Floodplain and In-Channel Sedimentation in the Bedrock Congaree River, SC

Mahsa Ahmadpoor

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FLOODPLAIN AND IN-CHANNEL SEDIMENTATION IN THE BEDROCK CONGAREE RIVER, SC

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For the Degree of Doctor of Philosophy in

Civil Engineering

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2023

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DEDICATION

I would like to dedicate this thesis to all my beloved people in my life. Thank you so much for everything! Words can hardly describe my thanks and appreciation to you. You all have been my source of inspiration, support, and guidance. I am truly thankful and honored to call you “my people”. You all have been the spark for me when my light blew out. Thank you for your unwavering love and support along this journey I have taken. I love you always and forever.
ACKNOWLEDGEMENTS

Thanks to NSF for providing the funding to do this study. Also, I dearly Thank Dr. Gary Parker and Dr. Alessandra Crosato for all their productive comments and support and also William Lagan and Ryan Johnson for helping me in this study.
ABSTRACT

The Congaree River planform is characterized by an abrupt increase in channel sinuosity in the downstream direction. Such a change is not typical of alluvial meandering rivers but has been observed in mixed bedrock-alluvial rivers. This motivated the first study of this dissertation, specifically designed to determine if the Congaree River is indeed a mixed bedrock-alluvial river in its low sinuosity (upstream) reach. To test this hypothesis, sonar-based measurements of channel bed and sublayer elevation were performed from Columbia to the Congaree River-Wateree River confluence. The sublayer is here defined as the first surface visible in the sonar measurements underneath the bed surface. Field measurements revealed the presence of numerous sublayer exposures on the channel bed and pictures of the bed surface confirm that this sublayer correspond to Cretaceous deltaic deposits. These deposits are significantly less erodible than alluvium and can thus be considered a bedrock surface. Further, data reveal that 99.5% of the Congaree River is mixed bedrock-alluvial with a relatively thin (smaller than 4 m) alluvial cover of the shallow bedrock that decreases downstream and is preferentially exposed in high curvature bends. In other words, channel sinuosity is highest where the alluvial cover is thinnest, and the initial hypothesis had to be rejected. The second part of the dissertation is centered on the study of floodplain sedimentation in the downstream part of the Congaree River floodplain located in the Congaree National Park. The study was designed to test current floodplain sedimentation models based on the sharp distinction between channel bed material (sand) and floodplain material (wash load or mud). These models predict 1) high
sedimentation rates close to the main channel with an exponential decay toward the floodplain interior, and 2) coarse sediment (sand) trapping in levees close to the main channel with mud being deposited in the floodplain interior. Sedimentation rates measured with sediment tiles, grab samples and results of a previous study were used to characterize floodplain deposits in high and low relief areas, close to the Congaree River main channel and in the floodplain interior. High sedimentation rates and sand collected in the floodplain interior clearly show that traditional floodplain sedimentation models fail to describe sedimentation in wide, complex floodplains such as the Congaree River National Park, while capturing levee formation close to each channel. The analysis of relief maps and hydrodynamic modeling results of floodplain flow revealed that floodplain channels play a critical role in conveying water and sand far from the main channel during overbank and sub-bankfull inundation. Data shows that floodplain sedimentation rate has no relation with floodplain relief. Further, sand is preferentially found in high velocity areas connected to the main channel through floodplain channels. Finally, the comparison between sand from the Congaree River main channel and the floodplain reveals that floodplain material (mud) is a mixture of wash load and of bed material transported in suspension above the floodplain channel bottom.
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CHAPTER 1

INTRODUCTION

This dissertation is structured into two main studies presented in chapter 2 and 3, this introduction and a conclusion chapter with indication of research needs for the future. Each study addresses a fundamental problem of channel-floodplain morphodynamics: the presence of a shallow, hardily erodible layer controlling the morphodynamics of coastal plain rivers, and the quantification of floodplain sedimentation. Field work was conducted in the Congaree River and in the portion of the Congaree River floodplain located in the Congaree National Park, in the Southeastern coastal plain of the United States. The Congaree River is known to be a meandering sand bed river originating at the confluence of the Saluda River and the Broad River (approximately at the Gervais Street Bridge) in Columbia, SC. It flows approximately 85 kilometers to the southeast until it merges with the Wateree River.

The first study was motivated by the observation that the Congaree River main channel is characterized by a sharp increase in channel sinuosity at kilometer 45. Similar changes in sinuosity have been observed in mixed bedrock-alluvial rivers (Viparelli et al., 2015; Wohl, 2015; Turowski, 2018; Pizzuto et al., 2018), with bedrock reaches showing a smaller sinuosity than alluvial reaches. Based on these observations, on the presence of exposed bedrock in the Congaree River main channel in Columbia, and for the presence of 10 stable bluffs, along the river (marked with yellow dots in Figure 1.1), I hypothesized
that the Congaree River might have been a mixed bedrock-alluvial river upstream of kilometer 45, with distance measured from the Congaree River headwaters at the Gervais Street bridge (Figure 1.1). The high sinuosity downstream of kilometer 45 suggested that in this reach the Congaree River reach might be an alluvial, meandering, sand bed river. In other words, I hypothesized that a bedrock-alluvial transition was located approximately 45 kilometers downstream of the Congaree River headwaters.

The literature reveals a paucity of studies on the morphology and morphodynamics of not tidally influenced coastal plain rivers in Southeastern USA. These rivers are thought to be alluvial, meandering, sand bed rivers (Lauer and Parker, 2008a). Presence of shallow bedrock significantly alters fluvial processes, planform evolution, and river morphodynamics, underscoring the importance of determining whether a river falls within the category of mixed bedrock-alluvial or not. In other words, distinguishing between mixed bedrock and fully alluvial rivers holds direct relevance for river management and restoration, as indicated by, for example, studies of Nittrouer et al. (2011) and Viparelli et al. (2015) on the Mississippi River and by the exposure of fix layers in the incising Rhine River, Netherlands.

The above differentiation is critical because flow resistance, sediment transport, and morphological dynamics (such as dune and bar shape and migration) in mixed bedrock alluvial channels are significantly different than in alluvial rivers, (Chatanantavet & Parker, 2008; Zhang et al., 2015, Jafarinik et al., 2019, Papangelakis et al.; 2021). In addition, alluvial cover distribution and specific locations where the bedrock is exposed strongly control sediment transport and the alluvial morphodynamics of mixed bedrock alluvial reaches (Turowski, 2018; Papangelakis et al.; 2021). Hence, it is imperative to possess a
profound understanding of the dynamics and morphology of mixed bedrock-alluvial rivers for effective river engineering and management (Papangelakis et al., 2021).

To determine if a bedrock-alluvial transition was located around kilometer 45 of the Congaree River, I used an echo sounder sub-bottom profiler called StrataboxTM, along with high precision GPS measurements to determine the depth of various bed layers of the Congaree River channel (Bruckner, 2013; Zhang et al., 2013; Cossu et al., 2018; Heatherington et al., 2021; Jaijel et al., 2018; Syqest, 2006). The first bed layer corresponded to the bed surface, the second layer visible in the data indicated the presence of materials with characteristics that differ from the channel bed surface. The survey spanned 82 kilometers, starting at Rosewood Landing, approximately 3 kilometers downstream of the Congree River headwaters, to the confluence with the Wateree River. The data revealed that the first sublayer became exposed on the riverbed surface in more than 20 instances. These exposures were not necessarily observed in proximity of bluffs, where the bedrock outcrops in hydraulic right. Exposures were also found in far from the bluffs, particularly in regions characterized by high channel curvature. Surprisingly, the number of exposures was highest in the downstream, high sinuosity reach. To determine if the sublayer could be interpreted as bedrock, I collected pictures of the riverbed surface using a GoPro camera. These underwater images confirmed that the exposed sublayer closely resembled bluff outcrops, which are made of cretaceous coastal plain deposits, i.e. material much less erodible than loose sand that can thus be considered bedrock.

Field data were also used to construct longitudinal profiles of both the riverbed (first bed layer) and of the bedrock (second layer coinciding the with first layer at exposure sites) surfaces. The profiles allowed us to classify the surveyed reach of the Congaree River
as mixed bedrock-alluvial with thickness of alluvium (sand) decreasing downstream. As a result, the research hypothesis was rejected because the downstream highly sinuous reach presents more exposures and a thinner alluvial cover than the upstream, low sinuosity reach. Thus, an abrupt increase in sinuosity was not indicative of the presence of an alluvial-bedrock transition.

The comparison of the longitudinal profiles of the riverbed and of the bedrock surface with a georeferenced 1883 hydrographic survey and a longitudinal profile collected in 2018 indicated the presence of a relatively coarse sediment front made of sand and pea gravel (Logan, 2023 and Parker, 2023 for definition of pea gravel). The front was located approximately 12 kilometers downstream of the Congaree River headwater in 1883 and it traveled approximately 24 kilometers in 140 years, with a consequent reduction of alluvial cover in the upstream, less sinuous part or the study site. The presence of this coarse, downstream migrating sediment front clearly shows that the river is not in a state of equilibrium as it is indeed experiencing alluviation of the channel bed.

Floodplain deposition models, in general, predict deposition rates that are highest close to the main channel and that decay toward the floodplain interior (Parker et al., 1996). Suspended sand is expected to be deposited along the banks near the main channel, contributing to the formation of natural levees, while wash load (also known as mud) is transported in the floodplain interior. Wash load is generally defined as sediment finer than 62.5 or 75 microns that is found in large quantities in the upper part of the floodplain (Church, 2006). Field observations and recent modeling work, however, reveal that the problem is more complex for the presence of a network of channels and connected depressions that transport water, sediment, nutrients, and contaminants toward the
floodplain interior (Dietrich et al. 1999; Day et. al, 2008). In the third chapter of this dissertation I present a thorough field study of floodplain sedimentation conducted in the Congaree National Park, which is located in the floodplain of the highly sinuous reach of the Congaree River indicated with the blue circle in Figure 1.1.

Notable feature of the Congaree National Park floodplain is a dense network of channels that serve as primary conduits to transport of sediment and water to the floodplain interior (Xu et al., 2021, van der Steeg et al., 2023, Logan, 2023). Floodplain sedimentation was measured with annual surveys of 27 measurement sites where sediment tiles were installed between 2020 and 2022. In 2022, 16 grab samples were collected to further characterize the fractions of sand and mud in recent floodplain deposits. Additionally, I used previously published data (Kaase and Kupfer, 2016) to characterize floodplain sedimentation in the downstream part of the floodplain. Field data were used to test if sedimentation rates were highest and coarsest close to the Congaree River main channel and in high relief areas (natural levees), as expected according to current floodplain sedimentation models.

Analysis of floodplain sedimentation data integrated with relief maps and results of 2D hydrodynamic modeling of floodplain flow highlighted the critical role played by floodplain channels in transporting water and sand to the floodplain interior during periods of overbank and sub-bankfull inundation. Sedimentation rate in the floodplain was found to be highest in regions where flow velocity is low. These regions depend floodplain hydraulics and not on topographical relief, that is low relief areas do not necessarily correspond to low velocity areas. Additionally, sand tends to accumulate predominantly in high velocity zones that are hydraulically connected to the primary channel through
floodplain channels. Lastly, when comparing grain size distributions of sand sampled in the Congaree River main channel and in the floodplain, it becomes evident that deposits in the upper part of the floodplain contain a mixture of mud and suspended sand, roughly corresponding to the finest 50% of the Congaree main channel sand.

Figure 1.1 – The Congaree River and floodplain with location of bluffs and National Congaree Park.
CHAPTER 2

BEDROCK EXPOSURES IN THE COASTAL PLAIN, MEANDERING CONGAREE RIVER, SOUTH CAROLINA, USA

2.1 INTRODUCTION

Mixed bedrock-alluvial rivers have more than 5% of bedrock exposure on the channel bed and a relatively thin alluvial cover of the bedrock surface in one or more reaches (Howard, 1998; Jafarinik, 2019; Nittrouer et al., 2011; Sklar & Dietrich, 2004). Mixed bedrock-alluvial rivers can form, for example, when bedrock incision is followed by sedimentation on the bedrock surface (Inoue et al., 2014; M. S. Jafarinik, 2019; L. Zhang et al., 2015) and can be found both in uplands, where the bed material is relatively coarse (Chatanantavet et al., 2013; R. Hodge et al., 2016; R. A. Hodge et al., 2011; Inoue et al., 2014; Turowski et al., 2007, 2008; K. X. Whipple et al., 2000; K. X. Whipple & Tucker, 2002; L. Zhang et al., 2015, 2018), and in lowland areas, where the bed material is relatively fine (Nittrouer et al., 2011; Shaw et al., 2013).

Distinguishing between mixed bedrock and fully alluvial river has direct applications for river management and restoration (Nittrouer et al., 2011; Viparelli et al., 2015) as flow resistance, sediment transport and alluvial morphodynamics differ from that of fully alluvial rivers (Chatanantavet & Parker, 2008; Viparelli et al., 2015). For example, if sediment supply is less than sediment transport capacity, alluvial rivers reduce the sediment transport capacity by lowering bed slope with channel bed erosion. In mixed

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1 Manuscript in preparation for submission to Water Resources Research
bedrock-alluvial rivers, the erosion of alluvium results in a decrease of alluvial cover (increase of bedrock exposure), which limits sediment availability to the flow and thus the sediment transport capacity. Due to the increased bedrock exposure, tool availability for bedrock abrasion is also reduced (Gilbert, 1877; Howard, 1998; L. Sklar & Dietrich, 1998; L. S. Sklar & Dietrich, 2004; Turowski, 2018; Turowski et al., 2007, 2008). When sediment supply is greater than sediment transport capacity, on the contrary, alluvial rivers aggrade to increase bed slope and transport capacity. Mixed bedrock rivers increase transport capacity by increasing alluvial cover (reducing bedrock exposure) and tool availability for the abrasion of exposed bedrock (Shepherd, 1972; Hodge et al., 2016; Johnson, 2014; Nelson & Seminara, 2012; Turowski et al., 2008; Zhang et al., 2015).

Bend flow and bend evolution in mixed bedrock-alluvial rivers are also different than in alluvial reaches (Nelson & Seminara, 2012). In alluvial meandering rivers, bend evolution, flow field, bar formation and bar geometry are mainly controlled by channel curvature. In mixed bedrock-alluvial rivers the problem is more complex as sediment supply, bedrock exposure and channel curvature simultaneously control bend evolution and bend flow. As a result, bar shape and location of the high-velocity core in mixed bedrock-alluvial rivers and in alluvial rivers are different (Eke et al., 2014; Inoue et al., 2016; Nelson et al., 2014; Nelson & Seminara, 2011, 2012, Fernandez et al., 2019).

The different morphodynamic response of alluvial and mixed bedrock-alluvial rivers to unbalance between sediment supply and transport capacity, as well as the differences in bend flow and bend evolution, clearly indicates that morphodynamic evolution of a mixed bedrock-alluvial river may significantly differ from that of an alluvial river subject to the same hydrologic regime, base level change, sediment supply and grain
size. Hence, proper characterization of river reaches is critical for long-term management decisions (Sloff, 2010, Papangelakis et al., 2021). In this paper we present and interpret data characterizing bedrock exposures and alluvial cover on the Congaree River, a coastal plain, non-tidally influenced river in the Southeastern US.

The Congaree River flows in the upper coastal plain, which is mainly covered by quaternary alluvium (sand, clay and peat) overlying undifferentiated Cretaceous coastal plain deposits which include weathered clay (hard), cemented sandstone, sand-clay and sand with rock color ranging from white to purple to red (Shelly et al. 2004, Shelly and Meitzen, 2005; Shelley et al., 2012; Shelley & Cohen, 2007) (Figure 2.1). Cretaceous deposits outcrop in bluffs along the right bank (Shelly and Cohen, 2007). The analysis of 80 years of aerial photos shows that these bluffs are stable in time, i.e. channel migration rates close to the bluffs are close to zero (Logan, 2023).

2.1.1 Research hypothesis

The Congaree River originates at the confluence of the Saluda River with the Broad River in Columbia, South Carolina. It flows roughly 85 kilometers to the southeast to the confluence with the Wateree River, as shown in Figure 2.1, where bluffs are indicated with yellow dots. Distances in this manuscript are expressed in downchannel kilometers from the Congaree River headwaters (approximately located at the Gervais Street bridge in Columbia, SC). Channel bed material is a mixture of coarse sand and pea gravel with geometric mean diameter equal to 1.17 mm up to kilometer 40. In the remaining 45 km the channel bed material is well sorted sand with geometric mean size of 0.7 m (Logan, 2023).
The planform shape of the Congaree River varies downstream (Figure 2.1). A semi-straight reach of 5 km is followed by a ~40 km long reach with low sinuosity (reach-average equal to 1.5), and by a ~40 km long highly sinuous reach (reach average equal to 2.3) with large meander bends (Figure 2.1). As shown in Figure 2.1, the change in sinuosity occurs in a very short reach close to west boundary of the Congaree National Park. Such sudden change in river planform is not common in alluvial, sand bed, meandering rivers (Brice, 1973; Hickin & Nanson, 1984; Nanson & Hickin, 1986).

It can be argued that not all the bends of a meandering river evolve in the same way due, for example, different hydrologic regime, sediment supply and grain size, type of riparian vegetation, spatial distribution of floodplain sediments, presence of bluffs and terraces, and changes of channel bed composition (Hickin & Nanson, 1984; Nanson & Hickin, 1986). In other words, curvature and geometry of active meandering rivers vary in time, between reaches of the same river and from one river to the other and the spatial change in sinuosity observed on the Congaree River can be due to sediment transport, erosion and deposition processes typical of single thread, alluvial rivers. It should be noted, however, that in alluvial meandering rivers changes in bend characteristics and sinuosity tend to be gradual (Brice, 1973) and not abrupt, as in the case of the Congaree River (Figure 2.1).

A review of the literature on planform shape of single thread rivers suggests that abrupt changes in channel sinuosity can characterize mixed bedrock-alluvial rivers (see Viparelli et al., 2015; Wohl, 2015 and references therein). Examples of such rivers are the Yukon River in Alaska, the Yangtze River in China, and the downstream most portion of the Mississippi River in Louisiana (Hudson and Kesel, 2000; Wohl, 2015). Channel
sinuosity of the Yukon River, the Mississippi River and the Yangtze River abruptly increases from bedrock to alluvial zones (roughly from 1.22 to 1.76 in the Yukon River, from 1.48 to 1.69 in the Mississippi River and from 1.3 to 1.47 in the Yangtze River) with average values that are similar to those measured on the Congaree River.

Previous comparisons between bedrock and alluvial reaches suggest that it is reasonable to expect bedrock exposure in low sinuosity reaches and a fully alluvial bed in more sinuous reaches (e.g. Pizzuto et al., 2018). We thus hypothesize that the spatial change in sinuosity observed on the Congaree River is due to the presence of a shallow, hardily erodible layer (bedrock) that interacts with sand transport processes in the river channel. In other words, we hypothesize that the Congaree River is a mixed bedrock-alluvial river with a bedrock-alluvial transition located around kilometer 45. This transition separates the upstream, low sinuosity mixed bedrock-alluvial reach from the downstream, high sinuosity alluvial reach. This hypothesis is further reinforced by exposures of various types of bedrock at the Congaree River headwaters and in bluffs (Figure 2.1).

A recent analysis of 1883 hydrographic survey, aerial photos, LiDAR and field data further substantiate the hypothesis of a transition at kilometer 45 (Logan, 2023). Congaree River bankfull width and area, which generally increase in the flow direction in alluvial rivers (Leopold & Maddock, 1953), decrease downstream and remain relatively uniform downstream of kilometer 45. Further, 20-year average channel migration rate increases from 0.9 m/yr to 1.8 m/yr at kilometer 45, with higher migration rates in the highly sinuous reach (Logan, 2023 and Figure 2.1c). Exposed or shallow bedrock surfaces can reduce bank retreat rate and lateral accretion to very low values, as observed in the South River in Virginia (Pizzuto et al., 2018).
2.2 METHODS

To determine if the Congaree River upstream of kilometer 45 mixed bedrock-alluvial, we need to quantify bedrock exposure (Whipple, 2004). We thus measured elevation of the channel bed (top of the alluvium) and of the topmost sublayer in the Congaree River, as illustrated below.

2.2.1 Sublayer measurements using sub-bottom profiler

StrataBox™, an echo sounder acoustic sub-bottom profiler, was used to measure layers of different characteristics under the channel bed surface (Brook et al., 2018; Cossu et al., 2018; Davis et al., 2002; Falmouth, 2008; Heatherington et al., 2021; Holbrook & Schumm, 1999; Limin, 2017; Muter et al., 2019; Navy, 2012; Robinson, 2010; Shen et al., 2011; Z. Zhang et al., 2013). StrataBox™ uses reflected sound velocity to portray different sediment/rock layers underneath the riverbed and can be effectively used in shallow water bodies, such as rivers (Bates, 2011; Bruckner, 2013; Jaber et al., 2021; Jaijel et al., 2018; Limin, 2017; Z. Zhang et al., 2013). It was used, for example, to portray bed layers with high-resolution in the benthic area close to Australia (Cossu et al., 2018), and to identify and measure sand layer thickness in tidal settings (Heatherington et al., 2021). It was also operated in rivers to reconstruct geomorphological structures and distinguishing between substrate types (Jaijel et al., 2018; Purkis et al., 2019; Syqest, 2006). Ren et al. (2012) used StrataBox™ in the Yellow River showing that the instrument can operate in muddy water flows. Thus, this instrument should be able to operate at high flow when suspended sediment concentration may be relatively large (Ren et al., 2012) and the water depth is deep enough (more than 2.5 m) to collect reliable measurements and consistent data.
StrataBox™ is portable, with vertical resolution of 6 cm and its signal can travel up to 40 m under the riverbed surface. The instrument is composed of a cone that sends the signal through water to be reflected at riverbed layers and receive it back. This cone is controlled by a black box connected to a battery and a laptop computer with StrataBox™ software. The box shares the signal received by the cone with the StrataBox™ software, which is a tool to present and record the measured data, as well as to control cone signal frequency transmitted.

StrataBox™ does not have an embedded GPS to accurately locate measurements. It was thus connected to a Trimble R8, high-precision GPS receiver. GPS easting and northing (x,y) are used directly by StrataBox™ (Figure 2.2). GPS-based elevation measurements of the antenna (z) relative to North American Vertical Datum 1988 (meter) are stored in the GPS system and are used to determine the elevation of various layers in the channel bed, estimate slopes and thickness of the topmost sand layer during post-processing. The installation of StrataBox™ on the research boat and the various components of the instrumentation are presented in Figure 2.2. We designed the frame to hold StrataBox™ and GPS antenna. The structure was built to securely keep the cone inside the water and hold the GPS antenna above the cone while keeping the two instruments safely attached to a boat (Figure 2.2). We measured ~ 82 km of the Congaree River close to the centerline, from Rosewood boat landing (kilometer 3.8) in Columbia, SC, and to the river confluence with the Wateree River (kilometer 85). A total of 9 cross sections were also surveyed close to bluffs. Due to poor GPS reception close the west boundary of the National Congaree Park, there are two gaps (each gap length is 2.2 km) in our measurements.
2.2.2 Data analysis

Measured data were post-processed using SonarWiz, a software to identify and
digitize bed layers (Brook et al., 2018; Cossu et al., 2018; Falmouth, 2008; Heatherington et al., 2021; Shen et al., 2011). Post-processing was done in three steps. First, the riverbed surface was identified as the upper and strongest positive reflector indicating change from fluid to solid medium (Figure 2.3a). This layer is indicated with a red line in this study. Noise and multiple reflectors were then removed (Figure 2.3b). Multiple reflectors are signals parallel to the riverbed located at a distance from the cone equal to twice the distance between the riverbed and the cone. These reflectors form because signal energy is not sufficiently damped in shallow waters and bounces between water surface and riverbed few times to damp its energy.

Reflectors showing the presence of the topmost bed sublayer, i.e. the layer that is underneath the alluvial layer, were identified and classified in two classes. Class 1 reflectors were the most obvious signals showing a well-defined bed layer and were easy to detect (yellow line) (Figure 2.3c). Class 2 reflectors were less obvious than Class 1 reflectors (pink line) (Figure 2.3d). The result of this analysis is shown in Figure 2.3e. It is important to mention here that while the riverbed surface is easily detected in the entire reach, the sublayer is not captured in the entire reach due to limitations associated with shallow water operation of StrataBox™.

Alluvial cover thickness computation was done in SonarWiz software. This software computed the cover thickness by subtracting riverbed depth below the cone tip from the tracked sublayer depth, both measured by the sub-bottom profiler. Elevations of bed layer top were determined by correcting StrataBox™ measurements with GPS.
measurements using an in-house developed MATLAB script that combines bed layers
depth and cone position (northing, easting and elevation) stored in the GPS. Integrated data
are used to estimate bed surface and sublayer slopes.

2.2.3 Identification of exposed bedrock

To understand the origin of the first sublayer, we surveyed exposure locations and
took underwater pictures of the bed surface. To do so, we attached a GoPro camera with a
light to the bottom of an anchor to capture images from a boat and visually characterize the
riverbed where sub-bottom profiler showed exposure.

2.3 RESULTS

We surveyed the Congaree River from kilometer 3.8 (Rosewood boat landing) to
the confluence with the Wateree River in four trips. Data presentation and analysis is
organized as follows: results from the sub-bottom profiler are first presented. We then
describe the longitudinal profiles and the streamwise variations of alluvial cover and we
finally discuss the influence of channel planform on bedrock exposures.

2.3.1 Bedrock exposure and characteristics

In the post-processing phase, we identified the presence of a sublayer close to the
riverbed that outcrops on the riverbed surface in reaches with length ranging between few
meters and 500 m. To ground truth bottom profiler measurements and determine if the
sublayer corresponded to cretaceous, coastal plain deposits reported in geological maps of
the area (Shelly et al. 2004, Shelly and Meitzen, 2005; Shelly and Cohen, 2007), we took
pictures of the riverbed in seven locations. Figure 2.4a shows the Congaree River digital elevation model (DEM) with bluffs indicated by red markers, named B1 to B10 from upstream to downstream, and exposures by light blue markers. Nine bedrock exposures occur close to a bluff and 14 in areas where bedrock does not outcrop on the riverbanks. Most exposures in our study site occur in locations with high curvature, starting from upstream of the bend, at the opposite side of a bar and adjacent to high steep banks, which agrees with results of laboratory experiments (Fernandez et al., 2019, Papangelakis et al. 2021). In particular, bedrock outcrops on the channel bed surface upstream of all bluffs, where it remains for distances up to several hundred meters, as indicated in Table 2.1.

Pictures of bedrock exposures on the channel bed are named alphabetically in yellow and presented in panels c-e. Sand covered bed is shown for comparison in panel b. The pictures clearly show that a hard surface outcrops on the channel bed at exposure locations and that this surface is clearly different from the modern sand of Figure 2.4b. The hard surface is made of material similar to the cretaceous bedrock exposed in outcrops on the right bank of the Congaree River main channel, shown in Figure 2.4a. These images present exposed sublayer has a solid structure, similar texture and colors to the bluffs material. For example, the purple rock that outcrops in Bluff 3 is also visible in the subaqueous exposures at locations 2 and 4 (Figures 2.4c and 2.4e). The conglomerate found at location 3 is similar to the bedrock found at Bluff 1.

In Figure 2.5a, the DEM of Figure 2.4a is used to show different measurement locations. Examples of bedrock exposures (marked by yellow numbers in Figure 2.5a) in sub-bottom profiler measurements are presented in the inset of Figure 2.5a (for a cross section with flow direction inside the page) and in panels b, c and d for longitudinal sections
with arrows indicating flow direction. Typical feature of the Congaree River exposure in cross sections is the presence of alluvial sandbars in the inner bank, which limits the exposure location to the thalweg and the outer bank, as shown in Figure 2.5a. The presence of sand bar limiting bedrock exposure in bends was also observed in laboratory experiments by Fernandez et al., (2019).

A close look at the longitudinal sections further reveals that exposed bedrock found close to bluffs has a somewhat more irregular profile than bedrock exposed away from bluffs. As shown in Figure 2.4c to 2.4e bedrock elevation close to the bluff (Figure 2.5b and 2.5d for bluffs B2 and B10, respectively) can vary up to 5 m – 6 m in the exposure reach indicating possible erosion of the bedrock surface. The variability of bedrock surface elevation observed far from bluffs (Figure 2.5c) is on the order of 1 m or 2 m, which is comparable with the size of the dunes in the alluvial reaches, based on StrataBox™ measurements performed during floods.

The procedure to measure the bedrock surface irregularity, corresponding to the macroroughness height defined by Johnson (2014) and Zhang et al. (2015) and used herein to distinguish between alluvial and bedrock reaches, is presented in Figure 2.6 for the bedrock exposure at bluff B3, where the exposed bedrock surface is 4 m lower than the alluvial bed upstream.

2.3.2 Bedrock elevation profile and distribution of alluvial cover

Longitudinal profiles of riverbed surface (red) and sublayer elevation (blue) are presented in Figure 2.7 with moving average trend lines over 100 points to help identify reaches with different slope. In particular, we divided the study reach into three sub-reaches
differing in slope. The upstream most sub-reach ends at kilometer 34 and has an average slope of 0.14 m/km. Slopes of the central (kilometer 32 to kilometer 52) and of the downstream most sub-reaches are equal to 0.22 m/km and 0.15 m/km respectively. It should be noted that the slope of the bedrock and riverbed in each segment is quite similar (Figure 2.7a), as expected in a mixed bedrock-alluvial river (Viparelli et al., 2015). Similar streamwise changes in bed slope were identified by Logan (2023) with a break point analysis of a 2018 survey. In particular, Logan divided the Congaree River in 4 reaches: from the headwaters to kilometer 18.5 with slope of 0.12 m/km, between kilometers 18.5 and 41.7 the slope was 0.10 m/km, the reach between kilometer 41.7 and 54.1 was the steepest with slope equal to 0.18 m/km and the downstream reach had a slope of 0.19 m/km. The lack of data coverage between kilometer 32 and kilometer 42 did not allow us to perform a meaningful breakpoint analysis.

The longitudinal profiles confirm the presence of sublayer exposure close to bluffs (same elevation of bed surface and sublayer) and in other locations. Interestingly, the bed surface and the sublayer get closer in the downstream direction showing alluvial cover (elevation difference between bed surface and sublayer) decreasing downstream (Figure 2.7b & 2.7c). According to Howard (1998), reaches with more than 5% exposure are mixed bedrock-alluvial. In the Congaree River exposure length is 7.82 km corresponding to 9.2% of the river length. Thus, the Congaree River is a mixed bedrock-alluvial river.

To characterize the spatial distribution of alluvial cover, we first distinguished the alluvial from the mix bedrock-alluvial reaches and then classified the latter based on the thickness of alluvium. In an alluvial reach, the alluvial cover is larger than the minimum thickness of alluvium for the complete alluviation of the channel bed, $L_{ac}$ (Viparelli et al.,
L_{ac} is the sum of the macroroughness height characterizing the irregularities of the bedrock surface (see Figure 2.6) and of the equilibrium bedform height during floods in an alluvial river subject to the same hydrologic regime and sediment supply (see Figure 2.1 in Jafarinik & Viparelli, 2020). If the alluvial cover is smaller than L_{ac}, the bedrock surface is expected to interact with sediment transport and the river reach is classified as mixed bedrock-alluvial.

In the Congaree River, height of bedrock irregularities varies between 0 and 5 meters with largest values observed at the bluffs, as shown in Figures 2.5 and 2.6. We used StrataBox™ measurements to estimate reach-average macroroughness height to be 2.5 m and the equilibrium dune height to be 1.5 m, roughly equal to 1/3 of the bankfull depth. Thus, L_{ac} equals 4 meters. Only 0.5% in length of the Congaree River has an alluvial cover larger than L_{ac}, as shown in Figures 2.8a and 2.8b where red identifies alluvial sub-reaches, blue mixed bedrock-alluvial sub-reaches and magenta bedrock exposures, i.e. areas with alluvial cover smaller than 0.5 meters that are mainly located downstream of kilometer 45 (Figure 2.8b). Frequency distribution of alluvial cover is presented in Figure 2.8c with blue indicating the reach upstream of kilometer 45 and orange the reach downstream of kilometer 45. Figure 2.8c confirms that reaches with alluvial cover smaller than 2 m are more frequent in the downstream part of the study site.

2.3.3 Bedrock exposure and channel curvature

A close look at Figure 2.5 suggests that there may be a relation between exposure location and channel curvature. We thus computed channel curvature using three points with 100 meters distance along the entire river channel and plotted it against exposure
location in Figures 2.9. Figure 2.9 clearly shows that bedrock exposure mainly occurs in areas with high curvature corresponding to sharp bends, which is in agreement with the experimental observations by Fernandez et al. (2019). One exposure was also found in a low curvature location downstream of Highway 601 bridge (km 78). It is important to note, however, that there is not a unique relation between local curvature and exposure as exposure occurs in locations that have local high channel curvature; but there are sharp bends without bedrock exposure. This is in agreement with numerical results obtained by Inoue et al. (2014) showing that the most possible exposure location is in pools close to the outer bank of channel bends.

2.4 DISCUSSION

Based on previous studies describing planform configuration and geometry of single thread rivers (Inoue et al., 2016; Nelson et al., 2014; Nelson & Seminara, 2011, 2012; Nittrouer et al., 2011; Pizzuto et al., 2018; Turowski, 2018; Viparelli et al., 2015; Wohl, 2015), we hypothesized that a bedrock-alluvial transition was located at kilometer 45 of the Congaree River due to the abrupt streamwise increase in reach-averaged sinuosity and 20 year migration rate observed at that location.

The data presented above, however, show that this hypothesis cannot be accepted, as the Congaree River is a mixed bedrock-alluvial river from the headwaters to the Wateree River confluence with more exposures in the downstream highly sinuous reach and alluvial cover decreasing downstream. The streamwise decrease in alluvial cover may be representative of a disequilibrium state of the Congaree River main channel, as further discussed in the Conclusion chapter of this dissertation. The longitudinal profile of the
Congaree River channel reconstructed from a 1883 hydrographic survey (blue) (Logan, 2023) is plotted with measured elevation of the bedrock (yellow) and the present elevation of the channel bed surface (green) in Figure 2.10.

The long profiles of Figure 2.10 suggest in-channel deposition (reduction in bedrock exposure) in the past 140 years between kilometer 12 and kilometer 36, corresponding to the low sinuosity reach. River kilometer 36 roughly corresponds to the location downstream of which pea gravel, defined here as sediment with size between 1 mm and 5 mm (Parker et al., 2023), was not found on the channel bed and in bars (Logan, 2023) substantiating the hypothesis that there is a relatively coarse front migrating downstream in the Congaree River.

Reasons for the alluviation of the Congaree River main channel are unknown. They cannot be associated with human activities in the watershed as dam construction results in channel bed erosion and logging results in an increase in fine sediment supply, i.e. sediment not in the pea gravel range. We thus speculate that the Congaree River is still responding to changes in hydrology that occurred toward the end of the last glaciation, when erosion of the valley occurred in response to high discharges caused by an increase in precipitation, as indicated by the presence of the Pleistocene meander belt (17,000-14,000 years ago) in the downstream part of the floodplain (Shelley et al., 2007). The analysis of available sediment cores collected in the Santee River and Santee River delta represents an attempt to test this hypothesis to be pursued in the near future. It is important to note, however, that sea level during the last glaciation was more than 100 m lower than it is today, so that sediment eroded from the Congaree River meander belt might have bypassed the current shoreline and be deposited further downslope.
Figure 2.1 – The Congaree River planform and geometry: (a) Google Earth image of the Congaree River from the headwater (the Gervais Bridge) to the Congaree River - Wateree River confluence, Bluff locations are indicated with yellow dots. The river is divided in two reaches differing in sinuosity: the upstream 45 kilometers corresponds to the low sinuosity reach, and the downstream 40 kilometers are the high sinuosity reach. Landmark locations are indicated with orange stars, (b) Congaree River channel sinuosity, computed over a 6 km long reach, (c) Channel migration rate during four different 20-year periods.
Figure 2.2 – Measurement set up: (a) Schematic drawing (not to scale), (b) StrataBox™ cone position attached to the frame, (c) Instruments and connections during the measurement, (d) GPS mini-computer and StrataBox™ software controlling the data collection.
Figure 2.3 - Bed layer tracking process in SonarWiz: (a) Raw data and indication of the riverbed surface, (b) Identification of multiple reflectors, (c) Identification of strong sub-layer reflector, (d) Identification of weak sub-layer reflector, (e) Processed data
Figure 2.4- (a) Digital Elevation Model (DEM) of the Congaree River floodplain network from I-77 to its confluence with the Wateree River, with bluffs and sublayer exposure. (b) Picture taken from the alluvial bed section at close to I-77. (c) Picture taken form sublayer exposure on the river surface at B2, kilometer 23. (d) Picture taken from sublayer exposure on the river surface between B2 and B3, kilometer 31. (e) Picture of sublayer exposure on the river surface at B9, kilometer 76.
Figure 2.5 – (a) Digital Elevation Model (DEM) of the Congaree River floodplain network from I-77 to its confluence with the Wateree River, with bluffs and sublayer exposure and the inset shows a cross section measured at the exposure located at B2, kilometer 23. (b) Interpreted measurements of a bedrock exposure 1 at kilometer 23. (c) Interpreted measurements of a bedrock exposure 2 at kilometer 31. (d) Interpreted measurements of a bedrock exposure 3 at kilometer 84.5. Blue arrows denote flow direction.
Figure 2.6 - Longitudinal profile showing a deep cross section with bedrock exposure by bluff B3.
Figure 2.7 – Red and blue dots and 100 moving average lines respectively showing riverbed surface and sublayer of the Congaree River with bluff locations. (a) Entire river reach with riverbed and sublayer slopes respectively in red and blue. (b) Low sinuosity reach. (c) High sinuosity reach.
Figure 2.8 – Classification of alluvial cover along the Congaree River. (a) Alluvial and bedrock reaches upstream of kilometer 45. (b) Alluvial and bedrock reaches downstream of kilometer 45. (c) Frequency distribution of alluvial cover upstream (blue) and downstream (orange) of kilometer.
Figure 2.9 – Congaree River channel curvature in blue and exposure locations in pink.
Figure 2.10 – Longitudinal profile of the Congaree River, in 1883 (blue) and 2018 (grey), along with the sublayer profile (orange).
Table 2.1 – Bedrock exposure length close to bluffs in the Congaree River

<table>
<thead>
<tr>
<th>Bluff name</th>
<th>Exposure length close to bluff(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>7</td>
</tr>
<tr>
<td>B2</td>
<td>470</td>
</tr>
<tr>
<td>B3</td>
<td>340</td>
</tr>
<tr>
<td>B4</td>
<td>121</td>
</tr>
<tr>
<td>B5</td>
<td>246</td>
</tr>
<tr>
<td>B6</td>
<td>4</td>
</tr>
<tr>
<td>B7</td>
<td>75.8</td>
</tr>
<tr>
<td>B8</td>
<td>96</td>
</tr>
<tr>
<td>B9</td>
<td>175</td>
</tr>
<tr>
<td>B10</td>
<td>110</td>
</tr>
</tbody>
</table>
CHAPTER 3

OVERBANK AND SUB-BANKFULL SEDIMENTATION IN THE LOW SLOPING CONGAREE RIVER FLOODPLAIN, SOUTH CAROLINA, USA

3.1 INTRODUCTION

Modeling floodplain morphodynamics is challenging for the complex interactions between physical, biological, geochemical and ecological processes that simultaneously govern floodplain construction and deconstruction (Asselman, 1999; Day et al., 2008; Gautier et al., 2010). Floodplain sedimentation is traditionally described as occurring when river stage is higher than bankfull and water spills onto the floodplain (Dunne et al., 1998; Junhua et al., 2021; Lauer et al., 2016; Lauer & Parker, 2008b, 2008a; G. Parker et al., 2011; P. G. Parker, 1996; Swanson et al., 2008; Thayer & Ashmore, 2016; Viparelli et al., 2013). In these conditions, a mixture of fine sand and mud is transported from the channel to the floodplain, where highest deposition rates are expected near the channel banks and lowest deposition rates in the floodplain interior (Hubbard & Striffler, 1973; Lauer & Parker, 2008b; Whiting et al., 2005). Deposition models further predict sedimentation of coarse sediment on the main channel banks and sedimentation of fine material in the floodplain interior (Lauer & Parker, 2008b). Near-channel deposition of relatively coarse sediment results in the formation of natural levees (Ali & Roy, 2018; Arboleda et al., 2010; Franklin et al., 2009; J. a Kupfer & Meitzen, 2012). The decline in sediment deposition

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2 Manuscript in preparation for submission to the Journal of Geophysical Research – Earth Surface
rate toward the floodplain interior is often modeled with an exponential decay function of
distance from the main channel (see e.g. Parker et al., 1996).

Recent studies, however, demonstrate that floodplain sedimentation is not as
simple, because coarse material can also be found in the floodplain interior far from the
main channel (Aalto et al., 2008; Day et al., 2008; Swanson et al., 2008). Research
conducted in the Fly River and Strickland River floodplains in Papua New Guinea (Day et
al., 2008; Swanson et al., 2008) revealed that the relatively coarse sediment found far from
the main channel was generally not too far from a floodplain channel. Floodplain channels
are small, self-formed channels with width on the order of 10% of the main channel width
(Dietrich et al., 1999) that are responsible for floodplain inundation when the discharge in
the main channel is lower than bankfull (Blake and Ollier, 1971; Dietrich et al., 1999).
During floods, floodplain channels transport sediment from the main channel to floodplain
interior, where suspended sediment may overflow the floodplain channel banks and
contribute to the formation of natural levees in the floodplain interior (Day et al., 2008).

These studies notwithstanding, quantitative data on sedimentation rate and spatial
variability of sediment grain size an alluvial floodplain are scarce. Understanding how
sediment travels from the main channel to the floodplain and vice versa is fundamental to
formulate quantitative relations constraining sediment budgets at watershed scale (Beck et
al., 2019), sediment fluxes and sedimentation rates, and to incorporate these relations in
models describing transport of tracers, nutrients and contaminants, floodplain morphology
and ecology (Alcantara, 2014; Gautier et al., 2009, 2010; J. a Kupfer & Meitzen, 2012;
Here we present results of a study specially designed to measure floodplain sedimentation rates and spatial variability of sediment grain size in floodplain deposits and answer the following research questions: a) Is there any relation between floodplain elevation and relief, and the characteristics of the deposited sediment? b) Is there a relation between deposit characteristics and distance from the network of floodplain channels and connected depressions?

To answer these questions, we measured sedimentation rates and grain size distributions in the Congaree National Park with sediment tiles and grab samples (Reid & Dunne, 2005). This, integrated with the results of a previous study by Kaase and Kupfer (2016), allowed us to quantify spatial distribution of sedimentation rates and grain sizes across the floodplain. We then integrated the analysis of floodplain sedimentation data with maps of floodplain relief and channel network (Xu et al., 2020), and results of detailed hydrodynamic modeling (van der Steeg et al., 2023) to identify preferential areas of sand and mud deposition.

This paper is organized as follows: an overview of the study area highlighting its geographic and environmental characteristics is first presented. We then describe methods for data collection, measurement, and analysis of sediment samples. Results are presented in terms of spatial distribution of sedimentation rates and sand content and how they relate to the floodplain topography and distance from the floodplain channel network. Sediment transport capacity on the floodplain during sub-bankfull and overbank inundation and the origin of the floodplain sands are then discussed, and the main findings of this work are summarized in the conclusion section.
Methods and results of this study are readily applicable to characterize the movement of particles other than sediments, such as nutrients and contaminants, across floodplains (Beck et al., 2019; Loos & Shader, 2016) with implications for floodplain restoration and the well-being of local ecosystem (Natale et al., 2022). Outcomes of this study can thus be of aid to improve decision-making related to the management of civil engineering infrastructures, such as roads, railroads, and levees that interfere with floodplain flow and sedimentation for long distances (Kaase & Kupfer, 2016).

3.2 FIELD SITE DESCRIPTION

The study site is the portion of the Congaree River floodplain located in the Congaree National Park, South Carolina, in the coastal plain of Southeastern United States. The digital elevation model (DEM) of the part of the Congaree River floodplain used for hydrodynamic modeling by van der Steeg et al. (2023) is presented in Figure 3.1 and was used to obtain the relief maps used in this study. Rivers in Southeastern USA have, in general, meandering patterns, sand beds, and broad, low-gradient floodplains (Hupp, 2000; Hupp et al., 2008). These floodplains are naturally covered with a combination of forests in high elevation areas and swamps in low elevation areas (Hupp et al., 2008; Wharton et al., 1982). A significant amount of sediment and nutrients is generally trapped in these floodplains which act as sinks of main channel sediment (Hupp et al., 2008).

The Congaree River is a single thread meandering river. It experienced flow regulation with the closure of the Saluda dam in 1930 and received higher than natural sediment supply rates due to timber harvesting since 1700s (Johnson & Adams, 2009). In the park area, the Congaree River is relatively mobile with a 20-year average migration
rate between 1883 and 2010 equal to 1.8 m/yr and has a reach averaged channel sinuosity of 1.7 (Logan, 2023; Xu et al., 2021). Top channel width varies between 80 m and 160 m, and the longitudinal bed slope is $1.5 \times 10^{-4}$ (Xu et al., 2021). Grab samples obtained from the main channel of the Congaree River, within the park boundaries, indicate that the riverbed primarily consists of sand, with an average sand size of 0.7 mm (Logan, 2023).

The Congaree River and Wateree River delimit the study area to the south and to the east, respectively. The portion of the Congaree River in the Congaree National Park is 42 km long and flows through a dense natural forest. The floodplain area is 93 km$^2$ and contains five tributaries, the most important of which are Cedar Creek and Toms Creek. This floodplain is characterized by the presence of a network of channels and connected depressions, that is presented in Figure 3.1 (Kupfer et al., 2015; Xu et al., 2021). Natural levees (high elevation areas) are mainly located in the upstream part of the study site with lateral extent varying from 13 to 1000 meters. Low-elevation areas (swamps) are in East and North-East portions of the park (Xu et al., 2020, 2021).

Floodplain inundation in the Congaree National Park is mainly controlled by main channel hydraulics (Xu et al., 2021). Flooding in portions of the Congaree River floodplain occurs at discharges smaller than bankfull through floodplain channels transporting water and sediment to the floodplain interior (sub-bankfull inundation) (Kaase and Kupfer, 2016; Xu et al., 2021). When the main channel discharge is higher than bankfull, flooding is also associated with overbank flow (overbank inundation) (van der Steeg et al., 2023; Xu et al., 2021) and the inundated area increases with main river discharge and flood duration (Kaase & Kupfer, 2016; Xu et al, 2021). Overbank flows occur when the stage at the USGS station Congaree River at Congaree NP Near Gadsden SC (02169625) is equal to 32.58 m or
higher and sub-bankfull starts at Gadsden stage equal to 29 m (Xu et al., 2021; van der Steeg et. al, 2023).

Kaase & Kupfer (2016) classified flood frequency in the Congaree National Park in 3 classes using flow discharges measurements at the USGS station in Columbia (Congaree River at Columbia, SC – 02169500). Areas flooded when discharge is between 150 m$^3$/s to 320 m$^3$/s were classified as high flood frequency and covered 35% to 38% of the National Park. High flood frequency areas are mostly located in the downstream part of the park, where relief is lowest. Intermediate flood frequency areas are flooded when the discharge is between 400 m$^3$/s to 850 m$^3$/s and the sum of the areas inundated with high and intermediate frequency corresponds to 40% to 85% of the National Park. These areas are located in the central part of the floodplain. Low flood frequency areas are found in the upstream part of the floodplain, where the Congaree River main channel levee is highest and widest. Low flood frequency areas are flooded when discharge at Columbia is above 1660 m$^3$/s (Kupfer et al., 2015; Kaase & Kupfer, 2016). According to Kupfer et. al (2015), the discharge corresponding to complete inundation of the national park is 850 m$^3$/s that is when 95% of floodplain is hydrologically connected to the main channel.

Hydrodynamic modeling results presented in Figure 4e and Figure 5c of van der Steeg et al. (2023) are considered to be representative of floodplain flows in the Congaree National Park during sub-bankfull and overbank inundation respectively. Van der Steeg et al. (2023) showed that in the Congaree National Park flow velocity in floodplain interior is higher than close to the main channel and that this flow is partially contributed from the Congaree River floodplain upstream of the park. In the park, floodplain channels act as
vessels connecting the main channel to the floodplain interior and controlling inundation pattern with their orientation (van der Steeg et al., 2023).

Kaase & Kupfer (2016) measured sedimentation rates and volume fraction contents of sand with feldspar plates installed in the downstream part of the Congaree National Park, indicated with dark red box in Figure 3.1. Measurements were performed for two years, and the average annual sedimentation rate was estimated to be between 0.05 cm/yr and 7.8 cm/yr. Kupfer & Kaase (2016) data were collected from August 2012 to July 2014, which was a relatively wet period with several storms events and are used to complement the data collected in this study.

3.3 METHODS

Annual sedimentation rates and grain size distribution of floodplain deposits were measured with twenty-seven 30 cm × 30 cm sediment tiles installed in the Congaree National Park since 2019. Figure 3.2a presents tile locations across the floodplain on a relief map obtained from the DEM of Figure 3.1. Tile location was chosen considering that sediment samples should be collected 1) in high and low relief areas (Figure 3.2a), 2) close to main channel, floodplain channels and in the floodplain interior (Figure 3.2b), 3) in areas that are easily accessible, and 4) in areas that did not overlap with Kupfer & Kaase (2016) study site. Tiles are named based on the geographic name of the location where they were installed. Names of tiles that are adjacent to the Congaree River main channel start with the word River followed by the number of the cross section, which increases upstream, and letters indicating the bank side (LB: hydraulic left bank and RB: hydraulic right bank). For example, River2-LB indicates a tile located near the main channel in cross section 2 on the
left bank. Names of tiles installed in floodplain interior are obtained with the combination of FP and the location name. If more than one tile was installed in a location, for example close to triangles of water level sensors used to determine flow directions (van der Steeg et al., 2021), a number indicating installation order follows the location name. For example, the first tile installed at French Pond (Figure 3.2a) is called FP-FrenchPond-1.

Five locations were selected close to the main channel (River1 to River 5 with tile installation in 2019), where tiles were installed on both banks to observe any sedimentation difference between inner and outer bank. Five locations were selected in the floodplain interior to monitor sedimentation in low-relief areas (FP-Rail, FP-French pond, FP-West - all installed 2021) and close to floodplain channels (FP-Secondary channel, FP-River - all installed 2021), as shown in Figures 3.2c and 3.2d. To increase recovery rate and to protect tiles from wildlife curiosity, tiles have been installed adjacent to a marked stick since 2021 (Figure 3.2a). The recovery rate of tiles installed with no marked stick was 80% on the main channel banks and dropped to 33% in the floodplain interior. The recovery rate increased to 100% when the marked stick was used.

Tiles were recovered annually, mainly in late summer/early fall when river stage was low, floodplain was mostly dry and floodplain sedimentation was limited to the occurrence of few tropical storms. For each recovered tile we measured the thickness of deposited sediment in the field. Sediment was then scraped off the tiles and stored in plastic bags, and the tile was re-installed in place (pictures in Figure 3.2a). Sedimentation rate at each sampling location was measured using the thickness of the sediment deposited on the tile divided by the number of days the tile had been installed.
Each sediment sample was dried in the oven for at least 24 hours. Sediment was described in terms of two grain size classes separated by the #200 sieve, sand (sediment coarser than 0.075 mm) and mud (sediment finer than 0.075 mm) (An et al., 2022). Mud grain size distribution was measured with standard hydrometer tests, for samples larger than 20 gr, otherwise with a Coulter Counter MS4. In the continuing of this chapter, we use the geometric mean diameter of sand $D_{g,sand}$ and mud $D_{g,mud}$ to characterize sediment found in floodplain deposits.

To further characterize the spatial distribution of sediment sizes in floodplain deposits, 16 grab samples were collected in 2022 close to the upper border of the park, in areas characterized by mainly low or moderate relief. We chose sampling locations that are mainly located in highly channelized areas that experience high flow velocity during overbank inundation (van der Steeg et al, 2023), presented in Figure 3.2 with pink dots. Grab samples were collected close to park trails (~5 m inside the floodplain, away from the trail). The thickness of each sample was 3 cm, which is close to the max annual sedimentation rate estimated with sediment tiles. Sediment was brought to the lab and the grain size distribution was measured with the same procedure used for tile samples.

3.4 RESULTS

Sedimentation data from tile recoveries and grab samples are presented in Tables 3.1-3.3. Table 3.1 displays the sedimentation rate at each site. In this table, "0" signifies that the tile was located but contained no stored sample, while "-" indicates that either the tile was not found or had not been installed during that time frame. Tables 3.2 and 3.3 provide information on the grain size characteristics ($D_{g,sand}$, $D_{g,mud}$, and volume fraction
content of sand) of samples recovered from tiles and grab samples, respectively. Sampling locations are categorized based on the floodplain relief map (Figure 3.2a) into three distinct categories: 1) low relief (LR), characterized by relief heights between -4.3 m and -0.39 m, 2) medium relief (MR), where the relief falls between -0.39 m and 0.4 m, 3) high relief (HR), representing areas with relief heights ranging from 0.4 m to 10.3 m.

3.4.1 Sedimentation rates and correlation with water discharge in the main channel

Table 3.1 provides data on sedimentation rates measured in the years 2020, 2021, and 2022, which exhibited variations between 0 to 15 cm/yr. Sedimentation rates in certain locations (River3-RB) remained consistent across different years, while in other areas (River1-LB) varied from one year to the next. Floodplain averaged sedimentation rates in 2020, 2021, and 2022 were 2.91 cm/yr, 2.19 cm/yr, and 0.65 cm/yr, respectively. The higher rate in 2020 is attributed to the fact that 2020 was a wetter year compared to 2021 and 2022, as shown by the discharge data at the USGS station Congaree River at Columbia (02169500) in Figure 3.3.

Each panel of Figure 3.3 corresponds to the time interval between tile installation and recovery or between two sequential recovery periods. Green lines represent a discharge at Columbia equal to 235 m$^3$/s, which is the threshold discharge for the onset of sub-bankfull inundation in the national park (Kupfer et al., 2015). Red lines in Figure 3.3, indicate a discharge of 850 m$^3$/s corresponding to the threshold for overbank inundation in the park (Kupfer et al., 2015). Both Table 3.1 and Figure 3.3 show how floodplain
sedimentation rates tend to be lower during years with relatively low numbers of flood events.

Sedimentation rates in the National Park increase downstream, as evident from both Figure 3.4a, in which our data are shown along with measurements by Kaase and Kupfer (2016), and Table 3.1. Interestingly, sedimentation rates do not show a correlation with relief. Rates as high as 2.05 cm/yr (and as low as 0 cm/yr) were found in both high and low relief areas. Further, no discernible relationship was found between tiles position on the inner or outer bank of the Congaree River main channel and sedimentation rate. Overall highest sedimentation rates are observed close to the main channel or to floodplain channels in the floodplain interior, as predicted by floodplain sedimentation models describing high and relatively coarse sedimentation close to channels.

3.4.2 Grain size specific floodplain sedimentation

The volume fraction content of sand in both tile and grab samples is detailed in Tables 3.2 and 3.3, and Figure 3.4b, including data collected by Kaas & Kupfer (2016). In samples collected upstream of Highway 601, the sand fraction exceeds 0.55, with a floodplain average of 0.76. Downstream of Highway 601, the maximum sand fraction drops to 0.55, with a floodplain average value of 0.14. This decrease in sand content may be attributed to the presence of a high relief area just upstream of Highway 601, corresponding to an old Congaree River levee (as indicated with the red arrow in Figure 3.4b), which may restrict the downstream transport of coarse sediments. This area blocks the flow and creates a pool upstream of the downstream most part of the floodplain. This
pool is an area with suitable hydrodynamic conditions for sand deposition limiting the transport of sand downstream, as further discussed below.

Samples collected on the inner bank and on the outer bank of the Congaree River main channel exhibit a high sand fraction content (values as high as 0.93). High sand fractions are also consistently found in samples from the interior floodplain, with minimum of 0.7 and a maximum of 0.98 suggesting significant transport of sand-sized particles in this region.

Floodplain sand geometric mean size ranges from 0.15 mm to 0.84 mm, with a floodplain average of 0.4 mm, which is smaller than the geometric mean size of the bed material, equal to 0.7 mm. This indicates that sand is transported on the floodplain and the floodplain sand is generally finer than the channel bed material.

The spatial distribution of $D_{g,\text{sand}}$ and $D_{g,\text{mud}}$ is presented in Figures 3.4c and 4d, respectively. Figure 3.4c highlights preferential deposition of coarse sand ($D_{g,\text{sand}}$ coarser than 0.4 mm) in low relief areas of the floodplain interior close to the north-west and west park boundaries (upstream part of the floodplain). In contrast, sand collected in high/medium relief areas close to the main channel has a geometric mean size that is finer than 0.4 mm, on average. Figure 3.4d shows the spatial distribution of mud sizes. Coarse mud ($D_{g,\text{mud}}$ coarser than 50 microns) is primarily located in the upstream part of the floodplain, particularly in low-relief floodplain interior. Lastly, no significant relationship was found between mud grain size and samples location collected from both the inner bank and the outer bank of a main channel cross-section.

This distribution of sand grain sizes indicates that floodplain channels can effectively transport suspended sand (bed material) to the floodplain interior and challenges
the traditional floodplain sedimentation model, which typically assumes an exponential decay in sedimentation rate, sand fraction, and grain size from the main channel to the floodplain interior. The presence of levees, high sedimentation rates and sand close to the main channel and to the floodplain channels (Xu et al., 2021), however, suggests that the exponential deposition model remains valid for each channel.

In summary, the analysis of sedimentation rates in the Congaree National Park reveals several key features: 1) sedimentation rates vary from year to year, with the highest rates occurring in wettest years, 2) data do not indicate a significant relationship between sedimentation rate, floodplain relief, or inner/outer bank location, 3) sedimentation rates and sand fraction content tend to be highest in the floodplain interior, especially close to the floodplain channel network, where the coarsest sand fractions are also found, 4) the traditional floodplain sedimentation model predicting high and coarse deposition close to the main channel appears to hold for each individual channel within the park but not for the floodplain as a whole.

These findings raise questions regarding the origin of floodplain sand, specifically whether it originates from the Congaree River main channel or comes from reworked floodplain deposits. This is discussed further in the next section.

3.5 DISCUSSION

To determine whether the sand found in the floodplain originates from the Congaree River main channel or from reworked floodplain deposits, we must determine if sand can be transported from the main channel to the floodplain interior. To do this, we first determine the coarsest grain size that can be transported in suspension across the
floodplain, and then we determine the grain size of suspended sediment transported in the main channel that can overflow into floodplain channels or being transported overbank. To achieve this, we use results of 2D hydrodynamic simulations of floodplain flow conducted by van der Steeg et al. (2023) that we consider representative of sub-bankfull and overbank inundation conditions. The analysis of the results presented in Figures 3.4e and 3.5c of van der Steeg et al. (2023) corresponding to peak flows of 268 m$^3$/s and 1495 m$^3$/s (recorded on 04/11/2019, at 7:00 PM and 11/17/2018 at 9:45 PM, respectively) provides floodplain average mean velocity during sub-bankfull inundation equal to 0.05±0.03 m/s. In contrast, during overbank inundation, flow velocities exhibit a wider range, fluctuating between 0.04 m/s and 0.85 m/s.

To identify possible sediment paths and track the movement of sediment across the floodplain, we used an in-house developed MATLAB script that is available as Supporting Information. This script utilizes model results provided by van der Steeg et al. (2023) to compute streamlines. Streamlines for overbank inundation are presented on the digital elevation model of Figure 3.1 in Figure 3.5a. As reported in van der Steeg et al. (2023), the streamlines show that flood flow reaches the upper boundary of the Congaree National Park due to the overbank flow upstream of the park boundary. A close look at the streamlines reveals that floodplain flow is influenced by the presence of floodplain topography, such as an old channel scour upstream of the park boundary corresponding to an area where the flow ponds (streamlines are deflected to the north and to the south), and by floodplain channels within the park boundary close to the main river (Figure 3.5a). Figures 3.5b and 3.5c show the distribution of velocity magnitude and water depth, respectively. The floodplain interior experiences higher flow velocity than areas close to
the Congaree River main channel. Upstream of the old channel levee in the low relief, downstream part of the floodplain, the water depth is highest but the flow velocity remains high enough to transport some sand over the old levee (Figure 3.5c and Figure 3.4b).

3.5.1 Suspended transport on the floodplain

To determine the sediment sized that can be transported in suspension on the floodplain, grain size classes between 0.075 mm and 0.7 mm were considered and we used the Bagnold criterion for significant suspension of sediment with grain size D: sediment with grain size D can be transported in suspension when the ratio of shear velocity $u^*$ to settling velocity $v_s$ is equal to 0.8 (Bagnold, 1966).

The shear velocity on the floodplain was computed using Eqs. 3.1 and 3.2 with a dimensionless Chezy roughness coefficient $C_z$ equal to 5 (Viparelli et al., 2013; Viparelli & Eke, 2021) on the grid points of van der Steeg et al. (2023). We determined the friction factor $C_f$ using Eq 1 and the shear velocity using $C_f$ and the average velocity magnitude $U$.

$$C_f = C_z^{-2} \quad (3.1)$$

$$u^2 = C_f U^2 \quad (3.2)$$

Given the value of $u^*$, the threshold settling velocity was computed as $u^*/0.8$. The Dietrich (1982) relation was then used to determine the grain diameter representing the coarsest sediment size that can be transported in suspension.

Suspended sediment is classified in terms of five size classes: $D < 0.075$ mm, $0.075$ mm $< D < 0.2$ mm, $0.2 < D < 0.4$ mm, $0.4$ mm $< D < 0.7$ mm, and $D > 0.7$ mm and the areas where each size class can be transported in suspension over the fully inundated floodplain is presented in Figure 3.6. Dots in each panel of Figure 3.6 report the average
fraction content of sediment in each grain size class measured at tiles and grab samples. Figure 3.6a shows that mud (D < 0.075 mm) can be transported everywhere on the floodplain. Mud fraction is notably higher in the downstream part of the park, which is characterized by lower elevation, lower relief and higher inundation depth (Figure 3.5c). The comparison of Figure 3.6a with Figure 3.5c and Figure 3.4d reveals that larger mud sizes are found in locations with inundation depth exceeding 1.2 meters.

Figure 3.6b shows that approximately 92% of the floodplain has the potential to transport and receive sediment sizes smaller than 0.2 mm. This result agrees with our measurements showing volume fraction content of sediment in this size class varying between 0.13 to 0.8. Figure 3.6c suggests that 0.4 mm sand is transported in suspension in 74% of the floodplain area and streamlines indicate that this sand can originate from the Congaree River main channel. This finding should not be surprising, as the average diameter of sand grain sizes across the floodplain is approximately 0.4 mm.

Suspended sediment transport capacity for particle sizes coarser than 0.4 mm but finer than 0.7 mm is presented in Figure 3.6d. Streamlines show that the west border of the park is the only area with the potential to receive this size class through floodplain channels. In addition, the map shows the presence of zones of preferential deposition along streamlines where suspended transport capacity drops (white areas indicated with arrows). Downstream of these areas, sediment in this grain size range cannot be transported due to the absence of a connected path with a sediment source. Thus, any sediment coarser than 0.4 mm found downstream of coarse sediment deposition areas will likely have a source that is not the Congaree River main channel or is transported during a larger flood than that considered here. Sediment sizes exceeding 0.7 mm, which is the geometric mean size of...
Congaree River channel bed sediment in the park, can be suspended in small areas in the floodplain interior (Figure 3.6e). The absence of connected flow paths from the channel to these areas indicates that the Congaree River is not the source of coarse floodplain sand. Sand coarser than 0.7 mm was found in few of our samples. This material may not have a Congaree River origin or might have been transported on the floodplain during flood events more intense than that considered here.

Suspended transport capacity during sub-bankfull inundation, when the southern part of the park becomes inundated due to the presence of floodplain channels and connected depressions, is presented in Figure 3.7, where the color scale represents the coarsest grain size that can be transported in suspension. The figure clearly illustrates the role of floodplain channels in transporting relatively coarse materials (up to 0.4 mm) to the floodplain interior when the discharge in the main channel is below bankfull. It is important to note here that in the downstream part of the park the flow can suspend sediment coarser than 0.4 mm but, due to the lack of a connected path with the Congaree River main channel, this sediment can only be reworked in previous floodplain deposits.

3.5.2 Suspended sand availability in the Congaree River

The above analysis is based on the assumption that sand finer than 0.7 mm can be suspended in the Congaree River main channel and conveyed into floodplain channels. To determine whether this is reasonable, we used the Rouse equilibrium profile of suspended sediment concentration (Brown, 2010) for the Congaree River main channel during floods. We considered flow velocities associated with the overbank inundation event modeled by van der Steeg et al. (2023) and bankfull flow conditions reported in Logan (2023). We
calculated the Rouse profile (Parker, 2004) for sand diameters of 0.2 mm, 0.4 mm, and 0.7 mm to determine the normalized suspended sediment concentration above the floodplain channel bed. In this analysis the distance of the floodplain channel bed from the bank top was taken to be smaller than 1.6 m, as reported in Xu et al. (2020). In the calculations we used bankfull shear velocity of 0.077 m/s and bankfull depth of 4 m (Logan, 2023), and overbank flow velocity and in the main channel equal to 2.5 m/s and 6 m respectively (van der Steeg et al., 2023) corresponding to a shear velocity or 0.25 m/s with a dimensionless Chezy coefficient equal to 10 (Logan, 2023).

The analysis is summarized in Figure 3.8 in terms of relative sediment concentration $\bar{C}/\bar{C}_b$ and relative height above the channel bed $z/H$. In Figure 3.8 $\bar{C}$ represents the local suspended sediment concentration averaged over turbulence and $\bar{C}_b$ is a near bed reference value evaluated at a distance from the channel bed equal to 5% of the water depth $H$ and $z$ is the height above the channel bed. At bankfull condition (Figure 3.8a), the relative height of the floodplain channel bottom is higher than 0.6 and the sediment in suspension at relative heights ranging from 0.6 to 1 is considered available to overflow into floodplain channels. Figure 3.8a shows that at bankfull conditions 0.2 mm sand only can be transported from the Congaree River main channel to the floodplain interior through floodplain channels.

During overbank flow (Figure 3.8b), sediment transport to the floodplain occurs via floodplain channels and overbank flow. In Figure 3.8b, floodplain channel bottom is at relative elevation 0.4 and bankfull depth corresponds to relative elevation 0.66. The orange area in Figure 3.8b represents the height of the water column between the deepest floodplain channel bed and the bankfull depth. The blue area of Figure 3.8 represents the
portion of the water column that can spill over the floodplain via overbank flow. In Figure 3.8b, the relative sediment concentration at floodplain channel elevation ranges between 0.45 and 0.58, for 0.2 mm sand, between 0.125 and 0.24 for 0.4 mm sand, and between 0.02 and 0.07 for 0.7 mm sand. These values suggest that sediment 0.2 mm sand can be transported high enough in the water column to enter the floodplain during both sub-bankfull inundation and overbank flow. Sand with grain size of 0.4 mm can be transported to the floodplain interior through floodplain channel and overbank flows during overbank inundation. Finally traces of 0.7 mm sand can be transported in floodplain channels during relatively high flow events.

In summary, in the upper part of the Congaree National Park, sediment is transported to the floodplain interior through floodplain channels and overbank flow due to the floodplain sloping toward the north, as illustrated by the relief map and the floodplain channel network in Figure 3.9a and in sections A-A’ and B-B’ of Figures 3.9b and 3.9c. However, in the downstream part of the floodplain corresponding to sections C-C’, D-D’ and E-E’ in panels 3.9d, 3.9e, 3.9f, the lack of transverse floodplain slope and of a well-developed channel network do not allow main channel sediments travel far into the floodplain. Difference in floodplain cross-section and no dense floodplain channels can be counted as an explanation for the differences between downstream deposit measurements (Kaase & Kupfer, 2016) and the data collected in this study.
3.5.3 Relation between floodplain sedimentation and flow velocity during overbank inundation

Figure 3.10 present a comparison between channel bed sand (black lines) and floodplain sand, with blue and red lines respectively represent samples collected in high and low velocity areas during overbank inundation. The figure illustrates how sand grain size distribution varies across the floodplain. As floodplain flow velocity increases, the floodplain sand size distribution coarsens but remains finer than the bed material sediment size distribution. The sediment size distributions of Figure 3.10, however, consistently show a paucity of floodplain sediment coarser than 0.7-0.8 mm, which can hardly be transported high enough in the water column to overflow in floodplain channels or overbank (Figure 3.8). The majority of the samples collected in low velocity areas have \( D_{g,sand} \) smaller than 0.2 mm, in agreement with the observation that 0.4 mm sand can hardly be transported overbank (Figure 3.8).

Velocity magnitude and vectors are plotted in Figure 3.11 where dots represent sedimentation rates (Figure 3.11a), sand fraction content in the sediment samples (Figure 3.11b) and \( D_{g,sand} \) (Figures 3.10c). Figure 3.10d presents \( D_{g,mud} \) of our samples and the spatial distributions of flow depth during overbank inundation. Figure 3.11a shows sedimentation rate is highest in locations that experience low flow velocity, primarily close to the main channel, as also observed by (Kaas & Kupfer. 2016). Sand content is highest in areas with the highest flow velocity during overbank inundation (Figure 3.11b). When considering particle size, Figure 3.11c reveals that coarse sand (\( D > 0.4 \) mm) is deposited in the interior floodplain, characterized by high-velocity areas, in contrast to fine sand found in regions with lower flow velocities (see Figure 3.11c). There are some exceptions
to this rule. Samples collected from “Rail” tiles (red arrow in Figure 3.11c) can have $D_{gsand}$ as low as 0.31 mm in a high-velocity zone. This can be due to the to a deposition zone upstream of the tiles (see Figure 3.6d) and/or to complex hydrodynamics of this specific location that experiences back water from old levee downstream.

The combination of low-velocity flow and high inundation depth results in high mud fractions and large mud particles upstream of the old Congaree River channel (Figure 3.11b and 3.11d). Overall, these findings highlight the complex interplay between flow dynamics and sediment deposition in the floodplain, emphasizing the role of flow velocity and inundation conditions in shaping the distribution of sediment sizes and characteristics.
Figure 3.1 – Digital elevation model of the Congaree Rover floodplain corresponding to van der Steeg et al. (2023) computational domain. The floodplain channel network in the Congaree National Park (Xu et al., 2021) is reported in blue.
Figure 3.2 – Sediment sampling locations in the Congaree National Park on a relief map of obtained from the DEM of Figure 3.1. (a) Location of tiles (purple dots) and grab samples (pink dots) relative to floodplain relief. (b) Location of tiles and grab samples relative to the floodplain channels. (c) Tiles and grab samples at the west border of the Congaree National Park. (d) Tiles adjacent to the main channel.
Figure 3.3 - The flow discharge at USGS Congaree River, Columbia, SC in sedimentation sampling period associated with sub-bankfull (235 m$^3$/s) and overbank inundation (850 m$^3$/s) thresholds. (a) From September 2019 to September 2020. (b) From September 2020 to November 2021. (c) From November 2021 to November 2022.
Figure 3.4- Spatial distribution of sediment sample characteristics (average value of 2020, 2021 and 2022 recoveries) and relation with sampling location (relief map). (a) Sedimentation rate. (b) Sand fraction. (c) Mean sand diameter. (d) Mean mud diameter.
Figure 3.5 – Streamlines for overbank inundation on base maps describing floodplain flow. (a) Floodplain DEM. (b) Velocity magnitude. c) Water depth.
Figure 3.6 – Suspended transport of sediment differing in grain size during overbank inundation. (a) Sediment size less than 0.075 mm, (b) Sediment size more than 0.075 mm and less than 0.2 mm. (c) Sediment size more than 0.2 mm and less than 0.4 mm. (d) Sediment size more than 0.4 mm and less than 0.7 mm. (e) Sediment size more than 0.7 mm.
Figure 3.7 – Floodplain channels and sediment sizes that can be transported during sub-bankfull inundation in the Congaree National Park.
Figure 3.8 – Equilibrium suspended sediment concentration profile (Rouse profile) for different sand diameters. (a) Bankfull condition. (b) Over bankfull condition. The height above the channel bed where the relative suspended sediment concentration is equal to 1 is equal to 5% of the water depth in the main channel.
Figure 3.9 – The DEM file of the Congaree River floodplain, floodplain channels and sampling points. (a) Location of 5 cross-sections derived from the DEM fill. (b) Floodplain cross-section at the upper part of the CNP. (c) Floodplain cross-section at the upper-middle part of the CNP. (d) Floodplain cross-section at the middle part of the CNP. (e) Floodplain cross-section at the lower-middle part of the CNP. (f) Floodplain cross-section at the lower part of the CNP.
Figure 3.10 – Sand size distribution of sand collected in the Congaree River channel (black), high velocity zone on the floodplain (blue) and low velocity zone on the floodplain (red).
Figure 3.11 – Spatial distribution of sediment characteristics (average value of all recoveries) and relation with flow velocity and depth during overbank inundation across the floodplain. Velocity arrows (small arrows refer to low velocity and large arrows refer to high velocity) and water depth. Dots respectively indicate (a) Sedimentation rate, (b) Sand fractions, (c) Mean sand diameter, (d) Mean mud diameter
Table 3.1 – Sedimentation rate measured from tiles based on 3 years of recoveries (“0” = we found the tile and there was no sample stored on the tile and “-” = the tile was not found or not installed at that time)

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Table 3.2 – Collected samples characteristics from 3 years of tile recoveries (“0” = we found the tile and there was no sample stored on the tile and “-” = the tile was not found or not installed at that time).

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<th>(D_{\text{gsand}}) 2021 (mm)</th>
<th>(D_{\text{gsand}}) 2022 (mm)</th>
<th>(D_{\text{gmud}}) 2020 (mm)</th>
<th>(D_{\text{gmud}}) 2021 (mm)</th>
<th>(D_{\text{gmud}}) 2022 (mm)</th>
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<th>Sand Fraction 2021</th>
<th>Sand Fraction 2022</th>
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Table 3.3 – Collected grab samples characteristics in 2022

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<th>$D_{gmud\ 2022}$ (mm)</th>
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CHAPTER 4

CONCLUSION

Motivation of the first study presented in chapter 2 is that the planform shape of the Congaree River, known to be a sand bed, meandering river, differs from the typical shape of alluvial rivers. An alluvial meandering river is characterized by bars and bends, each exhibiting distinct shapes and variable migration rates, with no sharp changes in channel geometry. The Congaree River planform, on the contrary, presents an abrupt increase in sinuosity in the downstream direction. Such abrupt change is unusual for an alluvial river but has been observed in mixed bedrock-alluvial rivers. This observation, along with the presence of bedrock outcrops, led to the assumption that the Congaree River might have been a mixed bedrock-alluvial river with a bedrock-alluvial transition located close to the change in sinuosity. To test this hypothesis, we measured the elevation of the riverbed surface and of the first substrate layer (corresponding to a change in substrate physical properties) with StrataBox™. Data were analyzed in terms of longitudinal profiles of riverbed surface and substrate layer elevation, as well as the spatial distribution of alluvial cover thickness.

The data revealed that the first substrate layer was exposed on the riverbed surface in various locations along the river, spanning distances of up to 500 meters and that this layer corresponded to Cretaceous coastal plain deposits, which outcrop in bluffs along the river. The sublayer measurements allowed us to quantify the irregularity of the bedrock surface (macro roughness height), which corresponds to the minimum thickness of alluvium
needed to cover the bedrock surface (Zhang et al., 2015). In an alluvial river sediment transport and bedform migration are not influenced by the presence of a hard substrate. Thus, the bedrock surface should be covered with an alluvial layer as high as dunes that will form during flood flows. The sum of the macroroughness height and of the dune height at formative conditions is here considered to be representative of the minimum thickness of alluvial cover for the complete alluviation of the channel bed (Viparelli et al., 2015). This classification revealed that the Congaree River is mixed bedrock-alluvial with all exposures consistently linked to high channel curvature, demonstrating a one-sided relationship (but not all sharp bed showed exposed bedrock).

The most surprising finding of this study is the downstream decline in alluvial cover with the potential existence of a downstream migrating coarse front corresponding to a wave of alluviation of the channel bed. In 1883, this front was located at kilometer 12. Beyond this point, the riverbed closely follows the bedrock profile until the confluence with the Wateree River. In 2018, this front had advanced all the way to the park boundary at kilometer 36, with little differences between the present longitudinal profile and the profile measured in 1883. Hence, this analysis indicates that the Congaree River is not in equilibrium and is experiencing the alluviation of the channel bed.

Identifying the causes of this disequilibrium is challenging, as the literature on not tidally influences coastal plain rivers is scarce. Noting that the front cannot be associated to human activities in the watershed as dam construction would have resulted in an increase in alluvial cover and timber harvesting caused a pulse of fine sediment (not sand or pea gravel), we hypothesize that the front is associated with the river response to the increased
precipitation and discharge that occurred at the end of the last glaciation in southeastern USA.

The comprehensive analysis of sedimentation and sediment deposit size with sediment tiles and grab samples of floodplain deposits in the Congaree National Park provided critical information to test floodplain sedimentation models describing high deposition and trapping of coarse sediment close to the main channel. Data on floodplain sedimentation rate and sediment size were integrated with other field data on floodplain sedimentation (Kaase and Kupfer, 2016). Data surprisingly showed coarser sand and higher sand content in the floodplain interior than close to the Congaree River main channel. These coarse samples were collected in close proximity to the floodplain channels.

The integration of floodplain sedimentation data with relief maps and the results of 2D hydrodynamic modeling of overbank and sub-bankfull inundation of the Congaree River floodplain, allowed the identification of the sediment sizes that can be transported in suspension in different parts of the floodplain. The interior floodplain tends to experience higher flow velocities (low relief areas), making them receptive to sediments with a higher content of coarser particles (sand coarser than 0.2 mm) under varying inundation conditions. Mud deposits were found to be distributed across the entire floodplain, with a greater concentration in the downstream part of the park. This area is located downstream of a high relief line corresponding to the bank of an old Congaree River channel that causes deep inundation depth and low flow velocities upstream with consequent deposition of coarse sediment before it can be transported further downstream. Additionally, sand coarser than 0.4 mm was found in samples collected close to the western park boundary and this could be attributed to the elevated flow velocities and good hydraulic connections.
with the Congaree River main channel. To determine if these floodplain sands may have originated from the Congaree River main channel, I computed equilibrium profiles of suspended sediment concentration at bankfull flow and for overbank inundation. This exercise revealed that at bankfull flow, fine sand (diameter smaller than 0.2 mm) can overflow in floodplain channels (Figure 3.8a). At higher flood flows, sand with sediment size finer than 0.7 (Figure 3.8b) can be transported from the Congaree River to the floodplain interior. Further, the comparison of sediment size distribution curves obtained from both the riverbed and floodplain deposits clearly shows that sediment with grain size finer than 0.7 mm can be transported from the Congaree River to the floodplain interior during floods. Thus, floodplain deposition models should be revised to account for transport of water and sediment to the floodplain interior through floodplain channels.

The presence of a downstream migrating front in the Congaree River channel and of floodplain channels delivering sand in the floodplain interior in the downstream part of the Congaree River floodplain corresponding to the high sinuosity reach suggests Congaree River morphodynamics may change 35-45 kilometers downstream of the Congaree River headwaters. This assumption is further justified by main channel bed sampling revealing the absence of pea gravel in the channel bed material downstream of kilometer 35 (Logan, 2023), absence of floodplain channels upstream of kilometer 37 (Xu et al., 2021) and streamwise decreasing channel width upstream of kilometer 42. The question that naturally arises is whether all these observations are interrelated, given that they occurred in the same area, and if they collectively indicate that the entire river-floodplain system is not in a state of equilibrium.
To address this question, I estimated floodplain erosion due to channel migration using Eq. 4.1 (Lauer and Parker, 2008b, Viparelli et al., 2013) and compared it to the floodplain deposition rate in the park boundary. Sediment fluxes associated with changes in channel width were neglected because Logan (2023) showed no change in bankfull channel width between 1883 and 2022.

Floodplain equilibrium is here defined as a state in which floodplain erosion for channel migration is balanced by floodplain construction due to point bar deposition and floodplain sedimentation (Lauer and Parker, 2008b). In Eq. 4.1, $E_{mig}$ represents the net volume of sediment per unit channel length eroded from the floodplain for channel migration, $\Delta \eta$ denotes the height difference between the newly deposited point bar and the eroding bank, which is on average equal to 1.3 meters in the national park (Table 4.1), $\lambda_p$ is the bulk floodplain porosity set equal to 0.45, and $c$ is channel migration rate. The 20-year average migration rate of 1.8 m/yr (Figure 4.1) is used in the calculations.

$$E_{mig} = \Delta \eta (1 - \lambda_p) c \quad (4.1)$$

As a result of these calculations, the average net floodplain erosion rate is 1.3 m$^2$/yr. The floodplain deposition rate was determined by multiplying the average valley width 4 km by the floodplain average of sedimentation rate of 1.5 cm/yr (based on our measurements and Kaase and Kupfer (2016) data), resulting in a floodplain deposition rate of 60 m$^2$/yr, which is based on short-term data and can thus overestimate the decadal sedimentation rates. If we try to do a floodplain sediment budget, it becomes evident that deposition exceeds erosion.

The sediment budget reveals that the Congaree River floodplain in the national park is not in equilibrium as sediment deposition is larger than sediment erosion. Indeed, this
observation raises the question of whether the inability of the current floodplain deposition model to accurately portray this floodplain dynamics is related to the ongoing floodplain construction. This point highlights the need for further investigation and research in this area to better understand the details of the floodplain processes and to potentially adapt or develop models that can better capture the dynamics of this specific system and other highly channelized floodplains worldwide.
Figure 4.1 – Short-term channel migration rate (in 20 years) for four different periods of
time. On average, channel migration year is close to 0.9 m/yr upstream the park (in low
sinuosity section), and in park boundary, it is close to 1.8 m/yr (in high sinuosity section).

Table 4.1 – Measured height differences between bar and bank along the river in the park
boundary

<table>
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REFERENCES


and Geographical Survey, Rocky Mountain Region, General Printing Office.


