INVESTIGATION OF SEDIMENT BUFFERING FUNCTION OF THE GATBERG FLOODPLAIN WETLAND IN THE UPPER TSITSA RIVER CATCHMENT, SOUTH AFRICA

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Abstract

Floodplain wetlands are important components of river systems that provide various ecosystem services such as sediment buffering. These wide and often expansive storage areas have a substantial impact on downstream water quality by trapping sediment and storing 'contaminants' adhered to sediment thus improving water quality.

The planned construction of the Ntabelanga and Lalini Dams in the Tsitsa River Catchment has been proposed; however, due to the steep landscapes and erodible soils, this promotes high erosion rates that can potentially reduce the lifespan of the proposed dams. The existing wetlands in the Tsitsa River Catchment have therefore been identified as key sediment buffers that can reduce sediment transport, but the effectiveness of these buffers is poorly researched. This study attempts to investigate the current sediment buffering function of the Gatberg Floodplain Wetland over one wet season (August 2019 to August 2020).

Time integrated samplers were installed above and below the wetland to determine relative sediment volume and character coming in and out of the wetland. Five transects were surveyed across the wetland width to evaluate the topography and vegetation characteristics. Surface sediment samples on the floodplain were taken at key morphological features along each transect and along the river longitudinal profile to determine organic content, particle size, and type of stored sediment. Astro turf mats were deployed on targeted transects and on key floodplain features to determine sediment accumulation rates. Field measurements of vegetation parameters (height, density, and stem diameter) were taken to calculate vegetation-induced hydraulic roughness to understand possible sedimentation feedbacks.

The relative sediment volume coming into the wetland was greater than that leaving the wetland. This implies that some of the sediment is buffered within the wetland. An approximate proportion of 73% trapping efficiency of the incoming sediment was buffered within the floodplain wetland during the wet season. This accumulated approximately 4 tons within the wetland over the monitoring frame. Bed particle size in the longitudinal profile increased with distance downstream, this was due to localized tributary and hillslope inputs.

Inundation depth varied across the floodplain wetland with deeper inundation depths at the head of the wetland than at the bottom; where particle size was larger with an increase in water level depth. This may be linked to both high stream velocities and variability of the floodplain topography. However, the observed trends were inconclusive and uncertain.

Stronger correlations with particle size were shown by vegetation roughness ($b^* = 0.41$) and distance from the channel ($b^* = -0.38$). Flood benches and banks had a coarser D50 particle size than back swamps and oxbows. Coarser sediment in flood benches are associated with proximity to the sediment-laden water that experiences abrupt flow velocity changes, while finer material in oxbows are due to minimal flow velocities which reduce with distance from the channel. Finer particles remain in suspension and are carried aloft for longer periods at very low velocities. Therefore, particle size decreased with distance from the channel due to longer travel distances and high surface area relative to weight.

Further results showed that finer surface sediment particle size was associated with high vegetation roughness whilst coarser material was associated with low roughness. This was due to vegetation geometry and type or changes in flow velocity and energy. Grassy vegetation induced finer particle size than shrubby vegetation that has a greater line spacing. Furthermore, vegetation roughness varied over the wet season; roughness was highest in late summer and low in early summer. Low roughness was due to fire occurrence in the study area which resulted in a decrease in biomass. Increasing vegetation roughness can be due to increased flood events, and the introduction of non-perennial species; which can increase sediment accumulation rates. Although studies have shown that vegetation density is the most essential factor affecting flow resistance and sedimentation processes; vegetation height and stem diameter for this study area seem to contrast these observations and rather may be the most significant contributing factors in sedimentation. This concluded that vegetation density may not always be the most essential component in sedimentation processes.

Sediment particle size was inversely proportional to organic content; finer particle size are more cohesive and more capable of carrying organics. Regions further away from the channel such as oxbows with stable moisture conditions favour plant growth and soil formation thus are susceptible to high organic content. Flood benches are closer to the channel, thus have coarser material and fluctuating moisture conditions that have unstable high water flow velocities. High sediment accumulation rates on flood benches and oxbows is due to high connectivity to sediment-laden water and high hydroperiods or high residence time for sediment accumulation in oxbows. Sediment accumulation rate was shown to be a function of particle size itself (b* = 0.67) rather than the expected vegetation roughness. Although a true representation of sediment accumulation rates in the Gatberg Wetland was limited by the disturbance of astro turf mats by animals and possibly by high flooding events; the wetland can be regarded as a good sediment buffer as some sediment was stored (e.g. up to 48,04 kg/m^2 in flood benches) within the wetland over the monitoring period.

Keywords: *Suspended sediment, floodplain-geomorphology, sediment buffering, vegetation roughness, organic content, inundation depth, topography*

Declaration

I, Sibuyisele Sweetness Pakati, declare that the thesis titled: *Investigation of sediment buffering function of the Gatberg Floodplain Wetland in the upper Tsitsa River Catchment, South Africa* is my own work and that all sources that have been used or quoted have been indicated and acknowledged by complete references. This thesis has not been submitted for a degree from any other higher institution.

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This thesis is dedicated in memory of my late father (Nqaba Pakati) who would have been proud to see how much I have accomplished and to follow in his footsteps.

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1. Introduction

The first chapter introduces the background and importance of the study and further elaborates on the problem statement, study aim, and objectives to achieve the research.

1.1 Background

Wetlands are defined as “distinct ecosystems that are mostly inundated by water, either permanently or seasonally, and form at interfaces between terrestrial and aquatic environments and between groundwater and surface-water systems, thus supporting both aquatic and terrestrial species” (Ellery *et al.*, 2009, p15). Therefore, the term “wetland” can be used to classify a variety of ecosystems depending on the hydrogeomorphic setting of the area which can range from floodplain, depression, seeps, valley bottom to river wetlands (Ngetar, 2011). Furthermore, wetlands are crucial ecosystems that are considered nature-based solutions for human-kind, providing ecosystem services in various forms with social, economic, and environmental value (Karim *et al*., 2019; Thorslund *et al*., 2017).

The Millennium Ecosystem Assessment (2005) defined ecosystem services as “the benefits people obtain from ecosystems”. These include provisioning services such as food and water; supporting services such as soil formation, nutrient cycling; cultural services such as recreational, spiritual, religious, and other nonmaterial benefits; regulating services such as sediment buffering, regulation of floods, drought, and land degradation.

Wetland ecosystem services, such as sediment buffering, can improve downstream water quality and in-stream habitat, prolong the lifespan of water infrastructure, and improve sediment impacted channels downstream (Saaltink *et al*., 2018; Hefting *et al*., 2013; Zierholz *et al*., 2001). Sediment buffering by wetlands also improves sorption processes that retain suspended particulates (contaminants) contained within sediments that can particularly cause eutrophication downstream. This is due to reduced water velocities in wetlands compared to rivers and streams, which causes sedimentation processes to be much greater in wetlands thus advancing ‘pollution’ control (Mitsch *et al*., 2014; Olde -Venterink *et al*., 2009; Fennessy *et al.*, 1994).

In a South African context, sediment buffering refers to sediment trapping which is a function of sediment deposition and storage in floodplain environments. The term sediment trapping as referred to in ecosystem services was not used for this study area and rather the term sediment buffering is used. Sediment buffering provides a holistic approach that describes the storing and release of sediment within a system (receives sediment and temporarily stores it) whereas trapping refers to as a function of depositing sediment. Therefore, the study uses the term sediment buffering as wetlands are regarded as ecosystems that can trap and store sediment for a period of time.

The understanding of a wetland's ecosystem functioning state as well as how it changes seasonally is crucial for both management and conservation purposes (Mitsch & Gosselink, 2000). Fundamental to understanding and determination of sediment buffering function is establishing the quantity of sediment being buffered in different hydrogeomorphic wetland settings and the relative rates of sediment transport and deposition (Saaltink *et al.*, 2018). In light of the aforementioned, Fennessy *et al*., (1994) further elaborates that it has been proven that restored freshwater wetlands can retain suspended sediments and associated contaminants which make up to 80% of the total suspended sediment entering a wetland over an 8-year period, this, therefore, serves as an important concept of the importance of wetlands.

Despite the innumerable functions and values that wetlands provide to humanity and biodiversity, wetland ecosystem services still continue to undergo degradation or loss due to anthropogenic factors such as land degradation caused by humankind and other environmental pressures (Lisenby *et al*., 2019; Collins, 2006). For example, sediment accumulation in wetlands due to land-use activities can cause wetland degradation. Changes in wetland systems due to excessive sediment inputs automatically have a negative impact on the ecological functioning of a wetland and other wetland service delivery (Luo *et al*., 1997).

Research by Yan & Zhang, (2019), Ricaurte *et al*., (2017), and Karstens *et al*., (2016) all show that human activities, especially that of land-use practices that are poorly managed, are the main sources of erosion occurring in wetlands across the world. It is estimated that global wetland area decreased by 73% since the early 1950s with associated reductions in ecosystem services which affected the overall quality and extent of wetland services in a catchment (Yan & Zhang, 2019). Furthermore, natural geomorphic processes such as climate change, the formation of gullies, and erosion can also result in wetland degradation or loss irrespective of human activities (Ngetar, 2011). It is therefore important to determine accurate estimates for both erosion and deposition in wetlands for a clear or better understanding of net sedimentation resulting both from fluvial and autogenic processes (Mitsch *et al*., 2014). Although erosional processes play a big role in re-suspending sediment and possibly degrade the wetland, this study only focuses on sediment deposition and accumulation.

The Mzimvubu River Catchment is the only primary catchment in South Africa without a large dam (Le Roux, 2018; Pretorius, 2016). Recently, the Department of Water and Sanitation has planned a water resource project that involves the construction of the Ntabelanga and Lalini Dams on the Tsitsa River, which is the main tributary to the Mzimvubu River (Le Roux, 2018). However, recent studies have shown that large parts of these catchments are susceptible to soil erosion and produce large volumes of sediment due to land degradation. The Gatberg Floodplain wetland is situated in the upper Tsitsa River Catchment.

In the Tsitsa River Catchment, northern Eastern Cape, South Africa; numerous wetlands have been mapped using high-resolution aerial images (Schlegel *et al*., 2019). The study report indicates the degradation state of these wetlands and erosional features that have the potential of threatening the ecosystem services and lifespan of these wetlands (Schlegel *et al*., 2019). The study further indicates that large portions of the wetlands are in a degraded state.

Furthermore, a catchment restoration and sustainable land management initiative, the Tsitsa Project, has been initiated to reduce sediment transport down the catchment to prolong the lifespan of the proposed dams. Because of the narrow valleys, steep landscapes, and high slope instability in the catchment; such characteristics enable little or no chance of sediment buffering. Therefore, the existing wetlands are identified as key sediment buffers that can reduce longitudinal sediment transport and prevent siltation downstream, prolonging the lifespan of the proposed dams (Schlegel *et al*., 2019). However, it is still uncertain as to what extent these floodplain wetlands function as sediment buffers, hence the importance of investigating and understanding the current sediment buffering of these wetlands. The current study will therefore attempt to address this research gap of sediment buffering function of the Gatberg Floodplain Wetland in the upper Tsitsa River Catchment.

1.2 Rationale

Wetlands are important ecosystems that can store sediment and water, which ultimately provides beneficial services to humankind (Luo *et al*., 1997). They are therefore important sediment buffers. Quantifying the relative sedimentation of wetlands will assist in providing information on the current functioning of floodplain wetlands in terms of sediment buffering effectiveness. The study, therefore, investigates how well the Gatberg Floodplain Wetland is serving this function. This will assist in the management and conservation purposes of wetlands.

1.3 Problem statement

According to the Department of Environmental Affairs, 35% - 60% of South African wetlands have already been lost or have been severely degraded, resulting in a reduction of ecosystem services (Department of Environmental Affairs, 2015). The Tsitsa River Catchment is also one of the catchments that have been affected by land degradation (gully erosion) processes such that the lifespan of the newly proposed water infrastructure of the Ntabelanga and Laleni dam will be threatened due to high sediment yield in the catchment, filling the dams with sediment and silt within the next few decades. This limits the wetland's ability to function effectively (Le Roux, 2018; Ngetar, 2011). Furthermore, the Tsitsa River Catchment has various wetland types that are recognized as potential sediment buffers. This study will focus particularly on floodplain wetlands that act as pivotal 'tools' in sediment buffering as they have relatively large flat surfaces to act as sediment buffers; however, the extent of the current sediment buffering is unknown. This research was conducted in the upper Tsitsa River Catchment in the northern Eastern Cape. Conducting this study will not only bring an understanding of the Gatberg Floodplain Wetland system but also provide information and guide to any future conservation or remediation measures to floodplain wetlands.

1.4 Aim, research question, and objectives

1.4.1 Aim

The study aims to investigate the sediment buffering function of the Gatberg Floodplain Wetland in the upper Tsitsa River Catchment, South Africa.

1.4.2 Research question

How do hydrology, vegetation roughness, and floodplain wetland geomorphology influence patterns of sedimentation in a floodplain wetland over a wet season in the Tsitsa River Catchment?

1.4.3 Objectives

Below are the objectives to meet the aim:

1. Investigate the relative suspended sediment quantity coming into and leaving the wetland.
2. Investigate the spatial variability of bed sediment particle size

3. Investigate the spatial variability in inundation depth at a certain flood level, topography, vegetation roughness, organic content, rate of sediment accumulation, and sediment characteristics.
4 Investigate the relationships between inundation depth at a certain flood level, topography, vegetation roughness, distance from the channel, organic content, and sediment characteristics.
5 Summarize the sediment buffering function of the Gatberg Floodplain Wetland.

1.4.4 Thesis outline

The thesis is divided into 7 chapters. Chapter one introduces the background on wetlands, the motivation of the study, followed by research aims and objectives. Chapter two outlines some key literature, to provide an insight into how sedimentation occurs in floodplains i.e. sediment transport along with the longitudinal profile of river systems and the likelihood of sedimentation on its geomorphological units, overbank flows, floodplain buffering, how different floodplain geomorphological features influence sedimentation processes and lastly what are some of the controls that influence sedimentation in floodplain environments. Chapter three gives an insight as to where the research study was conducted i.e. geographic setting, climate, and geology, topography, vegetation, and soil type. It also elaborates on the different methods and techniques that can be used in carrying out this type of research. The methods chapter four highlights the various data collection and analysis methods that were involved in this study. A representation of topographical surveying, collection of vegetation parameters to calculate hydraulic roughness were done, bed and surface sampling that were analyzed for sediment particle size as well as installation of mats to 'quantify' the rate sediment accumulation on targeted floodplain settings. Chapter five reports on the results that were obtained. A desktop analysis was done to give a better understanding of how the spatial and temporal variations influence the sediment accumulation and type found and the estimation of sediment buffering function of the wetland over a wet season. The discussion in chapter six discusses the results found. The last chapter provides a conclusion of the study and recommendations based on the outcomes. All sources that have been used or quoted are indicated or acknowledged by complete references in chapter 8. The very last section includes appendices of the report.

2. Literature review

This chapter reviews some key literature that informs this study. It introduces the importance of floodplain system processes; the processes of sediment transport in river systems, overbank floodplain sedimentation at inundation events, and an overview of floodplain buffering on the different floodplain depositional environments. It also provides an insight into some contributing factors that lead to the spatial and temporal variability in sedimentation patterns. Emphasis on the different techniques used for assessing sedimentation on floodplains is discussed, which are often used in quantifying wetland sedimentation.

2.1 Introduction

Floodplain environments across the world have been recognized as important constitutes in sediment deposition which is imperative for sediment and contaminant budget of river systems as they provide important components of storing and releasing sediments (Thonon *et al*., 2007, Middlekoop & Van Der Perk, 1998; Asselman & Middlekoop, 1995). Furthermore, a catchment's landscape and its configuration shape the functioning and operation of geomorphic processes over temporal and spatial scales. The resulted spatial relations assist in determining an overview of the patterns and rates of sediment, water, and nutrient flux in a catchment. On a regional scale, the amount and sedimentation patterns are controlled by factors such as channel gradient, sinuosity, floodplain, and valley width while morphology and flow mechanisms are of importance on a local scale phenomenon (Thonon *et al*., 2007 & Middlekoop, 1995).

Although studies have shown that floodplain systems have a pivotal impact in storing sediment like 'water', it has also been documented that little is known about the details of overbank deposits (Asselman & Middlekoop, 1995). This relates to the amount of sediment stored and what factors influence the rates at which these sediments are deposited onto these floodplain systems. This is important for gaining key insight into the variables that determine the spatial variability of sediment deposition in floodplains (Curran & Hession, 2013; Asselman & Middlekoop,1995; Pizzuto,1987). They, therefore, have a crucial impact on the sediment dynamics both on temporal and spatial scales during overbank flows (Asselman & Middelkoop, 1995; Walling & He, 1998).

The main objective of this literature review is to develop an understanding of sedimentation processes during overbank flows. It mainly focuses on the vertical accretion of overbank deposition (influenced by the slow accumulation of overbank sediment without channel migration aspects), which is the primary process that most lowland floodplains develop.

Furthermore, floodplain sediment buffering in terms of the transportation and deposition of sediment in different floodplain environments and the different techniques used to assess the amount of sediment deposited on floodplain wetlands over a wet season is reviewed. Sediment transport processes in river systems are also explained as it provides a foundation as to how sediment is transported and what is likely to be deposited on the floodplain.

As aforementioned, exploring floodplain sediment buffering by measuring variables that influence sedimentation (e.g. flow resistance, elevation, inundation frequency) will assist in documenting the spatial variability of sediment deposition quantity, pattern, and processes. Contemporary, floodplain wetlands have also been known to play an important role in storing pollutants such as organic content and the review will give an overview of the formation and variability of organic content across floodplain wetlands. This will include the key type of sediments which are most likely to have the ability to be adhered to pollutants.

2.2 Importance of floodplain systems

The ecological significance of floodplains as buffer systems are well documented as they are important potential sinks of fluvial sediment deposits and act as flood storage and control mechanisms (Benedetti, 2003; Walling & Owens, 2003). As such, overbank floodplain sedimentation has an important role in the reduction of suspended sediment during periods of inundation. They, therefore, represent a significant component in the catchment sediment budget for river basin management. To understand overbank sedimentation of floodplains, information on floodplain overbank deposits, sediment accumulation and rates, and sediment patterns are vital in understanding their development and functioning. This information contributes to understanding the mechanisms of floodplain overbank flows and transport of sediment. The information is also used in the development or validation of models that are important for quantifying the temporal and spatial variability of sedimentation on floodplains (Walling & Owens, 2003; He & Walling, 1997).

There have been well-documented studies on the hydrological behaviour of rivers in periods of floods (Walling & Owens, 2003; He & Walling, 1997). However, the prediction of suspended sediment deposition is still uncertain hence the importance of studies that quantify suspended sediment (Benedetti, 2003). Wetland functioning can constantly change due to surrounding landscape changes thus it is vital to acknowledge the extent of these changes and better understand their impacts.

2.3 Sediment transport and deposition in river fluvial systems

The process of sediment deposition on floodplains begins with processes within river channels. River channels can transport sediment of different calibre (boulders, cobbles, gravel, sand, silt, and clay) either longitudinally, laterally, or vertically. This can give rise to various kinds of morphological features, such as the formation of bedforms in river channels and levees on the floodplain surface (Fryirs & Brierley, 2012). Sediments are subjected to three types of processes when in fluvial systems i.e. sediment erosion or entrainment, transport, and deposition. These variables can be explained through the Hjulstrom curve diagram (Figure 1), which shows the relationship of different grain size and the concept of how much velocity (energy) is needed for entrainment, transport, and deposition of different sediment calibre (Fryirs & Brierley, 2012).

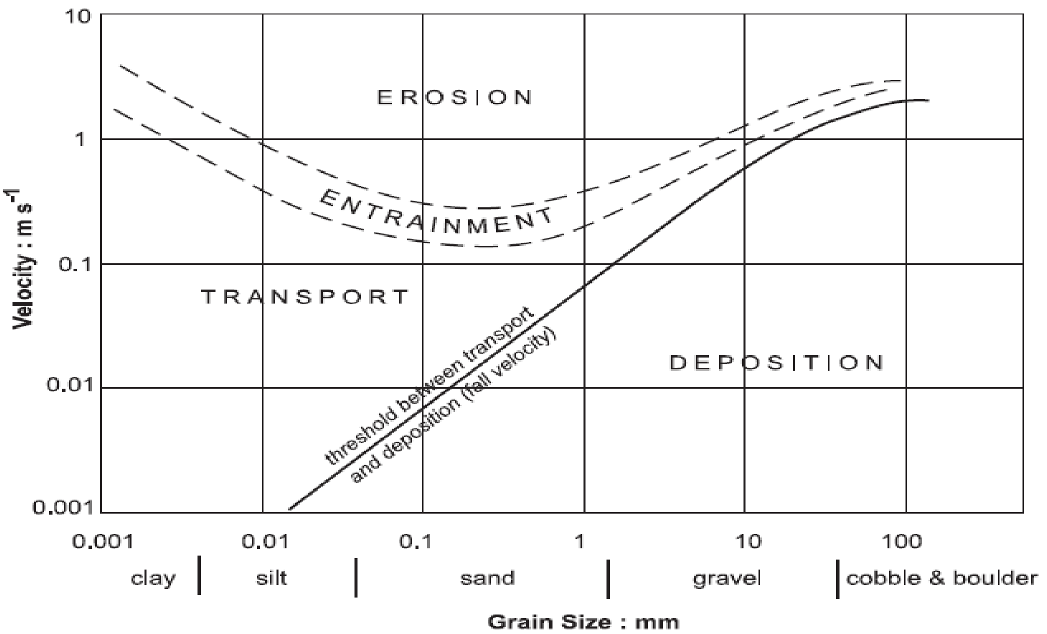


Figure 1: Hjulstrom diagram showcasing the relationship between grain size and velocity needed to entrain, transport, and deposit sediment (copy from Fryirs & Brierley, 2012; page 84).

The entrainment curve shows the minimum velocity needed to pick up the sediment of different calibre (Figure 1). Gravel, cobbles, and boulders need much higher velocities to be entrained due to their low surface area relative to weight, thus need more energy to be entrained. Though clay particles are quite small in size, they relatively need as much energy as the larger particle size. This is due to their cohesiveness caused by strong electron bonds which makes the particles stick together (Fryirs & Brierley, 2012; Gordon *et al*., 2004).

The transport zone is the movement of sediment within the flow and is kept within the water column through turbulence acting upon it. This form is therefore responsible for the downslope movement of sediment. A certain critical velocity is needed to transport sediment and the time in which sediment remains in transport varies for each sediment calibre. The transport zone has lower velocity requirements than the entrainment (Figure 1). Smaller particle size remain in suspension and can travel for longer distances while coarser sediment travel for shorter distances and have the likelihood of being deposited first (Fryirs & Brierley, 2012; Gordon *et al*., 2004).

The deposition curve is when there are low velocities such that sediment settles out of suspension to be deposited as the energy is inadequate to transport and carry sediment in motion. Sediment, therefore, settles out or gets deposited when fall velocity is reached, this is due to its density being greater than that of water or differentials in size, density, and shape (Fryirs & Brierley, 2012). As velocity decreases coarse sediment particles get deposited first and smaller or finer sediment are maintained in motion. Deposition can occur even with the slightest drop in velocity (bedload and coarser sediment) and a very large drop in flow velocity and energy can deposit suspended load sediment. It also occurs when the river capacity is exceeded i.e. the available stream power is unable to move all the available material within channels (Wainwright *et al*., 2015; Fryirs & Brierley, 2012).

2.3.1 Deposition on river channel geomorphic units

2.3.1.1 Longitudinal variation in instream geomorphic units

Streams are considered as open channels as they experience inflows and outflows of energy and matter continuously and this occurs continually over a range of time scales. As water moves from upstream to downstream, energy is expended on transport, and sediment is rearranged in channel bedforms and its banks, thus can create different depositional geomorphic units such as bars, pool-riffle sequences, and braided deltas. Among other factors, bed sediment can be influenced by discharge, changes in channel slope, and width as these impact channel hydraulic properties. Furthermore, analysis of the depositional sequence can give insight into the flow conditions under which the geomorphic unit was formed and reworked (Fryirs & Brierley, 2012; Gordon *et al*., 1992). In many cases, each geomorphic unit consists of certain sediment structures, e.g. longitudinal point bars consist of gravelly sediment structures which are most likely to receive high occurrence of sediment transport due to scour and deposition (Curran & Hession, 2013). Local flow or flow capacity conditions can also affect the sediment sorting and type e.g. coarser material are commonly found on riffles and regions of high shear stress. Finer material are associated with pools, bends with shallower flowing water, and between boulders of headwater streams and confluences.

Bedrock are non-deformable channel features in which flow and sediment transport and accumulation have to adjust to i.e. the morphology of a river can be more the result of the physical characteristics of bedrock than the hydrology and sediment transport hydraulics (Heitmuller & Hudson, 2009; Brierley *et al*., 2006). Thus, the bedrock structure is likely to influence valley slope and the hydraulics associated with the bedrock which in turn is liable for erosion, sediment transport, and depositional processes around the bedrock feature. This causes transport capacity to be greater than sediment supply which can induce deposition around these areas (Heitmuller & Hudson, 2009; Frings, 2008). Channels composed of bedrock can be susceptible to erosion due to the mass failure of large rocks and the grinding of channel beds by stream transported debris. Therefore, sediment size and the distance the sediment has travelled from sources can be recommended as an effect of geology and hydrology (Heitmuller & Hudson, 2009).

Pools are usually the deeper regions of the river channel with deeper-flowing water and sediments are typically composed of finer-grained particle size whilst a riffle is associated with faster shallower-moving water and coarser material. Pool-riffle sequences act in a 'pseudo-cyclic' manner. Pool depth is determined by the topography of the riffle. They are commonly found in river systems of high flow variability and in meandering rivers; with pools in the meander bends and riffles at crossover stretches (Fryirs & Brierley, 2012).

Bars are generally larger bed form units formed by sediment deposition at high discharges. They remain in place to define the path of flows and have a variety of shapes with different grain sizes (Fryirs & Brierley, 2012; Frings, 2008; Moussavi-Harami *et al*., 2004; Surian, 2002). Substrate pattern size only change during high flows, especially in streams with coarser material. Therefore, the spatial distribution of bed material is typically more related to previous flood events than the standard flows that are conveyed by the stream. In headwater regions, bed material is usually large, thus exceeding the sediment carrying capacity of the flow. These large bed materials often disintegrate with distance from their source. Thus, the mean grain size generally decreases through fragmentation and abrasion where finer particles are sorted and carried out in suspension (Frings, 2008; Surian, 2002). This is governed by two processes namely abrasion (the breakdown of particles during transport) and selective transport (preferential transport of finer particles downstream) (Frings, 2008; Moussavi-Harami *et al*., 2004). Bed sediment can change flow hydraulics and therefore channel morphology (Surian, 2002). Abrasion and selective transport are not be the only aspects influencing spatial distribution of particle size; headwaters, hillslope, channel geometry, lateral inputs of coarser material from tributaries also attribute to bed sediment variation (Menting *et al*., 2015).

Furthermore, sediment in a channel can be transported as bedload, suspended load, and dissolved load (Figure 2). Suspended sediment is comprised of clay, silt, and sand. This material is carried aloft and is suspended above the channel bed by turbulent flow and transported downstream. The finest of suspended sediment is wash load and constitute particles with diameters less than 0.0063mm whilst bed-material load are much coarser particles in the water column (Fryirs & Brierley, 2012; Charlton, 2008).

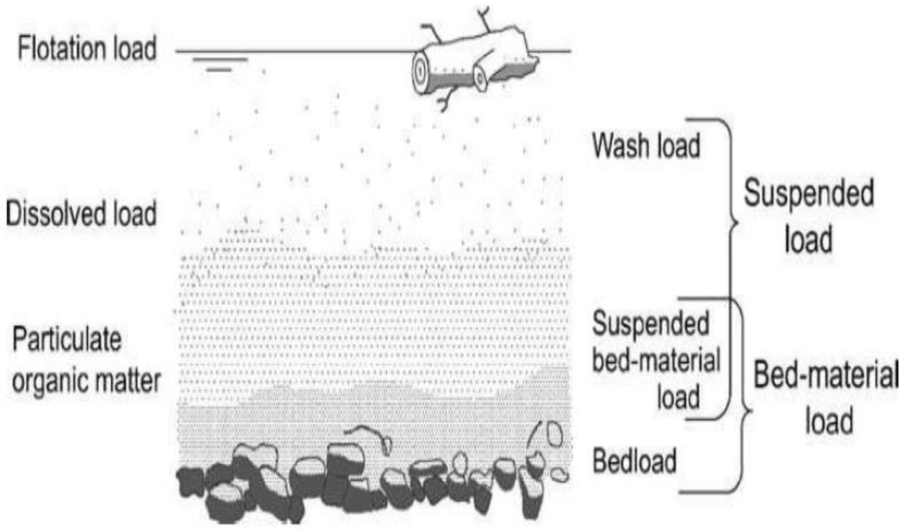


Figure 2: Description in the variation of sediment calibre in a river system (copy from Fryirs & Brierley, 2012; page 83)

2.4 Processes of overbank floodplain sedimentation

The Hjulstrom curve diagram (Figure 1) can also be considered when explaining the spatial relations of sediment transport dynamics in fluvial systems. Floodplain systems have the ability to frequently inundate, such that when water flows from the river channel to the floodplain, there is a decrease in water depth and an increase in 'channel width' as water spreads out (Maltby & Barker, 2009). This results in a decrease in flow energy and results in sediment deposition once the fall velocity is reached.

The energy of flow dissipates across the floodplain landscape, such that finer-grained sediment is typically found in oxbows, back swamps, and possibly in abandoned channels. This is due to their low energy transportation, ability to remain in suspension for longer periods, and longer travel distances (Fryirs & Brierley, 2012; Maltby & Barker, 2009).

Furthermore, (Yang, 1977) described the complexities of the rates at which sediments are transported and their dependence on various parameters. These ranged from differences in flow velocity, discharge, water depth, shear stress, stream power, the energy of slope, and turbulence. In the context of sediment transport, rivers expend energy and do geomorphic work, however, this is initiated when a certain energy level is reached to entrain and transport sediment (Fryirs & Brierley, 2012).

Three forms of geomorphic work exist in rivers i.e. when a river has surplus energy; it will have more energy than the required to transport water and sediment which can form erosion. It can also have the exact amount of energy needed (stable) or have an insufficient amount of energy to transport sediment thus leading to deposition. Aggradation and deposition results when the sediment supply is larger than transport capacity such that sediment transport processes are unable to occur. Erosion occurs when transport capacity or the relative energy in a system is in excess relative to the available sediment such that energy is consumed in erosion (Fryirs & Brierley, 2012).

Figure 3, known as the Lane Balance diagram can be used to explain this dynamic as a function of impelling forces at a given point in a river system. This leads to the erosion and deposition mosaic that indicates that the channel is active. The basic concept of the Lane Balance diagram exemplifies how the channel can respond to different channel parameters such as available water flow supplied to a system, sediment load, and the relationship between sediment size and stream slope. For example, less sediment supply results in channel erosion, and a reduction in the water supply to transport sediment results in aggradation. A decrease in stream slope decreases energy in the system to transport sediment thus aggradation occurs.

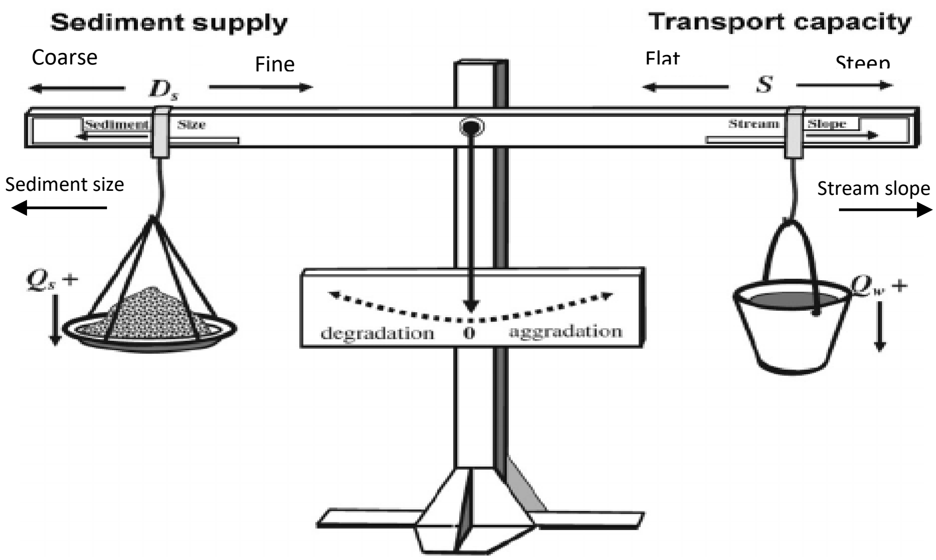


Figure 3: Lane Balance diagram (copy from Childs, 2010; page 11).

Therefore, to better understand the sediment dynamics, conceptual frameworks are quite useful tools in describing the processes involved and will provide a visualized perspective of understanding in the spatial and temporal distributions (Fryirs & Brierley, 2012; Vercruysse *et al*., 2017; Yang, 1977).

2.5 Sediment transport at overbank flows

When floodplain systems are overtopped during inundation events, floodplains can either be composed of bedload, suspended sediment, or a combination of bedload and suspended sediment transported during high energy events (Figure 2). Intermittently suspended sediment consisting of sand is transported by saltation and is deposited above bed load and finally the fine sand, silt, clay that comprises the bulk of floodplain sediments. The transfer and deposition of sediment on the floodplain occur by lateral and vertical accretion that is formed by channel migration and overbank deposits respectively (Middelkoop & Asselman, 1998; Pizzuto, 1987). Lateral accretion results when bedload and intermittently suspended sediment deposits on the convex slope of bends are incorporated with the floodplain when the channel migrates (Figure 5). Vertical accretion occurs when there is a large increase in flood frequencies and magnitude such that sediment supply and sediment transport mechanism cause vertical accretion on the floodplain (Fryirs & Brierley, 2012; Figure 5).

The exhibited sediment accumulation patterns during periods of inundation is correlated to the presence of dykes, the topography of the floodplain, and the transporting mechanisms of sediments. This spatial variation in sedimentation during overbank flows can also be affected by local factors such as vegetation, the frequency, and magnitude of floods, flow velocity, flow patterns, suspended sediment concentration, the morphology of the floodplain, and distance (Benedetti, 2003; Pierce & King, 2008; Middelkoop & Van Der Perk, 1998; Table 1).

Pizzuto (1987), simplified and illustrated the distribution of water and suspended sediment during inundation events within a steady and uniform flow (Figure 4). At inundation events, the flow is relatively fast and deep in the channel than its adjacent floodplain surface where there is shallow slow water flow. Deeper fast flows are more capable and competent of transporting suspended sediment than flows in shallower areas, because of this reasoning; high concentrations of suspended sediment will be expected within the river channel compared to its adjacent floodplain. If the valley is fully inundated and the flow is steady, turbulent diffusion and advective suspended sediment transport become the dominant sediment transport mechanisms across the floodplain. Sediment will therefore be carried out from the high sediment concentrations in the channel onto lower sediment concentrations across the floodplain.

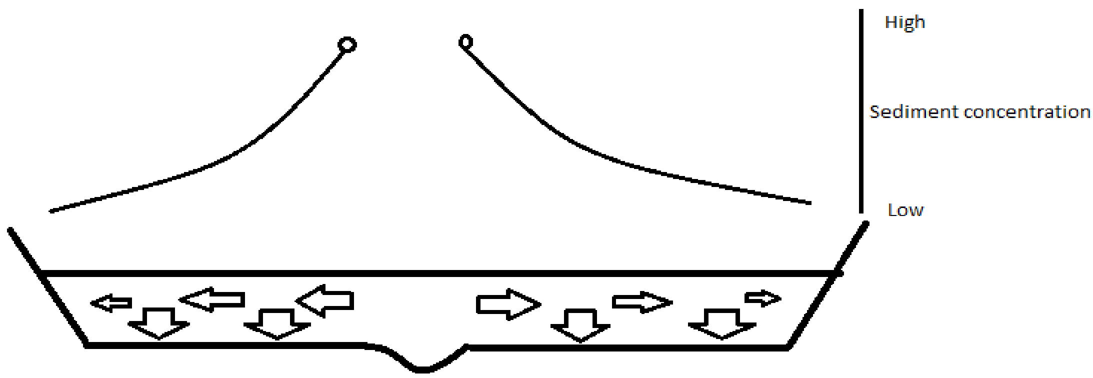


Figure 4: A systematic diagram illustrating sediment distribution and how sediment is likely to transport during overbank flows. Vertical arrows show the net sedimentation while horizontal arrows illustrate lateral accretion of suspended sediment (adapted from Pizzuto, 1987).

As sediment diffuses further away at a larger distance from the channel, sediment overload the floodplain flows and deposit some suspended sediment. The arrows (presentation of sediment concentration) decrease with distance from the channel. As the flood progresses, suspended sediment concentrations decrease with space and time as the amount of sediments deposited on floodplain areas is directly dependent on the suspended sediment concentration found in the main river channel (Middelkoop & Asselman, 1998; Pizzuto, 1987).

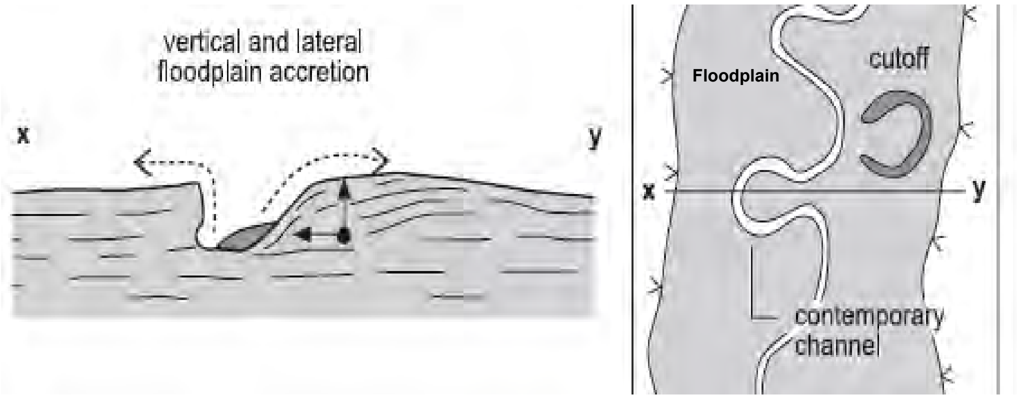


Figure 5: Vertical accretion resulted from the overbank deposition of suspended load during high flow events (copy from Fryirs & Brierley, 2012; page 162).

Two forms that characterized vertical accretion deposits are distal and vertical fining (Figure 6). When channel flow breaches its banks, suspended load sediment gets deposited on top of banks such that coarser sediments are deposited first and finer sediment are deposited further away from the channel (distal fining) as transport capacity decreases away from the channel (Fryirs & Brierley, 2012; Pizzuto, 1987). The transported suspended sediment and its resultant overbank sedimentation during inundation events, therefore, result in the spatial variability of particle size across the floodplain. Investigating the spatial variability of sediment particle size is therefore an important component of understanding overbank floodplain sedimentation (He & Walling, 1997). It assists in understanding sediment transport processes and suspended sediment deposition over river floodplains during periods of inundation.

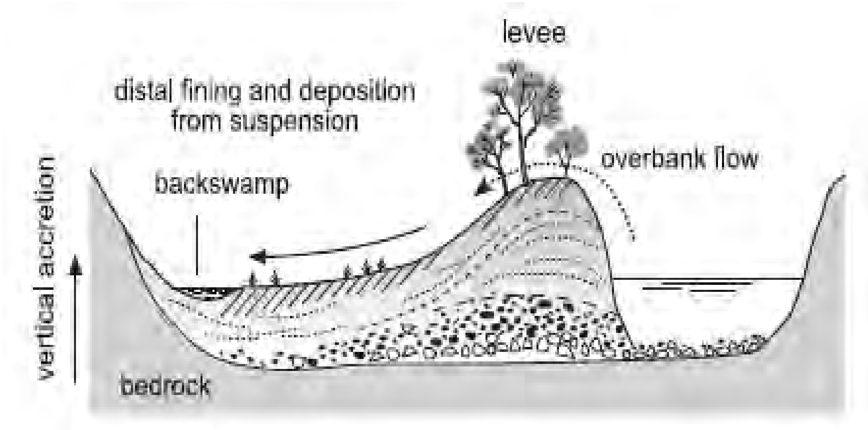


Figure 6: Vertical accretion over a levee to the back swamp floodplain setting (copy from Fryirs & Brierley, 2012; page 158).

Kesel *et al*., (1974), Gretener & Stromquist (1987), and Zwolinski (1992) noted that high overbank sedimentation rates are initially at frequently inundated low lying floodplains with mainly finer sediment accumulating in the lower regions of floodplains. Furthermore, Hupp *et al*., (2008) noted that sediment deposition rates vary across floodplain transects and revealed three types of spatial sediment deposition patterns; a relative uniform or no clear trend from the levees to back swamps, decreasing deposition from levees to back swamps, and an increase in deposition from levees toward back swamps.

Table 1: Table showing a summary of the key influences on sedimentation patterns on floodplains

Key factors	**Expected particle size**	**Volume of sediment received**	**Organic content**
Morphology	Pools, bars, oxbows, and back swamps are likely to have finer particles while riffles, bedrock controlled, channel bed, benches, banks, and levees are likely to have coarser particle size (Fryirs & Brierley, 2012)	Higher elevated areas such as levees induce less sediment accumulation than the lower depositional sinks such as oxbows and back swamps (Hupp *et al*.,2008)	Coarser material commonly found in riffles, benches, banks, and levees have low organic content than in pools, oxbows, and back swamps (Schorer, 1977)
Flood frequency and magnitude	High flood frequencies and magnitude have coarser particle size while low flood frequencies and magnitude have finer particle size (Hupp *et al*.,2008)	Higher flood frequencies and magnitude are likely to induce high volumes of sedimentation (Guan *et al*., 2015)	Low organic content with higher flood frequencies and magnitude (Hupp *et al*.,2008)
Flow velocity	Coarse material are associated with high velocities and low flow velocities in finer material	Flow velocity can promote erosion and deposition. However low velocities can be associated with high sediment accumulation (Guan *et al*., 2015)	High organic content in slow-flowing velocities (Schorer, 1977)
Topography	Higher elevation is likely linked with coarser sediment size whilst lower elevation is likely to have finer particle size (Hudson & Heitmuller, 2003)	High elevated topography promotes low sedimentation rates compared to lower elevated areas than areas with low elevation (Hupp *et al*.,2008)	High organic content in areas of low elevated areas (Hupp *et al.,* 2008)
Vegetation	Particle size differs for each vegetation type or vegetation geometry. However, denser vegetation promotes finer material (Steigner *et al*., 2001)	The denser the vegetation the more sediment is accumulated (Fennessy *et al.,* 1994)	Higher organic content in vegetated areas (Wan, 2019)
Distance	Coarser particle closer to the channel and finer particle size with distance away from the channel (Kesel, *et al*.,1974)	The greater the distance from the channel, the lesser sediment accumulation rates are. (Pizzuto ,1987)	More organic content on features far away from the channel e.g. depositional areas like back swamps (Hupp *et al.,* 2008).
Hydro period	A longer hydro-period results in finer particle size (Hupp *et al.,* 2008)	Longer hydro-period results in high sedimentation rates (Hupp *et al.,* 2008)	High organic content is associated with longer hydroperiods (Hupp *et al.,* 2008)

However, Steiger *et al*., (2001) noted that sediment deposition rates in floodplain systems are mainly reflected by local hydro geomorphological controls, including flood overbank flow patterns and geometry of the channel, which impact grain size variability in overbank flood deposits. While Maltby & Barker, (2009) noted that sedimentation is not only a function of velocity but also the size of particles being transported.

Furthermore, water flow movements from the river channel to floodplain systems are not only controlled by vegetation but also by other topographical features that restrict flow such as levees, oxbow, depressions, floodplain micro-channels which are later discussed in the literature review.

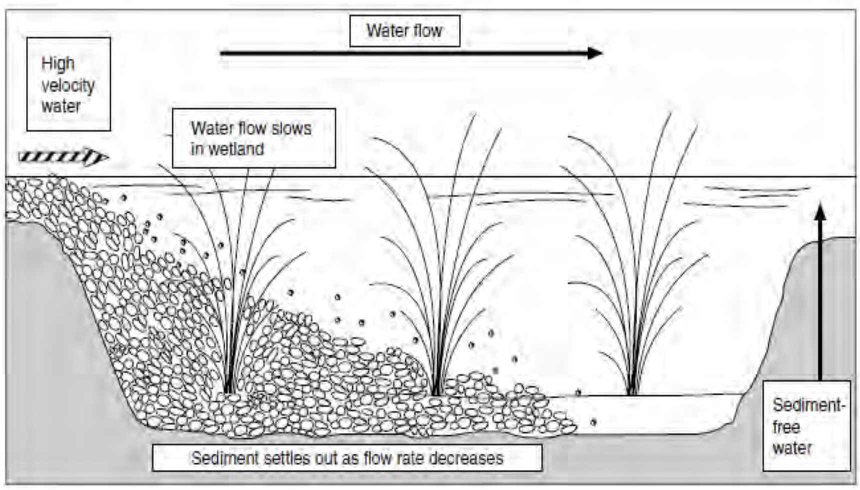


Figure 7: An example of how sediment deposition occurs with varieties of flow velocities in a depression feature (copy from Maltby & Barker, 2009)

2.6 The dis-connectivity of sediment conveyance in floodplain landforms

When fluvial systems carry sediment like water from land to ocean, only a certain proportion of sediment that gets eroded is delivered to a basin outlet in a catchment and is represented as sediment yield (Brierley *et al*., 2006). Fryirs, (2013) denotes that rivers behave as a "jerky conveyor belt" where sediment is transported episodically through a catchment. Throughout this conveyor belt, sediment can be eroded and stored or be eroded and added to the conveyor belt. It has been documented that in most catchments, sediment rather remains in storage than in transport such that sediment delivery to other parts of the catchment is reduced by storage (Fryirs, 2013; Maltby & Barker, 2009). The type of landform and where sediment is stored and recurrence of reworking is considered as the main driver of resilience to sediment delivery. Sinks such as floodplains, terraces, and slopes are more considered as permanent zones of sediment storage as they have longer residence times compared to other wetland types such as valley bottoms (Fryirs, 2013; Fryirs & Brierley, 2012; Fryirs *et al*., 2007).

Sediment conveyance across floodplain systems is maintained through the longitudinal, lateral, and vertical linkages or connectivity (transfer of water, sediment, or substance between slope-channel or within a whole system e.g. river channel or between surface and groundwater ecosystems of sediment cascade) (Fryirs, 2013; Brierley *et al*., 2006).

The longitudinal linkage consists of upstream-downstream and tributary trunk stream relationships. They can transfer sediment of variable calibre. Lateral linkages include the relationships between the channel network and the wider landscapes e.g. slope-channel and floodplain-channel. Slope-channel relationships record the frequency with which the channel processes rework material from hill slopes to channel. Channel-floodplain linkages are driven by the magnitude and frequency of flood inundation events. Vertical linkages include the surface and subsurface linkage of water and sediment (Fryirs *et al*., 2007). However, this can be restricted or disrupted by various forms that impede or dis-connect sediment conveyance, constraining sediment transfer by limiting the connectivity between landscape compartments. This is affected by the existence of buffers, barriers, and blankets which act as sediment sinks or storages thus removing sediment from the conveyor belt over a period of time as they act as floodplain sediment buffers.

Buffers are forms that restrict sediment from entering the channel network thus serving as sediment storage sinks (deposition). Once sediment is within the channel, barriers disrupt the movement of sediment along the channel i.e. restraining the transport of sediment and entrainment in and along channels. Dis-connectivity's that operate at various magnitude-frequency domains can therefore disrupt the transport and deposition of sediment at any position in a catchment either from hill slopes, alluvial plains or within channels. The nature, type, and position of a floodplain landscape dictate the strength of connectivity between two compartments such that sediment fluxes maybe be disconnected (decoupled) or connected (coupled) over different timescales (Fryirs & Brierley, 2012; Fryirs *et al*., 2007).

Furthermore, buffers can distort the longitudinal and lateral connectivity. They can form floodplain alluvial pockets along margins of a valley thus disrupting the lateral movement of sediment (Fryirs *et al*., 2007). An example of a low relief floodplain buffering system that is affecting the sediment entrainment is described in a research study by Fryirs *et al.* (2007). The study reports that large volumes of sediments are sourced from mass movement processes that are directly entrained into the channel. The author noted that at high transport capacities, only finer sediment particles are deposited downstream and that low transport capacity induces the formation of debris fans that act as sediment buffers. Examples of other buffer systems are features namely flood outs and valley fills with little or no watercourses.

Barriers mostly disrupt the longitudinal linkage through the bed profile of a channel e.g. bedrock steps such that slope is reduced in introducing a local base level control. Sediment, therefore, has the likelihood of being trapped as they backfill areas immediately upstream of the step, inducing local discontinuity in sediment transfer. Barriers are frequently reworked and breached units such as levees (Fryirs *et al.*, 2007). Blankets mostly affect the vertical linkages on the subsurface and surface interactions as well as the entrainment and transfer of sediment. They can occur in-stream or on floodplain surfaces as sand sheets or gravel material that can infill entices of gravel bars. Therefore, the distribution of sediment stored and deposited within the floodplains determines or influences the routes and the sediment transport which may provide a discontinuity in sediment transport of that given landscape. The processes of sediment discontinuity in sediment transportation causes a jerky conveyor belt to form which has an impact on the variability of sediment patterns spatially and temporally (Fryirs *et al.*, 2007).

Blankets are described as sediments that 'cover' other landforms and temporarily prevent reworking of sediment in the sediment cascade thus affecting sediment entrainment. For example, bed amour are features that prevent reworking of subsurface material.

To fully understand and gain a full understanding of the sediment dynamics in floodplains, a framework on the understanding of sediment delivery, sediment movement, and processes from the channel onto the floodplain is needed. This will give an insight as to why certain spatial and temporal variations of sediment dynamics are observed (Fryirs, 2013). This includes the understanding of identifying whether blockages are of the longitudinal, lateral, and vertical linkages.

2.7 Floodplain depositional environments

The following section gives some insight into the dynamics of floodplain sedimentation of different floodplain depositional environments. Sections covered include; floodplain oxbows, levees, back swamps, and flood benches.

2.7.1 Floodplain oxbows

Oxbows are one of the distinct floodplain landform features that are fundamental to mobile floodplain rivers (Constantine *et al*., 2010; Hooke, 1995). Oxbow lakes and meander bends are often situated in low-lying areas and often contain larger amounts of silt, clay, and organic content. Their formation and their persistence in landscapes have a manner of influencing sediment trap efficiencies (Constantine *et al*., 2010). This also determines their importance as sinks for contaminants by adsorbing to finer suspended sediment fractions (Constantine *et al*., 2010). Oxbow lakes situated near river channels normally have high sedimentation which may sometimes be induced by anthropogenic erosion (Sedláček *et al*., 2016). Old meanders and oxbows can act as ideal sediment buffers for suspended sediments. In some instances, deposition in these areas is caused by various phases of blockage of former meander bends and abandoned channels or persistence of lake stage (Sedláček *et al*., 2016; Hooke, 1995).

Constantine *et al*., (2010) further described that deposition in abandoned or old channels and oxbows is dependent on the diversion angle between active and abandoned channels. The author noted that abandoned channels with a high angle of diversion lose their capability to transmit bed material faster which results in rapid aggradation in the entrance of the abandoned channel (Figure 8). This concept forms an oxbow filled with the finest sediment proportions delivered during flood events. However low diversion angles are capable of transmitting both bed material and finer sediment from the active channel which slowly transition into oxbow lakes with a greater representation of coarser material. The sediment load vary temporally and spatially due to differences in river discharge and sediment availability itself (Sedláček *et al*., 2016; Constantine *et al*., 2010)

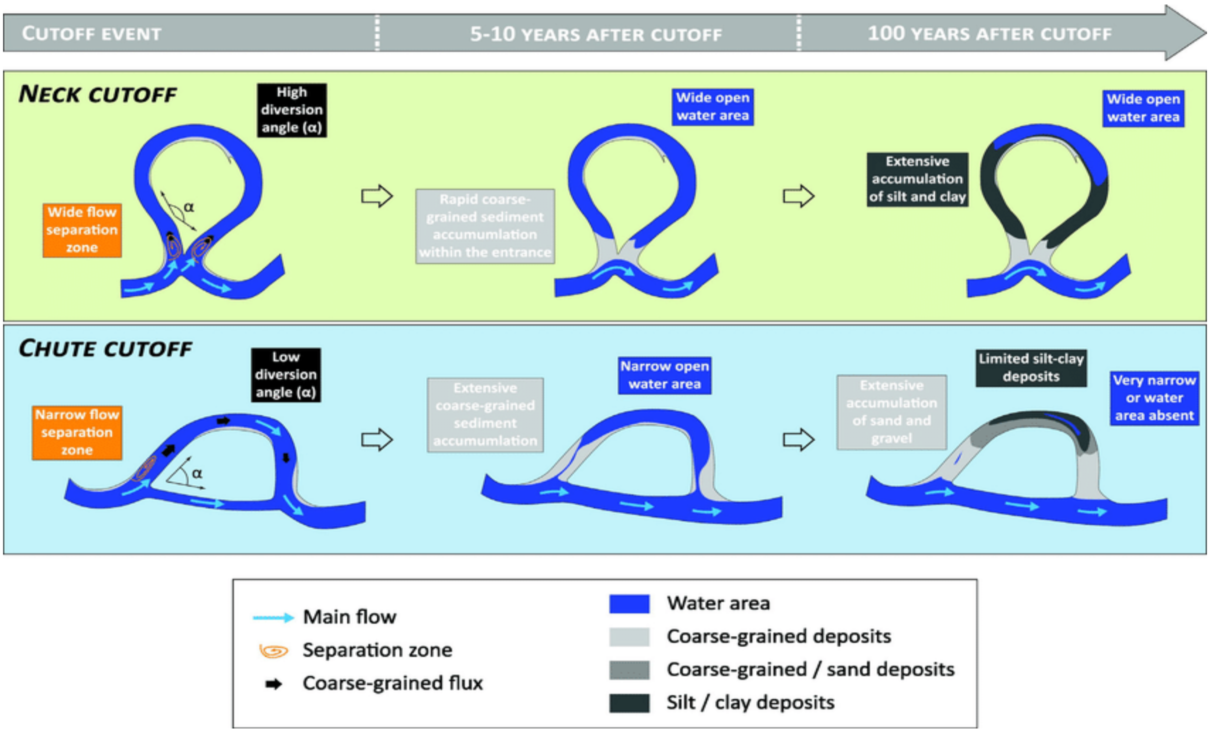


Figure 8: A schematic diagram describing how changes in diversion angles influence channel flow and sediment accumulation (copy from Dépret *et al*., 2017; page 100).

2.7.2 Natural Levees

Natural levees are formed from overbank flood deposits thus creating sinuous ridges along river channels. During overbank flows, sediment sorting results in lateral fining of flood deposits (Hudson, 2015; Hudson & Heitmuller, 2003). This process, therefore, forms landforms sloping towards low-lying floodplain reaches that later form the highest components of floodplain topography. Sediment material found on a levee represents the form of flow regime that has occurred at that specific time (Hudson, 2015; Smith & Pérez-Arlucea, 2008; Hudson & Heitmuller, 2003). They are more associated with low-lying meandering rivers although they can also form in different types of river-floodplain systems that flood regularly.

Natural levees can extend and overlay onto former channel deposits and back swamps in active meandering river floodplains and on the inside of meander bends which are normally densely vegetated (Hudson, 2015; Smith & Pérez-Arlucea, 2008; Hudson & Heitmuller, 2003). When in-situ channel flow exits the channel; upon flowing onto the floodplain, an abrupt change in the flow velocity over the levee results. This leads to deposition; mainly of coarser sand and silt sediment material. These sediment particles are later transported along the surface of the floodplain as a form of bedload material which gets finer and gets deposited primarily in back swamps and oxbows (Hudson & Heitmuller, 2003). This variation of sediment particle size can be expressed by quantitative means through observing the exponential decrease in the D50 particle size or as a linear increase in the percentage of sediment finer than 0.016mm, varying from very fine sand to silt (D50 particle is known as a median diameter to describe particle distribution of a desired sample, for example, if a given sample has a median diameter of 17.08µm, then this means that 50% the particles is greater than 17.08µm and the other 50% is less than 17.08µm) (Cazanacli & Smith, 1998; Middelkoop & Asselman,1998). During high velocity flows, this results in planar bedding and formation of ripples and cross strata at low velocities as sediment particles are transported by bouncing action (Hudson, 2015; Hudson & Heitmuller, 2003; Middelkoop & Asselman, 1998).

An increase in bank height results in a reduction of coarser sediment deposition and rather finer sediments are along levee back slopes. As overbank deposition continues, the banks and levees, therefore, become higher which makes it 'difficult' for coarser sediment to be transported from the channel to the floodplain than finer sediment that are transported more easily over the banks and across the floodplain (Cazanacli & Smith, 1998). Findings by Smith & Pérez-Arlucea, (2008) supported the theory of coarser-grained silt and sand sediment particles in newly formed levee deposits. Most of the thicker and coarser flood deposits displayed ripple lamination and cross-stratification. This can also be attested in a study by Middelkoop & Asselman (1998), the author showed that sandy sediment particles were mostly found near the channel on the levees upstream of the floodplain.

Levees can therefore act as disruptions in depositional patterns and rates, channel-floodplain/floodplain-channel connectivity, and can increase the flood risk by reducing water storage in overbank flows (Hudson & Heitmuller, 2003). Levees generally trap the least sediment accumulation rates due to the relatively high elevations with shorter hydro-period and or have little or no hydraulic connectivity to the sediment-laden river channel (Hupp *et al.*, 2008).

2.7.3 Back swamps

Back swamps are major units of fine-grained storage areas that are also vertically accreted through suspended sediment deposition and more likely situated on low regions of floodplains (Hupp *et al.*, 2008). Back swamps can remain saturated for lengthy periods of time and are isolated from the river channel. Back swamps normally receive less sedimentation compared to oxbows due to aggradation occurring elsewhere in the floodplain. This is mainly caused by a reduction in energy gradients dissipating from the main river channel. Thus allowing suspended load sediment to be deposited and transported to back swamp areas resulting in slow fine-grained accumulation rates (Lisenby *et al.*, 2019). However, back swamps that receive high rates of sedimentation are at sites with low elevation and have high sediment-laden water from near sources of sediment that create low and slow velocities through hydraulic damming. The resulted difference in textural segregation of sediment in back swamps is therefore due to energy differences. Another factor is the dense aquatic and swampy vegetation that colonizes the area, resulting in fine sediments trapped thus promoting the accumulation of cohesive and organic-rich mud (Hupp *et al*., 2008).

2.7.4 Floodplain benches

Flood benches are in-channel geomorphic units that are step-like features, usually of different heights situated below the floodplain surface but above the channel bed (Davis & Kimbrow, 2010). Flood benches can function as storage environments for fluvial transported sediments and play an important role in transporting content matter in river systems. (Mitsch *et al*., 2014; Steiger *et al*., 2001). Flood benches are exposed to a variety of flow mechanisms but mostly through laminar accrual over time (Steiger *et al*., 2001). This close linkage between the river channel and floodplain benches is recognized when changes in flow regulations and sediment transport regime result in a change in the form, location, and sedimentation rate (Mitsch *et al.*, 2014). Low-lying areas such as flood benches with longer hydro-periods and with high hydraulic connectivity to the river channel experience high sedimentation rates and coarser sediment particle size (Hupp *et al*., 2008).

2.8 Impact of vegetation on floodplain processes

2.8.1 Vegetation roughness

Vegetation roughness in fluvial systems is one of the most critical components that influence the hydrodynamics of fluvial systems which have an impact on water surface elevation, sedimentation transport mechanism, and variability of sedimentation (Nehal *et al*., 2012; Curran & Hession, 2013). This also has long-term consequences for geomorphology, such as the formation of levee-basins with vegetated platforms. Natural floodplains tend to have more diverse vegetation due to the frequent flooding, this leads to a diverse spatial variability of flow.

Vegetation roughness affects the intensity of turbulent flows, flow resistance, and structure. Flow resistance and its structure (velocity, water depth) are however mainly affected by vegetation characteristics i.e. the density of vegetation, vegetation type, flexibility, height, vegetation distribution, orientation, shape as well as climate seasonal changes (Järvelä, 2004; Malty & Barker,2009; Fathi-Moghadam *et al*., 2011; Curran & Hession, 2013; Wang *et al.*, 2015). Furthermore, the hydraulic dynamics and vegetation have an impact in influencing the channel form by governing the transportation, trapping, and storage of sediments (Nehal *et al*., 2012). It has therefore gained more interest as it influences the conveyance of the channel (Järvelä, 2002; Nehal *et al*., 2012).

In light of the aforementioned, vegetation roughness differs, each vegetation characteristic contributes to the total drag which therefore influences the flow resistance of that particular area. For instance, studies by Wang (2015) showed that vegetation structures such as stems and leaves can cause a blockage or resistance of flow, decreasing flow velocity. Once this occurs, the ability of the flow to carry sediment decreases, causing sediment to accumulate in that particular area. Furthermore, if vegetation is concentrated on that particular part of the channel or floodplain system, it will cause a decrease in flow velocity around the center resulting in deposition (Li *et al*., 2015, Wang *et al*., 2015).

Several flow resistance models and formulas have been put into place to calculate and account for resistance for the different vegetation characteristics (Järvelä, 2004). However, research has been found to be limited with the case of low velocities and with the flow depth being less than the vegetation height which is more commonly found in floodplain wetland and low-lying gradient valley streams conditions. The need for more evaluation of resistance caused by vegetation on floodplains needs to be more articulated and implemented (Järvelä, 2004).

Steigner *et al*., (2001) denotes that vegetation roughness acts as a controlling factor in floodplain systems as it acts indirectly proportional to velocity i.e. an increase in hydraulic resistance, decreases velocities and capacity thus increases sediment deposition and particulate matter. The authors also noted that grass species is an important component in filtering sediments as well as shrubs which are quite effective in trapping sediments. In cases where there are isolated shrubby vegetation, floodplain scour occurs. Dense vegetation promotes uniform distribution of water flow in a wetland and an increase in vegetation density increases roughness that promotes sedimentation (Fennessy *et al*., 1994; Rowntree, 1991).

Primarily, sedimentation varies as a function of distance from the main river channel, when vegetation has not yet channelized flow but differs with the type of wetland and the rate of inflow water. In between vegetation patches or grouped vegetation, the flow velocity is enhanced which leads to reduced sedimentation and can also promote erosion. Furthermore, Rountree *et al*., (2000) explained that during large flooding events, large deposition of sediment is accumulated in dense reeds over time, increasing elevation and the development of preferential flow. Additionally, Fu *et al*., (2020), conducted a study based on plant stem arrangements effects on sediment transport. The author noted that, although plant stem arrangement and diameter have impacts on hydrological flow regimes and parameters, hydraulic connectivity, and transport capacity; the results showed no clear relationship between stem arrangement, sediment transport capacity, and hydrological parameters. However, Zhao *et al*., (2016) and Clarke, (2002) denoted that an increase in stem diameter and plant growth decreases frictional forces acting upon the water column. This, therefore, implied that sediment transport capacity is reduced, inducing local sedimentation. Reef *et al*., (2018) conducted a similar study which investigated vegetation height effects and biomass on sediment budgets, the author noted that these parameters are some of the key controlling factors in sedimentation and may usually have a non-linear relationship; depending on the flow conditions and climatic changes. Results showed that there was no link in vegetation height and sedimentation in some saltmarshes but did find a correlation in other types of marshes. These studies suggest that the effects of vegetation morphology on sedimentation can be site dependent.

2.8.2 Calculation of vegetation roughness

As aforementioned, vegetation has an influence on the hydraulic roughness in channel flows and on floodplains as there is an undoubted interaction between vegetation, friction, and flow that can cause turbulence and deposition in a river system (Wang, 2015). Understanding the relationship between flow resistance and vegetation is important as it provides a proper or an improved description and understanding of flow resistance and vegetation presence on vegetated floodplain wetlands (Järvelä, 2005; Baptist *et al*., 2007).

Calculating vegetation resistance can provide a platform for providing the probability of sedimentation. Vegetation resistance coefficient estimation methods are therefore used to predict resistance which is water depth-dependent or a relative computed water depth. Upon calculation of vegetation resistance; vegetation characteristics, bed resistance, water depth as well as the resistance co-efficient need to be determined. Traditional approaches such as Manning's formula for calculating flow resistance used a single resistance coefficient which has failed to eloquently describe the physics phenomena correctly (Li *et al*., 2015). Malty & Barker (2009) noted that traditional roughness calculations such as Manning's are often not sufficient to calculate or estimate surface flow within wetland systems as vegetation densities and their spatial variability in wetlands far exceed the densities incorporated in these equations such that large error bars occur in flow calculations. The Chézy formula is therefore one formula that can be used in calculating vegetation resistance which derives the concept of flow-through and above vegetation, taking into account vegetation density, height, and stem diameter (Baptist *et al*., 2007).

Vegetation resistance is therefore represented as a drag force that is created when water flows through vegetation and thus changes water surface elevation due to changed velocities (Bendix & Cowell, 2010). This component, therefore, creates differences in velocity gradients that lead to loss of momentum and more sedimentation processes. Differences in the Chézy value can be caused by variation in flow depth, vegetation density, and particle size. For instance, Nehal *et al.,* (2012) noted that an increase in vegetation height can decrease Chézy value, thus increasing sedimentation rates.

The Chézy formula can be used for both non-submerged and submerged vegetation. Moreover, this method uses equations to calculate flow resistance classified into two categories; tall non-submerged and submerged vegetation, non-submerged being the tall and woody plants, and submerged being the flexible herbaceous plants e.g. grass and shrubs (Baptist *et al*., 2007; Fathi-Moghadam *et al*., 2011; Nehal *et al*., 2012; Li *et al*., 2015). Resistance can be differed by the differing vegetation structure and water depth, shallower water depth with likely herbaceous and dead plants are likely to have low resistance than vegetation with shrubs, reeds, and trees; with high resistance (Malty & Barker,2009).

2.8.3 Influence of submerged and non-submerged vegetation roughness

According to Nehal *et al.,* (2012), the influence of non-submerged vegetation has been unclear thus needs to be studied more. The authors conducted a flume experiment of a non-submerged species using artificial vegetation to simulate the species focused on (Acorus calmus), to investigate how the flow resistance and velocity are affected. The results of the study indicated that flow resistance and velocity increase as a result of an increase in vegetation density and increased water surface levels. Nehal *et al*., (2012) also found out that the pattern distribution of the vegetation significantly influences flow resistance i.e. staggered vegetation with greater heights had a greater impact in increasing hydraulic roughness than sparse vegetation. This is because vegetation on rivers and floodplains consume a lot of energy and momentum from the flow. These results can also be attested to in a study by Wu (2008) where the results showed that hydraulic roughness increases due to staggered vegetation patterns and density. Hydraulic roughness increases with increasing water depth. An increased flow depth can be assumed to have little changes in flow velocity when flow depth is below vegetation height; therefore flow resistance varies with depth (Feng *et al*., 2007). Furthermore, Temmerman *et al*., 2005 noted that for emergent vegetation with shallow inundation; spatial sedimentation is relatively similar. Further, results of low roughness can be attributed to grazing and high flooding events that have the potential to remove or flatten vegetation (Dorji *et al*., 2014)

Submerged vegetation also has an impact on water flow velocities by influencing channel conveyance through shear stress reduction, flow resistance, and its carrying capacity. Once vegetation is submerged, the spatial patterns of sedimentation are relatively homogeneous thus this kind of vegetation effect explains a change in flow directions (changes to sheet flow) during single inundation periods. This, therefore, promotes sedimentation and retention of particles (Nepf & Ghisalberti, 2008; Temmerman *et al.*,2005). Nepf & Ghisalberti, (2008) and Feng *et al*.,(2007) noted that submerged vegetation has the ability to bend to some extent when water flows which then leads to a change in flow resistance and velocity. For fully submerged vegetation with increasing water flows, sediment deposition increases. Hydraulic roughness tends to decrease at low water depths but increases at a constant rate as the water level rises. This is due to the vegetation's thickness such that flow through the vegetation is negligible compared to that passing above it (Feng *et al*., 2007; Temmerman *et al*., 2005). Furthermore, the Chézy method has been used by various authors and has been proven to be successful (Lama *et al.,* 2020; Nassam, 2013; James *et al.,* 2010; Baptist *et al.,* 2007). This method will therefore be used for this research study.

2.9 Impact of elevation and water inundation depth on sediment deposition

Elevation and water level fluctuations have an impact on sediment deposition. The resulting sedimentation depositional patterns are therefore key variables in understanding the ecological and geomorphic relationships of floodplains over single inundation events (Temmerman *et al.*, 2005). Temmerman *et al*., (2005) noted that the spatial relationship of deposition of sediment is related to elevation, elevation exerts a relatively positive influence on the hydro-period of marshes. Local low elevated areas of the floodplain such as oxbows collect flows and are susceptible to more sedimentation compared to high elevated areas that normally remain dry for longer periods and receive less sediment. The author also noted that, on higher elevated marsh areas away from marsh edges, less sedimentation rates occur, this variation is caused by larger distances from the nearest stream.

Shallower regions of the floodplain contain less sediment accumulation rates than deeper areas with a longer hydro-period and water column (e.g. oxbows). High sediment accumulation rates of fine sediment are therefore expected in these regions due to slow-moving water (Table 1). It is therefore evident that a reduction in floodplain topography does influence the depth and sediment accumulation rates (Lecce & Pavlowsky, 2004b). Hupp *et al.*, (2008) also supported this study which the author noted that elevation across the floodplain can vary by few meters, thus small differences in flood and groundwater stages due to elevation can have a significant impact on inundation frequency and hydro-period. Areas with low elevation and high connectivity to the river channel receive high sedimentation rates.

Van Maren, (2007) and Pitlick & Cress, (2002) highlighted that particle size is a function of elevation and inundation depth; levees with high elevated areas and low inundation depth have coarse particle size compared to oxbows with low elevation and high inundation depth.

On the contrary Dorji *et al.*, (2014) found a positive relationship between elevation and vegetation roughness exists; low elevated regions are typical of high roughness due to frequent inundation and high water levels.

2.10 Approaches for short term floodplain sedimentation monitoring

There are several methodologies used in determining sedimentation rates on floodplains including, sediment trap bottles, astro turf mats, horizon markers, rare earth stable tracers, and dendrogeomorphic approaches. Quantifying sedimentation in wetlands both for the long and short term can be limited due to difficulties in methodology or measurement techniques, the difficulty in working in environments with temporary and infrequent flood events, the need to collect data and information on sediment rates for both short and long term periods that are capable of providing long term averages, the difficulties of measuring low rates of sediment accretion and lastly, the complexities of dealing with high spatial variability of surface and hydraulic condition (Walling & Bradley, 1989). However, the use of horizon markers and sediment traps has been recognized to be efficient (Fennesy *et al.*, 1994). Elliott *et al.*, (2017) noted that the use of automatic or instantaneous methods are much more expensive, time-consuming and an insufficient mass for geochemical analysis. Low-cost passive samplers, such as Astro turf mats and time integrated samplers were therefore used for this study

2.10.1 Time integrated samplers

The use of sediment traps started since the early 1950s to account for sediment deposited in oceans and lakes. Time integrated sediment traps are the most commonly used devices to measure suspended sediments for small catchments, mostly because they are simple, cost-effective, can operate unattended without the requirement of power methods to use, and are generally used for collecting frequently suspended samples in flood durations (Steiger *et al.*, 2003; Phillips *et al.*, 2000). This type of sampler traps sediment that is very fine and can allow a collection of suspended sediments over the entire flood duration. The sample mass can also be used for laboratory analyses i.e. to identify sediment mode and nutrient concentration (Phillips *et al*., 2000). Suspended sediments collected through time integrated samplers can be good sediment traps, they are however not good representatives for long-term sedimentation particularly because they can overestimate particle flux. This is because the sediment traps will be 'contaminated' by secondary sediments thus the sediment traps will not represent the initial direct measurement of primary sediments (Steiger *et al.*, 2003; Flower, 1991).

The Phillips tube sampler was mostly designed for unidirectional flow, giving insight on flow characteristics over the monitoring time frame within the sampler and the relationships between the ambient, inlet, and sampler flow velocities (Elliott *et al*., 2017). Flow enters as ambient flow through the 4mm inflow tube, the velocity decreases in proportion to the cross-sectional area when flow approaches the main body (98 mm) thus sediment settle within the inlet (Elliott *et al*., 2017; Perks *et al*., 2014). Once sediment is settled within the inlet tube, water flows throughout the outlet spacing (4mm). This method minimizes bias sampling which is usually inevitable in other sampling methods. The assessment of the distribution of suspended sediment fluxes and properties spatially can often be difficult or not be met when using established sampling techniques. Time integrated samplers are therefore the most efficient to use to bridge this gap to further understand the sediment delivery on fluvial systems (Perks *et al*., 2014).

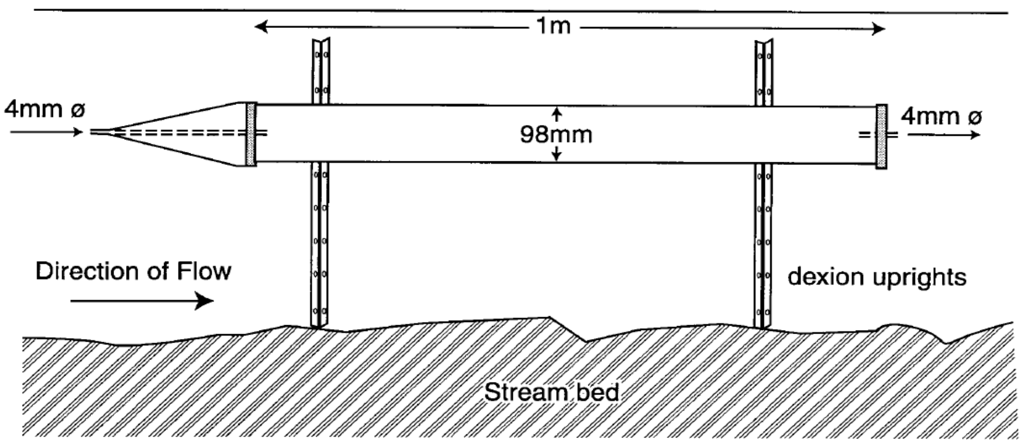


Figure 9: A diagram illustrating the installing of the time integrated sampler (copy from Phillips *et al*., 2000, page 3).

2.10.2 Artificial turf mats

This type of sampling technique has been the most used technique to quantify sediment deposition in the fluvial system as it provides detailed information on sediment properties i.e.

chemical and physical properties of the sediment samples from the turf mats (Steiger *et al.,* 2003). They provide credible results on sediment estimate deposition on different environmental conditions, simply because: they have a high surface roughness that can reduce sediment removal problems by floodwater, can resist shear stress of river flows, their robust and flexibility permits an easy installation on ground surfaces and lastly, the sediment deposited can be fully recovered for accurate measurement, thus supporting a wide range of analyses. Steiger *et al.,* (2001) in a study of riparian woodland zones in the River Severn over a flood event, noted that this type of technique is a more dependable sediment sampling design as it provided more reliable accurate results than ceramic tiles and erosion pins. The author found that small flat replicated sediment traps may not always provide plausible results than the ones with larger and single sample flat devices (Steiger *et al*., 2001; Steiger *et al.,* 2003). Differences in sedimentation thickness on astro turf mats suggest that there is a strong variability in sedimentation patterns and that the method is sensitive to local variation in sedimentation (Middelkoop & Asselman, 1998).

2.11 Organic content

Floodplain systems are recognized as important sink functions of sediment particulate matter thus improving water quality downstream (Saaltink *et al*., 2018; Lisenby, 2019). It has been documented that high organic content is correlated with the abundance of clay and smaller sand particles (Schorer, 1997).

Depending on the movement of water, some of these organic content properties include – carbon content, volatile substances, or the loss of ignition phosphate, nitrogen. This sediment organic content can originate from allochthonous sources such as vegetation, plankton from the riverine, or eroded rocks and soils (Remeikaite-Nikiene *et al*., 2016; Strong *et al*., 2012). Furthermore, since sediments are considered as potential sinks and sources of contaminants, determining pollutant partition on sediment of different size fractions is therefore important and since each particle size has different transport processes and remobilization (Schorer, 1997). Strong *et al*., 2012 noted that organic content increases with distance from the main river channel in the Pearl River estuary, this is due to controlling factors such as depositional processes and dispersal of sediment, and last but not least to cycling and biological processes. However, it may also be a function of particle size and the morphology of floodplain geomorphic features. Furthermore, Hupp *et al.*, (2008) conducted a study, investigating sedimentation patterns at the Atchafalaya basin. Results showed that organic content tended to increase with low deposition rates regardless of the site or floodplain features. In this study, sediment particle size across the floodplain were used to determine the relationship between particle size and organic content. However, knowledge on the spatial and temporal distribution of organic content is still limited (Neachell, 2014).

3. Study area

The Mzimvubu River Catchment is located in the northern region of the Eastern Cape Province of South Africa. It has a catchment area of 19 852km^2 that extends from 29° 54' 51" to 31° 38' 35" south and 27° 55' 56" and 29° 39' 14" east (Le Roux, 2018). The Drakensberg Escarpment is the main water source of the Mzimvubu River Catchment and it has four main tributaries namely the Tsitsa, Tina, Kinira, and Mzintlava (Figure 10). These tributaries flow down through the deep river valleys that are incised into the coastal belt and discharge to the Indian Ocean at Port St Johns (Pretorius, 2016). The current study is based in the Tsitsa River Catchment which is estimated to have a drainage area of 4924 km^2 that lies between 30° 46' 58" to 31° 28' 55" and 27° 55' 56" to 29° 13' 47" east of the Eastern Cape Province (Le Roux, 2018). The study research is situated in Maclear town (31° 04' 60.00" and 28° 21' 59.99"), in the upper Tsitsa River Catchment.

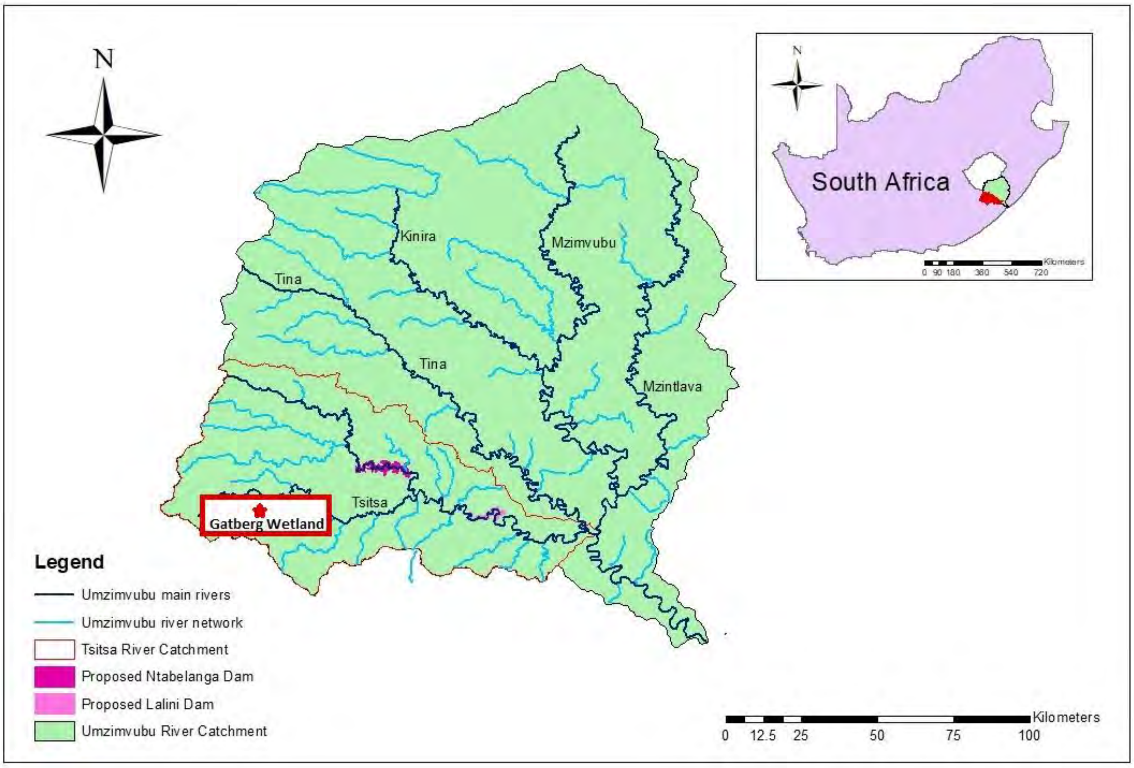


Figure 10: Study area map of the upper Tsitsa River Catchment with the five main river networks on the Umzimvubu River Catchment along with the location of the Gatberg Floodplain Wetland.

3.1 Geology and soil type

The Tsitsa Catchment geology consists of a variety of geology mainly from the Karoo Supergroup. The upper reaches of the catchment are basalt of the Drakensberg Formation. The Gatberg Floodplain Wetland lies within the Elliot and Molteno Formations (Figure 12).

The Elliot Formation is characterized by a succession of mudstones and medium-grained feldspathic sandstones that are reddish colored due to high oxidation rates. This formation is associated with meandering, and marshy floodplain environments. The upper part of the Elliot Formation is composed of sediments that were deposited in playa environments that were eventually replaced with aeolian dunes 190 Ma (Pretorius, 2016). The underlying Molteno Formation is composed of felsic, mudstones, sandstones, and shale interlayers that were deposited by perennial braided river systems. These layers vary in rock hardness and erodibility, therefore forming a terraced present-day morphology of hill slopes, containing scattered coarse-grained sandstones on slopes (Botha *et al.*, 2012). Such alterations affect the type of sediment supplied to and deposited within wetlands.

These formations are associated with high clay content and duplex soils which consist of a distinct soil structure, texture, and consistency from the topsoil to the subsoil due to leaching and paedogenesis (Le Roux*,* 2018). The high clay content availability results in low soil permeability that limits water flow through the subsurface of the soil matrix (Flügel *et al.*, 2006; Le Roux, 2018) thus high organic content levels are expected. The erosion susceptibility of these soils is not only caused by high sodium adsorption but is also coupled with overgrazing and croplands, hence the high erosion rates observed in the catchment (Le Roux, 2018; Pretorius, 2016).

3.2 Climate

The Tsitsa River Catchment is characterized by temperate subtropical or sub-humid climate, receiving most of its rain during the summer (Flügel *et al.*, 2006). The Mean Annual Rainfall can range from as low as 625 mm in lower altitude plains to 1327 mm in mountainous regions of the catchment. Maclear town has an average annual rainfall of 786mm with high rainfall from November to March (Le Roux, 2018; Moore, 2016; Department of Water and Sanitation, 2016; Flügel *et al.*, 2006). January has the highest average rainfall (± 130 mm) whilst July has the lowest average rainfall (± 15mm) (Figure 12). The normal rainy season usually begins in October and ends in April, however; 75% of the time, the rainy season begins in November and ends in March. These high precipitation rates are usually from high-intensity thunderstorms (Herd-Hoare, 2019; Le Roux, 2018). However, for the past four years, the greater upper parts of the Tsitsa River Catchment has been prolonged to drought (Herd-Hoare, 2019). The average temperature of the Tsitsa River Catchment lies between 21°C and 26.5°C in the summer months, with January being the hottest month. Low temperatures are experienced in winter with an average of 3.2°C, with July being the coldest month (Department of Water and Sanitation, 2016). This, therefore, implies that the Tsitsa River Catchment is characterized by a warm wet summer and cooler dry winter.

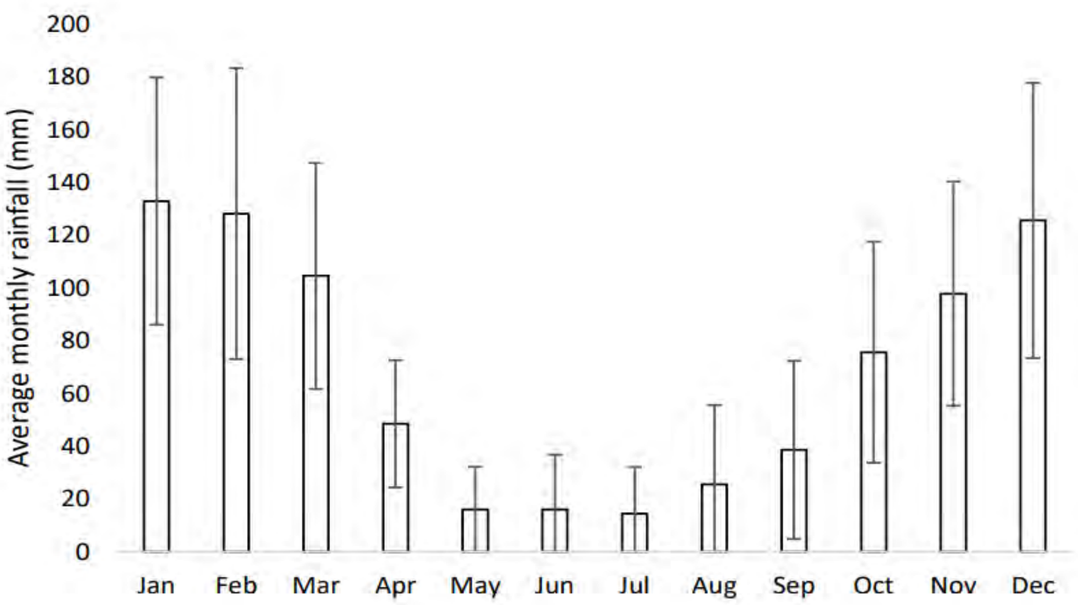


Figure 11: Monthly average rainfall (1978-2012) in Maclear (copy from: Snyman, 2020; page 16).

3.3 Topography

The Tsitsa Catchment has a variable altitude that ranges from the source of the Drakensberg Mountains at 3000m above sea level (asl) to 1200m above sea level, the Tsitsa River runs at an approximate length of 200km into the Mzimvubu River (Le Roux, 2018; Pretorius, 2016). The catchment is characterized by hilly landscapes and slopes facing a south eastern direction from the Great Drakensburg Escarpment Mountains (Le Roux, 2018; Pretorius, 2016; Flügel *et al.*, 2006). The presence of dykes and sills from the Drakensberg Formation has a distinctive geological control on tributary streams which showcases deeply incised river valleys and are likely to control the valley slopes which have a likelihood of promoting floodplain wetland formation that can act as longitudinal buffers (Pretorius, 2016).

3.4 Vegetation

The catchment lies in the Grassland Biome, with mainly Highveld Sourveld in the upper regions as well as Dohne Scourveld and thorn trees in the lower parts (Flügel *et al.*, 2006). Small patches of Afromontane Forests along the river networks at the lower regions that are preserved from fires are also found in the catchment (Flügel *et al.*, 2006; Le Roux, 2018). According to a study done by Weepener & Berg (2014), 72 % of the total land cover is made up of natural vegetation of which 90% is grassland, 6% thicket, 3% forest and 0.1% is shrubland

4. Methodology

This chapter outlines the procedures that were adhered to for determining the sediment buffering function of the Gatberg Floodplain Wetland. The study consisted of desktop, field, and laboratory work to meet the aims and objectives of the study. Figure 12, shows the location of the installed astro turf mats, time integrated samplers, well, loggers, and location of conducted transects (GT2, GT3, and GT4) and sediment samples. The study focused on: (1) determining the relative suspended sediment coming in and leaving the wetland, (2) Investigating the spatial variability in bed sediment characteristics, (3) determining the spatial variability in inundation depth, topography, vegetation roughness, organic content, rate of sediment accumulation and sediment type, (4) Investigating the relationships between inundation depth, topography, vegetation roughness, distance from the channel, organic content and sediment type (5), summarizing the sediment buffering function of the Gatberg Floodplain Wetland. Preliminary to the field trips which had initiated in August 2019, three wetlands were chosen and delineated as potential study sites using Google Earth Pro. Thereafter, noting down the different wetland characteristics i.e. geographic position, wetland size, topographical features, geological controls, and any infrastructure that may cause or influence the natural flow regime of the wetland (such as restoration weirs and gabions). Site visits were taken to observe recent signs of wetland flooding and whether the desktop study was the direct representative of what was in the wetland before finalizing the one wetland that was to be studied. This, therefore, provided an insight into understanding the wetland's diversity in terms of the wetland's characteristics and as to which wetland would be the best fit to implement the study. The Gatberg Floodplain Wetland was, therefore, the chosen study site as it was easier to access, had a guaranteed safety of equipment from being disturbed by people, and had most of the key floodplain geomorphological units that would be interesting to be studied.

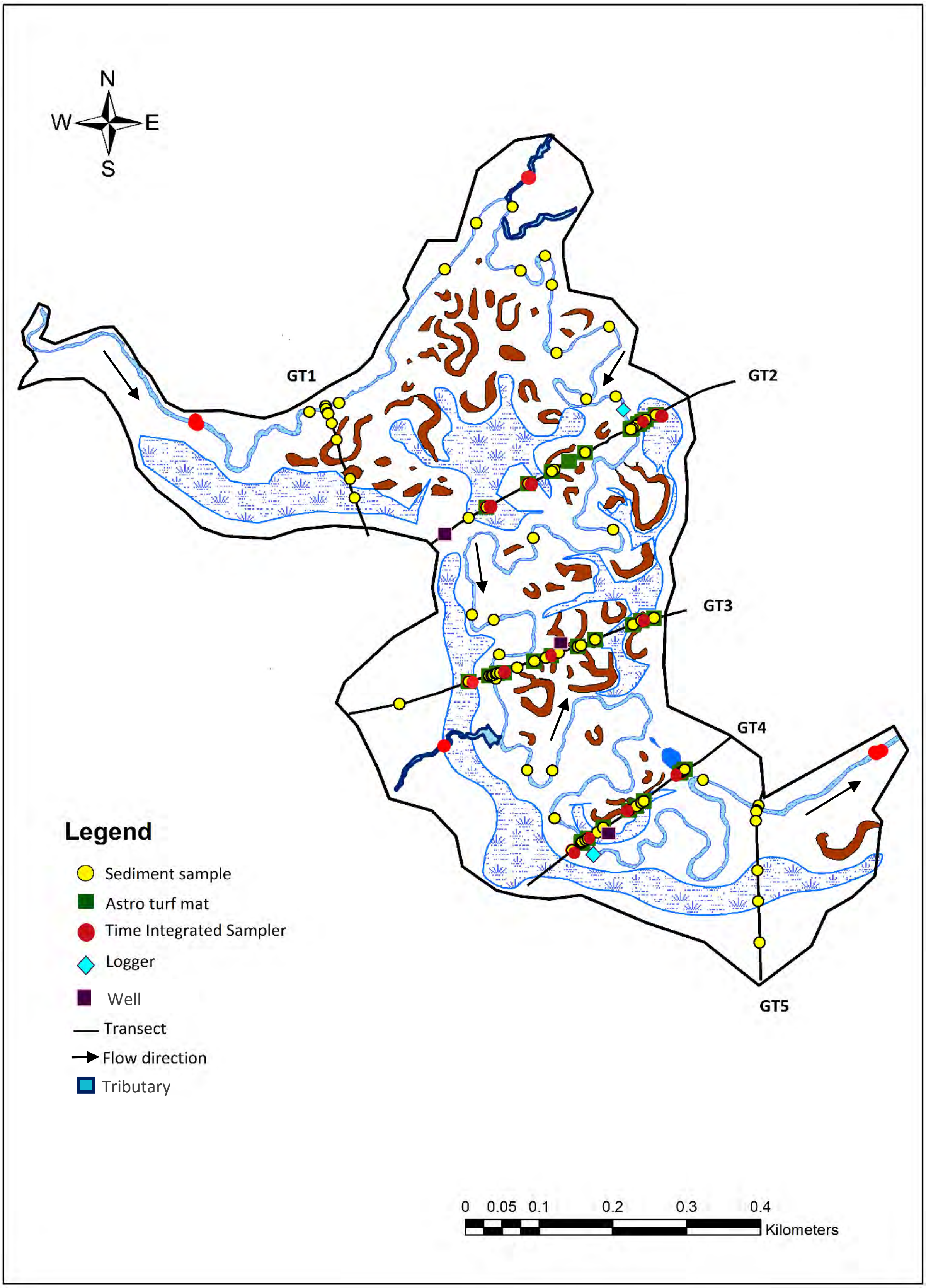


Figure 12: A map showing locations of sediment samples, astro turf mats, time-integrated samplers, water level loggers, well, and survey transects on the Gatberg Floodplain Wetland.

4.1 Sampling design

Data collection on the study site was done over one wet season which started in winter 2019 to winter 2020. Time integrated samplers were installed at the top and the bottom of the wetland as well as on the floodplain surface (installed in winter 2019). These were collected and emptied in winter 2020. Astro turf mats were installed across the floodplain in winter and were uninstalled in winter 2020 to account for sediment accumulation rates. Topographical surveys and sediment sampling of the floodplain and channel took place in winter 2019. Samples were analyzed for D50 particle size variation while topographical survey points were used to construct the longitudinal profile of the river channel and cross-sections of the floodplain. Vegetation parameters (vegetation density, vegetation height, stem diameter) were taken in winter 2019, early summer, late summer, and winter 2020 to analyze vegetation changes over the wet season. Solinst pressure transducer loggers were installed in winter 2019 in the channel and early summer in wells. These measured continuous flow variation over a ten-month period. The loggers were used to measure inundation water level changes throughout the flood event; data from these loggers was downloaded in winter 2020. Organic content quantity variation across the floodplain geomorphic features was also measured. The relationships between these variables were therefore studied to create a baseline of how they may have an impact on the sediment buffering function of the Gatberg Floodplain Wetland.

4.2 Determine the relative suspended sediment quantity coming in and leaving the wetland.

This objective was conducted by installing a total of three time-integrated samplers (similar to Phillips *et al.*, 2000) at the head and three at the bottom of the wetland (at the extents of the wetland). This was done to have some data, in case of losing one in high flooding events (no specific spacing of the samplers was done). The time integrated samplers were to be collected and cleaned every second month during the wet season and reinstalled (from winter 2019 – early winter 2020), however, due to high flows in the wetland, this restricted the collection of the time integrated samplers during the next visit in early summer as it was unsafe to do so. These were therefore not taken out and rather left out for the wet season to end so as to not disturb the settled sediment within the tube. A numbering system of the samplers before installation was used to identify which sampler was placed where within the river channel. These were first cleaned with clean water before installing at a horizontal position (ensuring that the inlet of the sampler is faced in a direction of the incoming flow) in the river channel at a mean bank full depth of 0.6 (with no even spacing between samplers) as outlined by Phillips *et al.,* (2000). The samplers were secured in place with 1 metre long steel rods, stainless steel wires, and plastic cable ties. The time integrated samplers were however modified by only using end caps instead of the Phillips *et al.,* (2000) design to suit the environment i.e. to avoid driftwood and cattle damage. The dimensions were 1m in length for in-stream channel and 50cm for floodplain surface, with end cap diameters of 110mm and 40mm respectively. The end caps were sealed using glue and placed a hole at the top of the end cap and on the outlet to make sure water only leaves on the outlet. Each sampler location was recorded using a Differential Global Positioning System (DGPS).

4.2.1 Incoming and outgoing suspended sediment of the wetland

Sediment trapped within the time integrated samplers were therefore used to provide the relative sediment mass and an insight as to what the sediment size and the organic content of the sediment entering and leaving the wetland is. The collected time integrated sediment samplers were cleanly washed out and poured in 20L buckets. A minimum waiting period of four weeks was done to let the sediment settle out or until the water was clear. Thereafter, the clear water was carefully siphoned with a J-tube; leaving sediment residue that was then dried in a fume cupboard at room temperature. Dried sediment was weighed on a Mettler PC 440 balance.

Samples that were still murky after the waiting period were filtered through a 24.0 cm diameter Whatman 1 filter paper. Filter papers were then dried in an oven at a low temperature (50^{o}C). Sediment mass was calculated by subtracting pre-weighed filter paper from oven-dried filter paper with sediment.

Thereafter, a comparative study of the relative sediment loadings at the top and bottom of the wetland was be done. Sediment particle size was determined by analyzing 10-15g in a Mastersizer 3000 (uses laser diffraction techniques on the wet, measured dispersed sample) in the laboratory to calculate the D16, D50, and D84 sediment particle size.

This was used as a form of representing sediment particle size differences and mass of incoming and outgoing sediment over the monitoring timeframe of the study.

4.3: Determine sediment particle size variability of the Gatberg Floodplain Wetland

Determination of sediment particle size is of importance in geomorphological studies such as river bed evolution and sediment deposition (Yhang, 1977; Zierholz *et al*., 2001). The following section involves the determination of bed and floodplain sediment variability along the Gatberg Floodplain Wetland channel.

4.3.1 Bed sediment particle size characteristics

Bed surface samples were taken along the longitudinal profile of the Gatberg River channel using a portable sediment sampling corer, sampling only the first 5cm of the bed surface. This amounted to a total of 22 sample site collections. Samples were packaged in plastic sample bags. Sample bags were labelled with a permanent marker noting the Global Positioning System of the location. The collected samples were oven-dried at 50°C for 48 hours or more until the samples were fully dry. A mortar and pestle were used to disintegrate the sample then screened through a 2.0 mm sieve to take out any dead plant material.

A mechanical sieve shaker was used for sandy and gravelly samples. These were then placed through a mechanical sieve shaker analysis to calculate grain size distribution and to determine sediment characteristics. The sieve shaker consisted of six to eight sieves, depending on the type of sample sediment. For gravel sediment samples; 8 sieve plates were used and for sandy to silty sediment, six sieve plates were used. These ranged from 8 mm, 4mm, 2mm, 1mm, 0.5mm, 0.25mm, 0.125mm, 0.063 mm, and the base of the sieve plate. Sediment ranging from 1mm to 0.063 mm are considered as the finest sediment particle size of sand, silt, and clay whereas sediment particle size above 2mm can be boulder, cobble, and gravel-sized sediment particles (Table 2). Prior to sieve shaking, the mass of each sieve plate was weighed and recorded thereafter each sample was poured into the mechanical sieve shaker and shaken for 10 minutes as outlined by (Gordon *et al.,* 2004). The total mass of each sieve plate after sieve shaking was recorded to calculate the total of sediment retained in each plate. Recorded data was imported to Microsoft Excel to calculate and construct particle size distribution curve and evaluate and estimate D50 sediment particle size (Appendix A).

4.3.2 Floodplain sediment particle size characteristics

A portable sediment corer was also used for floodplain surface sampling on targeted transects (GT2, GT3, and GT4) and on key floodplain geomorphological features. Samples were packaged in plastic sampling bags and labelled. The samples were then placed in an oven to dry out at 50°C for 48 hours or until samples were fully dry. A mortar and pestle were also used to disintegrate the sample which was then screened through a 2.0 mm sieve to remove any unwanted material. Only samples of less than 1mm (silt) were analyzed using a Mastersizer 3000 (analyzed samples were less than 5g). Recorded data was exported to Microsoft Excel to extract D16, D50, and D84 particle size values. For the purpose of the study research, D50 particle size was used as it is the most common and important parameter that characterizes particle size of a sample.

Table 2: Udden-Wentworth grain size classification (adapted from Wentworth, 1992)

Particle size (μm)	Sediment class
8000-4000	Pebbles
4000-2000	Granule gravel
2000-1000	Very coarse sand
500-1000	Medium coarse sand
500-250	Medium sand
250- 125	Fine sand
125-63	Very fine sand
<63	Silt, clay

4.4 Determine the spatial variability in inundation depth at a certain flood level, topography, vegetation roughness, organic content, rate of sediment accumulation (weight/area), and sediment type.

To determine and understand the variability in sediment deposition, an integrated approach from hydrology and geomorphology was needed.

4.4.1 Sediment type on the floodplain surface sediment

After samples were oven-dried and disintegrated; a measure of 10-15 g was taken and placed in beakers with an added 150 ml of hydrogen peroxide (H_2O_2) of 30 % concentration. The samples were then placed in a fume cupboard oven to burn off any organic matter left for a maximum period of 7 hours or up until the organic material was burnt off. These samples were disintegrated using a spoon and were taken for analysis.

4.4.2 Organic content

For organic matter content, crucibles were cleaned and placed in a furnace at 450°C for 12 hours to burn out any unwanted material. The crucibles were then placed in a desiccator to cool down and to avoid any chemical reactions that may occur and influence the total organic content. Crucibles were pre-weighed on a Mettler PC 440 balance and a fraction of 10 - 50g of sample was placed into a crucible which was weighed and recorded. The crucibles were placed in a furnace at 450°C for 24 hours and placed in a desiccator for an hour to cool down thereafter calculating the mass and retrospective organic content through the loss of ignition method (Gordon *et al*., 2004). The following formulas were used to calculate LOI:

- Empty crucible
- Mass of crucible & sample before ignition (g)
- Mass of crucible & sample after ignition (g)

Mass of original sample = Mass of the crucible before ignition (g) - Empty crucible (g)

Mass of sample after ignition = Mass of the crucible & sample before ignition (g) - Mass of crucible & sample after ignition (g)

LOI = (Mass of crucible & sample after ignition (g)/ Mass of original sample (g))*100

4.4.3 Inundation depth

Pressure transducers loggers are important components in water resource research. They provide useful data in hydrogeological and hydrological sciences to monitor water level fluctuations on a time series-based analysis thus gaining an understanding of the hydrological processes in fluvial and groundwater systems (Jewell & Wilson, 2011; Freeman *et al*., 2004).

For this study, water levels were monitored in the channel and on the floodplain to determine water level variations over one wet season and how it impacts sedimentation processes of the Gatberg Floodplain Wetland. Solinist pressure transducer loggers consist of micro-processers that are connected to the transducer installed in the piezometer/ well, which allow an automated water level data collection over a certain period. They were then installed in transect GT2, GT3, and GT4, and were set at a 10 minute time interval to record water level data; both in the channel and on the floodplain.

In the channel, loggers were installed in transect GT2 (at the top of the wetland) and GT4 (at the bottom of the wetland. Loggers were placed into a metal cover that was attached to a metal pole. The metal pole was hammered below bank full, either into the bed or into the channel banks. Logger height was noted with a Differential Global Positioning System to do calibration for the next field visit.

On the floodplain, wells of 2m in length of perforated PVC pipes were installed by firstly drilling a hole using a Dutch auger (Figure 13; Figure 14) then inserted vertically into the ground and backfilled with a sand column around the pipe. These were at the top (GT2), middle (GT3), and bottom (GT4) of the wetland. During field visits of the wetland site, water level depths from wells were measured using a measuring tape to account for an ‘estimation’ of maximum inundation depth. This provided maximum and minimum water levels that give an insight as to how much the wetland had overtopped. Although they would not provide a spatial variation in inundation depth over the monitoring study time frame; these measurements were done to get some data in case the loggers failed to record data.

The Solinst system combines temperature and pressure transducer. When in-situ, the total pressure transducer combines the sum of water and atmospheric pressure above the sensor. Thereafter, fluctuations of atmospheric pressure must be accounted for calculating water levels so as to obtain height of the water column above the total pressure transducer. A barometric compensation was therefore done using a Solinist Barologger to account for the absolute water level elevation. Data from transducers was transferred to data loggers to a central computer via hardwire. Furthermore, water level data from the channel and the floodplain was represented in a graph form to evaluate water level changes with time over the wet season.

Figure 13: Drilling process of a well installation (photo credit: Benjamin van der Waal).

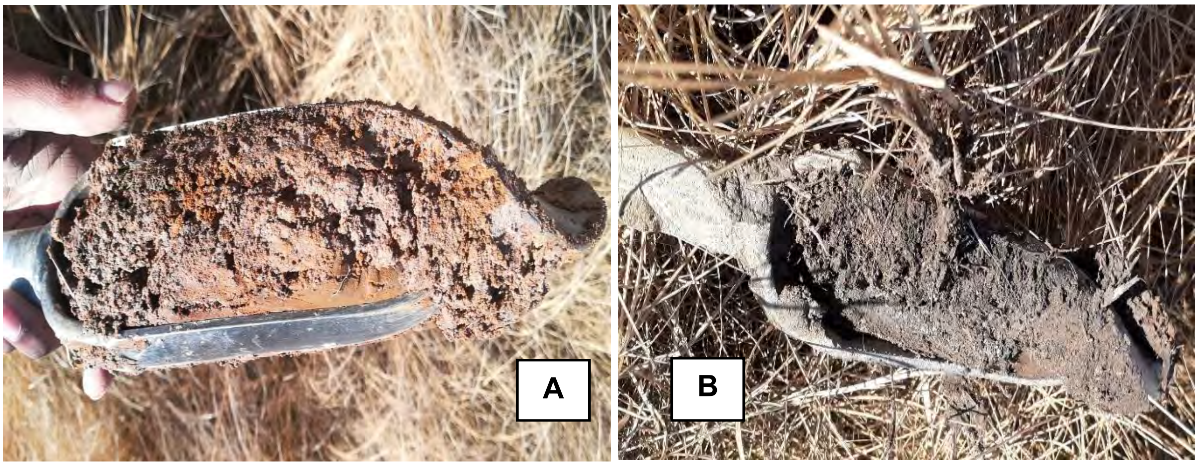


Figure 14: Soil profile showing sandy soil at the top (A) and clay (B) at the bottom of a piezometer installation site (photo credit: Benjamin van der Waal).

4.4.4 Topography

The elevation of various topographical features, such as banks, levees, flood benches, oxbows, and back swamps was measured along five transects (top, middle, and bottom of wetland) using a Differential Global Positioning System (DGPS) to account for the relative elevation with distance (Figure 16). An example of how the transects were conducted is shown in Figure 15. Topographical data from the DGPS was downloaded and exported to Microsoft Excel for processing and producing a surveyed topography of the wetland. The data was used to calculate distance from one point to another to construct graphs of elevation against distance from the left to the right bank. Conducting cross-sectional surveys and a longitudinal profile help reveal how elevation changes for various geomorphological features. This was done through incorporated data from the DGPS and exported to Microsoft Excel to construct a graph showing cross sections across the wetland surface.

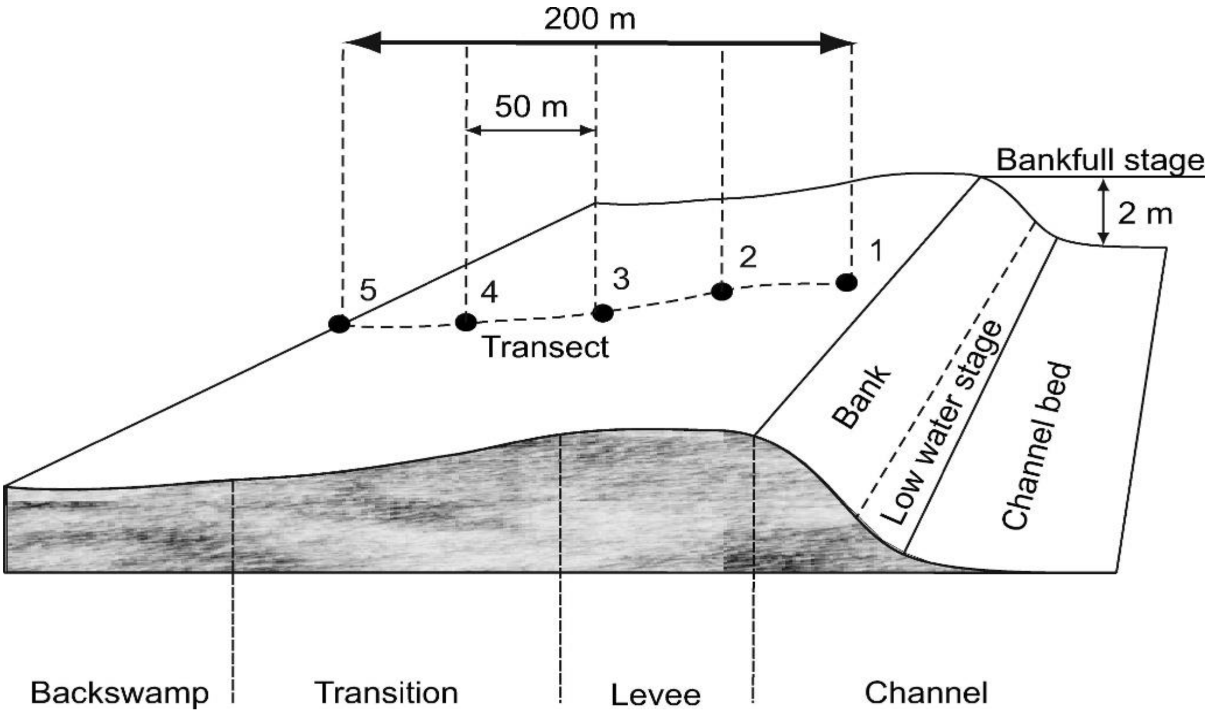


Figure 15: An example of how transects were conducted (copy from Hupp et al., 2008, page).

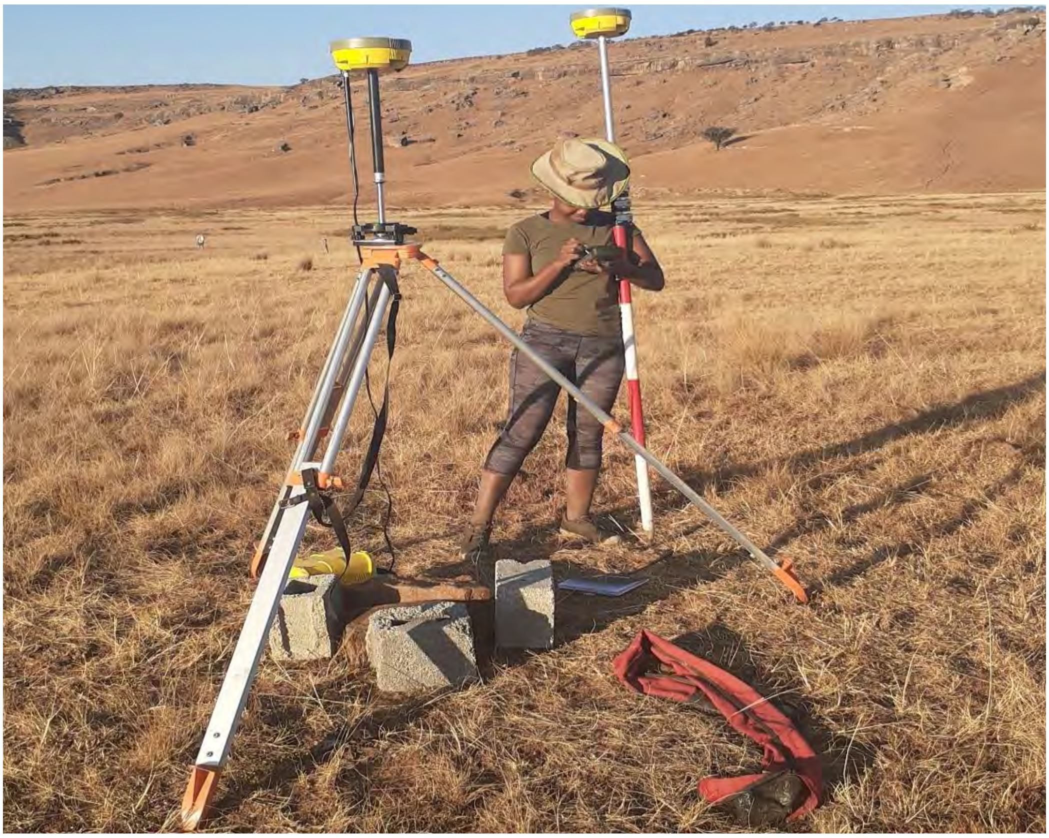


Figure 16: Elevation surveying using a DGPS (photo credit: Nicholas Huchzermeyer).

4.3.5 Vegetation roughness

Chézy is a water-dependent formula that can be used for both submerged and non-submerged vegetation (emergent) (Baptist *et al*., 2007). The study used Chézy formula to determine the hydraulic roughness values across each transect on key floodplain morphological features. Vegetation drag coefficients for different types of vegetation are listed in Table 3. Vegetation drag-coefficient for the study area was 1.8. Water depth for floodplain oxbow was measured in the field in late summer (after inundation event). Thereafter, hypothetical water depths for floodplain features were used as logger data was collected at a later stage of the study to determine whether vegetation was submerged or non-submerged. The following formula was therefore used to incorporate the vegetation parameters for roughness calculations across each transect as the vegetation was assumed to be emergent based on field measures.

$$Ck = \sqrt{\frac{2g}{C_d mDh}}$$

Where:

Ck = Chézy value representative

Cd = bulk drag coefficient to account for the flexibility of vegetation (Table 3)

m = number of stems per square meter that was measured in the field

D = stem diameter (m)

h = water depth (m)

g = acceleration due to gravity, 9.8 $m.s^2$

Vegetation plots to calculate roughness were done along three transects (GT2, GT3, and GT4). However, this was dependent on the nature of the surface cover and specific points of interest. Ten to twelve plots per transect were conducted. 1x1 metre plots were used and within these metre plots, vegetation height and stem count (vegetation density) were measured by a measuring tape, stem diameter was measured using a set of callipers (Figure 18). A transect sampling technique was used to account for the vegetation density per square meter, this was done by placing a 1m (measuring tape) transect across the quadrant and counting each stem that intersects with the transect. The total number of stems in a quadrant was then multiplied by 50 to account for the 'whole' total surface area. For each 1x1 meter plot of the vegetated area, the location of the plot was recorded using a DGPS. To calculate the total roughness per quadrant; vegetation parameters such as vegetation height, stem density, and stem diameter were incorporated into the Chézy formula. Chézy value is inversely proportional to roughness; the higher the value the lower the roughness (Chalton, 2008).

Table 3: Bulk drag co-efficient values for each vegetation type (adapted from Velzen *et al*., 2003)

Vegetation type	C_D
Trees with 1 stem per m^2	1
Forest, thorn scrub forest, shrubs	1.5
Grass, reeds, sedges, rush	1.8

Graphs for transects GT2, GT3, and GT4 were conducted in Microsoft Excel to have an insight into the spatial distribution of vegetation type and its roughness against D50 particle size. The error bars (Figure 27) shown on each category reveal the uncertainty of a data set, where shorter error bars indicate a concentration of values and values are more likely to be more accurate while longer error bars indicate that the values are less reliable as they are more spread out. They give information on how each data set is dispersed around an average. Field data collection of the vegetation characteristics is provided in Appendix B.

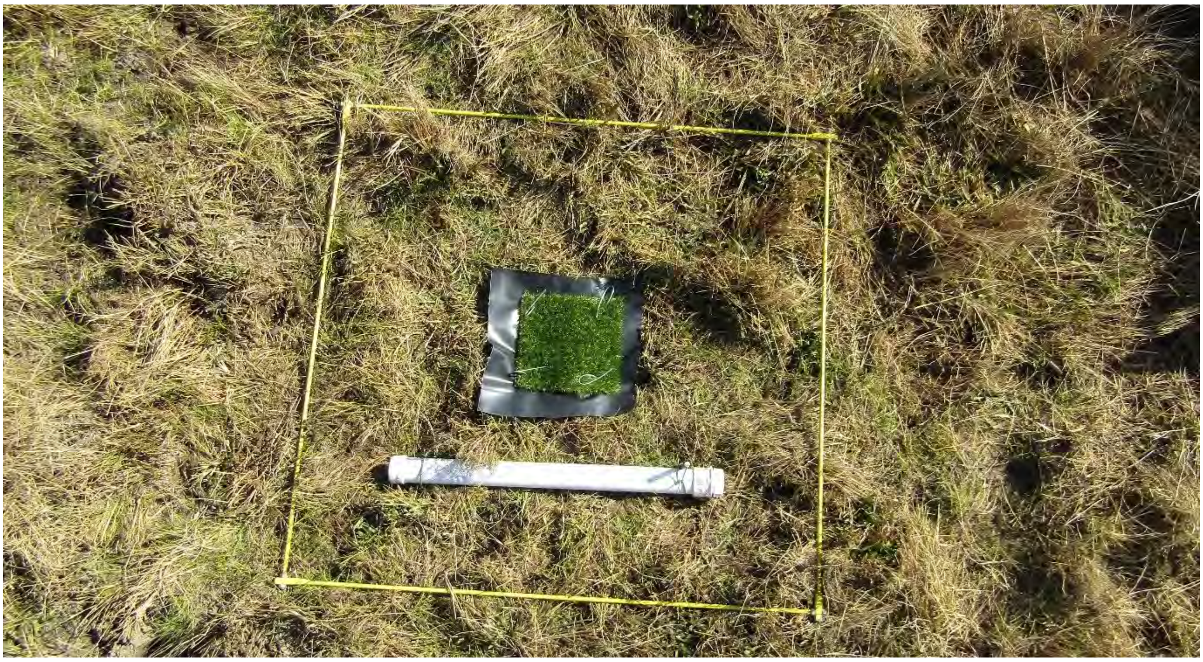


Figure 17: Demonstration of the 1x 1 metre quadrant, time integrated sampler, and astro turf mat installation on the floodplain surface.

Figure 18: Vegetation parameter measurements in GT2 (photo credit: Benjamin van der Waal).

4.3.6 Sediment rate and accumulation

Astro turf mats were placed on the floodplain surface (Figure 17) and used as sediment traps for the overall overbank flooding event to collect deposited sediment (this accounted for calculating the rate of sediment accumulated at different geomorphological units of the wetland measured in weight/area). These mats were deployed to provide the degree of variety of sediment accumulated in relation to distance from channel and topography of the different floodplain environment. The mats permitted the approximate measurement of short-term net vertical accretion. The astro turf mats were placed to mimic the roughness of the floodplain wetland vegetation. Astro turf mats measured 20 x 20 cm and were placed on 25 x 25 cm of plastic sheeting. Mats were numbered to identify which wetland feature it was placed on. These were fixed on the floodplain surface with 20-25cm long handmade wire pins, noting that no dust or soil is splashed onto the mats during installation. They were examined every second month. If they showed signs of sediment accumulation, they were collected for measuring the total mass of accumulated sediment.

Small PVC time integrated samplers placed on the floodplain surface were an addition to the installed astro turf mats (in case astro turf mats got washed away by the flood).

Out of the five transects that were conducted, only three transects (GT2, GT3, GT4) had astro turf mats which consisted of 10 to 12 mats per transect. Astro mats were placed at the main targeted geomorphological features to determine how sedimentation varied in each feature. All mats were taken to the laboratory after the wet season (winter 2020) to account for the amount of sediment deposited. Astro turf mats were dried in an oven at 50°C for a minimum of 72 hours or up until they were dry. Prior to the field installation, astro turf mats were pre-weighed using a Mettler PC 440 scale. Accumulated sediment mass was determined by subtracting the pre-weighted mat from the mat with sediment then calculating the difference. Some atsro turf mats were destroyed by fire and cattle, and were replaced during subsequent field trips. The weights of the mats with sediment were therefore not pre-weighted. These mats were then oven-dried and weighed. Thereafter, sediment from the mats was thoroughly removed by scraping off sediment into a bucket.

Astro turf mats were washed and oven-dried and the difference in mass calculated.

4.5 Investigate the relationships between inundation depth at a certain flood level, topography, vegetation roughness, distance from the channel, organic content, and sediment type

A series of bar graphs, scatter plots, multiple regression, and box and whisker diagrams were formulated to contextualize the interaction between inundation depth, topography, vegetation roughness, organic content, and the associated sediment type. The frequency of inundation depth graphs was evaluated to gain insight into how it changes over the wet season. Evaluating the investigated relationships provided a foundation for describing the sediment buffering function of floodplain wetlands. Such relationships can be used in determining whether they have an impact on the physical functioning processes of floodplain wetlands.

4.6 Summarize the sediment buffering function of the Gatberg Floodplain Wetland

The sediment buffering function of the Gatberg Floodplain Wetland was determined through calculations from the above objectives of the study research. This was done to have an insight of how much sediment is buffered within the wetland, where and why, as well as the relative sediment balance i.e. how much sediment is coming in and leaving the wetland, and to determine whether the wetland currently is a good sediment buffer or is eroding. The findings of the objectives were therefore integrated to summarize and describe the overall sediment buffering function of the Gatberg Floodplain Wetland over a wet season.

5: Results

Chapter five presents the results that were found for the study objectives to evaluate and determine the sediment buffering function of the Gatberg Floodplain Wetland. This section is therefore divided into sections in accordance with the objectives of the study: i) determine the relative quantity of incoming and outgoing suspended sediment and particle size, ii) determine and investigate the controlling factors of sediment buffering through the analysis of topography, geomorphic features, vegetation roughness, inundation depth, distance from the channel, organic content and thus establishing the relationships amongst these factors iii) summarize the sediment buffering function of the Gatberg Floodplain Wetland.

5.1 Quantity of suspended sediment coming in and leaving the wetland

The main aim of this objective was to quantify the relative amount of incoming and outgoing suspended sediment in the wetland. This was achieved by the use of time integrated samplers which produced sediment volumes ranging from 13.60g to 164.93g over one wet season. The average mass accumulated in samplers at the top of the wetland was 83.43g compared to 51.99g at the bottom. The mass at tributary 1 of the wetland was 45.11g and 61.78g at tributary 2 (Table 4). With the average mass of incoming sediment and outgoing in the wetland, calculations concluded that approximately 73% proportion of the incoming sediment into the system is retained within the wetland and a proportion of 4 tons was accumulated over the monitoring study time frame. Figure 19 derived from Figure 12 shows where sediment comes in, where it gets deposited and where it comes out of the wetland. Arrows represent sediment concentration and particle size; the bigger the arrows the bigger the sediment concentration, particle size decrease with distance from the channel. The figure also shows where most of the sediment lies within the wetland. The particle size at tributary 1 and tributary 2 were 25μm and 16.8μm, respectively (Table 4). Particle size averages were 23.47μm at the top of the wetland and 16.77μm at the bottom. Organic matter content at the top and bottom of the wetland differed by 0.30**%** with an average of 8.24% at the top and 7.94% at the bottom. The percentage organic content in the tributary 1 was 10.01% and 11.44% in tributary 2 (Table 4).

Table 4: A table showing the relative suspended sediment mass, D50, and organic content obtained at the top and bottom of the wetland (data acquired from instream samplers).

Sample no.	Description of sample	Mass (g)	D50 (μm)	Organic content (%)
GTIS 1	Top of the wetland	13.60	27.9	10.74
GTIS 2	Top of the wetland	164.93	20.8	6.19
GTIS 3	Top of the wetland	71.75	21.7	7.78
GTIS 8	Tributary 1	45.11	25	10.01
GTIS 7	Tributary 2	61.78	16.8	11.44
GTIS 4	Bottom of the wetland	39.10	15.7	8.72
GTIS 5	Bottom of the wetland	18.45	18.3	9.52
GTIS 6	Bottom of the wetland	98.43	16.3	7.17
Average suspended sediment mass at the top = 83.43			23.47	8.24
Average suspended sediment mass at the bottom = 51.99			16.77	7.94

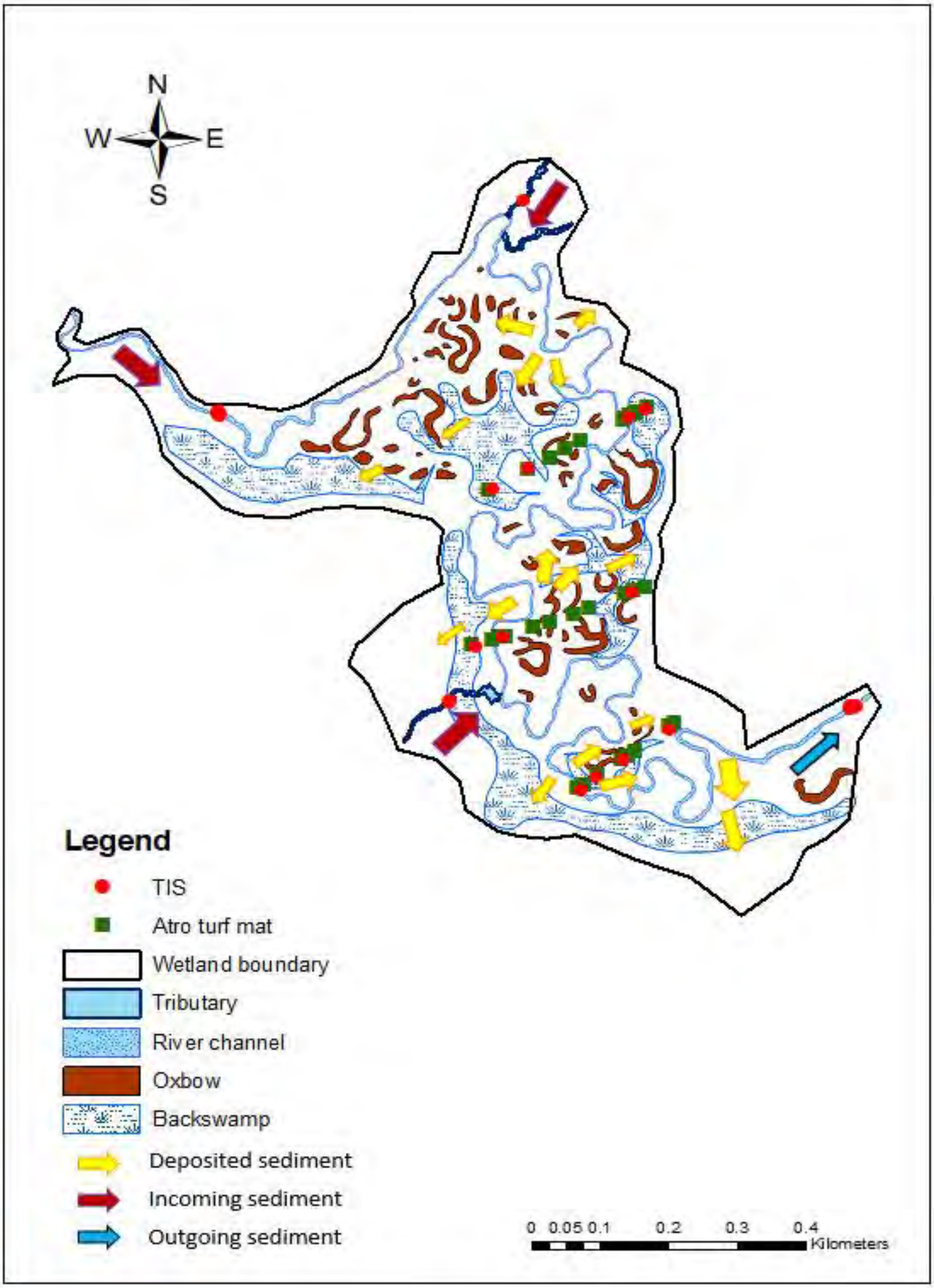


Figure 19: A figure showcasing where sediment comes in, where it is deposited, and where sediment is going out of the Gatberg Floodplain Wetland.

5.2 Spatial variability of bed particle size

5.2.1 Bed sediment particle size

Bed sediment characteristics were determined by establishing the spatial variation in D50 particle size along the channel. A comparison of the particle size distribution of different geomorphological units was done. Based on Figure 20 and 21, all sample sites along the channel bed are comprised of sand with medium sand to very coarse sand in bedrock controlled units (215μm - 1410μm), fine to medium sand in pools (185μm - 420μm), medium to very coarse sand in riffles (220μm - 510μm) and very fine sand for bars (170μm - 242μm). More data on particle size distribution analysis is provided in Appendix A.

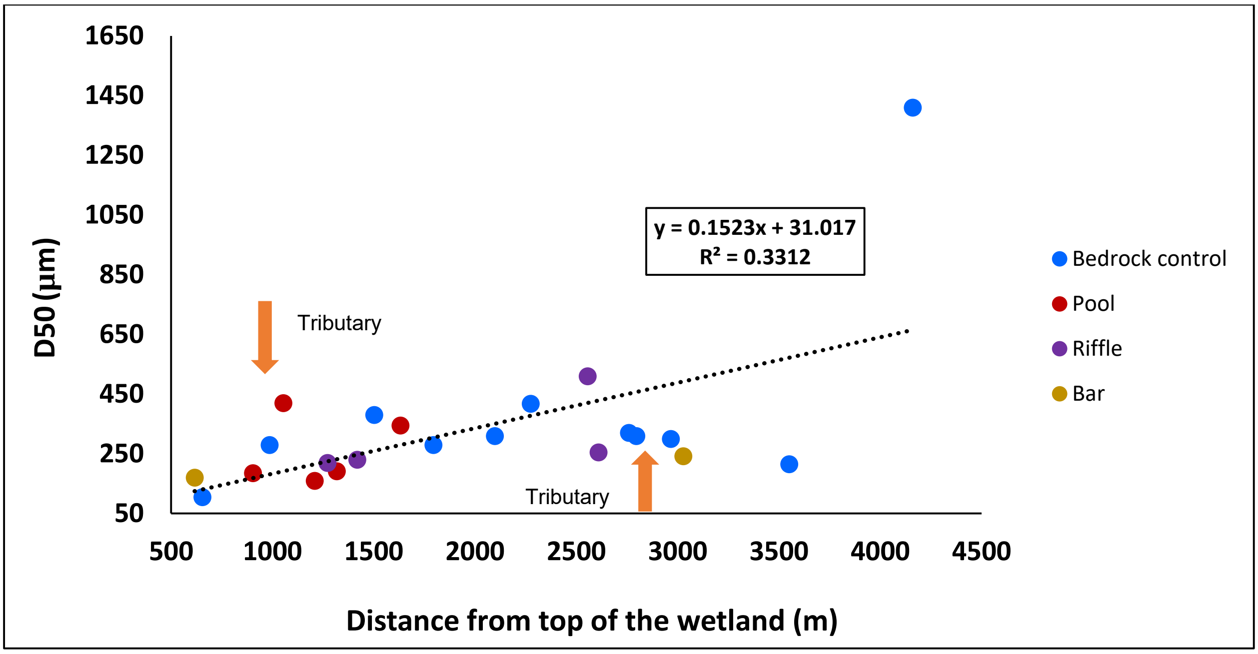


Figure 20: Longitudinal particle size (D50) variation with distance downstream.

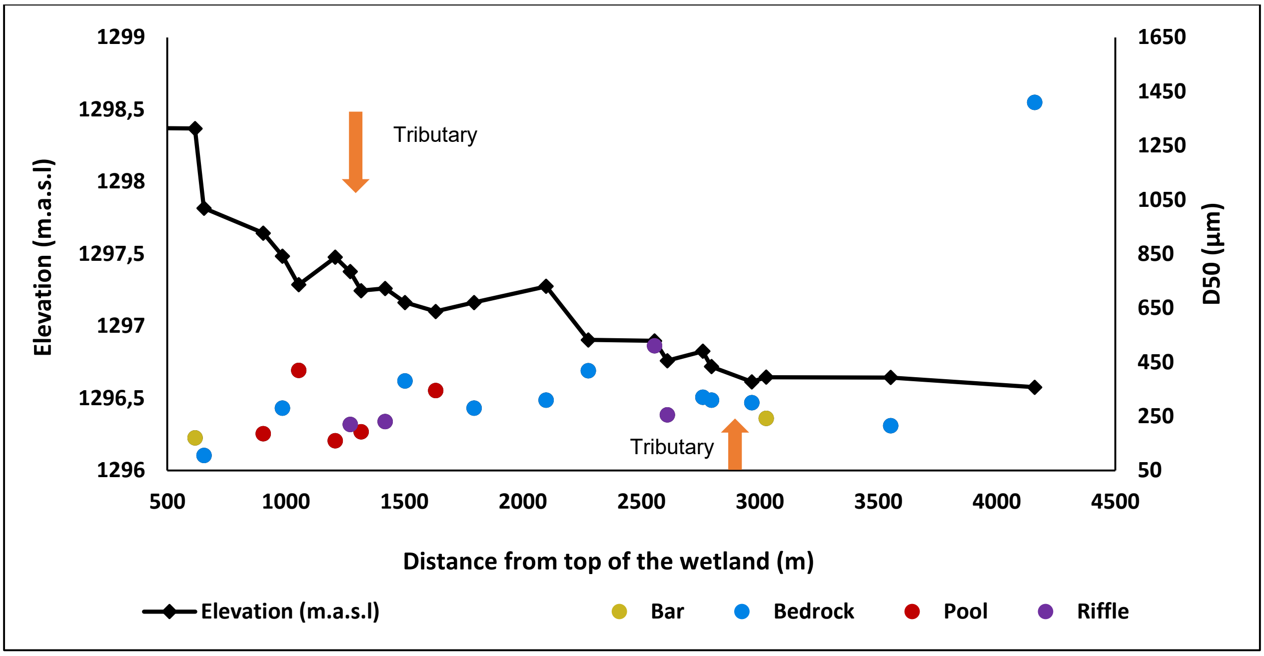


Figure 21: Particle size (D50) variation along the Gatberg River longitudinal profile.

Figure 21 shows the spatial variation of sediment particle size with distance from top to bottom of the wetland. The entire channel along the wetland is approximately 4.1km in length with a relative width of 4m. Based on Figure 20 and 21, particle size varies along the channel for the different geomorphological units. Previous studies (Frings, 2008; Moussavi-Harami *et al.*, 2004; Surian, 2002) have shown that particle size decreases with distance downstream, however, the Gatberg River channel exhibits a non-linear trend in particle size; particle size increases with distance (Figure 20). Finer particle sizes occur at a distance of 500-1500m and 3000-3500m. These are at point bars, near the bank, pools and at the channel bed. Bedrock controlled sites and riffles are associated with larger D50 particle size (coarser sand) (Figure 21). This difference was to be expected as flow velocity differs for each geomorphic unit. Finer particle size are situated in lower elevations compared to coarser particle size that are situated at higher elevations (Figure 21). At distances between 2700m and 3500m, D50 decreases with distance downstream. The location of tributaries are approximately at 1000m and at 2800m; which contribute as an external sediment source variables to the river channel. The coarse particle size dominance, controlled bedrock sites and the formation of point bars indicate that the channel is active in these particular regions of the channel bed. The linear regression model shows that there is a poor positive correlation between particle sizes with distance downstream (R^2 = 0.3312). The very coarse sand material is shown as an outlier on the graph and exceeds the range of most of the particle size (Figure 20).

5.3 Spatial variability in inundation depth, topography, vegetation roughness, organic content, rate of sediment accumulation, and sediment type for the different floodplain geomorphic units

5.3.1 Inundation depth

The undertaken water levels in the well shown in Figure 22 are once off-field measurements and were measured to observe whether they would correlate with the measured data from the Solinist loggers as they were also used for calibration. Therefore, a frequency analysis could not be done. Furthermore, Figure 22 does not give a full seasonal picture of flow depth variability, hence the application of Solinist loggers. However, the measurements show that between December 2019 and February 2020 (early to late summer), water level depths were rising and a drastic drop in depth occurred in August 2020 (winter) (Figure 22). December had the lowest water level depth with a minimum value of 0.35m, February had the highest water level depth with a maximum value of 2.019 m. This indicates that over this period; the flow had overtopped the floodplain surface with a few centimeters above the top of the end cap of the well as shown in GT3.

Figure 23 in GT2 shows a seasonal scale variability in inundation both for groundwater (well) and surface water (channel) relations. Water levels are constant and show similar hydrological characteristics, both in the channel and in the well at the beginning of the summer period (December 2019 - mid-January 2020). Water surface levels range from 1296.98-1299.79 m.a.s.l for the channel and 1297.19 - 1299.59 m.a.s.l for the well. They both start to show high water level fluctuations in mid-January which may be due to high rainfall events that caused water levels to rise. Lower water level depressions are more prominent between September and December 2019 (spring to early summer) which determine the timing of a dry period (minimum water level = 1296.98 m.a.s.l). Furthermore, water elevations in the channel remained high in February 2020 (late summer) compared to water levels in the well. Water levels start to rise again both in the channel and well between February and March. However, the water level in the well remained higher and relatively constant than in the channel (water levels start to decrease in March with peaking levels in May) for the remaining period. Although water levels are high, they both start to decrease in the winter months (end May- June). Water levels in the channel for GT4 also show similar trends in elevation water levels in the channel in GT2; water levels start to rise in January with peak levels between February and March 2020. Further data recording was limited by malfunctioning of the data logger.

According to Figure 23, the graphs can therefore be categorized into four sections 1) the rising water level period (December-January), 2) the high water period (February and March), 3) the low water period (September-October), and lastly the isolation period (November). It can therefore be expected that sediment accumulation rates are often higher in the rising and high water period. Water level data stopped recording from March in the channel for GT4; also, no data was recorded for the well in GT4 due to malfunctioning of the loggers.

Monitoring of water levels on the floodplain was not done but rather of maximum water level depths across the different geomorphic units for the upper and lower sections of the floodplain were done (Figure 24). Figure values written as text in Figure 24 are an indication of the inundation frequency of geomorphic features. Water level overtopped the floodplain levees (February 2020) three times at the top (GT2) and four times at the bottom (GT4) of the wetland. The water level depth was approximately 3 m from the channel bed to the top of the levee with a maximum flood duration of one and half a day. Water levels reached bank full (January 2020) level seven times and six times at the top and the bottom of the wetland, respectively. The maximum flood duration was 3 days and 14 hours. This, therefore, indicated that the flood was big enough to overtop the entire length of the wetland channel and allowed for the possibility of transporting sediment onto the floodplain. The maximum depth was approximately 2.95 m from the channel bed to the bank for GT4. Water levels reached the flood benches 11 times at the top and 9 times at the bottom of the wetland with a maximum flood duration of 12 days and 8 hours. The maximum inundation depth from the channel bed to flood benches was 1.11m. There is a reduction in the frequency at the lower part of the wetland which may indicate that there is low sediment accumulation.

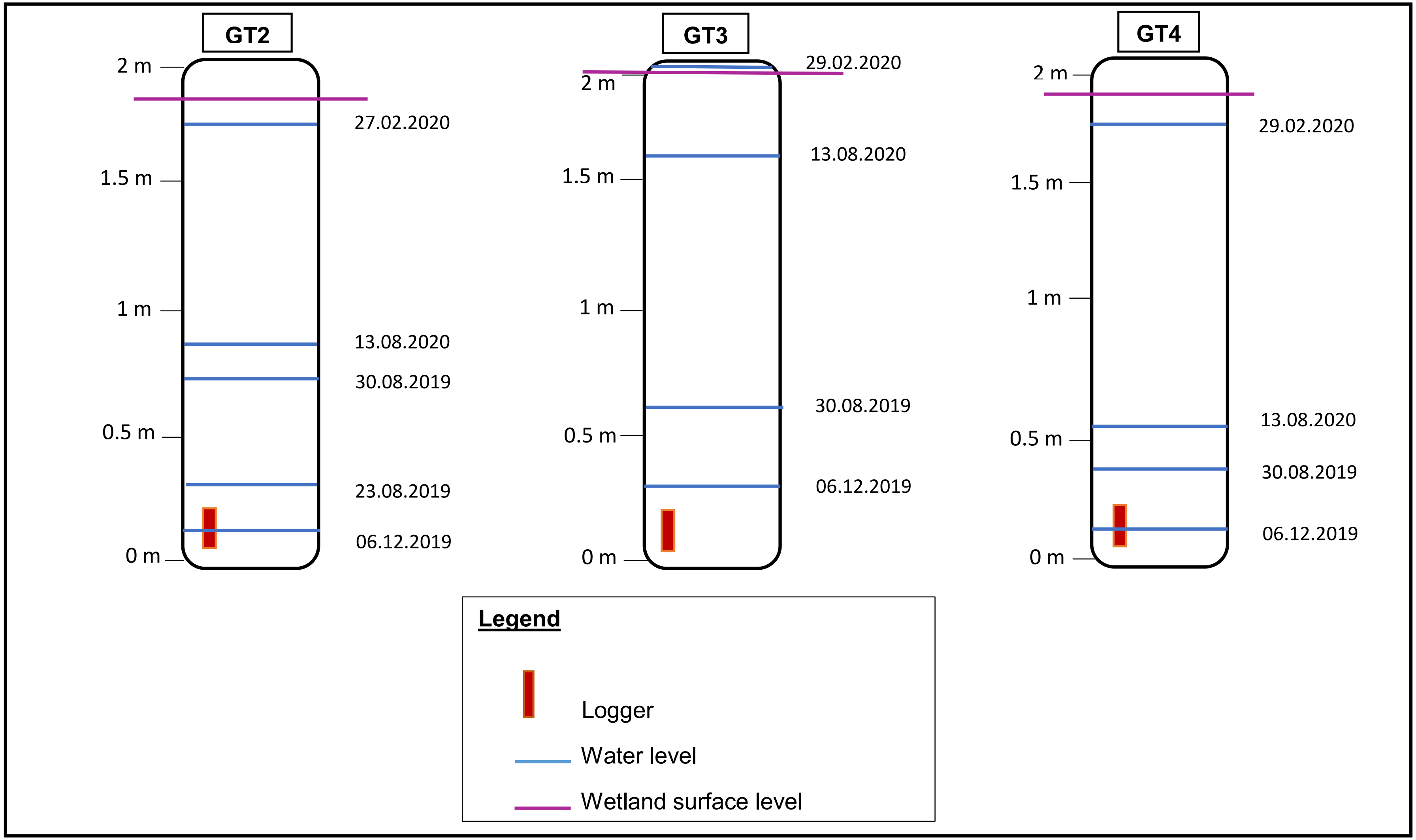
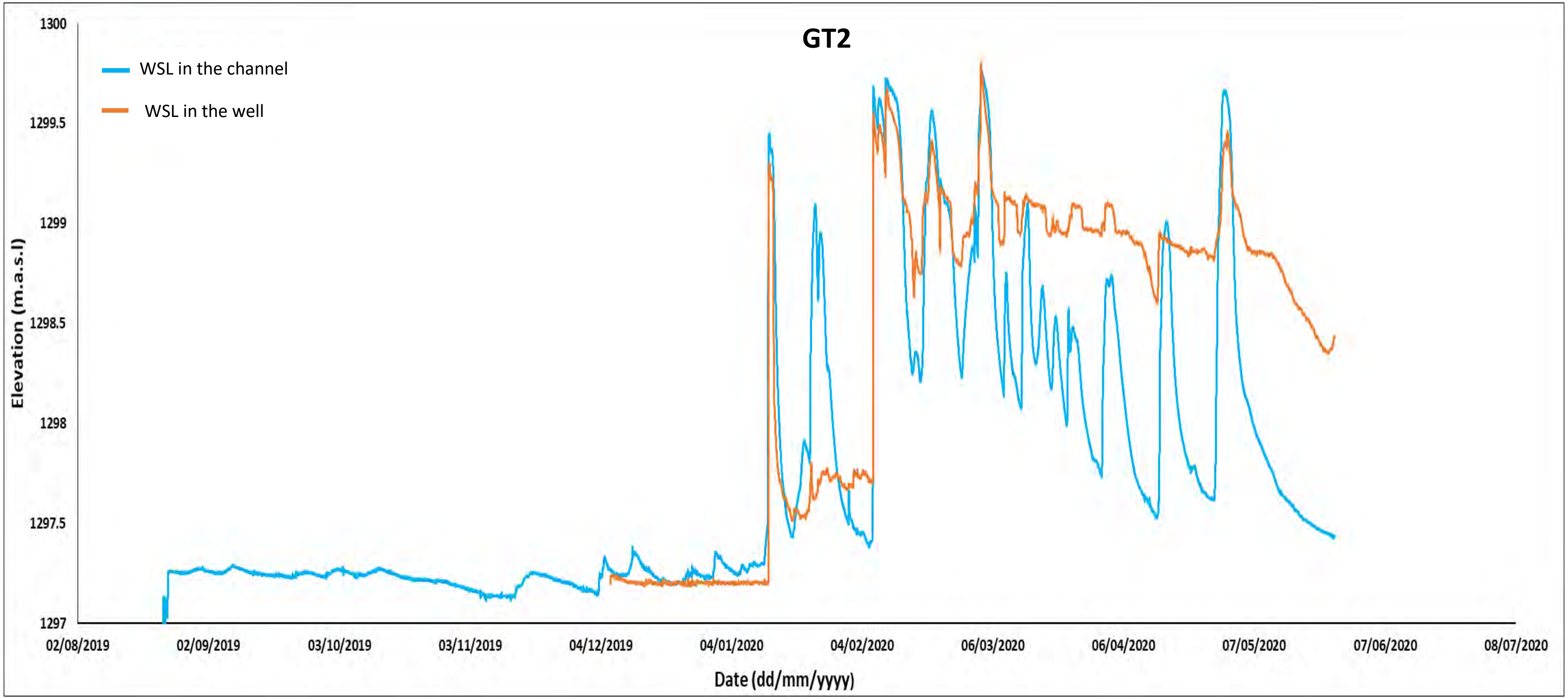


Figure 22: Water level depth in well GT2, GT3 and GT4 from August 2019- August 2020.


GT2
WSL in the channel
WSL in the well
Elevation (m.a.s.l)
1300
1299.5
1299
1298.5
1298
1297.5
1297
02/08/2019
02/09/2019
03/10/2019
03/11/2019
04/12/2019
04/01/2020
04/02/2020
06/03/2020
06/04/2020
07/05/2020
07/06/2020
08/07/2020
Date (dd/mm/yyyy)

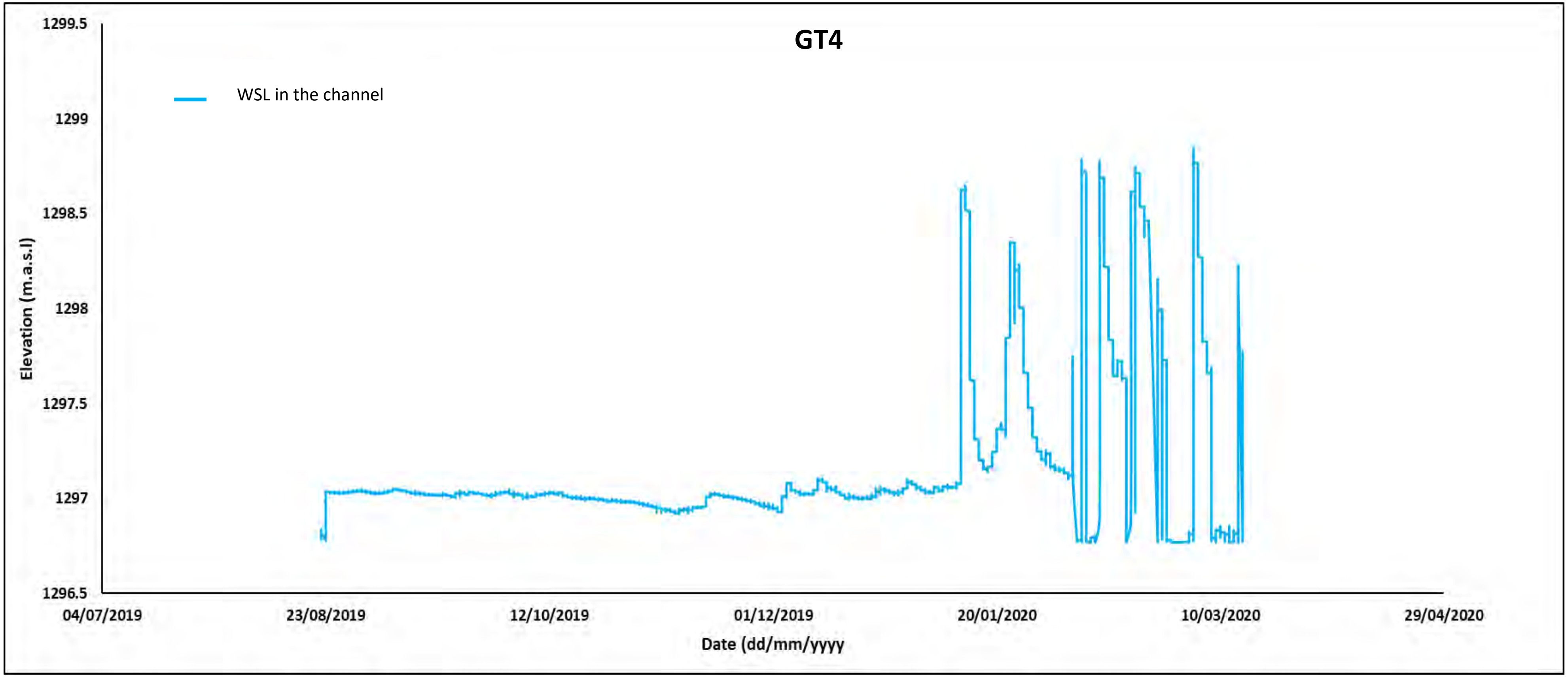


Figure 23: Seasonal water level depth variation in the channel in GT2 and GT4 and water level depth variation in the well for GT2.

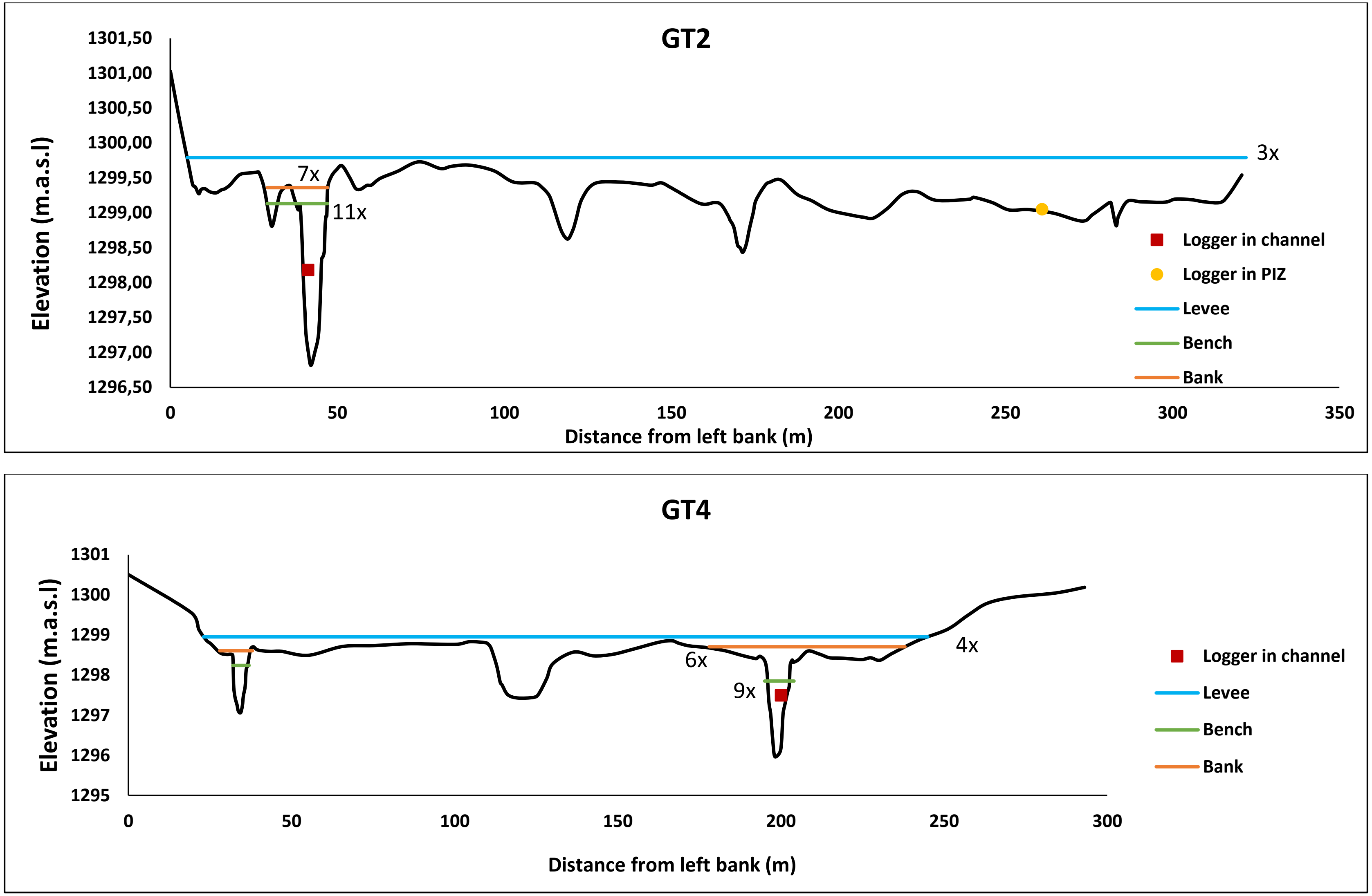


Figure 24: Maximum flood water level and frequency of inundation of the various geomorphic features at the top part of the wetland (GT2) and the bottom part of the wetland (GT4).

5.3.2 Topography

Topography contributes to the spatial variation on several aspects such as vegetation, slope/elevation, wetness indexes, soil formation, infiltration, runoff, and erosion. Determining local elevation and evaluating how such aspects influences particle size is therefore important to consider (Wang *et al*., 2015). Figure 25 and Figure 26 shows the long profile and five cross-sections that were conducted; representing the surface elevation of the wetland. The graphs show elevation against distance with sediment samples taken at the different geomorphic features of the floodplain. Elevation beyond levees have a low variation and slightly decrease towards the outer margins of the floodplain. The Gatberg Floodplain Wetland is steeper at the top and wider at bottom of the wetland (Figure 26). The channel is deeper in GT1 and GT5 with approximately 2.96m and 2.70m deep, respectively. Distinct high points are seen in levees whilst low depression points are seen in oxbows (this can indicate high sediment deposition rates of finer sediment as low elevations are associated with such).

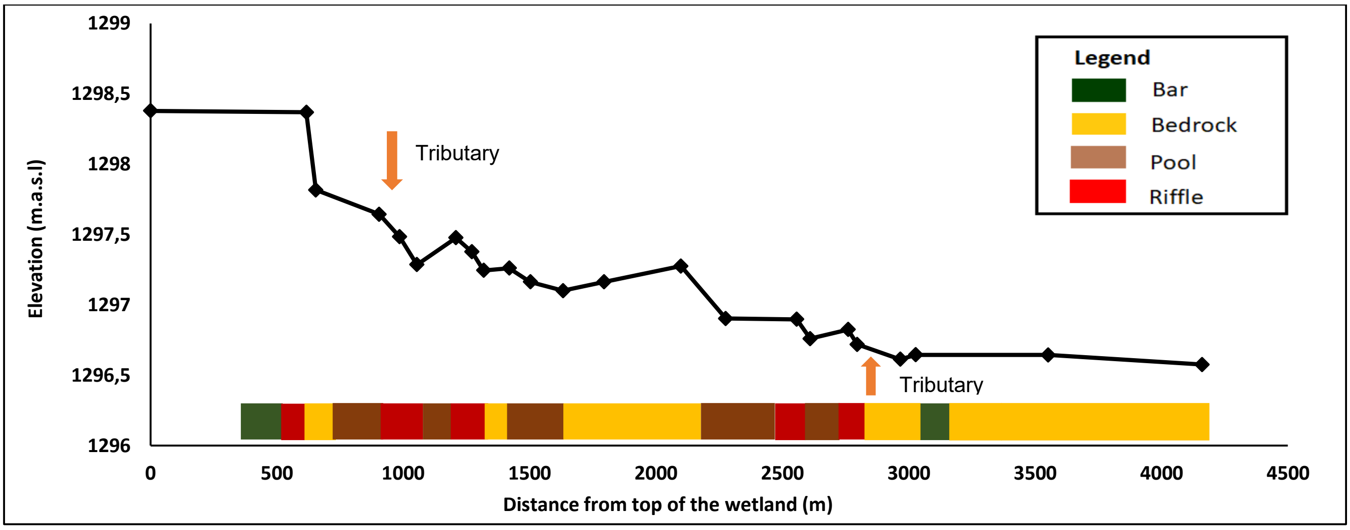
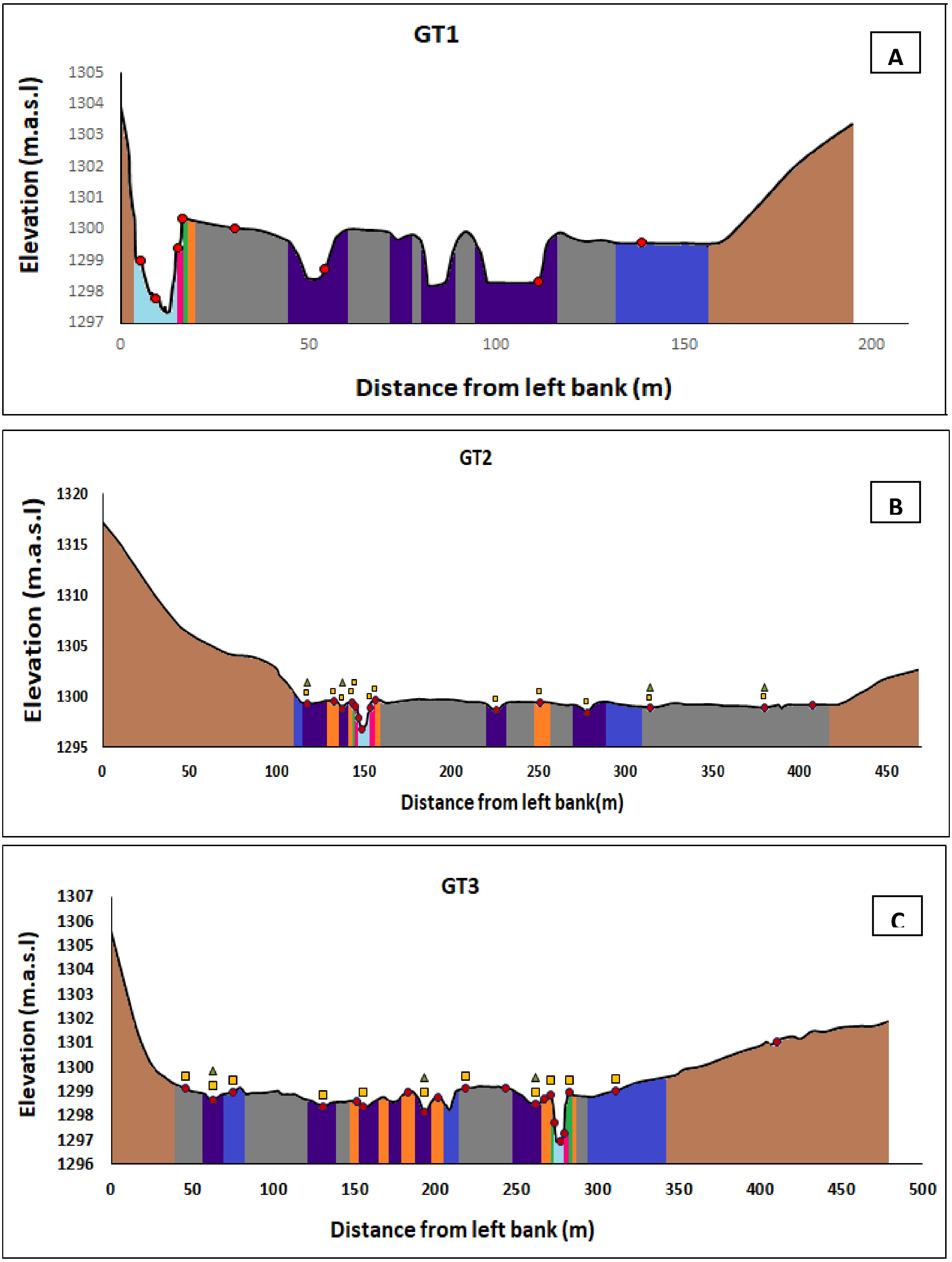
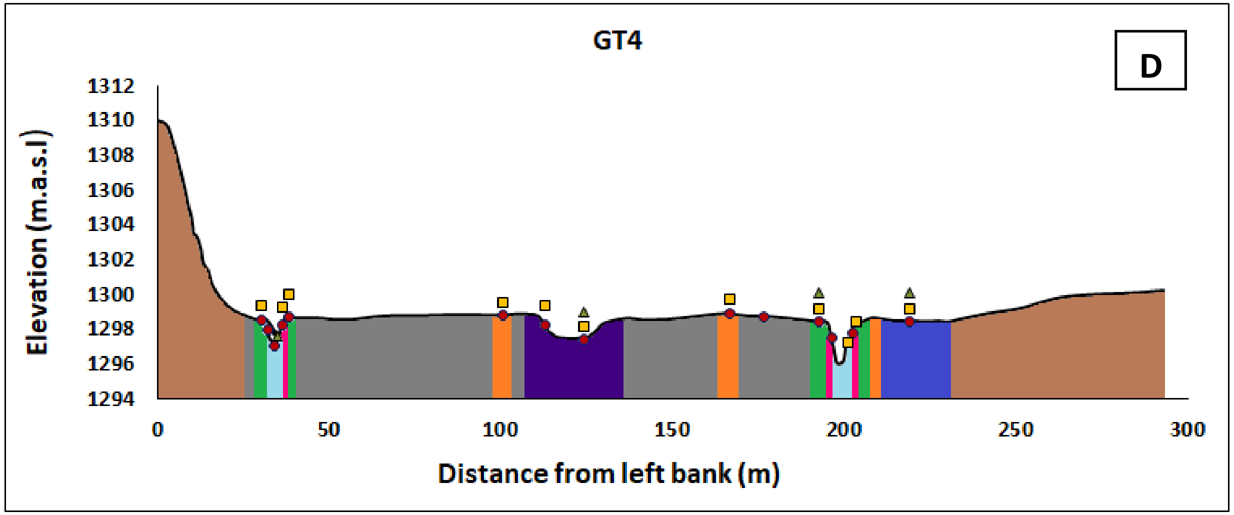


Figure 25: Longitudinal profile of the Gatberg river channel with tributaries and geomorphic features.

The longitudinal profile of rivers depicts how elevation changes from the headwaters to its mouth, therefore showcases how the rate of gradient changes with distance downstream (Brierley & Fryirs, 2012). The conducted longitudinal profile of the Gatberg Wetland River channel begins at 1298 m.a.s.l and ends at 1296 m.a.s.l. The slope of the channel is 6% (0.06). The top of the Gatberg Wetland is the steepest part and is between 0 -1000 m distance and is associated with bars, riffles, and bedrock, it follows a non-uniform pattern between 1000m and 3000m. Between 3000m and 4000m, the bed topography is relatively flat and is associated with pools and bedrock sections. Two tributaries entered the wetland river channel, one from the left bank and one from the right bank of profile GT2 and GT4, approximately 1000m at the top and 3000m at the bottom.


GT1
A
Elevation (m.a.s.l)
1305
1304
1303
1302
1301
1300
1299
1298
1297
0
50
100
150
200
Distance from left bank (m)
GT2
B
Elevation (m.a.s.l)
1320
1315
1310
1305
1300
1295
0
50
100
150
200
250
300
350
400
450
Distance from left bank(m)
GT3
C
Elevation (m.a.s.l)
1307
1306
1305
1304
1303
1302
1301
1300
1299
1298
1297
1296
0
50
100
150
200
250
300
350
400
450
500
Distance from left bank (m)



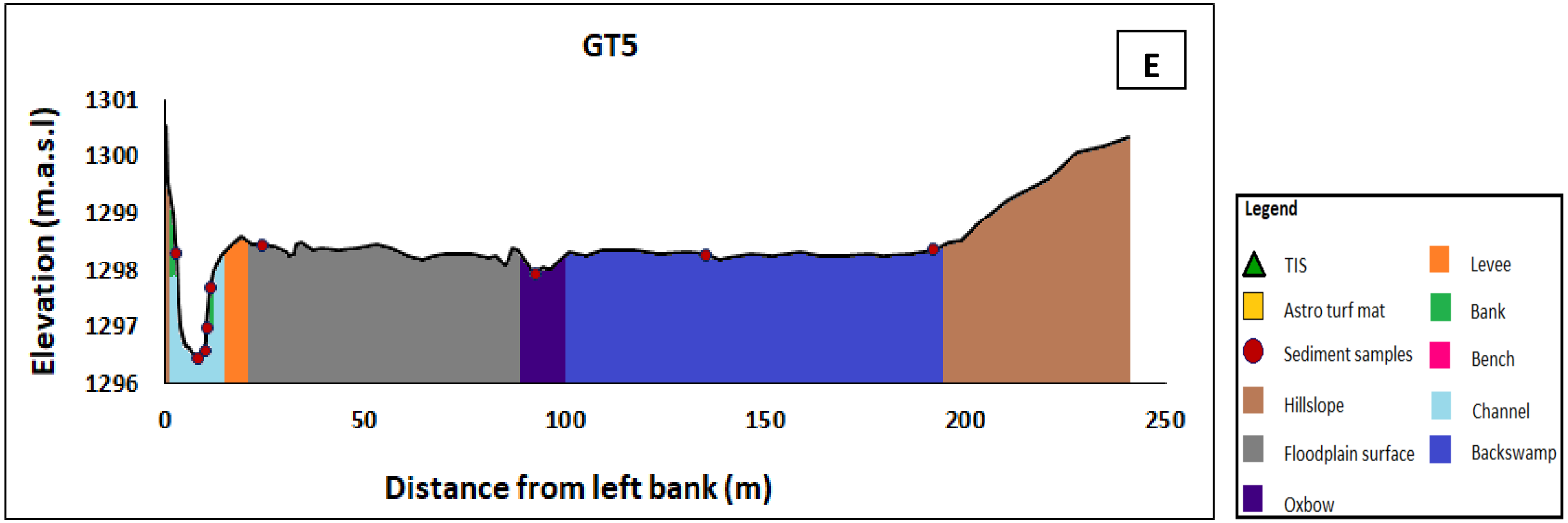


Figure 26: Cross-sectional surveys of the Gatberg wetland conducted for GT1 to GT5 indicating geomorphic features and location of sediment samples, astro turf mats, and time integrated samplers, August 2019.

5.3.3 Vegetation seasonal trends

Seasonal trend of vegetation characteristics (stem density, height, and stem diameter) as well as roughness in winter 2019, early summer, and late summer and winter 2020 are shown in Figure 27 and Figure 28. Stem density is relatively high for all features in late summer and winter 2019, with average high densities in back swamps, banks, and floodplain surfaces whilst the lowest densities are seen in oxbows. Density decreased in early summer in all features (Figure 27A) due to fire occurrence. Vegetation density also has a high variability over time in back swamps and in the floodplain surface.

High vegetation heights are seen in late summer and winter 2020 and low in early summer. High vegetation heights are seen in oxbows and flood benches whilst low vegetation heights are typically seen in back swamps and floodplain surface environments (Figure 27B). Stem diameter generally increases with time over the wet season starting from early summer to winter 2020, larger stem diameters are seen in winter 2020, and in some features in early summer such as levees and banks stem diameter remains high even after the fire occurrence, this may constitute to high sedimentation rates. Low stem diameter is seen in back swamps and floodplain surface while high stem diameters are seen in oxbows and benches (Figure 27C). A constant variation in stem diameter over time is also seen in back swamps and flood benches. Furthermore, no increasing trend was observed in vegetation characteristics with the growing season; the expected outcome was that vegetation characteristics would initially be low at the start of the wet season and increase towards the end of the wet season. A reduction in vegetation characteristics in early summer is due to a fire occurrence (Figure 30) which might have an effect on resistance and sedimentation. The general trend of Chézy values with stem characteristics shows a good correlation i.e. the lower the Chézy values the higher the resistance roughness (stem density, diameter, height). Therefore, it can also be observed that roughness gradually increases in winter 2019 and remained lower in early summer than the approaching late summer (Figure 28). Figure 29 shows vegetation changes of the floodplain wetland from winter 2019 - winter 2020. High diversity in vegetation was seen towards the late summer period (e.g. sedges, forbs, and some aquatic plants) whilst winter 2019 and 2020 had a low diversity (mostly dominated by grass and shrubs).

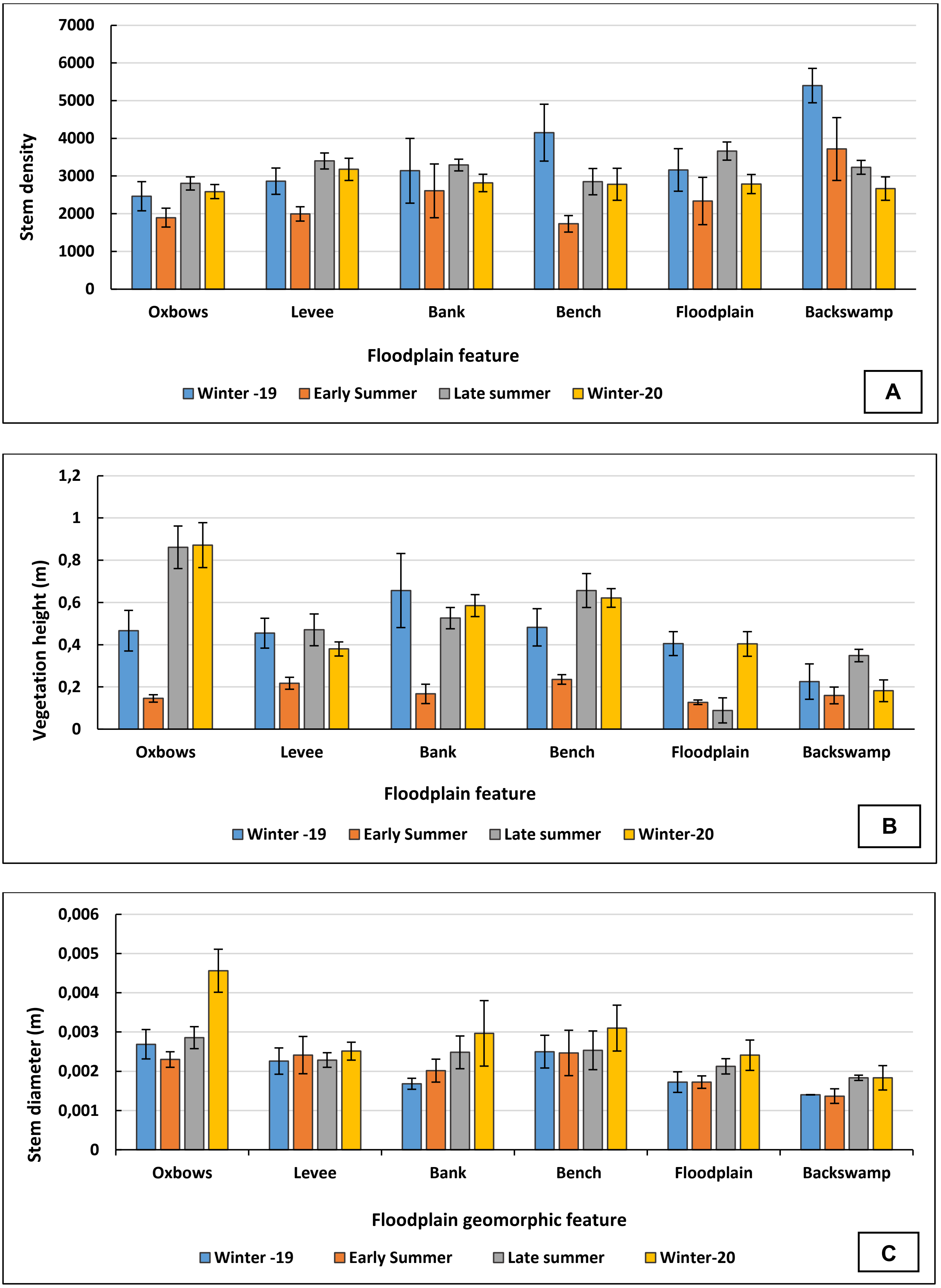


Figure 27: Variation in vegetation characteristics; A – stem density, B- vegetation height and C- stem diameter in winter 2019, early summer, late summer and winter 2020.

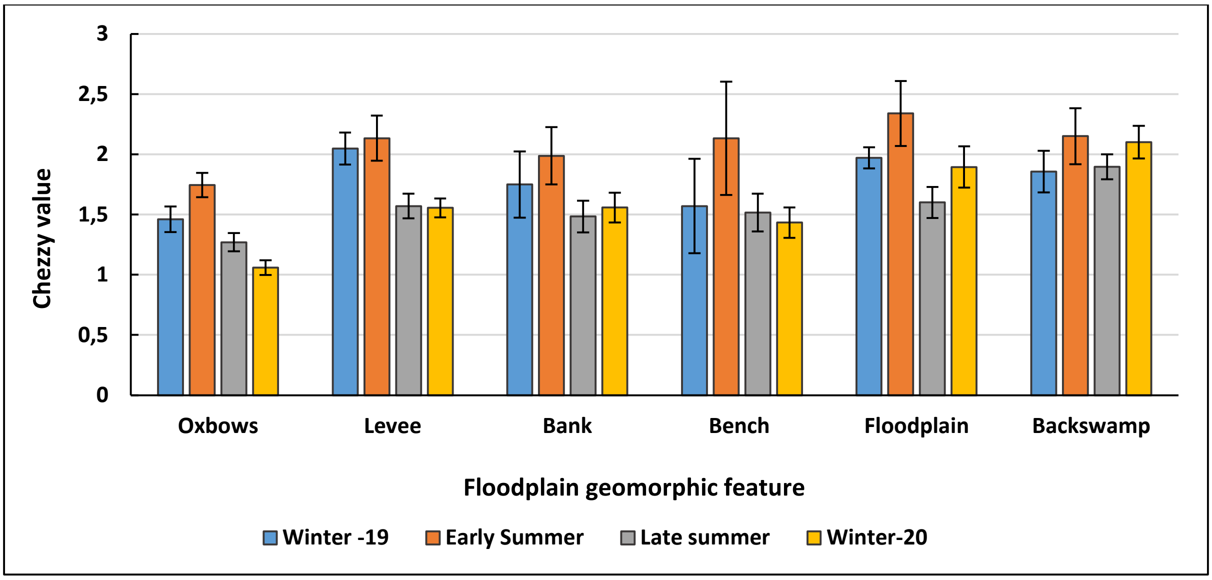


Figure 28: Variation in Chézy value with floodplain features in winter 2019, early summer, late summer and winter 2020

Figure 29: Vegetation changes in the wetland site from winter 2019 to winter 2020

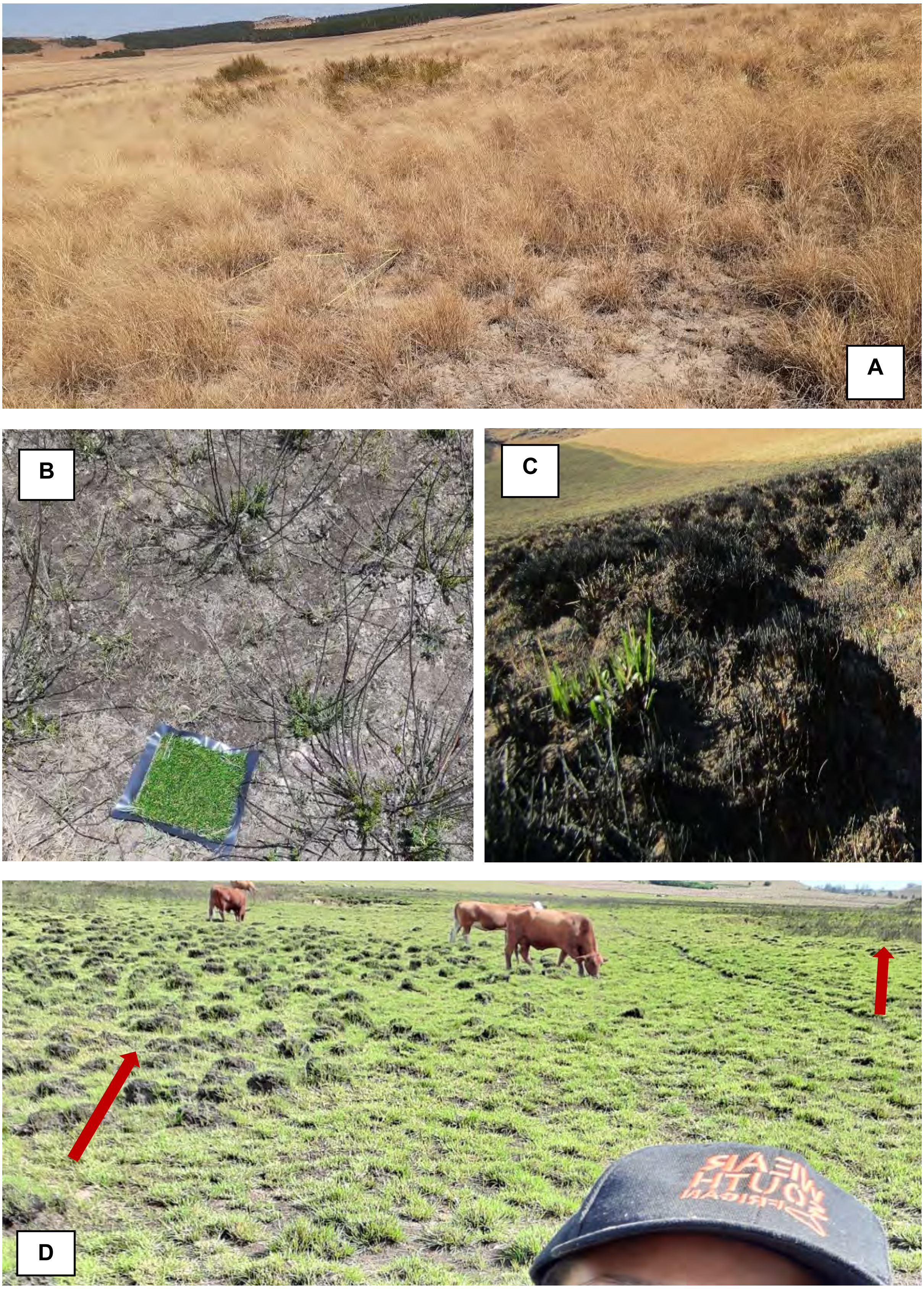
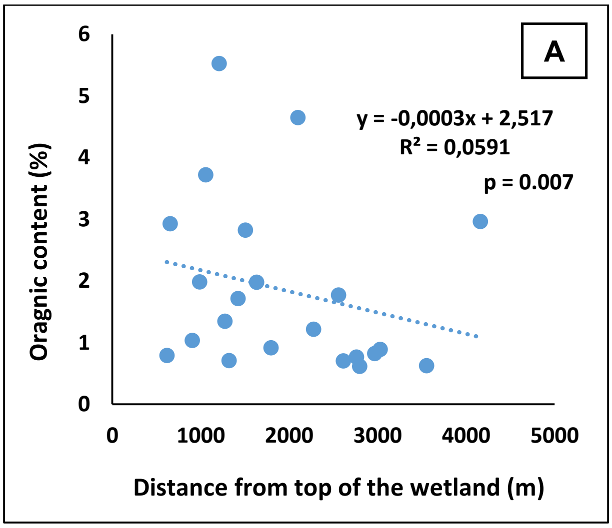
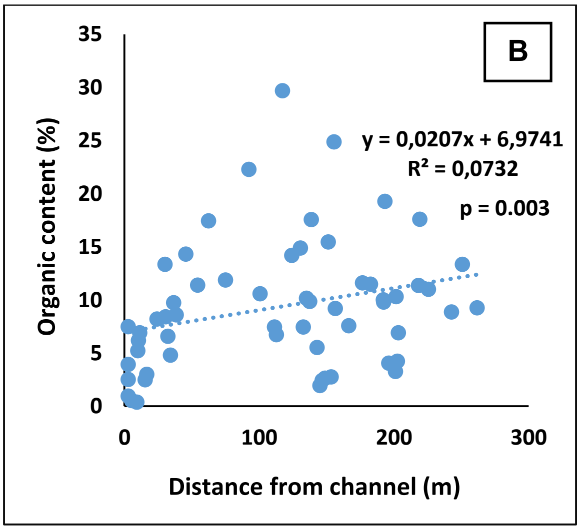


Figure 30: Vegetation state of the wetland site in winter 2019 before (A) and after the fire in late summer (B, C), exposing hummock clumps and showing the fire extent (D).

5.3.4 Organic content

Figure 31 shows a variation of organic content with distance from the top of the wetland, distance away from the channel, within the different floodplain geomorphic features and roughness. The organic content of bed sediment decreases with distance from the top of the wetland, however; floodplain sediment organic content increases with distance away from the channel on the floodplain surface. Both Figure 31A and Figure 31B show a poor correlation with distance (R^2 = 0.0591 and 0.0198, respectively). Maximum organic content is shown by oxbows and back swamps whilst floodplain benches had the least organic content (Figure 31C). Organic content increases with an increase in roughness (indicated by low Chézy scores) (Figure 31 D). However, based on the p values (less than 0.05) of Figure 31 A and B, it can therefore be concluded that there is a significant relationship between organic content and the measured variables (with distance from the channel being most significant). The correlation between Chézy value and organic content was not significant and that the data is be due to random chance. Low error bars are seen at flood benches and higher standard errors in oxbows. Low standard errors are due to low variability and represent a good representation of the population.





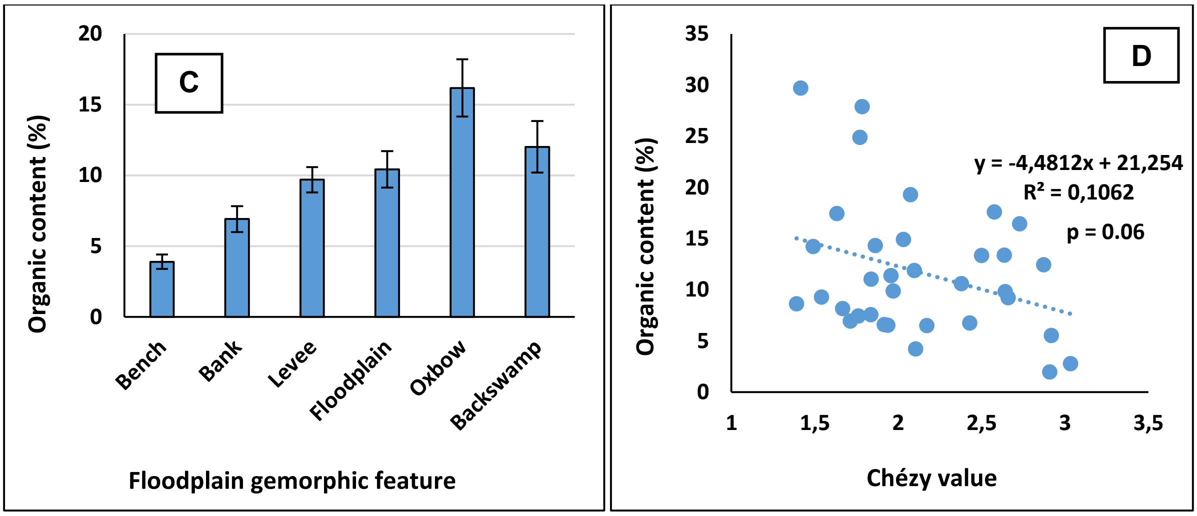


Figure 31: Organic content variation from the: A) top of the wetland (bed sediment in channel); B) distance from the channel; C) and within different floodplain geomorphic features; D) and vegetation roughness.

5.3.5 Rate of sediment accumulation and sediment type

Sediment accumulation variation across floodplain features is shown in Figure 32; Figure 32A is based on astro turf mats (astro turf mats in banks were installed at the surface of the bank; before levee point) and small time integrated samplers in Figure 32B. Accumulated sediment in Figure 32B was presented in a unit form of grams rather than grams per litre as no sediment concentration and discharge measurements were taken to calculate sediment loadings. This was also due to the fact that data was not collected in a time series and rather was taken at the end of the wet season. However, according to Figure 32A, sediment accumulation rates decrease with an increase in distance from flood benches towards the floodplain surface, and increases in oxbows and back swamps. Floodplain benches and oxbows have the highest accumulation rates with values of 48.04 kg/m^2 and 14.51 kg/m^2, respectively. Levee and the floodplain surface have the least accumulation rates with values of 6.12 kg/m^2 and 1.11 kg/m^2, respectively.

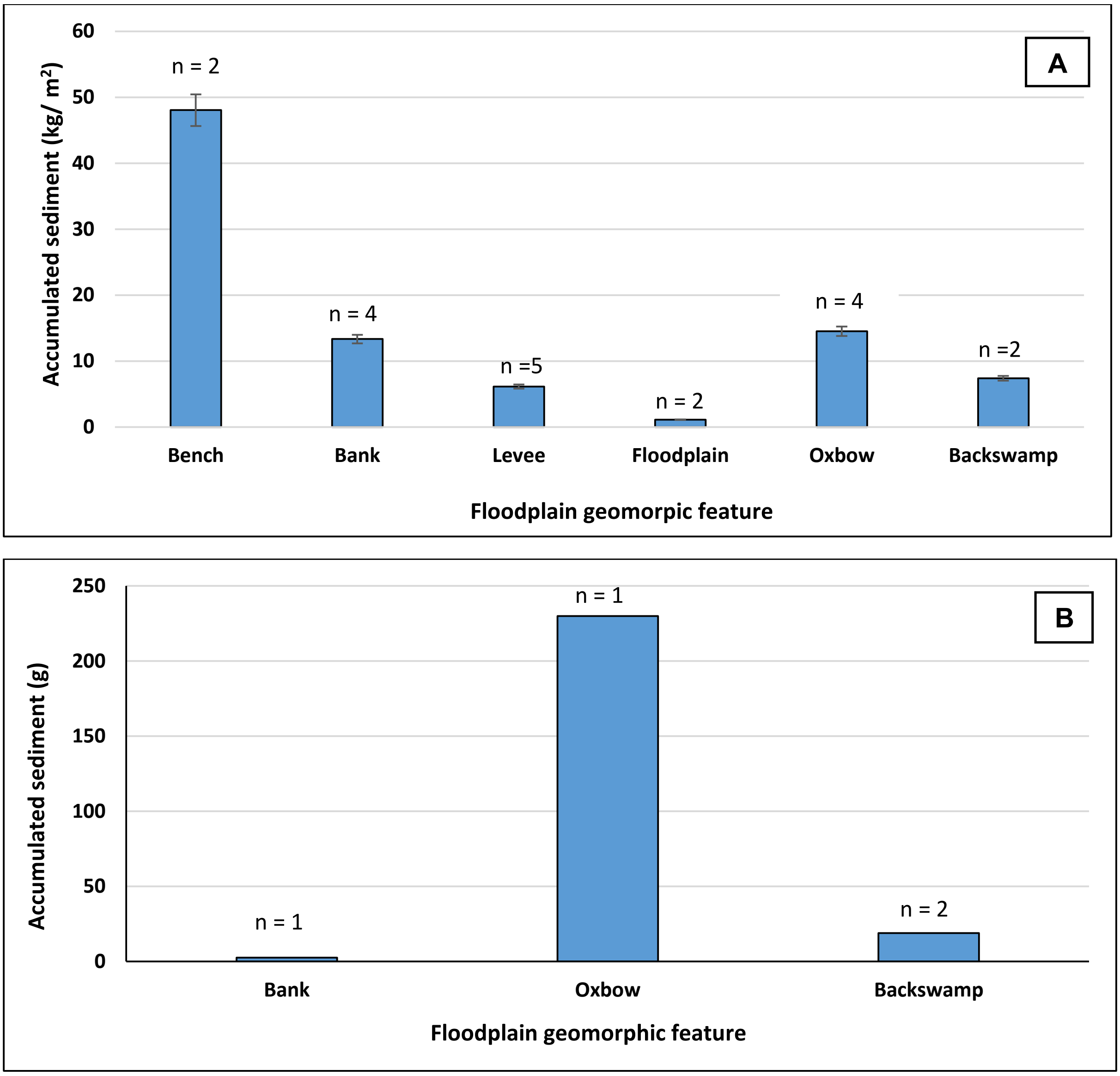


Figure 32: Mean variations in accumulated sediment on the different floodplain features for: A) astro turf mats; D) and time integrated samplers.

Sediment accumulated in time integrated samplers interpreted that most sediment is deposited in oxbows compared to banks and back swamps (Figure 32B). The relative total sediment accumulation rate was also restricted by fire occurrence and cattle disturbance (Figure 30C & Figure 33).

A regression model that predicts the most significant relationship with sediment accumulation is shown in Table 5.

Table 5: A statistical multiple regression analysis for sediment accumulation with various predictor variables (D50, Chézy value, distance from the channel, elevation above thalweg, and inundation depth).

N=34	R= .72625579 R^2= .52744748 Adjusted R^2= .44306310 F(5,28) = 6.2505 p					
	b*	Std.Err. of b*	b	Std.Err. of b	t(28)	p-value
Intercept			-64.4422	433.9863	-0.148489	0.883021
D50 (µm)	0.671916	0.152536	8.4462	1.9174	4.404982	0.000141
Chézy value	0.026750	0.157488	23.4698	138.1779	0.169852	0.866348
Distance from the channel (m)	-0.085801	0.154919	-0.3255	0.5877	-0.553848	0.584079
Elevation above thalweg (m)	-0.039367	0.249333	-24.4325	154.7428	-0.157891	0.875676
Inundation depth (m)	0.127849	0.232100	93.6196	169.9592	0.550836	0.586115

Table 5 above shows a multiple regression summary analysis to predict the most significant predictor of sediment accumulation. Based on Table 5, D50 particle size is the most significant predictor (highlighted in red) with a positive strong correlation (b* = 0.67, p value = 0.000141). This implies that the rate of sediment accumulation is influenced by particle size itself. Although inundation depth has a poor relationship with sediment accumulation, according to Table 5, it shows that it is the second most important predictor amongst the other variables. Deeper floodplain regions such oxbows with stagnant water and high inundation depths have higher capabilities of storing and accumulating sediment. The expected outcome was that Chézy value would be the most significant, however; it showed the least significant predictor (b* = 0.02). Nonetheless, Table 5 shows that there is a medium correlation of sediment accumulation with the measured variables (R^2 = 0.52744748). This is contributed to the fact that sediment accumulation can be impacted by various factors and not necessarily by one component.

Figure 33: Destroyed TIS and astro turf mat due to fire and cattle in the wetland site.

5.4 Relationships between topography, inundation depth, vegetation roughness, distance from the channel, organic content, and sediment type.

5.4.1 Topography

Figure 34 focuses on D50 particle size variation with elevation above thalweg water level and how this varies for the different floodplain geomorphic features and how roughness changes with elevation. Graphs were plotted based on which regression model fitted best on the graph. Based on the regression model of the graphs, there is a general negative relationship between elevation above water level and D50 particle size, however, the distal features of the floodplain are at low elevation (e.g. oxbows and back swamps) and receive and trap fine sediment only.

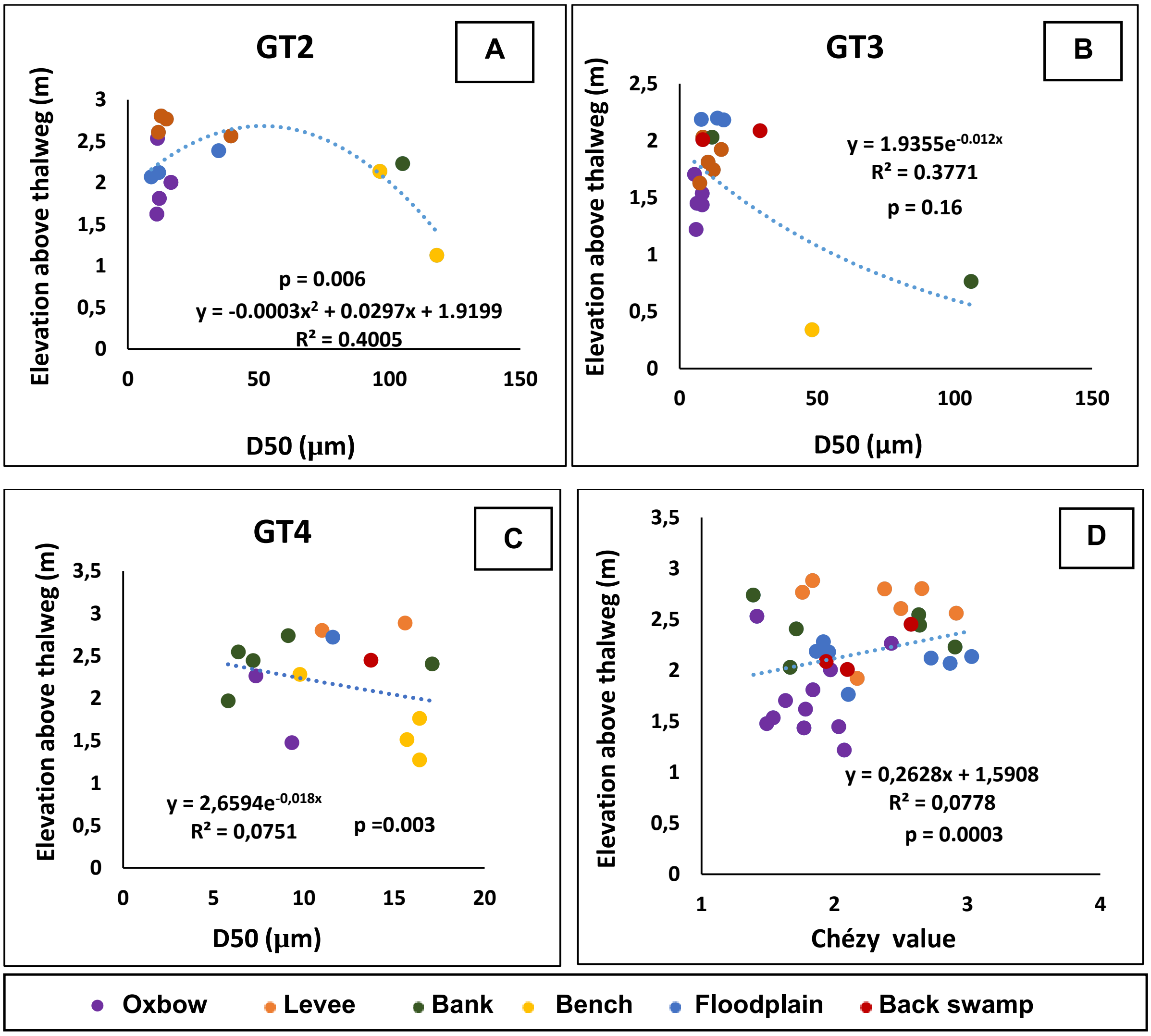


Figure 34: Variation in elevation above water level with the D50 particle size in transect GT2, GT3 and GT4 and with elevation and roughness.

In Figure 34A, most of the observed topographical points lie between elevations of 1.5 m and 2.5m above the base flow water level with particle size ranging from 8.9μm to 118μm (very fine sand). Sandy material was typically deposited on flood benches, thereafter sediment dramatically fined to levees, floodplain surface, oxbows, and back swamps. During flood events, it would be expected that the lower elevations, such as that of benches, frequent inundation would occur in these regions and deposit coarser sediment. Particle size for oxbows and levees is approximately constant while flood bench particle size decreases with elevation. The floodplain surface elevation above thalweg water level has a direct relationship to particle size, an increase in elevation above thalweg water level, particle size increases. The graph has an R^2 value of 0.4005 which is a fairly poor relationship.

Almost all of the data is situated at elevations between 1m and 2.5 m above the base flow water level with particle size ranging from 5.41μm - 106μm (very fine sand) in Figure 34B. Transect GT3 also shows a poor relationship of particle size and elevation above thalweg water level, $R^2 = 0.3771$. Particle size decreases with an increase in elevation above thalweg water level in bank surface and back swamps whilst levees relatively increase with elevation in GT3 (Figure 34B). Oxbows and floodplain surfaces have a relatively constant relationship.

Based on Figure 34C, GT4 has the poorest relationship between elevation above thalweg water level against D50 particle size compared to the other transects ($R^2 = 0.0751$). Particle size increases with elevation in levees but decreases in oxbows with a decrease in elevation. Flood benches initially have a relative larger D50 but constantly increases with elevation whilst D50 in bank surface increases with elevation above water level. The overall evaluation is that; D50 in oxbows decreases with a decrease in elevation and increasing elevation above thalweg water levels induces larger D50 particle size in levees and banks. Particle size increases with a decrease in elevation for benches. D50 particle size range decreases from GT2 to GT4 as well as R^2 value, for instance, GT2 ranges from 8.9μm to 118μm, GT3 has a range of 5.41μm to 106μm whilst GT4 has a range of 5.08μm to 17.10μm. R^2 value also decreases from GT2 – GT4; 0.4005- 0.0751. However, the relationship between elevation above thalweg water level and D50 is not significant as some of the p values were greater than 0.05 (Figure 34).

Although the regression model (R^2 value = 0.0778) in Figure 34D showed that there is a poor correlation between elevation above thalweg water level and roughness, it shows that there is a significant relationship ($p = 0.0003$). Where elevation is low, roughness is high and low roughness is associated with high elevation. High roughness (Chézy value between 1 and 2) with low elevation (1297 m.a.s.l - 1298.5 m.a.s.l) is shown by oxbows, benches, and back swamps whilst high elevation with low roughness is shown by levee, banks, and floodplain surface. Lower elevation and high roughness have a greater potential of trapping sediment.

5.4.2: Inundation depth and particle size

Figure 35 focuses on variation in maximum inundation depth at a certain flood level (based on year data) with D50 particle size and how it varies for the different floodplain geomorphic features. A linear regression model was used as it best described the trend of the data and to the main objective of this data set.

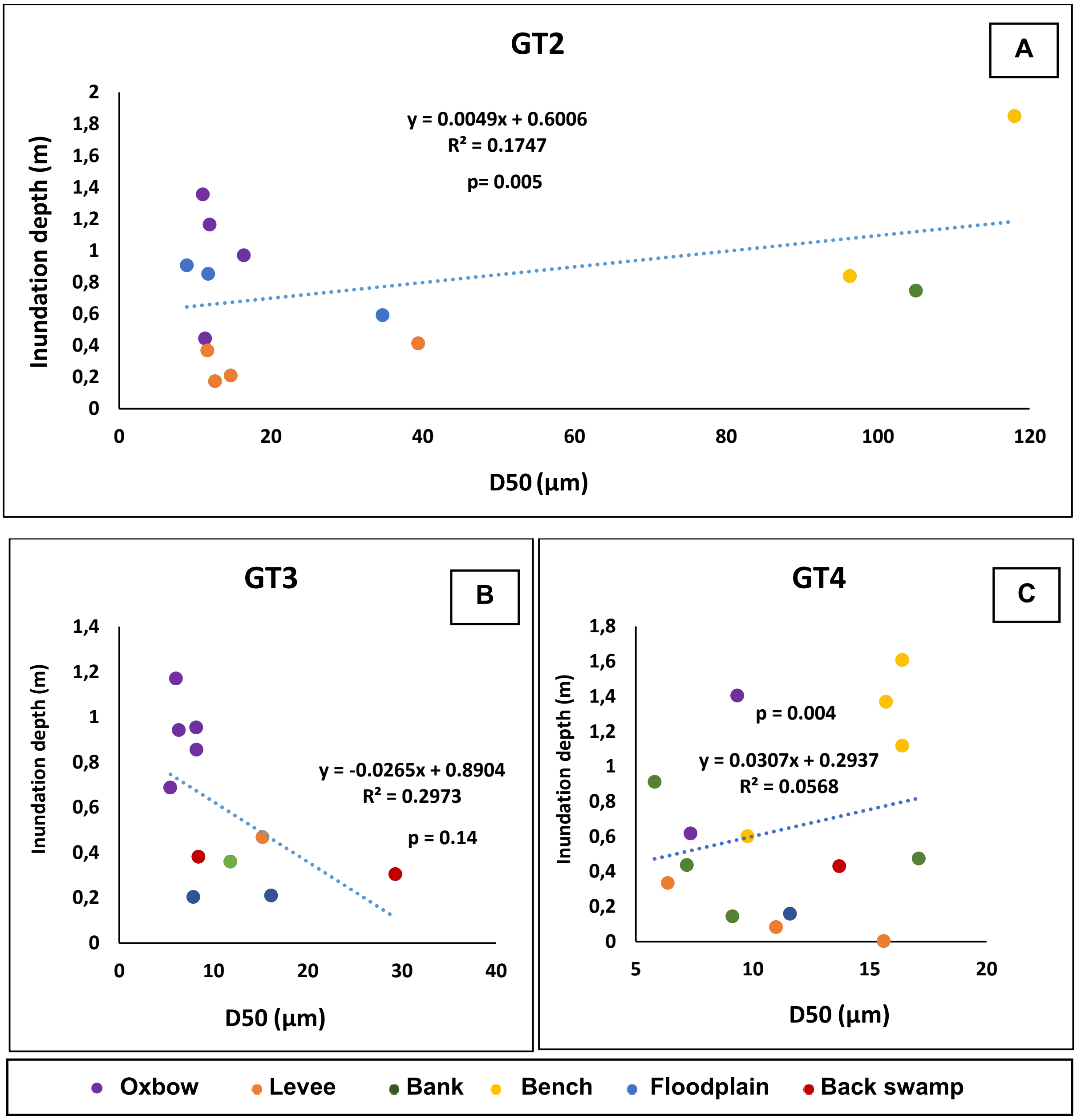
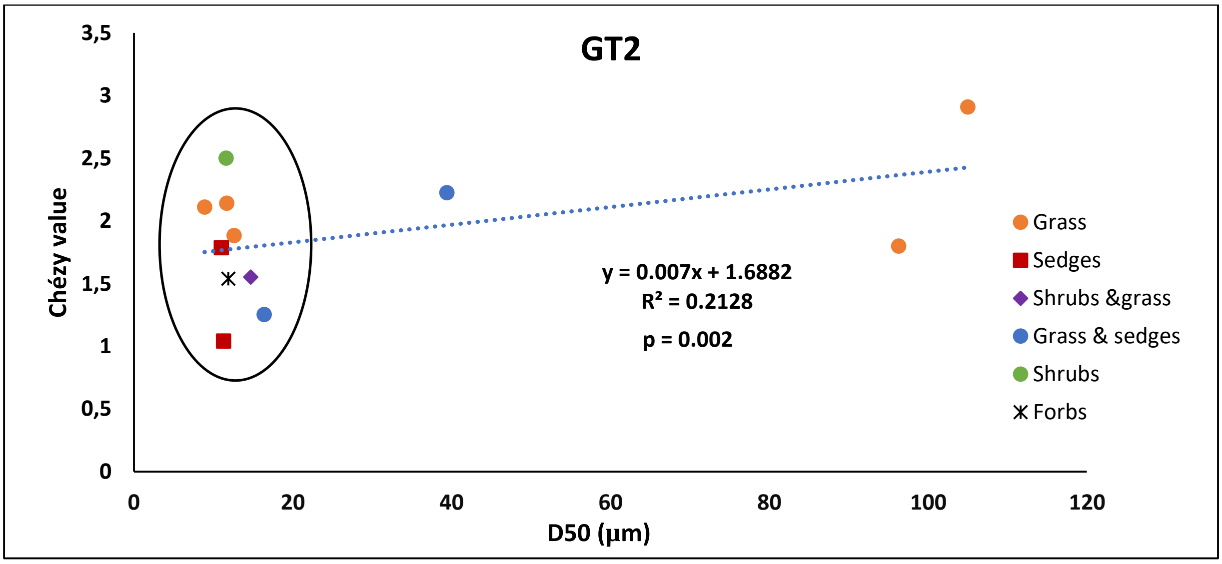


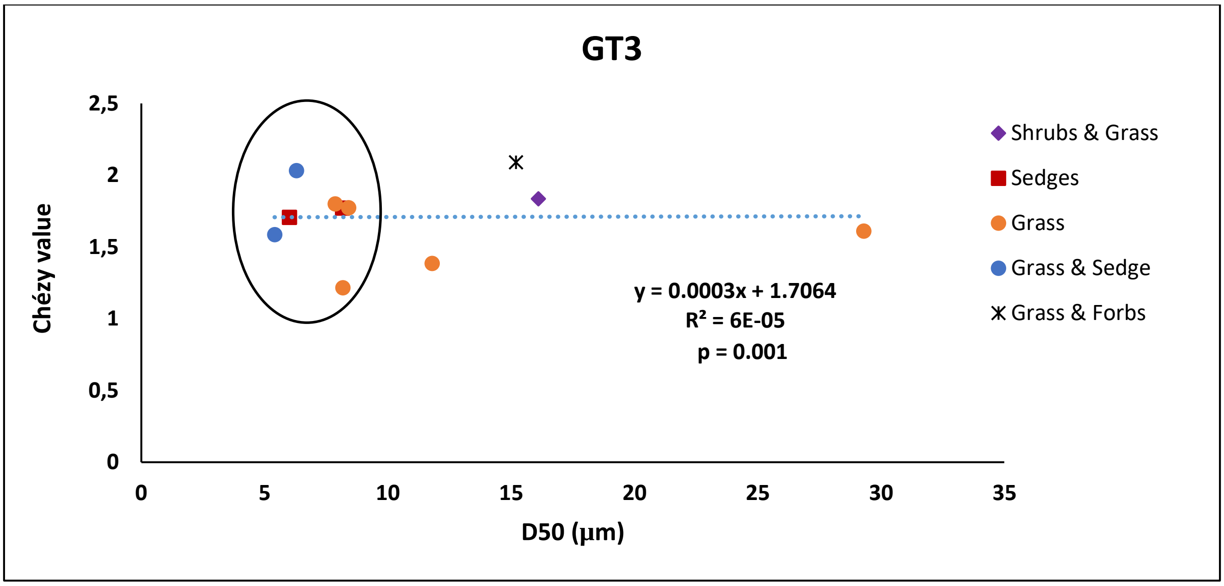
Figure 35: Variation in inundation depth and D50 particle size in transect GT2 and GT4.

Based on the regression model of the graphs, there is a poor positive relationship between inundation and D50 particle size in all transects (Figure 35). However, it shows that particle size increases with an increase in inundation level especially that of levees and benches. Bank and floodplain surface decrease in particle size when inundation depth increases. Although there is a significant relation in Figure 35A (p value < 0.05), determining trends is fairly inconclusive and uncertain as there is a non-uniform trend.

5.4.3 Vegetation roughness

The following section includes analysed results of obtained Chézy values and explores how these values change with the difference in vegetation and D50 particle size*.* A total of 33 vegetation roughness calculations were conducted for the three main transects i.e. GT2, GT3, and GT4 to measure resistance that will 'represent' how strongly vegetation influences water resistance. Vegetation roughness was calculated using three types of vegetation parameters which were incorporated in the Chézy formula to calculate roughness values i.e. resistance. The relationship between Chézy values was used to conduct a relationship against the D50 particle size to provide information on how roughness can influence particle size in each transect. Due to the Chézy value being inversely proportional to roughness, this means that where there is a high Chézy value, the value will represent low hydraulic roughness conditions i.e. low resistance. A straight-line trend was fitted to best describe how particle size changes with roughness.





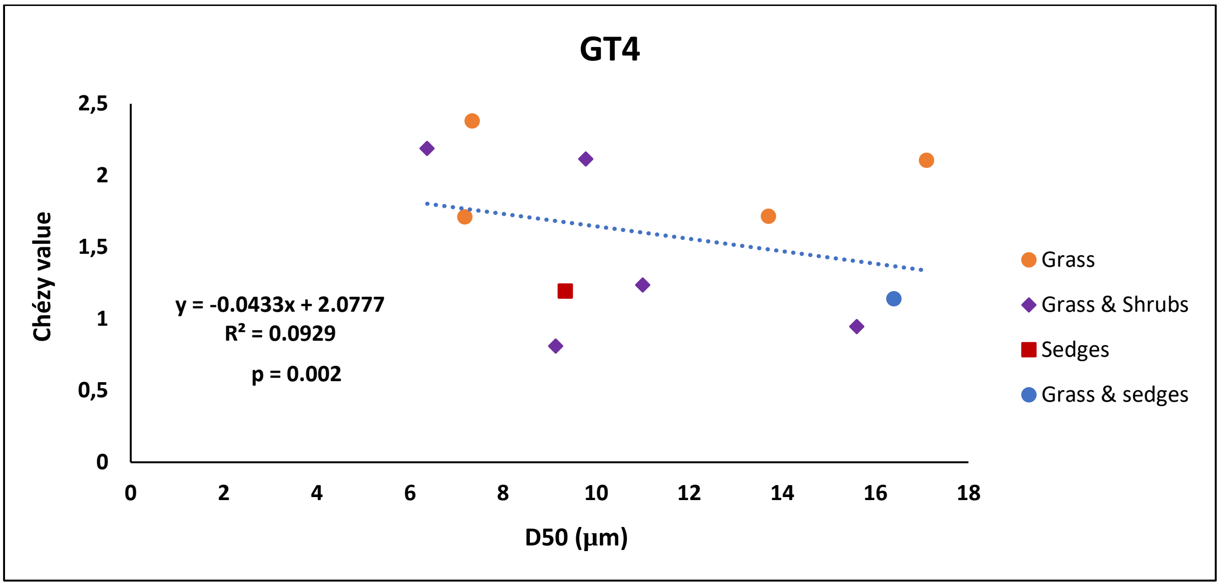


Figure 36: The relationship of the Chézy value with D50 particle size at GT2- GT4.

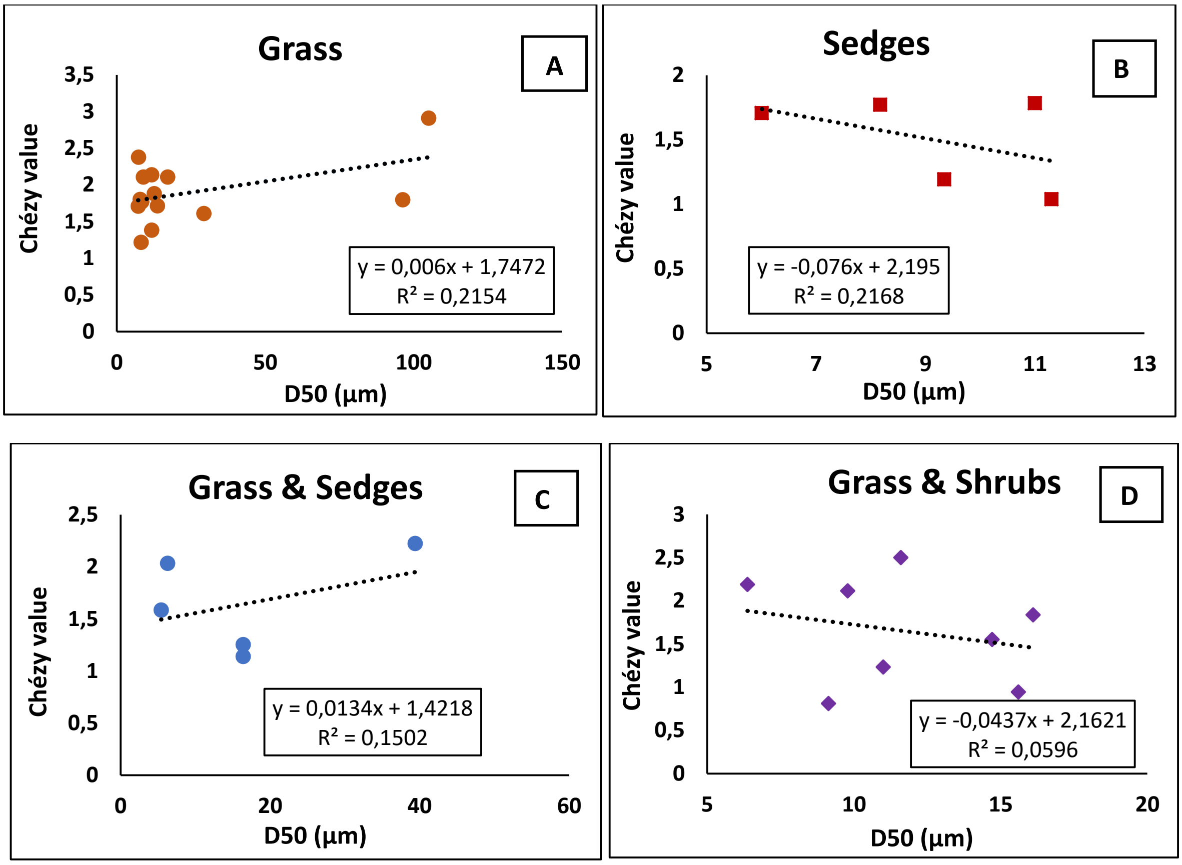


Figure 37: Relationship of vegetation roughness with : A) Grass; B) Sedges; C) Grass & Sedges; D) and Grass & Shrubs.

Figure 36 shows a relationship of a resistance factor against sediment particle size (D50). In GT2, most of the Chézy values lie between 1.03 and 2.5 with particle size ranging from 8µm to 16µm (very fine sand). Shrubs and grassy vegetation generally show higher Chézy values with the highest value being 2.9 and the lowest being 1.03. Lowest Chézy values are shown by sedges, grass & sedges. There is a poor relationship between Chézy resistance values and particle size, however, it shows a negative correlation trend i.e. the higher the Chézy values the smaller particle size. Transect GT3 is dominated by grass and shows the poorest regression model, $R^2 =$ 0.0339. Most of the Chézy values lie between 1.2 - 2.03 with high Chézy values shown by grass & sedges whilst the lowest values are shown by grass. According to transect GT4, grassy vegetation has the highest Chézy value (2.3) whilst shrubby vegetation show the lowest Chézy value (0.8). It is dominated by grass & shrubs vegetation and have wide distribution of roughness values compared to GT2 and GT3. The graph also shows a poor negative relationship between resistance values and the sediment particle size. Although the graphs show a positive weak correlation, the relationship between Chézy value and particle size is stronger at the bottom (GT4) of the wetland compared to the centre (GT3) and top of the wetland (GT2) of the wetland. Roughness variability decreases at the top of the wetland compared to the centre and bottom of the wetland.

Particle size decreases with roughness in grass and grass & sedges whilst it increases with roughness in sedges and grass & shrubs. The overall conclusion is that D50 increases with an increasing Chézy values for grass, forbs, grass & sedges and decreases with an increasing roughness for sedges, shrubs & grasses (Figure 37). The overall p value of roughness and particle size was 0.0021 which indicates that the relationship is significant.

5.4.4 Distance from the channel

The relationship between particle size and distance from the channel is shown in Figure 38. Coarser particles are defined with smaller distances from the channel (e.g. flood benches, the surface of banks, and levees) whilst finer particles are defined with larger distances from the channel such as oxbows and back swamps. Although the power function regression model shows a poor correlation (R^2= 0.3589); distance away from the channel showed a significant correlation with particle size (p = 0.01). Particle size decrease with increasing distance away from the channel (Figure 38).

The relationship of the different floodplain geomorphic features and how D50 particle size changes with each geomorphic feature is also shown in Figure 39. D50 particle size ranges from 5.08μm to 709μm (silt to very coarse sand) with maximum and minimum values indicated by the whiskers; the channel bed has the largest particle size while oxbows have the finest particle size with mean values of 289.31μm and 9.73μm respectively. At least 75% of D50 particle size in the channel bed is greater than 400μm (medium sand). The channel bed and banks have the highest average mean (indicated by an X in the whisker box). Outliers in the bank and levees are indicated by a dot in the graph which indicates that the value is distant from the rest of the data set and is out of the interquartile range. Levees, floodplain, oxbow, and back swamp box and whisker plots are of a consistent size and low variation compared to the box and whisker plots of the channel bed, bench, and bank.

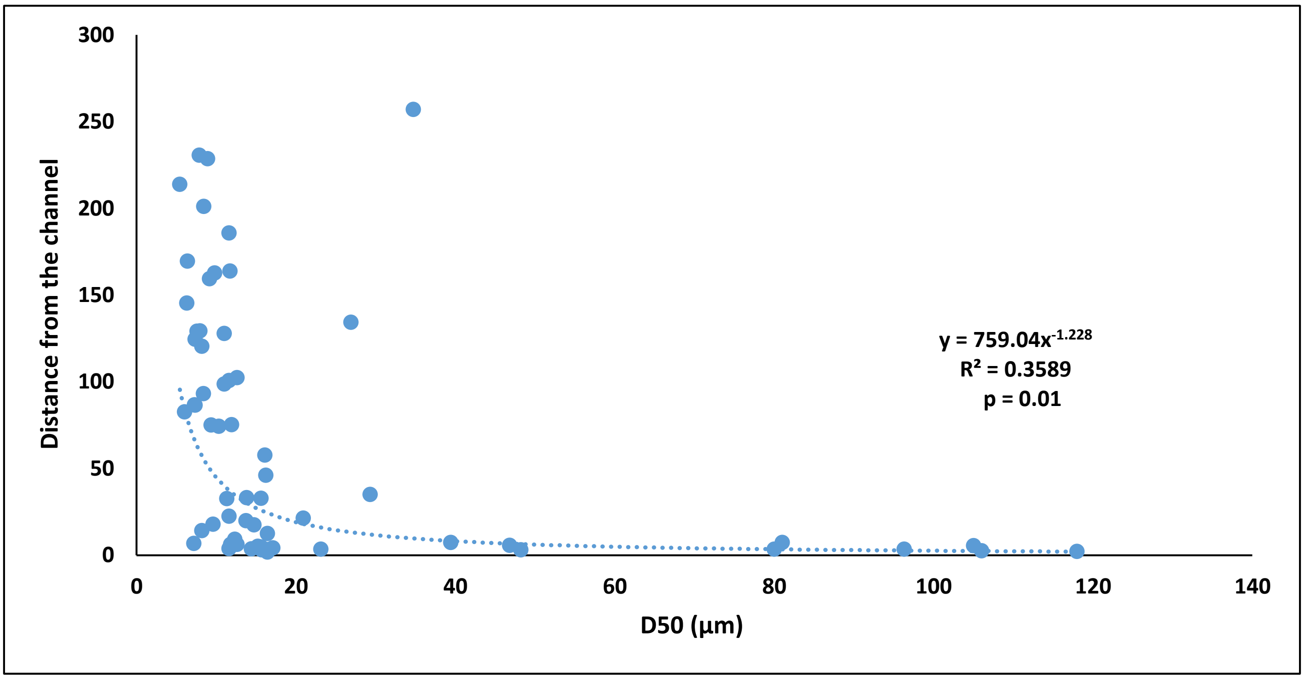


Figure 38: Variation of D50 particle size with distance from the channel.

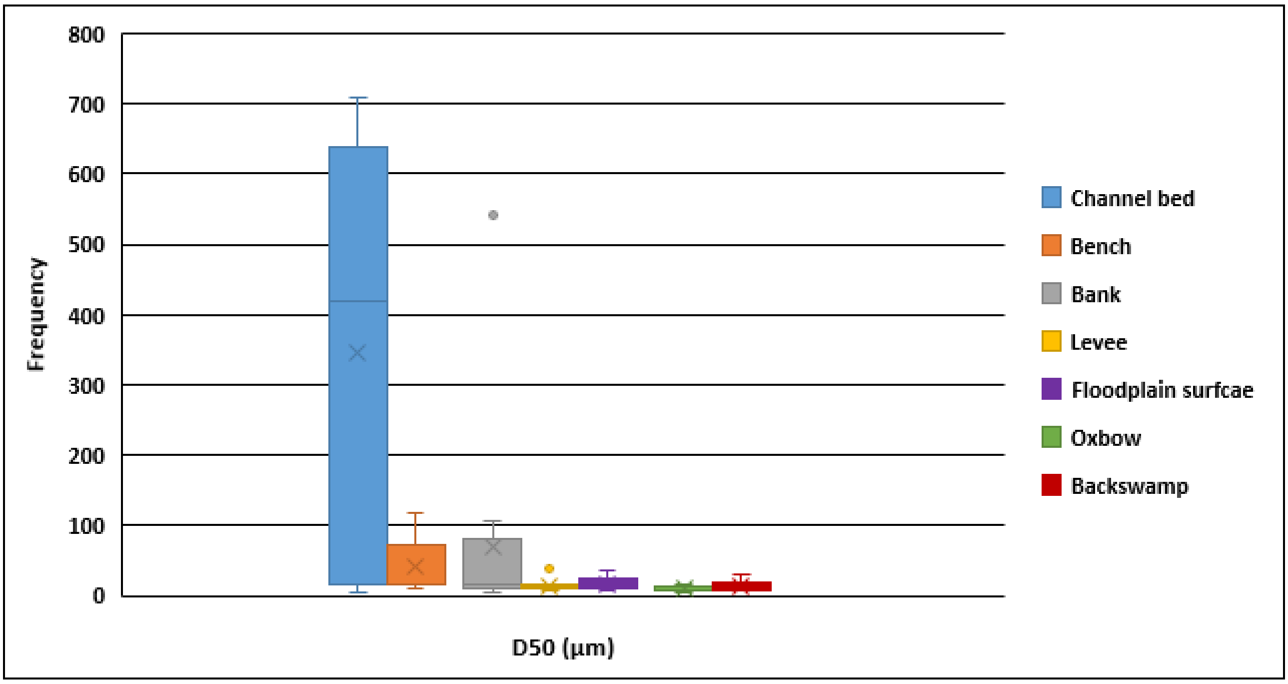


Figure 39: Box and Whisker plot variation in D50 particle size of the different floodplain features. The whiskers are a representation of a standard deviation.

5.4.5 Organic content

Organic content percentages were plotted against particle size (D16, D50, and D84) in Figure 40. The data was based on 70 samples that were taken from the entire wetland. Changes in organic content were calculated and plotted against particle size. There is a good relationship between the two variables as they show a good negative correlation (R^2 above 0.7). The graphs show that organic content decreases with an increase in particle size. The regression model fitted best with D84 (R^2 = 0.7911). Most of the particle size D16, D50, and D84 percentiles are concentrated between 0µm – 50µm, 0- 100 and 10µm -100µm for respectively. This shows that the wetland surface particle size ranges from clay to sandy material, and organic content ranges from 0.41 to 29.72. Oxbows and back swamps had the highest organic content whilst levees and banks had the lowest organic content.

A regression model that predicts the most significant relationship with D50 particle size is shown in Table 6.

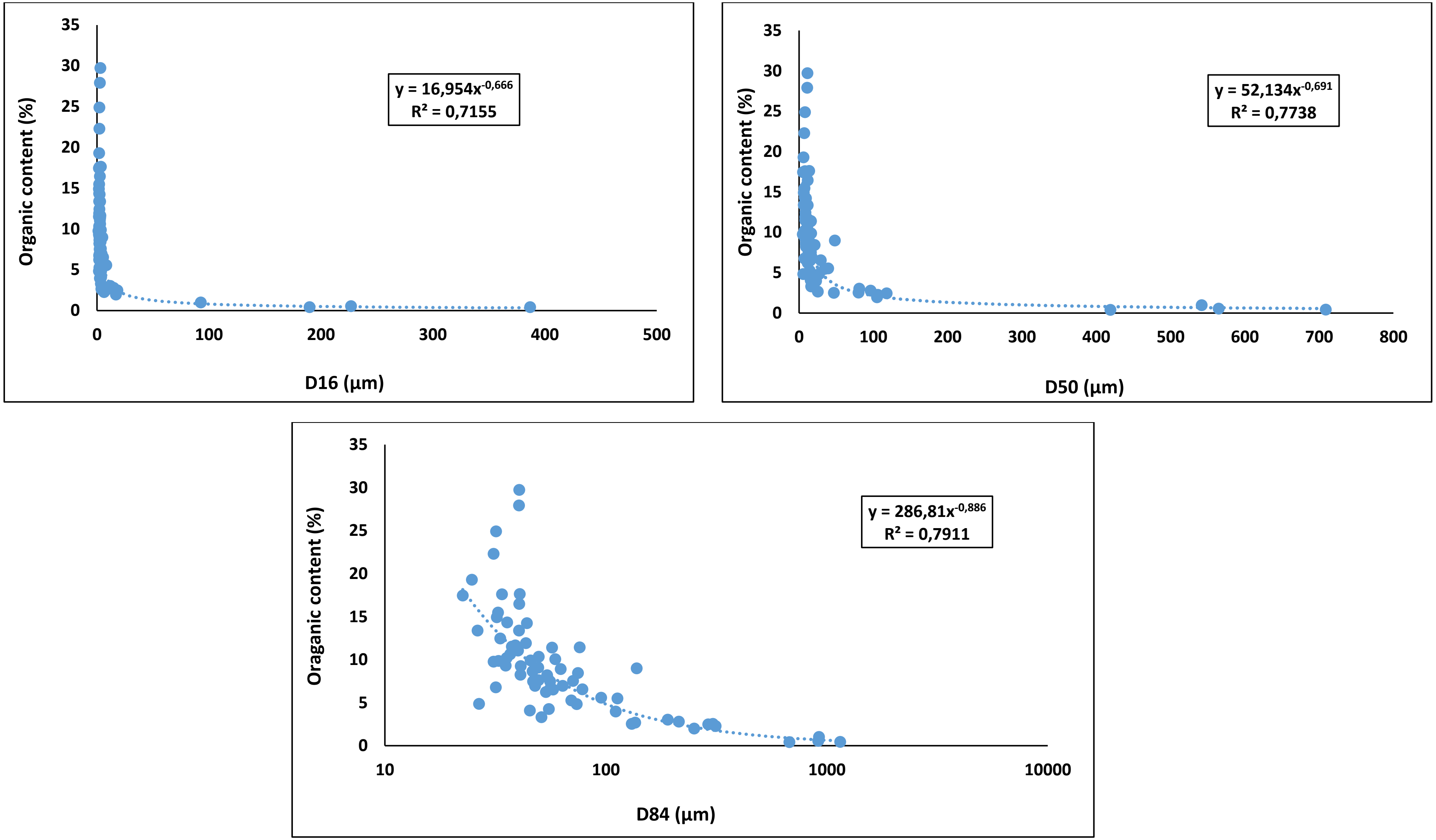


Figure 40: Overall relationship between the organic content and D16, D50 and D84 particle size of transect 1 to 5 (GT1- GT5).

Table 6: A statistical multiple regression analysis for D50 particle size with various predictor variables (chézy value, distance from the channel, elevation above *thalweg*, and inundation depth).

N=34	R= .52407502 R^2= .27465462 Adjusted R^2= .17460698 F(4,29)=2.7452 p					
	b*	Std.Err. of b*	b	Std.Err. of b	t(29)	p-value
Intercept			-39.7293	41.37468	-0.96023	0.344877
Chézy value	0.414451	0.175598	28.9263	12.25578	2.36022	0.025205
Distance from the channel (m)	-0.379826	0.174910	-0.1146	0.05279	-2.17155	0.038212
Elevation above thalweg (m)	0.055677	0.303357	2.7487	14.97661	0.18354	0.855655
Inundation depth (m)	0.294983	0.277195	17.1828	16.14662	1.06417	0.296031

This section aimed at computing a multivariate regression analysis to predict significant variables with particle size based on the investigated variables in the results section. Table 6 above shows that particle size is mostly influenced by the variables highlighted in red (Chézy value and distance from the channel). Therefore, particle size decreases with an increasing distance from the channel as there is a negative correlation (b* = -0.38, p value = 0.04). Chézy value has the strongest relationship with particle size (b* = 0.41, p value = 0.03); an increase in Chézy value increases particle size. Elevation above thalweg and inundation depth has a poor correlation with particle size such that statistical tests showed p values that were greater than 0.05. For every one unit increase, elevation above thalweg increases by 0.05 units and has a larger unstandardized value i.e. points are more spread out from the regression line which implies that elevation above thalweg is a poor predictor. There is a poor positive correlation between D50 and the measured predictor variables (overall R^2 = 0.27)

6: Discussion

The following chapter discusses and evaluates the objectives of the study and the results that were presented in the previous chapter to better understand the overall sediment buffering function of the Gatberg wetland. Implications and recommendations of the study area are outlined towards the end of this chapter.

6.1 The relative suspended sediment quantity and quality coming in and leaving the wetland.

Suspended sediment (composed of clay, silt and sand) is considered one of the most transported materials in fluvial systems. Vale *et al*., (2016) noted that the main sources of suspended sediment can include washed-in material from hill slopes and the release of fine sediment from bank erosion in the channel. Sediment is temporarily stored in the floodplain during low flows and re-suspended and transported during high discharge events. Variability in sediment delivery both spatially and temporally upstream and downstream of floodplain wetlands therefore differ due to factors such as morphology, stream velocities, flood frequencies, height, and its duration (Hupp *et al*., 2008).

In this study, time integrated samplers were used to determine and evaluate the relative suspended sediment quantity coming in and leaving the wetland over one wet season. Sediment type at the top of the wetland consisted of coarser sand material and finer sand at the bottom of the wetland with an average suspended sediment mass of 83.43g and 51.99g at the top and bottom of the wetland, respectively (Table 4, Figure 19). The transport of sediment into and out of a wetland is unbalanced due to changes in velocity and the morphology of the wetland (Abed, 2009), and such differences in the morphology of the wetland study area were observed (Figure 26). These observations also mean that there is a progressive loss of suspended sediment that gets deposited onto the floodplain such that, sediment deposition rates can be expected to also decrease with distance downstream. The predicted outcome was that high sediment accumulation rates are generated by high flows or flood-dominated wetlands as shown in studies by Hupp *et al*., (2008), Pierce (2008), and Kleiss (1996). Furthermore, based on the trapping efficiency calculations; higher sediment input at the top of the wetland than at the toe of the wetland suggested that approximately 73% of the incoming sediment was trapped within the floodplain wetland. This predicted an accumulation of 4 tons over the monitoring time frame of the study. Although these observations for floodplain wetlands are not unique, these results were much higher than can be accounted for based on the low rainfall conditions within the study area (Figure 11). High trapping efficiencies during low flow conditions can be related to higher suspended sediment concentrations than the relative available water/inflow rate, localized rain storm events, the impact of cattle crossing and grazing in the wetland, and or can be an effect of 'sufficient' water levels that overtopped the wetland. In addition, land degradation, infrastructure such as roads, forestry and agriculture occurring in the Tsitsa River Catchment also have an impact in sediment inputs which may elevate sedimentation in the study area. Furthermore, early winter inundation also cause high sedimentation in wetlands (Fennessy *et al*., 1994) and the declining water depths (Figure 23) over the growing season may have induced recirculation of sediment. These findings are similar to a study done by Mitsch & Reeder (1992). Fryirs & Brierley (2012) and Childs (2010), had noted that a reduction in the water supply to transport sediment results in aggradation or a decrease in stream slope decreases energy to transport sediment thus aggradation occurs (Figure 3). Furthermore, when there are low velocities, sediment settles out of the suspension to be deposited as the energy is inadequate to transport and carry sediment in motion (Figure 1). The small, localized tributaries draining into the wetland that showed low levels of erosion have an impact in sediment inputs. The tributary at the bottom of the wetland contributed a higher mass than the tributary at the top of the wetland (Table 4, Figure 19) which constituted high sediment inputs. Organic content was high at the top of the wetland and low at the bottom of the wetland. These observations can be compared with the impacts on other wetlands around the study area. Vale *et al*., (2016) noted that excessive sediment supply downstream result in sediment deposition and accumulation that can impact channel morphology, water quality and can have major influences on dam sedimentation thus deteriorating its operational full capacity and longevity. It is, therefore, crucial to quantify the amount of suspended sediment coming in and out of river systems as this has future implications such as erosion processes.

Larger particle size at the top of the wetland than that at the bottom of the wetland may be linked with high stream power as it has the ability to suspend larger particles. It can be related to steeper gradients at the top of the wetland (Figure 26A) which are associated with high flood frequencies (Figure 24), inundation depth, and settling velocities. These observations may also be correlated or similar to fluvial processes such as abrasion or weathering.

Sediment concentration and discharge measurements were not measured within the study area, this limited the calculations of sediment loadings that could be accounted for. This was due to the fact that time integrated samplers were not collected on a time series and rather were collected once, after the wet season.

6.2 Spatial variability in bed particle size

6.2.1 Bed sediment particle size

The analytical results of the sampled Gatberg channel bed that included a 4.1km reach (Figure 20), revealed that the channel is mostly characterized by bedrock control features with coarse material mixed with some gravel, sand and clay material in the channel bed. Bed sediment particle size have been documented to decrease with distance downstream i.e. from boulders, cobbles to sand; particularly in large river channels (Frings, 2008; Surian, 2002). However, the D50 particle size in the Gatberg River does not decrease with distance downstream and rather the channel bed generalized two aspects: the channel bed shows a non-uniform trend in particle size with distance downstream as well as the occurrence of sediment zonation e.g. riffles and bedrock controlled sites have coarser material while pools and bars have finer material. This can be assumed to be caused by sedimentological processes of the river such as the dominance of selective transport mechanisms in channel bed, variability in frequency, discharge, flood magnitude, and the influence of tributaries (Wang *et al*., 2009; Frings, 2008; Surian, 2002; Figure 20). The poor correlation (R^2 =0.3312) of particle size with distance from the top of the wetland can be linked to sediment contributions from surrounding hill slopes and tributaries. Particle size from the time integrated samplers at the top of the wetland had coarser particle size than at the bottom of the wetland (Table 4), which is the opposite from the observations on the channel bed. This may be linked to erosional processes along the channel which may introduce coarser material into the channel bed.

Figure 21 showed that pools have relatively finer particle size than the nearby riffles that are situated in elevated areas with coarser sediment. The high-flow velocities over larger particles in riffles cause turbulent mixing in pools which results in energy and velocity dissipation, thus inducing finer sediment deposition in pools (Brierley & Fryirs *et al*., 2012; Wang, 2009; Brierley & Fryirs, 2005; Gordon *et al*., 2004; Surian, 2002). Coaser particle size in riffles are caused by the high-flow energy turbulences that increase roughness during high flows. This induces deposition as resistance causes a decrease in velocity over the riffle which is usually accumulated by boulders, cobbles, and gravel. Figure 20 & 21 showed that only two points were taken at point bars, this, therefore, did not give a good platform to give reasoning on the variability of particle size on point bars. However, point bars are usually filled with finer-grained particles which tend to rework during high flows.

Bedrock controls are recognized as local resistant units that can erode due to high turbulent flows which can induce mass failure, plucking, corrosion and abrasion such that larger particle sizes are contributed to the stream (Brierley & Fryirs, 2012; Gordon *et al*., 2004). Bedrock controlled regions in this channel may have therefore undergone such processes as they have larger particle size on the channel bed.

6.3 Spatial variability in inundation depth, topography, vegetation roughness, organic content, rate of sediment accumulation and sediment type, and the relation to floodplain particle size.

6.3.1 Inundation depth

Spatial groundwater-surface seasonal water level fluctuations were measured from December 2019 to May 2020. Results from the top of the wetland showed that a correlation of high water levels occurred in the high rainfall period which was between January and March, with maximum high peaks in February (Figure 23) such that inundation events were high, overtopping the Gatberg Floodplain Wetland (Figure 22; Figure 24). This also shows that the catchment has a quick response to rainfall-runoff processes. Wu & Liu (2017) also stated that rises in rainfall events subsequently increase surface water flow thus inducing water flow from the river channel to the floodplain. Rainfall has a temporal influence on the seasonality and frequency of water level regimes (Wu & Liu, 2017). Therefore, high fluctuation intensities can be associated with more significant frequent changes in water levels due to rainfall.

This high flooding event period in the wetland can therefore be recognized as an important constituent of entrainment, transport, and re-suspension of sediment; thus playing an important factor in wetland sedimentation (Wu & Liu, 2017; Walling & He, 1998). Other hydrological characteristics observed from December till mid-January showed that at some point during the wet period, water levels were higher in the well than the relative channel. This was due to groundwater-surface interactions i.e. surface water outflow to groundwater. Given this, it indicates that the Gatberg Floodplain Wetland is hydrologically connected to groundwater. Low water levels in the channel can have an impact on the effectiveness of re-suspension and redistribution of sediment.

Further results showed that water levels started to decrease towards the end of May with prominent water level depressions between September and December (Figure 22; Figure 23). This is due to a drier period approaching i.e. water drains from the floodplain to the channel; and by low local watershed rainfall and high evapotranspiration rates (Mao *et al*., 2002). Based on Figure 23, the graph can be categorized into four sections; (1) the rising water level period shown between December and January (which suggests that water levels had reached flood benches, banks, and levee elevation), (2) connection phase (February- March 2020) or high water period where water levels overtop the banks and flow onto the floodplain surface. Flood benches, oxbows, and back swamps are likely to receive sediment as these geomorphic features are hydrologically connected during the high water period. Figure 23 was also sectioned into the (3) low water period that was observed between September and October 2019 (water levels are below bank full) and lastly; (4) the isolation period which was seen in November 2019 (little or no hydraulic connectivity between the channel and the floodplain wetland). High sedimentation can be expected in the rising and high water periods.

Water levels at the top of the wetland are significantly different than the bottom of the wetland, this is due to changes in elevation as the wetland is steeper at the top and gently becomes wider and flat the bottom (Figure 24) and therefore respond differently to water level fluctuations. Furthermore, Wu & Liu (2017) noted that the connection duration downstream of the wetland can slightly decrease, and this was observed in the study area as there were lower water levels in the channel.

Inundation depth was higher at the top of the wetland and had a larger particle size as opposed to the bottom of the wetland (Figure 24; Figure 35; Table 4). Larger particle size with high inundation levels are linked with high stream velocities and as a result variability of the floodplain topography (Figure 24; Figure 26). Guan *et al.*, (2015) and Lecce & Pavlowsky (2004) noted that this is a result of increased flood competence and capacity. Although inundation depth showed significance with particle size in GT2, Table 6 showed that there is no statistical significance between particle size and inundation depth ($b^* = 0.29$); determining the trends was fairly inconclusive and uncertain as they were non-uniform (Figure 35).

6.3.1 Topography

The study evaluated D50 particle size variability with elevation and also evaluated how elevation changes with distance from the top to the bottom of the wetland (Figure 26; Figure 34). Elevation variation decreased with distance from the top of the wetland (Figure 26). This is commonly known in floodplain wetlands to decrease in distance downstream due to less variability in geomorphic feature heights over longer distances downstream (Fryirs & Brierley, 2012; Jain *et al.*, 2008).

Particle size changed with elevation above the thalweg water level on the floodplain surface (Figure 34). Larger particle size on higher elevations can be used as indicators of higher flow velocity and higher energy (e.g. on levees) whilst lower elevations are associated with lower energy and velocity (e.g. oxbows). Although a poor correlation of elevation above thalweg water level with D50 particle size was seen, flood benches, levees, and banks however had the coarsest particle size with lower elevation above the water level. This is due to frequent inundation associated with high velocities that deposit coarser particles as benches are sinks of larger particle size and are closely linked to the river channel. Furthermore, sediment found on the levees represent the form of flow regime that had occurred in that specific time (Hudson, 2015; Smith & Pérez-Arlucea, 2008; Hudson & Heitmuller, 2003), therefore the coarser particle size found on levees for this study area mean that flow velocities were high. Steeper gradients produce turbulent high-energy transport mechanisms that are associated with larger sediment size (Hudson & Heitmuller, 2003). This is evident in transects GT2 and GT3 (Figure 34A & B) as there is large variability in D50 particle size found in levees with coarser particle size. GT4 in Figure 34C showed finer particle size with lower elevation above the thalweg water level while GT2 and GT3 revealed larger particle size.

Oxbows and back swamps had the finest particle size with a low elevation above the thalweg water level. This was also evident in studies done by Constantine *et al.*, (2010) and Hooke (1995) which stated them as ideal sediment buffers for suspended sediment; mainly silt and clay with lower elevations. Floodplain surfaces consisted of finer particle size with high elevations above the thawleg water level in transect GT3, this also showed a correlation with studies by Thanon *et al.*, (2007) and Benedetti (2003); that floodplains are sinks of finer particle size during overbank flows. The differences in particle size of the floodplain geomorphic features can give insight into the complexities of sediment processes involved which then control sediment quality received. Furthermore, the D50 particle size range decreased from GT2 to GT4; larger particle size is seen at the top of the wetland (GT2) than the relative particle size at the bottom of the wetland (GT4). This suggests that relative elevation with the distance of the floodplain system is tapering towards the bottom of the system (Figure 26) and due to the fact that the coarsest sediment are deposited first as flow velocity decreases away from the channel (Figure 38) thus the lower the elevation is, the finer the sediment. This may also be the main reason why elevation was a poor predictor (Table 6) with D50 particle size (Figure 34B & C ($p > 0.05$)).

Further results showed a close association of roughness with elevation ($p = 0.003$; Figure 34D); High vegetation roughness with low elevation occurred in oxbows and on benches while elevated regions such as levees had low roughness. Boscutti *et al.*, (2018) and Garssen *et al.*, 2017 found similar results where plant roughness decrease with an increasing elevation, this is particularly caused by nutrient availability and length of flood inundation (decrease with an increasing elevation). Therefore elevated regions with low roughness are limited in buffering sediment than regions closer to the channel (benches) with low elevation where plant development and survival are determined by flooding.

6.3.2 Vegetation roughness

The Gatberg Floodplain Wetland consisted of a high vegetation diversity (e.g. grass, shrubs, forbs, and sedges). Vegetation roughness variation in this study was established for each location point with particle size (Figure 36). There is a negative correlation between roughness and D50 particle size such that coarser sediments are typically associated with lower roughness. However, each vegetation type showed variability changes on each transect, pointing to complex interactions that are locally variable. Shrubs had a general trend of high roughness with bigger particle size while grasses had a high variability of roughness i.e. low roughness with smaller particle size in some transects, high roughness with smaller particle size, and low roughness with bigger particle size. Sedges & grass showed a high roughness with smaller particle size and in some areas with low roughness and bigger particle size (Figure 37). The overall estimation is that low roughness induces a larger particle size and high roughness induces a smaller particle size. This is also evident in Table 6 where the Chézy value is the most significant predictor of particle size (b * = 0.41). Furthermore, variation in particle size can be implicated by flow velocity and energy variations through the effect of turbulence and drag force exerted on the water flow. Low roughness allows faster flow and larger particle transport/deposition.

Furthermore, differences in vegetation geometry i.e. type, shape, flexibility, and distribution also play a role. For example, Stephen (1999) had described that flexible vegetation such as grass accumulate finer sediment due to high roughness cover than shrubby vegetation that has a greater line spacing and more upright rigid vegetation inducing low roughness and larger particle size. Furthermore, Dorji *et al*., (2014) noted that sedges and grass tend to reproduce faster than forbs, this correlates to the high roughness throughout the wet season in sedges which were found in oxbows for this study area. This causes differences in particle size and sediment type; high roughness causes a reduction in particle size. Moreover, flexible vegetation are bent and tend to have a streamline form that mimics stream flows, such that finer particles are deposited when there are low flow velocities (Wang *et al.*, 2014).

Vegetation parameters (density, diameter and height) changed over the wet season (Figure 27; Figure 29). High vegetation densities were seen in late summer whilst high stem diameter and vegetation height were observed in late summer and winter 2020. The possible reason in increasing vegetation height in late summer would be that of an increase vegetation due to increasing flood events (Figure 23), soil richness properties enhancing vegetation growth, an introduction of non-perennial species, or possibly due to thicker vegetation stems at the end of a growing season. High vegetation height in winter 2019 would be caused by little or no grazing such that vegetation from the wet season was still standing on the floodplain. Vegetation density, height and stem diameter was lowest in early summer this was caused by fire occurrence (Figure 30). Decreasing vegetation characteristics can also be caused by grazing or due to low flows that can only inundate the channel or regions near the channel such that vegetation far away from the channel receive small amounts of water. This causes a reduced biomass which can take time to recover until the next big flooding event.

High vegetation densities were mostly seen in floodplain surface, back swamps and banks whilst oxbows had low densities. Vegetation height and stem diameter were high in oxbows and flood benches. An increase in these vegetation parameters can have an effect in sedimentation rates i.e. vegetation growth causes an increase in resisting forces that slows down water flow thus causing deposition. Shorter but dense vegetation such as shrubs will also have a similar roughness effect as density is one of the most crucial components in increasing roughness. Furthermore, factors such as inundation is important on the arrival, development and survival of plant species (Garssen *et al*., 2017; Wang *et al.,* 2015; Curran & Hession, 2013; Järvelä,2004). For instance, frequent wet conditions and standing water in oxbows have the ability to provide prolonged wetland conditions that sustain growth of vegetation.

Although studies by Shang *et al*., (2020), Li *et al*., (2019), Garssen, 2017; Chen, (2013) have documented that vegetation density is the most essential factor affecting flow resistance thus have a larger influence in sedimentation processes; vegetation height and stem diameter for this study area seem to contrast these observations and rather are one of the most significant contributing factors in sedimentation as seen in oxbows and flood benches (Figure 32A). Based on Figure 27 and 28, the study, therefore, concludes that; vegetation density may not always be the essential factor in flow resistance.

Topography and floodplain geomorphic features also play a role in the high vegetation height and stem diameter; low elevated geomorphic units such as oxbows and depression points have the ability to retain water during dry periods, sustaining vegetation growth. In addition; the implications involved with an increase in vegetation parameters (vegetation height, density and stem diameter) is that it increases roughness thus can induce sediment deposition which can also lead to changes in channel-floodplain morphology such as formation of bars (Kleinhans & van den Berg, 2011). This supports the theoretical predictions and previous studies conducted by Zhao *et al*., (2016) and Clarke (2002).

Floodplain geomorphic features showed a variation in roughness over the wet season (Figure 28). Late summer and winter 2020 had high roughness whilst early summer had low roughness. The rapid decrease in roughness observed in early summer was due to the fire that had occurred in the study area. This played a significant role in changes in vegetation height, stem density and diameter thus decreasing roughness and vegetation biomass (Figure 30); roughness increased as vegetation grew during the wet and rainy period. A sudden decrease in roughness can otherwise be induced by high flooding events and discharge that cause vegetation to wash away or flatten thus inducing low hydraulic roughness (Doncker *et al*., 2009; Figure 28). Roughness can decrease with an increasing discharge as vegetation and bed features are drowned out. Therefore, this variation in roughness may not only be influenced by discharge but by both discharge and the type of vegetation itself. High roughness in late summer and winter 2020 related to density, is due to substantial increase of flood events that induce plant growth with time. Oxbows and benches had the highest roughness whilst floodplain surface and back swamps had the lowest roughness. High roughness induces higher sediment accumulation whilst low roughness induce low sedimentation. Vegetation roughness increased closer to the expected flood season and decreased after the flood season, this means that sedimentation potential peaks occurs during this period of time as roughness and channel-floodplain connectivity is at its highest and decreases as inundation decreases. Furthermore, roughness can vary with distance from the main channel depending on the variety and amount of vegetation that is found, regions near the channel tend to have higher roughness thus inducing sedimentation (Doncker *et al*., 2009). Although vegetation correlations showed a weak positive correlation with particle size, it showed a significant relationship with particle size ($p = 0.002$).

Understanding flow resistance caused by vegetation is important as it has a great potential in channel-floodplain sediment conveyance which have the ability to transform channel morphology e.g. high roughness induces sediment trapping; resulting in flow diversion and channel abandonment (Makhonco, 2019; Juarvela, 2004; Nehal *et al*., 2013; Juarvela, 2002).

6.3.3 Organic content

The expectation was that during large flood events, particulate matter in the longitudinal movement of water in fluvial systems is exported from upstream and concentrates with distance downstream of the wetland (Strong *et al*., 2012; Wipfli *et al*., 2007). However, the spatial distribution along the river channel showed that there is a decrease in organic content with distance downstream (Figure 31A). Organic content entering the wetland was also higher than that leaving the wetland, suggesting that some organic material is trapped by the upper parts of the wetland (Table 4). Figure 20 outlined that particle size increases with distance from the top of the wetland in the Gatberg River channel. Therefore, a possible reason for a decrease in organic content can be a function of particle size (larger particle size are not likely to be associated with high organic particulate matter) or how the wetland stores sediment. Strong *et al*., (2012) noted that decreasing organic content with distance downstream would be correlated with decreasing sedimentation rates downstream. This observation can be attested by the sediment balance from the head to the bottom of the Gatberg wetland where the relative incoming suspended sediment was higher than the outgoing, which can indicate that sedimentation processes are lower at the bottom of the wetland. Although studies by Wipfli *et al*., (2007) have shown that there is an increase in organic content with distance downstream, the lack of similar patterns in this study area can also be attributed to differences in terrestrial biological processes (e.g. biodegradation) and changes in river beds e.g. bed form (Strong *et al*., 2012). However, Fennessy *et al.,* (1994) noted that the main sources of organic content may also be found to be the organic content of the incoming sediment themselves.

Organic content fraction ranged from 0.4 % to 29 % for the individual samples for the Gatberg Floodplain Wetland (Appendix C). Organic content increased with distance from the channel ($p = 0.003$) (Figure 31B); this general trend in turn, supports study findings by Neachell *et al.,* (2014). In addition, particle size decrease with distance from the channel (Figure 38), therefore the observed spatial increase in organic content with distance on the floodplain surface is a function of particle size. Regions closer to the floodplain margin have finer particle and have stable conditions that favor soil formation and plant growth (Neachell *et al.,* 2014) thus are susceptible to high organic content compared to areas near the channel with high flow velocities and coarser particle size. Nonetheless, further results showed that there was a strong negative correlation between particle size and organic content i.e. the smaller the particle size, the higher the organic content (Figure 40). As previously noted, this is due to the fact that the finest particle size can concentrate more nutrient and contaminants and are more cohesive thus have the highest potential of adhering pollutants (an increase in particle size, decreases cohesiveness) (Shi *et al*., 2018). Organic content with particle size showed a regression model which fitted best with D84 particle size (Figure 40). Organic content increased with an increasing roughness, however, there was no significance ($p = 0.06$) (Figure 31D).

High organic content percentages are shown by oxbows and back swamps while floodplain benches have low organic content (Figure 31C). Constantine *et al*., (2010) detailed that high organic content is correlated with high abundance of clay and smaller sand particles. Therefore, oxbows and back swamps for this study area consisted of silt and very fine sand (Figure 39). Due to frequent moisture availability in back swamps and oxbows at overbank inundation and local rainfall events and the consistent residence time of standing water in these regions after flood events can therefore enable wetter conditions that would permit temporary wetland type conditions that are in favor of vegetation growth, thus inducing high organic content matter. High temporal vegetation density and roughness are seen Figure 27 and Figure 28. This cause may also be a function of distance from the channel; back swamps and old oxbows are at a relative further distance from the channel; during inundation, the slow-moving water travel at larger distances across the floodplain reaching these regions with lower elevations where flow conditions are slow and stable. Floodplain benches have a shorter distance from the channel and larger particle size (Figure 39) and therefore have less time for the organic content matter to adhere to the sediment particle size. These observations imply that floodplain benches rapidly accumulate sediment with unstable conditions that are not yet ideal for soil formation. This therefore can suggest that autochthonous material have a significant impact in the overall organic content.

6.4 Rates of sediment accumulation and sediment characteristics

Local variability of sediment accumulation rate on the Gatberg Floodplain Wetland on a spatial scale was studied. Sediment accumulation rate decreased with distance from the channel where floodplain benches and oxbows had the highest sediment accumulation rate whilst levees and the floodplain surface had the lowest sediment accumulation rate (Figure 32). The high sediment accumulation rate evidenced in floodplain benches is due to their ability to function as storage of fluvial transported sediment and to its close linkage with the river channel thus increasing the diffusion or transfer of suspended sediment out of the river channel onto the floodplain bench. That is, the total amount of suspended sediment in flood water over a given location is a function of connectivity of the location to sediment-laden river water (Hupp *et al*., 2008). Areas along floodplain flow paths that are low in elevation and typically not restricted (e.g. levees) and are near the river channel relatively have high rates of sedimentation compared to the floodplain geomorphic features with a larger distance from the overflowing river channel (Hupp *et al*., 2008; Figure 32A, Figure 38, Figure 39). The low-lying depression morphology of oxbows and the effect of high vegetation roughness have a manner of influencing high sediment trap efficiencies; vegetation increases hydraulic roughness and resistance thus increases sediment accumulation. Furthermore, the high exhibited sediment accumulation rate in oxbows is due to a greater inundation depth which enables greater amounts of available sediment for settling in these regions during inundation events. However, Walling & He, (1998) had noted that it should, however, be noted that other depression-like areas near the outer regions of the floodplain such as back swamps, sediment accumulation can also be high; this may be due to the contribution of tributaries and or deposition of suspended sediment from ponded floodwater during flood recession. As previously discussed, differences in sediment accumulation rates on the floodplain may be a function of a variation in sediment-laden sources; hydro-period also plays an impact, longer hydro-period induces high sedimentation. Flood benches and oxbows therefore have longer hydro-period and possibly connectivity to sediment-laden water thus susceptible to high sedimentation rates as seen in Figure 32A. Furthermore, high sediment accumulation can be correlated to a high concentration of suspended sediment material carried in water, resuspension or redeposition (Fennessy *et al*., 1994).

Low sediment accumulation rates on geomorphic features such as levees can be associated with its high elevated morphology and partly due to low inundation frequency (Figure 24). Furthermore, studies by Hupp *et al*., 2008 noted that hydro-period is inversely proportional to elevation, thus high elevated areas (above bank height) tend to have less sediment accumulation rates than low elevated areas with a longer hydro-period. Otherwise, low accumulation rates can also be associated with the effect of distance from the channel and the amount of sediment concentration in the river channel. Therefore, sediment deposition varies with respect to elevation, differences in flow velocity, sediment availability and inundation. The temporal and spatial variation in accumulated sediment between floodplain geomorphic features therefore does reflect the dynamic and complex nature of wetlands in terms of sedimentary processes, grain size, magnitude and frequency.

Figure 39 showcased oxbows with finer particles, this is associated with distance from the channel and the slow-flow moving water associated with oxbows lead to deposition of finer material. Abrupt changes in velocity from channel to levees and the dominant turbulent diffusive transport mechanism lead to deposition of coarser sand and silt material closer to the channel banks. This can be a function of differences in settling velocities for the different particle size; coarser and heavier particles have higher settling velocities and are deposited first compared to finer particles that can remain in suspension and travel for longer distances (Brierley and Fryirs, 2012). Based on Table 5, it was expected that vegetation roughness (Chézy value) would be the most predictor of sediment accumulation as previous studies done by Steigner *et al.,* (2001), Li *et al*., (2015) and Wang (2015) had attested that vegetation roughness is one of the major factors in sediment accumulation. However, the results showed that; for this study area, sediment accumulation is not only a function of velocity but also a function of sediment particle size itself ($b^* = 0.67$). This may be reasoned to the fact that process of sediment deposition firstly begins with river channel processes such as transportation mechanisms and flow velocities. Finer particles in the water column remain in suspension and only gets deposited when sediments settle out of suspension due to a decrease in energy or when fall velocity is reached (Figure 1). Coarser particles require much higher velocities to entrained and have the likelihood of deposited first (Fryirs & Brierley, 2012; Gordon *et al*., 2004). Fennesy *et al*., (1994) also noted that sediment deposition from the water column into the wetland is dependent on factors such a hydrolic regime, sediment particle and texture. Further results showed that, although inundation depth had a weak correlation with sediment accumulation, it was recognized as the second most predictor of sediment accumulation. Inundation water level may play an impact in sedimentation processes, for example, regions with deeper slow moving flows and longer hydro-period such as oxbows have the likelihood of high sediment accumulation rates. This is due to low flow velocities that allow sediment to settle out of suspension and reduce re-suspension of sediment.

A true representation of sediment accumulation was partly limited by low water levels during the expectation of flooding event (Figure 23) and the constant disturbance of astro turf mats by cattle and fire (Figure 33). Astro turf mats had a good representation of accumulated sedimentation rates compared to time integrated samplers on the floodplain surface. This was due to the fact that a higher number of astro turf mats were deployed or can be an effect of low water levels are not sufficient enough for small time integrated samplers to be activated as sediment traps.

6.5 Summarize the sediment buffering function of the Gatberg Floodplain Wetland

The study used a range of data and data analysis to give insight into the sediment buffering function of the Gatberg Floodplain Wetland. Although channel bed particle size increased with distance downstream along the wetland (which is due to tributary effects, hill slope and bedrock), it highlighted that sediment deposited within the river channel is composed of sand and silt material which was also found on the floodplain surface. Particle size on the floodplain surface decreased with distance from the channel due to decreasing flow velocities with distance. Particle size at the top of the wetland was coarser than that at the bottom of the wetland (this can therefore conclude that the Gatberg Floodplain Wetland buffers coarser sediment in the upper reaches compared to the lower reaches during inundation events).

Floodplain geomorphic units showed a variation of particle size, it decreased with an increasing distance from the channel and along the length of the floodplain. Regions closer to the channel with low elevation above water level such as flood benches and banks are composed of coarser material whilst oxbows and back swamps are composed of finer material. Particle size decreases with an increasing vegetation roughness whilst particle size increases with an increase in inundation depth and elevation above thalweg (relationship was not significant). Organic content increases with a larger distance from the channel with maximum organic content in oxbows and back swamps while lower organic content was seen in levees and banks. However, the inverse is true within the longitudinal profile i.e. organic content decreases with an increasing distance along the longitudinal profile. Organic content increases with an increase in roughness and decreases with an increase in particle size. Higher inundation frequencies and depths were seen at top of the wetland than the bottom of the wetland. The relative sediment accumulation rate at the top of the wetland could therefore be higher at the upper part of the wetland. Furthermore, sediment accumulation rates are higher in depression zones such as oxbows and those linked to the channel i.e. flood benches and banks as compared to the elevated levees. Based on the conducted figures and tables of the study research, sediment accumulation rate is a function of particle size itself ($b^* = 0.67$) and inundation water level. Particle size variation on the floodplain surface is a function of roughness ($b^* = 0.41$) and distance from the channel ($b^* = -0.38$).

7. Conclusion and Recommendations

7.1 Conclusion

The aim of the study was to determine the sediment buffering function of the Gatberg Floodplain Wetland. This aim was met by five objectives; determining the relative suspended sediment quantity coming in and leaving the wetland, determining the longitudinal spatial variability in bed particle size of the river channel, determining spatial variability in inundation depth, topography, vegetation roughness, distance from the channel, organic content, rate of sediment accumulation and sediment type on the different floodplain geomorphic features, investigating the relationships of the above components and lastly by summarizing the sediment buffering function of the Gatberg Floodplain Wetland.

The results showed that incoming suspended sediment was greater than that of the outgoing suspended sediment which indicated that some of the suspended sediment is deposited on the floodplain surface (a proportion of 73 % was buffered within the wetland). This was related to high sediment concentrations relative to water level/inflow rate. Increasing D50 particle size on the channel bed with distance downstream was due to the contribution of hill slopes and tributaries found within the study area. This, therefore caused organic content to decrease in the channel with distance along as this was regarded as a function of particle size. The organic content of suspended sediment at the top and bottom of the wetland was relatively similar, however, higher organic content at the top of the wetland was due to the incoming sediment itself that contained high organic content. Furthermore, although it has been documented that abrasion is one of the contributing factors in downstream fining; selective transport or sorting may however be the most likely explanation in the increasing D50 particle size downstream.

The study did not illustrate the conventional belief that the presence of vegetation and elevation have major impacts on sediment accumulation, however, it was shown that sediment accumulation is a function of particle size itself. High accumulated sedimentation rates were found in oxbows than the higher elevated regions such as levees. High sediment accumulation rates are linked to a function of connectivity to sediment-laden water, longer hydro-period, vegetation roughness, the complex nature of the floodplain, and or the morphology of the geomorphic feature.

Furthermore, astro turf mats and time integrated samplers were implemented with reasonable success. However, in this study research, the application of astro turf mats over a single flood appeared not to be entirely successful. This was due to the frequent disturbance by animals, occurrence of a fire and probably due to high floods that washed them away which then limited a true representation of sediment accumulation rates across that various features.

Particle size decreased with an increasing vegetation roughness, this was influenced by flow velocity, energy variations and differences in vegetation geometry and type. A reduction in vegetation parameters (stem diameter, vegetation height and density) in early summer was due to fire occurrence, otherwise, a reduction in vegetation can also be caused by increasing flooding events that washes away vegetation or grazing by cattle. Furthermore, increasing flood events can cause vegetation growth and introduction of non-perennial species which may be the reason for increased vegetation roughness in the wet period (February). Based on the conducted figures (Figure 27 & Figure 28) it was therefore concluded that stem diameter and vegetation height were seen to be the most essential factors in flow resistance and might have major impacts on sedimentation. Particle size increased with an increasing elevation above thalweg water level (e.g. levees) and decreased with distance from the channel; lower elevated regions such as oxbows have stable low flow conditions than levees with high elevations and abrupt changes in velocities. In addition, decreasing particle size from transects GT2 to GT3 suggested that elevation variation with distance along the floodplain system is tapering towards the bottom of the system whilst increasing vegetation roughness with a decreasing elevation was due to high moisture content. The correlation with elevation and particle size was found not to be significant but was significant with vegetation roughness and distance from the channel.

Furthermore, regions closer to the channel were composed of coarser material (e.g. levees and banks) than regions on the outer edges of the floodplain (e.g. oxbows and back swamps), this was due to a function of distance from the channel and vegetation roughness. Larger particle sizes are much heavier and are deposited first closer to the channel compared to the finer particle size that can be carried in low flow velocities and are much lighter in weight. Organic content increased with an increasing roughness, however, this relationship was not significant (0.06) but was significant with distance from the channel ($p = 0.003$). Increasing organic content from the channel was a function of particle size and velocity; high organic content in depression zones such as oxbows have low flow velocities that can allow more residence time for pollutants to adhere to sediments. Furthermore, the standing water in oxbows promoted vegetation growth thus high organic content input. Inundation varied across the wetland with higher inundation depths at the top of the wetland than at the bottom; where particle size was larger with an increase in water level depth. This may be linked with high stream velocities and the high variability of the floodplain topography. Increasing water levels in the wet period (February) have the ability to enhance high sedimentation rates. The study research however, had experienced much drier periods (Figure 11) which had a negative impact on the sediment buffering function of the Gatberg Wetland. Therefore, this inhibited sediment accumulation rates that the Gatberg Wetland could potentially buffer. This can therefore be used as the ‘first’ approximation of ‘low-flow’ floodplain wetland in terms of sediment accumulation capacity in retaining sediments based on the study results given. However, in light of the aforementioned, the Gatberg Floodplain Wetland can still be regarded as a good sediment buffer.

7.2 Study limitations and recommendations

- Time integrated samplers were meant to be collected for every second month but due to high flows, this inhibited the collection of the samplers as it was unsafe to do so and to avoid sediment loss when trying to uninstall it. This would have therefore miss-represented and underestimated data (e.g. trapping efficiencies). Furthermore, some of the astro turf mats and the small PVC time integrated samplers installed on the floodplain surface captured little or no sediment. As a result, this limited a representation of seasonal or monthly variation of sediment captured. The study therefore recommends the use of sediment dating techniques as astro turf mats and time integrated samplers did not give a true representation of sediment accumulation rate due to animal and fire disturbances. Furthermore, material that is not susceptible to burning such as steel rods and horizon marker method can be used. A better communication with the people involved in the management of the study area can be applied so as to get notifications when there is going be a planned fire.

- The study research had experienced a dry year, a study for a longer period or over a wet year would give key trends over wetter conditions and potentially a better indication of the natural range of variability.

- The application of Chézy calculations to determine roughness was successful, however, the study assumed that vegetation was emergent. Although logger data was available to determine the proportion of when vegetation was submerged or non-submerged; data was only collected at the end of the writing period and analysis was restricted by time. Therefore, an in-depth study of how roughness changes for both non-submerged and submerged vegetation is needed. Furthermore, collection of vegetation roughness data from the field in early winter was limited by the Covid-19 pandemic, such that no data was recorded for that period. This inhibited the full representation of vegetation variation over one wet season.

- A time series analysis of vegetation roughness variation over longer periods would be more recommendable; where there are no fire disturbances or further research into how grazing and fire effects changes in vegetation character and roughness.

- An evaluation of hydraulic roughness in terms of vegetation characteristics such as biomass and structure needs to be considered. An increase in the number of quadrant plots would improve certainty.

- The study recommends that more studies should be done to confirm whether local hillslopes and local tributaries can be classified as significant sediment sources that can contribute to the spatial distribution of sediment character as it was not thoroughly assessed in this study. Furthermore, a holistic understanding of variation of particle size with distance downstream at a larger or catchment scale is needed as only a catchment proportion was done for the study area.

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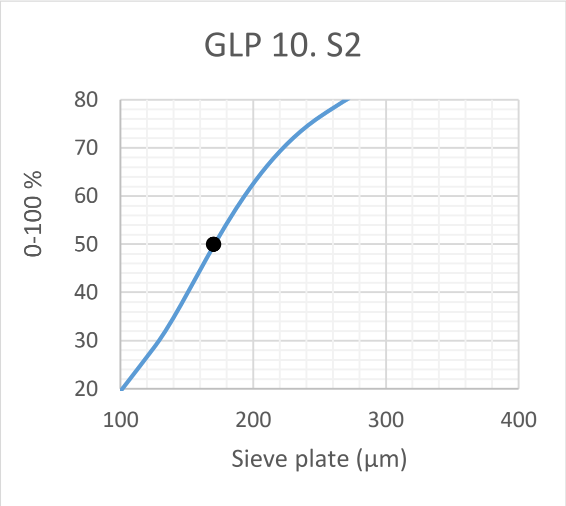
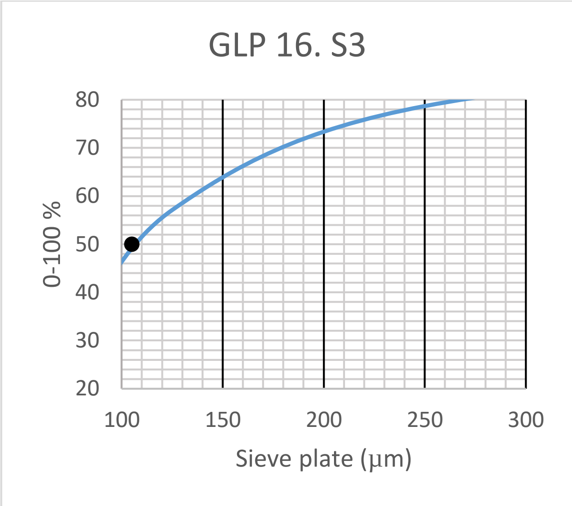
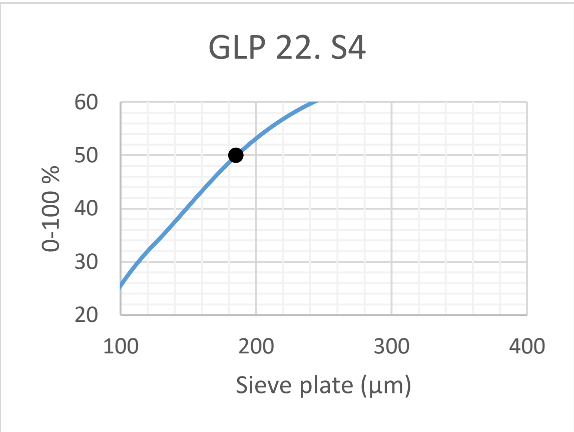
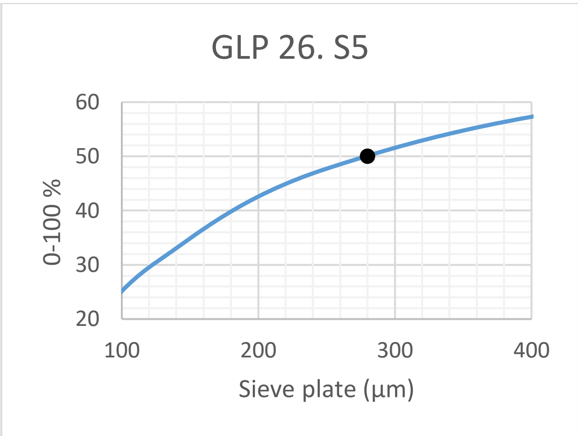
9: Appendices:

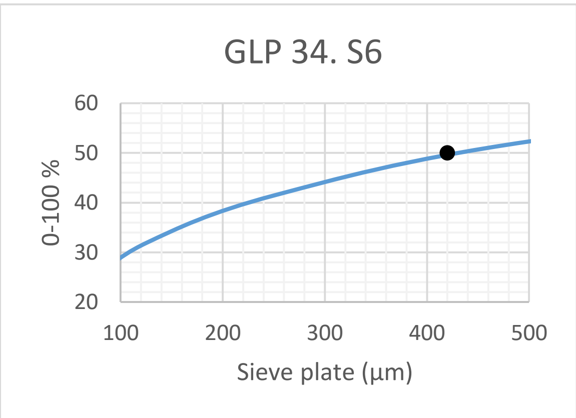
Appendix A: Particle size distribution curves for longitudinal profile samples

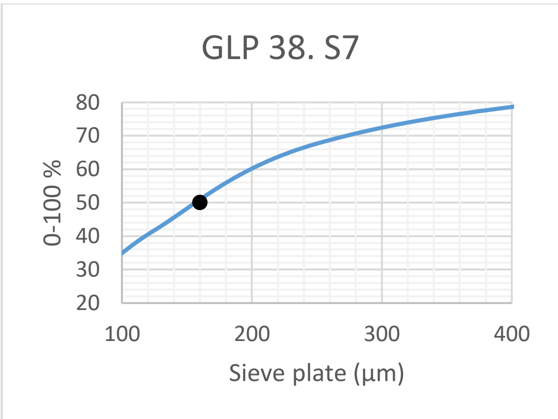


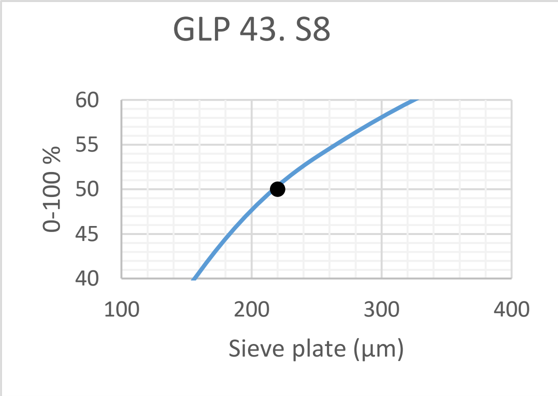


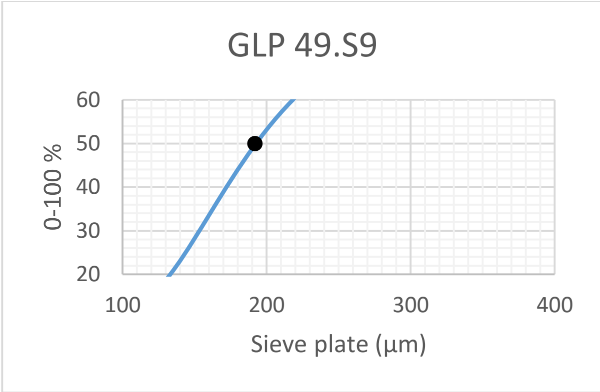


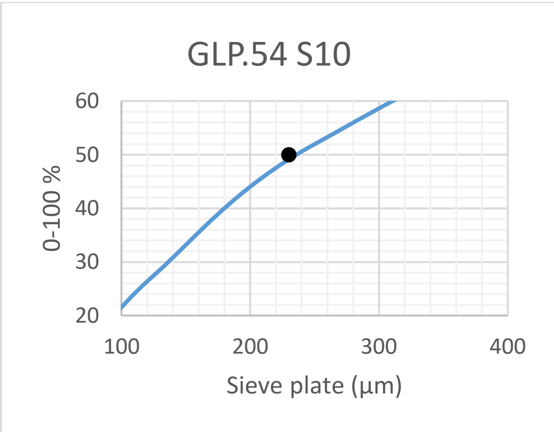


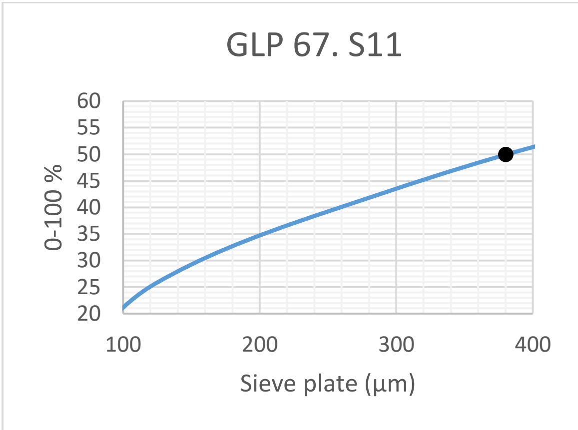


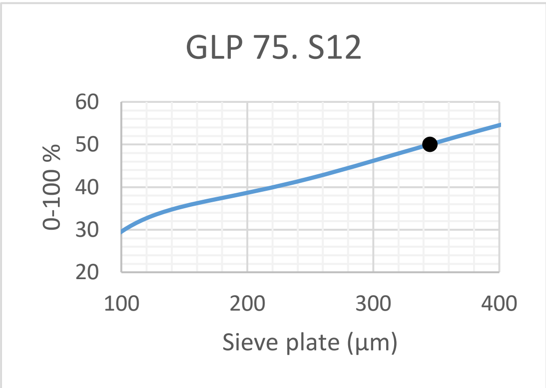


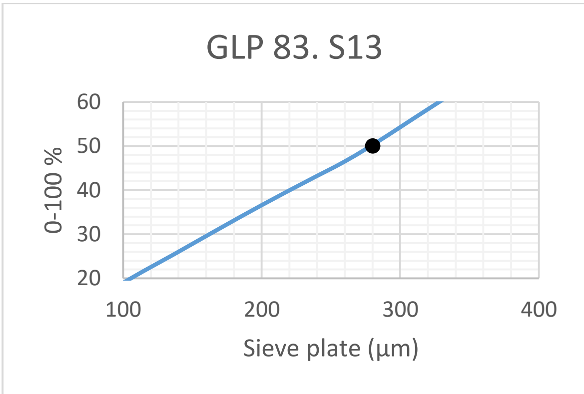

GLP 43. S8
0-100 %
60
55
50
45
40
100
200
300
400
Sieve plate (µm)

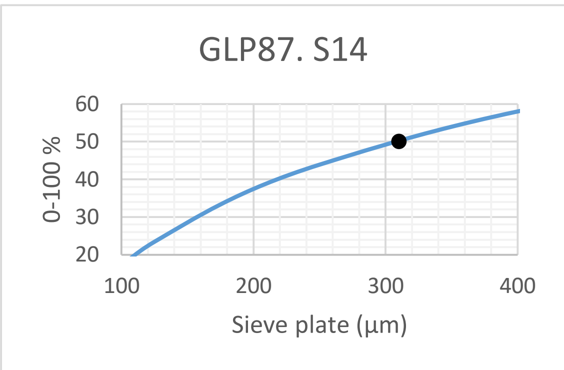

GLP 49.S9
0-100 %
60
50
40
30
20
100
200
300
400
Sieve plate (µm)

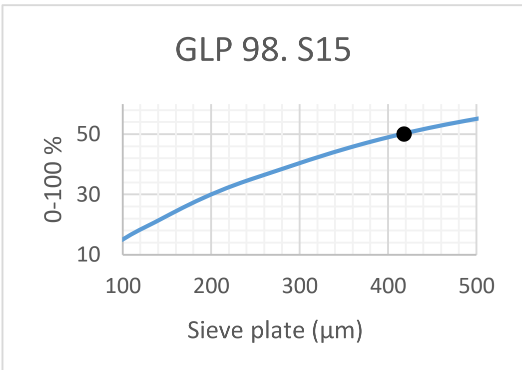

GLP.54 S10
0-100 %
60
50
40
30
20
100
200
300
400
Sieve plate (µm)

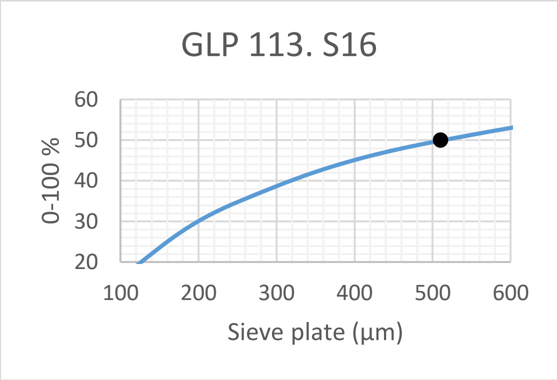

GLP 67. S11
0-100 %
60
55
50
45
40
35
30
25
20
100
200
300
400
Sieve plate (µm)

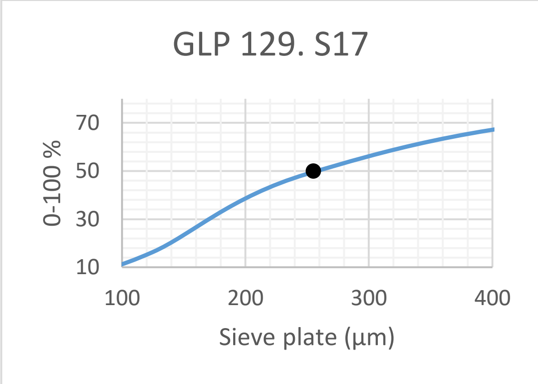

GLP 75. S12
0-100 %
60
50
40
30
20
100
200
300
400
Sieve plate (µm)

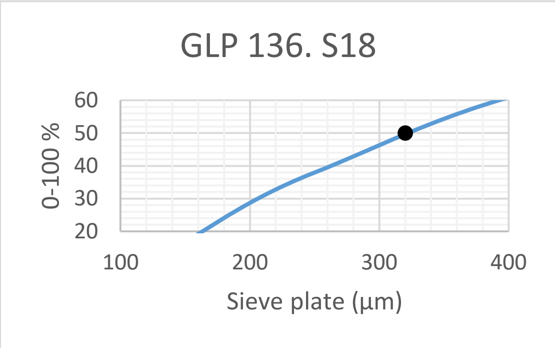

GLP 83. S13
0-100 %
60
50
40
30
20
100
200
300
400
Sieve plate (µm)

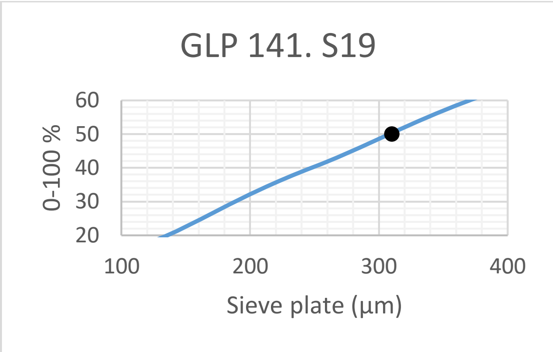

GLP87. S14
0-100 %
60
50
40
30
20
100
200
300
400
Sieve plate (µm)

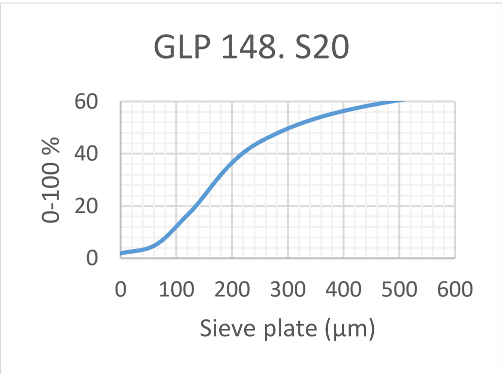

GLP 98. S15
0-100 %
50
30
10
100
200
300
400
500
Sieve plate (µm)

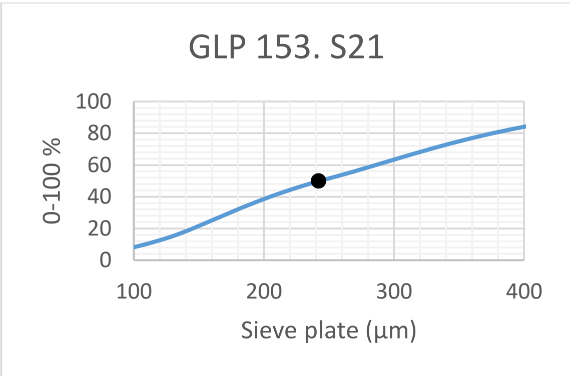

GLP 113. S16
0-100 %
60
50
40
30
20
100
200
300
400
500
600
Sieve plate (µm)

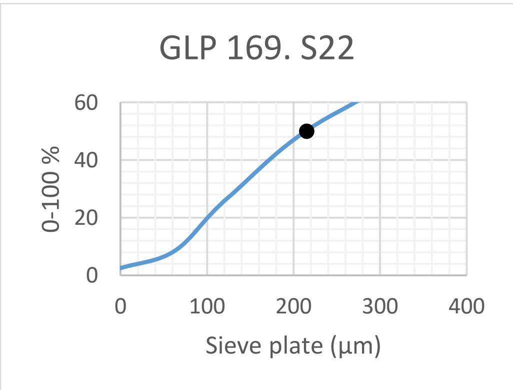

GLP 129. S17
0-100 %
70
50
30
10
100
200
300
400
Sieve plate (µm)

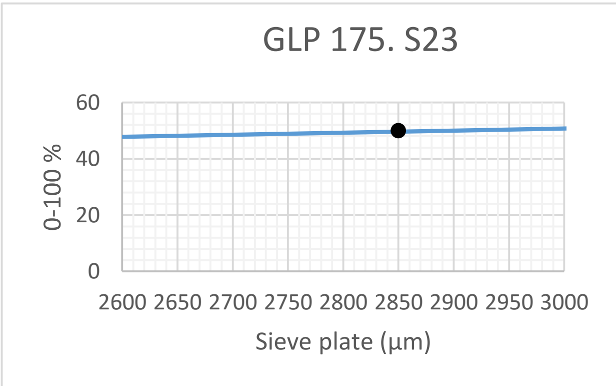

GLP 136. S18
0-100 %
60
50
40
30
20
100
200
300
400
Sieve plate (µm)


GLP 141. S19
0-100 %
60
50
40
30
20
100
200
300
400
Sieve plate (µm)


GLP 148. S20
0-100 %
60
40
20
0
0
100
200
300
400
500
600
Sieve plate (µm)


GLP 153. S21
0-100 %
100
80
60
40
20
0
100
200
300
400
Sieve plate (µm)


GLP 169. S22
0-100 %
60
40
20
0
0
100
200
300
400
Sieve plate (µm)


GLP 175. S23
0-100 %
60
40
20
0
2600 2650 2700 2750 2800 2850 2900 2950 3000
Sieve plate (µm)

Appendix B: Example of vegetation field measurements on the Gatberg Floodplain Wetland

Transect 2	GPS point name	Vegetation type	Vegetation height	Stem diameter	Number of stems	Elevation	Est. Max WL	Water depth	Chezzy value
	S32 GT2.27	Sedges and rushes	0.9175	0.0042	2400	1299.18	1300.26	1.09	1.04
	S33 GT2.35	Shrubs and some grass	0.4807	0.0038	2600	1299.17	1300.26	1.09	1.55
	S34 GT2.40	Grass with some few sedges	0.5631	0.0021	3300	1299.18	1300.26	1.08	1.25
	S35 GT2.44	Grass	0.733	0.002	2000	1298.43	1300.26	1.83	2.22
	S36 GT2.46	Grass	0.557	0.0018	1100	1298.53	1300.26	1.73	2.91
	S39 GT2.61	Grass	0.449	0.0017	3050	1298.75	1300.26	1.51	1.80
	S40 GT2.65	Grass	0.3015	0.0013	4300	1299.25	1300.26	1.01	1.88
	S41 GT2.85	Forbs	0.226	0.002	2300	1298.95	1300.26	1.31	1.54
	S42 GT2. 92	Shrubs	0.468	0.002	1900	1297.27	1300.26	3.00	2.50
	S43 GT2.103	Sedges	0.014	0.0038	900	1299.38	1300.26	0.89	1.78
	S44 GT2. 115	Grass	0.456	0.0014	3400	1299.40	1300.26	0.86	2.14
	S45 GT2.127	Grass	0.3883	0.0014	3500	1300.03	1300.26	0.24	2.11
Transect 3	S64 GT3.23	Grass	0.1574	0.0014	6000	1299.01	1299.50	0.49	1.61
	S65 GT3.31	Grass	0.4595	0.0019	4600	1298.96	1299.50	0.54	1.38
	S69 GT3.46	Grass and groundcover forbs	0.3811	0.00151	3000	1298.85	1299.50	0.65	2.09
	S71 GT3.52	Little Grass	0.206	0.0018	4100	1298.46	1299.50	1.04	1.21
	S73 GT3.67	Dominated by shrubs and some little grass	0.347	0.0025	1550	1299.11	1299.50	0.39	1.84
	S75 GT3.85	Sedges	0.7592	0.0034	1100	1298.15	1299.50	1.35	1.71
	S77 GT3. 109	Sedges	0.5625	0.0022	1600	1298.36	1299.50	1.14	1.77
	S79 GT3.120	Grass dominated and some sedges	0.316	0.0017	1550	1298.38	1299.50	1.12	2.03
	S80 GT3.141	Start of rooi grass	0.3915	0.0014	4500	1298.94	1299.50	0.56	1.77
	S81 GT3.146	Grass, sedges	0.0635	0.0017	2550	1298.63	1299.50	0.87	1.58
	S82 GT3.153	Long grass	0.43	0.0016	4200	1299.12	1299.50	0.38	1.80
Transect 4	S47 GT4.12	Grass	0.1268	0.0013	3250	1298.42	1299.42	1.00	2.19
	S48 GT4.20	Grass	0.6982	0.00234	5700	1298.37	1299.42	1.05	1.71
	S49 GT4.24	isolepus, grass & sedges	1.489	0.0015	1050	1297.24	1299.42	2.18	1.96
	S52. GT4.35	Grass	0.649	0.0031	5600	1297.48	1299.42	1.94	1.14
	S54 GT4.43	Shrubs and grass	0.28	0.0052	2400	1298.41	1299.42	1.01	1.71
	S55 GT4. 52	Sedges	0.632	0.0015	2350	1298.85	1299.42	0.57	0.94
	S56 GT4.57	Grass	0.289	0.0021	5100	1297.44	1299.42	1.98	1.19
	S57 GT4.62	Grass and shrubs	0.209	0.0022	2200	1298.77	1299.42	0.65	2.38
	S58 GT4.71	Grass and shrubs	0.188	0.0031	3900	1298.70	1299.42	0.72	1.23
	S61 GT4.73	Shrub and grass	0.454	0.0014	6450	1298.25	1299.42	1.17	0.81
	S62 GT4.87	Grass and shrubs	0.3477	0.0014	3800	1298.51	1299.42	0.91	2.11

Appendix C: Maximum calculated values for all measured parameters for the study research in the main transects.

Sample #	Floodplain feature	D50	O. content	Chezzy value	V. density	V. height	S. diameter	Elevation above WL	Topography	Inundation depth(m)	Sediment accumulated (g)
GT2.27	Oxbow	11.3	29.7151085	1.416745728	3150	0.9175	0.0042	2.531	1299.34494	0.445061	
GT2. 35	levee	14.7	7.46128322	1.760536291	3650	0.4807	0.0049	2.766142	1299.58008	0.209919	3.07
GT2. 40	Oxbow	16.4	9.88887368	1.970268211	3300	0.599	0.0029	2.004952	1298.81889	0.971109	19.43
GT2. 44	levee	39.4	5.54643074	2.918091864	3600	0.733	0.0023	2.562159	1299.3761	0.413902	
GT2. 46	Bank	105	1.96406224	2.908723969	3450	0.63	0.0071	2.228799	1299.04274	0.747262	385.72
GT2.61	Bench	96.3	2.77579536	3.033887068	3350	0.613	0.002	2.136328	1298.95027	0.839733	1544.26
GT2.65	levee	12.6	9.22543933	2.659080117	4300	0.3015	0.0018	2.801767	1299.61571	0.174294	42.33
GT2. 85	Oxbow	11.9	11.03818	1.838924281	2900	0.829	0.0028	1.810448	1298.62439	1.165613	
GT2.92	levee	11.6	13.3582674	2.500398692	4050	0.583	0.003	2.60731	1299.42125	0.368751	8.57
GT2.103	Oxbow	11	27.9028092	1.784344597	2900	1.525	0.0058	1.620545	1298.43448	1.355516	
GT2.115	floodplain	11.7	16.455797	2.728624949	3850	0.485	0.0021	2.12184	1298.93578	0.854221	23.03
GT2. 127	floodplain	8.9	12.434408	2.87213479	4250	0.591	0.002	2.068257	1298.8822	0.907804	21.54
GT3.23	Backswamp	29.3	6.53529344	1.938563631	6000	0.318	0.0019	2.086217	1299.01477		4
GT3.31	Bank	11.8	8.17814991	1.666772969	6000	0.6	0.0021	2.030291	1298.95885		94.2
GT3.46	levee	15.2	6.50266295	2.171129824	3750	0.799	0.0022	1.922476	1298.85103		161.55
GT3.52	Oxbow	8.18	9.29395803	1.540229511	4100	0.689	0.0025	1.535296	1298.46385		146.54
GT3.67	floodplain	16.1	11.3769196	1.957515532	3150	0.405	0.0027	2.180876	1299.10943		
GT3.85	Oxbow	6.01	19.2861372	2.074586381	1900	1.374	0.006	1.219554	1298.14811		
GT3.109	Oxbow	8.17	24.8983916	1.77093216	2000	1.271	0.0064	1.436249	1298.3648		
GT3.120	Oxbow	6.3	14.9156873	2.032831929	3650	0.772	0.0049	1.448412	1298.37697		
GT3.141	Backswamp	8.41	11.8955916	2.097510683	4500	0.3915	0.0019	2.008907	1298.93746		
GT3.146	Oxbow	5.41	17.4519634	1.633660098	3100	1.08	0.0057	1.703278	1298.63183		
GT3.153	floodplain	7.87	14.3221043	1.863687149	4200	0.43	0.00354	2.187293	1299.11585		
GT4.12	Backswamp	13.70	17.62049	2.576735608	5700	0.407	0.0018	2.450863	1298.41709	0.43091	276.21
GT4.20	Bank	17.10	6.93386553	1.714342836	2850	1.489	0.0022	2.40727	1298.3735	0.474503	
GT4.24	Bench	16.40	4.24186064	2.105179852	5600	0.782	0.004	1.764254	1297.73048	1.117519	
GT4.35	Bank	7.18	9.83073362	2.641979746	3400	0.779	0.002	2.444781	1298.41101	0.436992	38.87
GT4.43	levee	15.60	7.58754683	1.83631234	2900	0.632	0.0034	2.888309	1298.85454	0.002464	
GT4.52	Oxbow	9.34	14.2255026	1.490711985	5100	1.024	0.0075	1.477707	1297.44393	1.404066	338.65
GT4.57	Oxbow	7.34	6.7643442	2.429369629	3350	0.851	0.0029	2.264453	1298.23068	0.61732	76.03
GT4.62	levee	11.00	10.6004949	2.37835356	3900	0.297	0.0032	2.799895	1298.76612	0.081878	29.54
GT4.71	Bank	9.13	8.630724	1.390301714	6450	0.454	0.0026	2.737794	1298.70402	0.143979	12.15
GT4.73	Bench	9.78	6.60215909	1.917718255	3800	0.681	0.0034	2.281038	1298.24727	0.600735	377.53
GT4.87	Bank	6.37	13.3799663	2.635651642	3600	0.6982	0.0045	2.547261	1298.51349	0.334512	