in the channel. Mud and riparian vegetation also interact with each other. However, it is still unknown how interactions between mud deposition and erosion processes and riparian vegetation development affect the morphological development and patterns of river systems. A better understanding of these interactions and their effects on river morphology would be useful to improve predictive models for river management and renaturalisation. The aim of this study is therefore to investigate the combined effects of mud and vegetation on the morphological development of a river system on centennial timescales.

The combined effects of mud and vegetation on river morphology were investigated with a numerical model loosely based on the meandering river Allier. The river Allier is a sandy gravel-bed river of about 800 m wide, located close to the Alps, with a relatively steep gradient and discharge peaks that are about 10 times larger than the low flow. The model includes, for the first time, both mud erosion and deposition processes and settlement, growth and mortality conditions for two riparian vegetation species (*Salix* and *Populus*), that affect flow resistance depending on vegetation density and sizes. The main model scenarios are: (1) both vegetation and mud, (2) only vegetation, (3) only mud, (4) no vegetation or mud. Important additional boundary conditions that were varied were the upstream mud supply and the critical shear stress for mud erosion. Spatial mud and vegetation patterns obtained with the model were compared to field observations. For validation, mud deposition patterns were also compared with an established floodplain sedimentation model.

In the vegetation-only model, the vegetation pattern is highly dynamic with variations in age and density as a result of the morphodynamics. Vegetation growth along channels focuses flow causing deeper and more confined channels. The vegetation induces formation and migration of meander bends, but also promotes avulsions over a wider part of the floodplain and leads to a relatively high braiding intensity by increasing water levels and diverting flows. The larger braiding intensity opposes many field and experimental studies. One of the possible explanations is that in our study floodplain confinement by the valley walls caused higher water levels and hence avulsions. Mud, as opposed to vegetation, has little impact on river morphology due to the large shear stresses compared to the critical shear stress for mud erosion in this particular system.

The morphology of a river system with a combination of vegetation and a moderate mud supply is similar to a system with only vegetation. Moderate mud supplies had limited impact on river morphodynamics even though vegetation promotes mud deposition closer to the river channel and in abandoned channels which are important locations for the morphological development of rivers. Therefore, mud also had no large impact on the vegetation development. Vegetation in combination with an extreme mud supply of relatively cohesive mud leads to a relatively stable river system with a low braiding intensity, where high muddy banks prevent overbank flooding causing a narrow riparian zone.

These results indicate that in high-energy gravel-bed river systems such as the Allier, vegetation has a large impact on river morphodynamics, while (interaction with) mud is generally of minor importance because mud is relatively easily eroded. Mud deposition in the floodplain can, however, facilitate other vegetation species by altering the substrate composition. Effects of this interaction on river system ecology and morphology are an interesting topic for future research.

Keywords: river morphodynamics; cohesive sediment (mud); vegetation; biogeomorphology; numerical model

Content

List of Figures

List of Tables

1. Introduction

1.1 Problem definition

Rivers form unique habitats for various vegetation types and animal species and have economic and recreational value. Development of river systems is complex involving many interactions between flow, sediment, flora and fauna which are affected by humans and climate change.

Both cohesive sediment (mud) and vegetation are known to interact with river morphodynamics (for review on vegetation, see Gurnell, 2014). Furthermore, previous research showed that mud and vegetation affect the development of river channel patterns with distinct channel and floodplain characteristics by affecting bank strength (Kleinhans, 2010). This previous research includes qualitative descriptions (Ferguson, 1987 in Kleinhans, 2010), flume experiments (e.g. Gran and Paola, 2001; Peakall et al., 2007; Tal and Paola, 2007, 2010; Van Dijk et al., 2013a,b) and numerical modelling studies (e.g. Perucca et al, 2007; Van Oorschot et al., 2015; Braat and Kleinhans, in preparation).

Mud and riparian vegetation are also known to interact with each other, for example, vegetation traps sediment and particular vegetation species favour soils with either high or low mud contents (Gurnell et al., 2012; Duel and Specken, 1994 in Weeber, n.d.). However, it is still unknown how the interaction between mud and riparian vegetation affects the morphological development of river systems.

Recent advances in modelling made it possible to realistically study the effect of dynamic vegetation on the morphological development of a river system (Van Oorschot et al., 2015). The morphology part of the model of Van Oorschot et al. (2015) runs in the widely used Delft3D morphodynamic modelling software for which a bed module has recently been developed that allows the incorporation of sediment mixtures and takes into account the effect of bed composition on erosion properties of the bed (Van Kessel et al., 2012). Therefore mud can be added as a second sediment type beside a sand/gravel fraction. All in all, it now appears to be possible to realistically study the interaction between mud and vegetation and its effect on river morphology using numerical modelling.

Knowledge about the combined effects of mud and vegetation on river morphology can help understanding effects of climate change, river restoration activities and other human interventions in riverine systems. A better understanding of the interaction between mud and vegetation can be used to improve predictive models for river management. Therefore, the main aim of this study is to investigate the combined effects of mud and vegetation on the morphological development of a river system on centennial timescales.

1.2 Study objectives

This study investigates the combined effects of mud and vegetation on the morphological development of a river system on centennial timescales.

Both numerical and experimental modelling are suitable to study the combined effects of mud and vegetation on river morphology on centennial timescales. Such long timescales are required to get an insight in long-term trends, dynamic equilibria and river pattern formation. Thus far, there were no experimental set-ups or numerical river models in which cohesive mud and dynamic vegetation were combined. Within the scope of this research a recently developed numerical model is used to study the interaction between mud and dynamic vegetation and their effect on river morphology. As numerical modelling incorporates a risk that processes are oversimplified, outcomes are compared with a field study, remote sensing data and results obtained with the established floodplain sedimentation model SEDIFLUX. The numerical model is only loosely based on an existing river in

France, because the goal of this research is not to exactly model how this particular river develops, but to get a more generic understanding of the interaction between mud and vegetation in river systems and how this affects the evolution of river patterns and morphology.

The current study has four objectives:

1. To investigate spatiotemporal patterns of mud and vegetation, to study how these are related and to assess the separate and combined effects of mud and vegetation on the long-term (150-300 years) morphological development of a river system with a numerical Delft3D model;
2. To compare mud and vegetation patterns obtained with the numerical model to field (spatial) and remote sensing data (spatial and temporal).
3. To investigate the sensitivity of the numerical model outcomes to some uncertain model parameters in Delft3D;
4. To compare the mud concentrations and deposition pattern obtained with the Delft3D model with mud concentrations and deposition fluxes as calculated by the numerical floodplain sedimentation model SEDIFLUX.

1.3 Structure of this thesis

This thesis starts with a thorough review on river morphodynamics, channel pattern formation, mud, riparian vegetation and a short description of the study site (Chapter 2). At the end of the review, knowledge gaps are clarified and hypotheses are given. Then, the methodology and methods are presented including the boundary conditions and parameters of mud properties that were varied (Chapter 3). After that, results are described (Chapter 4). The main results are presented first. Then, mud and vegetation patterns obtained from the model and the relation between them are described. Thirdly, the individual and combined effects of mud and vegetation on river morphology are discussed. Fourthly, results from a short field trip of spatial mud and vegetation patterns in the river Allier are presented. Finally, the model sensitivity and validation is considered. Then, the results are discussed and some options for future research are provided (Chapter 5). The thesis ends with the conclusions (Chapter 6).

2 Review

2.1 River patterns and morphodynamics

2.1.1 River pattern classification and morphology

Many different types of rivers exist around the world. Their channel patterns can be distinguished based on bar pattern, number of parallel channels and on whether multiple channels are separated by channel sediment or floodplain (Kleinhans and Van den Berg, 2011).

River channel patterns are commonly classified as being braided, meandering or straight (Figure 1 , left) (Leopold and Wolman, 1957; Ferguson, 1987 in Kleinhans and Van den Berg, 2011; Nanson and Knighton, 1996). Straight rivers have laterally inactive channels, but confusingly their channels are not necessarily straight (Kleinhans and Van den Berg, 2011). River channel patterns form a continuum and hard discrimination between them should be avoided (Leopold and Wolman, 1957).

Ferguson (1987) cited by Kleinhans (2010) made a classification of river channel patterns based on stream power versus amount and size of bedload, width-to-depth ratio and channel instability (Figure 1, right). For sand-bed rivers, increasing stream power results in a transition of channel pattern from straight to meandering and finally anabranching. For gravel-bed rivers, an increase in stream power leads to a transition from a straight pattern to slightly sinuous with alternating bars and finally braided rivers (Ferguson, 1987 in Kleinhans, 2010; Kleinhans, 2010). The formation of river patterns is discussed in more detail in Chapter 2.1.2.

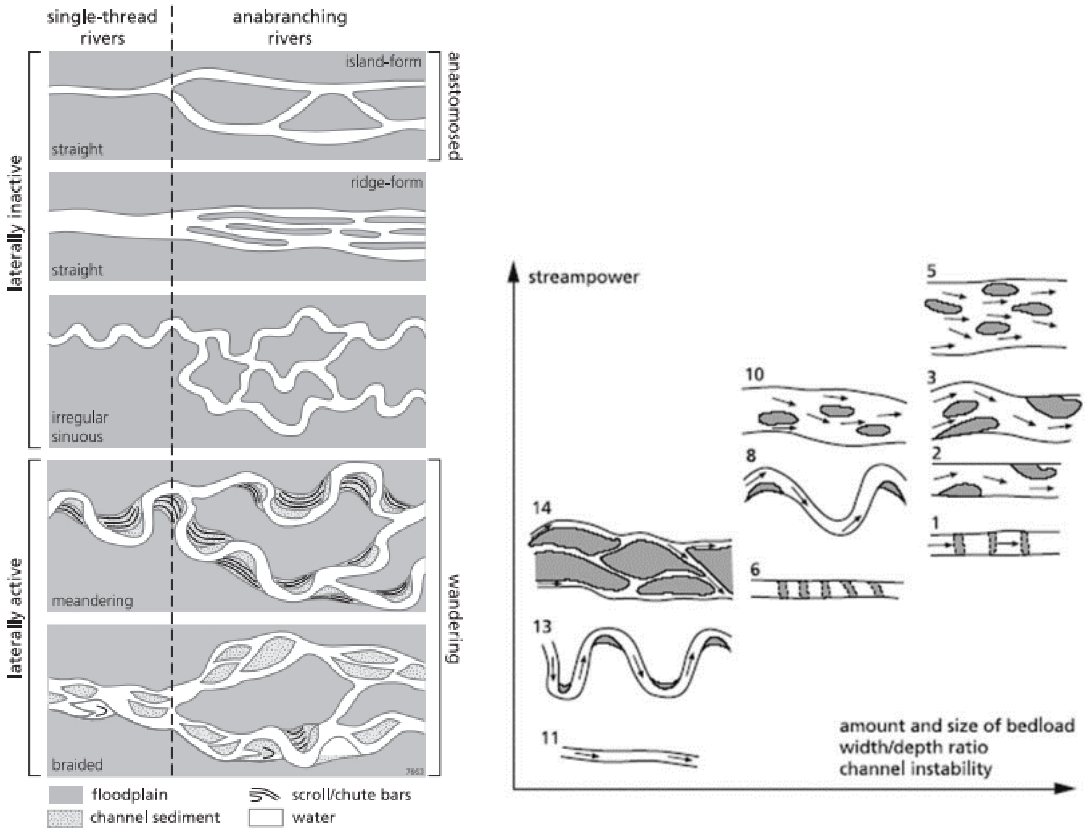

Figure 1 River channel pattern classifications. Left: river channel pattern classification including a distinction between laterally active and laterally inactive river systems (Kleinhans and Van den Berg, 2011, modified after Nanson and Knighton, 1996). Right: river channel pattern classification based on stream power versus amount and size of bedload, width-to-depth ratio and channel instability (Kleinhans, 2010 after Ferguson 1987).

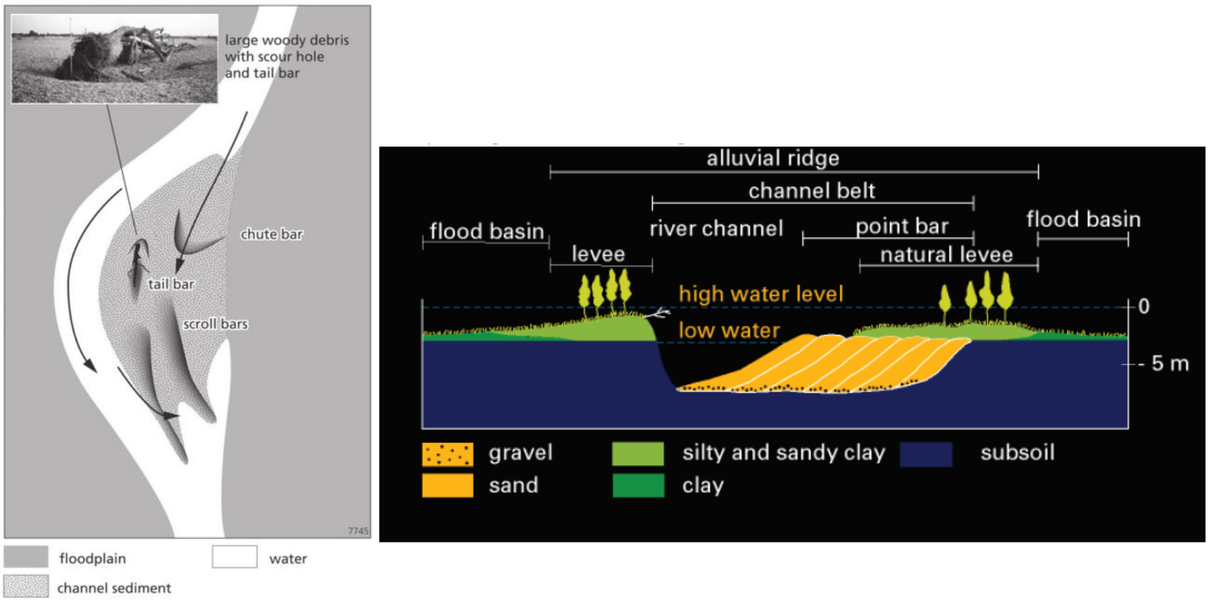

Figure 2 Meandering river morphology. Left: bar types in the inner bend of meandering river systems (Kleinhans and Van den Berg, 2011). Right: cross-sectional view of a meander bend (Berendsen and Stouthamer, 2001, taken from Teske, 2013).

A meandering river system (Figure 1, left) is characterized by its large meander bends that migrate both laterally and in downstream direction over the floodplain. The channel curvature can be characterized by the sinuosity, which is defined as the channel length along the centreline divided by the bend wavelength. Other recognizable features are the large point bars formed in the inner bends of the meanders and oxbow lakes that remain visible in the landscape after a bend cut-off.

In the inner bank of meanders scroll bars, chute bars and tail bars may be present (Figure 2, left). Point bars are build up from scroll bars (Figure 2, right), which are curvilinear ridges located more or less parallel to the channel (Kleinhans and Van den Berg, 2011). Scroll bars form in the accretionary inner meander bend at peak discharge and emerge at a lower water stage. As a result of meander migration, the vertical profile of a point bar shows a fining upward sequence with relatively coarse channel deposits at the base, finer sediment towards the top capped by floodplain deposits (Nichols, 2009). Tailbars form at the downstream side of obstacles such as tree trunks (Kleinhans and Van den Berg, 2011). Chute bars form at the downstream end of a chute or chute channel. Chute bars are common in braided river systems and in meandering rivers with relatively high specific stream power. Chute bars disappear when chute-cut offs take place and new braids are formed. Appearance of chute-cut offs therefore indicate the transition from meandering to braiding.

Braided river systems are also laterally active (Figure 1) and are wide rivers with multiple bars in their cross-section (Kleinhans and Van den Berg, 2011). The braiding intensity can be defined by the (active) braiding index: the number of parallel (active) channels. Both chute and tail bars are common in braided systems. The morphology of straight rivers is characterised by the presence of (stable) islands between the laterally inactive channels.

2.1.2 River channel pattern formation

Rivers planform development involves feedbacks between bars, channels, floodplain and vegetation (Kleinhans, 2010). These feedbacks are affected by the spatial sorting of bed and wash load sediments. The ratio between flow strength and bank strength is the key for channel pattern formation.

Classical explanations for the formation of a river channel pattern include variation in flow strength and type and amount of sediment supply and are still debated (Figure 1, right) (Kleinhans, 2010). Flow strength is the result of a channel-forming discharge and energy gradient, which together give a (unit) stream power or bed shear stress. The type of sediment is important regarding bank stability. Sinuosity has been found to increase with increasing proportions of cohesive material (clay, silt) or vegetation in channel banks and bed (Kleinhans, 2010). Furthermore, changes in the supply of bed sediment may cause changes in channel pattern. For example, increasing the sediment supply of a river to an amount larger than its transport capacity may cause a system to become braided, whereas a decrease in sediment load may result in a meandering pattern (Church, 2006).

Flume experiments of Peakall et al. (2007), Gran and Paola (2001), Tal and Paola (2007, 2010) and Braudrick et al. (2009) showed that three combined factors cause a river to become meandering (Kleinhans, 2010):

1. reduction of floodplain flow strength and focussing of flow (strength) into the channel due to addition of vegetation, which increases hydraulic resistance;
2. increase of bank strength due to addition of vegetation or cohesive sediment;
3. infilling of abandoned channels and lower parts of the floodplain with vegetation and lightweight sediment thereby limiting the formation/reoccupation of multiple channels.

Based on these experiments and the work of Ferguson (1987) cited by Kleinhans (2010) it can be concluded that meandering rivers form when the bank strength is relatively large compared to flow strength, while braided rivers form when the bank strength is relatively low (Kleinhans, 2010).

River channel patterns are closely related to the nature of bars (Kleinhans, 2010; Kleinhans and Van den Berg, 2011). The balance between floodplain formation and bank erosion determines channel width and with that bar pattern. The bar pattern in turn determines the location of bank erosion. However, alternating bars can migrate so fast that banks erode at both sides of the channel resulting in a braided pattern (Seminara and Tubino, 1989 in Kleinhans, 2010). Floodplain formation by vegetation growth and cohesive sediment deposition on bars or armouring can decrease bar migration rates. This results in alternating erosion of the floodplain banks and meandering (Kleinhans, 2010).

Variation in floodplain type affects river channel pattern formation due to differences in erodibility. Floodplains form by overbank sedimentation and disappear due to bank erosion. Different floodplains develop due to the variety in type and intensity of processes which cause spatial sorting of fine and course sediment over the floodplain (Kleinhans, 2010). The differences in erodibility of various floodplains affect the width-to-depth ratio of channels, which in turn affects the flooding frequency and hence, completing the circle, floodplain formation.

Vegetation affects floodplain formation, because it increases hydraulic resistance, traps sediment and adds strength (Kleinhans, 2010). This way, vegetation can promote the transition of bars into levees and islands.

Fine sediment deposition generally occurs further away from the channel where it forms cohesive sediment (Middelkoop and Asselman, 1998; Nicholas and Walling, 1998). Over time, sediment compaction and vegetation succession provide additional bank strength (Geerling et al., 2006; Kleinhans, 2010).

All in all, river channel patterns are formed due to the complex interactions between bars, channels, floodplain, vegetation and sorting of sediment sizes. Changes in river systems due to climate change or human impact such as a change in discharge, amount and type of sediment supply or amount of vegetation can hence result in a change of river channel pattern and behaviour.

2.2 Mud

Mud consists of both silt (0.004-0.063 mm) and clay (<0.004 mm) particles (Van Ledden et al., 2004). Mud behaves differently from sand in river systems, because clay is cohesive and mud is dominantly transported in suspension.

The distribution of mud within river systems plays an important role in river morphodynamics, because cohesive clay particles within mud affect bed erosion rates and bank stability. Furthermore, mud indirectly affects river morphodynamics, because mud concentrations in the water and floodplain sediments affect the vegetation distribution in a river system.

2.2.1 Mud distribution in a river system

The knowledge about mud distribution in river systems is limited to general knowledge on sediment deposition patterns in floodplains (e.g. Middelkoop and Asselman, 1998; Walling and He, 1998) and knowledge on grain size distributions near individual vegetation patches (e.g. Cotton et al., 2006).

The percentage of mud in bottom sediments increases with distance from the channel. A study of Middelkoop and Asselman (1998) at event scale showed that when topographic disturbances are absent, the amount of silt and clay deposition in a floodplain is approximately constant with distance from the channel. However, the amount of sand deposition decreases exponentially with distance from the channel. In the Rhine-Meuse delta this results in silty clay deposits at distances larger than 50-100 m from the channel.

Topographic differences in floodplains and local hydraulic conditions strongly affect the pattern of sediment transport and deposition (Middelkoop and Asselman, 1998; Walling and He, 1998). In case a minor dyke - larger than a natural levee - is present, sediment with a relatively high amount of clay deposits at locations where the water flows across the dyke (Middelkoop and Asselman, 1998). Besides, high sedimentation rates occur in depressions (Middelkoop and Asselman, 1998; Walling and He, 1998). Ponding in these areas results in the deposition of suspended sediment including mud (Walling and He, 1998).

2.2.2 Bed erosion

Experiments showed that the erosion characteristics of a sand bed change dramatically when limited amounts of mud are added (Bisschop, 1993 in Van Ledden et al., 2004; Mitchener and Torfs, 1996) or when sand is added to a mud bed (Williamson and Ockenden, 1993 in Van Ledden et al., 2004). For example, Torfs (1995) found that the critical shear stress for erosion became 2-5 times higher in case 10 % mud was added to a sand bed.

Outcomes of research to find the percentage of mud that is needed to change the behaviour of a sand bed from non-cohesive to cohesive differ, e.g. Mitchener and Torfs (1996) found this transition when 3-15 % mud was added, while Houwing (2000) found a value of 20 % during field experiments in the Wadden Sea (The Netherlands). Van Ledden et al. (2004) found that clay content (% < 0.004 mm) is a more generic predictor for the transition towards cohesive behaviour of the bed than mud content (% < 0.0063).

2.2.3 Impact of mud on vegetation in river systems

Both mud concentrations in the water and deposition patterns of mud in the floodplain affect the distribution of vegetation within a river system. First of all, high concentrations of mud in the water decrease light penetration in the water which can be detrimental to aquatic vegetation (Edwards, 1969; Davies-Colley et al., 1992). Secondly, the deposition pattern of mud in floodplains affects the soil composition and hence its hydraulic characteristics (Noy-Meir, 1973) and organic matter content (e.g. Burke et al., 1989). Particular vegetation species favour soils with either low or high mud (or clay) contents (e.g. Duel and Specken, 1994 in Weeber, n.d.). Finally, results of large scale estuarine morphodynamic numerical modelling showed that increased mud deposition in vegetated areas can elevate vegetation into zones with decreased physical stresses in estuarine systems promoting further vegetation development (Lokhorst, 2016).

2.3 Riparian vegetation

Riparian vegetation is “one of the biotic communities living close to the river banks, which is sustained by and interacts with the stream to a great extent” (Hughes, 1997; Perucca et al., 2006 following Naiman and Décamps, 1997).

Riparian vegetation both affects and responds to fluvial processes and is a highly important element of fluvial systems as it controls both the river corridor form and its dynamics (Corenblit et al., 2007; Gurnell, 2014). The interactions between vegetation and hydromorphodynamics occur at many different spatial and temporal scales (Camporeale et al., 2013): from within vegetation patches to planform scale and from seconds to many years. Interactions between hydrogeomorphic processes and vegetation dynamics can shift from dominantly abiotic interactions, such as destruction of vegetation by for example flooding, desiccation or uprooting and seed dispersal by water flow, to more biotic interactions, such as vegetated fluvial landform stabilization (Corenblit et al., 2007). This shift occurs as a result of biostabilisation and passive bioconstruction processes.

In this section, I will firstly discuss the effects of vegetation on flow and sediment processes including river bank stability (Chapter 2.3.1). Then, the effects of river flow and sediment processes on vegetation are described (Chapter 2.3.2). Finally, the formation of fluvial landforms and vegetation patterns due to the interaction between vegetation and the river system is considered (Chapter 2.3.3).

2.3.1 Effects of vegetation on river flow and sediment processes

Effects of vegetation on river flow

Presence of vegetation increases hydraulic roughness causing a decrease in flow velocities (Figure 3, left) (Baptist et al., 2007) and change in water level (Figure 3, right) (Siniscalchi et al., 2012). The extent to which vegetation increases hydraulic resistance depends on many factors including vegetation density and frontal area, vegetation height relative to water depth, rigidness of plants and presence of leaves (Järvelä, 2002; Baptist et al., 2007).

Vegetation generally slows down flow due to an increase of the hydraulic roughness. However, locally accelerated flow may occur between vegetation patches (Cotton et al., 2006). Vegetation also alters turbulence patterns within a channel, which is important for sediment transport, deposition and erosion. Flow patterns within a river may change over the seasons due to changes in vegetation characteristics and growth pattern (Figure 4) (Coon, 1998; Cotton et al., 2006).

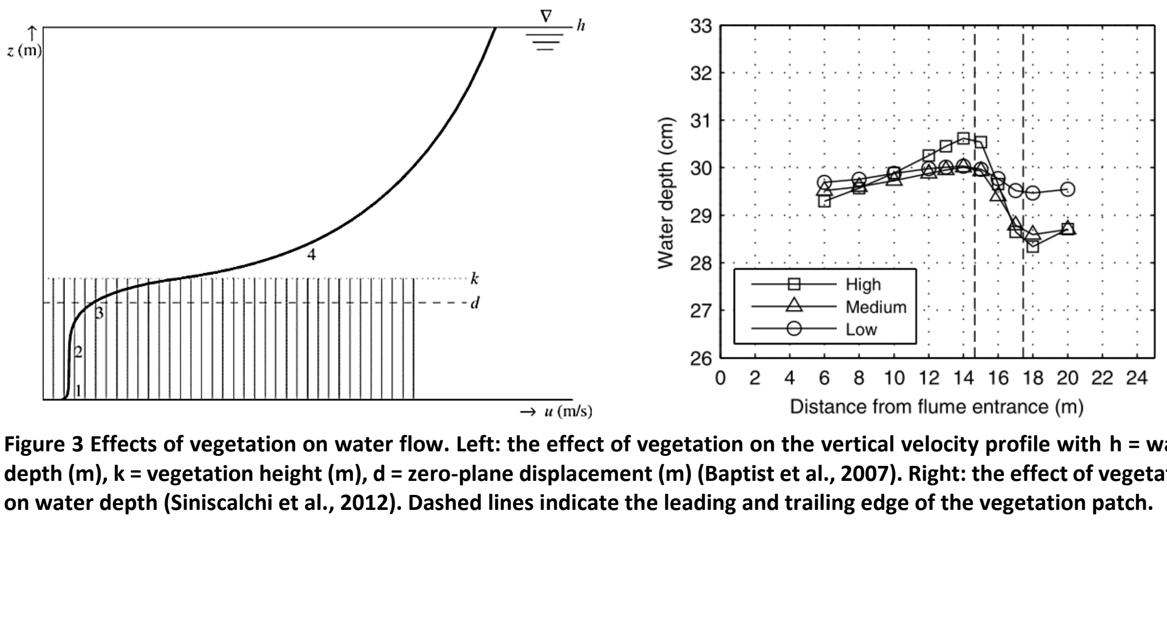

Figure 3 Effects of vegetation on water flow. Left: the effect of vegetation on the vertical velocity profile with h = water depth (m), k = vegetation height (m), d = zero-plane displacement (m) (Baptist et al., 2007). Right: the effect of vegetation on water depth (Siniscalchi et al., 2012). Dashed lines indicate the leading and trailing edge of the vegetation patch.

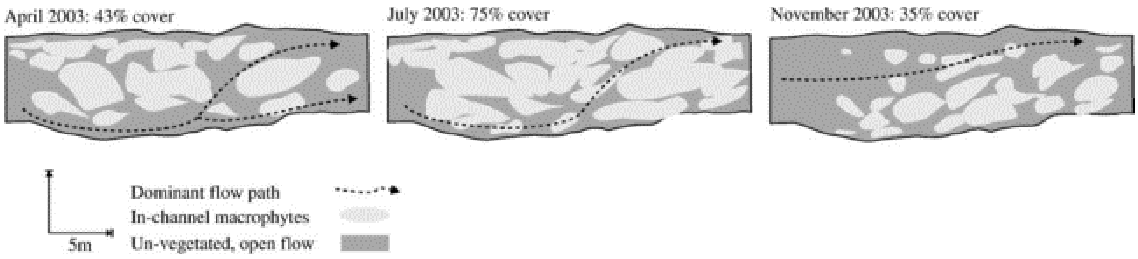

Figure 4 Seasonal changes in flow path as a result of in-stream macrophyte growth (Cotton et al., 2006).

Effect of vegetation on transport, deposition and erosion

Presence of vegetation decreases bedload transport rates. However, both suspended transport and sediment deposition/erosion either increase or decrease depending on vegetation(patch) characteristics.

The effect of vegetation on bedload and suspended sediment transport has mainly been studied using laboratory observations with artificial vegetation (Solari et al., 2015). Bedload transport rates were found to be significantly smaller in vegetated areas compared to areas without vegetation. The effect of vegetation on suspended transport is more complex. Vegetation can cause a decrease in bed shear stress resulting in lower sediment entrainment, but can also locally increase turbulence (e.g. Zong and Nepf, 2011; Ortiz et al., 2013) which may result in removal of fine sediment (Solari et al., 2015). Besides, by acting on the flow pattern, vegetation also affects sediment transport rates by altering the sediment supply to a river channel by stabilizing banks and retaining sediment on the floodplain.

The deposition pattern within and around vegetation patches depends on stem density, the total projected frontal surface area and the ability to dampen turbulent flows (Gacia et al., 1999; Sharpe and James, 2006; Bos et al., 2007; Mudd et al., 2010;). Vegetation generally acts as a sediment trap (Figure 5) (Gurnell et al., 2006; 2012; Perignon et al, 2013). However, increased turbulence within low-density vegetation patches and accelerated flows outside vegetated areas may lead to erosion (Nepf, 1999; see review Jones et al., 2012). Grains size patterns are also affected by vegetation: Kleeberg et al. (2010) observed finer sediment within aquatic vegetation patches and coarser sediment between them.

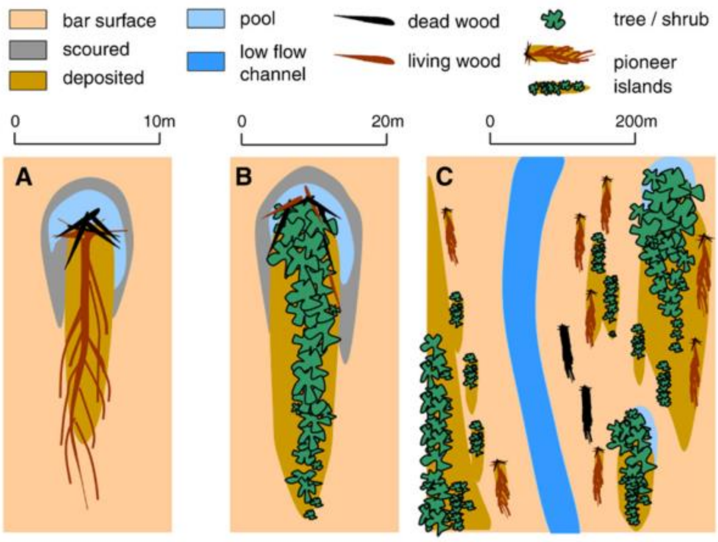

Figure 5 Sediment trapping by wood, trees and shrubs (Gurnell et al., 2012). Interactions between hydro-morphodynamic processes and vegetation lead to the development of fluvial landforms: a pioneer island forms around a deposited tree (A), which traps additional fine sediment and plant propagules leading to (more) vegetation growth. C represents growing and coalescing pioneer islands along a river channel.

Effect of vegetation on bank stability and bank dynamics

Mass movements of streambanks depend on gravitational forces on the bank material and hydraulic forces that act within the channel (Pollen-Bankhead and Simon, 2010). Riparian vegetation can have both positive and negative effects on bank stability (e.g. Simon and Collison, 2002), but usually increased vegetation density can be related to increased bank strength (Pollen-Bankhead and Simon, 2010).

The impact of vegetation on bank stability can be divided in mechanical and hydrological effects. The first mechanical effect is that roots of vegetation increase the strength of the bank soil material (Thorne, 1990 in Simon and Collison, 2002). Furthermore, vegetation affects the stability of stream banks by increasing the surcharge (Simon and Collison, 2002). The addition of mass usually has a detrimental effect on bank stability due to steep surface slopes of streambank failures, but may also increase shear strength due to friction. Hydraulic effects of vegetation on stream bank failure are related to pore-water pressures in the soil and matrix suction (Simon and Collison, 2002). Vegetation can decrease the chance of streambank failure by intercepting rainfall and transpiration (Simon and Collison, 2002), but can destabilize banks because of increased infiltration (Durocher, 1990 in Simon and Collison, 2002) near stems and the formation of macropores by roots (Simon and Collison, 2002).

Plant characteristics are important factors in whether plants increase or decrease bank strength. For example, tree roots can protect the substrate up to depths of a few meters, which can lead to development of root-plate abutments (Rutherford and Grove, 2004). However, large trees may also lead to bank failure due to susceptibility for gravitational movement enhanced by effects of strong wind forces (Abernethy and Rutherford, 2001). The substrate in the riparian zone may be better protected by roots of semi-rigid shrubby and flexible herbaceous vegetation, which are able to resist strong flow and are less susceptible to gravitational movements (Corenblit et al., 2007).

It should be noted that vegetation growing near channel banks also affects bank failure, because it reduces near-bank shear stresses and hence the potential of the river flow to erode the banks (Solari et al, 2015).

2.3.2 Effect of river flow and sediment processes on vegetation

Riparian vegetation development strongly depends on river flow (e.g. Corenblit et al., 2007; Camporeale et al., 2013). First of all, the river flow regime controls the seed dispersal and supply of other vegetative fragments and is therefore of great importance for vegetation colonization (Figure 6) (e.g. Camporeale et al., 2013). Secondly, rivers supply water for plants by controlling water table levels (Corenblit et al., 2007). Thirdly, river flow controls vegetation mortality as the inundation duration, flow velocity and sediment transport cause e.g. drowning, desiccation, uprooting, burial and scour (e.g. Van Oorschot et al., 2015). Aquatic plants also are sensitive to light penetration and hence sediment concentrations in the water (Davies-Colley et al., 1992). A final important effect of river flow and sediment processes on vegetation is related to the fact that river flow and sediment processes lead to the spatial sorting of different sediment size fractions. Soil texture determines the soil moisture balance (e.g. Noy-Meir, 1973), which is important for the establishment of riparian vegetation (see review Gurnell et al., 2016).

The extent to and the processes via which the river flow and sediment processes affect colonization, growth and mortality of riparian vegetation varies spatially. Gurnell et al. (2016) divided the river corridor in five different zones where vegetation is affected by different hydrogeomorphological processes depending on magnitude of inundation, fine sediment deposition and sediment erosion and deposition (Figure 7). The importance of each of these zones differs depending on river planform type and river valley confinement (Figure 7). Zone 1 is the most hostile zone for vegetation: it is continuously inundated and experiences the highest flow velocities and shear stresses. The high shear stresses and flow velocity induce erosion and sediment mobilization thereby increasing the potential of plants to be damaged, uprooted or buried. In general, frequency, depth and duration of inundation decrease towards zone 5. In zone five, inundation is extremely rare and subsurface and overland flows become the dominant hydrogeomorphological controls on vegetation.

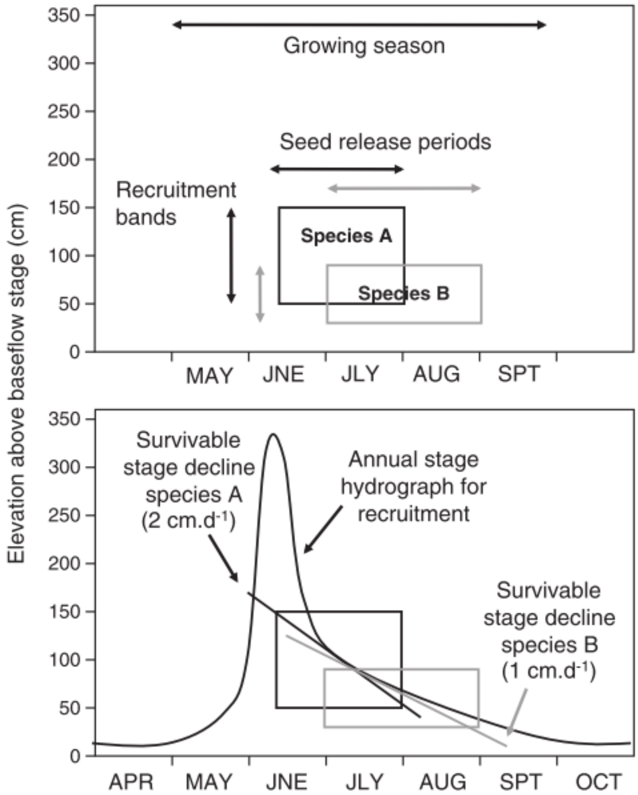

Figure 6 Example of the recruitment box model of Mahoney and Rood (1998) (Camporeale et al., 2013). Success of seedlings is determined by flow stage during and after seed dispersal.

2.3.3 Formation of fluvial landforms and vegetation patterns

Ongoing interaction between riparian vegetation and hydro-morphodynamic river processes results in the development of fluvial landforms and recognizable vegetation patterns.

Riparian vegetation succession and fluvial landform development

Ecological succession is “a directional sequence of changes through time in species composition and other plant community characteristics (productivity, biomass, diversity, etc.)” (Camporeale et al., 2013 after Odum, 1969). The ecological succession of riparian vegetation is often interrupted and reset due to high variability in river flows resulting in e.g. flooding and droughts. Variation in the degree of disturbance and recovery time leads to a spatially varying and dynamic pattern of riparian vegetation patches at different successional stages (Décamps and Tabacchi, 1994 in Camporeale et al., 2013).

Vegetation succession is linked to fluvial landform development. In riparian environments, ecological succession takes place as pioneer species colonize bare substrate and are then gradually replaced by older, post pioneer species (Figure 8) (Camporeale et al, 2013). Over time, pioneer shrub and tree species start to trap fluvial sediments including plant propagules and seeds that can germinate and sprout in the developing vegetation patches (Figure 5; Figure 9). These vegetation patches grow by aggradation, progradation and coalescence thereby increasing the vegetation cover and species richness (Camporeale et al., 2013).

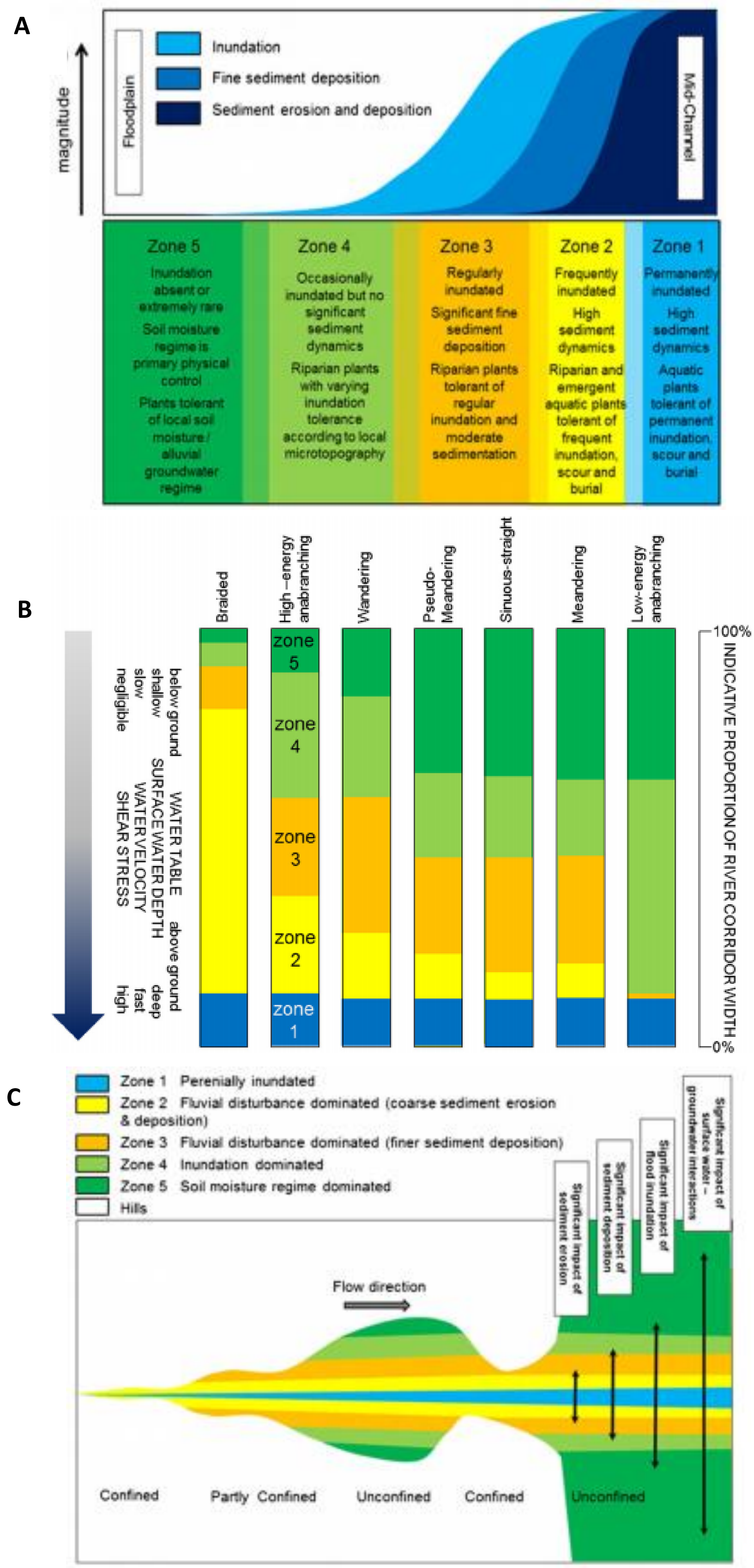

Figure 7 River corridor zonation based on hydrogeomorphological impacts on vegetation. A: Five river corridor zones in which vegetation is affected by different hydrogeomorphological processes depending on magnitude of inundation, fine sediment deposition and sediment erosion/deposition (Gurnell et al., 2016). B: Effect of river planform type on relative proportion of the five river corridor zones from A. C: Effect of river valley confinement on longitudinal and lateral variations in dominant hydrological and fluvial processes that affect vegetation composition, growth and turnover.

The process of interaction between fluvial and vegetation processes leads to development of fluvial landforms (e.g. the development of a bar into an island) (Figure 9). Bar, island and floodplain surfaces change both in lateral and vertical direction due to this process leading to a change in physical conditions (Camporeale et al., 2013). For example there is a change in frequency and duration of flooding and a change in the soil water regime due to both a change in sediment composition (usually finer on higher parts further away from the main stream) and groundwater table level. The changes in physical conditions cause a gradual change in species that live on a specific surface (e.g. Richter and Richter, 2000) which have special traits and tolerances (e.g. Bendix and Hupp, 2000) regarding soil moisture, inundation and shear conditions (Camporeale et al., 2013). In time, bars and islands are inhabited by post pioneer species that are able to live on higher, less disturbed, more competitive and drier locations (Camporeale et al., 2013).

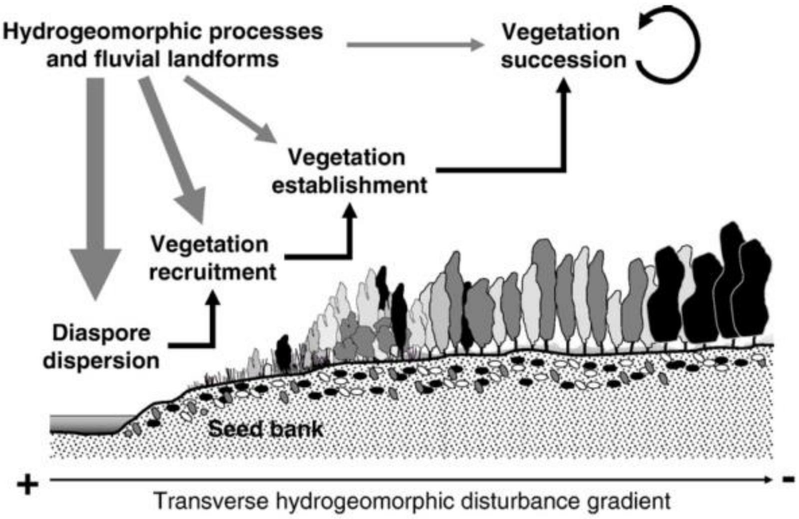

Figure 8 Schematization of effects of hydrogeomorphic processes and fluvial landforms on vegetation succession (Corenblit et al., 2007). Gray arrows point out hydrogeomorphic controls on different vegetation succession stages (size indicates importance). Dark arrows indicate time and spatial evolution.

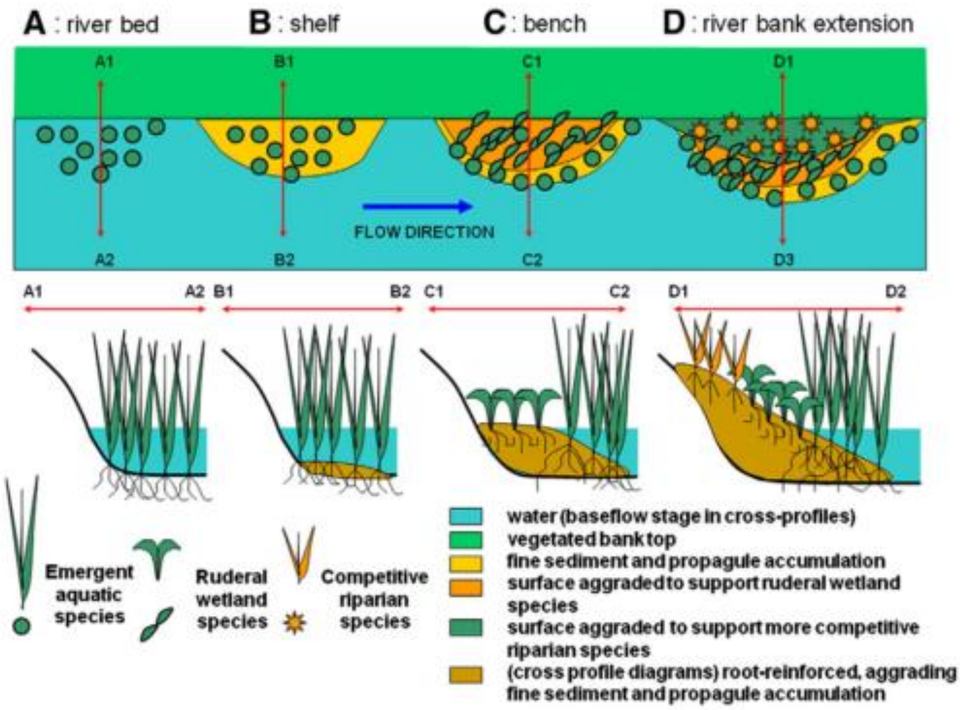

Figure 9 Example of fluvial landform development (extension of river bank) and vegetation succession. Emergent macrophytes growing on the river bed (A) trap sediment (B). The increased bed level of the shelf creates space, first for ruderal wetlands species (C) and later for competitive riparian species (D) (Gurnell et al., 2012).

Formation of riparian vegetation patterns

Interaction between vegetation and river system dynamics result in the formation of distinctive spatial riparian vegetation patterns. River disturbances that affect vegetation growth, mortality and succession and hence riparian vegetation patterns include not only flooding and droughts, but also processes such as channel migration, channel abandonment and the formation of oxbow lakes (Nanson and Beach, 1977; Perucca et al., 2006). Some studies use quantitative models to investigate the formation of vegetation patterns (e.g. Perucca et al., 2006; Van Oorschot et al., 2015). Figure 10 shows examples of spatial vegetation patterns that developed due to the interaction between vegetation and river dynamics. Figure 10 (a) shows an increase in vegetation density with distance from the river channel on the point bar and Figure 10 (b) shows parallel bands of even-aged trees that are aligned with the (former) channel (Perucca et al., 2006).

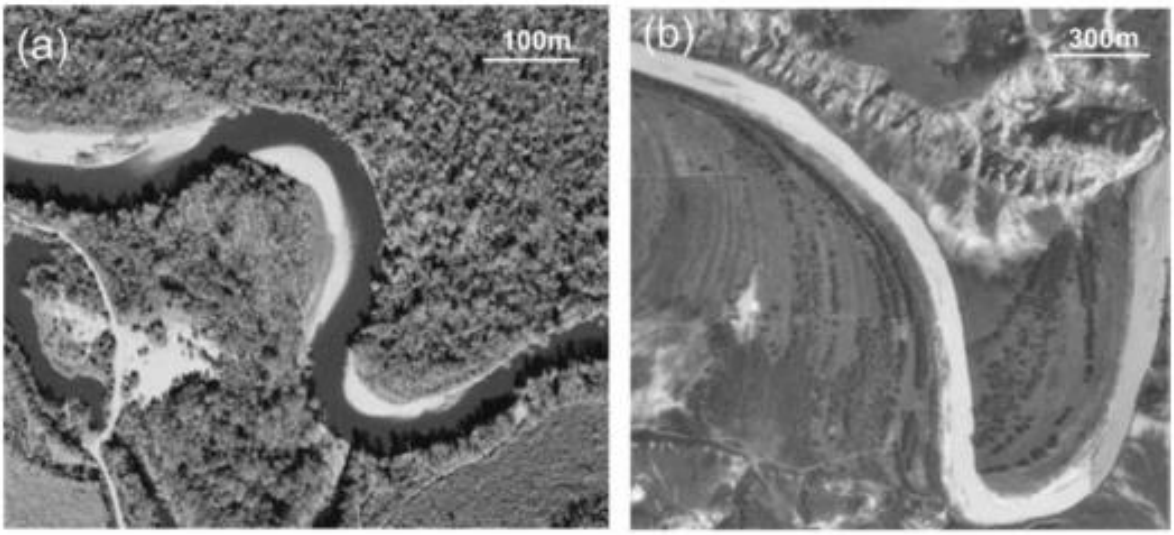

Figure 10 Riparian vegetation along (a) the Bogue Chitto River (Louisiana) en (b) Little Missouri River (North Dakota) (Perucca et al., 2006). Note the increase in vegetation density with distance from the river on the point bar and the parallel bands of trees that are aligned with the (former) river channel.

2.4 Case study site: Allier

2.4.1 Location and main characteristics of the river Allier

The river Allier, located in France (Figure 11, left), has its source in the French 'Massif Centrale' at an altitude of 1500 meter (Wilbers, 1997 in Geerling et al., 2006) and converges with the river Loire after 410 km at Bec d'Allier at 186 meter altitude.

The Allier is a meandering gravel-bed river (Geerling et al., 2006; Van Oorschot, 2015) which is most remarkable in the stretch just below the city of Moulins that shows a beautiful meandering pattern with large point bars. A part of the Allier upstream of Moulins was turned into a nature area in the 1990s (Geerling et al., 2006). In this area, the river is not used for navigation and the channel is not regulated or excavated, making it an ideal location to study meander processes.

The Allier is a rain fed river with a mean annual discharge of 148 m^3/s and 160 m^3/s over the periods 1968-1995 and 1850-1980 at Moulins (Figure 11, right) (Gautier et al., 2000; Crosato and Saleh, 2011). The minimum and maximum averaged annual discharge was 27 and 788 m^3/s in 1968-1995, respectively. The river has an unpredictable discharge, whereby seasonal variability is doubled by inter-annual irregularities especially in intensity of annual flooding (one-in-10 year peak discharges of 1200 m^3/s) (Gautier et al., 2000). Typically, peak discharges occur in winter and spring, while in summer the discharge is low (Gautier et al., 2000; Geerling, 2006). The riverbed sediment is characterized by strong horizontal and vertical variation as a result of sorting and armouring. The bed is armoured about 3-4 months per year especially at discharges below 200 m^3/s (Crosato and Saleh, 2011). Median particle diameters of the gravel range between 4.5 and 16 mm.

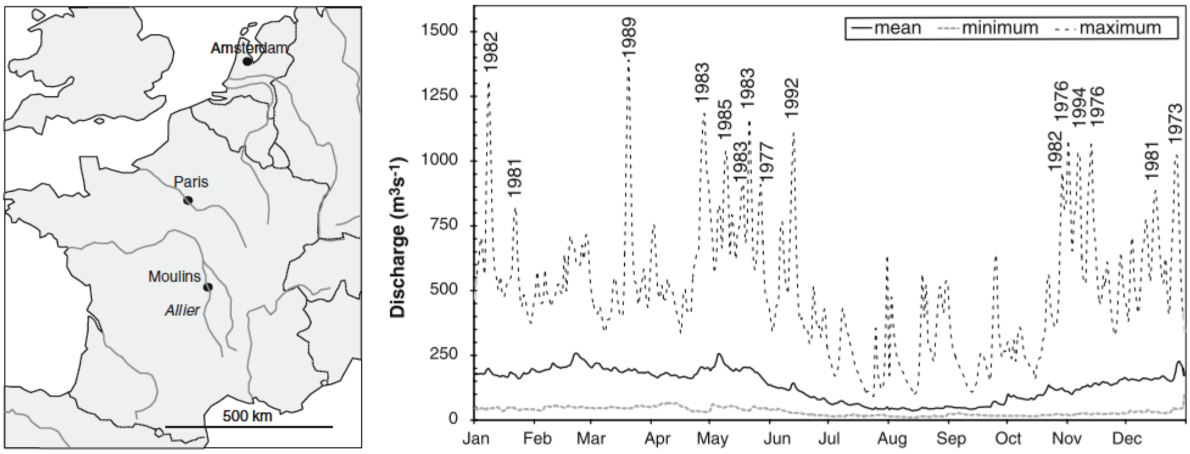

Figure 11 Location of river Allier in France (left) and the mean, minimum and maximum discharge in Allier at Moulins in the period 1968-2000 (right) (Geerling et al., 2006).

2.4.2 Short field site description: morphology and vegetation

At the fieldwork site (Appendix 1), just upstream of Moulins, the river Allier is in a transitional state between meandering and braiding: it has more than one conveying channel and multiple chute cutoffs can be observed (Crosato and Saleh, 2011; Kleinhans and Van den Berg, 2011). The location of scroll and chute bars depends on the curvature of the channel (Figure 12, Van den Berg and Middelkoop, 2007). In relatively gentle bends, chute bars migrate downstream and are present about halfway the point bar. In tight bends, chutes generally crosscut a larger part of the point bar and coalesce with scroll bars.

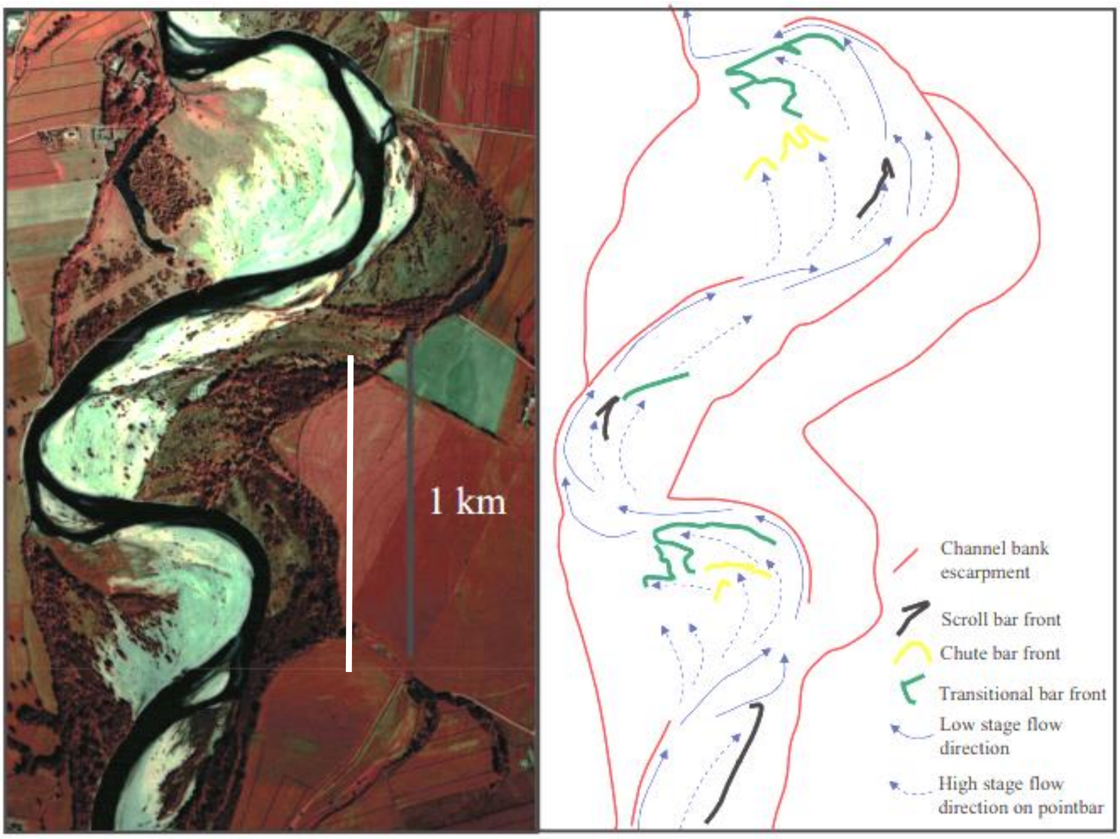

Figure 12 Aerial photograph and sketch of chute and dynamic scroll bars in gentle and tight bends in the river Allier (Kleinhans and Van den Berg, 2011, adapted after Van den Berg and Middelkoop, 2007). Aerial photograph (IR false colour): Inventaire Forestier National, Lyon, France.

The riparian vegetation of the Allier consists of pioneer trees, herbaceous vegetation, softwood forest, hardwood forest, shrub and grass (Figure 13; Van Oorschot et al., 2015). The pioneer vegetation cover was estimated to be 32% of the floodplain in the study area (Peters et al., 2000). Furthermore, one-third of the floodplain area is covered by grass or grass with some bushes and isolated trees. Finally, further away from the main river channel, one third of the area is covered by softwood forest, mainly white willow (*Salix Alba*) and black poplar (*Populus Nigra*).

Young alluvial forests of *Salix Alba* and *Populus Nigra* are common along chutes, abandoned channels and on meadow habitats (Van den Berg and Balyuk, 2004). On clay deposits in the Allier the small vegetation species Sedum Album and Mathricaria Maritima can be found.

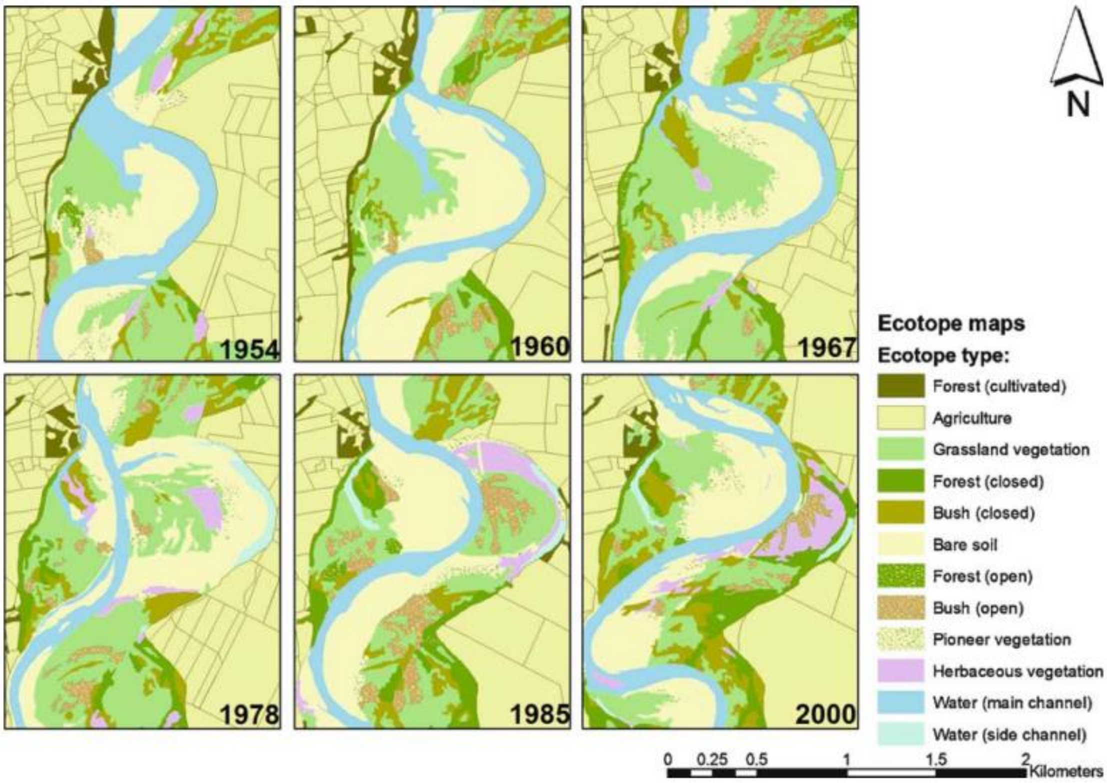

Figure 13 Ecotope maps of the Allier, just upstream of Moulins, in the period 1954-2000 (Geerling et al., 2006).

2.5 Gaps in knowledge

Mud and riparian vegetation are known to interact with each other (Chapter 2.2.3 and 2.3.1), but it is still unknown how the interaction between mud and riparian vegetation affects the morphological development of river systems. Therefore the main aim is "To investigate the combined effects of mud and vegetation on the morphological development of a river system on centennial timescales". To reach this aim, knowledge is required about the mud and vegetation distribution in a river system, the interaction between mud and vegetation, separate effects of mud and vegetation on river morphology and finally the combined effects.

At the moment, it is not well-known how the distribution of mud (thickness of layers, concentration in sediments) depends on topographic disturbances in the floodplain. Furthermore, there is limited knowledge on how the spatial and temporal distribution of mud depends on vegetation presence on floodplain scale. Previous studies generally did not discriminate between deposition of cohesive and non-cohesive sediment types and mainly focused on small scale effects of vegetation.

In addition, knowledge about the two-way interaction between vegetation and river morphology is still limited. Few models include this two-way interaction between vegetation and morphodynamics (Solari et al., 2015). Many numerical modelling studies do take into account the effect of vegetation on flow, but not the other way around. Although models are available which investigate the effect of hydromorphological processes on vegetation processes, often conceptual models are used, probably because the processes are complex (Solari et al., 2015). Therefore it is still not well known how vegetation in the floodplain establishes and how this is related to boundary conditions which affect the river morphology such as the mud supply.

2.6 Hypotheses

2.6.1 Mud and vegetation patterns and interaction

General mud and vegetation patterns

Field observations of floodplain sedimentation along the rivers Waal and Meuse indicate that the proportion of fine-grained sediments increases at larger distances from the channel (Middelkoop and Asselman, 1998). Suspended sediment deposition increases in topographic depressions such as abandoned channels (Middelkoop and Asselman, 1998; Walling and He, 1998). Infilling of abandoned channels generally shows a fining upward sequence with fine sediments including clay on top (e.g. Toonen et al., 2012).

Pressures on vegetation in the river system, such as high flow velocities, flooding and desiccation, can cause strong variations of the amount and location of vegetation patches in the floodplain over time (Geerling et al., 2006; Camporeale et al., 2013). Interaction between the river and riparian vegetation is expected to result in recognizable vegetation patterns, such as an increase in vegetation density with distance from the main channel on point bars and the alignment of trees along the (former) channel with older trees at larger distances from the channel (Figure 10; Perucca et al., 2006).

I hypothesize that:

1. In river systems without vegetation the proportion of mud relative to bedload sediment generally increases with distance from the main channel and increased mud deposition occurs in topographic depressions such as abandoned channels in the final stages of the infilling sequence;
2. Vegetation succession, from pioneers to older vegetation, occurs and is interrupted near migrating river banks and the vegetation density on point bars increases with distance from the river.

Effect of vegetation on mud pattern

Vegetation causes a decrease in flow velocities (Baptist et al., 2007), which leads to increased deposition of fines (Cotton et al., 2006; Kleeberg et al., 2010) within vegetation patches. The reduction of flow velocities is stronger for high density vegetation with a large frontal area and height (Baptist et al. 2007). The trapping of fines may lead to a depletion of suspended sediments, including mud, behind vegetation patches and hence a reduction in mud deposition at larger distances from the channels. Seasonal and yearly variations in vegetation cover likely cause temporal changes in the trapping efficiency of the total river system and hence the area covered by mud deposits. It is expected that the total amount of mud deposition in floodplains is larger in a river system with vegetation compared to a system without vegetation.

I hypothesize that:

3. Vegetation affects the mud distribution over the floodplain:
    a. mud deposition increases within dense vegetation patches;
    b. vegetation causes increased mud deposition close to the active channel and decreased deposition at larger distances from the channel;
4. The amount of mud cover and/or deposition follows temporal variations in vegetation cover;

5. The total net amount of mud deposition in floodplains is larger in a river system with vegetation compared to a system without vegetation.

Effect of mud on vegetation development and pattern

Mud is expected to promote vegetation development in multiple ways. First of all, results of large-scale estuarine morphodynamic numerical modelling showed that increased mud deposition in vegetated areas can elevate vegetation into zones with decreased physical stresses (Lokhorst, 2016). Secondly, mud can stabilize areas (Kleinhans et al., 2010) and hence reduce vegetation mortality due to scour. The above effects of mud on vegetation are expected to be more prominent when the mud supply is higher and/or the mud is more cohesive.

I hypothesize that:

6. Mud supply causes an increase in vegetation cover in a river system, because:
    a. deposition of mud elevates vegetation into a zone with lower physical stresses;
    b. mud stabilizes areas and hence decreases vegetation mortality due to scour;
7. An increase in mud supply or cohesion increases the vegetation cover in the river floodplain.

2.6.2 Effects of mud and vegetation on river morphology

Individual effects of mud and vegetation on river morphology

Mud increases bank strength (Kleinhans, 2010), which is expected to result in lower channel migration rates and channels with a relatively low width-to-depth ratio (Friedkin, 1945 in Van Dijk et al., 2013a; Schumm and Khan, 1972; Van Dijk et al., 2013a). Settling of mud in abandoned channels may reduce recapture of former channels (Braudrick et al., 2009). Both increased bank strength and reduction of the recapture of former channels is expected to result in a decrease in chute cutoff frequency (Braudrick et al., 2009; Van Dijk et al., 2013a). This may in turn promote a more meandering river pattern and hence also a higher channel sinuosity.

Vegetation increases the hydraulic roughness in the floodplain (Baptist et al., 2007) causing flow to focus in the main channel. Decreased flow velocities in the floodplain will generally result in increased sedimentation in the floodplain and decreased floodplain erosion. Acceleration of the flow between vegetation patches (Cotton et al., 2006) can cause erosion between vegetation patches (see review Jones et al., 2012). Channel erosion rates are therefore expected to increase. Positive feedback between vegetation growth, flow conditions and sediment deposition is expected to result in extension of river banks (Figure 9, Gurnell et al., 2012; Schuurman et al., 2016). Finally, like mud, vegetation is expected to settle in abandoned channels, which reduces recapture of former channels and the chute cutoff frequency (Braudrick et al., 2009) and may promote a more meandering channel pattern and higher sinuosity.

I hypothesize that:

8. Mud and vegetation have similar effects on river morphology. They lead to a river system with:
    a. a more stable channel;
    b. a deeper and more confined main channel;
    c. a lower braiding index;
    d. a higher sinuosity;

Effect of mud-vegetation interaction on river morphology

Vegetation is not only expected to increase mud deposition in general, but also to increase mud deposition at morphologically important locations, namely along the channels and in abandoned channels. Therefore, addition of vegetation to a river system is expected to enhance individual effects of mud on river morphology.

The other way around, addition of mud to a river system may promote vegetation development. Therefore, mud is expected to enhance individual effects of vegetation on river morphology. An increase in mud supply and cohesiveness likely strengthens this even further.

Continuing interaction and positive feedback between mud and vegetation could cause significant changes in river morphology over long periods of time. Such changes can be related to fluvial landform formation (e.g. Figure 9). On top of that, large-scale changes in the river pattern may occur. It is possible that ongoing interaction between mud and vegetation stabilizes the river channel to such an extent that it stops migrating.

I hypothesize that:

9. Interaction between mud and vegetation in river systems enhances their individual effects on river morphology. Therefore, a river system with both mud and vegetation, compared to a river system with only mud or vegetation, has:
    a. a more stable channel;
    b. a deeper and smaller main channel;
    c. a lower braiding index;
    d. a higher sinuosity
10. Continuing positive feedback between mud and vegetation results, over a long period, in a laterally inactive river.

3 Methodology and methods

To investigate the combined effect of mud and dynamic vegetation on river morphology we used a numerical model loosely based on the meandering river Allier which includes both mud and dynamic riparian vegetation (*Salix* and *Populus*). Boundary conditions were systematically varied to investigate their effect on mud and vegetation patterns and river morphodynamics. Model outputs were verified by comparing them with data on mud and vegetation patterns gathered during a short field trip at the river Allier and mud deposition patterns obtained with an established floodplain sedimentation model.

The numerical modelling approach was chosen because it makes it possible to study the interaction between mud and vegetation and their effects on river morphology over long timescales of centuries in contrast to a field study or remote sensing analysis. Remote sensing was furthermore not selected as main method, because mud deposition patterns cannot be clearly observed especially in vegetated zones. Numerical modelling, however, does have the risk that processes are oversimplified. Hence, this study includes validation with field and remote sensing data. Ideally, the numerical modelling would be combined with physical experiments and more extensive field research, but this was not possible due to time constraints. The numerical model is only loosely based on the river Allier, because the goal of this research is not to exactly model how the Allier develops, but to get a more generic understanding of the interaction between mud and vegetation in river systems and how this affects the evolution of river patterns and morphology.

The river morphodynamics was modelled in Delft3D (version 4.01.00), which interacts with a dynamic vegetation model (Van Oorschot et al., 2015) programmed in Matlab (R2013b/R2014a) (Figure 14). The Delft3D model calculates flow, sediment transport (including mud) and dynamic morphology. Delft3D was chosen, because currently it is one of the most complete scientific morphodynamic models and has been used and validated many times in both scientific (e.g. Lesser et al., 2004; Gerritsen et al., 2007) and engineering studies (see Schuurman et al., 2013 for examples) with the latter requiring accuracies in the order of decimetres. The vegetation model is advanced as it takes effects of hydromorphodynamics on vegetation into account and vice versa. Vegetation patterns obtained with this model showed good resemblance to patterns found at the river Allier (Van Oorschot, 2015). The current study is innovative, because for the first time both cohesive mud and (dynamic) riparian vegetation are included in a spatially explicit numerical river model.

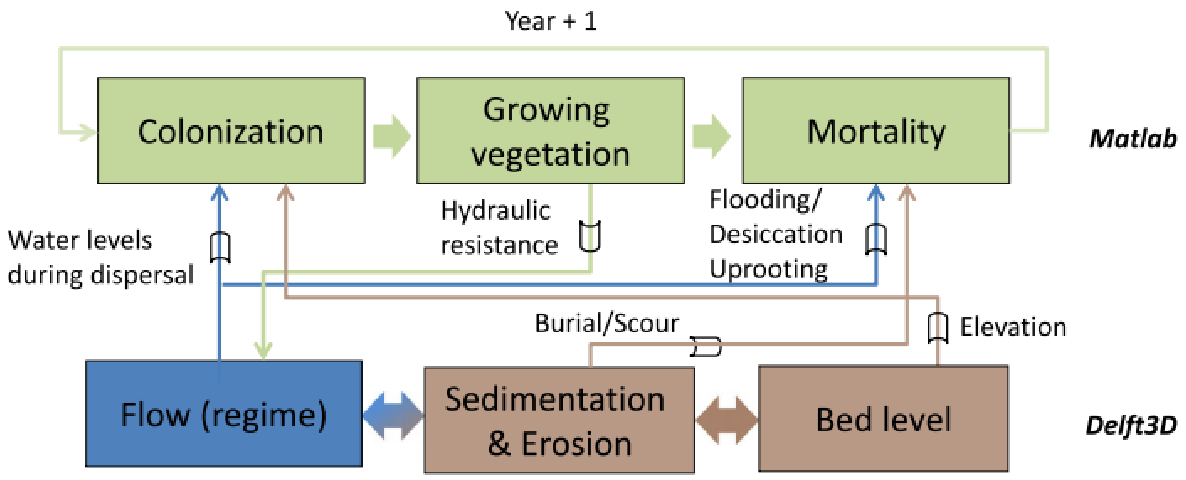

Figure 14 Flow diagram of processes and dynamic interactions of the morphodynamic (Delft3D) and vegetation (Matlab) model (Van Oorschot, 2015).

Below, firstly the morphodynamic and vegetation model are described. This is followed by an explanation of the model schematization, the different model scenarios used and data analysis of the model output. Then, the fieldwork set-up is discussed. Finally, the SEDIFLUX floodplain sedimentation model is described and the analysis performed to compare mud deposition patterns between the morphodynamic model and the SEDIFLUX model.

3.1 Morphodynamic model description

The numerical modelling of river morphodynamics was conducted in Delft3D (version 4.01.00) (Deltares, 2014). The Delft3D model is state-of-the-art and widely used and tested.

Flow

Hydrodynamics are calculated based on the Navier-Stokes equations for incompressible free surface flow with shallow water and Boussineq assumptions (Deltares, 2014). For more efficient calculation, the Delft3D model option was set to simulate two-dimensional, depth-averaged flow, which is appropriate if a fluid is vertically homogeneous (Deltares, 2014). The Navier-Stokes equations are based on continuity (3.1) and momentum equations (3.2 and 3.3):

$$\frac{\partial \eta}{\partial t} + \frac{\partial hu}{\partial x} + \frac{\partial hv}{\partial y} = 0 \qquad (3.1)$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + g\frac{\partial \eta}{\partial x} + \frac{gu\sqrt{u^2+v^2}}{(C^2h)} - v_w\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2}\right) + F_x = 0 \qquad (3.2)$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + g\frac{\partial \eta}{\partial x} + \frac{gv\sqrt{u^2+v^2}}{(C^2h)} - v_w\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2}\right) + F_y = 0 \qquad (3.3)$$

with η = water level with respect to datum (m), h = water depth (m), u = depth averaged velocity in x direction (m/s), v = depth averaged velocity in y direction (m/s), g = gravitational acceleration (m/s^2), C = Chezy friction parameter (m$^{0.5}$/s), v_w = eddy viscosity (m^2/s) and F_{xy} = the acceleration term due to stream line curvature (m/s^2) (Schuurman et al., 2013). The continuity equation states that a change in water level is caused by a gradient in discharge flux in x and y direction. The momentum equations describe the change in velocity in the x and y direction due to advection, eddy diffusivity, friction, water depth variations and stream line curvature (Lokhorst, 2016).

Sediment transport, erosion and deposition

Sediment transport of both the non-cohesive and cohesive sediment type in the model is calculated with the Engelund and Hansen transport equation (Engelund and Hansen, 1967; Deltares, 2014), which considers total transport and relates transport directly to flow velocity:

$$q_s = \frac{0.05U^5}{\sqrt{g}C^3\Delta^2 D_{50}} \qquad (3.4)$$

with U = magnitude of flow velocity (m/s), Δ = relative density $\frac{(\rho_s - \rho_w)}{\rho_w}$, D_{50} = median grain size (m). The fraction of the cohesive sediment type (mud) is calculated with Partheniades-Krone formulations (Partheniades, 1965; Deltares, 2014):

$$E_m = M_m\left(\frac{\tau_{cw}}{\tau_{cr,e}} - 1\right)\ \tau_{cw} > \tau_{cr,e} \qquad (3.5)$$

$$D_m = w_s c_b\left(1 - \frac{\tau_{cw}}{\tau_{cr,d}}\right) \qquad (3.6)$$

with E_m and D_m = erosion/deposition flux of mud (kgm^{-2}s^{-1}), M_m = erosion parameter (kgm^{-2}s^{-1}), τ_{cw} = maximum bed shear stress due to current and waves, $\tau_{cr,e}$ and $\tau_{cr,d}$ = critical shear stress for erosion/deposition (N/m^2), w_s = mud settling velocity (m/s) and c_b = the average sediment concentration near the bottom.

Bed composition

The effect of bed composition on bed erosion is incorporated in the model, which is important because sediment transport not only depends on the carrying capacity of a flow, but also on the sediment supply from the bed. The bed module for Delft3D that allows the incorporation of sediment mixtures and takes into account the effect of bed composition on erosion properties of the bed has recently been developed (Van Kessel et al., 2012). This module tracks the sediment composition and includes formulations that describe how the bed composition affects bed erosion.

There are two different regimes of erosion behavior of the bed in the model for which different erosion formulations are used (Van Kessel et al., 2012). If the mud fraction in the top layer remains below a prescribed critical value ($p_{m,cr}$, hereafter called PmCrit), the erosion behavior of the bed is non-cohesive, while in case the mud fraction exceeds this critical value the erosion behavior of the bed becomes cohesive. In the non-cohesive regime sand erosion is determined with the Engelund and Hansen transport equation (eq. 3.4) and mud erosion is calculated with Partheniades-Krone formulations (eq. 3.5). In the cohesive regime the erosion rate of sand is equal to the erosion rate of mud (Braat and Kleinhans, in preparation), because mud particles stick sand particles together.

To optimally model the bed composition, a mixed Eulerian-Langragian approach was used whereby the bottom is divided in 50 Eulerian layers and 1 Langrangian top layer. The Lagrangian layer can move up and down and has a constant thickness, while the Eulerian layers have a fixed position but can grow up to a maximum thickness. The advantage of using a mixed Eulerian-Langragian approach is that artificial diffusion due to movement of the grid is minimal with Eulerian layers (better to keep track of the mud fractions in the bottom), while the Lagrangian surface layer with constant thickness prevents undesired effects of layer thickness on the time scales of the system (Van Kessel et al., 2012).

Incorporation of vegetation

The bottom roughness in the morphodynamic model is computed according to Chézy:

$$C = 18\log_{10}\left(\frac{12H}{k_s}\right) \qquad (3.7)$$

with C = Chézy value (m$^{0.5}$/s), H = water depth (m) and k_s = equivalent geometrical roughness of Nikuradse (m). Hydraulic resistance due to vegetation was calculated for each grid cell for both flow through vegetation and flow above vegetation with the following equation of Baptist et al. (2007):

$$C = \frac{1}{\sqrt{\frac{1}{C_b^2}+\frac{C_d n h_v}{2g}}} + \frac{\sqrt{g}}{k}\ln\left(\frac{h}{h_v}\right) \qquad (3.8)$$

with: C = Chézy value of vegetation (m$^{0.5}$/s), C_b = Chézy value for the unvegetated parts, c_d = drag coefficient (-), n = vegetation density (stem diameter x number of stems per m^2) (m^{-1}), h_v = vegetation height (m), h = water depth, κ = Von Karman constant (0.41) and g = gravitational acceleration (9.81 m/s^2). Equation 3.8 takes into account drag as a result of vegetation density, diameter and height, which is common in vegetation modelling (Solari et al., 2015), but treats vegetation as rigid cylinders. The decrease of frontal area drag and lift force as a result of bending vegetation and possible additional resistance due to swaying vegetation are ignored (Baptist et al., 2007). Furthermore, this equation does not specify leave characteristics and changes in leave area over the year.

3.2 Vegetation model description

The dynamic vegetation model (Van Oorschot et al., 2015) is programmed in Matlab (designed in R2013b and run for current study in R2014a) and interacts with the Delft3D model at each ecological time step. The vegetation model retrieves data about bed levels, flow velocities and water levels from the Delft3D model and returns updated information about vegetation characteristics that are needed for the hydraulic resistance calculation in Delft3D (Figure 14). The model consists of two different riparian Salicaceae species, namely a *Salix* type (willow) and a *Populus* type (poplar). Riparian trees were chosen for the model, because these are the most important ecosystem engineering species on river floodplains in northwestern Europe (Corenblit et al., 2009; Gurnell, 2014). One model year consists of 24 ecological time steps of approximately two weeks, which is appropriate to represent ecological processes. At the beginning of each ecological time step, the morphodynamic model is paused, vegetation processes are calculated and new vegetation locations and characteristics are returned to the morphodynamic model. Different vegetation processes occur all within one year and are explained below.

General and life stage-specific vegetation characteristics

The two different riparian tree species in the model have different general and life stage-specific characteristics. General characteristics are maximum age, initial shoot and root length, initial stem diameter, growth factors for logarithmic growth of the shoot length and root and stem diameter and timing of seed dispersal. Life stage-specific parameters include the number of stems per unit area, the fraction of area covered per grid cell, a drag coefficient and mortality rules for flooding, desiccation and uprooting. The life stage-specific parameters are important, because the vulnerability of vegetation species to flow conditions and their effect on flow conditions differs for different stages. Therefore, life stage-specific parameters are necessary to model natural vegetation development and interactions with hydromorphology.

Vegetation colonization

Colonization of riparian tree seedlings occurs on bare, moist substrate located between minimum and maximum water levels during the seed dispersal window (Van Oorschot et al., 2015). Only sexual reproduction of plants by means of seeds, not asexual reproduction, is taken into account in the model, which is justified by the fact that in the study area along the river Allier most adult vegetation objects of *Populus Nigra* originated from seeds (Legionnet et al., 1997). In the dispersal window, vegetation is assigned to grid cells, whereby seed supply was assumed to be unlimited. This assumption is valid in case of dominant riparian trees which have a large seed production (Braatne et al., 1996). The density with which seeds were allowed to settle in each grid cell depends on the amount of antecedent vegetation cover. In case a grid cell was empty, a predefined initial cover fraction of a vegetation species was assigned to this cell. If the cell was already partly covered, the cell was filled up with seedlings to a fraction of one. This way to model settling makes it possible to have multiple vegetation types of different ages to reside in a single grid cell and initiates competition of space.

Vegetation growth

The shoot length, root length and stem diameter depend on age according to a logarithmic growth function:

$$G = F_v \log(a) \tag{3.9}$$

with G = shoot length, root length or stem diameter (m), F_v = vegetation-type dependent logarithmic growth factor (-) and a = vegetation age (years). The seedling dimensions were taken from the initial conditions in the first life stage. After each year vegetation that survived increases in age until they reach their species dependent maximum age.

Vegetation mortality

Mortality of vegetation in the model occurs due to flooding, desiccation, high flow velocities, burial, scour and senescence. The percentage of mortality due to flooding, desiccation and flow velocities is determined by dose-effect relations (Figure 15) that describe the percentage of mortality for a certain morphodynamic pressure. Each dose-effect relation consists of a threshold value from which vegetation starts to die and a slope indicating the sensitivity of the vegetation to the morphodynamic pressure. The threshold value and slope are user defined and differ per morphodynamic pressure type (flooding duration, desiccation duration, flow velocity) and per vegetation type and life-stage. Mortality is implemented in the model by decreasing the fraction of a certain vegetation type present in a grid cell by the percentage mortality from the dose-effect relation:

$$Mortality\ fraction = mortality \times initial\ fraction \quad (3.10)$$

$$New\ fraction = current\ fraction - mortality\ fraction \quad (3.11)$$

This means that all vegetation within a grid cell can die, even if the mortality percentage is not 100 percent. Vegetation also dies in case the whole plant is buried and due to scour if the amount of scour exceeds the root length of a plant. Sedimentation and erosion are calculated as the bed level difference between two ecological time steps. The maximum amount of sedimentation and erosion is saved for each year and used to calculate mortality by burial and scour. Finally, vegetation dies as a result of senescence after it has reached its maximum age.

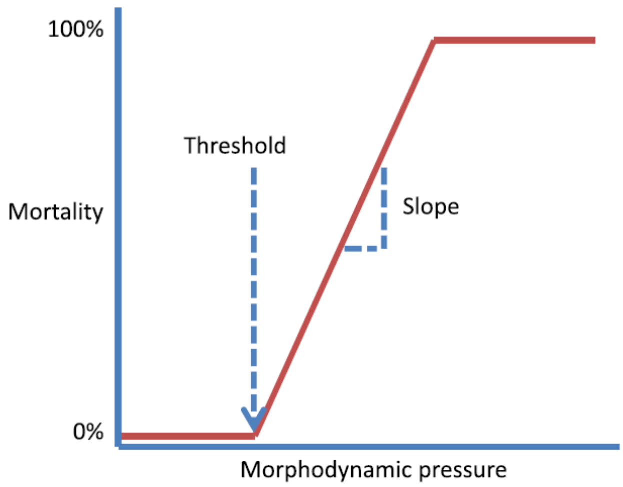

Figure 15 Dose-effect relation for vegetation mortality. The dose-effect relation in the vegetation model gives the percentage vegetation mortality for a certain morphodynamic pressure (duration of flooding, duration of desiccation, flow velocity). A threshold value has to be exceeded before mortality starts. The slope indicates the sensitivity to the morphodynamic pressure. In case of a vertical slope the threshold is sharp and all vegetation dies a soon as the threshold value is exceeded. Threshold and slope values are defined for each type of morphodynamic pressure and are specific for vegetation type and life stage (Van Oorschot et al., 2015).

The model does not directly take the effect of vegetation on bank strength into account. The influence of groundwater on vegetation is also only indirectly incorporated in the model by the relative low threshold for desiccation. Finally, vegetation development in the model is not directly dependent on the soil mud content.

3.3 Model schematization

The schematization of the numerical model is loosely based on the meandering river Allier in France. An overview of basic parameter settings of the morphodynamic model and sediment characteristics is given in Table 1 and Table 2, respectively. General and life-stage specific vegetation characteristics can be found in Table 3 and Table 4.

Initial bathymetry

The initial bed level of the model consists of three meander bends over a distance of 3.6 km (Figure 16). The length of these meander bends is based on aerial photographs of the Allier, bar length theory (Struiksma, 1985; Kleinhans and van den Berg, 2011) and values from literature (Geerling et al., 2006; Crosato and Saleh, 2011).

Time

The total simulation time is 300 years for the main model runs and 150 years for additional scenarios, with hydrodynamic and morphodynamic time steps of respectively 0.2 and 6 minutes. In the calculation of morphology the bathymetry is updated during flow simulation to account for the feedback between flow and bathymetry. Because morphology changes over much longer time scales than flow, a morphological scale factor was set at 30 so that the speed of changes in morphology is scaled up to a rate that it significantly impacts hydrodynamic flows (note the factor 30 difference in time steps between flow and morphology).

Discharge

The discharge implemented at the upstream boundary (Figure 17) was sampled from five generalized discharge years of the Allier and ranges between 50 m^3/s in summer and 400 m^3/s in winter. For computational efficiency the effect of sediment on fluid density was neglected.

Sediment types

Both a non-cohesive (sand/pebbles) and a cohesive (mud) suspended sediment type are included in the model (Table 2). At the start of the run the bed consists entirely of the sand/pebble sediment fraction. A constant settling velocity of mud was assumed in the model. To prevent accretion or erosion near the model boundaries, it was specified that flow at the inflow boundary should carry the non-cohesive coarser sediment fraction at its equilibrium concentration profile. The default mud input upstream was set at 20 mg/L. Note that the default mud concentration is not meant to exactly resemble the mud concentration in the river Allier. Also, the mud supply does not fluctuate with discharge, contrary to natural situations.

Mud settings

The default critical mud fraction ($p_{m,cr}$), the mass fraction mud above which the bed behaviour regime becomes cohesive (Van Kessel et al., 2012), is set at 0.4 following Braat and Kleinhans (in preparation). This is higher than many values from literature based on flume (0.03-0.15, Mitchener and Torfs, 1996) and field (0.2, Houwing, 1999; 2000) experiments. No single value for the critical mud fraction exists, because mud can consist of different proportions of silt and cohesive clay. Clay fraction was found to be a better discriminator between the cohesive and non-cohesive bed regimes than mud fraction (Van Ledden, 2004). The clay fraction is not used for the current model, because other model processes such as sediment settling favoured the use of mud over clay (Braat and Kleinhans, in preparation). The critical shear stress of erosion of mud was set at 0.2 N/m^2 based on Fig. 6 in Mitchener and Torfs (1996). A Chézy value of 25 $m^{0.5}/s$ was used for bare surfaces based on Van Dijk et al. (2014).

Zeta0

An important change compared to the model of Van Oorschot et al. (2015) is the use of a lower initial water level (Zeta0) in Delft3D. Delft3D starts with a relatively high water level and iterates at the beginning of a run until the water level is in equilibrium with the imposed upstream discharge. In the original model, the lowering of the water level resulted in ponding and numerical problems causing the presence of grid cells that could not be eroded. By lowering Zeta0, this problem was (partly) prevented.

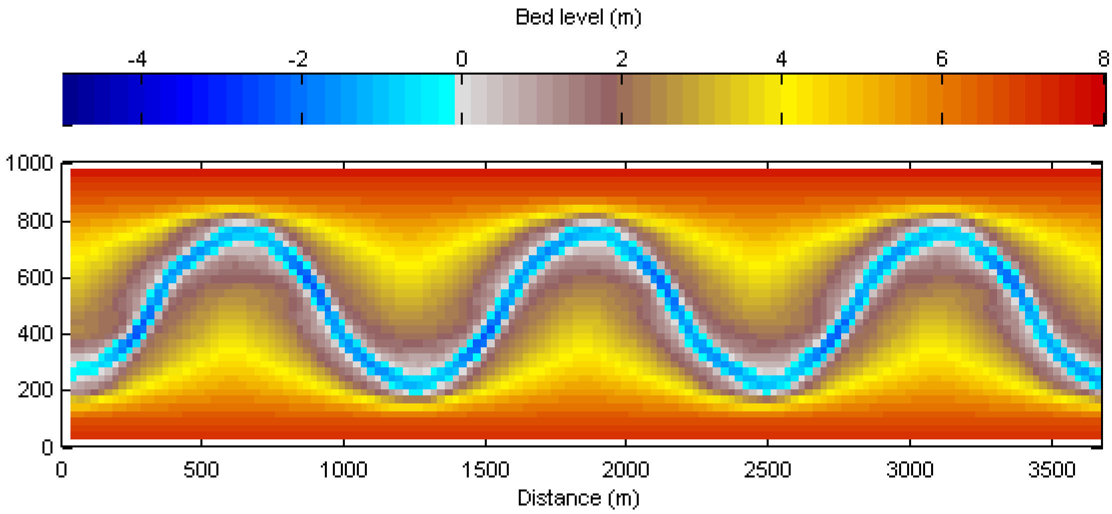

Figure 16 Initial detrended bathymetry of the model.

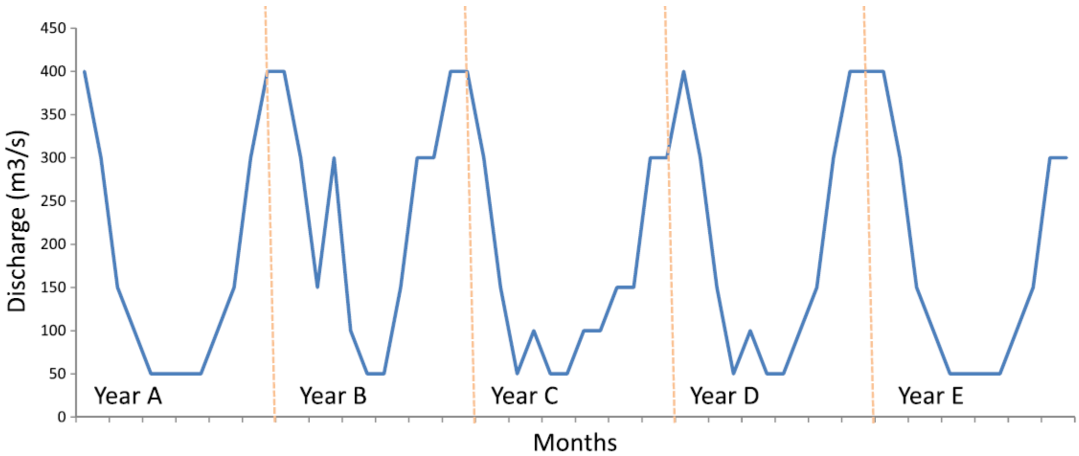

Figure 17 Upstream boundary condition inflow. Image represents five time series of flow discharge over 1 year, which were randomly selected for a time series of 300 years (Van Oorschot et al., 2015).

Table 1 Morphodynamic parameter settings (Table I from Van Oorschot et al. [2016], supplemented with mud conditions).

Parameter	Value (unit)	Unit	Reference or motivation
Timespan model run	300	yr	At least one life cycle of a riparian tree
Hydrodynamic time step	0.2	min	Based on grid cell size and flow velocity
Morphological scale factor	30	-	Schuurman et al. (2013)
Time step bed-level change	6	min	
Time step vegetation	21900	min	To capture main ecological processes
Grid size (width x length)	1000 x 3600	m	Covering a few meanders
Cell size (width x length)	25 x 25	m	Compromise between resolution and model efficiency
Chézy value bare substrate	25	$m^{0.5}/s$	Van Dijk et al. (2014)
D50	5×10^{-3}	m	Van Dijk et al. (2014)
Sediment transport predictor	Engelund-Hansen (EH)	-	Schuurman et al. (2013)
Initial sinuosity	1.3870	-	Geerling et al. (2006)
Critical mud fraction	0.4	-	Mainly based on dynamic river behaviour in test runs and following Braat and Kleinhans (in preparation). Supported by Panagiotopoulos et al. (1997).
Critical shear stress of erosion (mud)	0.2	N/m^2	Mitchener and Torfs (1996)

Table 2 Sediment characteristics of the two sediment types in the default model.

Sediment characteristic	Unit	Sediment1 (sand)	Sediment2 (mud)
Type	-	Non-cohesive	Cohesive
Reference density for hindered settling	kg/m^3	1600	1600
Specific density	kg/m^3	2650	2650
Dry bed density	kg/m^3	1600	1600
Median sediment diameter (D50)	µm	5000	-
Initial sediment layer thickness at bed	m	5	0.050000001
Fresh settling velocity	mm/s	-	0.25
Critical bed shear stress for sedimentation	N/m^2	-	1000
Critical bed shear stress for erosion	N/m^2	-	0.2
Erosion parameter	$kg/m^2/s$	-	0.0001

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Table 3 General vegetation characteristics of *Salix* and *Populus* (taken from Table II in Van Oorschot et al. [2016]).

Parameter	Unit	Vegetation type 1	Vegetation type 2	Reference
Vegetation type	-	*Salix* type	*Populus* type	Main riparian ecosystem engineers, Gurnell (2014)
Maximum age	yr	60	150	Braatne et al. (1996); Peters (2002)
Initial root length	m	0.1	0.5	Canadell et al. (1996)[a]
Initial shoot length	m	0.25	0.1	Van Velzen et al. (2003)
Initial stem diameter	m	0.002	0.036	Van Velzen et al. (2003)
Logarithmic growth factor root	-	0.85	1.15	Canadell et al. (1996)[a,b]
Logarithmic growth factor shoot	-	11.5	14	Kleyer et al. (2008)[a]
Logarithmic growth factor stem diameter	-	0.41	0.6	Van Velzen et al. (2003)[a]
Timing of seed dispersal	month	6 (June)	5 (May)	Kleyer et al. (2008); Van Splunder et al. (1995)

[a] Value extracted from the logarithmic growth curve created to fit the maximum parameter value found in the literature
[b] Fact sheet from Istituto di Biologia Agroambientale e Forestale (http://ww.ibaf.cnr.it/en/ consulted in 2014).

Table 4 Life stage-dependent vegetation characteristics of *Salix* and *Populus* (taken from Table II in Van Oorschot et al. [2016]). LS1 = seedlings, LS2 = bush, LS3 = forest, LS4 = degeneration.

		Life stages *Salix* type				Life stages *Populus* type				
Parameter	**Unit**	**LS1**	**LS2**	**LS3**	**LS4**	**LS1**	**LS2**	**LS3**	**LS4**	**Reference**
Number of years in life stage	yr	1	9	40	10	1	9	130	10	Adapted from Van Velzen et al. (2003)
Number of stems	stems/m^2	25	15	0.16	0.16	25	13	0.27	0.27	Van Velzen et al. (2003); Wolf et al. (2001)
Area fraction (0-1)	-	0.8	0.8	0.8	0.8	0.8	0.8	0.8	0.8	Initial guess
Drag coefficient	-	1	1.5	1.5	1.5	1	1.5	1.5	1.5	Van Velzen et al. (2003); Fortherby et al. (2012)
Desiccation threshold	days	25	190	240	365	35	210	260	365	Geerling et al. (2006)[a]
Desiccation slope	-	0.75	0.3	0.3	1.0	0.75	0.3	0.3	1.0	Geerling et al. (2006)[a]
Flooding threshold	days	70	260	310	365	60	240	310	365	Geerling et al. (2006)[a]
Flooding slope	-	0.75	0.3	0.3	1.0	0.75	0.3	0.3	1.0	Geerling et al. (2006)[a]
Flow velocity threshold	m/s	0.55	7.0	12.0	6.0	0.55	7.0	12.0	6.0	Geerling et al. (2006)[a]
Flow velocity slope	-	0.75	0.3	0.3	0.3	0.75	0.3	0.3	0.9	Geerling et al. (2006)[a]

[a] Age distribution in Geerling et al. (2006) used for mortality thresholds and slope determined after 10-year run.

3.4 Model scenarios

The model was run for different scenarios to determine effects of interaction between vegetation and mud on morphological development of a river (Table 6). The main scenarios are: (1) mud and dynamic vegetation, (2) only dynamic vegetation, (3) only mud and (4) no mud or vegetation. Additional model scenarios (Table 5; Table 6) were used to test the effect of combinations of upstream mud supply and mud cohesiveness on river morphology and to test the sensitivity of model outcomes to the critical mud fraction (PmCrit) and active layer thickness.

Table 5 Parameters changed in scenarios and sensitivity analysis.

Parameter	Unit	Low	Default	High	Extra
Mud supply	kg/m^3	5e-3	2e-2	5e-2	1e-1 & 5e-1 & 8e-1
Critical mud fraction (PmCrit)	-	0.2	0.4	0.6	-
Critical shear stress for mud erosion	N/m^2	0.1	0.2	0.5	-
Active layer thickness	m	-	0.03	0.1	-

Table 6 Overview of model runs

Run nr.	**Dynamic vegetation**	**Mud supply**	**Critical mud fraction**	**Critical shear stress for mud erosion**	**Active layer thickness**	**Remarks**
-	**-**	kg/m^3	**-**	N/m^2	m	
001	yes	2e-2	0.4	0.2	0.03	Main scenario 1
002	yes	**0**	0.4	0.2	0.03	Main scenario 2
003	**no**	2e-2	0.4	0.2	0.03	Main scenario 3
004	**no**	**0**	0.4	0.2	0.03	Main scenario 4
005	yes	**5e-3**	0.4	0.2	0.03	
006	yes	**5e-2**	0.4	0.2	0.03	
007	yes	**1e-1**	0.4	0.2	0.03	
008	yes	**5e-1**	0.4	0.2	0.03	
009	yes	2e-2	0.4	**0.1**	0.03	
010	yes	2e-2	0.4	**0.5**	0.03	
011	yes	**1e-1**	0.4	**0.5**	0.03	
012	yes	**5e-1**	0.4	**0.5**	0.03	
013	yes	**8e-1**	0.4	**0.5**	0.03	
014	**no**	**5e-1**	0.4	**0.5**	0.03	
015	yes	2e-2	**0.2**	0.2	0.03	
016	yes	2e-2	**0.6**	0.2	0.03	
017	yes	2e-2	0.4	0.2	**0.1**	

3.5 Analysis of model results

The most important data obtained from the model were maps with information on bed level, vegetation age, vegetation fraction and mud fraction in the top layer for each grid cell. Other data included information on water levels, flow velocities, maximum bed shear stresses and mud volume fractions in the bed below the top layer.

Data analysis was performed both qualitatively/visually and quantitatively. In general, data from the 24th ecological time step of each year was used for analysis representing high flow conditions in winter. Information from the 12th ecological time step, which is in summer during low flow conditions, was used for calculating the sinuosity and channel migration. The active braiding index is calculated for both summer and winter, but in general I refer to the active braiding index in winter. Bed level data were detrended over the length of the river stretch so that the valley gradient became zero. The upper and lower 500 m (20 grid cells) of the river stretch were excluded from statistics to reduce immediate boundary effects. The first 24 years of the simulations were excluded from statistics as well, because during these years the bed level rapidly changes and the system is far from a dynamic equilibrium. The maximum age in each grid cell was used as vegetation age. Vegetation was divided in three age classes: pioneer/seedling (1 year), bush (2-10 years) and forest (> 10 years) following Van Oorschot et al. (2015). In the results section a distinction is made between cover percentage and (cover) fraction. Cover percentage refers to the percentage of all grid cells together, while fraction refers to the cover fraction within a single grid cell.

The analysis of the model results is divided in three parts focussing on (1) mud and vegetation patterns, (2) effects of boundary conditions on morphology and (3) model sensitivity/validation.

Mud and vegetation patterns were studied by analysing the total amount and spatial distribution of mud and vegetation cover over time, correlating the amount of bed level change to vegetation (age and fraction) and mud fraction and by correlating the amount of mud to the presence of vegetation. Mortality due to flooding, desiccation, uprooting, burial and scour was calculated for each vegetation age class for both vegetation types together. Mud deposit dynamics were represented by the age distribution of mud deposits in the last year of the model simulations. Finally, the dependence of the mud and vegetation cover on the additional model boundaries (mud supply, critical shear stress for mud erosion, PmCrit and active layer thickness) was studied.

To study the effect of various boundary conditions on river morphology the development of the sinuosity, active braiding index, channel migration, median bed level and fifth percentile bed level was analysed over time. The statistics of these morphological parameters were calculated following the methods of Van Oorschot et al. (2015). To calculate the sinuosity and channel migration the location of the path with the maximum flow velocity in each cross-section was determined first. Large spatial shifts in maximum flow velocity, occurring when chute bars temporarily have a higher flow velocity than the main channel, were filtered out. When the distance between the y-location of subsequent maximum flow velocities exceeded four grid cells, approximately the channel width, these values were deleted. Finally, the flow path was smoothed using a moving average over three grid cells. Sinuosity was then calculated as the length of the (maximum) flow path divided by the valley length. The channel migration was calculated as the minimum shift of the (maximum) flow path in steps of 10 years. The active braiding index was determined as the mean number of channels over the cross-section in which the flow velocity exceeded 0.3 m/s. The fifth percentile was used as indicator for channel depth.

The model was validated by evaluating the sensitivity of the river morphology to the PmCrit and the active layer thickness parameters in Delft3D and by evaluating the flow velocity and water depth. Furthermore, spatial mud and vegetation patterns from the model were qualitatively compared to patterns in the field. Also, mud deposition patterns were both qualitatively and quantitatively compared to patterns obtained with the SEDIFLUX floodplain sedimentation model (Chapter 3.2.7).

3.6 Fieldwork set-up

A short field trip to the river Allier just south of Moulins in France was conducted in the last week of August 2016. The fieldwork area is located between UTM 31T 524000 5156000 and UTM 31T 528000 5139000. The river channel is currently not regulated or excavated at this location and many vegetation species are present, which makes it an excellent location to study river morphodynamics in relation to vegetation (Geerling et al., 2006).

Focus of the field trip was on the mud and vegetation patterns in the area and relations between them and river morphology. Measurements were performed along eight transects across four point bars perpendicular to the river channel and an additional transect at the edge of a point bar along the river channel (Appendix 1). Each transect consists of about 10-20 measurements with distances of 10-

20 m in between and locations were recorded using GPS. The locations of transects were chosen based on presence of interesting vegetation patterns, accessibility, overlap with an earlier fieldwork campaign of Van Oorschot (transect 1-8) and overlap with an area that is extensively studied by other students using remote-sensing (transect 1-5).

At each of the eight transects across point bars the sediment composition at the surface and at 10 cm depth was measured. At the surface, the sediment composition was determined by assigning area fractions of the surface to 15 classes of different grain size. The area fraction that fell into a certain grain size class was mostly determined by observing the ground from above and by taking and studying a sample in the hand. This last approach was used especially for smaller grain sizes. The division of sediment sizes into area fractions was discussed with four persons, especially at the start of the measurements, to improve reliability. Additional remarks about organic layers or dense vegetation were noted. The sediment composition at 10 cm depth was only divided in percentage gravel (> 2 mm), sand (0.062 - 2.0 mm) and mud (<0.062) and was determined after digging a small hole with a shovel and observing the sediment composition on the ground and on the shovel. Besides the sediment composition, a short morphological feature description and vegetation description, e.g. dense grass, trees, sparse shrubs, were noted at each location. It should be noted that especially the mud deposition pattern found at the surface may be different from winter conditions due to the large yearly discharge fluctuations.

3.7 Floodplain sedimentation model

The location of mud deposition in the Delft3D-vegetation model was compared to mud deposition fluxes obtained with the floodplain sedimentation model SEDIFLUX (Middelkoop and Van der Perk, 1998) to determine if the Delft3D model is reliable. SEDIFLUX is applicable to river reaches of several kilometres and takes the effect of irregularities in floodplain topography on sediment deposition into account, which is necessary for prediction of sediment deposition patterns in the modelled river stretch of the Allier where both topographic disturbances and presence of vegetation lead to a complex flow and deposition pattern. The SEDIFLUX model has been calibrated and validated with field data of sediment deposition after a major flood on the embanked floodplain of the lower river Rhine in the Netherlands (Middelkoop and Van der Perk, 1998). SEDIFLUX appeared to be a suitable tool to predict patterns and amounts of floodplain sedimentation, for both individual flood events and annual averages.

3.7.1 SEDIFLUX model description and settings

SEDIFLUX is a raster- and GIS-based floodplain sedimentation model (Middelkoop and Van der Perk, 1998). The model concept is based on the sediment balance in each grid cell, consisting of horizontal advective sediment fluxes in and out cells and a vertical deposition flux within a grid cell. SEDIFLUX calculates sediment deposition assuming steady flow conditions. The upstream boundary has a fixed sediment input concentration, while the lower boundary is considered open.

Output of the Delft3D model of subsequent ecological time steps consisting of maps of the water level, bed level, maximum shear stress and depth-averaged flow velocities in x- and y direction, was used as input for the SEDIFLUX model. The input sediment concentration upstream, fall velocity and critical shear stress for sediment deposition were set the same as in the Delft3D model. The critical shear stress for deposition in Delft3D is so high (1000 N/m^2) that the sediment deposition flux is not reduced when the shear stress in the river system is high (see section 3.1 equation 3.6). With SEDIFLUX an additional model run was performed with a much lower critical shear stress (2 N/m^2), similar to the value used by Middelkoop and Van der Perk (1998), to test whether it is correct to have such an extremely high value for the critical shear stress for mud deposition in Delft3D.

For each ecological time step in Delft3D, the SEDIFLUX model creates raster maps with the sediment concentration in the water and the sediment deposition rate following an iterative procedure for each raster cell (for a full description of equations see Middelkoop and Van der Perk, 1998). SEDIFLUX determines the incoming sediment concentration in a grid cell from the incoming sediment fluxes from adjacent upstream cells. The sediment deposition flux is calculated using the concept of Krone (1962) (see Chapter 3.1 equation 3.6). Finally, the outgoing sediment flux is calculated by subtracting the loss by deposition from the incoming concentration, weighted according to the height of the water column in the cell. Between each iteration step, full mixing of sediment in the water column is assumed. The iteration is repeated until equilibrium is reached.

3.7.2 Analysis

Mud concentrations and deposition patterns obtained with Delft3D (with high critical shear stress for deposition) and the SEDIFLUX models (with high and low critical shear stress for deposition) were compared for the main model run in Delft3D with mud and vegetation over the period between year 105 and 109. This particular period was chosen, because it is characterized by the formation of mud deposits. Each year consists of 24 ecological time steps in Delft3D hence the output of SEDIFLUX consists of 120 maps with mud concentrations and deposition.

Maps with the concentration and deposition fluxes averaged over five years were created for the Delft3D model and the SEDIFLUX models with high and low critical shear stress for mud deposition. For this, the deposition flux in Delft3D at each time step is calculated by multiplying the sediment concentration in grid cells with the fall velocity. Besides the maps with average concentrations and deposition fluxes, a map is created which indicates net deposition in Delft3D by subtracting the mud fraction in the top layer in Delft3D at the beginning of year 105 from the mud fraction in the top layer at the end of year 109. In SEDIFLUX the mean deposition fluxes also represent the net deposition, because erosion is ignored. Spatial patterns in the created maps of the models were compared and linked with floodplain bathymetry and the vegetation distribution.

Scatter plots were created to see if mud concentrations, deposition fluxes and net deposition in SEDIFLUX and Delft3D correlate. In these scatter plots also relations were sought between concentrations and water depths, between deposition fluxes and vegetation fractions and between deposition fluxes and distance from the upstream boundary.

Finally, mean deposition fluxes for classes with different vegetation fractions were calculated for each of the three models.

4 Results and interpretation

The main result is that in high-energy river systems comparable to the Allier, vegetation strongly affects the spatiotemporal mud distribution and river morphodynamics, while mud has relative minor influence on both vegetation development and morphodynamics.

Temporal and spatial patterns of mud strongly depend on the distribution and dynamics of vegetation. When both mud and vegetation are present in the river system, mud deposition occurs at locations with vegetation, which is often along channel margins (Figure 18 A), and in (partly) abandoned channels. When vegetation is absent, mud deposits in (partly) abandoned channels often further away from the active channel (Figure 18 C). The mud cover follows temporal variations in the highly dynamic vegetation cover.

Vegetation generally has a much larger impact on morphodynamics than mud. Vegetation causes flow to focus in a single channel, resulting in deeper, more confined channels and a wandering river pattern with meandering river characteristics (Figure 18; Figure 19). The floodplain morphology in the main model scenarios in which the only difference is mud supply is approximately the same, while the morphology differs significantly when there is a change in vegetation presence (Figure 18; Figure 19). An extremely high mud supply and relative large cohesiveness in combination with vegetation causes channel deepening and confinement (Figure 18 F) and leads to a reduction of the hydrological connectivity between channel and floodplain. Therefore, the vegetation cover is strongly reduced to a narrow zone along the channel.

Interaction between mud and vegetation does not result in a markedly different morphology than a system with only vegetation in the main model runs. However, a combination of vegetation and an extreme mud supply and relatively large cohesiveness causes channel deepening and more channel stabilization compared to the systems with only mud or only vegetation. The small effect which mud generally has on river morphodynamics is probably strengthened by vegetation presence, because vegetation promotes mud deposition at locations crucial for the morphological development of a river, namely near active channels and in (partly) abandoned channels. However, both in systems with a moderate or a high mud supply and cohesiveness, there is no ongoing positive feedback between mud and vegetation which results in large changes in river morphology.

A summary of the numerical modelling results is given in Appendix 3 and Figure 57.

In this Chapter I firstly elaborate on the temporal and spatial mud and vegetation patterns and the interaction between mud and vegetation (Chapter 4.1). Secondly, I discuss in more detail the individual and combined effects of mud and vegetation on river morphodynamics (Chapter 4.2). Then, I present results from field observations in the Allier (Chapter 4.3). Finally, I discuss the model sensitivity and validity, which includes a comparison of model outcomes with the field observations and the SEDIFLUX floodplain sedimentation model (Chapter 4.4).

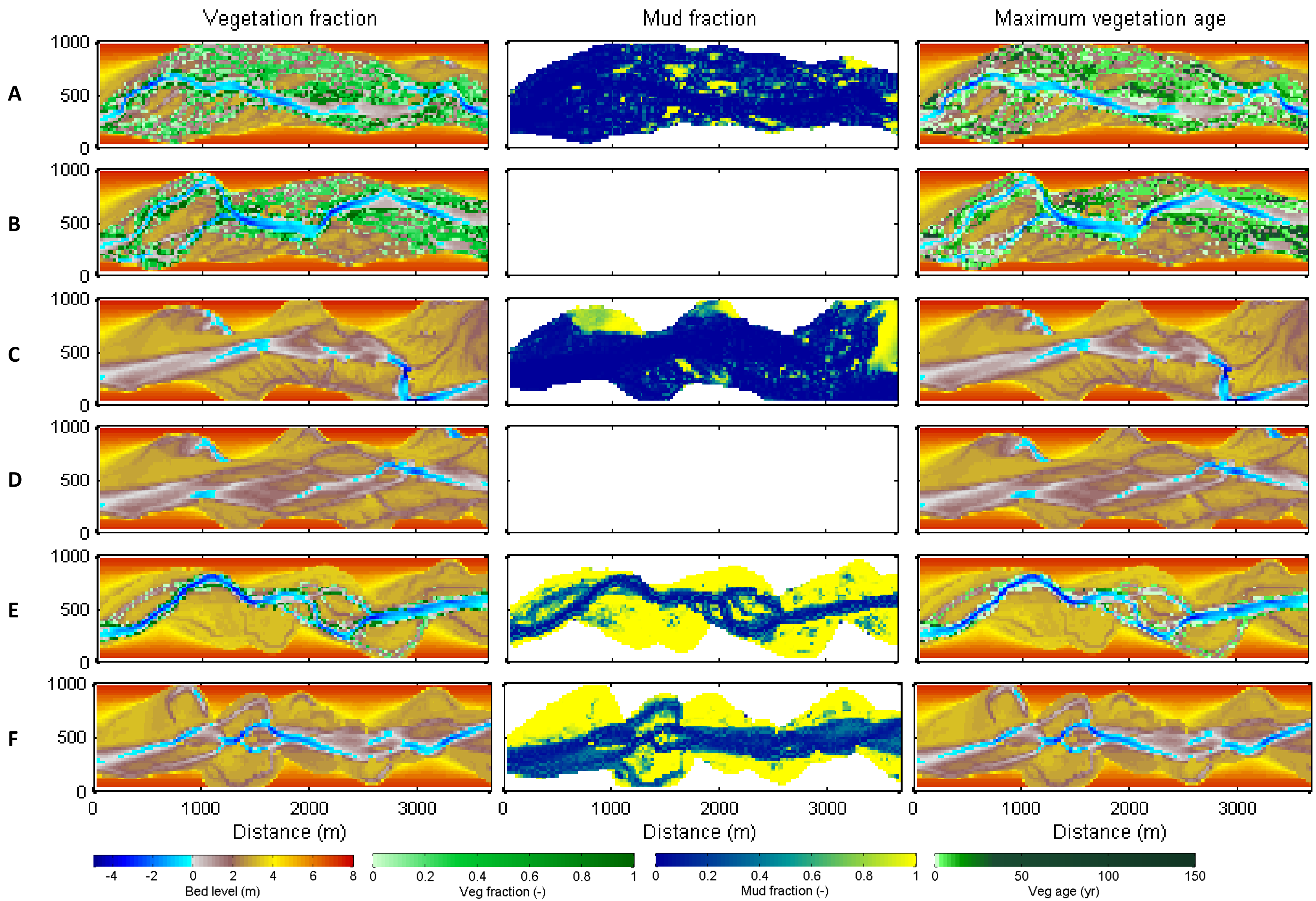

Figure 18 Bathymetry, vegetation fraction, mud fraction in top layer and maximum vegetation age for the four main scenarios after 300 years of simulation (A-D) and for two additional model scenarios with a relatively high mud supply (500 mg/L compared to 20 mg/L default) and cohesiveness ($\tau_{cr,\,ero}$ = 0.5 N/m² compared to 0.2 N/m² default) after 150 years of simulation (E-F). A: mud and vegetation, B: only vegetation, C: only mud, D: no mud or vegetation, E: high mud supply and cohesiveness with vegetation, F: high mud supply and cohesiveness without vegetation.

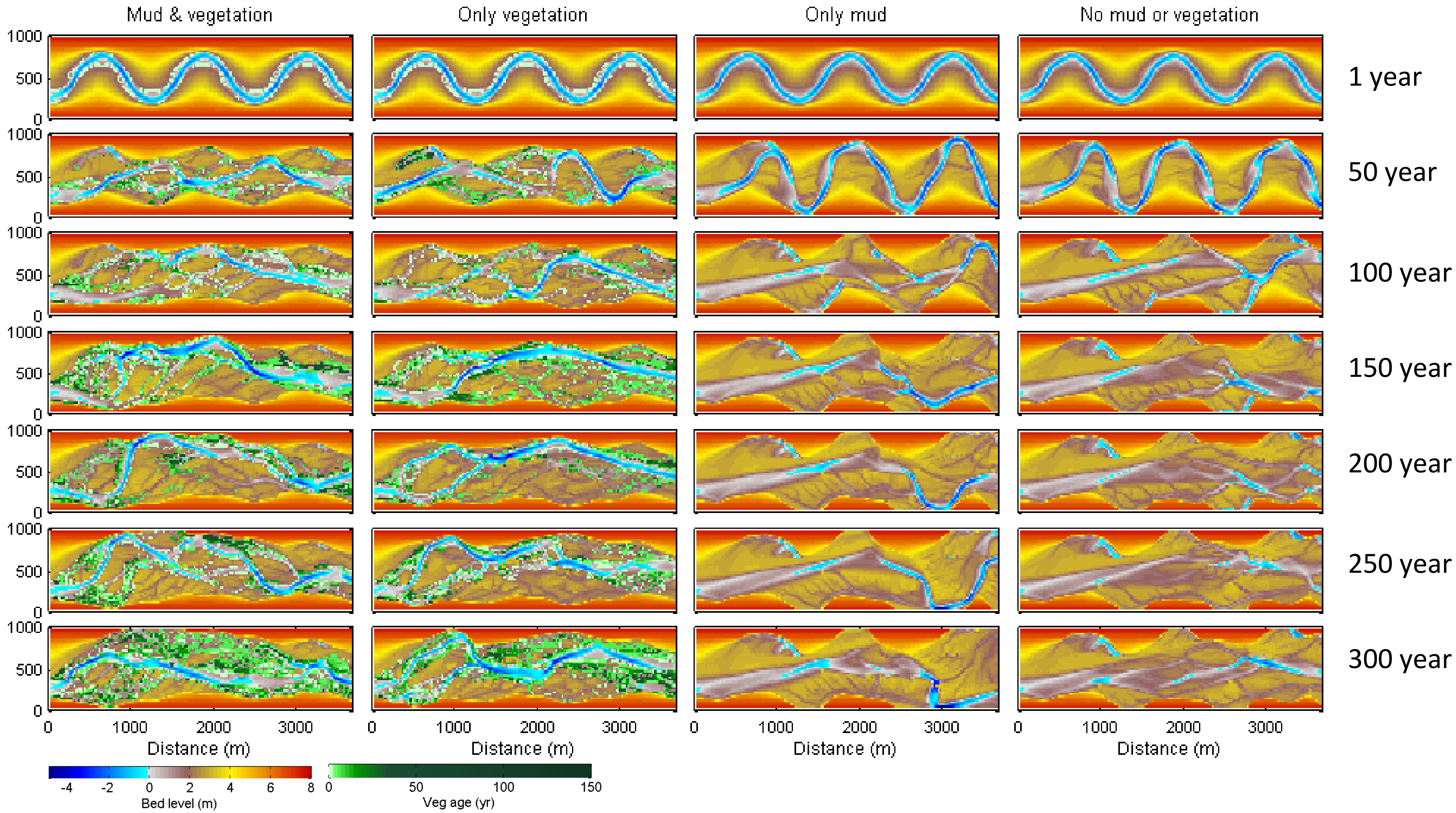

Figure 19 Bathymetry and maximum vegetation age for main scenarios at different times.

4.1 Mud and vegetation patterns and interaction

This paragraph describes temporal and spatial patterns of mud and vegetation and their interaction. Focus lies on the patterns in the four main model runs, which have a moderate mud supply of 20 mg/L and a critical threshold for mud erosion (from now on referred to as "mud cohesiveness") of 0.2 N/m^2. Additional remarks are made about changes in patterns that occur when the mud supply and cohesiveness are higher. Hereby, in general I refer to the runs with a mud supply and cohesiveness of respectively 500 mg/L and 0.5 N/m^2.

4.1.1 Temporal mud and vegetation patterns

Vegetation dynamics in the river system are high and vegetation can strongly affect the amount of mud cover, especially on decadal time scales. Mud on the other hand generally does not significantly alter vegetation patterns over time. However, an increase in the amount of mud supply leads to a lower vegetation cover in the river system.

Temporal patterns of mud and vegetation individually

Temporal mud patterns

The total area covered with mud increases gradually over time and then stabilizes (Figure 20, left). Independent of vegetation cover, the area with at least a fraction of mud in the top layer generally constitutes about 80 percent of the total area after 300 year. The area with mud represents the whole floodplain excluding the high banks that are not eroded. The area with mud is smaller, about 60 percent, when both the mud supply and cohesiveness are larger, because the floodplain is more confined.

In the absence of vegetation, the mean mud fraction in the top layer of the bed is relatively constant (e.g. Figure 20 C, right) and the mud deposit dynamics are low. In the main model run without vegetation the amount of mud in the top layer only rapidly increases between year 50 and 100 due to the infilling of three large meander bends, which are remnants of the initial bathymetry. The mud deposits formed in this period are not removed in the next 200 years and occupy a much larger part of the floodplain than other mud deposits, with ages that are generally below 10 years (Figure 24 B). The younger mud deposits are located closer to the channel and erode quickly because the shear stresses in the channels (main channel above 8 N/m^2, smaller channels mostly above 1 N/m^2) are much higher than the critical shear stress for mud erosion (default: 0.2 N/m^2, maximum value in additional scenario: 0.5 N/m^2). A higher mud supply and cohesiveness gives a similar pattern, namely an increase in mud cover in the first 50 years and after that low mud deposit dynamics.

Temporal vegetation patterns

Both the vegetation cover and the mean vegetation fraction are highly dynamic, especially on decadal time scale, and show a gradually increasing trend over 300 years in the main model runs (Figure 20). Sudden peaks in vegetation cover are the result of a year of successful colonization followed by a year in which most young plants die. Morphodynamic pressures on vegetation in the river system, and therefore mortality rates, are high. Only a small part of the vegetation cover reaches an age above 10 years (Figure 22). The main cause of vegetation mortality is desiccation, followed by flooding (Figure 21). Seedlings also die due to uprooting, scour and burial, while older vegetation is generally able to withstand these morphodynamic pressures.

When the mud supply and cohesiveness are high, the vegetation cover again shows variation especially on decadal time scale, but does not gradually increase during the model simulation.

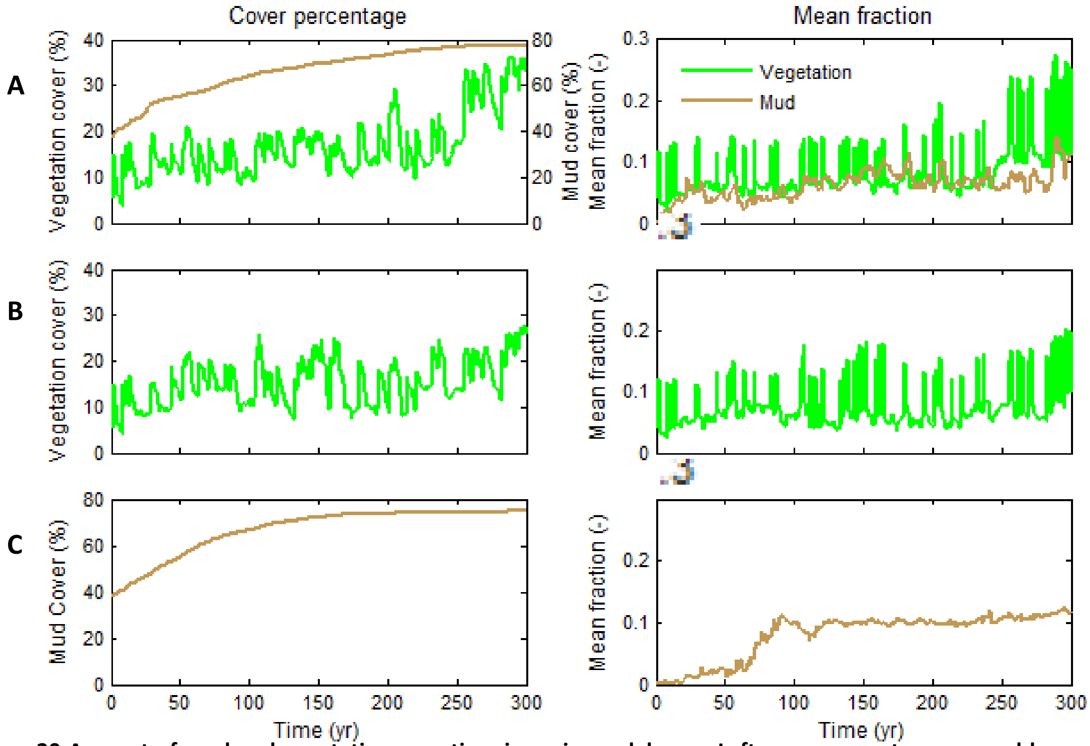

Figure 20 Amount of mud and vegetation over time in main model runs. Left: area percentage covered by mud and vegetation over time. Right: mean mud fraction in the top layer of the bed and vegetation fraction in total river stretch over time. Letters indicate model scenarios. A: mud and vegetation, B: only vegetation, C: only mud.

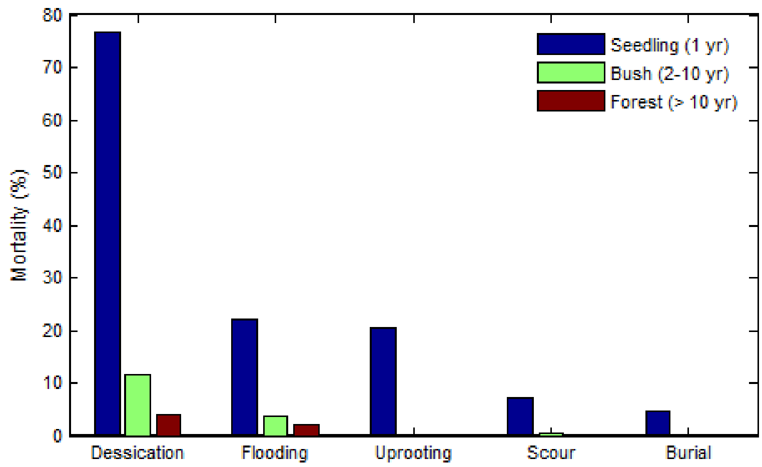

Figure 21 Mortality percentage of seedlings (1 yr), bush (2-10 yr) and forest (>10 yr) vegetation due to different morphodynamic pressures in main model scenario with mud and vegetation (similar to mortality percentages in run with only vegetation). The total mortality percentage per age class can exceed 100% because mortality thresholds of multiple different pressures can be exceeded in certain grid cells in a single year. When the mortality fraction is higher than the vegetation fraction present in a cell the new vegetation fraction is zero. Note that the mortality due to scour for forest is extremely small but not zero.

Effects of mud-vegetation interaction on temporal patterns

Effect of vegetation on temporal mud patterns

Vegetation strongly affects the temporal mud pattern (compare Figure 22 upper right-upper left). The amount of mud in the system generally follows the vegetation cover, especially on decadal time scale, with a small delay (Figure 23).

Strong variations in mud cover on decadal time scales can best be correlated to variations in cover of vegetation in the bush stage (2-10 years): changes occur with about the same frequency (Figure 22) (see also section 5.1.2). Mud cover furthermore seems slightly more correlated to *Salix* species than to *Populus*, which is probably related to the larger area covered with *Salix*.

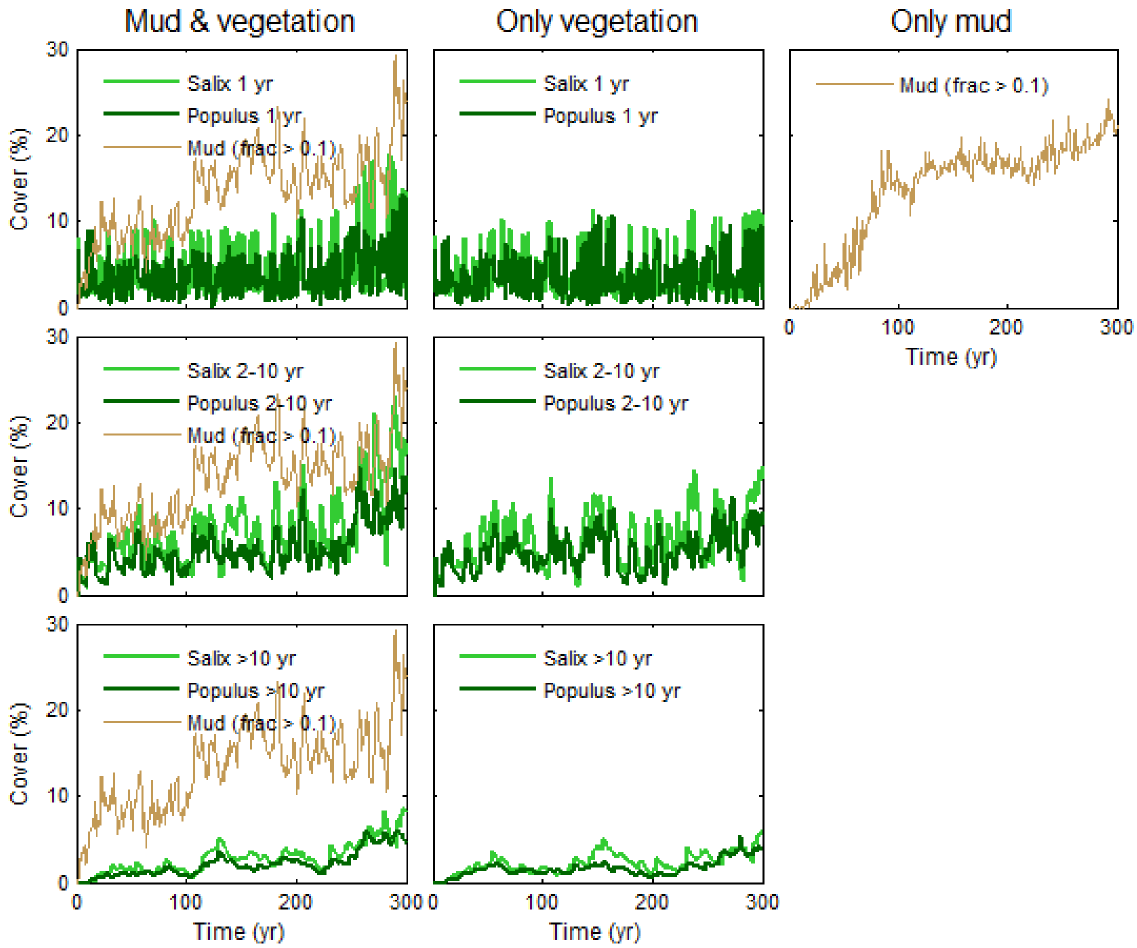

Figure 22 Area percentage covered with *Salix* and *Populus* species and at least a small amount of mud (fraction in top layer above 0.1) over time for main model scenario with mud and vegetation (left), only vegetation (middle) and only mud (right). Top: pioneer (1 yr). Middle: bush (2-10 yr). Bottom: forest (>10 yr).

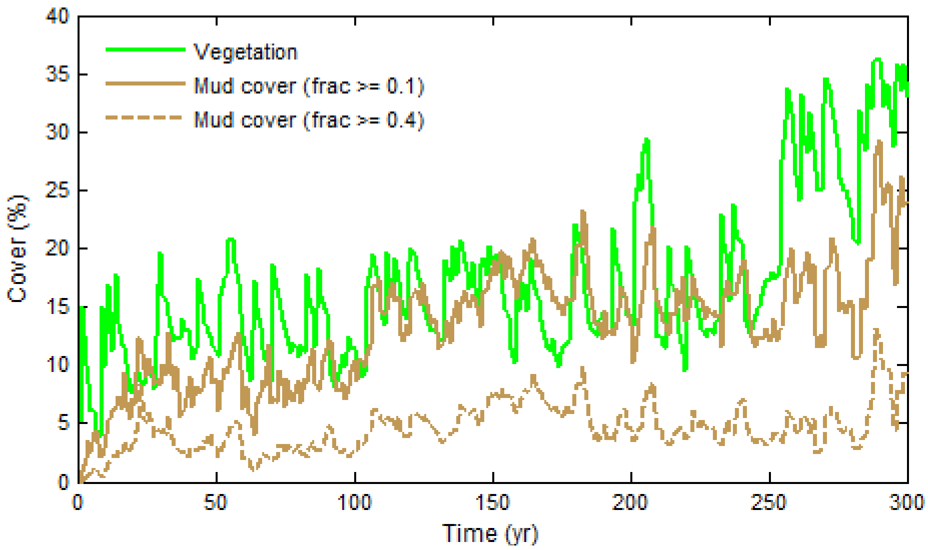

Figure 23 Area percentage covered with mud (locations where fraction in top layer is above 0.1 and 0.4 respectively) and vegetation over time in main model scenario with mud and vegetation.

Mud deposit dynamics in a system with vegetation are generally much higher compared to a system without vegetation. This is reflected in larger decadal variations in the amount of mud cover (Figure 22) and lower average mud deposit ages (Figure 24). Mud deposits often start to develop over several years at locations of vegetation patches and are eroded by the strong river currents within a few years after vegetation has died.

Variation in the mud cover is smaller than in Figure 23 when the mud supply and cohesiveness are large, which is partly related to the much lower vegetation cover and variation in the vegetation cover (Figure 25).

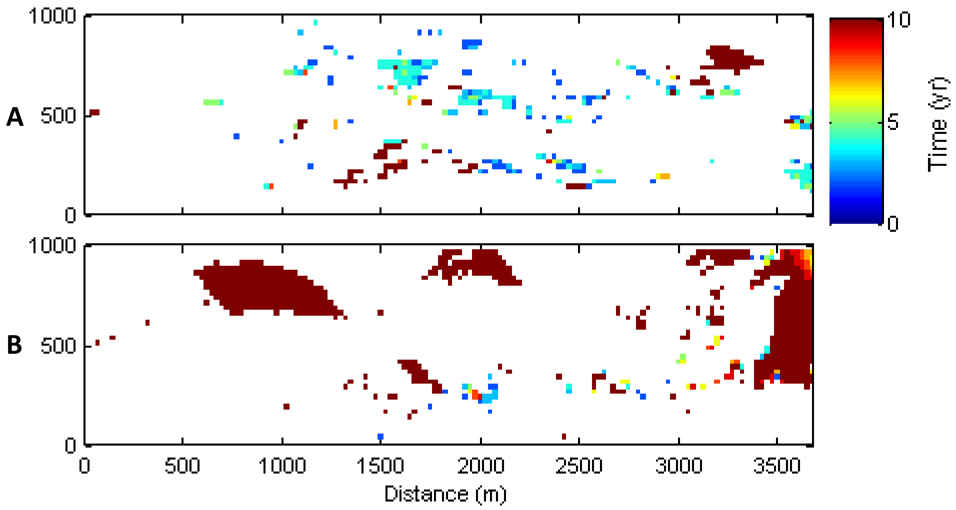

Figure 24 Age of mud deposits (here defined as fraction in top layer > 0.4) present in year 300 of the simulation. Top and bottom show main scenarios with A: mud and vegetation and B: Only mud. Note that deposits with dark red color have ages of 10 years and older.

Effect of mud on temporal vegetation patterns

Presence of mud in the river system has no large effect on the temporal patterns in vegetation cover and mean vegetation fraction (compare Figure 22 left-middle) in the main model runs. However, an increase in mud supply causes a reduction in vegetation cover, especially when the mud is relatively cohesive (Figure 25).

Differences in presence/absence of mud, mud supply and the critical threshold for mud erosion do not cause large changes in mortality percentages of vegetation. A combined increase in mud supply and cohesiveness also causes no large changes in the mortality causes of vegetation, even though the vegetation cover is significantly reduced. In this case, the vegetation mortality due to burial and scour increases relatively more than mortality due to other causes. However, burial and scour remain the smallest causes of mortality and are much smaller than mortality due to desiccation. The fact that mortality percentages do not drastically change in case of an increase in mud supply and cohesiveness suggests that the strong decrease in vegetation cover in this scenario is more influenced by decreased vegetation colonization than by an increase in mortality.

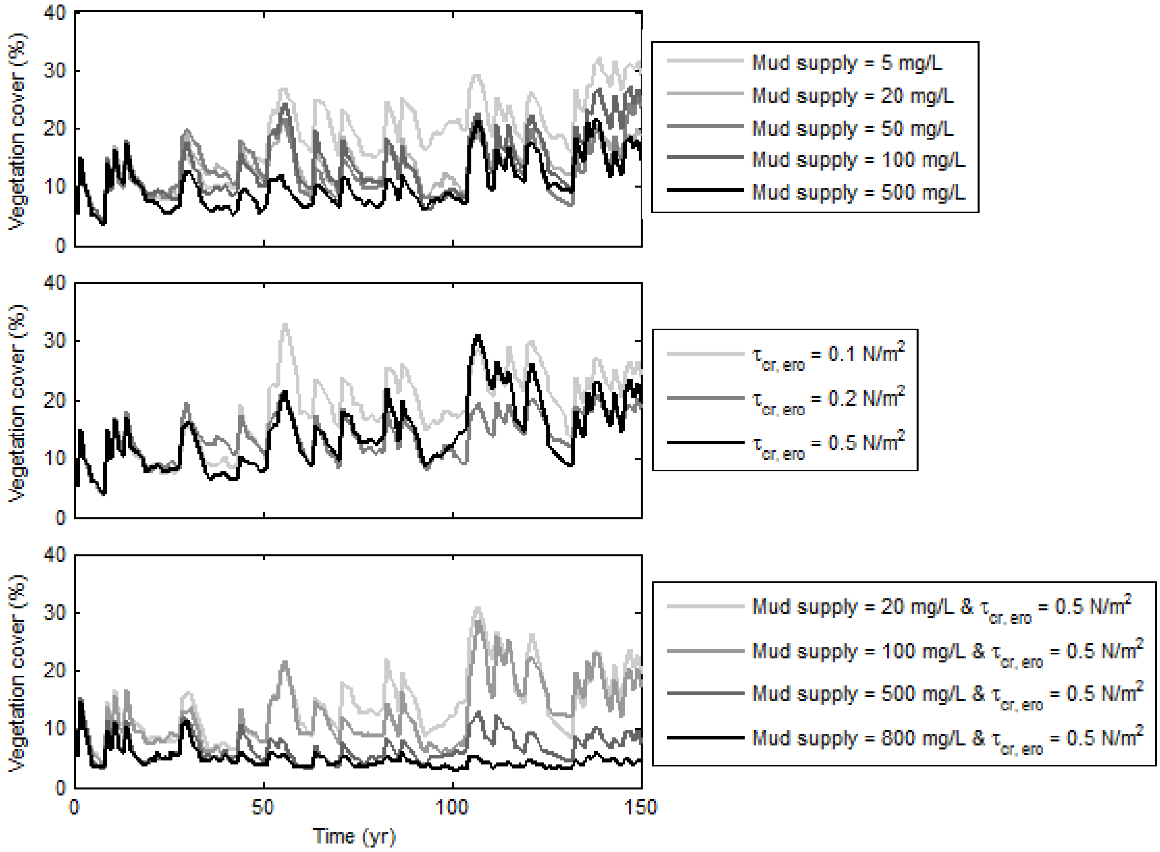

Figure 25 Vegetation cover percentage over time for scenarios with different A: mud supply, B: critical shear stress for mud erosion and C: mud supply in combination with a higher mud cohesiveness than default.

4.1.2 Spatial mud and vegetation patterns

Mud generally deposits further away from the main channel, while vegetation forms strips and patches close to active river channels. Oxbow lakes and other (partly) abandoned channels are common locations for mud deposition and vegetation development. Older vegetation and larger mud and vegetation fractions are predominantly present in zones with low morphodynamic activity.

Vegetation causes significant changes in the spatial mud distribution and promotes mud settling, especially closer to the main river channel. Mud generally has little effect on vegetation, but a large mud supply and cohesiveness restricts vegetation growth to a narrow zone directly along the active channel.

Spatial distribution of mud and vegetation individually

Spatial mud distribution

In absence of vegetation, mud deposits generally form at locations of (partly) abandoned channels, further away from the main channel (Figure 26). Abandoned channels, including oxbow lakes, first rapidly fill with sand/gravel. Mud deposition only takes place in the final stages of channel infilling (Figure 27, left). Total amounts of mud in the bed are mostly about 0.05-0.2 meter at the locations of mud deposits and below 0.05 meter near the main channel after 150 years (Figure 28).

When the mud supply and cohesiveness are larger, mud deposits everywhere along the channel. Rates of bed level change are still relatively small in zones with mud fractions in the top layer above 0.8, but bed level changes in these zones can be up to 1 meter in a single year. Mud still deposits in the final stages of the infilling sequence of abandoned channels, but forms a more substantial part of the infilling deposits (Figure 27, right). Total amounts of mud in the bed are much higher: about 2.5 meter in large abandoned channels and more than 0.5 meter close to the channel (Figure 28).

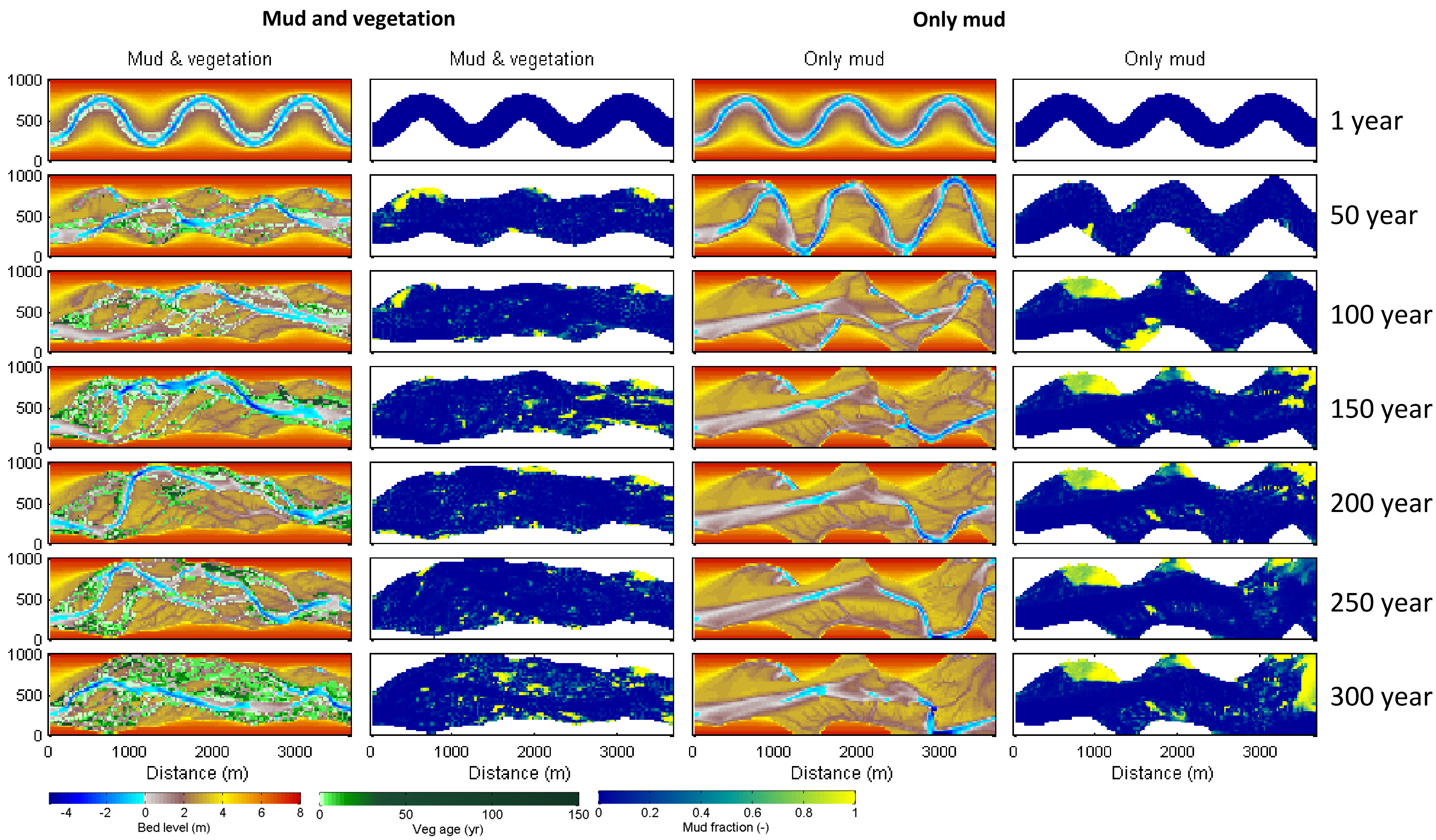

Figure 26 Bathymetry, maximum vegetation age and mud fraction in top layer for main scenario with mud and vegetation and main scenario with only mud at different times.

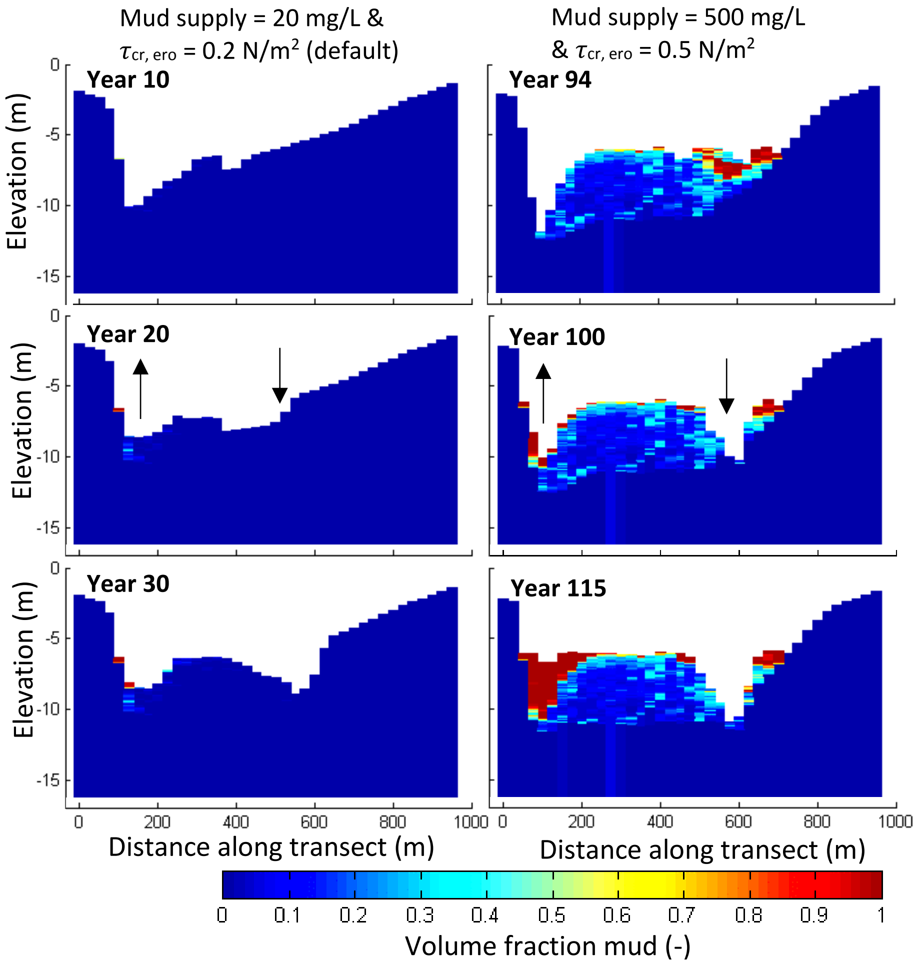

Figure 27 Infilling sequence of oxbow lakes in main scenario with mud and vegetation (left) and in scenario with a relatively high mud supply and cohesiveness and vegetation (right). The channels avulse from the left part of the transect towards the right part of the transect. Locations of transects are indicated in Figure 28. At the start of the infilling sequence mainly the coarsest sediment fraction (sand/pebbles) settles, while mud deposits in the final stages of the infilling sequence. In a system with a moderate mud supply and cohesiveness the largest part of the oxbow lake deposits consists of the larger sediment fraction, while in the system with a higher mud supply and cohesiveness the oxbow lake deposits mostly consist of mud.

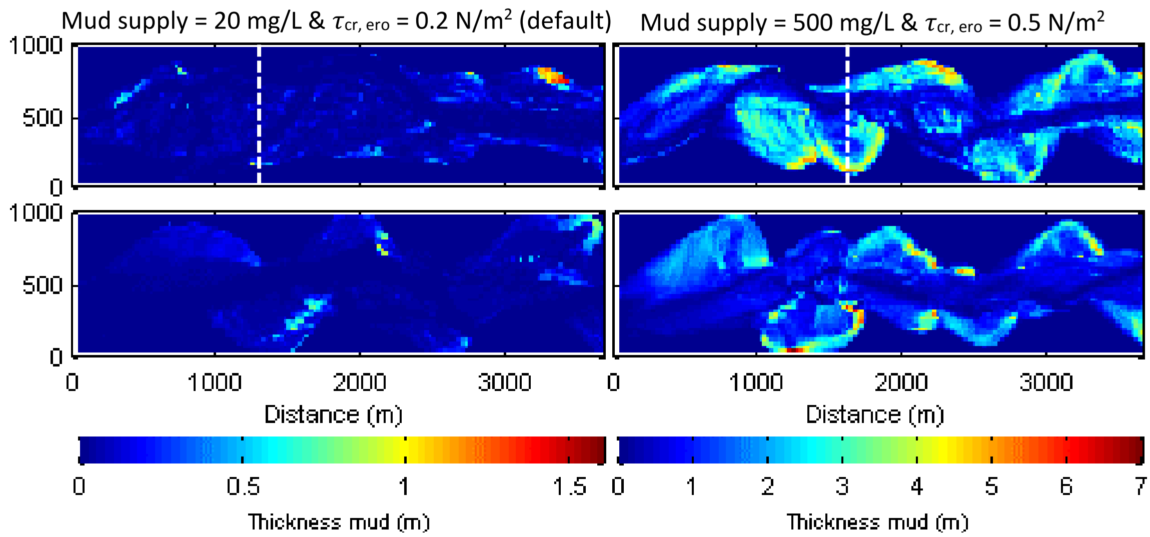

Figure 28 Mud present in bed after 150 years in scenarios with (top) and without (bottom) vegetation. Left: main model scenario with mud and vegetation. Right: scenario with high mud supply and cohesiveness. Note that for the calculation of 'thickness mud' it is assumed that all mud in the bed is present as a single layer consisting of only mud (no other sediment fraction). Dashed white lines indicate locations of transects in Figure 27.

Spatial vegetation distribution
The surface area covered with vegetation decreases with distance from the active channel(s) (Figure 19; Figure 26). This is because colonization occurs in the zone between low and high water levels near channels and because vegetation dies due to desiccation at larger distances from the channel. The vegetation fraction within grid cells also decreases with distance from the main channel (Figure 18; Figure 32). This is because the settling fraction of vegetation is high (0.8). A few years after settling, the channel has migrated away and a large part of the young vegetation has died leading to a reduction of the vegetation fraction.

Pioneer vegetation occurs both as strips along the main channel and more scattered in the floodplain in the main model runs, (Figure 19; Figure 26). Vegetation in the bush stage (2-10 years) is present in strips along the channels and as vegetation patches near locations of abandoned channels. Older vegetation covers a smaller part of the floodplain area and is present as small strips, often at a slightly larger distance from the main channel compared to 2-10 year old vegetation, and as vegetation patches.

Vegetation succession is visible upstream of migrating bends and along relatively stable and straight river stretches with an increase in vegetation age with distance from the channel (Figure 19; Figure 26, year 250-300). In case of relatively stable, straight river channels, vegetation closest to the channel is relatively young, while more distant vegetation seems to be protected by this first line of vegetation and hence has the opportunity to grow older.

Oxbow lakes and other (partly) abandoned channels are also locations where vegetation develops, but only when flow velocities have dropped significantly and water levels are moderate. Whether vegetation can develop into a forest within a (partly) abandoned channel is therefore strongly related to the degree of connection of the old channel to the new channel network. A vegetation patch with trees older than 10 year only develops occasionally in (partly) abandoned channels.

The vegetation cover on point bars is generally low (Figure 19; Figure 26) and related to vegetation development near a (partly) abandoned channel located on the point bar.

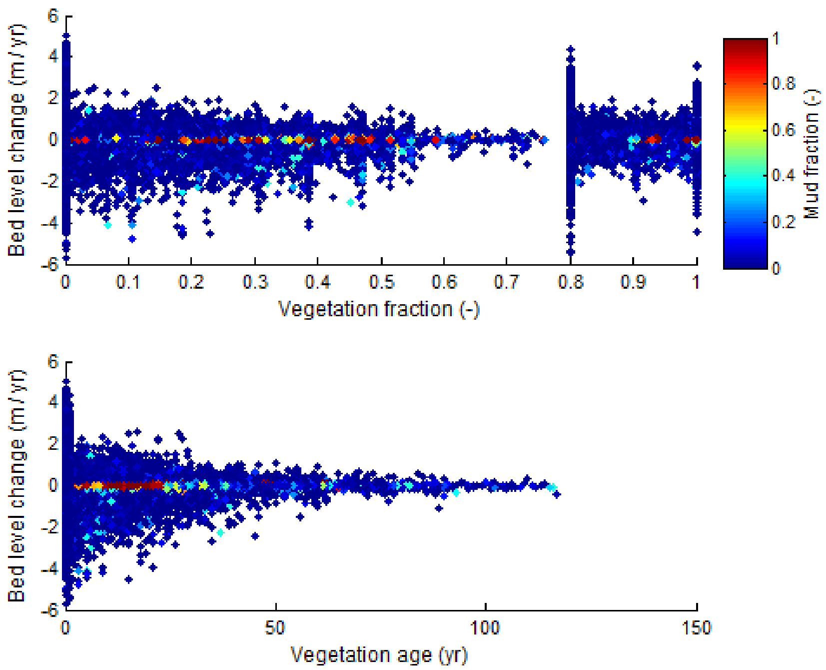

Figure 29 Vegetation (fraction, age) and mud presence at locations with different rates of bed level change in main scenario with mud and vegetation. Large mud and vegetation fractions and older vegetation are predominantly located in morphodynamically less active zones.

Older vegetation and higher vegetation fractions are associated with lower rates of bed level change both in the main scenario (Figure 29) and the scenario with a high mud supply and cohesiveness. The high rates of bed level change for vegetation fractions of 0.8-0.1, which disrupt the pattern for vegetation fraction, indicate the pioneer vegetation located in the highly active zone close to the main river channel. The colonization fraction of both vegetation types is 0.8 and vegetation fractions of 1 can occur when new vegetation colonizes a cell in which vegetation is already present or when a second vegetation type colonizes the same grid cell. It seems that only in morphodynamically quiet areas, the mortality fraction of vegetation is such low that vegetation fractions above 0.6 can remain present in grid cells.

Effect of mud-vegetation interaction on spatial patterns

Effect of vegetation on the spatial mud distribution

Addition of vegetation causes significant changes in the spatial distribution of mud over the floodplain and leads to more mud deposition closer near the active channel.

Vegetation generally causes an increase in mud deposition. Mud fractions in the top layer are on average higher at locations with vegetation (Figure 30 A). Furthermore, mud fractions above 0.1 occur relatively more often at locations with vegetation, while lower mud fractions are relatively more common at locations without vegetation (Figure 30 B).

An increase in vegetation fraction is generally associated with higher mean (Figure 31) mud fractions in the top layer of the bed, because larger vegetation fractions reduce flow velocities more. Around vegetation fractions of 0.8 the mud fractions are lower, because these higher vegetation fractions are associated with pioneer vegetation, located close to active channels, and hence with relatively high flow velocities.

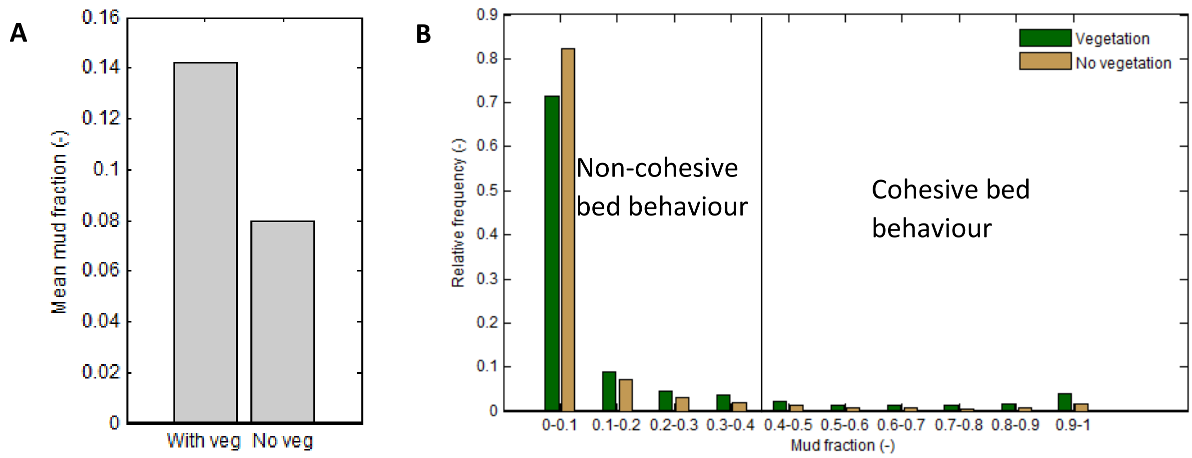

Figure 30 Correlation between mud and vegetation presence in main scenario with mud and vegetation. A: mean (over time and space) mud fraction in grid cells with and without vegetation. B: relative frequency of different mud fractions in the top layer in grid cells with and without vegetation. Frequencies are relative: it is taken into account that the number of locations with vegetation is much lower than the number of locations without vegetation. Starting at mud fractions of 0.4 the erosive behavior of the bed is cohesive meaning that the sand erosion rate equals the mud erosion rate because mud sticks the sand particles together. Note that the statistics of both for A and B are calculated over the period 25-300 years and only take into account grid cells located in the floodplain (in which mud fractions are above zero).

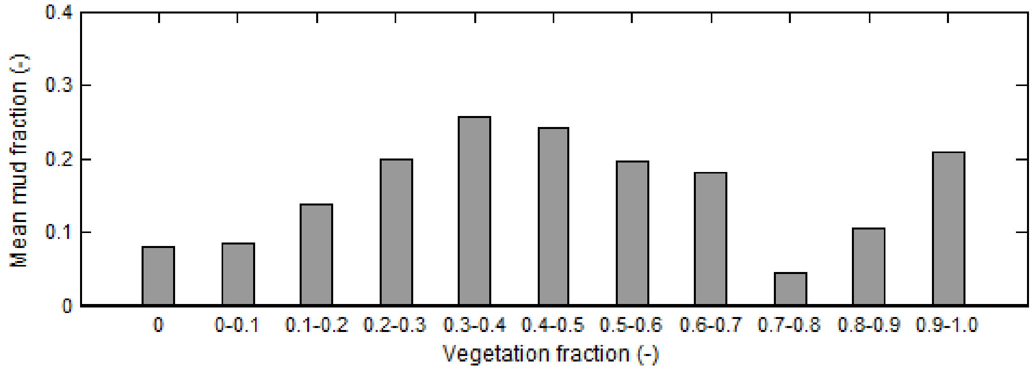

Figure 31 Mean (over time and space) mud fraction in top layer in grid cells with different vegetation fractions in main scenario with mud and vegetation calculated for the period 25-300 years. Note that only grid cells located in the floodplain (mud fraction above zero) are taken into account.

Although vegetation causes mud deposition there are still many locations with little mud even though vegetation is present (Figure 30 B) or with high mud fractions but without vegetation.

Mud deposition may be limited when the vegetation cover is too low, the drag force of the vegetation too small, or the incoming flow velocity too high and hence mud is not deposited or easily eroded. Another reason for the lack of mud in grid cells with vegetation is delay between vegetation colonization and mud deposit formation. It was found that mud only accumulates in a thin band along the edges of the channel when there is a significant ridge (±75 m wide or more) of vegetation. Thin strips of vegetation are unable to reduce flow velocities significantly.

Mud can be present at locations without vegetation when vegetation on a large mud deposit has died and the mud has not yet been eroded. Furthermore, in some (partly) abandoned channels mud is able to deposit without the need of vegetation to further reduce flow velocities. Vegetation does not create a large zone of decreased flow velocities and hence does not result in mud deposition around vegetation patches.

Mud deposition occurs closer near the channel thalweg when vegetation is present in a river system (Figure 32), because vegetation reduces flow velocities at the sides of the channel and causes the flow to focus into a smaller channel. The mud content in the top layer of the bed in a system with vegetation is more constant with distance from the channel, because in the system with vegetation no large mud deposits remain present at the sides of the floodplain.

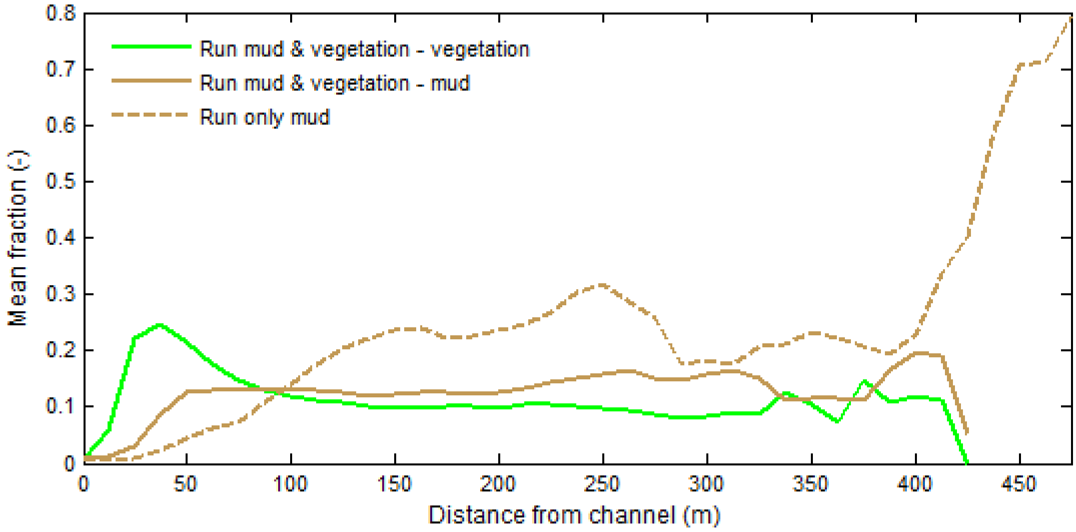

Figure 32 Mean mud fraction in the top layer of the bed and mean vegetation fraction at different distances from the channel thalweg averaged over time for main model scenario with mud and vegetation and main model run with only mud. Presence of vegetation leads to more mud deposition close to the channel thalweg. Note that only grid cells located in the floodplain (mud fraction above zero) are taken into account.

The total amount of mud in the river system and the thickness of mud in the bed after 150 years is similar in the main run with and without vegetation (Figure 28). In contrast, when the mud supply and cohesiveness are large, the total amount of mud in the river system is somewhat larger in a system with vegetation compared to a system without vegetation.

Effect of mud on the spatial vegetation distribution
Mud has no significant effect on spatial vegetation patterns in the main model scenario. A large increase in mud supply in combination with a relatively high mud cohesiveness restricts vegetation growth to a thin zone (25 m wide) directly along the channel.

4.2 Effect of mud and vegetation on river morphology

In this section the effects of mud and vegetation on river morphology are presented. An overview of these effects for different model scenarios can be found in Appendix 3 and Figure 57.

4.2.1 Effects of vegetation

Addition of vegetation to a system without mud or with a moderate mud supply (20 mg/L) and cohesiveness ($\tau_{cr,\,ero}$ = of 0.2 N/m^2) leads to a more dynamic river system with deeper, more confined channels and a higher active braiding index (Table 7; Figure 33). Vegetation leads to a wandering river pattern with meander characteristics. Without vegetation and without or with a moderate mud supply the river system dynamics are relatively low (Figure 33 E) and the channel is formed by a plain of water within which the channel thalweg shifts over the years. The braiding index is relatively low as well as there is a wide plain with water instead of many parallel channels (Figure 33 D). Addition of vegetation confines the flow in channels, but also causes avulsions over a wider part of the floodplain leading to a relatively high braiding index in winter of up to 3 (Figure 33 D), higher river system dynamics (Figure 33 E) and a lower median bed level (Figure 33 F). Vegetation also induces meander bend formation and stabilizes channels locally. Vegetation had no large effect on channel sinuosity (Figure 33 C), although peaks in sinuosity are generally higher. Despite the higher braiding index, systems with vegetation show more aspects of meandering, including deeper, more confined channels and more frequent formation and migration of meander bends, than the systems without vegetation.

When the mud supply and cohesiveness in a river system are relatively large, addition of vegetation causes channel deepening, confinement and, in contrast to systems with a lower mud supply and cohesiveness, a higher floodplain elevation (Figure 41 F, G). Towards the end of the model run with vegetation, the channel becomes more straight and channel migration decreases. From that moment, the channel in the system with vegetation seems more stable compared to the system without vegetation (Figure 41 E) where the channel migrates over a slightly wider plain of about 300 meters wide.

Table 7 Main effects of vegetation on river morphology.

In system **without** mud or with a **moderate** mud supply (20 mg/L) and cohesiveness ($\tau_{cr,\,ero}$ = of 0.2 N/m^2):	In system with **high** mud supply (500 mg/L) and cohesiveness ($\tau_{cr,\,ero}$ = 0.5 N/m^2):
➢ Channel deepening and confinement; ➢ Lower floodplain elevation; ➢ Higher channel migration; ➢ Higher active braiding index.	➢ Channel deepening and confinement; ➢ Higher floodplain elevation; ➢ Decrease channel migration.

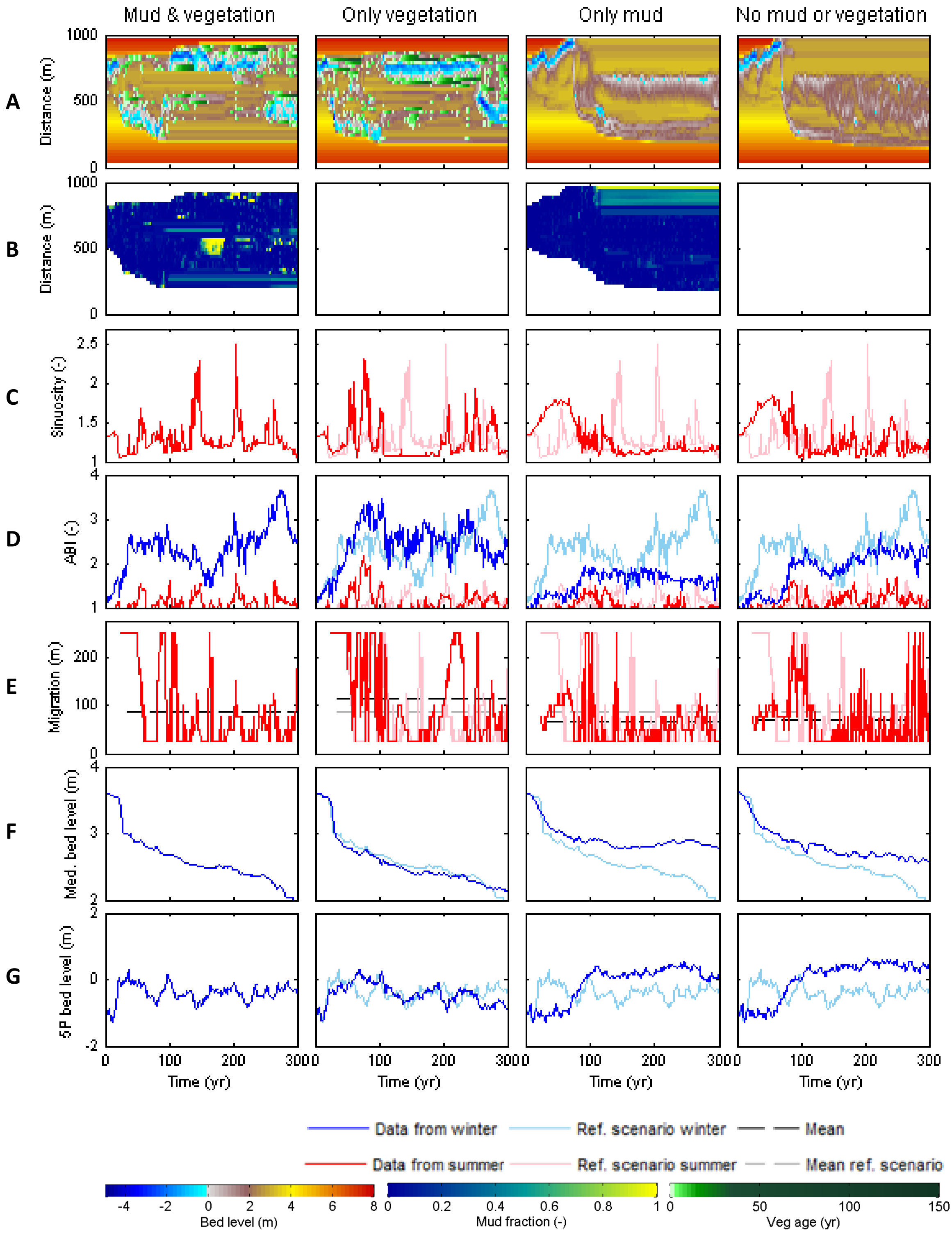

Figure 33 Effects of vegetation and mud (main scenarios) on river morphology. A: bathymetry and vegetation age in the middle cross-section of the river (timestack), B: mud fraction in top layer in the middle cross-section of the river (timestack), C: sinuosity of main channel, D: active braiding index, E: channel migration, F: median bed level, G: 5P bed level, indicative for channel depth, all plotted over time.

4.2.2 Effects of mud

Addition of mud

Addition of mud has no large effect on the river pattern or morphology in the main scenarios in which both the mud supply and cohesiveness are moderate (respectively 20 mg/L and 0.2 N/m^2) (Table 8). A relatively high mud supply and cohesiveness (respectively 500 mg/L and 0.5 N/m^2) causes a slightly deeper channel in a system without vegetation, but causes more significant changes in river morphology in combination with vegetation.

In a system without vegetation, a moderate mud supply causes a higher floodplain elevation (Figure 33 F). Furthermore, compared to the run without mud, the wide plain with water is a bit more confined. Addition of mud seems to cause a slightly deeper channel, lower active braiding index and lower channel migration towards the end of the model run (Figure 33 D, E, G), but this effect may be insignificant. In the model run with only mud a cell exists in the middle of the floodplain, which does not erode for 300 years. This may have caused the flow to focus slightly more. Another explanation for the deeper channel and lower braiding index is that mud deposits stabilized the channel (Figure 33 A, B). However, the mud in this run is relatively easily erodible.

In systems with vegetation the impact of mud on channel morphology is barely noticeable and no significant changes in channel depth, active braiding index, channel migration and sinuosity occur (Figure 33 A, C, D, E, G). Mud only causes a slight increase in floodplain elevation (Figure 33 F).

Addition of a high amount of mud with a relative large cohesiveness in a system without vegetation leads to a slightly more confined, deeper channel and higher floodplain elevation (Figure 41 A, F, G). The mean channel migration rate is higher than in systems without mud or with a moderate mud supply, but like in these systems the channel thalweg shifts within a limited part of the floodplain.
When vegetation is present, mud causes no further channel confinement, but does cause channel deepening, a decrease in the active braiding index, a significantly higher floodplain elevation and seems to cause a decrease in channel migration. The channel migration mode changes from shifts within the floodplain to more gradual meander migration.

Table 8 Main effects of mud on river morphology.

Moderate supply (20 mg/L) and cohesiveness ($\tau_{cr, ero}$ = of 0.5 N/m^2):	**High** supply (500 mg/L) and cohesiveness ($\tau_{cr, ero}$ = 0.5 N/m^2):
System without vegetation: ➢ Higher floodplain elevation; ➢ Channel confinement. System with vegetation: ➢ Slightly higher floodplain elevation.	System without vegetation: ➢ Higher floodplain elevation. ➢ Channel deepening & confinement; System with vegetation: ➢ Higher floodplain elevation; ➢ Channel deepening; ➢ Slightly lower channel migration; ➢ Lower active braiding index.

Effect of mud cohesiveness

The main effects of mud cohesiveness on river morphology are summarized in Table 9.
The increase of the critical shear stress for mud erosion from 0.1 to 0.2 and finally 0.5 N/m^2 for a moderate mud supply and cohesiveness (respectively 20 mg/L and 0.2 N/m^2) causes an increase of mud deposits in the river system and slightly higher median bed levels (Figure 34 F; Figure 35). It has no clear effect on sinuosity, active braiding index and channel depth (Figure 34 C, D, G).
In the run with a critical shear stress for mud erosion of 0.5 N/m^2 the channel seems to become slightly more stable after 125 years, although the migration rate does not clearly decrease (Figure 34, E). The channel is bordered by mud deposits (Figure 35), which are not completely eroded before the next period with increased vegetation cover. However even after 200 years, there are years in which the mud deposits almost completely erode. Also, the location of the river keeps shifting.

An increase in mud cohesiveness from 0.2 to 0.5 N/m^2 causes a higher floodplain elevation for a mud supply of 500 mg/L and a small increase in channel depth and a small decrease in active braiding index for mud supplies of 100 and 500 mg/L.

Table 9 Main effects of an increase in mud cohesiveness on river morphology in a system with vegetation.

Moderate mud supply (20 mg/L):	**High** mud supply (100 & 500 mg/L):
➢ Slightly higher floodplain elevation.	➢ Higher floodplain elevation (for 500 mg/L); ➢ Small increase channel depth; ➢ Small decrease active braiding index;

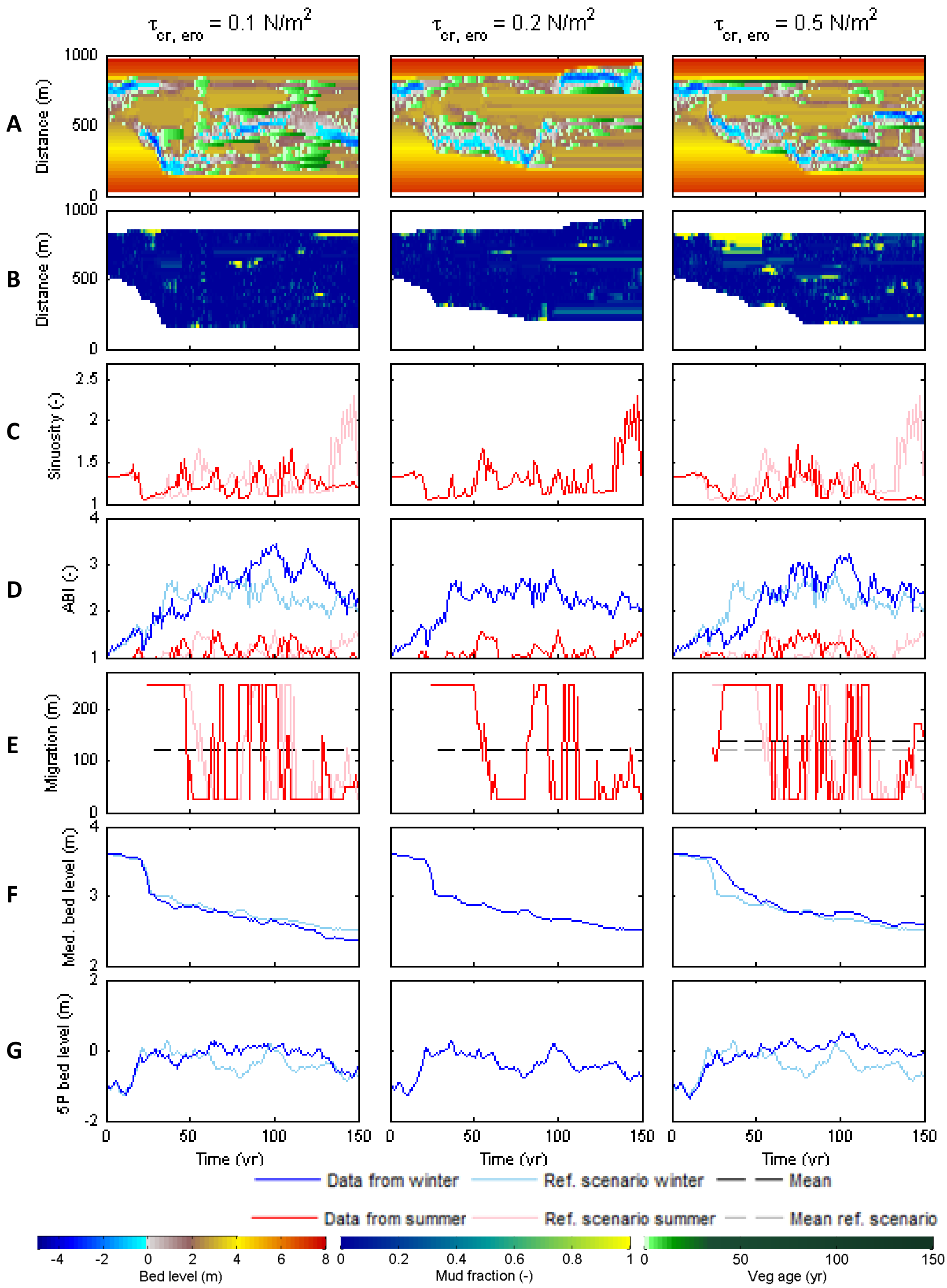

Figure 34 Effects of mud cohesiveness (critical shear stress for mud erosion) on river morphology. A: bathymetry and vegetation age in the middle cross-section of the river (timestack), B: mud fraction in top layer in the middle cross-section of the river (timestack), C: sinuosity of main channel, D: active braiding index, E: channel migration, F: median bed level, G: 5P bed level, indicative for channel depth, all plotted over time.

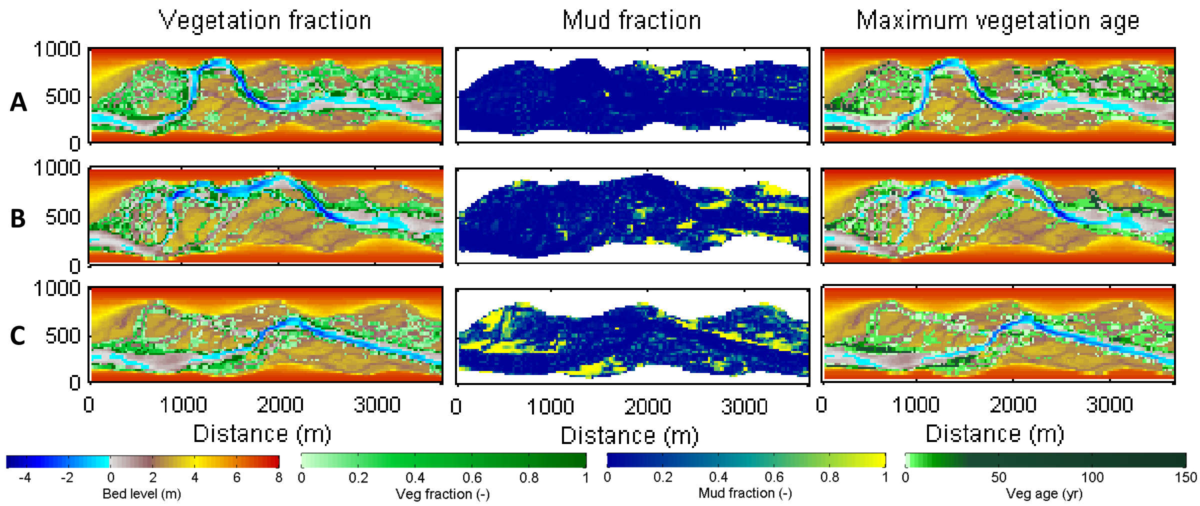

Figure 35 Bathymetry, vegetation fraction, mud fraction in top layer and maximum vegetation age after 150 years of simulation for scenarios with different critical shear stress for mud erosion. A: $\tau_{cr,\,ero}$ = 0.1 N/m², B: $\tau_{cr,\,ero}$ = 0.2 N/m², C: $\tau_{cr,\,ero}$ = 0.5 N/m².

Effect of mud supply

In combination with a moderate mud cohesiveness

An increase in upstream mud supply in a system with vegetation when the mud cohesiveness is moderate ($\tau_{cr,ero}$ = 0.2 N/m^2) leads to higher floodplain elevations and more mud deposits along the active channels (Figure 36; Figure 37 B, F). Also, channel depths are generally slightly lower (Figure 37 G). Links between mud supply and channel sinuosity, active braiding index or channel migration (Figure 37, C, D, E) are not systematic. The braiding index is generally lower in a system with high mud supplies, but is relatively high in the run with a mud supply of 100 mg/L (Figure 37 D) and also after 150 years in the run with a mud supply of 500 mg/L. The channel migration rate becomes relatively low at the end of the model runs with mud supplies of 100 and 500 mg/L (Figure 37 E), although meander bends keep migrating and mud deposits are easily eroded. Still, it seems that mud may stabilize a channel more when there is enough time for mud deposit formation.

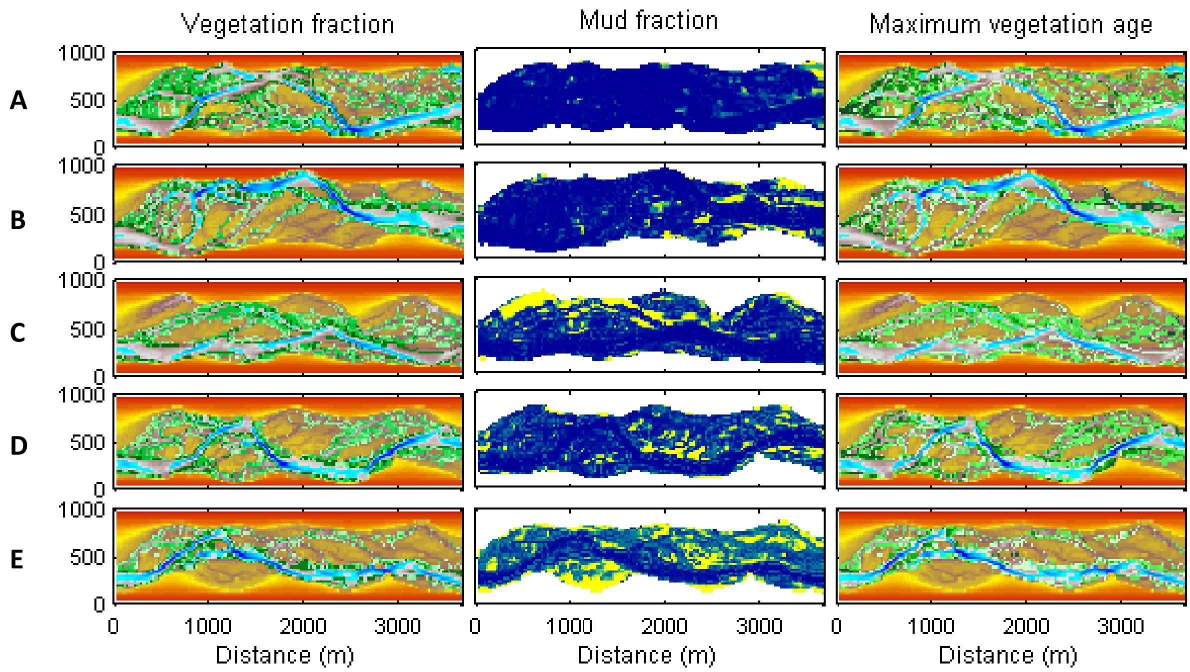

Figure 36 Bathymetry, vegetation fraction, mud fraction in top layer and maximum vegetation age after 150 years of simulation for scenarios with different upstream mud supply. A: mud supply = 5 mg/L, B: mud supply = 20 mg/L, C: mud supply = 50 mg/L, D: mud supply = 100 mg/L, E: mud supply = 500 mg/L. Legend: see Figure 35.

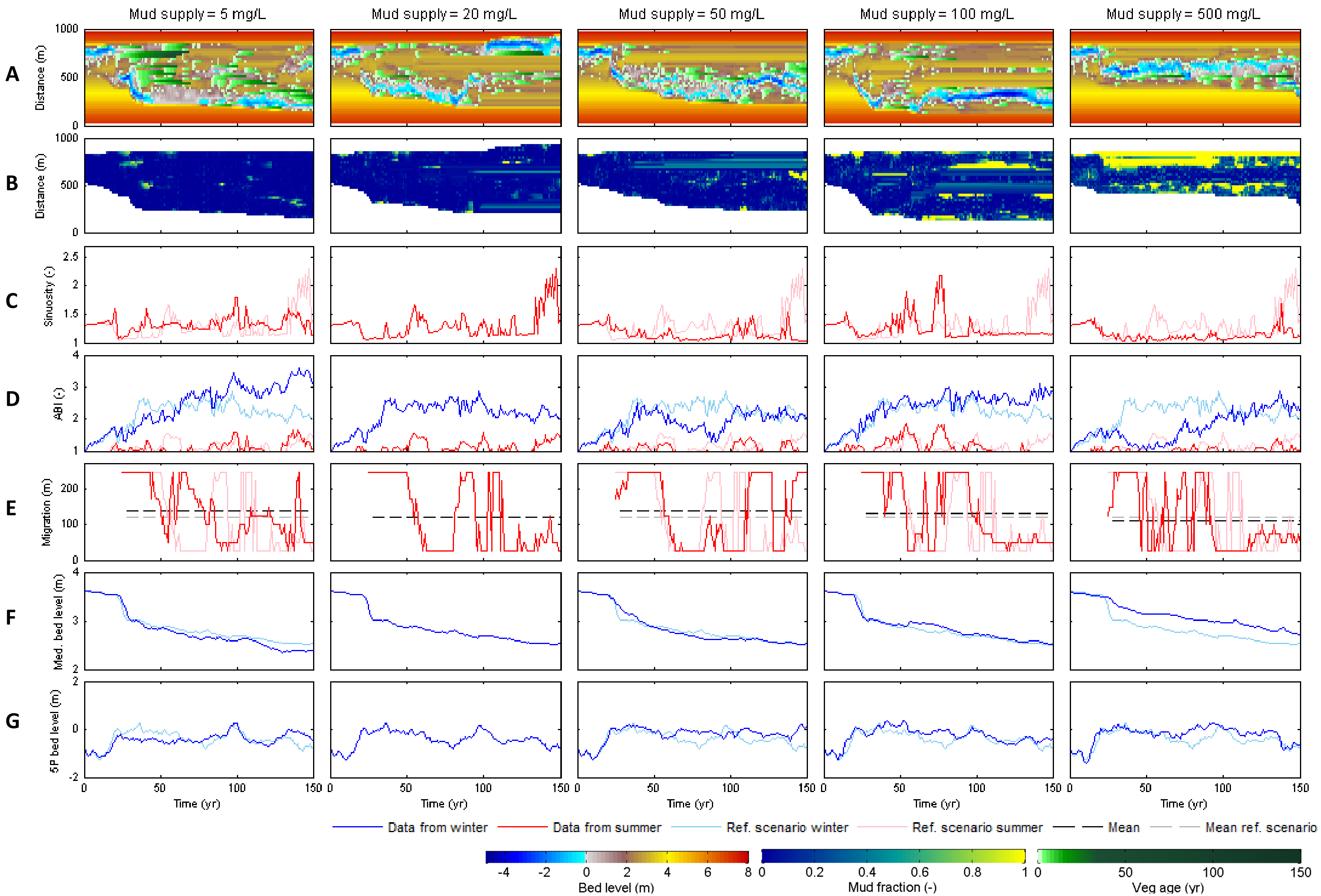

Figure 37 Effects of mud supply on river morphology. A: bathymetry and vegetation age in the middle cross-section of the river (timestack), B: mud fraction in top layer in the middle cross-section of the river (timestack), C: sinuosity of main channel, D: active braiding index, E: channel migration, F: median bed level, G: 5P bed level, indicative for channel depth, all plotted over time.

Table 10 Main effects of an increase in mud supply on river morphology in a system with vegetation.

Moderate mud cohesiveness ($\tau_{cr,ero}$ = of 0.2 N/m^2):	**High** mud cohesiveness ($\tau_{cr,ero}$ = of 0.5 N/m^2):
➢ Generally higher floodplain elevation; ➢ Generally lower active braiding index; ➢ High mud supplies (100 & 500 mg/L) seem to reduce channel migration after 100 years.	➢ Higher floodplain elevation for mud supply >= 500 mg/L; ➢ Lower active braiding index; ➢ Reduction channel migration; ➢ Channel deepening (except for mud supply of 800 mg/L);

In combination with a relatively high mud cohesiveness

High mud supplies in a system with vegetation and in combination with a relatively high mud cohesiveness ($\tau_{cr,ero}$ = 0.5 N/m2) generally cause a deeper and more stable channel and a lower active braiding index (Figure 39; Table 10). Extremely high mud supplies (500 and 800 mg/L) lead to a channel located between high muddy banks (Figure 38, Figure 39). An increase in mud supply is associated with a reduction in avulsion frequency probably due to the higher floodplain, increase in the rate of channel infilling and possibly also due to the increase in bank strength. An increase in mud supply leads to a shift in channel migration mode from a combination of avulsions and gradual channel migration to dominantly gradual migration and, in case of mud supplies of 800 mg/L, a relatively stable channel.

The location of floodplain perturbations relative to the location of meander bends rather than just the mud supply seems to determine channel sinuosity and may also have affected the mode of migration. In case of an extremely high mud supply of 800 mg/L, the river is unable to erode its outer and downstream banks due to either the high and cohesive banks or due to a model shortcoming which prevents bank erosion. Therefore the initial bends are cutoff and river becomes and remains straight and relatively stable. In the scenario with a lower mud supply of 500 mg/L a grid cell in the middle of the floodplain remains stable and prevents the migration of the middle meander bend. This seems to force an increase in sinuosity of the upstream meander bend. Multiple non-erodible grid cells seem to prevent the river from becoming straighter during a large part of the model run.

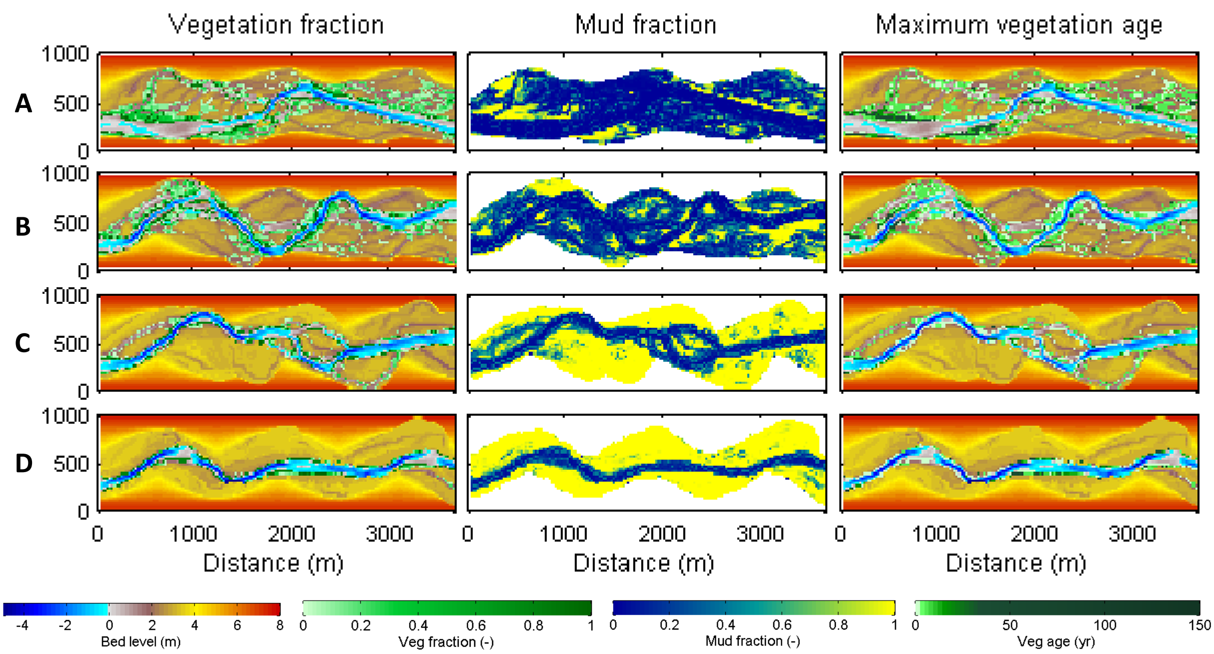

Figure 38 Bathymetry, vegetation fraction, mud fraction in top layer and maximum vegetation age after 150 years of simulation for scenarios with different mud supply in combination with a relatively high critical shear stress for mud erosion ($\tau_{cr,ero}$ = 0.5 N/m^2). A: mud supply = 20 mg/L, B: mud supply = 100 mg/L, C: mud supply = 500 mg/L, D: mud supply = 800 mg/L.

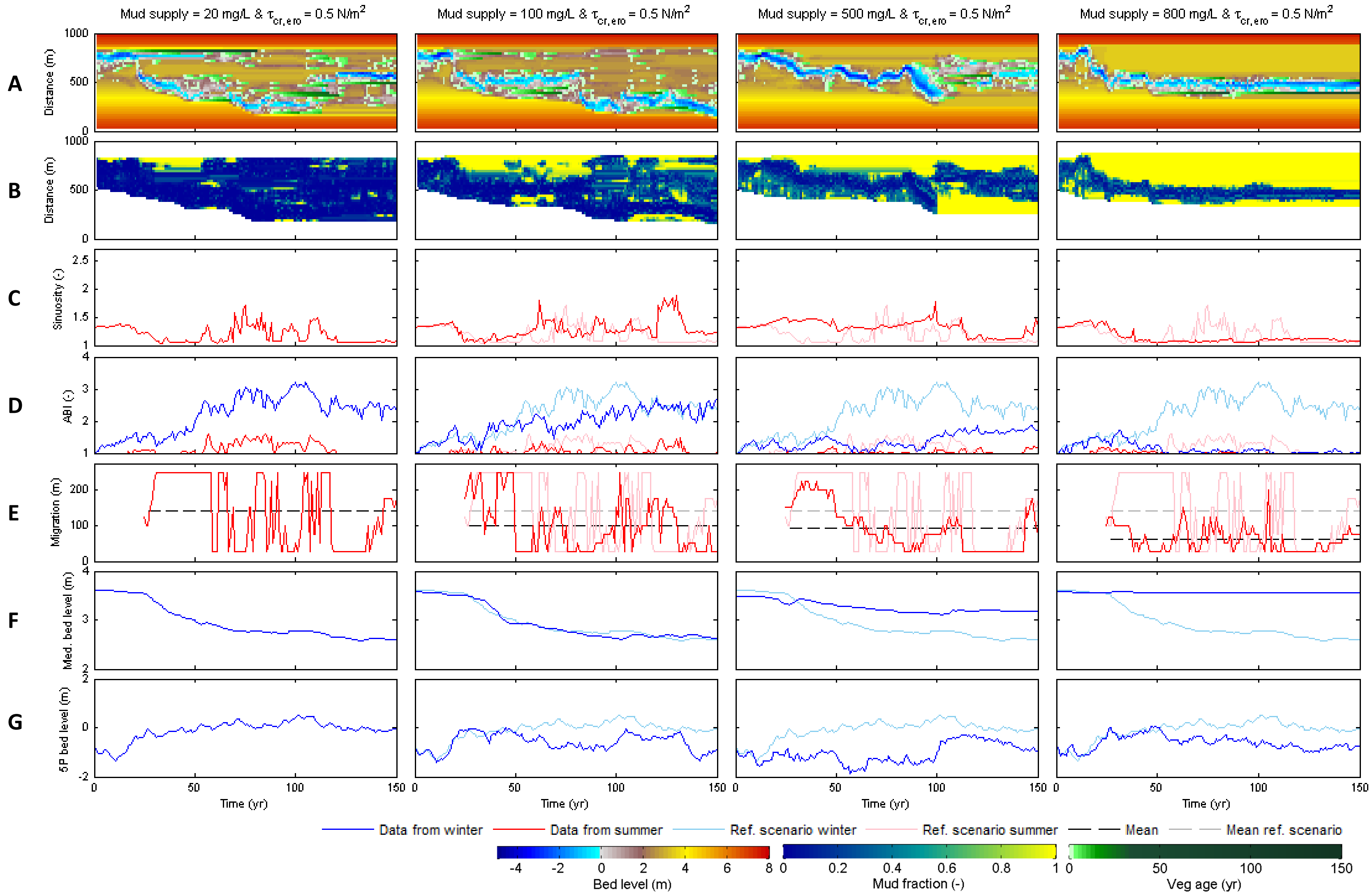

Figure 39 Effects of mud supply, in combination a with a relatively high mud cohesiveness ($\tau_{cr,\,ero}$ = 0.5 N/m²), on river morphology. A: bathymetry and vegetation age in the middle cross-section of the river (timestack), B: mud fraction in top layer in the middle cross-section of the river (timestack), C: sinuosity of main channel, D: active braiding index, E: channel migration, F: median bed level, G: 5P bed level, indicative for channel depth, all plotted over time.

4.2.3 Effect of mud-vegetation interaction

When the mud supply and cohesiveness are moderate (respectively 20 mg/L and 0.2 N/m^2) interaction between mud and vegetation does not result in a markedly different morphology: a river system with both mud and vegetation has a similar morphology as a system with only vegetation (Figure 18; Figure 19; Figure 33). Vegetation does probably strengthen the effect of mud on river morphology, because vegetation promotes mud deposition near active river channels and in (partly) abandoned channels, which are crucial locations for the morphological development of river systems. However, mud remains easily erodible and its impact on river morphology does not increase. Mud also does not affect vegetation development. Therefore, in a system with a moderate mud supply and cohesiveness, vegetation is dominant in determining the river morphology and there is no ongoing positive feedback between mud and vegetation which strongly alters river morphology.

When the mud supply and cohesiveness are larger (respectively 500 mg/L and 0.5 N/m^2) the combination of mud and vegetation leads to a higher floodplain elevation, a deeper channel and a more stable channel compared to systems with only mud or only vegetation (Figure 33; Figure 41). Although the vegetation cover is much lower, vegetation along the border of the river channel is still able to cause a significant change in channel morphology (compare Figure 40 C and D). The addition of vegetation reduces flow velocities and causes increased mud deposition/decreased mud erosion close to the active channel (Figure 40) similar to systems with a lower amount of mud. Addition of vegetation causes a reduction in floodplain elevation in the main model runs, but in combination with a high mud supply and cohesiveness it leads to a much higher floodplain elevation (Figure 41 F). Furthermore, vegetation does not increase the active braiding index or channel migration, which is the case in a system with a lower mud supply and cohesiveness or a system without mud. With presence of vegetation, mud is no longer important for channel confinement. However, mud does lead to a significant decrease in braiding index, which it does not in a system without vegetation. Again, there is no ongoing positive feedback between mud and vegetation which leads to great changes in river morphology.

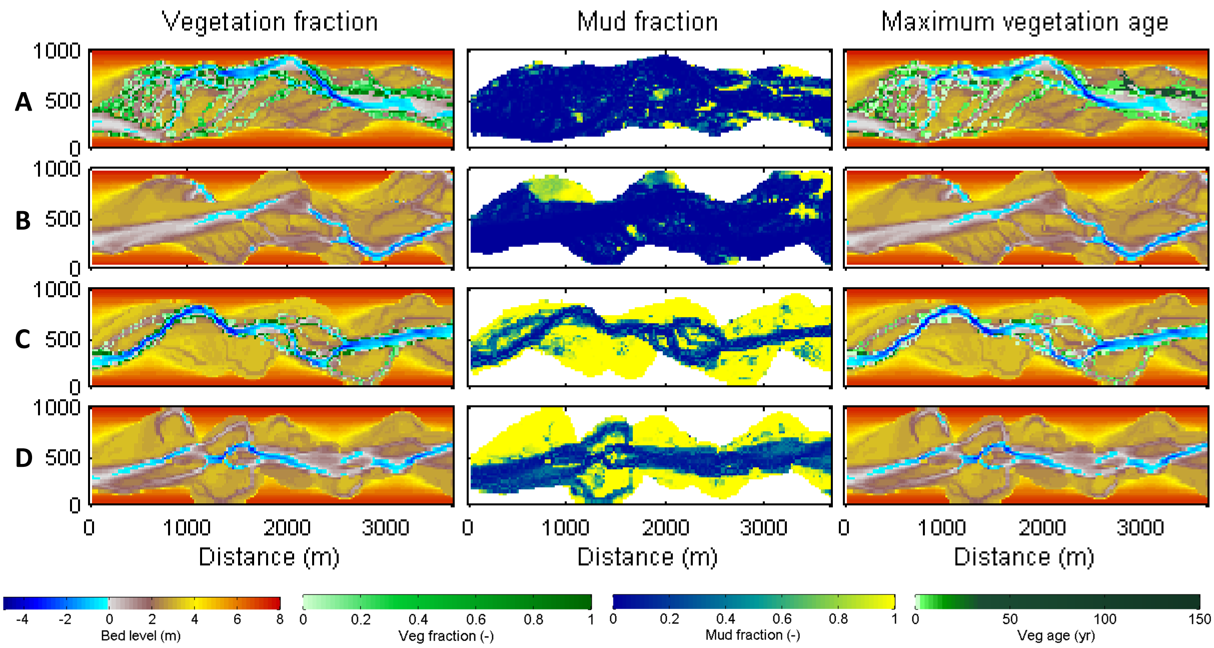

Figure 40 Bathymetry, vegetation fraction, mud fraction in top layer and maximum vegetation age after 150 years of simulation for scenarios with and without vegetation with default settings (mud supply = 20 mg/L, $\tau_{cr, ero}$ = 0.2 N/m^2) and with a relatively high mud supply and cohesiveness (mud supply = 500 mg/L, $\tau_{cr, ero}$ = 0.5 N/m^2). A: default settings with vegetation, B: default settings without vegetation, C: increased mud supply and cohesiveness with vegetation, D: increased mud supply and cohesiveness without vegetation.

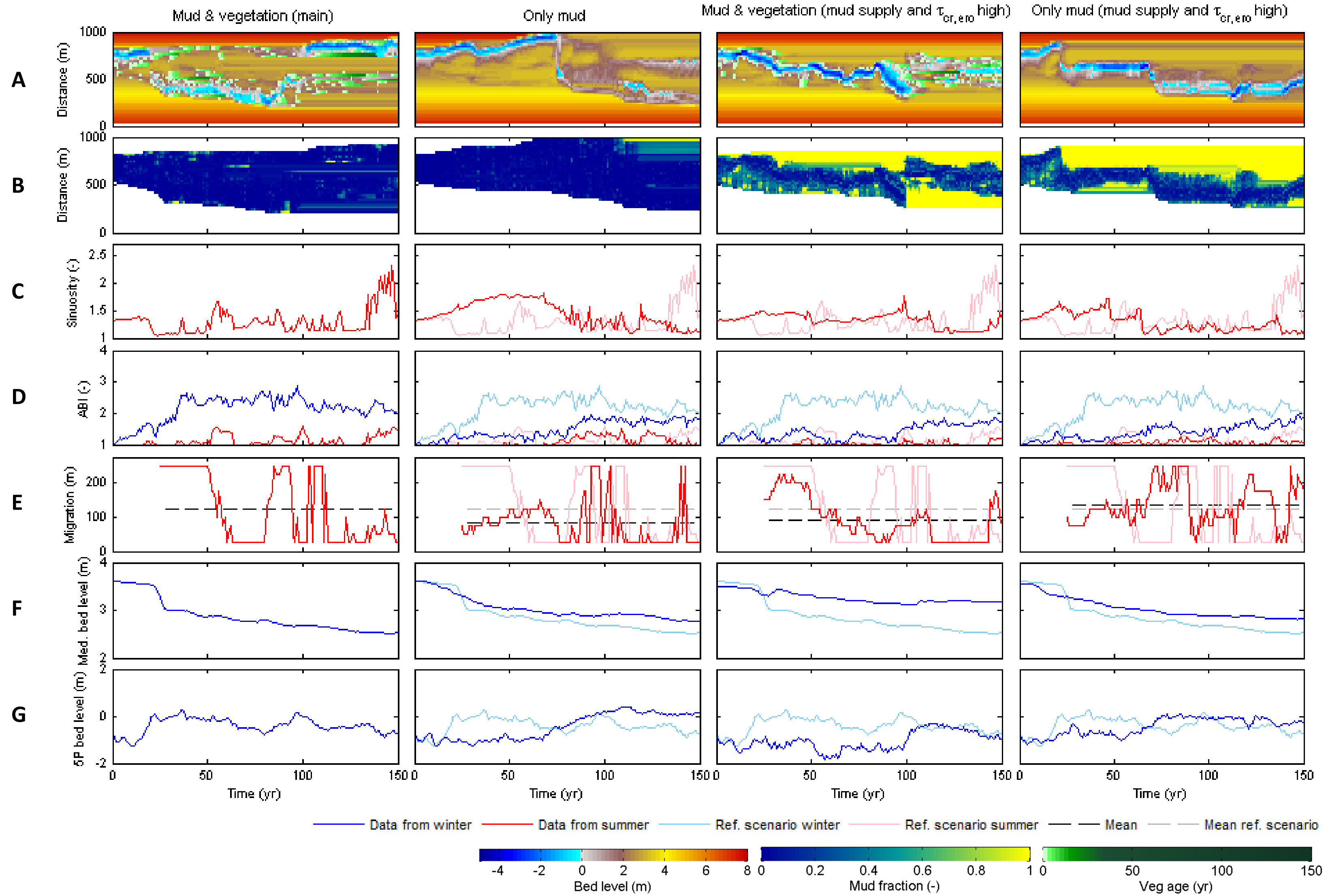

Figure 41 Effects of mud in combination with and without vegetation on river morphology for default settings (mud supply = 20 mg/L, $\tau_{cr,\,ero}$ = 0.2 N/m²) and for a relatively high mud supply and cohesiveness (mud supply = 500 mg/L, $\tau_{cr,\,ero}$ = 0.5 N/m²). A: bathymetry and vegetation age in the middle cross-section of the river (timestack), B: mud fraction in top layer in the middle cross-section of the river (timestack), C: sinuosity of main channel, D: active braiding index, E: channel migration, F: median bed level, G: 5P bed level, indicative for channel depth, all plotted over time.

4.3 Spatial mud and vegetation patterns in the Allier

4.3.1 Vegetation and sediment distribution

A general vegetation succession from near the active river channel towards the centre of a point bar was observed in the field. At several meters distance from the active river channel there is a strip with pioneer vegetation of a few meters wide that continues along the point bar (Figure 42).

Figure 42 Strips of pioneer vegetation along the active channel in the river Allier. Left: common case of sparse pioneer vegetation along a strip of about 3 m wide on a dominantly gravel surface. Right: extreme case with dense pioneer vegetation along a strip of approximately 1 m wide on a gravel surface with organic material.

The point bar consists of bare gravel for several tens of meters, which is followed by an abrupt transition towards a layer (approximately 0.5 m) of sand with sparse shrubs (Figure 43). The presence of and abrupt transition to these sand layers can sometimes be explained by presence of dead tree trunks or patches with large shrubs/trees growing directly on the gravel surface which cause a decrease in flow velocity: tailbars.

Figure 43 Layer of sand with sparse shrubs at the end of the large bare gravel surface at the point bars in the river Allier.

Continuing towards the centre of the point bar, a flat surface is present, located approximately 0.5-1 meter above the sandy surface. On this surface resistant grasses and mosses grow (Figure 44 A). Thin layers of several millimetres of mud may be present on this surface. Presence of gravel sized grains is common as well. At the transition between the sandy layer and this flat surface a resistant vegetation strip with larger shrubs and small trees is sometimes present.

Even further towards the centre of the point bar, on older scroll bars, the vegetation pattern is characterised by patches and/or strips of trees with undergrowth and fields with grasses in between (Figure 44 B).

Further towards the centre of all point bars the bushes get denser until they are no longer penetrable. Sometimes, there dense bushes are present at the upstream and/or downstream side of the point bars located more close to the active river channel.

Figure 44 Various biogeomorphological zones in the Allier. A: flat, relatively bare surface with moss and resistant grasses. B: part of older scroll bar with strips/patches of trees and a grass surface in between. C-E: moist low-lying environments with specific vegetation species. Often these environments are former river channels. F-G: dry riverbeds with relatively little vegetation and gravel (pebbles) at the surface.

Specific vegetation species grow at low-lying locations with moist, muddy soil (swamp) (Figure 44 C-E). These locations are often former river channels.

At some locations of former river channels however, the ground is relatively bare and the soil is dry with gravel on top (Figure 44 F-G). These former river channels were located mostly half-way on top of the point bar and may become active high-energy channels during high-flow conditions.

4.3.2 Sediment composition data

From the ground surface measurements (Figure 46-Figure 49) a general trend is visible of decreasing grain sizes going from the bare areas near the active channel towards the densely vegetated centre of the point bars. At 10 cm depth (Figure 50-Figure 53) the trend of decreasing grain size towards the centre of the point bar is less clear and gravel can still be found relatively far from the active channel. Also the decrease of the grain size from the upstream towards the downstream side of the point bars is less clear.

The soil mud content generally increases going from the bare areas near the active channels towards the more densely vegetated parts of the point bars (Figure 45-Figure 53). However, there is no gradual increase in soil mud content along the transects (Figure 45). Peaks in mud content relatively close to the channel may be caused by presence of rows with vegetation (Figure 46-Figure 48; Figure 50). It is notable that mud percentages at the surface are generally larger at the downstream side of the point bars than at the upstream side (Figure 46; Figure 47; Figure 49).

Mud layers are often only a few millimetres thick. This is reflected by the much lower soil mud percentages at 10 cm depth compared to those at the ground surface (Figure 45). Thicker mud layers are present at locations of abandoned channels (Figure 50; Figure 53) and far away from the channel in the part with dense vegetation consisting of grasses, shrubs and trees (Figure 50; Figure 52).

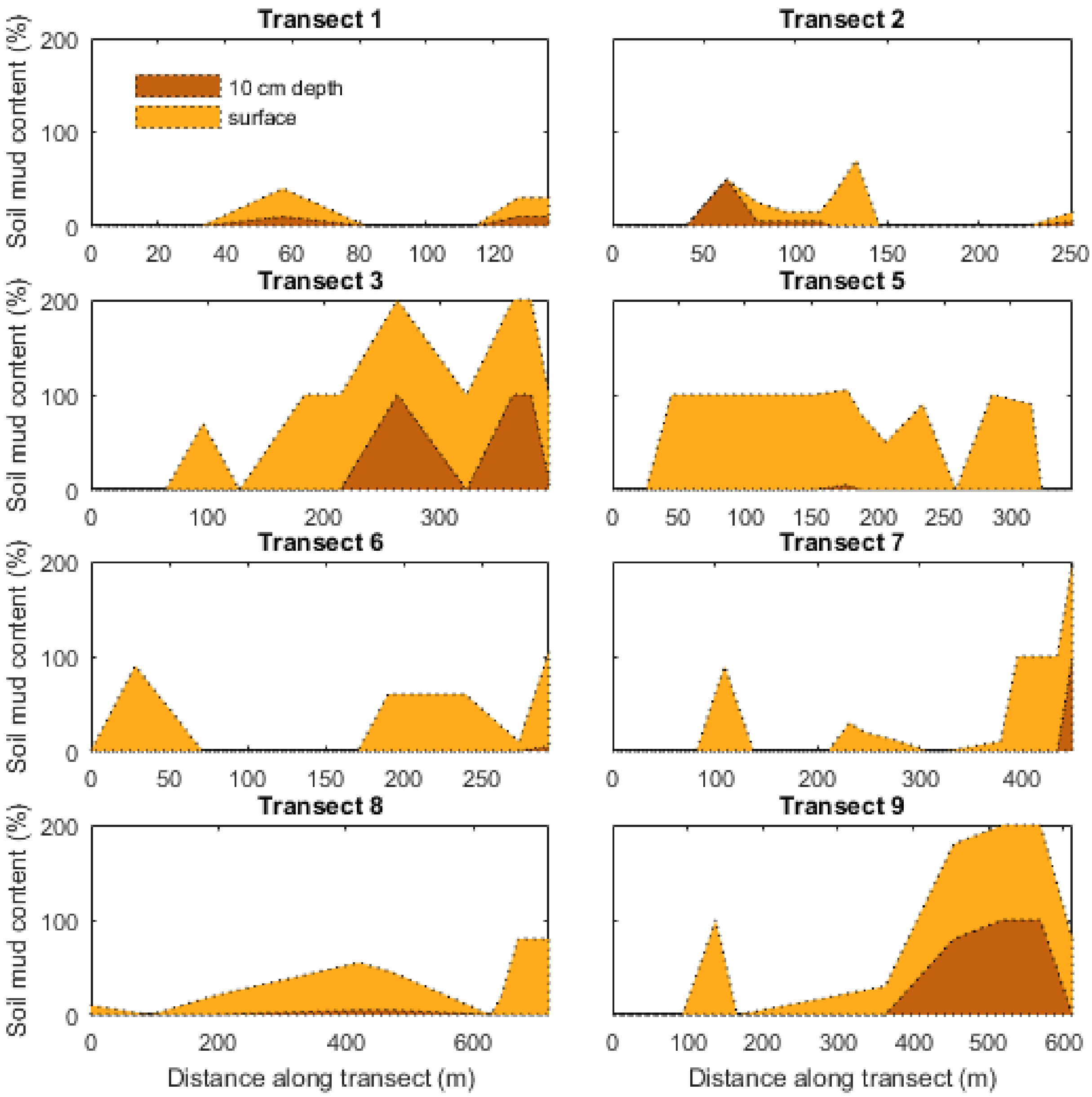

Figure 45 Mud percentage in bed sediment at the surface and at 10 cm depth along 8 transects in the river Allier. Transects start on the bare part of the point bar near the channel and generally end more towards the center of the point bar where vegetation is dense. The transect locations are indicated in Appendix 1. Note that the soil mud content can be 200 percent if both at 10 cm depth and at the surface the soil consists entirely of mud (not gravel or sand).

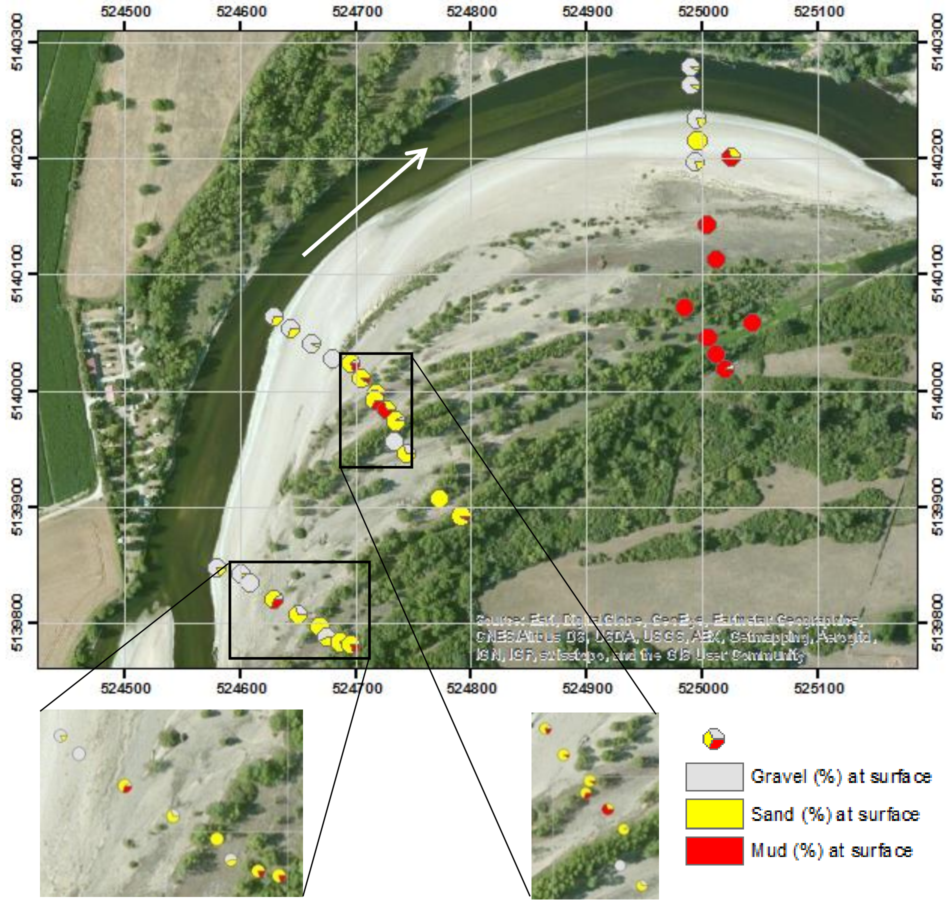

Figure 46 Sediment composition (gravel, sand, clay) at the ground surface along transect 1-3. Pie charts indicate gravel, sand and mud percentages in the soil. For location see Appendix 1. Datum: WGS84. Projection: UTM 31T. Source: basemap from ESRI ArcMap 10.3.1, aerial photograph from DigitalGlobe (2010). The aerial photograph is taken in an earlier year (October, 2010) than the fieldwork (August, 2016) was conducted.

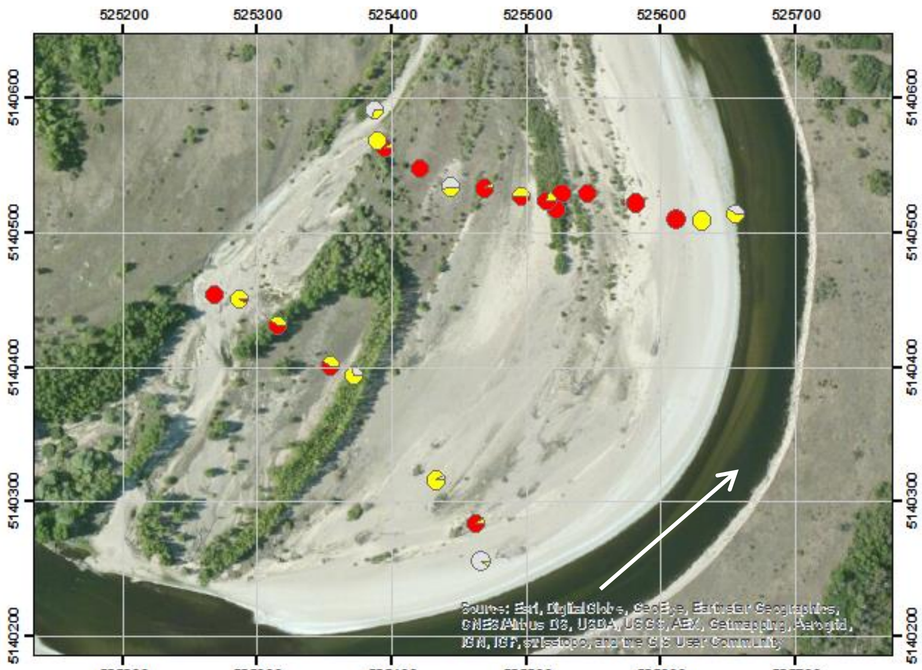

Figure 47 Sediment composition (gravel, sand, clay) at the ground surface along transect 5-6. Pie charts indicate gravel, sand and mud percentages in the soil. Legend: see Figure 46. For location see Appendix 1. Datum: WGS84. Projection: UTM 31T. Source: basemap from ESRI ArcMap 10.3.1, aerial photograph from DigitalGlobe (2010). The aerial photograph is taken in an earlier year (October, 2010) than the fieldwork (August, 2016) was conducted.

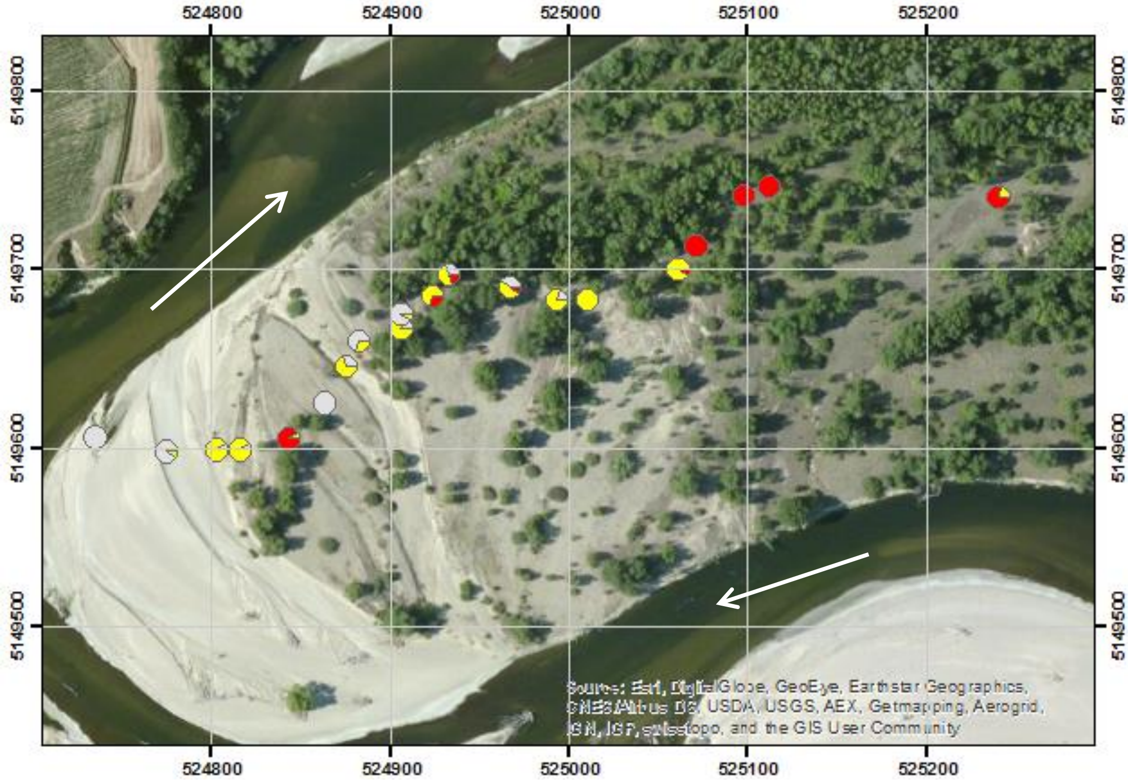

Figure 48 Sediment composition (gravel, sand, clay) at the ground surface along transect 7. Pie charts indicate gravel, sand and mud percentages in the soil. Legend: see Figure 46. For location see Appendix 1. Datum: WGS84. Projection: UTM 31T. Source: basemap from ESRI ArcMap 10.3.1, aerial photograph from DigitalGlobe (2010). The aerial photograph is taken in an earlier year (October, 2010) than the fieldwork (August, 2016) was conducted.

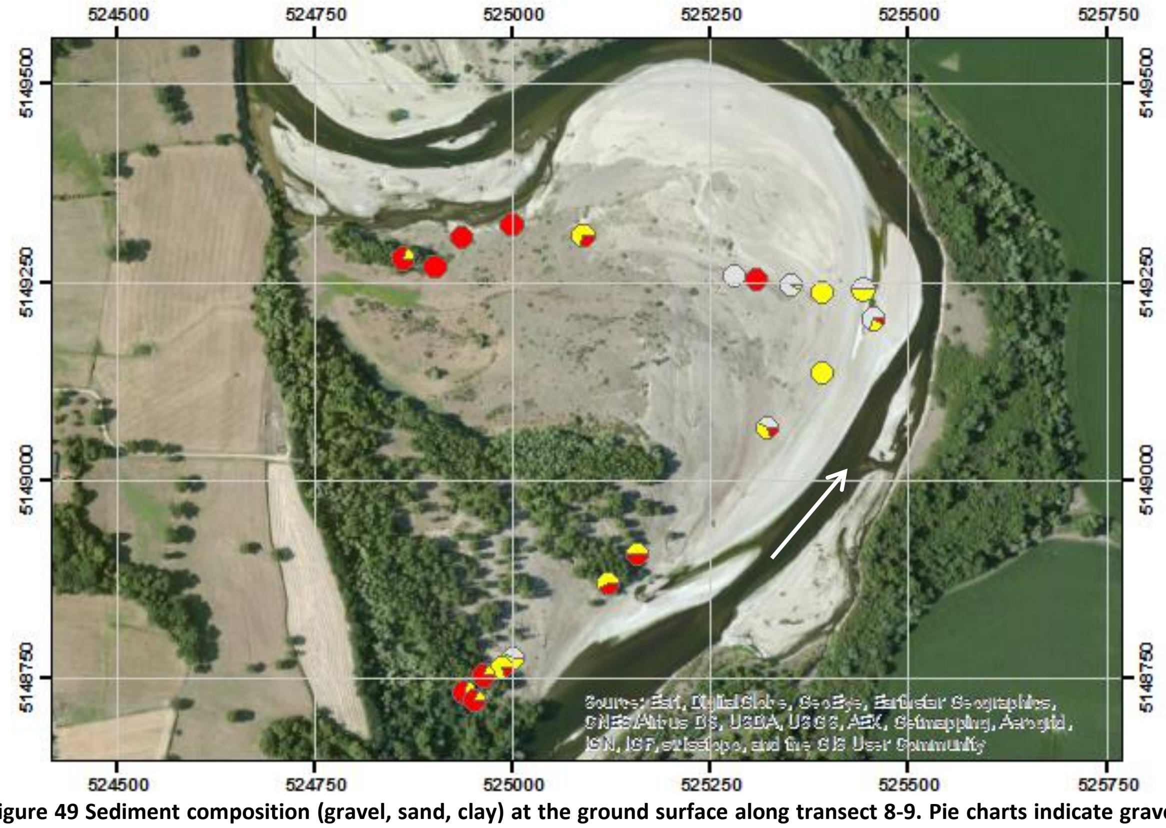

Figure 49 Sediment composition (gravel, sand, clay) at the ground surface along transect 8-9. Pie charts indicate gravel, sand and mud percentages in the soil. Legend: see Figure 46. For location see Appendix 1. Datum: WGS84. Projection: UTM 31T. Source: basemap from ESRI ArcMap 10.3.1, aerial photograph from DigitalGlobe (2010). The aerial photograph is taken in an earlier year (October, 2010) than the fieldwork (August, 2016) was conducted.

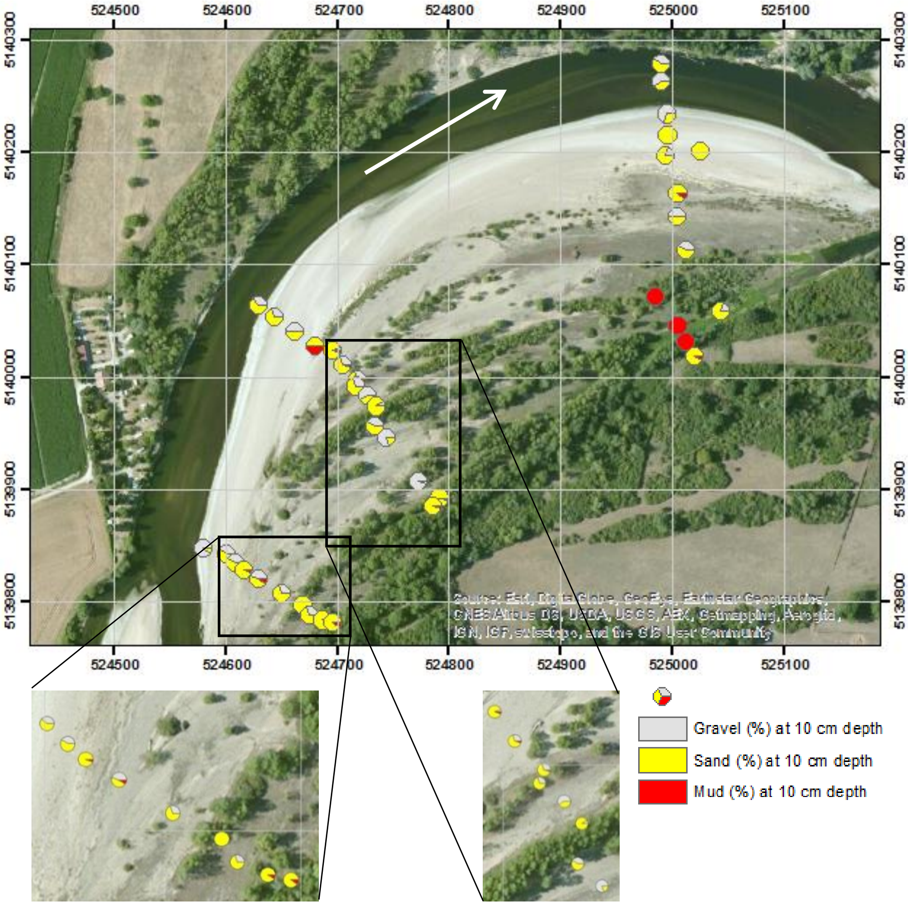

Figure 50 Sediment composition (gravel, sand, clay) at 10 cm depth along transect 1-3. Pie charts indicate gravel, sand and mud percentages in the soil. For location see Appendix 1. Datum: WGS84. Projection: UTM 31T. Source: basemap from ESRI ArcMap 10.3.1, aerial photograph from DigitalGlobe (2010). The aerial photograph is taken in an earlier year (October, 2010) than the fieldwork (August, 2016) was conducted.

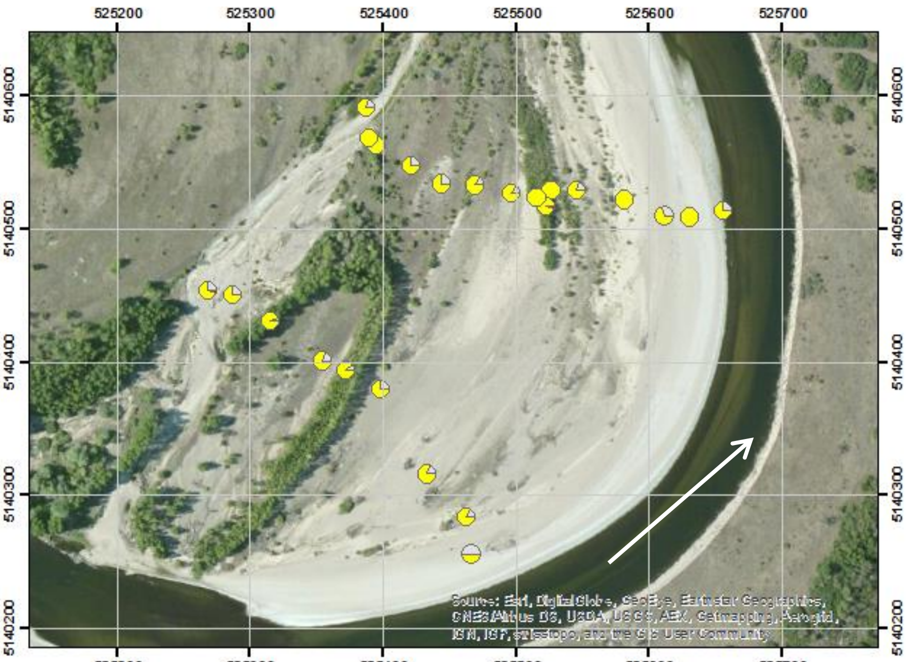

Figure 51 Sediment composition (gravel, sand, clay) at 10 cm depth along transect 5-6. Pie charts indicate gravel, sand and mud percentages in the soil. Legend: see Figure 50. For location see Appendix 1. Datum: WGS84. Projection: UTM 31T. Source: basemap from ESRI ArcMap 10.3.1, aerial photograph from DigitalGlobe (2010). The aerial photograph is taken in an earlier year (October, 2010) than the fieldwork (August, 2016) was conducted.

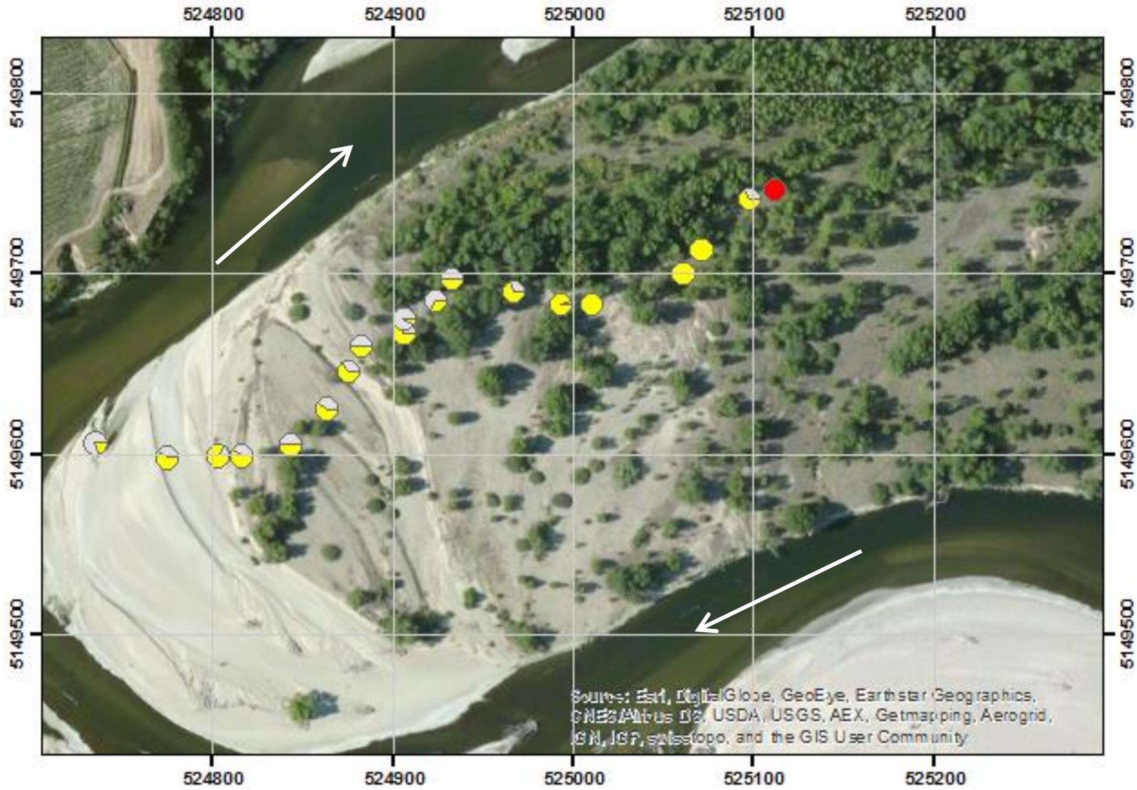

Figure 52 Sediment composition (gravel, sand, clay) at 10 cm depth along transect 7. Pie charts indicate gravel, sand and mud percentages in the soil. Legend: see Figure 50. For location see Appendix 1. Datum: WGS84. Projection: UTM 31T. Source: basemap from ESRI ArcMap 10.3.1, aerial photograph from DigitalGlobe (2010). The aerial photograph is taken in an earlier year (October, 2010) than the fieldwork (August, 2016) was conducted.

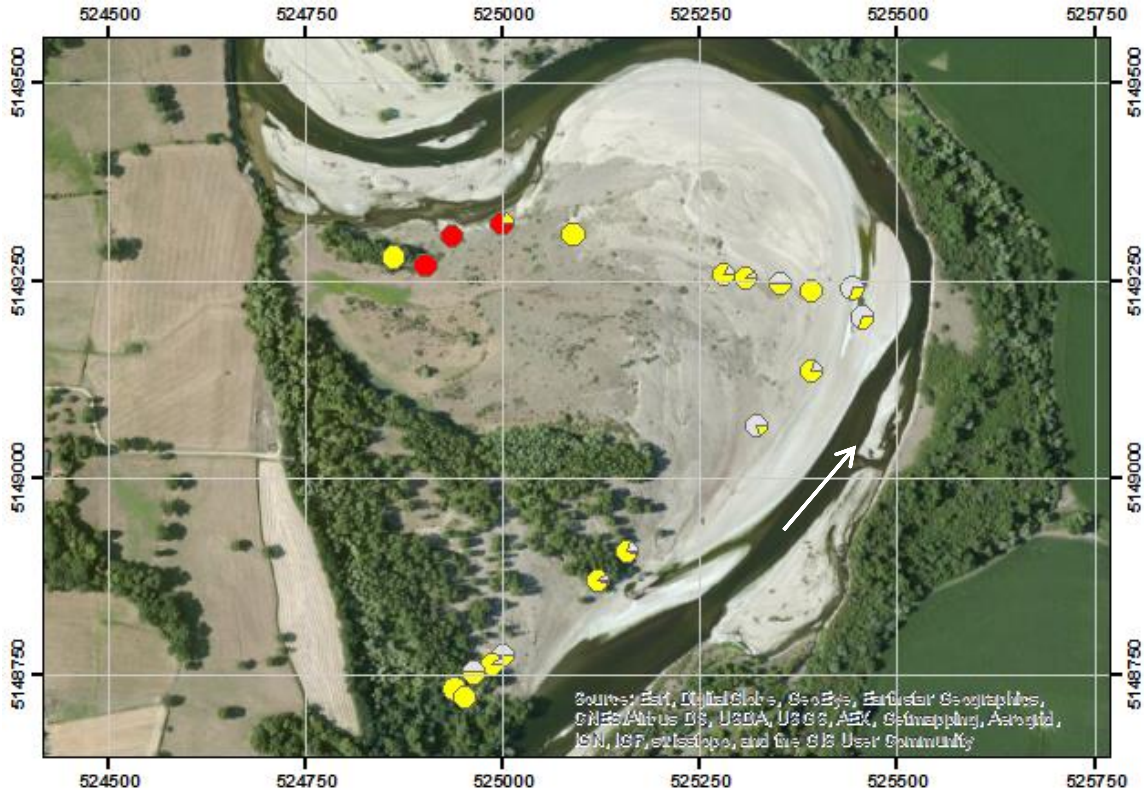

Figure 53 Sediment composition (gravel, sand, clay) at 10 cm depth along transect 8-9. Pie charts indicate gravel, sand and mud percentages in the soil. Legend: see Figure 50. For location see Appendix 1. Datum: WGS84. Projection: UTM 31T. Source: basemap from ESRI ArcMap 10.3.1, aerial photograph from DigitalGlobe (2010). The aerial photograph is taken in an earlier year (October, 2010) than the fieldwork (August, 2016) was conducted.

4.3.3 Link between mud and vegetation pattern

Mud deposition seems to increase at locations with high vegetation density on top of the point bars. During high flow conditions the higher part of the point bars is flooded. When the water level drops flow velocities go down and ponding may occur, both promoting mud deposition. The high vegetation density likely decreases flow velocities heavily and therefore leads to much higher rates of mud deposition compared to the rate at bare surfaces.

It is remarkable that mud was not present at all locations with dense vegetation on the higher part of the point bar. This can partly be explained by the fact that field measurements become impossible as soon as the vegetation gets really dense and therefore not many measurements were actually taken at the locations with highest vegetation covers. Another explanation may be that even in the densely vegetated zone there are preferential flow paths where flow velocities are still too high for mud deposition.

At some locations mud was only present at the ground surface. These locations consisted mostly of dried grass and were present on the flat planes at 0.5-1 m elevation above the gravel part of the point bar. These dried grass fields however were not totally covered with a thin mud layer and the presence of mud in the grass fields could not be related to height differences. Hence, a direct link between vegetation and the thin mud drapes remains unclear.

I found no clear evidence in the field that vegetation was present as the result of presence of a mud layer.

4.4 Model sensitivity and validation

The hypothetical model was loosely based on the river Allier, which is in a transitional state between meandering and braiding, and was able to simulate important morphodynamic processes such as avulsion, chute cutoffs and individual bend migration. Maximum flow velocities in the main model scenario are realistic and range between 1.3 and 2 m/s. Maximum water depths range between 5 and 8 m. The largest water depths are quite high and are related to the formation of scour holes in the main channel.

4.4.1 Sensitivity of model outcomes to PmCrit and active layer thickness

An increase in PmCrit, the threshold fraction of mud from when the sand/gravel beds start to erode proportionally with mud, does not significantly affect the amount of mud and mud deposits in the river system. However, the vegetation cover in the run with PmCrit equals 0.6 is relatively high. Therefore it is possibly that a higher value of PmCrit results in lower mud fractions in the bed if no vegetation is present. The higher vegetation cover in the run with PmCrit equals 0.6 might also have caused a relatively low channel migration. There is no systematic link between PmCrit and the river morphology characteristics channel depth, sinuosity, active braiding index and median bed level. The braiding index differs for systems with different values of PmCrit, but this seems to be related to internal system dynamics as the differences are not systematic.

An increase in active layer thickness from 3 to 10 cm results in less mud deposits. Mud plain formation is less common, because the periods with high vegetation cover and hence high rates of mud deposition are too short for the development of a 10 cm thick mud layer. Although it is more difficult to erode 10 cm thick layers of mud, the mud deposits that do form are still eroded, because erosion is a quicker process than mud deposit formation.

The river system with a thicker active layer of 10 cm has less deep channels and a lower sinuosity. More model runs with different active layer thicknesses are needed to determine the significance of these changes and to link the changes to river system characteristics.

4.4.2 Comparison to SEDIFLUX floodplain sedimentation model

Both the Delft3D model and SEDIFLUX floodplain sedimentation model show increased net mud deposition within vegetation patches when in the SEDIFLUX model a low critical shear stress for mud deposition is applied (Figure 54; Figure 55 A and D left). Note that when the critical shear stress for mud deposition is 1000 N/m^2, it is actually not taken into account and mud always settles. The critical threshold for mud deposition is never incorporated in the Delft3D model.

The sediment concentrations in Delft3D are much higher than in the SEDIFLUX model even when in the latter a critical shear stress for mud deposition is applied (Figure 55 B, C, D right). The spatial pattern of mud concentrations in the models is similar with high concentrations in and near channels (Figure 55 B, C, D right; Figure 56 C). Concentrations are much higher in Delft3D due to resuspension. Mud concentrations in SEDIFLUX, on the other hand, show depletion at the downstream part of the river especially when no critical shear stress for mud deposition is applied (Figure 56 A). It is notable that the mud concentrations are not highest at locations with the largest water depths, especially in Delft3D (Figure 56 C). This is probably also related to resuspension in Delft3D. All in all, resuspension affects sediment concentrations in the water more than the critical shear stress for mud deposition.

Although in both models mud concentrations decrease with distance from the main channel, the net mud deposition is generally higher at locations outside the channel (Figure 55 A, D left). This is the result of: (1) the critical shear stress for mud deposition in the SEDIFLUX model; (2) the erosion of mud in Delft3D; (3) the vegetation and topographic disturbances which cause a longer residence time of water in the floodplain compared to in the main channel.

The deposition fluxes of Delft3D and SEDIFLUX show similarities, especially when the critical shear stress for mud deposition in SEDIFLUX is not taken into account, but are not strongly correlated (Figure 55 A, B, C left; Figure 56 A, B). Although both models show increased net mud deposition within vegetation patches, the net deposition of both models is not clearly correlated (Figure 56 D).

The relation between vegetation fraction and mud deposition is the most logical and strongest in the SEDIFLUX model in which the critical shear stress for deposition is taken into account. The deposition flux clearly increases with increasing vegetation fraction and is low for vegetation fractions of 0.8, which represent colonizing vegetation and are associated with high flow velocities. Flow velocities are probably often too high for mud deposition between vegetation patches. The mean deposition fluxes in Delft3D and SEDIFLUX without the critical shear stress for mud deposition are similar, but not strongly related to the vegetation fraction (Figure 54). Concentrations, and hence deposition rates, are among others high within the channel where no vegetation is present. Erosion in Delft3D strongly affects the spatial mud pattern and correlation between mud and vegetation. The mean mud fraction in the top layer of the bed in Delft3D is correlated to vegetation cover (Figure 31) contrary to the mud deposition flux.

All in all, the net mud deposition patterns in Delft3D model seem reliable even though the critical shear stress for mud deposition is not taken into account. This is because mud erodes at locations with high flow velocities. The relation between vegetation and mud deposition may, however, be stronger when the critical shear stress for mud deposition is taken into account. Finally, this comparison has shown that in high-energy river systems like the Allier, resuspension should not be ignored.

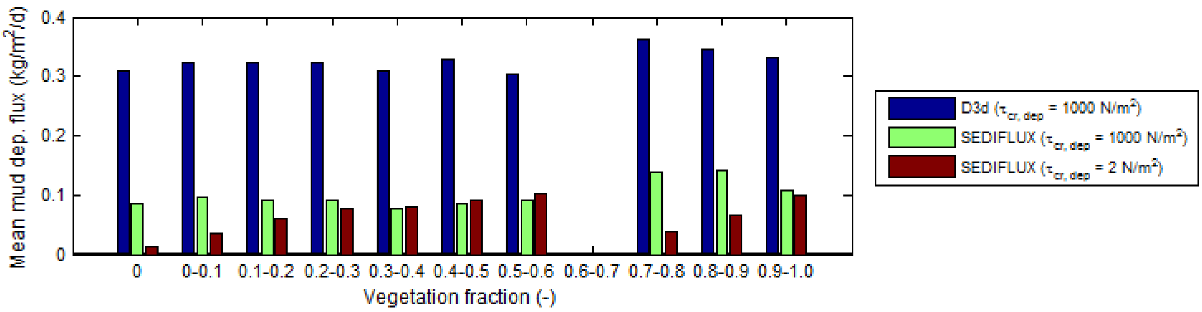

Figure 54 Mean mud deposition flux in Delft3D and SEDIFLUX model. The critical threshold for mud deposition is varied in the SEDIFLUX model. Note that only the floodplain (mud fraction in Delft3D above zero) is taken into account.

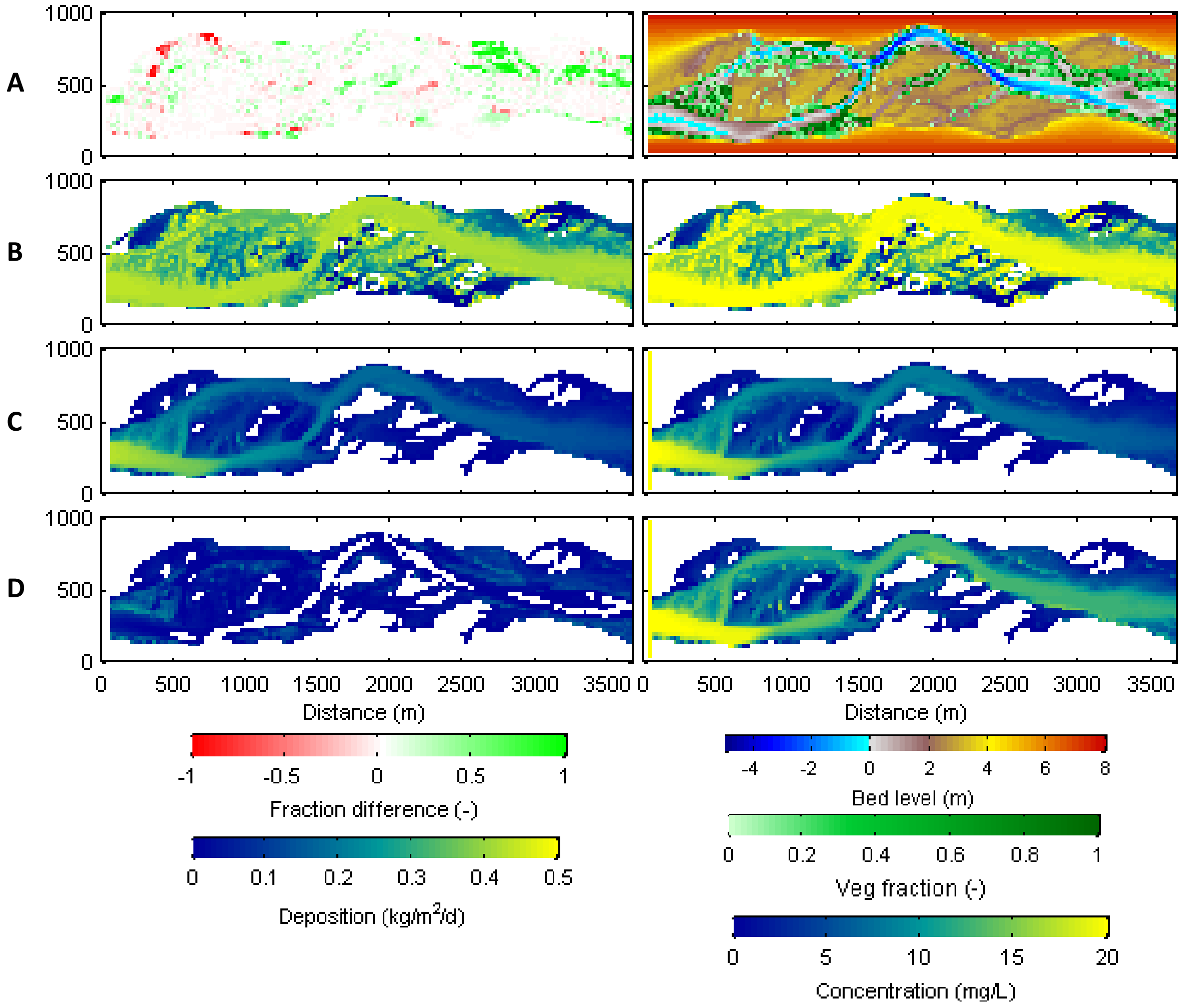

Figure 55 Comparison of mud deposition in Delft3D and SEDIFLUX model for main model run with mud and vegetation between year 105 and 109. A: Delft3D difference between mud fraction in the top layer at the beginning of year 105 and the end of year 109 indicating net deposition (left) and bathymetry and vegetation fraction (right); B: Delft3D mean deposition flux (left) and mean mud concentration in water (right); C: SEDIFLUX mean mud deposition flux (left) and mean mud concentration in the water (right) for the same critical threshold for mud deposition as in Delft3D ($\tau_{cr,dep}$= 1000 N/m²); D: SEDIFLUX mud deposition flux (left) and mud concentration in the water (right) for a much lower critical threshold for mud deposition as in Delft3D ($\tau_{cr,dep}$ = 2 N/m²) . Note that in Delft3D mud concentrations larger than 20 mg/L do occur (Figure 54).

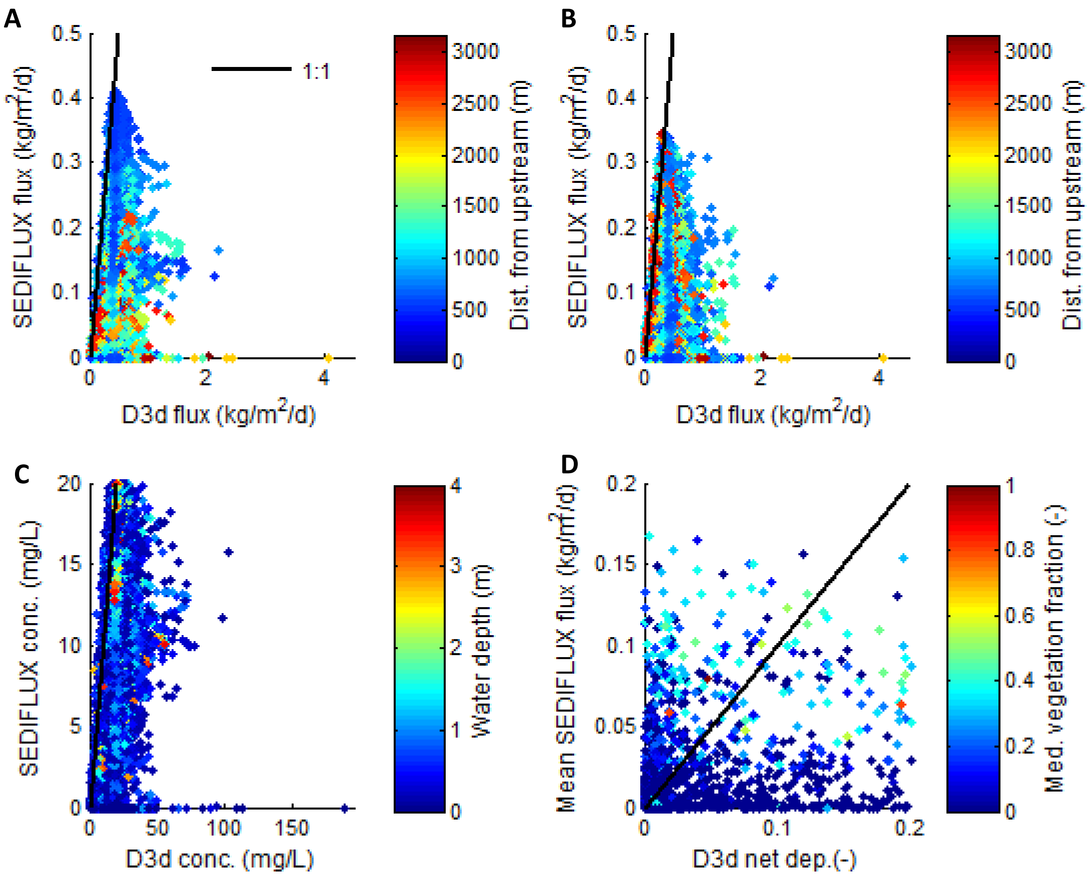

Figure 56 Comparison of mud deposition fluxes (A and B), concentrations (C) and net deposition (D) between Delft3D and SEDIFLUX model in year 105-109 for every location at every ecological time step. In A the critical theshold for mud deposition in SEDIFLUX is 1000 N/m² (equal to Delft3D), while in B, C and D it is 2 N/m² (unequal to Delft3D).

4.4.3 Comparison to field data Allier

The mud deposition pattern in the field and the model are similar, while the vegetation pattern is more different.

Mud deposits at locations with dense vegetation and mud layers are thin both in the field and in the model. Furthermore, mud deposition is enhanced in some abandoned channels, but not in all, depending on flow velocities in abandoned channels at high flow stages.

The trend of increasing mud deposition with distance from the channel as observed in the field differs from the model where mud deposits commonly are present along the channel border. This can be explained by the difference in vegetation pattern between the field and the model. In the field the vegetation cover increases with distance from the channel, while in the model this is less often the case. This does confirm the impact of the vegetation distribution on the mud pattern.

Both in the field and the model vegetation patches/forests develop at the upstream part of point bars. However, the model does not show an increase in mud deposition at the downstream part of point bars which is in contrast with the trend shown by field observations.

5. Discussion

Changing the boundary conditions of vegetation presence and mud supply and cohesiveness in our numerical model resulted in the development of different types of river systems (Figure 57; Appendix 3). Presence of vegetation has a relatively large effect on morphology and generally leads to dynamic multi-thread river systems with confined channels. Channel dynamics are relatively high as vegetation promotes avulsions over a wide part of the floodplain and leads to more frequent formation and gradual migration of meander bends (Figure 57 C). Even though vegetation promotes mud deposition along channel borders, an increase in mud supply or cohesiveness generally has little effect on morphology and the vegetation cover, because mud is easily eroded. However, a combination of an extreme mud supply and relatively cohesive mud in vegetated systems causes a shift towards a single-thread river system (Figure 57 A, C), whereby the channel is bordered by high muddy banks. In these systems the hydrological connection between channel and floodplain is low, which limits vegetation development to a small zone along the channel. Despite the low vegetation cover, vegetation is still of importance for channel confinement (Figure 57 B). Also, vegetation leads to a change in channel migration mode from avulsions of the channel thalweg within a limited part of the floodplain (from now on referred to as "quasi-stable") to dominantly gradual migration of a single confined channel (Figure 57 C).

5.1 Mud and vegetation patterns and interaction

5.1.1 General mud and vegetation patterns

General mud patterns

When vegetation is absent, mud deposits predominantly in abandoned channels and the mud fraction in the bed is generally larger further away from the main channel (Figure 18; Figure 32) as expected from large-scale field observations in floodplains (Middelkoop and Asselman, 1998; Walling and He, 1998). The increase in mud fraction at large distances from the channel thalweg in Figure 32 is extreme due to the formation of large plains with mud at the sides of the floodplain after cutoffs of the three initial meander bends. The increase in mud fraction with distance from the channel would probably have been less extreme if an initial bathymetry was used closer to the equilibrium of the system without vegetation. Mud deposits in oxbow lakes and other abandoned channels in the final stages of the infilling sequence (Figure 27) as observed in sedimentary records (e.g. Toonen et al., 2012). When the mud supply and cohesiveness are large, continuous mud deposits are present in the floodplain everywhere along the channel.

These results confirm the hypothesis that in river systems without vegetation the proportion of mud relative to bedload sediment generally increases with distance from the main channel. Also, increased mud deposition occurs in topographic depressions such as abandoned channels in the final stages of the infilling sequence.

General vegetation patterns

The vegetation cover in the model is highly dynamic (Figure 22) similar to the natural situation in the Allier (Geerling et al., 2006; Douma, 2016). Also, the strong drop in mortality percentages with increasing vegetation age (Figure 21) agrees with the exponential decrease in mortality with vegetation age which was found for the Allier by Douma (2016) using remote sensing. The main causes of mortality are desiccation followed by flooding.

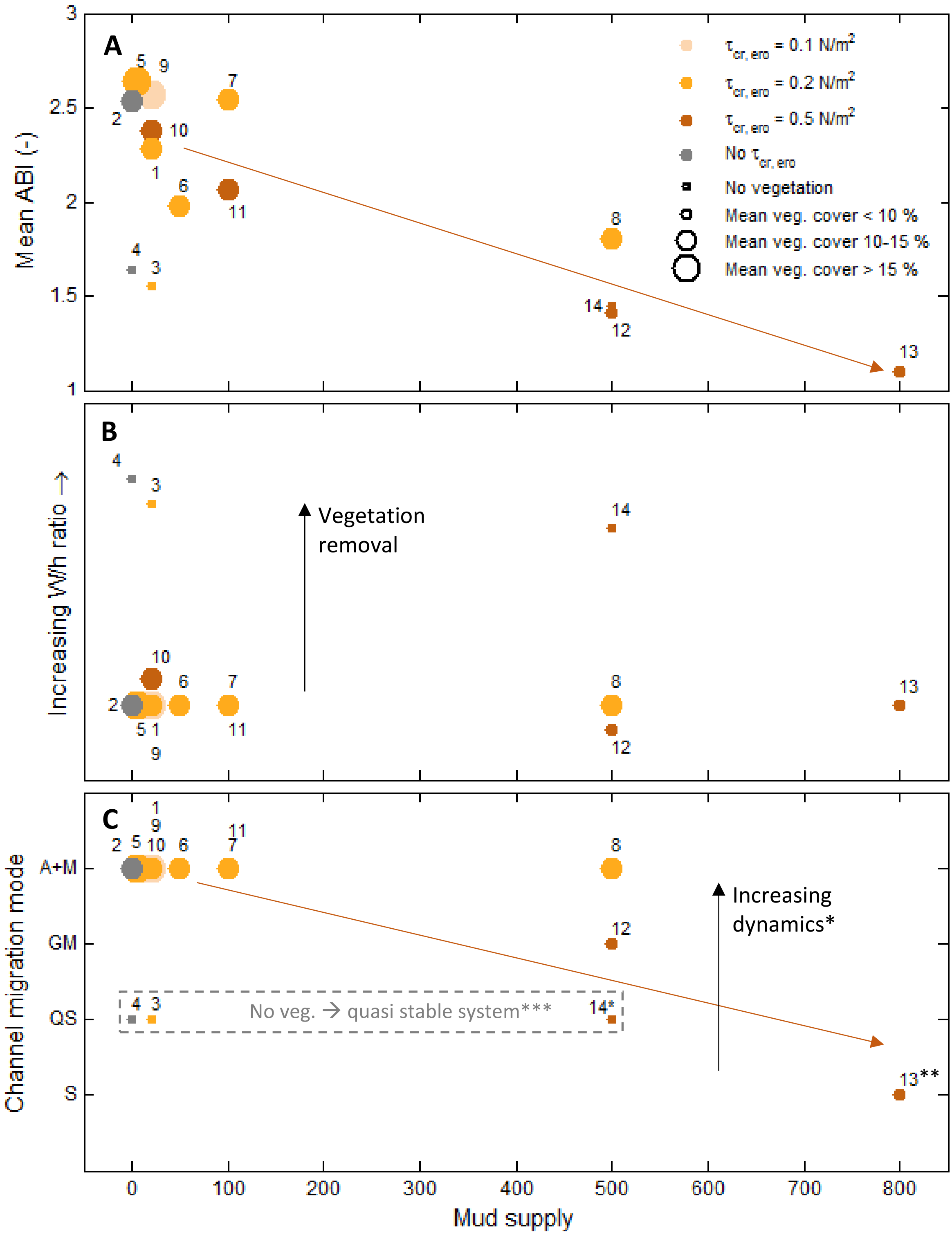

Figure 57 Combined effects of vegetation presence, mud supply and mud cohesiveness ($\tau_{cr, ero}$) on (A) active braiding index (ABI) in winter, (B) width-to-depth (W/h) ratio and (C) dominant mode of channel migration in the river system between year 25 and 150. Marker numbers indicate the model scenarios (Table 6). Migration modes are: mix avulsions and gradual channel migration (A+M), gradual channel migration (GM), quasi stable (QS) and stable (S). Brown arrows indicate trend of runs with a high mud cohesiveness. *Channel migration as calculated in the statistics is higher in run 14 than in run 12. This might be due to non-erodible grid cells which force migration (see section 5.4.1). **Large system stability might be caused by model limitation (see section 5.4.1). ***A quasi stable system is a system in which the channel thalweg shifts within a floodplain with limited width. A: an increase in mud supply causes a decrease in ABI, especially if mud is relatively cohesive. Higher ABI's are associated with larger vegetation covers. B: vegetation presence is required to obtain channels with a low W/h ratio, while mud supply, cohesiveness or a combination of both has little impact. C: without vegetation a quasi-stable system exists. Larger vegetation covers are associated with more dynamic systems with frequent avulsions, while an increase in mud supply in combination with more cohesive mud stabilizes the system.

The spatial vegetation patterns in the model are strongly determined by channel stability as described by McKenney et al. (1995). Along stable reaches, a relatively continuous vegetation cover develops. In more dynamic parts of the system the vegetation cover consists of multiple patches. Increased vegetation development was observed in zones with low morphodynamic activity (Figure 29). This can be the case because vegetation itself stabilizes areas or because vegetation can develop more easily in quiet zones as there is a smaller risk of mortality due to flooding, uprooting, scour and burial. Both processes play a role and it remains unclear which one is dominant. Vegetation succession occurs in low energy zones where channel migration leads to bar accretion (Figure 19), but is often interrupted due to frequent avulsions.

Vegetation in the model develops rapidly in abandoned channels, which is also observed in the Allier (Douma, personal communication) and in the Sacramento River (Stella et al., 2011). However, vegetation in abandoned channels in the model often dies relatively quickly due to either flooding or desiccation and does not often reach ages above 10 years.

The vegetation density in the model does not always increase on point bars with distance from the river (Figure 19) contrary to the natural situation in the Allier and expectations based on Figure 10a (Perucca et al. 2006). When the vegetation density does increase this is related to the development of forest at the location of a (partly) abandoned channel located on the point bar. This situation also occurs in the Allier (e.g. Figure 49). Possible explanations of the low vegetation cover on top of the point bars are that (1) vegetation colonization is restricted to the area closer near the channel, (2) vegetation dies due to desiccation on top of the point bar (see also section 5.4.1) or (3) the model does not take into account asexual reproduction. The third explanation is of minor importance for at least the *Populus* species in the model (Legionnet et al., 1997).

As hypothesized, vegetation succession occurs near migrating river banks. Vegetation succession is also often interrupted by avulsions. The increase in vegetation density on point bars with distance from the channel occurs when (partly) abandoned channels are present, like in the Allier. However, more often than in nature, point bars are bare further away from the channel.

5.1.2 Effects of vegetation on mud pattern

The mud cover follows spatiotemporal fluctuations in the generally highly dynamic vegetation cover (Figure 22; Figure 23; Figure 26). This agrees with previous channel-scale field studies on effects of in-stream macrophytes on fine sediment deposition (Cotton et al., 2006; Kleeberg et al., 2010) and a large-scale estuary modelling study with mud of Lokhorst (2016).

A difference with Cotton et al. (2006) is that they found that the largest part of deposition within vegetation patches consisted of sand-sized particles instead of mud. This may be because Cotton et al. (2006) investigated in-stream vegetation, so the shear stresses were possibly higher than at the location of riverbank vegetation. Another explanation is that the median grain size of the first sediment fraction in the model is larger than sand thus possibly this sediment is not able to reach the center of vegetation patches due to too low mobility. Finally, mud deposition in the model may be overestimated, because the model does not take the critical shear stress for mud deposition into account.

Presence of vegetation generally causes a dynamic distribution of mud deposits in the floodplain, because mud follows the vegetation dynamics. The vegetation dynamics in turn strongly depend on discharge, because vegetation colonization (Figure 6) and mortality (Van Oorschot et al., 2015) depend on flow velocities and water depths. Many studies already identified the importance of the flow regime for riparian plant development (Gurnell, 2014). Fluctuations in discharge thus not only directly affect the spatiotemporal pattern of mud deposits by affecting shear stresses in the system, but also have a significant effect on the pattern of mud deposits via vegetation. After vegetation removal, mud deposits often erode within a few years. This does not necessarily have to be the case: Cotton et al. (2006) found that die-back of in-stream vegetation can lead to lower average flow velocities so that fine sediment trapped by the vegetation is not eroded. In less dynamic river systems where channels are stabilized by either mud or vegetation, the vegetation cover is less dynamic resulting in lower mud deposit dynamics.

Mud is deposited closer to the channel when vegetation is included (Figure 18; Figure 32). A thick strip of vegetation is needed to reduce flow velocities enough for mud deposition. It seems that mud deposition at larger distances from the channel does not decrease due to presence of vegetation (Figure 32). However, this is difficult to observe and to compare with the scenario without vegetation as presence of multiple channels disturbs the pattern of both mud concentrations in the water and the bed. Besides, mud fractions in the bed at large distances from the channel in the run with only mud are extremely high as a consequence of the initial bathymetry (see section 5.1.1) and not necessarily due to the lack of vegetation near the channel borders.

The correlation between mud and vegetation over time and space is strongest for vegetation in the bush stage (2-10 years old) (Figure 22; Figure 29). This partly agrees with McKenney et al. (1995) who indicate that when vegetation ages, the density can decrease and with that the sediment trapping efficiency. We indeed found a clear relation between vegetation density and mud deposition (Figure 31) as expected from Baptist et al. (2007). Although pioneer vegetation has a higher density than vegetation in the bush stage it appears to be a less effective sediment trap. This is probably because pioneer vegetation is only present for a short time and hence there is little time for mud settling. Another possible explanation is that at locations with pioneer vegetation the amount of sand deposition is also high and therefore mud concentrations in the bottom sediment only slowly increase. The low correlation between forest vegetation and mud in Figure 22 is also a consequence of the low total forest cover.

Surprisingly, the total amount of mud in the floodplain after 150 years was about equal in the river system with and without vegetation when the mud supply and cohesiveness are moderate (Figure 28). This is partly interpreted as a consequence of initial bathymetry conditions which were out of equilibrium with especially the system without vegetation (see section 5.1.1). However, even with a more suitable initial bathymetry, differences in total mud amount possibly remain small. This is because vegetation patch sizes restrict mud deposit sizes. Besides, vegetation increases system dynamics causing erosion of mud.

In a system with a relatively high mud supply and cohesiveness the total amount of mud in the bed after 150 years is higher in case vegetation is present (Figure 28). This is because in the run with vegetation the river flow is more confined and did not erode the large mud deposits formed at the side of the channel at the beginning of the model run (Figure 40; Figure 41).

Results confirm that vegetation affects the distribution of mud over the floodplain. The mud cover and deposition follow temporal variations in the vegetation cover. Vegetation causes an increase in mud deposition within dense vegetation patches and more mud deposits closer to the channel. It remains uncertain whether mud deposition decreases further away from the channel when vegetation is added. The hypothesis that the total net amount of mud deposition in floodplains is larger in a river system with vegetation compared to a system without vegetation is not confirmed for a river system with a moderate mud supply and cohesiveness. However, in a system with an extremely high mud supply and cohesiveness this hypothesis was found to be true.

5.1.3 Effects of mud on vegetation development and pattern

The way in which addition of mud in a system with vegetation affects the large-scale river morphology is very important for its effect on the vegetation cover. A supply of 20 mg/L mud did not significantly affect river morphology or the amount of vegetation cover in the river system (Figure 19; Figure 20). However, in a system with vegetation and a high mud supply and cohesiveness, high river banks along the channel lead to a decrease in the hydrological connectivity between the river channel and floodplain and therefore the vegetation cover is restricted to a small zone along the river (Figure 40 C). The total vegetation cover is even more reduced because this river system has a lower number of parallel channels. Channel incision was suggested as one of the main causes of riparian wood dieback in the Garonne River in France, because an increase in the channel cross-section led to decreased overbank flooding (Steiger et al., 1998). In the model, the reduction of overbank flooding does not cause a large increase in desiccation mortality and the most important cause of the decrease in vegetation cover seems to be the strong reduction in area where vegetation colonizes. An increase in mud supply with an intermediate cohesiveness leads to a small decrease in vegetation cover (Figure 25). This may be related to the slightly higher floodplain elevations or the decrease in braiding index for an increase in mud supply (Figure 57) both associated with a decrease in area with land-water interactions. However, it is possible that the decrease in braiding index is a consequence of the reduced vegetation cover instead of the other way around.

Addition of mud did not result in enhanced vegetation development as expected based on results of Lokhorst (2016), who found increased *Spartina Anglica* cover in tidal systems when mud was supplied by the river. Possibly, the mud supply in high-energy systems such as the Allier is too low to significantly elevate vegetation into zones with decreased physical stresses when the mud supply is moderate, because mud is easily eroded. Besides, observations from the fieldwork at the Allier and results of Cotton et al. (2006) indicate that significant amounts of deposition around vegetation in streams can consist of sand-sized particles instead of mud. Therefore mud may not be the most important factor for elevating vegetation in high-energy environments. However, even high mud supplies did not result in higher vegetation covers.

Addition of a moderate amount of mud did not result in a significant decrease in scour mortality of vegetation, because mud generally did not decrease channel migration rates. In contrast to expectations, scour mortality increased in case of a high mud supply and cohesiveness, but this is probably related to the fact that in this scenario all vegetation is present close near the main river channel. Finally, scour was only a minor cause of vegetation mortality. Hence, impact of mud on scour mortality has little impact on the vegetation development.

The hypotheses that mud supply, or an increase in mud supply and/or cohesion, causes an increase in vegetation cover in a river system is not confirmed. An increase in mud supply and/or cohesion in a system with vegetation can decrease the amount of vegetation cover in a river system, because it leads to a larger elevation difference between channel and floodplain and hence leads to a smaller area where vegetation colonizes.

5.2 Effects of mud and vegetation on river morphology

5.2.1 Effect of vegetation on river morphology

Addition of vegetation to the river system generally leads to dynamic multi-thread river systems with confined channels (Figure 19; Figure 57). Straight and more sinuous channel stretches alternate and the system dynamics are a combination of both avulsions and gradual meander migration. The river pattern may best be described as wandering instead of truly meandering (Tal and Paola, 2010) and is comparable to patterns obtained with flume experiments by Gran and Paola (2001) and Tal and Paola (2007; 2010). Possible explanations for the lack of the development of a truly meandering river are discussed in paragraph 5.4.1.

Vegetation growth along the channels caused an increase in active braiding index, deeper and more confined channels and an increase in channel migration rates in systems with a moderate or no mud supply (Figure 19; Figure 33).

Vegetation increases the braiding intensity by inducing higher water levels and diverting river flows. This result is in contrast with many field and experimental studies (for review: Gurnell, 2014). A possible explanation for this difference is that the simulated river is located in a confined valley where water levels are more easily elevated (see 5.3). Furthermore, the reference scenario without mud and vegetation had a surprisingly low braiding index (~1.7 during high flow conditions) even though the pattern seemed to be braided, because a wide plain with water formed instead of a braided system with multiple channels. The braiding index of the river with vegetation was relatively high (~2.3 during high flow conditions), but this probably agrees with the natural situation in the Allier as this river is in a transitional state between meandering and braiding (Crosato and Saleh, 2011).

The channel deepening and narrowing agrees with flume experiments (e.g. Gran and Paola, 2001; Tal and Paola, 2007; Van Dijk et al., 2013b). Channel narrowing due to trees or reed which act as sediment traps is also found in field studies (e.g. Graf, 1978; Gurnell and Grabowski, 2016). Note that in these studies the change in channel dimensions is not only caused by a decrease in flow velocities but also partly by the effect of vegetation on bank strength which was not incorporated in the model. The location of vegetation along the channel borders is probably also important for its effect on channel dimensions: Huang and Nanson (1997) found that vegetation growth on the channel bed, as opposed to on the banks, can cause channel widening.

The increase in channel migration rates opposes the hypothesis based on experimental research of Gran and Paola (2001). However, at locations with dense vegetation patches along a relatively straight channel, the channel often seemed stabilized though it is possible that the dense vegetation patches formed due to a relatively stable channel instead of the other way around. The fact that addition of vegetation generally causes an increase in channel dynamics can be partly explained by the fact that the migration rate in the system without vegetation was unusually low. The channel which formed without vegetation was relatively wide and shallow, which may have caused low bank erosion rates. However, the channel thalweg did shift within a part of the floodplain. Secondly, vegetation probably increased system dynamics, because it induced avulsions by obstructing and diverting flow and increasing the water levels in the floodplain. Thirdly, vegetation patches may have acted as relatively stable points in the floodplain between which channel migration may be enhanced (Schwendel et al., 2015). Finally, the effect of vegetation on bank strength was not incorporated in the model.

Introducing vegetation to the river system caused some higher peaks in sinuosity after the three initial meander bends collapsed, but the change seems not large (Figure 33 C). This may be related to the fact that no truly meandering pattern was formed (Tal and Paola, 2010).

Vegetation no longer increases the braiding index and causes an increase in channel stability when the mud supply is extreme and cohesiveness is relatively large. In this case, avulsions are prevented by the large sediment supply.

The hypothesis that vegetation causes a river system with a deeper and smaller main channel is confirmed. However, vegetation increased channel dynamics, the active braiding index and had no large effect on sinuosity in systems without mud, contrary to our expectations. Still, the channel pattern showed more characteristics of meandering when vegetation was added. Introduction of vegetation to a system with an extremely high supply of relatively cohesiveness mud does cause a more stable channel and vegetation no longer increases the braiding index.

5.2.2 Effect of mud on river morphology

Addition of mud generally has little effect on river morphology (Figure 33), because it is easily eroded. This seems to agree with the low occurrence of significant mud deposits in the Allier river system, but was not expected based on previous flume experiments (Schumm and Khan, 1972; Smith, 1998; Peakall et al., 2007; Van Dijk et al., 2012; Van Dijk et al., 2013a).

An increase in mud supply in combination with a moderate mud cohesiveness in a system with vegetation has no large clear effects on river morphology, but generally causes a lower active braiding index. It seems that higher mud supplies prevent avulsions and migration over a large part of the floodplain because they raise the bed level. However, the fact that in the run with a relatively high mud supply of 100 mg/L the braiding index is high indicates the complexity of the system. Possibly, the higher braiding intensity is related to the higher vegetation cover in this scenario (Figure 25), but the higher vegetation cover could also be a consequence of the larger braiding intensity (see also 5.1.3). No gradual decrease in channel migration rate was observed for increasing mud supplies, although (extremely) high mud supplies of 100 and 500 mg/L seem to reduce channel migration in the last years of the model runs. The fact that there is no strong relation between mud supply and channel migration is most likely caused by the high erodibility of the mud deposits. Secondly, the formation of more mud deposits upstream can act as perturbations in the floodplain which may trigger the formation of meander bends that start to migrate downstream. Finally, the vegetation cover differs between the runs (Figure 25) and therefore (de)stabilizing effects of vegetation differ between the model runs.

An increase of the mud supply in combination with relatively cohesive mud in a system with vegetation is able to reduce the active braiding index and decreases channel migration. The increase in channel stability due to addition of cohesive sediment agrees with Van Dijk et al. (2013a). However, in our study a moderate supply of relatively cohesive mud was not enough to cause a clear decrease in channel migration.

In a system with vegetation, an increase in mud supply and cohesiveness generally results in channel deepening, while an increase in mud supply and cohesiveness in a system without vegetation only causes a slightly deeper channel. Deeper channels were also observed in flume experiments of Schumm and Khan (1972) and Van Dijk et al. (2013a), but in the former study cohesion is not scaled and in the latter study the amount of channel deepening was limited. Results agree with general theory that an increase in bank strength results in channel deepening (Kleinhans, 2010), but confinement of flow by vegetation seems a more important factor for the observed channel deepening. When the mud supply in combination with a relative large cohesiveness increases from 500 to 800 mg/L in a system with vegetation the channel becomes on average more shallow instead of deeper. This is probably because the increase in flow strength in the main channel due to a decrease in braiding index is no longer enough for the flow to be able to transport all the extra sediment.

Addition of mud does not cause an increase in sinuosity, which may be related to the lack of an upstream inflow perturbation (Van Dijk et al., 2012; Schuurman et al. 2016).

A moderate amount of mud (20-50 mg/L) had probably little effect on river morphology because of the relatively large shear stress in the river channels of the Allier compared to the critical shear stress of mud erosion. Supply of the same concentration of mud did cause a decrease in braiding index and channel mobility in a tidal system where the flow velocities are about two times lower (Lokhorst, 2016). Two of the experimental studies that found significant changes in channel morphology with addition of mud, namely Schumm and Khan (1972) and Smith (1998), did not scale sediment cohesion and possibly found too large effects of cohesive sediment on river morphology. Peakall et al. (2007) and Van Dijk et al. (2012; 2013a) did scale cohesion. Therefore it is interesting to compare the relative cohesion and sediment supply concentrations in these experimental studies with the supply and cohesiveness of the current numerical modelling study to see if the threshold from which mud starts to affect river morphology is similar.

The general effect of mud on morphology in a system with vegetation could also be limited, because mud is often located where vegetation already stabilizes the surface. Mud may have little additional effect on morphology at these locations. Braudrick et al. (2009) found that suspended sediment is important, because it can settle on the inner bank of rivers and close back bar chutes, thereby preventing chute cutoffs. Therefore, in abandoned channels, where no vegetation is present, mud deposition might be more important for morphology. However, a large part of channel infilling occurs with sediments with larger grain sizes and mud only settles in the final stages of the infilling sequence (Figure 27, left).

The hypothesis that mud causes a deeper, more stable and more confined channel, a lower braiding index and a higher sinuosity is partly confirmed. In contrast to the hypothesis, but in agreement with field observations mud generally causes no large changes in river morphology in a high-energy system such as the Allier. When vegetation is present, a high mud supply of relatively cohesive mud leads to a lower active braiding index, more stable channels and, when the mud supply is 500 mg/L, a deeper channel. Mud does not increase channel sinuosity.

5.2.3 Effect of mud-vegetation interaction

Interaction between mud and vegetation generally did not cause a markedly different morphology of a system with both mud and vegetation compared to one with only vegetation (Figure 18; Figure 19; Figure 33; Figure 57). This is contrary to a study of Lokhorst (2016) into large scale morphodynamics in a tide-dominated estuary. This study showed that feedback between mud and *Spartina Anglica* enhances the morphological development induced by *Spartina*. *Spartina* caused an increase in mud deposition and due to this *Spartina* elevated itself into a zone with decreased physical stress. The concentration of *Spartina* in the estuary increased due to this decrease of physical stress. Gurnell et al. (2012) describe for rivers this process of sediment trapping and landform stabilization by vegetation, which facilitates colonization by new plant species and leads to changes in river morphology. In the current study, vegetation does increase mud deposition on crucial locations for the morphological development of river systems, namely in (partly) abandoned channels (Braudrick et al., 2009) and along river banks. However, mud still has no large effects on river morphology and also does not affect the spatiotemporal vegetation pattern. Therefore there is no ongoing positive feedback between mud and vegetation. So, the main difference compared to the tidal system is the small effect of mud on morphology and vegetation development. This is probably due to the relatively high shear stresses in the river system compared to the tidal system or because the mud supply is insufficient to change the river margin morphology (Gurnell et al., 2012).

A combination of mud and vegetation results in a deeper and more stable channel compared to a system with only mud or only vegetation (Figure 33; Figure 41) when both the mud supply and cohesiveness are larger (respectively 500 mg/L and 0.5 N/m^2). Note that in case of a mud supply of 800 mg/L the channel is not significantly deeper than in a system with only vegetation (see 5.2.2). Again, vegetation causes increased deposition near the active channel, but it appeared to be impossible to measure whether this enhances the effect of mud on river morphology compared to a system with only mud, because vegetation impacts morphology as well. In this case, vegetation can trap enough sediment to elevate itself, but the changes in river pattern due to the increase in mud supply cause a decrease in vegetation cover instead of an increase. This is in contrast to expectations based on Gurnell et al. (2012) and Lokhorst (2016).

Presence of mud changes the effects of vegetation on river morphology in systems with a high mud supply and cohesiveness. Vegetation no longer destabilizes the system when the mud supply and cohesiveness are high: it no longer causes an increase in channel migration, active braiding index and decrease in floodplain height. Probably, the high river banks make avulsions impossible. Both the mud supply and cohesiveness seem important in preventing avulsions, but vegetation is needed as well to prevent small scale shifts of the channel thalweg in the floodplain (Figure 57 A, C). Mud only causes a decrease in braiding index when vegetation is present, but this is probably because the braiding index in the reference system without vegetation is already low (Figure 57 A).

The hypothesis that interaction between mud and vegetation causes a more stable, deeper and smaller main channel, lower braiding index and higher sinuosity compared to systems with only mud or vegetation is partly confirmed. Only when the mud supply and cohesiveness are high the combination of mud and vegetation leads to a more stable and, when the mud supply is 500 mg/L, deeper channel compared to systems with only mud or only vegetation. It remains unclear whether the individual effects of mud and vegetation on river morphology are increased due to their interaction. However, due to an extreme supply of relatively cohesive mud, vegetation no longer causes an increase in river system dynamics. The hypothesis that continuing positive feedback between mud and vegetation can result in a laterally inactive river is not confirmed.

5.3 Context channel pattern formation

The simulated rivers have a relatively high stream power and were located in a confined river valley which likely affected the morphological development of the rivers and channel pattern formation.

Simulated river patterns

Addition of various combinations of mud supply and cohesiveness and vegetation presence resulted in different river system characteristics (Figure 57) and patterns. A wandering river pattern (Figure 1, left) was found for systems with vegetation and without or with a moderate mud supply and cohesiveness. Addition of an extreme amount (500 mg/L) of relatively cohesive mud causes a transition towards a more meandering system (Figure 1, left), although meander bend formation and migration decreases towards the end of the model run. An even larger mud supply (800 mg/L) resulted in a straight river pattern although this may be related to a limitation of the model which resulted in non-erodible grid cells (section 5.4.1). The river patterns that form in systems without vegetation are difficult to link to the classification of alluvial channel patterns as given in Figure 1, because channels are generally laterally active, but classical meander bend formation and migration is often limited while the braiding index is low (see also section 5.4.1). Apart from the run with a mud supply of 800 mg/L, none of the river systems was laterally immobile, which matches expectations based on the river pattern prediction diagram of Kleinhans and Van den Berg (2011), which takes into account (potential specific) stream power and median grain size.

Effects of stream power and valley confinement on river pattern development

Results of our study imply that mud is generally not an important factor for the formation of meandering river patterns in high-energy gravel-bed river systems, such as the Allier. Vegetation and mud are both associated with an increase in bank strength and the formation of meandering river patterns (Kleinhans, 2010). However, mud had little impact on river morphology compared to vegetation in the model runs, because it was easily eroded due to the relatively high stream power related to the slope and discharge of the river. Mud only affected morphology when the mud supply was extreme. Observations in the Allier of thin mud layers (Figure 45) and abundant vegetation growth support the dominant influence of vegetation on river morphology. Especially since thicker mud layers are often present at locations where vegetation already stabilizes the surface. In the Allier, mud did deposit at locations of abandoned channels which can promote meandering because it limits reoccupation of the former river channel. However, model results showed that the largest part of channel infilling occurs with sediments with larger grain sizes (Figure 27, left).

Valley-confinement can increase the tendency of river systems to become braided, as observed at the Platte River in Nebraska by Fotherby (2009), as it causes flow confinement. In our models, vegetation may have raised water levels more compared to unconfined systems, which might be part of the reason that addition of vegetation in our model led to increased braiding intensities during high flow conditions. Mud will probably be eroded from floodplains more easily in confined systems due to the higher flow velocities in the floodplain. Hence, mud may be less important for the formation of meandering river patterns in confined systems. However, results showed that when channel confinement is (too) strong, as was the case in the scenario with vegetation and an extreme mud supply and relatively large cohesiveness, this forces the river to become single-thread.

5.4 Model performance

In this study, for the first time both cohesive mud and dynamic vegetation are included in a numerical river model. Analysis of the sensitivity and validity of the model generally indicated good model performance. The model was able to simulate important morphodynamic processes including avulsions, meander bend migration and cutoffs. Furthermore, mud deposition patterns agree with patterns found in nature and patterns obtained with the SEDIFLUX floodplain sedimentation model. Also, the vegetation patterns showed similarities with patterns observed in the field (section 5.1.1).

The critical fraction of mud from which the bed behaviour becomes cohesive (PmCrit, see Chapter 3.1) had no large influence on river morphology. This is fortunate for modellers as literature does not agree on a single value (e.g. Mitchener and Torfs, 1996; Panagiotopoulos et al., 1997; Houwing, 1999; 2000), because mud can consist of different silt/clay ratios and can thus have a different cohesiveness. Note that the effect of the critical mud fraction was only tested in a river system in which mud had no large impact on river morphology. Probably, the impact of the critical mud fraction is larger when both the mud supply and cohesiveness are larger. An increase in active layer thickness affects the amount of mud deposits. Furthermore, it resulted in less deep channels and a lower sinuosity, but the significance of this remains unclear. Researchers should take into account that the active layer thickness could cause differences in model outcomes.

5.4.1. Limitations

Modelling mud

The patterns of mud were generally realistic, but there are still some model settings that may need to be improved. Firstly, the critical shear stress for mud deposition is not taken into account. Differences in mud settling are therefore only caused by differences in sediment concentrations in the water and the residence time of the water in each grid cell. Due to erosion of mud at locations with high flow velocities most locations of mud deposits seem realistic. However, it is still possible that in the model mud deposits form at locations where no mud would have deposited. Furthermore, the mud supply concentration at the upstream part of the river was constant, while in nature it fluctuates with discharge. Mud deposition rates at larger distances from the river channel will likely increase when the mud supply fluctuates following the discharge.

Modelling vegetation

The vegetation patterns were generally realistic, but there are still some limitations. First of all, the amount of vegetation on higher parts of point bars in the model is sometimes lower than observed in the field (section 5.1.1). This can partly be attributed to the settings of the flooding-drying threshold and the mortality threshold for desiccation. Groundwater flow is implicitly modelled by a relatively high threshold for desiccation: plants can survive relative long periods without flooding. Still, the development of vegetation on higher parts in the floodplain remains limited. Another reason for the lack of vegetation growth on top of point bars is that colonization is restricted to the area close to channels. In nature, wind or vegetative reproduction of plants, without seeds, may promote vegetation development on higher elevations. However, in the study area most adult vegetation objects of the *Populus Nigra* originated from seeds (Legionnet et al., 1997) and not vegetative reproduction. A second limitation of the model is that the effect of vegetation on bank strength is not taken into account, while this is very important (for review: Kleinhans, 2010). Thirdly, the effects of mud on vegetation are not explicitly modelled yet. High mud contents are for example known to be less suitable for *Populus* (Duel and Specken, 1994 in Weeber, n.d.), but this is currently ignored.

Modelling a meandering river

Like rivers in the flume experiments of Gran and Paola (2001) and Tal and Paola (2007; 2010), who added vegetation to increase floodplain strength, the modelled river dynamics were dominated by avulsions and the river pattern became more wandering instead of truly meandering.

Probably, the lack of an upstream inflow perturbation prevents the sustained formation of meander bends as found by Van Dijk et al (2012). Schuurman et al. (2016) tested the effect of continuous inflow perturbations on meander migration using three numerical morphodynamic models. Results showed that a dynamic inflow perturbation is important to enhance meander development and leads to formation of higher-sinuosity channels. However, the impact of the dynamic inflow perturbation on meander dynamics was lower for low-sinuosity channels, which includes the Allier, than for high-sinuosity channels.

It might also be possible that the increase in mud supply and hence aggradation rate in the floodplain caused a more wandering pattern as proposed by Tal and Paola (2010). However, in my model the number of avulsions did not systematically increase with increasing mud supply.

Another possibility is that the relative low vegetation development on higher parts of the point bars prevented the formation of a meandering river. Vegetation can increase bank strength and can hence decrease the amount of chute cutoffs (Schuurman et al., 2016). This process of stabilization of the point bar is also referred to as bar-floodplain conversion or 'inner bank push' and can promote meandering. In the model, the effect of vegetation on bank strength is not incorporated, but vegetation still may prevent chute cutoffs by lowering flow velocities on the bar surface.

Finally, the downstream migration of meander bends in the model is limited. Possible explanations are (1) a too strong reduction of the flow velocity by vegetation on the banks, (2) a too high resistance of vegetation for high flow velocities and scour and/or (3) an underestimation of bank erosion rates by Delft3D or model shortcomings (see below).

Bank erosion in Delft3D

The bank erosion rates in the model runs are sometimes surprisingly low, which is probably partly caused by model shortcomings.

First of all, there are locations where the bed level does not change for long periods of time (more than 100 years) at isolated locations where this seems unnatural, for example in the middle of a continuously changing floodplain (Figure 58). The river does not migrate past these non-erodible points and deep scour holes form in the channel near these points. On the other hand, the non-erodible points sometimes seem to force the formation of a meander bend. At some locations where thin water layers remain, cells adjacent of the river stream are not eroded. A part of this problem could be solved by lowering the initial water level (Zeta0) to prevent ponding (Chapter 3.3). Despite this adaptation of the model, non-erodible cells still arise during the model runs. It is difficult to assess the impact of these errors on river morphodynamics. Moreover, the locations where the errors occur differ between model scenarios and therefore it is difficult to compare the morphodynamics between model scenarios. The cause of these non-erodible cells remains unclear and no solution was found to prevent the formation of these non-erodible cells.

Secondly, the bank erosion scheme in Delft3D leads to gradual decreases in bank height and no steep banks form. Therefore, banks are inundated with shallow flow which may limit erosion and hence gradual channel migration (Nicholas, 2013).

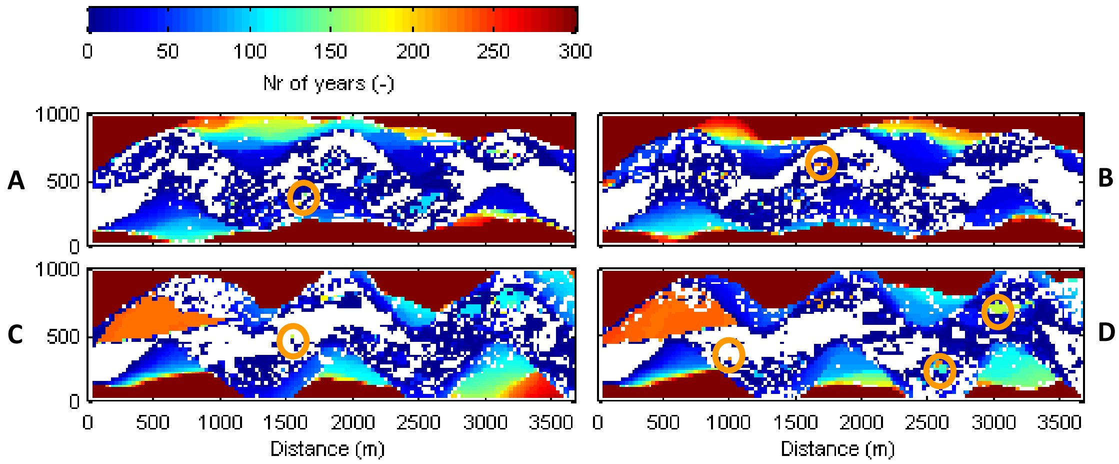

Figure 58 Number of years in a row that the bed level does not change. Letters indicate the main model scenarios. A: mud & vegetation, B: only vegetation, C: only mud, D: no mud or vegetation. Circles indicate locations where the lack of bed level changes is likely related to a model error. Note that there are a few more locations which are stable for relative long periods and may also be affected by model errors.

5.5 Contribution to theory, practice and society

The current study gives new insights in river system interactions between vegetation, mud and morphodynamics, which can help to understand the effects of river management measures and to make them more cost effective. This is especially important, because the number of hydromorphological restoration activities increased since the implementation of the European Water Framework Directive (WF-D; 2000/60/EG) in 2000, as there are now legal obligations to maintain or re-establish a good ecological status of all surface waters (Muhar et al., 2016). An example of a large scale restoration project in the Netherlands is the Room for the River programme, which aims at improving safety against flooding from larger rivers and improving the spatial quality, including ecology, of the riverine area (Rijke et al. 2012). Restoration of smaller streams is also common (Makaske and Maas, 2015).

The present study confirms the importance of vegetation as an eco-system engineer as described by Gurnell (2014). It was already known that vegetation patches can trap sediment (Chapter 2.3.1), but the significant impact of vegetation on the large-scale mud distribution in a floodplain was not yet known. The fact that different river patterns can develop due to addition or removal of vegetation (Figure 18; Figure 57) has important implications for the prediction of river channel patterns. River patterns can be predicted based on potential specific stream power and grain size (Kleinhans and Van den Berg, 2011), but our results indicate that for prediction of channel patterns it is also important to take vegetation conditions into account. Our modelling results, on the other hand, imply that mud and interaction between mud and vegetation is not important for the development of meandering river patterns in high-energy gravel bed river systems (section 5.3).

This study also provides more insight in large-scale spatio-temporal variations in mud deposition in the floodplain as the result of vegetation and river dynamics. Changes in soil mud content may affect the distribution of vegetation species (e.g. Duel and Specken, 1994 in Weeber, n.d.) and perhaps also biodiversity in the river ecosystem.

This study showed that interactions between vegetation, mud and river morphodynamics are complex and that the importance of and interactions themselves depend on characteristics of the river system. Therefore, river managers should carefully take characteristics of a river system, including vegetation characteristics and cohesive sediment supply, into account for determining the most effective management measures.

Results indicate that advanced prediction of river channel patterns requires numerical models, like the one used in this study, which incorporate feedback between morphodynamics, vegetation and cohesive mud and which are able to represent transitions between different channel patterns. This is because vegetation and mud not only affect the morphological development of rivers, but also depend on the river channel pattern and each other.

The fact that the numerical model used in this study was able to represent transitions between different fluvial styles by only changing mud supply and cohesiveness and vegetation conditions is notable, because generally, different river styles are modelled with separate approaches (Nicholas, 2013). Nicholas (2013) was able to simulate different river styles with a model that includes vegetation and mud as well. However, in his study multiple boundary conditions were changed simultaneously (slope, vegetation characteristics, bank erodibility) and attention to why certain combinations of different boundary conditions resulted in specific river patterns was limited so that comparison between the studies is difficult.

For restoration of (small) streams it is even more important to consider the characteristics of the system and feedbacks between vegetation, mud and morphodynamics than for larger river systems. Vegetation has a relative large impact on hydrology and bank strength in small streams, because it can settle more easily due to low water depths and flow velocities and because roots penetrate relatively deep in the banks (Makaske and Maas, 2015). The impact of mud in small streams is likely relatively high too, because it is less easily eroded when flow velocities are low.

Results of the current study further suggest that river management activities aiming at increasing the ecological value of an area should focus on river channel pattern and dynamics as these have a strong control on the vegetation pattern and dynamics. The hydrological connection between river and floodplain, needed for vegetation growth, increases when the number of parallel channels increases or the difference between channel depth and height of the banks decreases. Therefore, river restoration activities should aim at creating opportunities for secondary channels beside the main river channel, which is confirmed by an assessment of restoration effects in European mid-sized rivers (Poppe et al., 2016). Channel deepening, one of the measures against flooding (Rijke et al., 2012), should be avoided.

Finally, this study has shown that an improved bank erosion scheme in Delft3D and addition of a moving upstream boundary (section 5.4.1) are essential to improve river modelling. An improved bank erosion scheme is highly important for management issues among others related to fairway regulation, stream renaturalization and safety.

5.6 Future research

The model used in this study is very promising to further investigate development of river patterns due to changes in boundary conditions as (1) it includes feedbacks between morphodynamics, vegetation and cohesive mud and is able to represent transitions between different channel patterns and (2) it can easily be expanded with more complex interactions between vegetation and mud.

The first direction of future research is to investigate and resolve some limitations of the model. First of all, it is important to improve the bank erosion scheme and to apply an upstream inflow perturbation to promote gradual channel migration, a more meandering river pattern and more dynamic braided rivers. Secondly, effects of groundwater flow on vegetation can be incorporated more realistically to promote vegetation development on point bars. This may be achieved by adapting the critical threshold for vegetation mortality depending on the distance from the river and discharge fluctuations. Thirdly, vegetation can be made dependent on soil mud/clay content or mud concentration in the water to be able to better investigate those interactions between mud and vegetation. Finally, it is important to check to what extent the model outcomes change when the mud supply is in equilibrium with discharge and the critical threshold for mud deposition is implemented.

A second direction of future research is to support the current numerical modelling results of the interaction between mud, vegetation and morphology with physical experiments. Until now, cohesive sediment has not been combined with vegetation in flume experiments of rivers. Flume experiments in which vegetation and cohesive fines are combined can provide additional insights about the interaction between mud and vegetation and their combined effects on morphology.

Finally, the model can be used to assess the effects of many different boundary conditions on interactions between mud, vegetation and morphology and the development of different river channel patterns. It is interesting to investigate these interactions in lower-energy river systems than the Allier where especially mud likely has more impact and to investigate effects of different vegetation types. Besides, it is interesting to study the development of systems with multiple fine sediment fractions to further investigate the spatial sorting of sediment in a floodplain and to further assess effects of the spatial variation in floodplain bed material on river morphology and ecology.

A more specific example of an interesting research topic is to investigate morphodynamic effects of in-stream macrophytes in small streams. This topic is interesting, because vegetation within a channel may have different impacts on morphology compared to trees on banks at least in small streams (Huang and Nanson, 1997). Besides, in-stream macrophyte growth depends on mud concentrations in the water, because high mud concentrations prevent light penetration and therefore limit plant growth (Davies-Colley et al., 1992).

6. Conclusions

The combined effects of mud and vegetation on the morphological development of a river system on centennial timescales were investigated by numerical modelling. It was found that vegetation strongly affects river morphology and the spatiotemporal distribution of mud over the floodplain, while mud generally has little effect on river morphology and the vegetation distribution. An unrealistically large supply of relatively cohesive mud causes rapid sedimentation in the floodplain and a significant decrease in braiding intensity in systems with vegetation. These morphological changes decrease the hydrological connection between channel and floodplain and restrict vegetation growth to a narrow zone near the active river channel.

In vegetation-only systems, vegetation develops along the channels and deepens and confines these by focussing flow. The vegetation pattern is highly dynamic with variations in age and density as a result of the morphodynamics. Vegetation induces formation and migration of meander bends, but also promotes avulsions over a wider part of the floodplain by increasing water levels and diverting flows leading to a relatively high braiding intensity during high-flow conditions. This opposes many field and experimental studies which associate vegetation with a shift towards meandering single-channel systems. One of the possible explanations is that in our study, floodplain confinement by the valley walls caused higher water levels and hence avulsions. Furthermore, the effect of vegetation on bank strength is not taken into account, however, the increase in hydraulic roughness due to vegetation decreases flow velocities enough to retain sediment.

In mud-only systems, a moderate mud supply of 20 mg/L has little impact on river morphology due to the large shear stresses compared to the critical shear stress for mud erosion. An extremely high supply of relatively cohesive mud caused a slightly deeper channel than a moderate mud supply.

The morphology of a river system with a moderate mud supply and vegetation is similar to a system with only vegetation. A moderate supply of mud has little impact on the river morphology even though vegetation promotes mud deposition closer near the river channel and in abandoned channels which are important locations for the morphological development of rivers. The fact that mud has a limited impact on river morphology is supported by field observations at the high-energy meandering gravel-bed river Allier: mud layers are often thin or present at locations where vegetation already stabilizes the surface. Furthermore, model results indicate that coarser sediment is more important for (abandoned) channel infilling than mud. The mud distribution pattern followed the dynamic vegetation pattern. Mud, however, had no large impact on vegetation development, because it caused no significant changes in river morphodynamics.

An extreme mud supply in combination with relatively cohesive mud and vegetation leads to the development of a relatively stable river system, where high muddy banks prevent overbank flooding reducing the riparian zone to a small strip along the channel. The combination of mud and vegetation causes a higher floodplain elevation and stability compared to systems with only mud or only vegetation. Despite the low vegetation cover in the floodplain compared to systems with no or moderate mud supplies, vegetation is important for channel confinement and changed the channel migration style from frequent channel thalweg shifts within a limited part of the floodplain to dominantly gradual channel migration.

These results imply that vegetation is an important factor for the morphological development of high-energy gravel-bed river systems such as the Allier, while mud and interaction between mud and vegetation generally do not cause large changes in river morphology as mud is easily eroded.

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Appendices

Appendix 1 – Location fieldwork transects

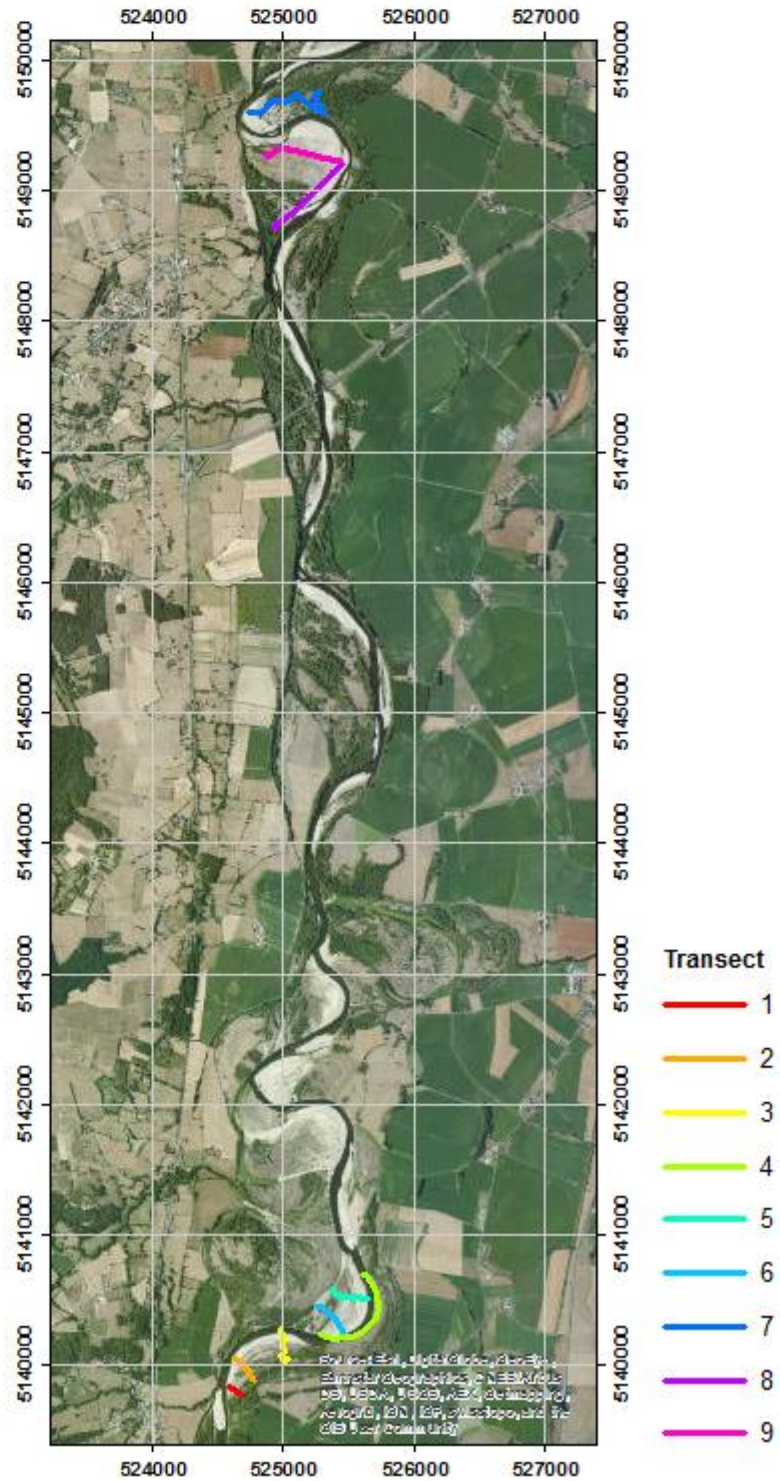

Figure 59 Location of transects along which field measurements were performed. Datum: WGS84. Projection: UTM 31T. Source: basemap from ESRI ArcMap 10.3.1, aerial photograph from DigitalGlobe (2010). Note that the aerial photograph is taken in an earlier year (October, 2010) than the fieldwork was conducted (August, 2016).

Appendix 2 – Delft3D input files

.MDF file

```
Ident          = #Delft3D-FLOW  .03.02 3.42.00.17790#
Commnt         =
Runtxt         = #Allier run#
                 #2 Salicaceae species#
                 #with mud#
Filcco         = #N40M148_meander.grd#
Fmtcco         = #FR#
Anglat         =  0.0000000e+000
Grdang         =  0.0000000e+000
Filgrd         = #N40M148_meander.enc#
MNKmax         = 149 41 1
Thick          =  1.0000000e+002
Commnt         =
Fildep         = #N40M148_meander.dep#
Fmtdep         = #FR#
Commnt         =
Commnt         =          no. dry points: 0
Commnt         =          no. thin dams: 0
Commnt         =
Itdate         = #2000-01-01#
Tunit          = #M#
Tstart         =  0.0000000e+000
Tstop          =  5.256000e+06
Dt             = 0.2
Tzone          = 0
Commnt         =
Sub1           = #   I#
Sub2           = # C #
Namc1          = #Sediment1     #
Namc2          = #Sediment2     #
Commnt         =
Wnsvwp         = #N#
Wndint         = #Y#
Commnt         =
Zeta0          =  -8.0000000e+000
U0             = [.]
V0             = [.]
S0             = [.]
I0             =  0.0000000e+000
C01            =  0.0000000e+000
C02            =  0.0000000e+000
C0             =  0.0000000e+000
Commnt         =
Commnt         =          no. open boundaries: 2
Filbnd         = #job1.bnd#
Fmtbnd         = #FR#
FilbcT         = #job1.bct#
FmtbcT         = #FR#
FilbcQ         = #job1.bcq#
FmtbcQ         = #FR#
FilbcC         = #job1.bcc#
```

```
FmtbcC          = #FR#
Rettis          =  0.0000000e+000
                   0.0000000e+000
Rettib          =  0.0000000e+000
                   0.0000000e+000
Commnt          =
Ag              =  9.8100000e+000
Rhow            =  1.0000000e+003
Alph0           = [.]
Tempw           =  1.5000000e+001
Salw            =  3.1000000e+001
Rouwav          = #    #
Wstres          =   6.3000000e-004   0.0000000e+000   7.2300000e-003   1.0000000e+002   7.2300000e-003
1.0000000e+002
Rhoa            =  1.0000000e+000
Betac           =  5.0000000e-001
Equili          = #N#
Ktemp           = 0
Fclou           =  0.0000000e+000
Sarea           =  0.0000000e+000
Temint          = #Y#
Commnt          =
Roumet          = #C#
Ccofu           =  2.5000000e+001
Ccofv           =  2.5000000e+001
Xlo             =  0.0000000e+000
Vicouv          =  1.0000000e+000
Dicouv          =  1.0000000e+000
Htur2d          = #N#
Irov            = 0
TraFrm          = #eh.tra#
Filsed          = #job1.sed#
Fmtsed          = #FR#
Filmor          = #job1.mor#
Fmtmor          = #FR#
Commnt          =
Iter            =     2
Dryflp          = #YES#
Dpsopt          = #MAX#
Dpuopt          = #MOR#
Dryflc          =  1.0000000e-001
Dco             = -9.9900000e+002
Tlfsmo          =  6.0000000e+001
ThetQH          =  0.0000000e+000
Forfuv          = #Y#
Forfww          = #N#
Sigcor          = #N#
Trasol          = #Cyclic-method#
Momsol          = #Cyclic#
Commnt          =
Commnt          =            no. discharges: 0
Commnt          =            no. observation points: 3
Filsta          = #job1.obs#
Fmtsta          = #FR#
Commnt          =            no. drogues: 0
Commnt          =
Commnt          =
```

```
Commnt          =               no. cross sections: 1
Filcrs          = #job1.crs#
Commnt          =
SMhydr          = #YYYYY#
SMderv          = #YYYYYY#
SMproc          = #YYYYYYYYYY#
PMhydr          = #YYYYYY#
PMderv          = #YYY#
PMproc          = #YYYYYYYYYY#
SHhydr          = #YYYY#
SHderv          = #YYYYY#
SHproc          = #YYYYYYYYYY#
SHflux          = #YYYY#
PHhydr          = #YYYYYY#
PHderv          = #YYY#
PHproc          = #YYYYYYYYYY#
PHflux          = #YYYY#
Online          = #N#
Flmap           =  0.0000000e+000 73 7.884000e+06
Flhis           =  0.0000000e+000 10  7.884000e+06
Flpp            =  0.0000000e+000 0  7.884000e+06
Commnt          =
Trtrou          = #Y#
Trtdef          = #veg.trd#
Trtu            = #veg.trv#
Trtv            = #veg.trv#
Chezy           = #Y#
Rough           = #Y#
```

.MOR file

```
[MorphologyFileInformation]
  FileCreatedBy    = Delft3D FLOW-GUI, Version: 3.42.00.17790
  FileCreationDate = Wed Aug 28 2013, 10:40:34
  FileVersion      = 02.00
[Morphology]
  EpsPar           = false                   Vertical mixing distribution according to van Rijn (overrules k-epsilon model)
  IopKCW           = 1                       Flag for determining Rc and Rw
  RDC              = 0.01             [m]     Current related roughness height (only used if IopKCW <> 1)
  RDW              = 0.02             [m]     Wave related roughness height (only used if IopKCW <> 1)
  MorFac           =  3.0000000e+001    [-]     Morphological scale factor
  MorStt           =  1.2000000e+003    [min]   Spin-up interval from TStart till start of morphological changes
  Thresh           =  5.0000001e-002    [m]     Threshold sediment thickness for transport and erosion reduction
  MorUpd            = true                   Update bathymetry during FLOW simulation
  EqmBc            = true                   Equilibrium sand concentration profile at inflow boundaries
  DensIn           = false                  Include effect of sediment concentration on fluid density
  AksFac           =  1.0000000e+000    [-]     van Rijn's reference height = AKSFAC * KS
  RWave            =  2.0000000e+000     [-]     Wave related roughness = RWAVE * estimated ripple height. Van
Rijn Recommends range 1-3
  AlfaBs           =  1.0000000e+000    [-]     Streamwise bed gradient factor for bed load transport
  AlfaBn           =  1.5000000e+000    [-]     Transverse bed gradient factor for bed load transport
  Sus              =   1.0000000e+000        [-]         Multiplication  factor  for  suspended  sediment  reference
concentration
  Bed              =  1.0000000e+000    [-]     Multiplication factor for bed-load transport vector magnitude
  SusW             =  1.0000000e+000    [-]     Wave-related suspended sed. transport factor
  BedW             =  1.0000000e+000    [-]     Wave-related bed-load sed. transport factor
  SedThr           =  1.0000000e-001     [m]     Minimum water depth for sediment computations
  ThetSD           =  5.0000000e-001    [-]    Factor for erosion of adjacent dry cells
  HMaxTH           =  1.5000000e+000    [m]     Max depth for variable THETSD. Set < SEDTHR to use global value
only
  FWFac            =  1.0000000e+000      [-]      Vertical mixing distribution according to van Rijn (overrules k-
epsilon model)
  Espir            =         1.0       [-]        Calibration         factor    spiral      flow
  ISlope           =         3         [-]        Flag       for        bed       slope       effect
  AShld            =         0.70      [-]        Bed        slope      parameter         Koch      &          Flokstra
  BShld            =         0.5       [-]        Bed        slope      parameter         Koch      &          Flokstra
[Underlayer]
  IUnderLyR        = 2              [-]     Stratigraphy schematisation
  ExchLyr          = false
  TTLForm          = 1              [-]     transport layer thickness (defined)
  ThTrLyr          = 0.03             [m]     transport layer thickness (if TTLForm = 1)
  NLaLyr           = 0              [-]     Number of Lagrangian layers
  NEuLyr           = 50              [-]     Number of Eulerian layers
  ThLaLyr          = 0.1             [m]     Max thickness of Lagrangian layers
  ThEuLyr          = 0.1             [m]     Max thickness of Eulerian layers
  IniComp          = morlyr.inb
  IDiffusion       = 0              [-]     0) no diffusion 1) mass fraction 2) volume fraction
  Flufflyr         = 0              [-]     Switch fluff layer mechanism
  DepFac           = 0.15             [-]     Deposition factor to bed layer
[Output]
  Frac             = true
  AverageAtEachOutputTime= true
```

.SED file

```
PmCrit                    = 0.4
[SedimentFileInformation]
  FileCreatedBy           = Delft3D FLOW-GUI, Version: 3.42.00.17790
  FileCreationDate        = Wed Aug 28 2013, 10:40:32
  FileVersion       = 02.00
[SedimentOverall]
  Cref              =  1.6000000e+003     [kg/m3]  CSoil Reference density for hindered settling calculations
  IopSus            = 0                   If Iopsus = 1: susp. sediment size depends on local flow and wave conditions
[Sediment]
  Name              = #Sediment1#             Name of sediment fraction
  SedTyp            = sand                 Must be "sand", "mud" or "bedload"
  RhoSol            =  2.6500000e+003     [kg/m3]  Specific density
  SedDia            =  5.0000000e-003     [m]      Median sediment diameter (D50)
  CDryB             =  1.6000000e+003     [kg/m3]  Dry bed density
  IniSedThick       =  5.0000000e+000     [m]      Initial sediment layer thickness at bed (uniform value or filename)
  FacDSS            =  1.0000000e+000     [-]      FacDss * SedDia = Initial suspended sediment diameter. Range [0.6
- 1.0]
[Sediment]
  Name              = #Sediment2#             Name of sediment fraction
  SedTyp            = mud                  Must be "sand", "mud" or "bedload"
  RhoSol            =  2.6500000e+003     [kg/m3]  Specific density
  SalMax            =  0.0000000e+000     [ppt]    Salinity for saline settling velocity
  WS0               =  2.5000000e-004     [m/s]    Settling velocity fresh water
  WSM               =  2.5000000e-004     [m/s]    Settling velocity saline water
  TcrSed            =  1.0000000e+003     [N/m2]   Critical bed shear stress for sedimentation (uniform value or
filename)
  TcrEro            =  2.0000000e-001     [N/m2]   Critical bed shear stress for erosion     (uniform value or filename)
  EroPar            =  1.0000000e-004     [kg/m2/s] Erosion parameter                        (uniform value or filename)
  CDryB             =  1.6000000e+003     [kg/m3]  Dry bed density
  IniSedThick       =  5.0000001e-002     [m]      Initial sediment layer thickness at bed (uniform value or filename)
  FacDSS            =  1.0000000e+000     [-]      FacDss * SedDia = Initial suspended sediment diameter. Range [0.6
- 1.0]
```

Appendix 3 – Summary of modelling results

Effect of:	Run(s)	Result
Vegetation (in system without mud)	2	• Channel deepening and confinement; • Higher channel migration; • Higher active braiding index; • Lower floodplain elevation; • Wandering river pattern with characteristics of meandering.
Mud (in system without vegetation)	3 & 14	Moderate supply and cohesiveness (run 003): • Higher floodplain elevation; • Channel confinement. High supply and cohesiveness (run 017): • Channel deepening and confinement; • Higher floodplain elevation;
Combination mud & vegetation	1 & 12	General: • Vegetation affects mud distribution over floodplain and increases mud deposition near channels; • Vegetation causes channel deepening and confinement; • Mud causes a higher floodplain elevation. Moderate mud supply and cohesiveness (run 001): • Vegetation increases mud deposit dynamics; • Vegetation leads to lower floodplain elevation, higher channel migration and higher active braiding index; • Mud does not affect vegetation development; • Morphology of river system with mud and vegetation is similar to the morphology of a system with only vegetation. High mud supply and cohesiveness (run 015): • Mud strongly reduces vegetation cover; • Deeper channel (on average), higher floodplain elevation and more stable channel****; • Mud causes a lower active braiding index.
Increase mud cohesiveness*	9-12	For mud supply of 20 mg/L: • Larger area mud deposits; • Slightly higher floodplain elevation. For mud supply of 100 and 500 mg/L: • Small increase channel depth; • Small decrease braiding index; • Higher floodplain elevation (for 500 mg/L).
Increase mud supply**	5-8	• Small decrease vegetation cover; • Larger area mud deposits; • Generally higher floodplain elevation; • Generally lower active braiding index (run 7 relatively large); • High mud supplies (100 & 500 mg/L) seem to reduce channel migration after 100 years.
Increase mud supply***	10-13	• Decrease vegetation cover; • Larger area percentage mud deposits; • Channel deepening (except run 13 with highest supply); • Lower active braiding index; • Higher floodplain elevation (when supply >= 500 mg/L); • Lower channel migration;
Increase PmCrit*	15-16	• No clear effect on river morphology.
Increase active layer thickness*	17	• Lower area mud deposits; • Lower channel sinuosity and depth, but more runs needed to confirm this effect.

* Vegetation included; ** In combination with moderate mud cohesiveness ($\theta_{cr,\,ero}$ = 0.2), vegetation included; *** In combination with a relatively high mud cohesiveness ($\theta_{cr,\,ero}$ = 0.5), vegetation included; **** Compared to system with only mud or only vegetation. Changes in active braiding index refer to the situation in winter.