Optimal conditions for floodplain sedimentation and land aggradation in river deltas

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Master thesis for Earth Sciences

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09-06-2020

Contents

Abstract

Crevasse splays are landforms created by breaching of river levees and are part of many large river systems over the world. Due to potentially high aggradation rates, they can be effective tools against relative sea level rise. Here we describe a combined field- and modeling effort, in which we assessed the effects of floodplain drainage on crevasse splay development. By mapping crevasse splays for the Rhine-Meuse- and Mississippi Deltas and linking it to floodplain size, we investigated the effect of the floodplain on crevasse formation. We used the morphodynamic model Delft3D-FLOW to test results found in the field. We found that the largest floodplains accommodate the largest crevasse splays. This was confirmed by our model simulations, in which simulations with large floodplains have slowly rising water levels, keeping lateral surface slopes high which ultimately result in large flow velocities and rapid crevasse growth. Additionally, we found that small flood durations increase erosion and thus further aid this effect. The combined effect of flood duration and floodplain size were combined into a parameter, which was proven to accurately predict crevasse growth in the model and allows for a first order comparison with field data. The conclusions drawn from this research increase our understanding in crevasse growth and my help in future restoration projects that involve artificial levee breaching.

1 Introduction

Crevasse splays are landforms resulting from levee breaching during flood events in large rivers, extending from the levee into the lower lying floodplain. As such, they are integral features in many river systems over the world. They consist typically of sand, silt and/or clay and are efficient sediment traps for (artificial) land building, potentially reaching sediment retention rates of more than 75% (Esposito et al. 2017). Crevasse splays are therefore considered effective nature-based solution for deltas facing relative sea level rise, with the West Bay Sediment Diversion (Miller, 2004) serving as an example of such a project for land restoration of the Mississippi Delta.

Crevasse splays span a wide variety of sizes and shapes, which for a large part is still poorly understood. Both river- and floodplain characteristics affect crevasse growth, which may change along the course of a river and between different river systems. We know that crevasse growth is dependent on the discharge of water and sediment from the river, where river discharge and bifurcation dynamics play a large role (Michelazzo et al., 2018; Kleinhans et al., 2008). Looking at floodplain conditions, it has been shown that well drained floodplains may promote crevasse growth due to increased water surface slopes (Millard et al., 2017; Hajek and Edmonds, 2014). However, variable and rising water levels during a flood have not yet been fully investigated. In line with previous research, we propose that large floodplains take a longer to time to fill, which keep flow velocities high and allow larger crevasse splays to form. We investigate the role of the floodplain by analyzing crevasse splays in the Rhine-Meuse – and Mississippi Deltas and comparing them to splays that we model in Delft3D (Deltares, 2014).

2 Literature review

In order to understand the effect of floodplain conditions on crevasse growth, we must know how crevasse splays develop and grow over their lifetime. Levee breaches tend to be activated during flood events, such that crevasse splays are made up of multiple floods (Slingerland and Smith, 1998; Shen et al., 2015). Therefore, we need to know how crevasse splays develop both (1) during a single flood and (2) over multiple floods, and how the floodplain affects both timescales. In this literature review, we first quickly describe the morphodynamic processes and factors involved in crevasse growth and how these may change over the course of a flood. Secondly, we investigate how crevasse splays typically develop over their lifetime and how drainage can affect this development, which gives a framework to analyze natural crevasse splays and compare these to modeled splays. Furthermore, we quickly discuss the geomorphological setting in the study areas, the Rhine-Meuse – and Mississippi Delta. Lastly, we use this knowledge to determine the approach and main hypothesis of this research.

2.1 Crevasse morphodynamics

Factors and processes determining crevasse growth

When applying models to crevasse formation, the balance between deposition and erosion (D/E ratio, Nienhuis et al., 2018) is an important factor in determining the morphology and size of a crevasse splay. This can also be described as the balance between the amount of sediment entering the crevasse and the potential sediment capacity of the main channel of the crevasse, called the throat (Slingerland & Smith, 1998). When the amount of sediment transported through the throat is larger than its capacity, the throat will start to fill with sediment. If the sediment load of the throat is under capacity, the channel erodes and the crevasse is able to expand further into the floodplain.

The throat capacity is determined by the amount of flow that can pass through a levee breach. It has been shown in a laboratory setting that the breach discharge is related to the discharge of the main river channel (Michelazzo et al., 2018). How this breach then evolves is related to the longer term morphodynamic response to subsequent floods. Aside from river discharge, also the height difference between levee and floodplain is expected to increase the erosive capacity of the channel (Chen et al., 2015).

Besides hydrodynamic properties of the river, floodplain conditions have a large influence on crevasse formation. Floodplain drainage, erodibility, vegetation and subsidence have been shown to have large impacts in modeling studies investigating crevasse growth (Nienhuis et al., 2018; Hajek and Edmonds, 2014; Millard et al., 2017).

This research will focus on the effect of drainage, specifically floodplain volume, on crevasse growth. Adams et al. (2004) find that for levee growth, which is also a landform created by floods, drainage is very important, determining whether the formation of the levee is formed by either diffusion or advection. By drainage, we mean the capability of the floodplain to accommodate water and keep lateral water surface slopes high.

When a floodplain is poorly drained, widespread ponding occurs in the floodplain. Due to the large velocity difference between the water in the channel of the river and in the floodplain, turbulent eddies form which transport and deposit sediment, which is called diffusive transport. When the floodplain is well drained, a significant lateral water surface slope is present, water is transported easily into the floodplain and advection is favored. It is expected that conditions favoring advection in a river system will enhance crevasse formation, as crevasse splays are formed under advective conditions.

To examine how drainage affects hydrodynamics, we look at two cases that represent well drained and poorly drained conditions are respectively the Saskatchewan river and the Columbia river. The Saskatchewan river system contains extensive floodplains, meaning water levels will rise slowly due to the large accommodation space for water. Contrarily, the Columbia river system has very narrow floodplains which serve more like water pathways than as water storage features (FILGUEIRA-RIVERA et al., 2007), resulting in along-river flows as opposed to lateral flows. Millard et al. (2017) showed that the Saskatchewan river diverts a lot more sediment relative to its discharge into crevasse splays than the Columbia river, which may be attributed to either differences in drainage, grain size or a combination of both (Millard, 2012). Modeling in the same study (Millard et al., 2017) shows that the largest crevasse splays are indeed formed in a scenario with intermediate grain size and good drainage, providing first insight into the governing and size-limiting role of the floodplain on crevasse growth. Because it concerns two very different systems with large differences in boundary conditions, where the floodplain behaves either as a pathway or a storage feature, it is still hard to quantify the effect of drainage. Other modeling studies also point out the effect of drainage (Hajek and Edmonds, 2014).

Knowledge gap: rising water levels during a flood

Besides variability in drainage between river systems, drainage may also vary during a single flood. Over the course of a flood, water levels rise as the crevasse transports cumulatively more water into the floodplain. As a result, lateral water surface slopes decrease and crevasse flows become less strong, which lowers drainage. This can shift the balance from erosion to deposition and may thus initiate filling in of the crevasse (Slingerland & Smith, 1998). Although this mechanism has been recognized, it has not yet been fully investigated using a modeling approach. This research will specifically investigate rising flood levels and the effect floodplain volume has on this.

2.2 Morphology and long term development

Crevasse growth in stages

Empirically, crevasse formation has been categorized into three stages (Figure 1) (Smith et al., 1989; Farrell et al., 2001). In the first stage, the crevasse splay can be characterized as a “small, km-scale, sub delta lobe in an interdistributary bay” (Farrel et al., 2001), formed by one or multiple flood events. The initial formation of the lobe is affected by the local slope of the floodplain and can have important consequences for growth after it is filled in, possibly redirecting the channel (Toonen et al., 2016).

If the crevasse splay evolves further into stages 2 and 3, the splay becomes larger in size, more channelized and multiple channels become increasingly connected, forming networks while deposits become narrower and thicker. As we see in Figure 1, crevasse splays grow through a combination of lateral accretion and down the basin progradation. Due to the latter, crevasses in stages 2 and 3 become more elongated in form.

Splays may never reach the last stage, which is related to healing of the crevasse. This happens if sedimentation becomes dominant over erosion, causing the splay to gradually fill with deposits and making flow eventually unable to surpass the crevasse throat. In case the crevasse does not heal and keeps evolving, the throat of the splay will continue to deepen and expand. Under the right circumstances, it may even take over all discharge of the river, in which case it becomes a successful avulsion (Slingerland and Smith, 1998; Kleinhans et al., 2011).

Because Smith et al. (1989) based their growth model for crevasse splays mostly on the deposits of the Saskatchewan river, it may not in all cases accurately describe the growth patterns of crevasse splays in other systems. Makaske et al. (2007) for example, found that the Schoonrewoerd system in the Rhine-Meuse Delta has more narrow and thicker channel deposits when going downstream. This means that the crevasse had a basin ward increasing scour depth, which can be attributed to the downstream dipping of erosion resistant strata in the subsurface. However, this actually enhances channelization and elongation during growth, so we assume that these are common features in the growth of crevasse splays.

The progressive channelization and elongation over time in the three-stage-model is confirmed in empirical findings of Millard et al. (2017), who find that large splays obtain a smaller width/length ratio and thus become narrower in form. They also show that width/length scaling relationships for the Columbia, Sandover- and Saskatchewan river systems follow similar patterns, although these trends only emerge when plotted logarithmically. It is uncertain whether this is also the case for other deltas. By looking at the Rhine-Meuse- and Mississippi River deltas, we investigate crevasse formation in a more deltaic environment, where floodplain size is expected to affect rising water levels. Furthermore, in deltas the floodplains are larger, river- and floodplain slopes are smaller and extensive peatlands may be present. However, we are still strictly looking at the fluvial dominated part of the delta, where waves and tides are of no influence on the morphodynamics.

The effect of drainage on crevasse growth

In order to properly analyze the effect of drainage on natural- and modeled crevasse splays, we need to know how drainage affects crevasse growth besides shear volume of splays. Using the assumption that drainage promotes crevasse growth and that larger splays become more elongated and channelized, we expect that drainage will also result in smaller width/length ratios and deeper crevasse channels.

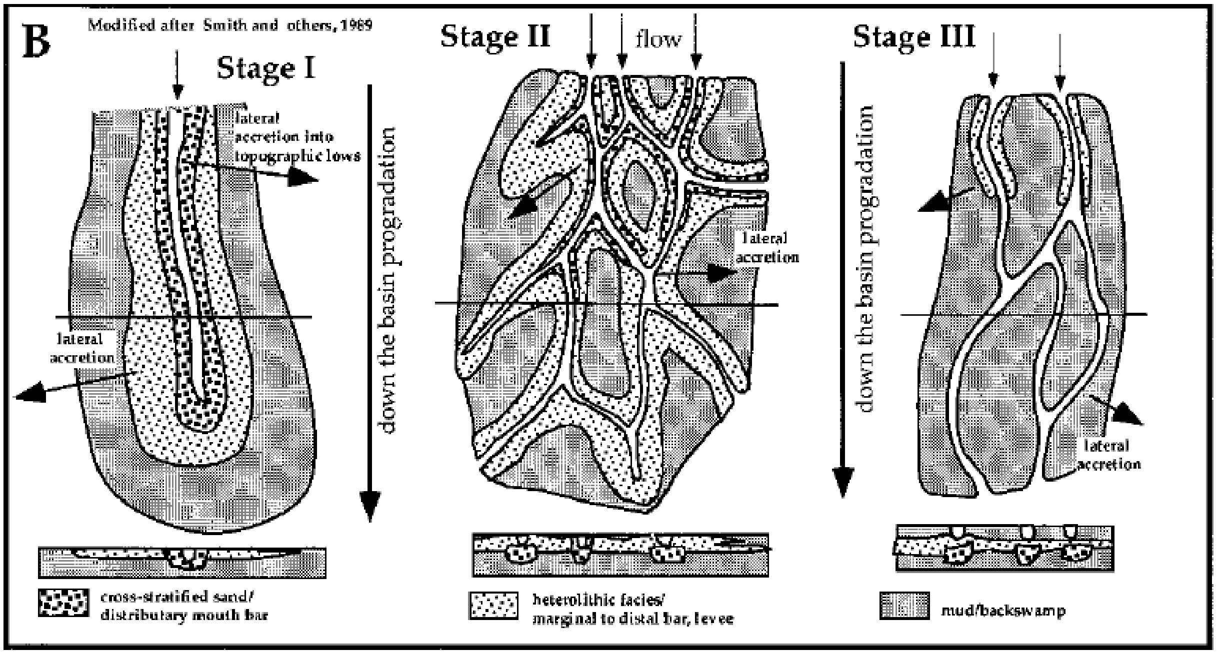

Figure 1 - Conceptual model of three stage crevasse growth according to Farrel et al. (2001), who modified it after Slingerland and Smith (1989) and others.

2.3 Geomporphological setting

Here we quickly discuss the most important characteristics of the Rhine-Meuse – and Mississippi Deltas concerning crevasse growth.

Rhine-Meuse Delta

The Rhine-Meuse Delta extends from the apex around the Dutch-German border to the western coast of the Netherlands. Multiple generations of channel belts are present, flanked by levee- and crevasse complexes, which themselves are located next to floodplains (Pierik et al., 2017). Levees and crevasse splays contain sediments varying from sand to clay. Floodplain deposits consist of clay upstream and peat downstream of which the transition point is located around X = 150,000 m (Figure 2). Peat is expected to cause narrowing in crevasse splays, related to enhanced channelization through subsidence, increased bank stability and sediment trapping of the vegetation and potentially downstream dipping of erosion resistant strata (Van Asselen et al., Toonen et al., 2016; 2011; Makaske et al., 2007).

The Rhine and Meuse have mean discharges of 2200 and 300 m3/s respectively (Stouthamer et al., 2011, originally obtained from Rijkswaterstaat data), of which the Rhine discharge is expected to have remained stable within a range of 10 % (Erkens et al., 2009). Contrarily, the flood regime of the Rhine-Meuse Delta is much different at present than it was. Due to embankments, the river is now fixed in the landscape, which leads to a different flood wave propagation (Toonen, 2013). A model simulation of a flood in the early Middle-Ages (According to B. van der Meulen, personal communication, April 2020) (Table S7), estimates that an extreme flooding event with a discharge of 12,000 m3/s occurring once every 100 to 500 years (Toonen, 2015, see Figure 8) has a peak duration that is estimated at roughly four days, although the whole flooding event lasts longer.

The delta is around 20 km wide upstream and then narrows to 10 km, after which it widens again until it reaches a 50 km width. Levee height varies between 1-2 meters. The highest levees occur in the narrowest part of the delta, where floods are amplified (Pierik et al., 2017), emphasizing the importance of floodplain geometry on levee morphodynamics. However, the differences in crevasse splays along the delta have not yet been investigated for the Rhine-Meuse Delta.

Mississippi Delta

The Mississippi Delta consists of 6 different distributary lobes that were active from 6 ka until now (Coleman et al., 1998). For this research we consider the present course of the river and the now abandoned Bayou Lafourche tributary, which was active between 1.5 – 0.6 ka (Törnqvist et al., 1996; Shen et al., 2015).

The same features (river, levees, crevasse splays, floodplains) are present, but there are some differences compared to the RM-delta. The relative channel belt width is larger for the Mississippi than for the Rhine-Meuse channel belts (Fernandes et al., 2016), while the levees are also more elevated, reaching up to 6 meters, as indicated by Shen et al. (2015) and LIDAR-maps of the region (atlas.lsu.edu/lidar/). The mean river discharge of the Mississippi is also higher, with a discharge of 18,400 m3/s just above the Atchafalaya River diversion (Hudson et al., 2008; Mossa, 1996).

Floodplain substrate also consists of either clay or peat (Shen et al., 2015). Wood peat typically underlies crevasse splays formed in the Bayou Lafourche lobe, indicating the presence of swamps also during formation (Törnqvist et al., 2008). Lastly, the floodplains in this region are unconfined, meaning in open connection to the ocean. Together with the large height difference between levee and floodplain, this results in a very large accommodation space for water during floods.

2.4 Approach and hypotheses

For this research, we look at the balance between deposition and erosion, and how drainage impacts this balance. Until now the D/E ratio has only been applied to well-drained floodplains where a constant and significant water surface slope is maintained (Nienhuis et al. 2018). We use a combination of field research and modeling to assess the effects of floodplain drainage on crevasse splay development, which includes also the transient part in a flood cycle. For this research, we consider the floodplain as strictly a storage entity that is being filled by flow of the crevasse. The main hypothesis is:

- Well drained floodplains enhance advection and thus favor the formation of large crevasse splays.

Applying this to crevasse splays in the Rhine-Meuse Delta, where many confined floodplains are present, we expect that the largest crevasse splays lie in the largest floodplains. Furthermore, we expect crevasse splays in the Mississippi Delta to be larger than those in the Rhine-Meuse Delta, because the floodplains here are unconfined and thus larger. Additionally, the larger river discharge and increased height difference between levee and floodplain in the Mississippi will promote bigger crevasse splays to grow. We expect the increase in size due to better drainage to go paired with an increase in channelization and a reduction in relative width/length ratio, following the three-stage-model.

Lastly, we model crevasse splays in Delft3D (Deltars, 2014), which allows us to test findings from natural crevasse splays and examine more in depth how floodplain size or drainage affects crevasse growth. We expect that for small floodplains, water levels rise quickly during a flood, decreasing the erosive capacity of the channel. This counteracts channel deepening and erosion, resulting in a faster transition into deposition and healing. A large floodplain will fill slowly, thus maintaining a large water surface slope for a long time, enabling the breach to erode deeper and further into the floodplain. This increases the discharge capacity of the channel, meaning the magnitude and duration of erosion increase. Consequentially, the potential accommodation space for deposition increases, resulting in larger end-member crevasse splays.

3 Methods

3.1 Mapping crevasse splays

We map and analyze crevasse splays for the Rhine-Meuse Delta using a geomorphological map of the Netherlands of 100 AD (Pierik et al. 2017) in combination with a channel belt map (Cohen et al., 2012). Because of many overlapping crevasse splays in this area, we limited our selection to splays that were straightforward to identify and measure in relation to the parent channel (see example in Figure 2c). Furthermore, we mapped crevasse splays along the abandoned Bayou Lafourche lobe and the present channel of the Mississippi, identified using LIDAR-maps (Figure 2b). We choose these two sites because the river systems are very different in terms of discharge, levee height, floodplain volume and erodibility so that we can investigate a broad spectrum of forming conditions.

We make sure that we only take crevasse splays in the fluvial dominated part of the deltas. For the Mississippi Delta, the tidal range is small (~ 0.20 m, according to Esposito et al. 2011) and considered unimportant. Therefore, we disregard its effect in this research. For the Rhine-Meuse, where tidal range in the considered time period can be up to 1.5 meters at the coast (Van der Molen & De Swart, 2001a) we only map splays that are located well above the zone that is affected by the (tidal) backwater effect (Fernandes et al., 2016).

For all crevasse splays, we measure their area, channel length, orthogonal extent, straight path length and width (see Fig. 2c), following methodology of Millard et al. (2017). Orthogonal extent is defined as the length of the tip of the crevasse splay to the parent channel at a 90 degree angle. Straight path length is the shortest path of the beginning of the crevasse splay to its end. By dividing channel length by straight path length, the sinuosity of the crevasse splay is obtained. Additionally, we map the (paleo-) floodplain area using ArcMAP.

Note that the flooded extent of the floodplain will vary between different floods, as the largest floods will flood larger areas of land. Furthermore, there is some uncertainty in the original relief in the landscape due to differential compaction and groundwater table management. Therefore, we map a maximum and minimum floodplain extent: the maximum extent includes the entire area of the levees, crevasse splays and adjacent floodplain. The minimum extent only contains the flood basin (see Figure 2c for the difference). The boundary between floodplain and levee is determined by lithology, relative elevation and pedology (Pierik et al., 2017).

After mapping all crevasse splays and their properties, we determine for every floodplain the largest and smallest crevasse splay in terms of area. All properties of the largest and smallest crevasse splays, as well as the mean values are tested for statistical significance in terms of their relation with floodplain area. All properties, except for sinuosity, are tested using linear regression with the criterium $P < 0.05$. Sinuosity is tested for its relationship with channel length, as it is expected that increased channelization, which we assume to be reflected in an increase in length, will affect sinuosity. Lastly we will compare the crevasse splay dimensions with existing crevasse data (using the dataset of Millard et al., 2017), in order to see how the crevasse splays found in the Rhine-Meuse and Mississippi deltas compare to them.

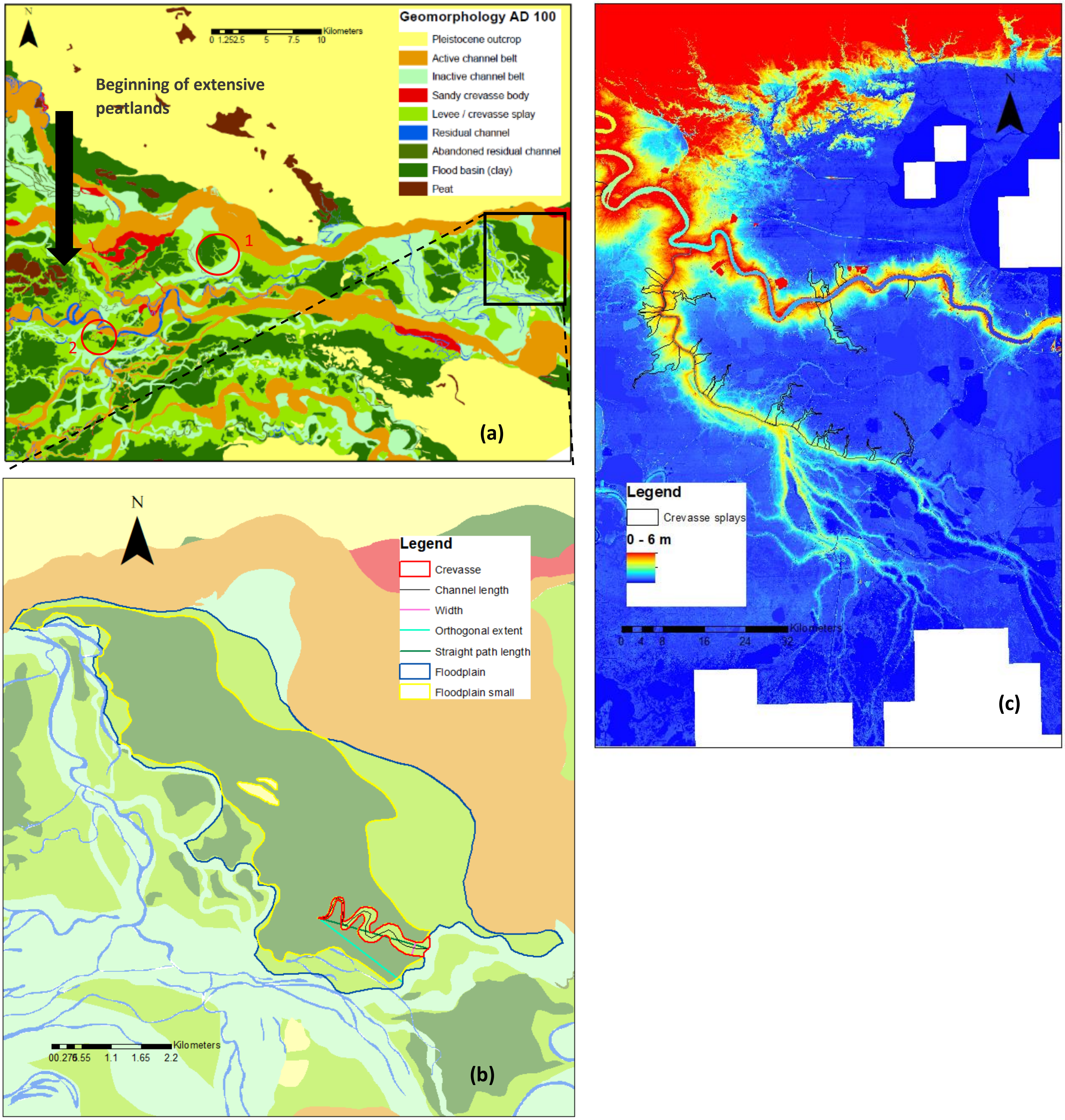

Figure 2 – (a) Geomorphological map of the Rhine-Meuse delta (Pierik et al. 2017). The red circles with number 1 and 2 are the locations of the two splays that are mentioned in the discussion. (b) Example crevasse splay map, where all mapped properties are shown. (c) Overview of the mapped crevasse splays in the Mississippi Delta, using LIDAR maps (atlas.lsu.edu/lidar/) of the abandoned Lafourche lobe of the Mississippi delta. The same properties are also mapped for the Mississippi delta, except for floodplain extent.

3.2 Morphodynamic model

Model set-up

We use the Delft3D model set-up of Nienhuis et al. (2018), which uses water level boundaries at the levee breach location and a location just downstream of the crevasse. This setup creates a fast and flexible model for generating a variety of crevasse splays and avulsions (Nienhuis et al., 2018) which specifically focuses on the role of floodplain characteristics on crevasse growth. The original model setup used a fixed downstream water level, representing a well-drained floodplain. Here we adapt the downstream water level and make it dependent on the water discharge entering the floodplain, representing the filling of a floodplain during a flood. We update the water level at the outflow boundary (Figure 3) once every hour. In this manner, the outflow water level increases as the floodplain fills and eventually reaches the same height as the upstream water level, mimicking natural behavior of flooding events in confined floodplains.

Both floodplain area and flood duration are predefined and can be varied to examine their effects. The flood simulation stops when the floodplain is filled and no more water (and sediment) flows through the breach, or when the maximum duration of the flood is reached.

To simulate the entire lifetime of a crevasse splay, we model multiple floods consecutively, each time expanding the crevasse splay. When after a certain number of floods the levee breach heals, we end the simulation. We focus on crevasse splays and do not consider flooding conditions that would lead to avulsions. We consider the breach to be healed if the discharge through the splay is < 10 m3/s. In this way we aim to model the entire lifespan of a crevasse splay. It is important to note that crevasse formation is induced only by fluvial processes in this modelling effort -- tidal- or wave related processes are not considered. The use of a variable floodplain makes it possible to implement floodplain areas found in the field into the model and test whether floodplain extent indeed influences crevasse area and volume.

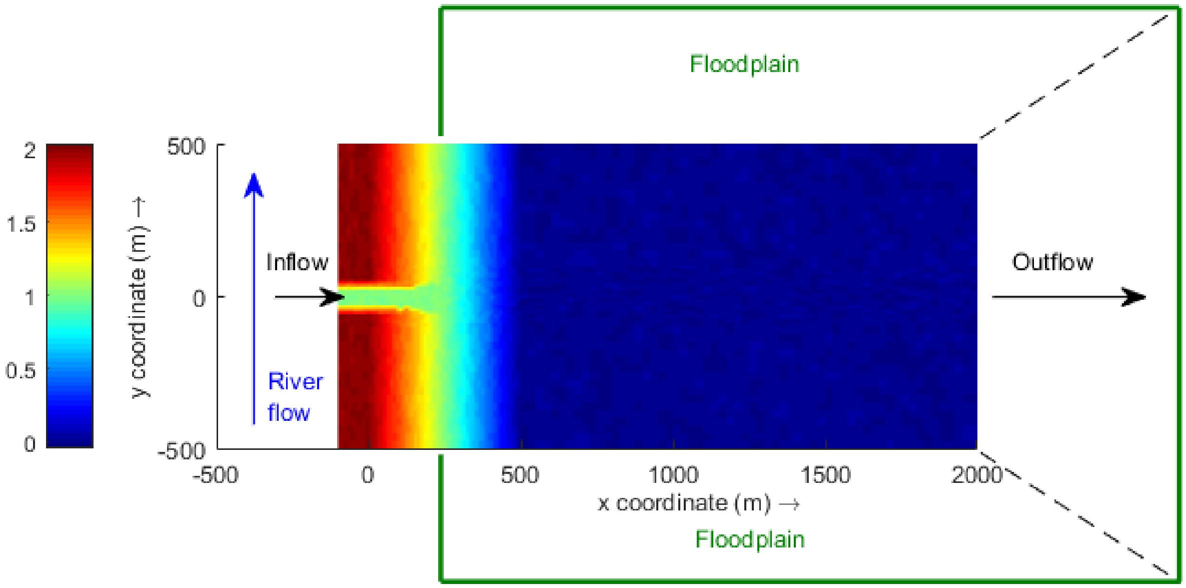

Figure 3 - Model domain, initial bathymetry and theoretical placement of the model in a natural setting, including a river and its floodplain. Left is the inflow boundary through a breach in the levee where flow enters the model domain. The model domain is part of the floodplain. Bed level is in meters.

Model parameters

Table 1 shows the most important model parameters. Besides floodplain area, we vary the flood duration to explore what its effect is on crevasse formation. For the critical shear stress of the cohesive clay and silt sediment fractions we use a value of 0.5 and 1.0 Pa respectively, which was found to work well for the chosen model set-up. This value is expected to be appropriate, as Weiming et al. (2017) found that for mud concentrations of around 100 % clay for the Mississippi, critical shear stress may vary between 0.5 -2 Pa. Roughness in the model is determined using the White-Colebrook formulation for the Chezy parameter:

$$C = 18 \log \frac{12 * H}{k_s}$$

Where C = Chezy coefficient ($m^{1/2}/s$), H = depth (m) and k_s = geometrical roughness of Nikuradse (m). A relatively large value for k_s is used, in order to simulate conditions of a vegetated floodplain, where roughness is large. For a complete overview of all model parameters, see Table S5.

Table 1 – Main Delft3D model parameters.

Model parameter	**Value**
Domain size	2000 * 1000 m
Water level at inflow boundary	2 m
Water level at outflow boundary (initial value)	1 m
Floodplain area	5, 10, 20, 50 and 100 km^2
Flood duration	2, 4 and 7 days
Morphological acceleration factor	45
Nikuradse geometric roughness (Ks)	0.025
Critical shear stress: mud	0.5 Pa
Critical shear stress: silt	1.0 Pa
Grain size sand (D50)	100 μm

Analyzing results

To explore the effect of floodplain size on crevasse morphology, we track both sediment volume and area over the course of the simulation every hour. Sediment volume is taken as the volume of sediment in the domain at a given time, minus the initial volume of the domain, whereas crevasse area is defined as the area of land that is located above the 1-meter contour line, which is the lowest water level.

Furthermore, we want to explore how the deposition/erosion balance changes over time. We therefore compute and track the average channel depth of the crevasse splay over the course of the simulation. The maximum channel depth reached during the simulation is marked as the transition from erosion to deposition. For the separate deposition and erosion phases we can then determine other characteristics like the mean discharge and mean water level difference, both indicators of the erosive capacity of the splay. Lastly, we compute the retention efficiency by computing the ratio of total outgoing/incoming sediment.

We show in Figures 4-7 some results of an example model run to explain how the model works. This simulation uses a floodplain of 20 km^2 and flood duration of 2 days. For this simulation, 5 floods occurred (Figure 5). During each flood, water levels rise as a response to the discharge. All singular floods are ended because the 2-day duration is reached before the floodplain is filled. The first and second flood reach levels of approximately 1.5 meters height, meaning the floodplain is not completely filled (maximum water level is 2 meters). After flood 2, floodplain water levels in consecutive floods rise even less, which can be explained for by the decreased discharge through the breach (Figure 6). This exemplifies the transition from erosion to deposition, meaning the crevasse splay starts to heal. The exact transition is during flood 3, slightly after day 5 (Figure 7). When the discharge reaches 10 m3/s after more than 9 days, the complete simulation is ends and the splay is considered healed.

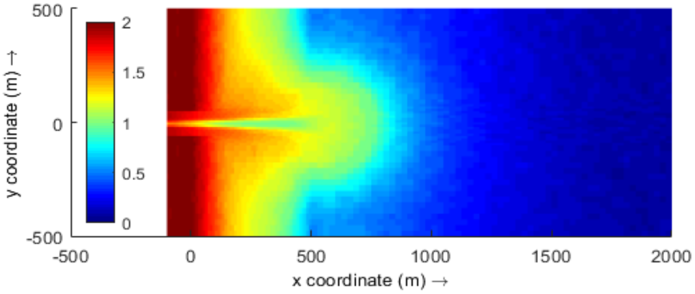

Figure 4 – Bed level elevation of model run 3, with a defined floodplain area of 10 km^2 and flood duration of 2 days.

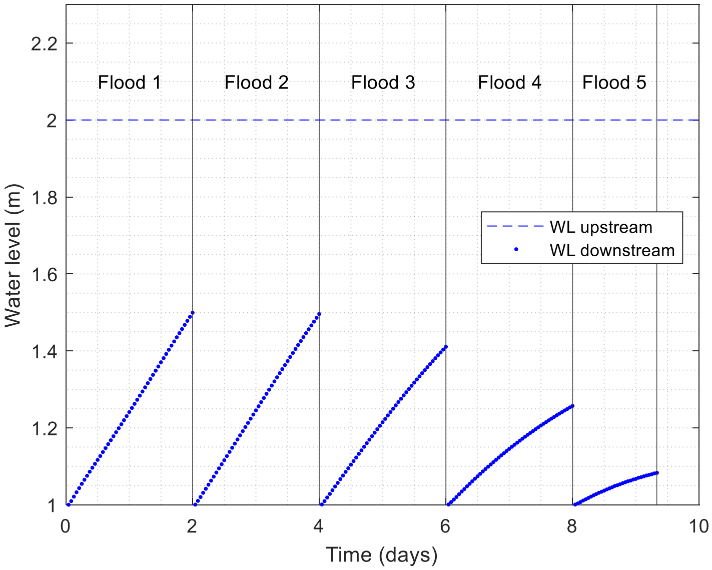

Figure 5 – Time series of the in- and outflow water level for model run 3. This is the hydrodynamic time-series.

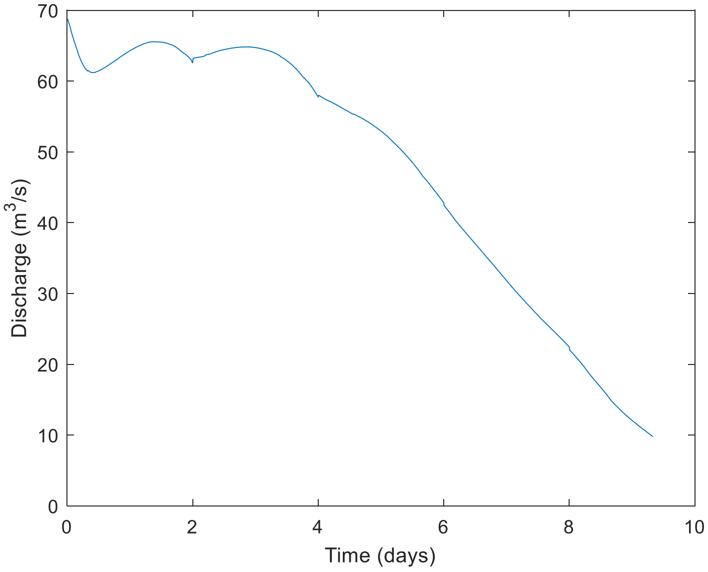

Figure 6 – Discharge timeseries of the inflow boundary for model run 3

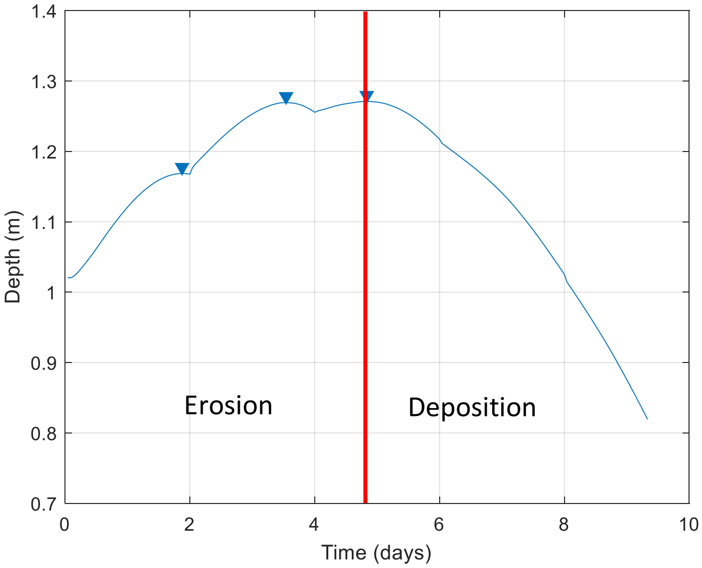

Figure 7 – Average channel depth for model run 3, showing the distinction between erosion and deposition at peak channel depth.

4 Results

4.1 Mapping results

Crevasse splay dimensions in the Rhine-Meuse and Mississippi Deltas

We mapped a total of 47 crevasse splays in the Rhine-Meuse delta spread over 12 floodplains. Crevasse splay surface areas vary between $1.2 *10^4$ and $9.4 *10^6$ m^2 and floodplain areas between $6.9 *10^5$ and $6.8 *10^8$ m^2 (see Table S1 and Figure S1). For the Mississippi delta we mapped an additional 24 crevasse splays varying between $7.5 *10^5$ and $2.3 *10^7$ m^2. There are no easily identifiable floodplain boundaries in the Mississippi Delta, so we did not map the floodplain extents here. In Figure 8 we see that the Mississippi crevasse splays are generally much larger than in the Rhine-Meuse Delta, as expected.

How do the crevasse splays of the Rhine-Meuse and Mississippi deltas compare to splays in other river systems? In Figure 9, we see that most of the mapped splays in this research follow the same width/length scaling relationships as Millard et al. (2017) found in the river systems in their research. With increasing channel length, crevasse splays shift away from the AR = 1 line in the direction of AR = 0.1, meaning crevasse splays become less wide. Lastly, the splays located in peat for the Rhine-Meuse seem to have a very small width compared to other splays that are comparable in length. This seems to confirm the expected effect of peat on crevasse formation (Makaske et al., 2007; Van Asselen et al., 2011; Toonen et al., 2016).

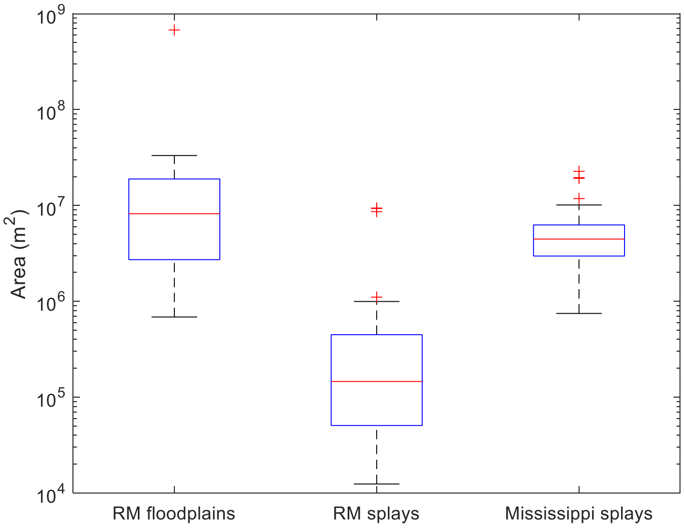

Figure 8 - Boxplots of the populations of the mapped floodplains and crevasse splays for the Rhine-Meuse- and Mississippi Deltas.

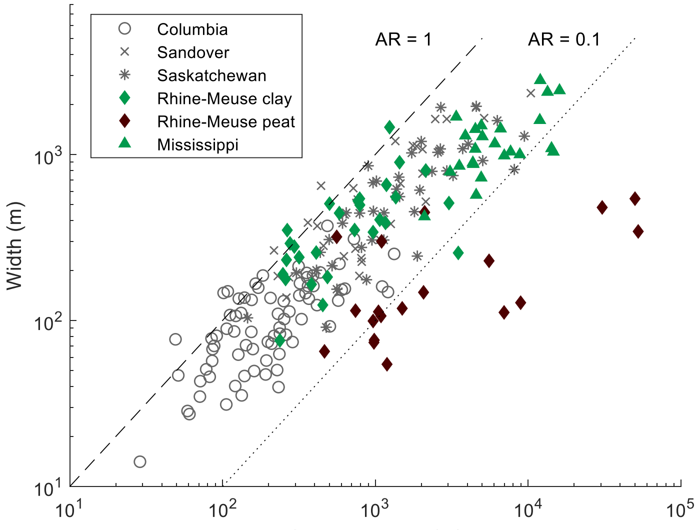

Figure 9 - Length and width of crevasse splays from multiple deltas. Data in grey is from the multiple river systems studied by Millard et al. (2017). AR is the aspect ratio: crevasse width divided by channel length. The green color represents crevasse splays in this study that follow the

Effect of floodplain size in the RM-Delta

All results of the linear regression models are given in Table S3 and in Figures S1.1 – S1.7. Figure 10 shows the most important findings. We find that maximum crevasse area is positively related to floodplain area (R^2 = 0.82473) (Figure 10a). Furthermore, we find that the maximum channel length and orthogonal extent (R^2 = 0.82509, R^2 =0.88287) also increase for increasing floodplain area. Floodplain area does not seem to affect maximum crevasse splay width. For crevasse area, channel length and orthogonal extent also the mean values are found to be positively related to floodplain area. None of the minimum values for these properties are related to floodplain area. Furthermore, sinuosity was found for the Mississippi to be linearly related to channel length. In the RM-delta this relation is absent, however. These relationships are not dependent on our floodplain definition. These results are not dependent on the area of the floodplain, as tests using the minimum floodplain extent resulted in similar significant relationships (see Table S3). All linear regression models bare the same statistical significance using the criterium of $P < 0.05$ (see Table S4).

Our mapping effort suggests that larger floodplains create the potential for larger crevasse splays (Fig. 10a). The increase in size is mainly due to an increase in length of the crevasse splays, of which both channel length and orthogonal extent are a measure. These findings agree with the formulated hypothesis t. Regardless of the definition (maximum or minimum extent) of the floodplain, these trends hold. Also mean crevasse area, channel length and orthogonal extent are related to floodplain area. This indicates that the population inside a single floodplain also increases with increasing floodplain area. The absence of any trends in the minimum values indicates that floodplain does not set any limits on the minimum size of crevasse splays. However, for some floodplains only one crevasse splay was measured, meaning that the mean, maximum and minimum values for this floodplain are equal. This makes the assessment of the mean and minimum less reliable. Lastly, we are unsure why sinuosity is only related to channel length in the Mississippi, and not in the Rhine-Meuse.

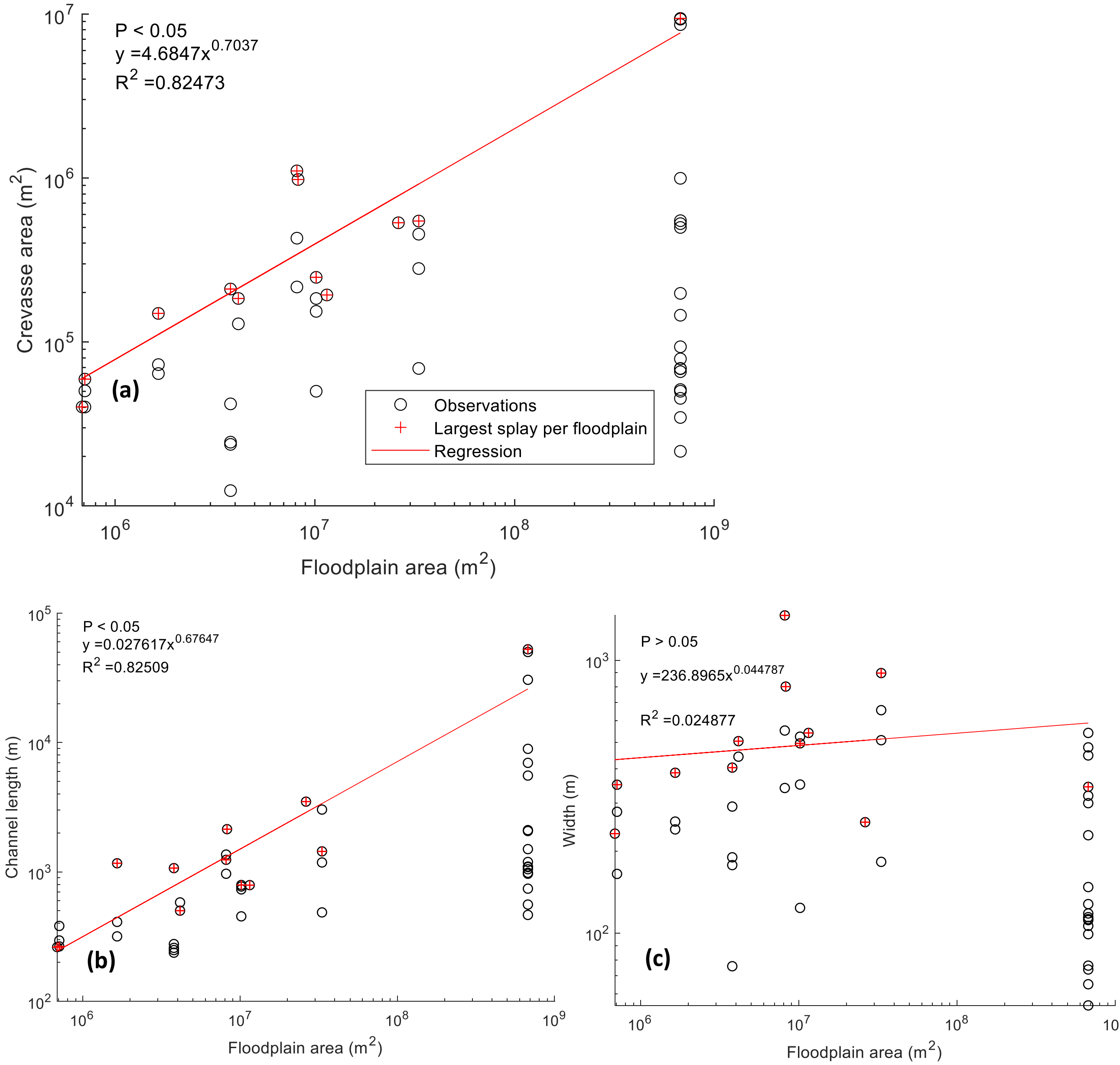

Figure 10 – Crevasse properties related to floodplain area for the Rhine-Meuse Delta. (a) Maximum crevasse area per floodplain as a function of floodplain area. (b) Crevasse channel length related to floodplain area. (c) Crevasse width related to floodplain area. We only consider the Rhine-Meuse delta in this figure. Both maximum crevasse area and channel length bare statistically significant relationships with floodplain area, whereas width does not.

4.2 Model results

We conducted fifteen stable model runs to investigate the effect of floodplain size and flood duration on crevasse formation. We used floodplains with sizes of 5, 10, 20, 50 and 100 km^2 and flood durations of respectively 2, 4 and 7 days. For all modeled crevasse splay morphologies, see Figure S2.

Effect of floodplain size and flood duration on crevasse morphology

We find that with increasing predefined floodplain areas, crevasse morphologies increase in volume (Figure 11), which is the case for all different flood durations. Looking at model runs 1-3 (Figure 12), this increase in volume is due to an increased extent into the floodplain and an increase in width. At a certain point, a maximum extent of the splay into the floodplain seems to be reached. When we look at model runs 4 and 5 (floodplain areas 50 and 100 km^2), we see that the channel of these splays reaches about the same length as run 3 at x = 500 m.

All crevasse splays seem to have formed clear levees to the side of the crevasse channel and a terminal deposit at the end of the channel that resembles a mouth bar (Figure12; Figure S2 for all morphologies). The levees are the most elevated part of the splay. For the larger crevasse splays, there is also large accumulation of sediment at the mouth bar. Furthermore, it seems that for decreasing flood duration, crevasse splays seem to become wider (Figure S2). Lastly, shorter flood durations also result in larger crevasse volumes (Figure 11), which we investigate further in the next section.

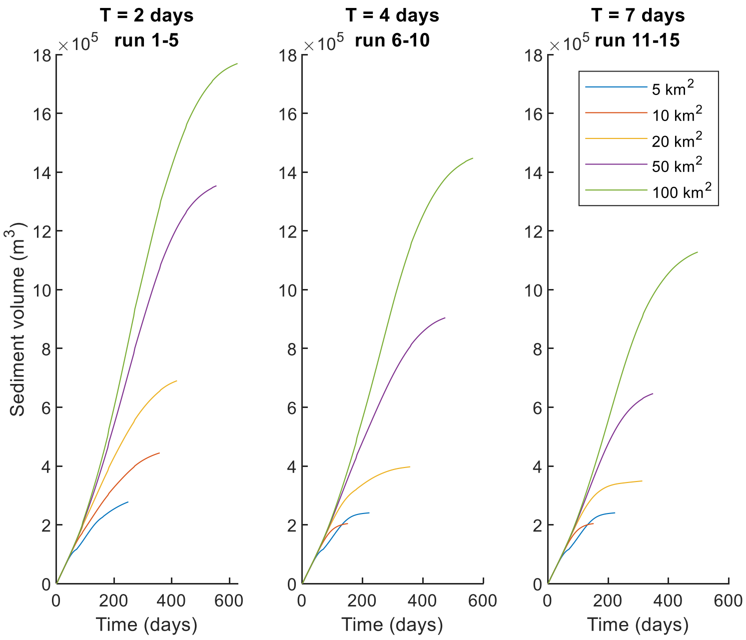

Figure 11 - Imported net sediment volumes for floodplain areas between 5 - 100 km^2 and flood durations of 2, 4 and 7 days.

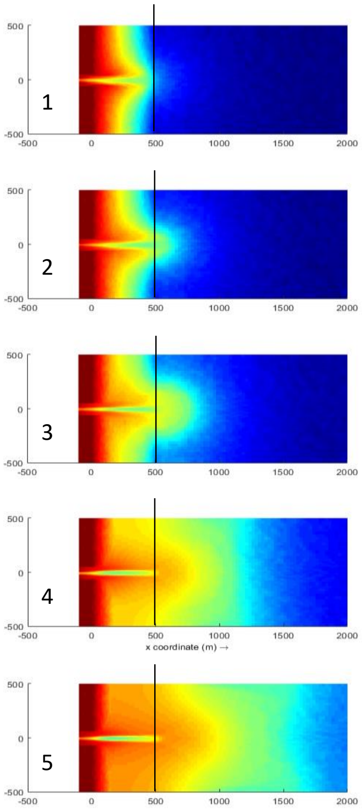

Figure 12 – Crevasse morphologies of model runs 1-5, with increasing floodplain areas going downward. The black line indicates the approximate maximum extent of the crevasse channel into the floodplain.

Assessing drainage: a combined effect of floodplain and flood duration

To investigate the combined effect of floodplain volume and flood duration, we theorize that when a flood takes a longer time, floodplain water levels are allowed to rise higher. This causes reduced flow during the later stage of the flood and enables quicker infilling. To better predict the combined effect of both floodplain volume and flood duration we define a parameter for drainage:

$$Dr = \frac{V_{fl}/Q_c}{T}$$

In which Dr = drainage ([-] , dimensionless), V_{fl} = floodplain volume (m^3), Q_c = characteristic discharge of the crevasse throat (m^3/s) and T = flood duration (s). The floodplain volume and flood duration are predefined for every scenario. Characteristic discharge of the crevasse throat is determined as the discharge through the breach on the first day of flooding, which is 69 m^3/s. By dividing the floodplain volume by the characteristic discharge, we find the typical duration if this discharge were to continue throughout the flood cycle. When we divide this duration by the set duration of the flood, the result is a dimensionless number which indicates whether the floodplain would be able to be completely filled with water coming from the crevasse throat (Dr <1), or would remain partly unfilled (Dr >1). Consequently when Dr << 1, we expect that the splay is controlled by floodplain size and when Dr >>1, the splay is controlled by flood duration. Although the discharge of the crevasse is not constant and will increase when the channel deepens, every simulation scenario starts off with the same discharge, which is expected to either increase or decrease as a function of the drainage parameter.

Besides predicting model results, this parameter also gives the opportunity to compare modeled crevasse volumes to splays found in the field for the Rhine-Meuse Delta. We use the largest splay per floodplain (Figure 10a) for comparison, since they were found to be correlated to floodplain area. The volume of the floodplain is calculated by multiplying the mapped area by 1 m, which is the average height difference between levee and floodplain (Pierik et al., 2017). The potential volume range of the natural splays is depicted by multiplying crevasse area by the deposit thicknesses of using the range 1-2 meter (Pierik et al., 2017). We assume (1) a characteristic discharge equal to the discharge in the model and (2) a flood duration of 4 days, using a model simulation of an extreme flood (Table S7). This is obviously a highly simplified approach to assess drainage for natural splays, but allows us to make a comparison between field and model and to potentially evaluate differentiating trends.

The drainage parameter seems to be a good predictor for both crevasse area and volume in the model, where increasing Dr results in larger crevasse areas and volumes (Figure 13a,b). This trend is clearest for larger values of Dr. Crevasse volumes from splays in the RM-Delta show a similar rising trend with increasing Dr, but plot systematically higher than crevasse splays in the model.

Furthermore, we see that the maximum channel depth increases significantly with increasing drainage (Figure 13c). Logically, the erosion duration also increases (Figure 13d), as we defined the duration of the erosive phase as the moment until maximum channel depth. The entire lifetime of the crevasse increases as a result of this (Figure 13e). The relation of deposition duration with Dr seems weak, as there is a lot of scatter (Figure 13f). The number of floods also increases with increasing Dr (Figure 13j), although this is less clear for small Dr values.

When looking at the water level difference between river and floodplain during the erosive face (Figure 13k), we see that for Dr < 1, the water difference is more or less constant around 0.75-0.80 m. When Dr > 1 the difference starts to rise until around 0.90 m. This seems to affirm the proposed transition from floodplain limited- to flood duration limited conditions of crevasse growth. At Dr < 1 the floodplain is completely filled, meaning the downstream water levels will always be able to rise up to 2 meters, making the average water level and thus the head difference more or less constant. When $Dr > 1$, the water level can not rise as much and the mean head difference increases.

Lastly, we show that although high values of Dr cause large splays to form, the retention efficiency becomes lower (Figure 13l). This is due to larger flow velocities that keep the sediment in suspension longer, transporting it out of the modelling domain.

Conclusively, we see that drainage consists of a combined effect of floodplain size and flood duration, encompassed in Dr. For small Dr, water levels rise quickly during a flood, decreasing the erosive capacity of the channel. This counteracts channel deepening and shortens the duration of the erosive phase, resulting in a faster transition into partial deposition/erosion and eventual infilling. A large Dr causes the floodplain to fill slowly, thus maintaining a large water surface slope for a long time during a flood, which enables the breach to erode deeper and further into the floodplain. This increases the discharge capacity of the channel, meaning the magnitude and duration of erosion increase. Because of this, the potential accommodation space for deposition thereafter increases, which results in larger end-member crevasse splays.

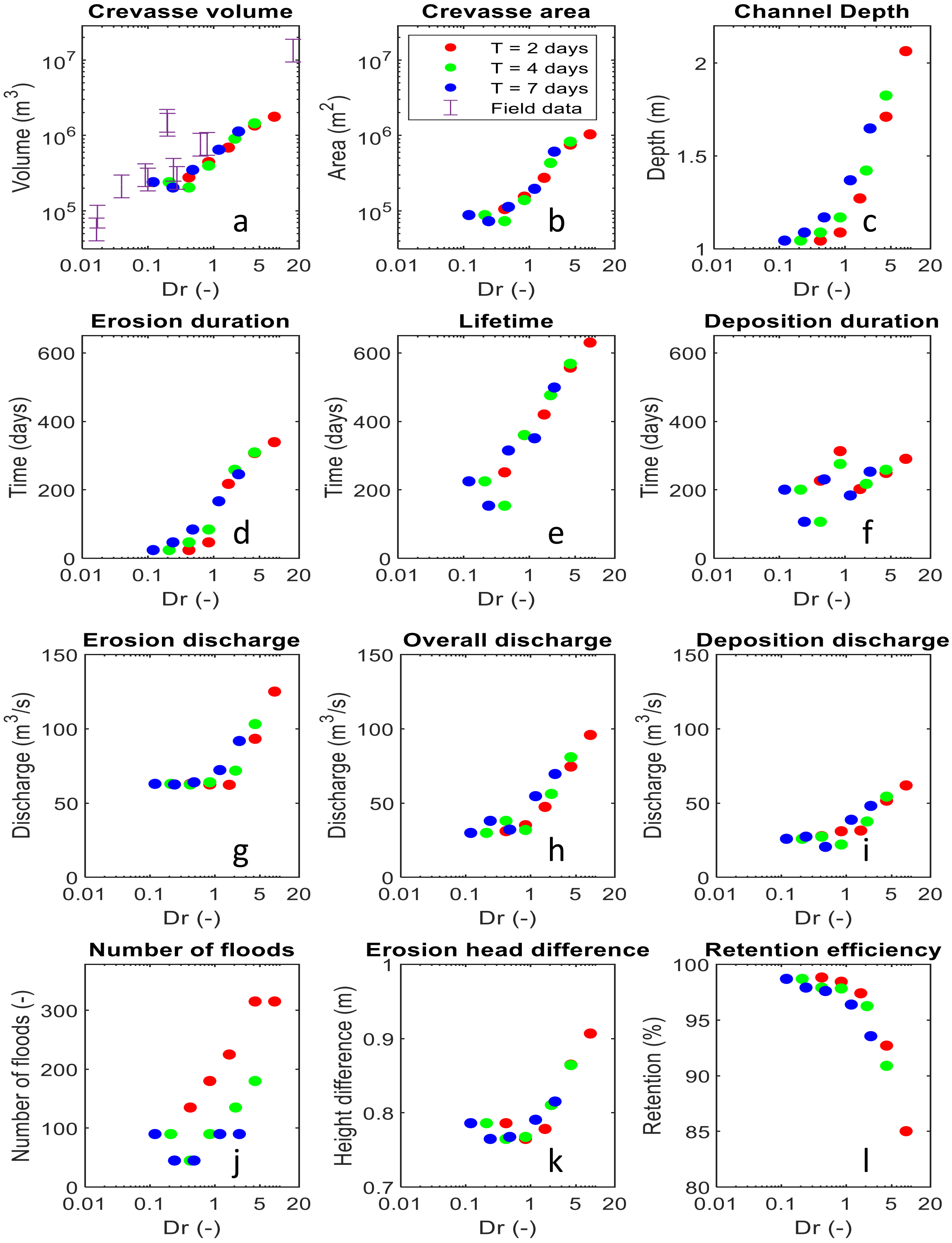

Figure 13 – Plots of the effect of Dr on crevasse volume, area, channel depth, erosion duration, lifetime, deposition duration, erosion discharge, overall discharge, deposition discharge, number of floods, the average head difference during erosion and retention efficiency. For subplot a, the volume of natural splays in the RM-delta are computed by assuming a potential deposit thickness between and 1 and 2 meters (based on Pieriks et al., 2017).

5 Discussion

Here we discuss the results from both the field- and modeling analysis and try to integrate both to come to a deeper understanding of crevasse growth. We will first discuss how reliable the drainage parameter is in assessing crevasse growth for modeled- and natural splays. Then we look at how a natural flood regime may affect crevasse growth and how this may be assessed in a more realistic way in future research. Furthermore we explore important factors in determining crevasse shape and size by comparing morphologies in field and model. Lastly, we shortly discuss how discovered mechanisms in this study may apply to the application on artificial sediment diversions.

5.1 Dr as a predictor for crevasse growth

Model

Overall, Dr seems to be able to accurately predict resulting crevasse volumes for the performed model simulations, with increasing Dr leading to larger splay volumes. For small values of Dr, the observed trends for crevasse area and volume are less obvious. This becomes evident when looking at Figure 13a,b. These inconsistencies are only found for the model scenarios with flood durations of 4 and 7 days. This is most likely a consequence of the set-up of the model and the implementation of a morphological acceleration factor. For simulations where $Dr < 1$, an increase in floodplain area means that the duration of the flood will increase, as the crevasse splay is floodplain limited. This causes more deposition of sediment in the domain, obstructing the flow and thus decreasing the discharge through the channel. Because of the implementation of a morphological acceleration factor, this deposition can be unrealistically high. This means that discharge in the next flood will be lower, which in this case causes it to drop below 10 m^3/s, ending the simulation. We can see this in the drop in the number of floods at small Dr values (Fig. 13j). We expect that with lower values for the morphological acceleration factor, this effect becomes less pronounced or even disappears, because deposition magnitudes decrease.

Field

As mentioned before, for field splays a similar increasing trend is found for crevasse volume as a function of drainage. There are two crevasse splays that deviate mostly from this trend (Figure 13a, both at approximately $Dr \approx 0.2$, Volume > 106 m3). We call these crevasse splays for simplicity splays 1 and 2 here (channel belt ID's 200 and 97, Cohen et al., 2012) (red circles in Figure 2a). Both splays are located just after the narrowest part of the delta, in very small and narrow floodplains, which may cause amplified flood levels (Pierik et al., 2017). This would increase accommodation space of the floodplain relative to its area, allowing larger splays to form. However, if this were the case, we would expect to see this as well in other narrow floodplains that were mapped.

What we expect to be more importance, is that both splays consist of multiple distributary channels: splay 2 consists of multiple levee breaches, while splay 1 has multiple channels originating from a single location. Most of the other mapped splays have splay areas that can be attributed to a main trunk channel. The existence of multiple channels is not taken into the Dr -parameter, but would also increase crevasse size. Additionally, multiple crevasse channels of one or multiple splays that discharge simultaneously into the floodplain would lead to very different flow conditions, filling the floodplain more rapidly and potentially allowing crevasse splays to interact with each other. This complicates crevasse growth, making Dr less applicable.

Conclusively, it seems that Dr seems to predict crevasse size best for single channel splays, preferably as the only splay in its floodplain. When considering more complex crevasse systems, one needs a more complete picture of the flow conditions during crevasse growth than simply floodplain size.

5.2 Flood regime and its implication for duration of formation

A shortcoming in this model is the use of a singular flood as being representative for the entirety of crevasse formation for a single splay. Flooding is a highly irregular process, with fluctuations in peak magnitude, recurrence and duration. Baring that in mind, it is still meaningful to compare naturally occurring floods with the ones used in the model, in order to get a grasp on typical flood regimes and their effect on crevasse dynamics.

As mentioned, we assume a 4-day flood, as a representative estimate for the studied crevasse splays in the RM-delta in this study, although this is a slight simplification, as for the downstream part of the delta flood duration is expected to be higher than upstream. Here we take a look whether the 100-500 year recurrence time of this flood would be realistic.

For crevasse splays in the Mississippi we find that for the large Attakapas Crevasse Splay in the Mississippi Delta, a lifetime of approximately 800 years was found (Shen, 2015), while Cahoon et al. (2011) describe a crevasse splay near the coast forming over decadal time scales. In the Rhine-Meuse Delta, two crevasse splays that were mapped in this study have maximum durations of formation of 500 and 1745 years (Cohen et al. 2012, channel belt ID’s 178 and 184 respectively, obtained via radiocarbon dating). A third splay in the RM-Delta, the Schoonrewoerd system, only took 100 years to form (Makaske et al., 2007), despite its large size. In the Saskatchewan River, The Muskeg Lake Splay has formed since the 1920’s and has in 2004 almost terminated its activity, indicating that its lifespan is in the order of decades to a hundred years (Toonen et al., 2016).

Because of the large range of lifetimes of crevasse splays from decadal to centennial and even millennial scales, it seems unlikely that a 100-500 year recurring flood can be typical for this complete range, assuming the splay is built up of multiple flood events. In order for crevasse splays to form on a decadal timescale, we expect that we need recurring floods at yearly to decadal timescales, which would likely also give a different typical flood duration than the 4 days we used here. Model results seem to indicate the same, because the smallest splays already consist of 45 floods, which would mean a minimum 4500 years of crevasse growth. However, we cannot draw too strong conclusions from the model due to its simplified projection of natural processes.

Furthermore, there is the possibility that crevasse growth does not completely cease after a flood is over and crevasse formation is not defined (solely) by singular flood events. Shen et al. (2015) show that for the Attakapass Crevasse splay aggradation, although predominantly occurring in distinct episodes, did not completely cease after such periods. Also research of Cahoon et al. (2011) on a Mississippi splay located very near to the coast, shows that parts of a crevasse splay may be flooded nearly year round.

Although extreme floods are thus unlikely to be the only morphodynamic drivers for crevasse splay formation, large floods will cause the most numerous and largest levee breaches (Toonen et al., 2015, see Table 2 for their flood classification) and have the highest erosive capacity for enabling splays to expand in size, making them still essential in crevasse formation. A potential consequence of this, is that extreme flood events mainly cause levee breaches, after which moderate flood events build the crevasse splay after this. To investigate how the flood regime affect crevasse growth, we would need to simulate different types of flood in terms of magnitude, recurrence and duration, which could possibly be achieved by using a historically accurate water level or discharge timeseries. How separate flood magnitudes affect crevasse growth is beyond the scope of this research, however.

5.3 Morphology

The crevasse splays seem to grow in length up to around 500 meters into the domain, after which the crevasse splay mostly builds out by increasing the area and height of its levees and terminal bar deposits (Figure 12, Figure S2). Translating this to the three-stage-model of crevasse growth, it seems that the model is quite able to form a stage 1 crevasse splay, of which the channel is then unable to attain more length and thus keeps expanding laterally (see Figure 1 for lateral accretion versus down the basin growth).

There are multiple possible explanations for this. Firstly, there is no floodplain slope present in the model. A floodplain slope would increase drainage and thus erosion (Hajek and Edmonds, 2014), enabling the channel to extent further into the floodplain. Additionally, a slope would likely have a strong influence on the shape of the crevasse, as it can determine the direction of the initially formed crevasse lobe (Toonen et al., 2016). After the lobe is filled, the splay may relocate to try to circumvent the obstruction of its own deposits, extending its channel further into the floodplain and causing more distal deposition. The splays modeled here were indeed unable to do this.

Another factor that may play a role, is the fact that only a single channel is present in this model. As crevasse splays progress in stage, they become more complex, having multiple channels and often consisting of several levee breaches that become connected, potentially increasing their total discharge and ability to prograde down the basin.

Furthermore, the effects of vegetation and subsidence are ignored. Both are expected to enhance channelization. Previous modeling has already showed that vegetation indeed influences channel pattern and the efficiency of sediment retention (Nienhuis et al., 2018), while subsidence leads to longer living splays with larger volumes. In natural splays it is also known that vegetation, subsidence and deposition interact and greatly influence crevasse formation. Cahoon et al. (2011) show that for a Mississippi crevasse splay, there are distinct sections in a splay with differential vegetation, flooding and sedimentation, making crevasse morphodynamics much more complicated and delicate.

Conclusively, we think that our modeling approach allows the formation of a stage 1 splay in a relatively realistic way, which already allows us to investigate and evaluate how drainage affects crevasse growth. To create more realistic morphologies also in further growth stages, it is likely required to add a floodplain slope, vegetation and subsidence and potentially additional breaches to the model.

5.4 Consequences for artificial sediment diversions

For future sediment diversion projects, the Dr parameter may assist as a predictor for determining the necessary conditions to restore a certain area of land. Increasing the area that is allowed to be flooded and decreasing flood duration will likely result in larger areas of new land for such projects. Besides this, by predefining the size of the breach (which is always the case in an artificial breach) the discharge through it can be manipulated, a factor that is also encompassed in Dr.

Retention rate is also considered vital in delta restoration projects (Paola et al., 2011). We saw that with increasing Dr the retention efficiency of the splay decreases, an effect which rapidly accelerates at $Dr > 1$. The sediment retention rates in this modeling study are still very high (> 80 %), which is expected for crevasse splays located in protected flood basins without the influence of waves and tides (Xu et al., 2016), although this ratio is highly dependent on the area of the region for which you are considering this number. So even though crevasse volume will increase with Dr, this may be an unwanted effect because sediment may be deposited too far away from the target area. Likely, the correct balance is thus a tradeoff between high incoming sediment volumes and retention efficiency.

6 Conclusion

In this research, we combined analysis of crevasse splays in the Rhine-Meuse- and Mississippi Deltas to modeling crevasse splays. Previous findings on the effect of floodplain drainage are confirmed in this research: large floodplains allow for larger crevasse splays to form, which we observed in both nature and model. This modeling set-up gives additional insight into the effect of drainage by also including the transient part of a flood. Modeling results have shown that besides floodplain size, also flood duration can have a significant influence on crevasse growth, a combined effect which we encompassed in the parameter Dr. Applying this parameter to natural splays shows promising results and allows for a first order comparison between nature and model. Lastly, this research may also aid delta restoration projects by providing additional understanding in the size limiting potential of the floodplain, affecting both crevasse volume and retention efficiency.

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Appendices

Table S1: all Rhine-Meuse data

Table with all RM data

Table S2: all Mississippi data

Table with all MS data

Table S3: mean, minimum and maximum values of the Rhine-Meuse data

Table with all the maximum values of RM delta

Table S4: regression statistics

Table with all the regression values of the minimum, maximum and mean crevasse per floodplain for the RM- delta crevasse properties that were measured. Formulas are given as:

$$y = y = Ax^B.$$

Table S5: Model parameters

Folder with all model parameters and boundary conditions

Table S6: Model results

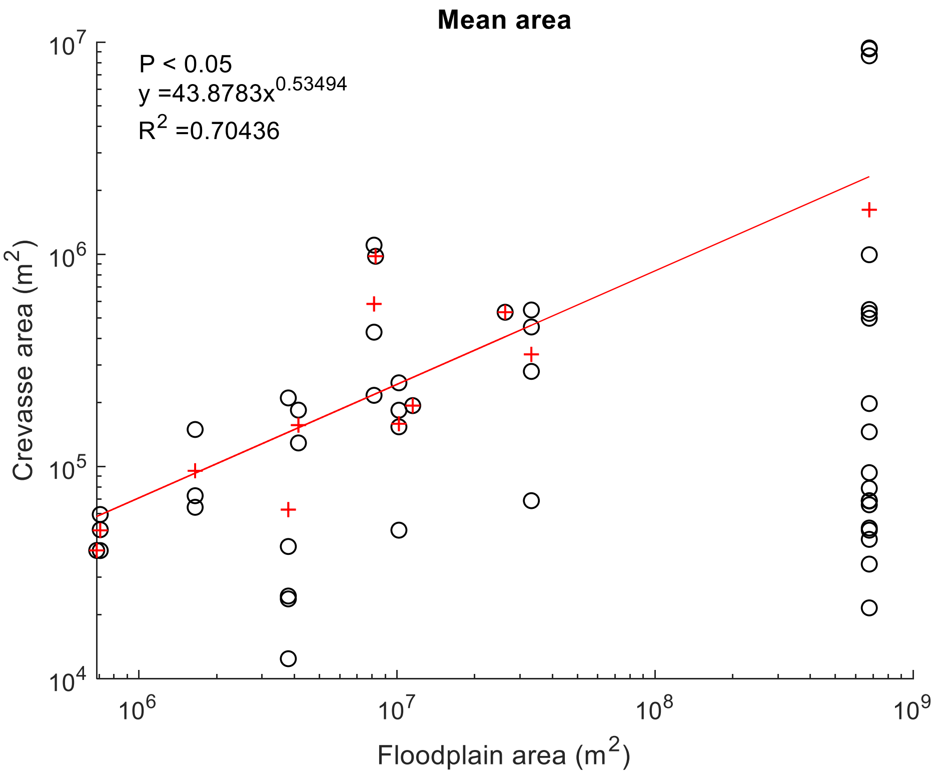
Table with all modeled outcomes

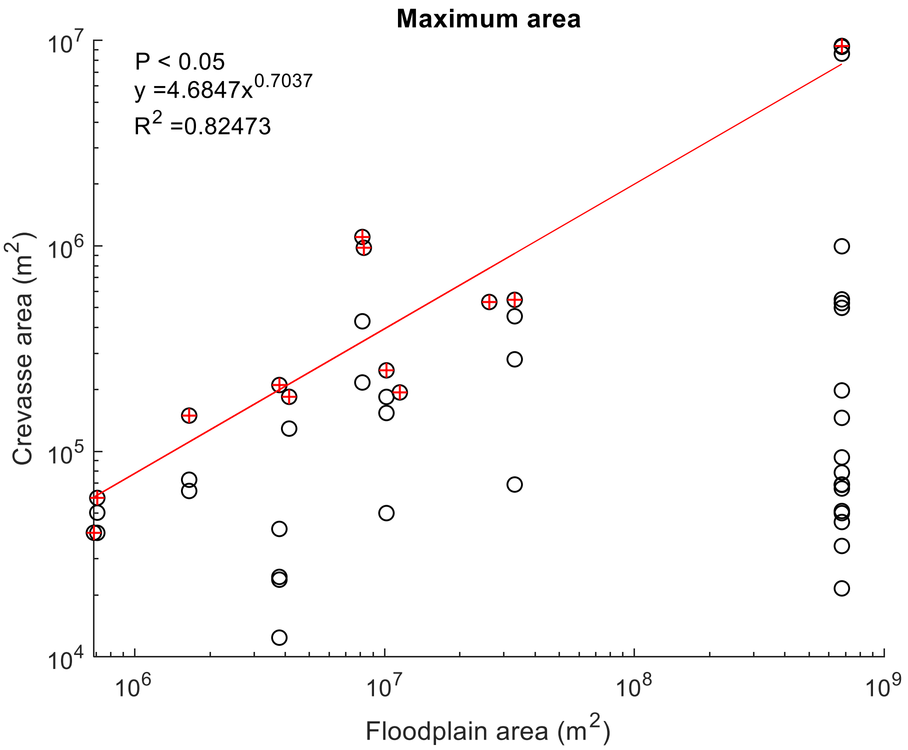
Table S7: Simulation of a Medieval flood

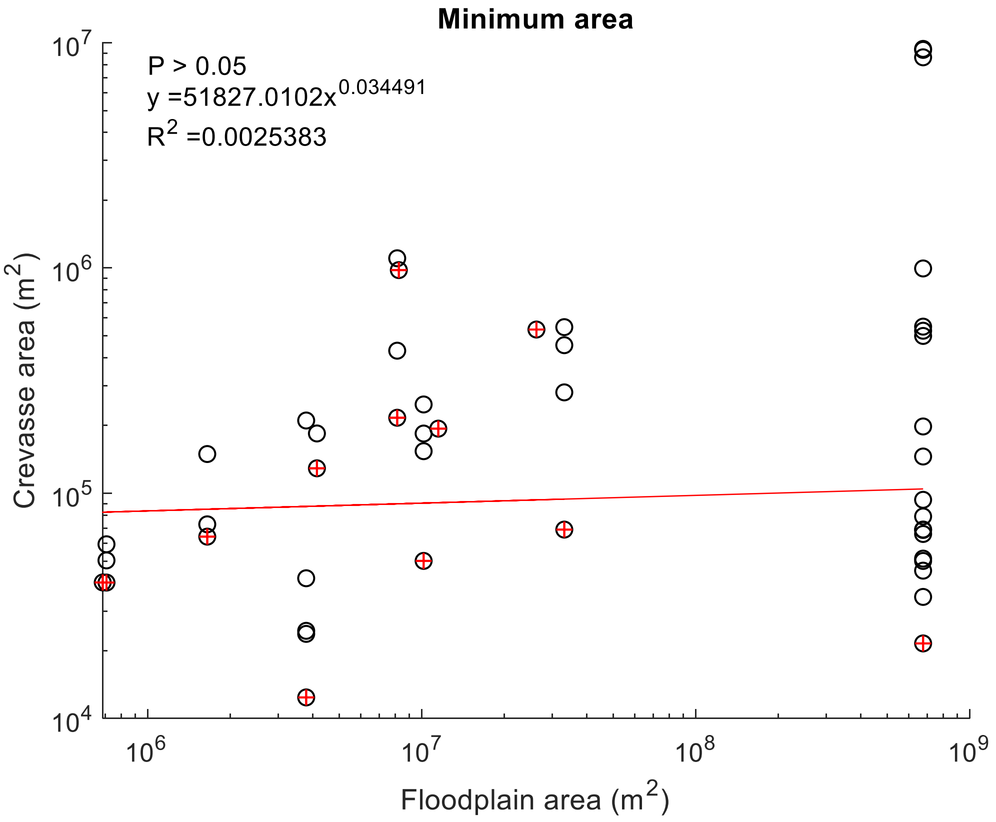
Model simulation by B. van der Meulen, (B. van der Meulen et al., in prep., 2020).

Figure S1

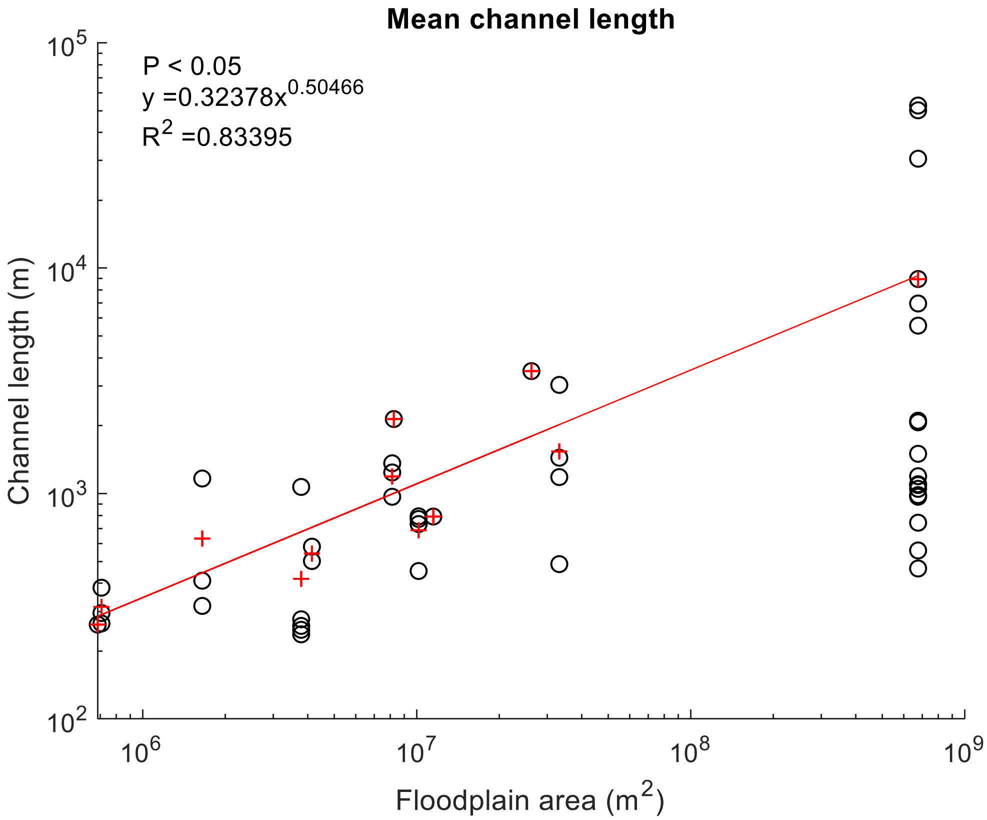
S1.1: Regressions for crevasse area


Mean area
P < 0.05
y =43.8783x^0.53494
R^2 =0.70436
Crevasse area (m^2)
Floodplain area (m^2)
10^4
10^5
10^6
10^7
10^6
10^7
10^8
10^9


Maximum area
P < 0.05
y =4.6847x^0.7037
R^2 =0.82473
Crevasse area (m^2)
Floodplain area (m^2)
10^4
10^5
10^6
10^7
10^6
10^7
10^8
10^9


Minimum area
P > 0.05
y =51827.0102x^0.034491
R^2 =0.0025383
Crevasse area (m^2)
10^7
10^6
10^5
10^4
10^6
10^7
10^8
10^9
Floodplain area (m^2)

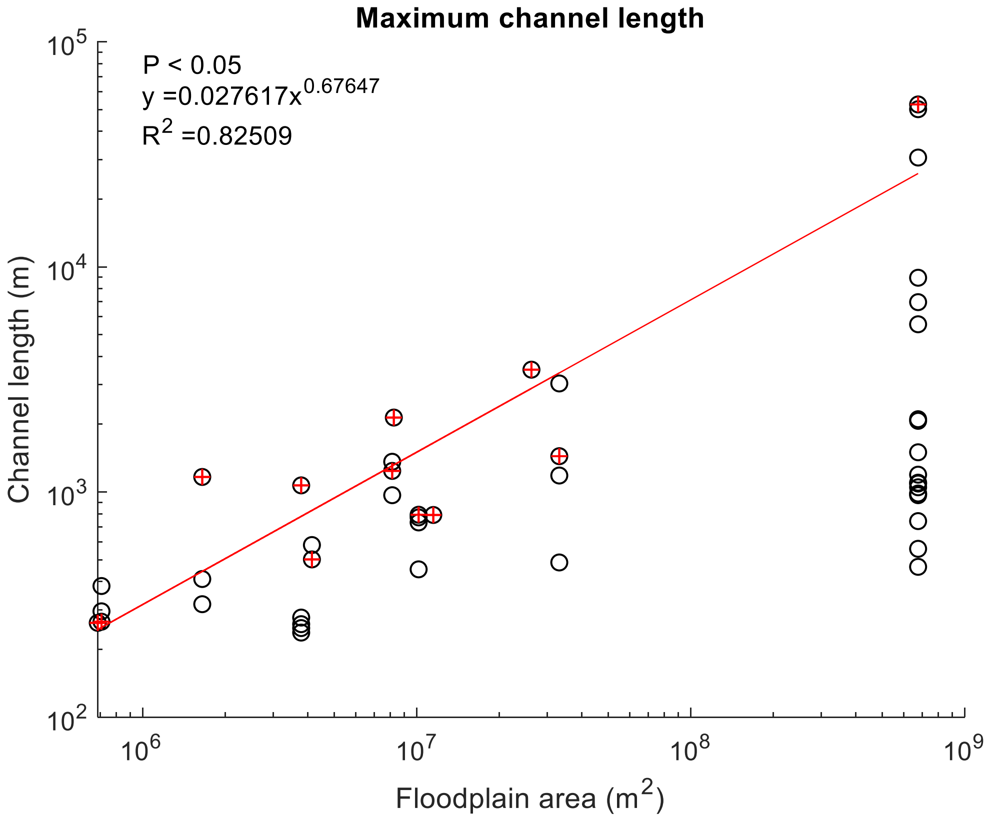
S1.2: Regressions for crevasse channel length


Mean channel length

P < 0.05

$y = 0.32378x^{0.50466}$

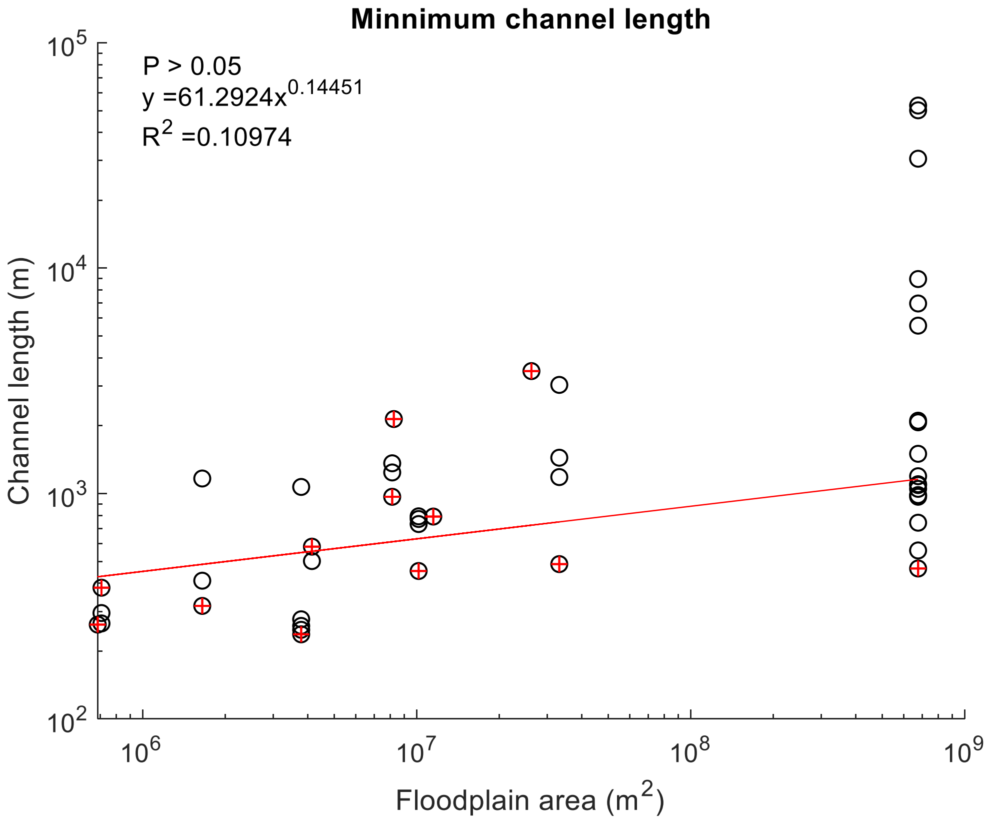
$R^2 = 0.83395$


Maximum channel length

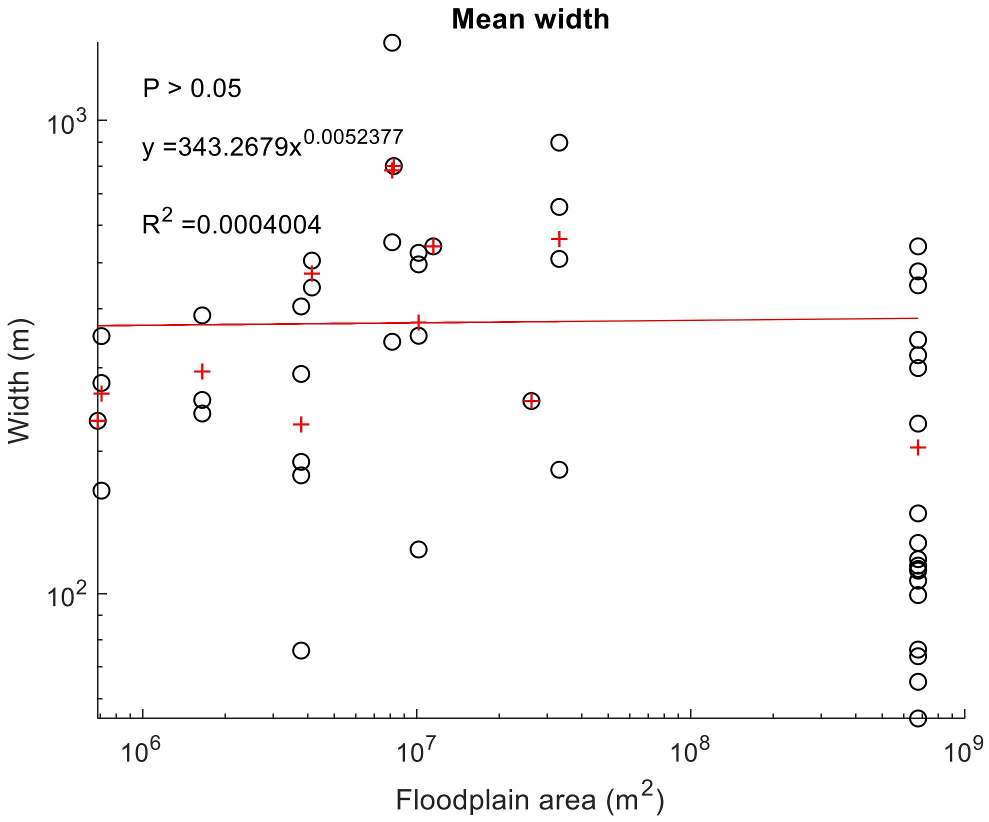
P < 0.05

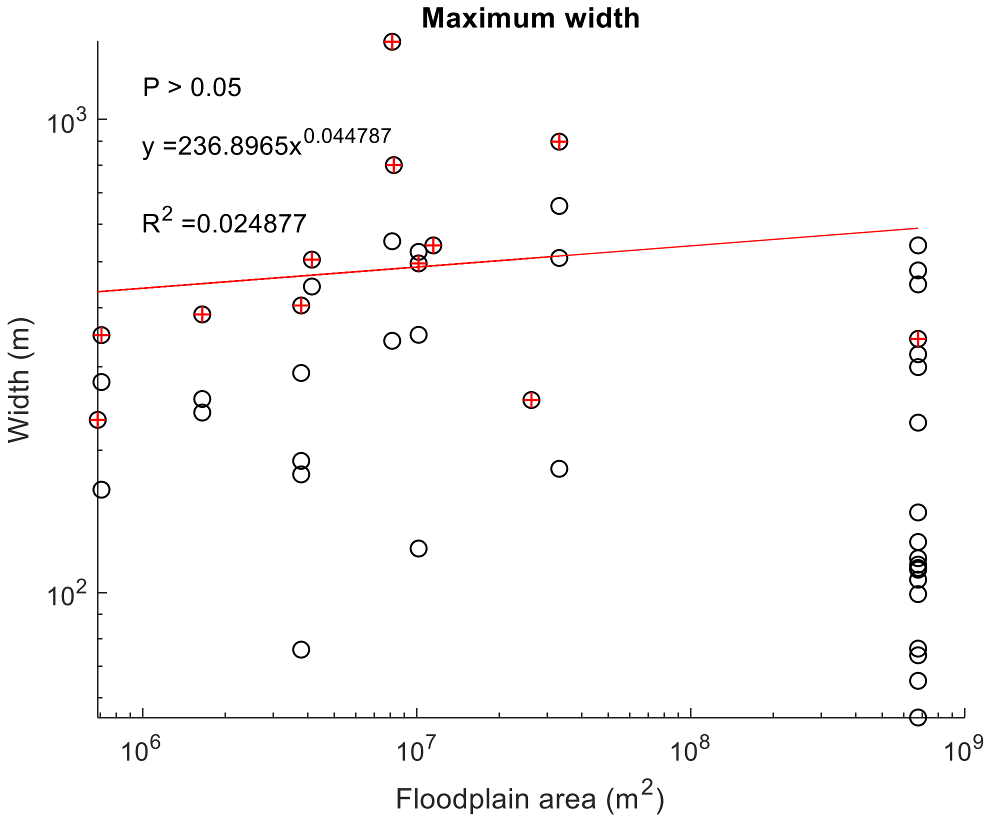
$y = 0.027617x^{0.67647}$

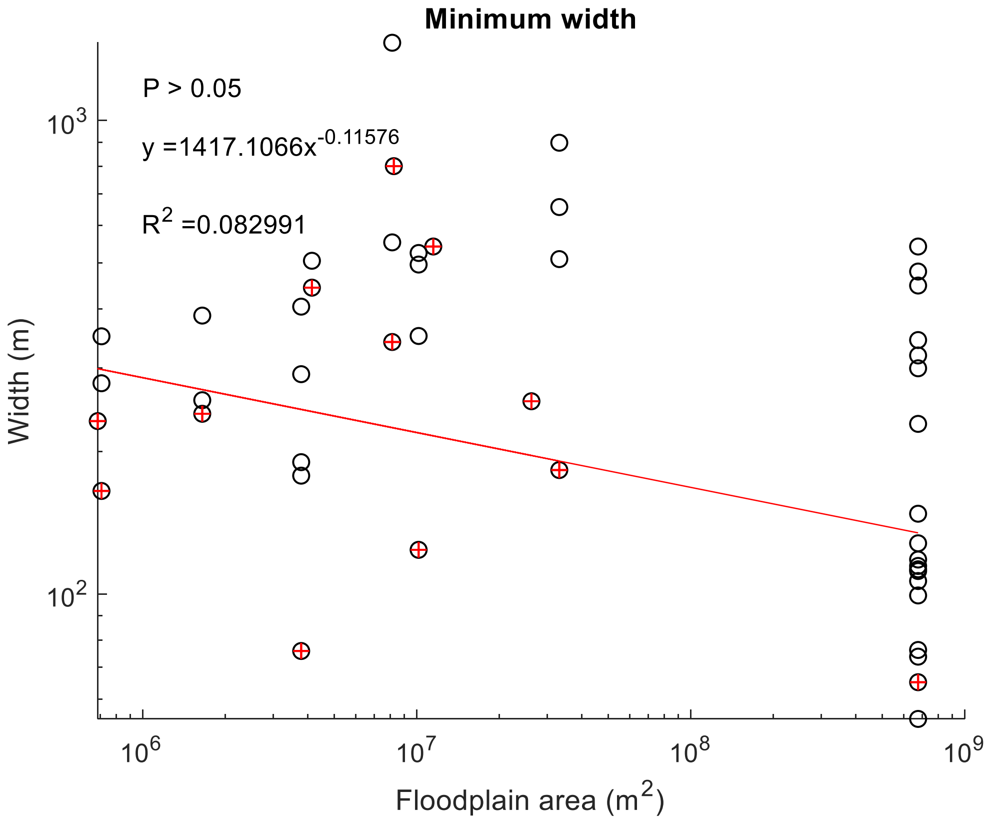
$R^2 = 0.82509$


Minnimum channel length
P > 0.05
y =61.2924x^0.14451
R^2 =0.10974
Channel length (m)
10^5
10^4
10^3
10^2
10^6
10^7
10^8
10^9
Floodplain area (m^2)

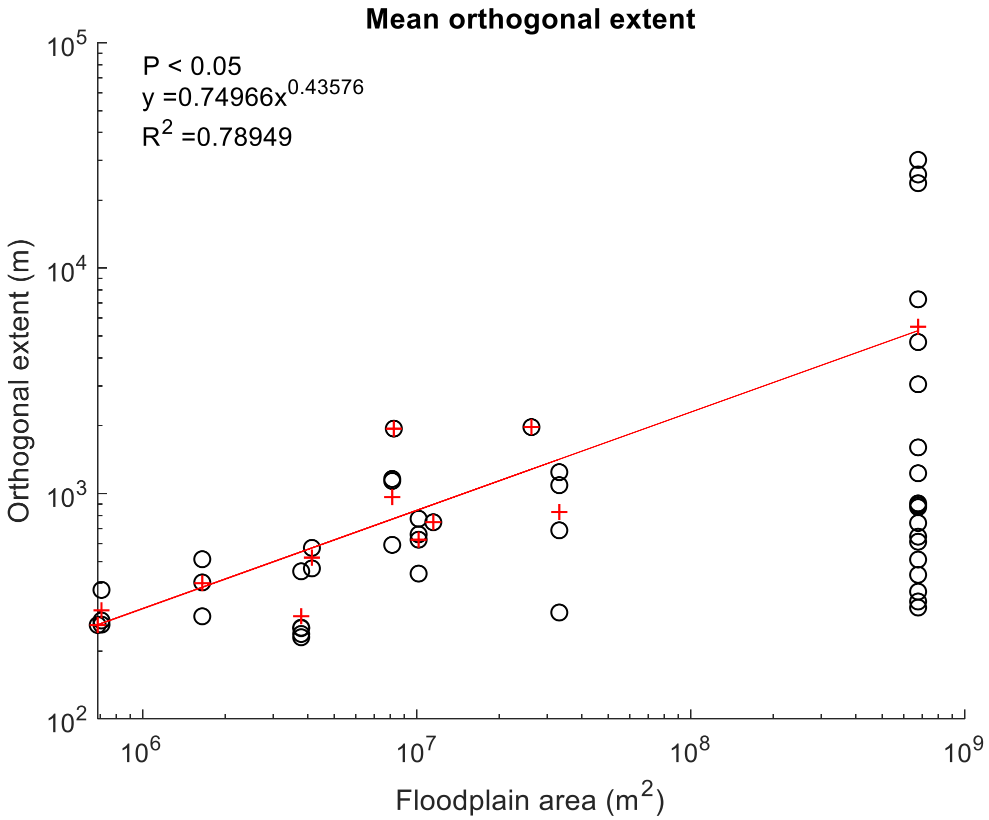
S1.3: Regressions for crevasse width


Mean width
P > 0.05
y =343.2679x^0.0052377
R^2 =0.0004004
Width (m)
10^3
10^2
10^6
10^7
10^8
10^9
Floodplain area (m^2)

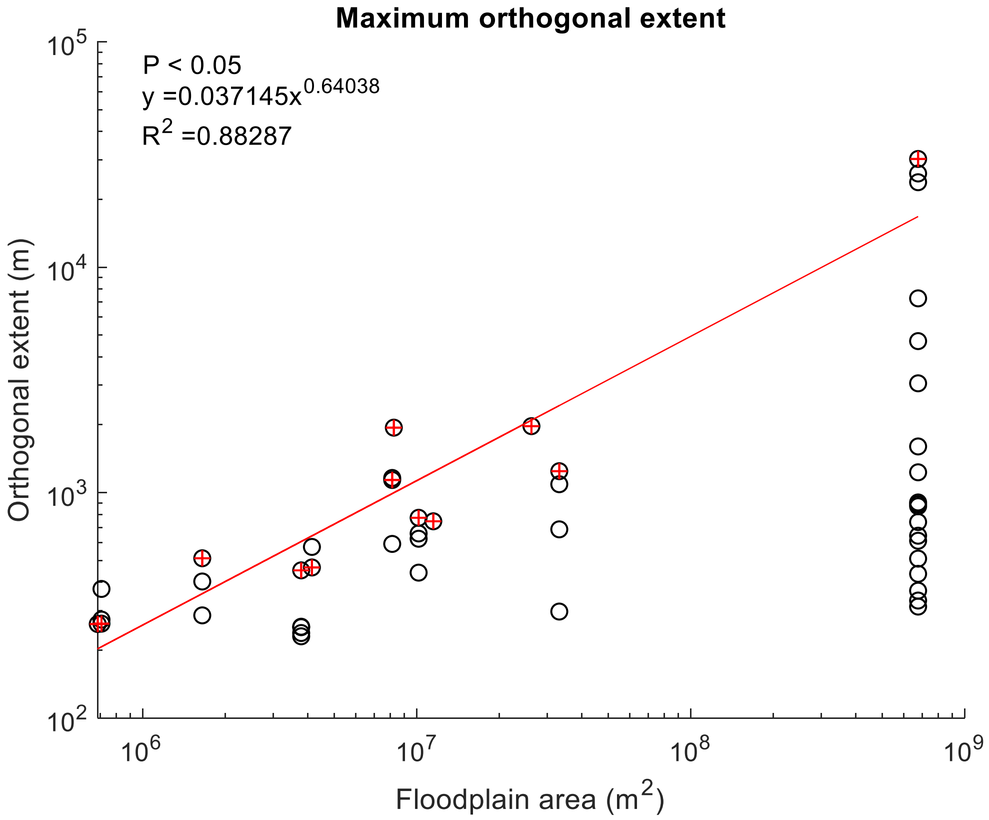

Maximum width
P > 0.05
y =236.8965x^0.044787
R^2 =0.024877
Width (m)
10^3
10^2
10^6
10^7
10^8
10^9
Floodplain area (m^2)


Minimum width
P > 0.05
y =1417.1066x^-0.11576
R^2 =0.082991
Width (m)
10^3
10^2
10^6
10^7
10^8
10^9
Floodplain area (m^2)

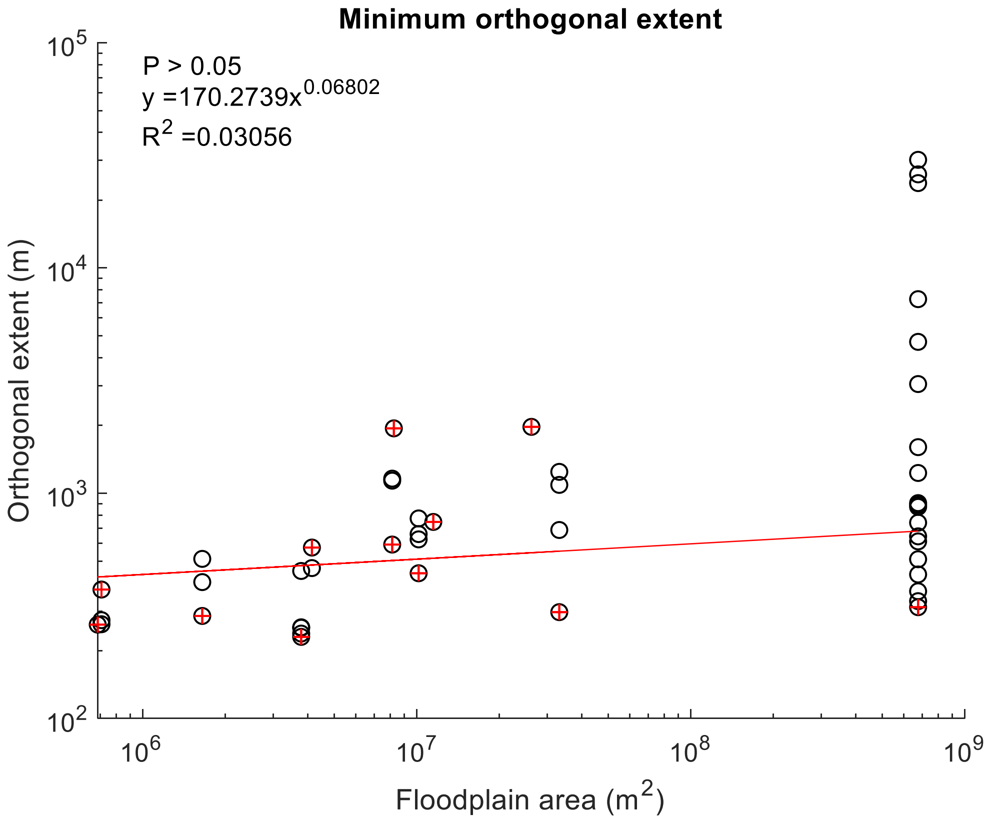
S1.4: Regressions for crevasse orthogonal extent



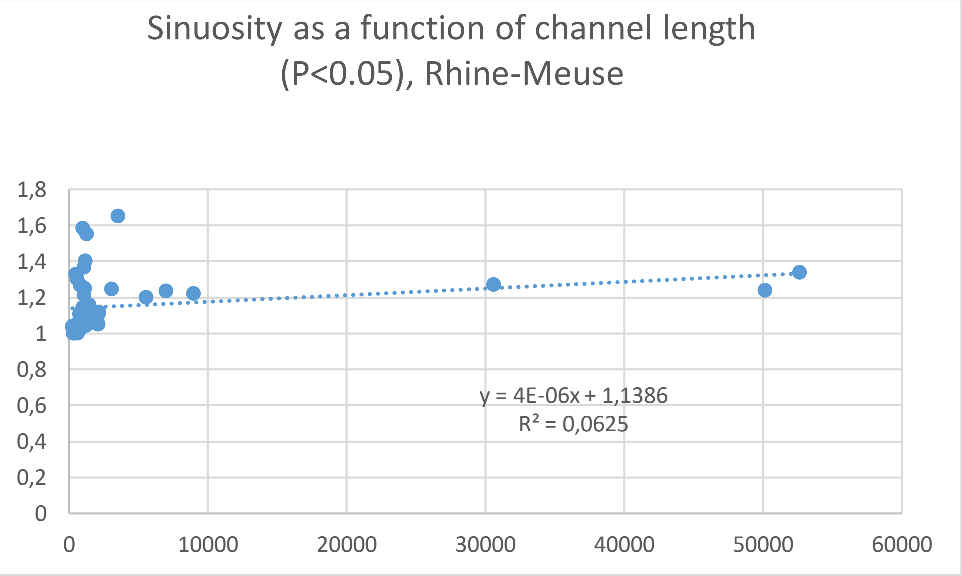
Mean orthogonal extent



Maximum orthogonal extent


Minimum orthogonal extent
P > 0.05
y =170.2739x^0.06802
R^2 =0.03056
Orthogonal extent (m)
10^5
10^4
10^3
10^2
10^6
10^7
10^8
10^9
Floodplain area (m^2)

S1.5: Sinuosity related to channel length for RM



S1.6: Sinuosity related to channel length for MRD

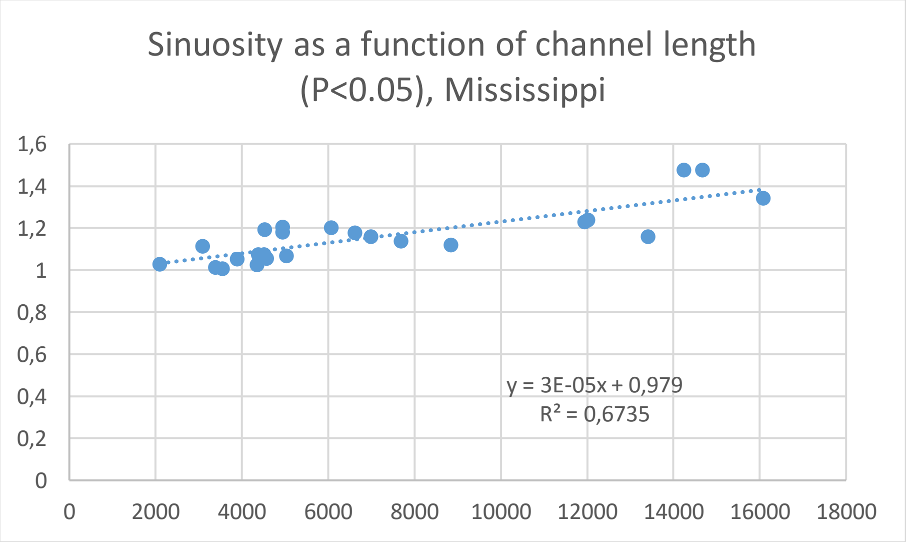


Figure S2: Morphologies for all 15 model runs at the end of the simulation