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An analysis of flood activity over the past century based on the sedimentary deposits in the Mfolozi floodplain

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Abstract

Floods are natural phenomena that are of widespread interest to the scientific community, particularly in the context of understanding the impact of climate change as well as changing land use patterns and the security of infrastructure such as towns and roads. In northern KwaZulu-Natal, large flood events have been a reoccurring feature over the past century. The geographical position and extent of the region means that is affected by both inland and coastal weather phenomena, each with the potential to cause large flood events. While information pertaining to large floods in the region in the form of flow data is readily available, flow data is often incomplete and limited in terms of how far back in time the records extend. The Mfolozi River floodplain itself also houses a record of flood activity in the region in the form of sedimentary deposits, which have the potential to reveal flood activity over a much longer timescale, even when monitoring of flood activity in the region was not present. Establishing a link between the hydrological and sedimentary features of floods may be useful in establishing a record of flood activity extending beyond the limits of historical records.

The aim of this project was to construct a record of major flood events on the Mfolozi River floodplain over the last century and determine their source. The first objective involved establishing the history of flood events in the Mfolozi River catchment utilising hydrological data recorded throughout the catchment. Thirty nine different large floods (defined as being over 800 $m^3.s^{-1}$) were recorded on the floodplain over the past century. The data also highlighted differences in the extent of known coastal and inland systems (tropical cyclones and cut-off lows respectively), allowing for inferences to be made about the area of the catchment most likely affected by each event; some flood events were identified as having mostly affected the upper reaches of the catchment, while others mostly affected the lower reaches, closer to the coast.

The second objective was to identify the various physical, mineralogical and geochemical features of the sediment deposited on the Mfolozi floodplain. Multiple individual flood deposits were identified in the sedimentary record, with sediment tracing analysis providing insight into the source of the deposits within the catchment; no traces of igneous or metamorphic material could be found within the sediment. The source rocks were identified

as mostly quartzite, with minor shale and sandstone deposits as well. This put the source of the sediment in the upper to middle reaches of the catchment.

The sedimentary analysis was combined with the hydrological records to establish a chronology of flood events extending back to the 1960’s. Unfortunately, this record could not be extended further due to the limited amount of sediment collected as well the limits of readily available analytical techniques; radionuclide dating methods were unsuccessful due to the low amounts of fallout radionuclides present in the sediment. The study has however successfully established a history of flood events in the region, as well as providing a link between the hydrological and sedimentary features of flood events that could potentially be useful for current and future research.

Acknowledgments

Many thanks go to my supervisor, Professor Fred Ellery, for his invaluable input to this project. From the idea for the project itself, to the procurement of funding for the project, to guidance with regard to the collection/analysis of data, and the final writing up process, I cannot stress how invaluable your guidance has been. This project could not have proceeded without your immense contribution. The valuable contributions to this project of my co-supervisor, Dr Simon Pulley must also be acknowledged. Your experience and expertise, particularly in the area of sediment source tracing, proved to be invaluable. I would also like to express my gratitude towards Dr Mike Grenfell and Dr Marc Humphries for their invaluable guidance and assistance during fieldwork.

I wish to thank the main funders of this project. Funding provided by the NRF was instrumental in ensuring adequate data collection and analytical techniques could be employed by this project. I also wish to acknowledge the additional funding provided by the RISE agency, whose contribution further ensured this success of the project. I also wish to thank the Geography Department at Rhodes University for providing an environment conducive to research and continuous learning.

Lastly, special thanks must be given to my family. The moral support and continuous encouragement provided by my parents in particular were crucial over the entire duration of this project. The advice and encouragement provide by my brothers was also very helpful over the duration of the project.

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Chapter 1: Introduction

Floods are natural phenomena of widespread interest to the scientific community. Climate scientists are interested in conditions that lead to flooding, hydrologists in the volume of water released during floods compared to typical river discharges, and landscape scientists such as geomorphologists on the impact of floods on the form and function of landscape features affected by rivers. Sedimentologists may be interested in the evidence of flood events in the sedimentary record while social scientists may be interested in how flooding affects communities of people living in flood-prone environments. Economists may have an interest in the economic impacts of flood events of various magnitude and agricultural scientists may be interested in the impact of floods on agricultural production.

In an African context floods are of interest to a variety of scientists due to the increasingly vulnerable state of the landscape, changes in climate, political and economic instability and an increasing human population. This is especially the case in large regions of sub-Saharan Africa, where the impacts of high magnitude, low frequency natural phenomena are expected to have increasingly significant impacts on the physical and socio-economic environment in coming decades.

There are potential benefits to knowing the history of flood events. With climate change threatening to intensify high magnitude, low frequency events, knowledge of the frequency with which such events occur is important for planning developments as well as disaster management. One aspect of floods that is of scientific interest, especially in areas that are prone to large floods, is the historical record of flood activity. Flood records are of use to scientists wishing to investigate the development of a given landscape, especially as it pertains to the development of river channels as well as floodplain dynamics. Although historical records of rainfall and flow rates do exist, research on flood sedimentary deposits that links with historical data is lacking. This study aims to investigate the possibility of reconstructing flood history using historical records and the sedimentary record of a large floodplain in a depositional setting on the eastern seaboard of Southern Africa.

1.1 Floods on the eastern seaboard of southern Africa

On the eastern seaboard of Southern Africa, floods are generally associated with one of two types of meteorological phenomena, namely cut-off lows and tropical cyclones (Grenfell *et al.*, 2009). These weather systems both deliver large amounts of rainfall to the region and are associated with the generation of floods throughout the region. There are however, differences in the nature of the delivery of the rainfall that are important considerations if one is to differentiate floods associated with the one system from those associated with the other. A cut-off low is a low pressure system in the upper atmosphere that becomes detached or “cut-off” from the westerly air current and moves independently of it (Barey *et al.,* 2003). Such systems may remain stationery for several days and draw in considerable amounts of moisture, leading to prolonged heavy rainfall. These systems occur mostly between March and May in Southern Africa, although they may occasionally occur between August and September (Singleton and Reason, 2006). Cut-off lows also differ from tropical cyclones in the duration of time over which rainfall is delivered to the environment. Cut-off lows move slowly over the subcontinent and steadily deliver rainfall over a number of days (up to about a week), extending a considerable distance into the interior of the subcontinent. Given these factors, floods associated with such systems are built up more slowly than those of tropical cyclones. This means that stream discharge tends to lag behind rainfall during a cut-off low event.

In contrast to cut-off lows, tropical cyclones are low pressure systems characterised by a cyclonic movement of clouds and intense rainfall (Trenberth, 1991). For the east coast of southern Africa they originate in tropical areas of the Indian Ocean during the summer months of December to February, and travel westwards towards Madagascar and Mozambique. Occasionally these systems drift southwards into coastal areas of southern Mozambique and northern KwaZulu-Natal. Rainfall records and stream discharges associated with tropical cyclones will thus be reflected in the summer months. Given the very large amount of rainfall delivered over extremely short periods of time by tropical cyclones, these systems produce large flood events that respond immediately (Barey *et al.*, 2003; Reason and Keibel, 2004). This is because tropical cyclones derive energy from warm ocean water and generally dissipate within a number of hours once they make landfall. The result is a much more sudden influx of water than is associated with a cut-off low.

Discharges for floods associated with tropical cyclones will thus respond immediately and coincide with rainfall records. There has only been one documented instance of a tropical cyclone making landfall over South Africa (Forbes and Cyrus, 1992; Reason and Keibel, 2004). The cyclone in question, Cyclone Demoina, caused extensive flooding and scouring of the landscape in Northern KwaZulu-Natal between the 29th of January and the 2nd of February 1984 (Forbes and Cyrus, 1992).

1.2 Flood sediment transport and deposition

As flood waters flow downstream they entrain sediment from the surrounding catchment and transport it to depositional environments such as large floodplains on the coastal plain (Waugh, 2000). An example of such an environment is the Mkuze River floodplain, situated on the Maputaland coastal plain of northern KwaZulu-Natal. The floodplain, which covers an area of about 450 km^2 (Ellery *et al*., 2013), is regularly inundated by the Mkuze River during the high rainfall summer months (Humphries *et al*., 2010). Surface flow from the Mkuze River is the primary source of clastic sediment deposited on the floodplain. This clastic sediment is mostly distributed in proximal reaches and generally within close proximity of the main river channel, forming distinct levees (Humphries *et al.,* 2010). However, larger flood events will distribute sediment further down the floodplain and further from the main river (Humphries *et al.,* 2010). The Mkuze floodplain sediments illustrate the role of floodplains as providing a record of floods in the sedimentary deposits (Humphries *et al.,* 2010). Simply put, such environments house a record of flood activity in the form of sediment deposited by floodwaters.

Analysis of the morphological characteristics of the sediment deposited by floodwaters reveals a systematic variation in particle size with distance from the river channel. The sediment deposited more proximal to the river channel is the coarsest and becomes finer lateral to the main channel and further down the floodplain (Waugh, 2000; Humphries *et al.,* 2010). As the floodwaters are transported in the river channel the concentrated flow possesses enough energy to carry larger sediment particles (Waugh, 2000). However, when the river overtops its banks and the floodwaters disperse over the floodplain the energy of the water dissipates and the coarsest particles settle out of the water first. As the energy of the water progressively dissipates away from the main stream the size of the particles the water can transport decreases such that eventually the finest particles are deposited furthest away from the river channel (Walling *et al.,* 2004; Humphries *et al.,* 2010).

It should also be noted that particle size of the deposited sediment also varies according to the magnitude of the flood event. Larger events will have floodwaters with more energy, capable of carrying larger particles of sediment further, and will deposit coarser sediment further from the main channel than a smaller event (Forbes and Cyrus, 1992; Ellery *et al.,* 2009). Analysis of the particle size distribution of the sediment at a given point on the floodplain therefore provides clues as to the magnitude of the flood event.

1.3 Flood signatures in the sedimentary record

An analysis of the sedimentary record in the environments of flood sediment deposition can be used to provide information about past floods where long term records are unavailable. A fairly straightforward sedimentary signature of floods is the thickness of the sedimentary deposit. As floodwaters move over the floodplain, sediment will be deposited in higher quantities than normal, whereas during periods of low flow, water will be confined to the channel and no sediment will be deposited on the floodplain. The result is a sequence of sedimentary layers on the floodplain that signifies the nature of flood events (Baker *et al.* 1983; Forbes and Cyrus, 1992).

As previously mentioned, the relatively higher energy of floodwaters allows for the transport and subsequent deposition of larger particles on the floodplain than those that would be transported by normal flow. Thus large flood sedimentary layers are generally coarser than the overlying and underlying smaller flood sequences (Baker *et al.,* 1983). In addition, floodwaters will generally deposit material that is clastic in nature. In environments dominated by prolonged flooding but limited clastic sediment input, organic sediment will form (Ellery *et al.,* 2012; Grundling *et al.,* 2013). In such environments, floods will introduce clastic sediment which will be free of organic sediment, which again provides insight into flood event magnitude and frequency.

The mineralogical make-up of the flood sedimentary deposit is another valuable flood signature. In catchments with a clear variation in lithology from the headwaters of the mainstream to the environment of deposition, the sediment deposited by the floodwaters will reflect the degree of penetration of the catchment by storms producing storm water runoff and suspended sediment. This allows one to infer the nature of the flood-producing event. For instance, the floods associated with weather systems that penetrate deep into the interior, such as cut-off low weather systems, can be distinguished from the more coastal tropical cyclone events by tracing the source of sediment within the catchment based on sediment mineralogy.

Sediment properties that can be used to trace sediment sources include the magnetic as well as mineralogical signatures of the sediment. The use of environmental magnetic signatures in sediment source tracing is well established in the literature (Dearing e*t al.,* 1986; Oldfield, 1999). The analysis of the mineralogical make-up of sediment also represents a proven method of sediment source tracing, especially when used in conjunction with other sediment source tracing techniques (Walden, 1999).

The layers of sediment deposited by floods can be dated using techniques such as carbon, unsupported Lead-210 ($^{210}Pb_{un}$) and Caesium-137 (^{137}Cs) dating. Dating the layers in this way can be used to provide information about the chronology of large floods. The use of Lead-210 ($^{210}Pb_{un}$) and Caesium-137 (^{137}Cs) dating can only provide dates of sediment deposited up to approximately 100 years ago, which means it can generally be cross referenced with available historical data of rainfall and flow levels, giving a useful account of flood activity over the historical period being looked at.

In this study various analytical techniques will be used to analyse sediment from the Mfolozi floodplain in northern KwaZulu-Natal. The data obtained from this analysis will be cross referenced with historical data in the form of the flood record of the Mfolozi River provided by the Umfolozi Co-operative of Sugar Producers (UCOSP) as well as the available rainfall record from weather stations in the catchment of the Mfolozi River. The data derived from this study will provide a detailed link between climate, rainfall and sediment deposition on the Mfolozi floodplain that can be used to construct a record of large floods extending further back in time than provided by the historical record of flood events. The study will thus focus on informing current and future researchers of the signatures of different types of flood event in the sedimentary record. Given this background, the aim of this study is to construct a record of major flood events on the Mfolozi River floodplain over the last century and determine their source using hydrological records.

Given this aim the objectives were to:

- Determine a history of flood events for the Mfolozi River catchment,
- Identify the signature of each flood event in the sedimentary record, including the various physical, geochemical and mineralogical features of each flood event.

Chapter 2: Literature Review

2.1 Erosion, deposition and the stream longitudinal profile

As floodwaters flow downstream they entrain sediment from the surrounding catchment and transport that sediment to depositional zones (Waugh, 2000). This section deals with the principles of sediment erosion, transport and deposition.

The longitudinal slope of a river, from the source of the main stream to the mouth of the river as it flows into the ocean, typically forms a logarithmic profile. Steep slopes characterise the region associated with the headwaters of the stream and more gentle slopes are associated with the lower reaches (Leopold *et al.,* 1964; Kondolf, 1997). A key concept related to the development of a logarithmic longitudinal profile relates to circumstances that lead to erosion and deposition of sediment.

Streams use kinetic energy to lift and transport sediment downstream. The amounts of sediment a stream can theoretically transport is related to its velocity and discharge (Ellery *et al.,* 2008) and is known as its "capacity". The amount of sediment a stream actually transports can be measured and is known as its "load". Streams do not always carry the same amount of sediment that they are able to, such that erosion occurs where the capacity of a stream is greater than the load being transported. This may occur where weathering does not produce sufficient sediment for a stream to transport, such that the supply of sediment is weathering limited. Alternatively, however, where the load is greater than the capacity, such as where a tributary flowing from a steep mountain front enters a gently-sloping trunk stream, deposition occurs (Tooth *et al.,* 2004).

A second important concept to grasp is that erosion generally occurs where the slope is too steep for the available discharge and sediment supply, and the outcome of erosion is a lowering of the longitudinal slope (Ellery *et al.,* 2008). In contrast, deposition typically occurs where the slope is too low for the available discharge and sediment load. Deposition of sediment leads to a steepening of the longitudinal slope, thereby allowing continuity of flow and sediment transport. Given that erosion and deposition are related to stream power in relation to how much sediment the stream is transporting, it is generally the case that small streams such as in the headwaters of catchments, have very steep slopes as they lack the stream power to erode and therefore reduce slope. Conversely, large streams are able to erode their beds to a very gentle slope. Interactions between velocity, discharge, sediment supply and the slope of the bed of the stream therefore interact to produce a longitudinal profile that is steep in the headwaters and shallow near the mouth of the stream: a profile generally referred to as a "logarithmic" profile (Figure 1).

A further key concept related to the logarithmic longitudinal profile of a stream is that of "base level", which for all rivers flowing into the sea is represented ultimately by sea level. A stream flowing into the ocean cannot erode its bed to a level below sea level (Tooth *et al.,* 2004; Ellery *et al.,* 2008). This is due to the fact that as a stream erodes its bed; the slope of the bed is reduced, which leads to a lowering of velocity and stream power, such that below a certain slope the stream is no longer able to erode its bed. For this reason, in the absence of any externalities such as tectonic events or a rise in sea-level, streams always have a downward slope towards the base level.

The Mfolozi Floodplain is close to the coast and is in the dispersing zone of the catchment. It is a massive depositional feature that has filled with sediment to a substantial depth given that just 10 000 years ago sea level was between 120 and 150 m below current sea level due to the trapping of water in the ice caps during the last ice age (Ramsay, 1995). At this time the Mfolozi would have eroded its bed in a similar way as the Mkuze River, which eroded its bed to a depth greater than 40 m below its current elevation (Ellery *et al*., 2013). The rise in sea level following the last glacial period drowned the lower Mfolozi River valley, which became a site of active deposition. The Mfolozi has been an active sediment sink since then.

Material deposited on the Mfolozi floodplain is derived ultimately from its catchment, and the generation of such sediment is dependent upon the geology and land use practices, as well as the location and magnitude of rainfall events in the catchment.

2.1.1 Erosional Zones

Certain sections along the profile of a stream are mainly associated with erosion. These environments develop in areas along the course of the stream where the capacity of the stream exceeds what is required to transport the available sediment load. These areas along the profile of a stream are characterised by steep gradients, highly energetic waters (fast flowing) and stream channels that are v-shaped in cross-section (Figure 1; Waugh, 2000; Ellery *et al.,* 2008). Where such conditions exist the stream is not in equilibrium and erosion of the bed of the stream occurs as the stream attempts to modify its channel shape and/or gradient such that capacity decreases and a move towards equilibrium of the stream is initiated (Waugh, 2000). The conditions necessary for the development of erosional environments generally occur in the upper reaches of a river, where relatively small stream channels (compared to the broad stream channels characteristic of the lower reaches of a stream) with fast flowing waters occur in areas of steep gradient (Baker, 1984; Ellery *et al.,* 2008).

2.1.2 Transport Zones

Along the longitudinal profile of a stream, certain environments are associated mainly with the transport of sediment. The conditions in transport zones include channels that are wider, with a longitudinal gradient that is lower and capacity that is higher compared to the corresponding conditions in the upper reaches (Figure 1). At the same time the channels in transport zones are narrower, and the gradient and capacity lower, than in the depositional zone.

2.1.3 Depositional Zones

Along the longitudinal profile of a stream, certain environments are associated with the deposition of sediment. These environments are found along sections of the stream where capacity is exceeded by the sediment load (Ellery *et al.,* 2008). In general, depositional environments such as floodplains are found in the lower reaches of a stream (Waugh, 2000). The conditions in the lower reaches of a stream include lower gradients, wider stream channels and less energetic waters (gently flowing streams) compared to the corresponding conditions in the upper and middle reaches of the stream (Figure 1). The Mfolozi River floodplain, which is where this particular study was undertaken, is in a zone dominated by deposition.

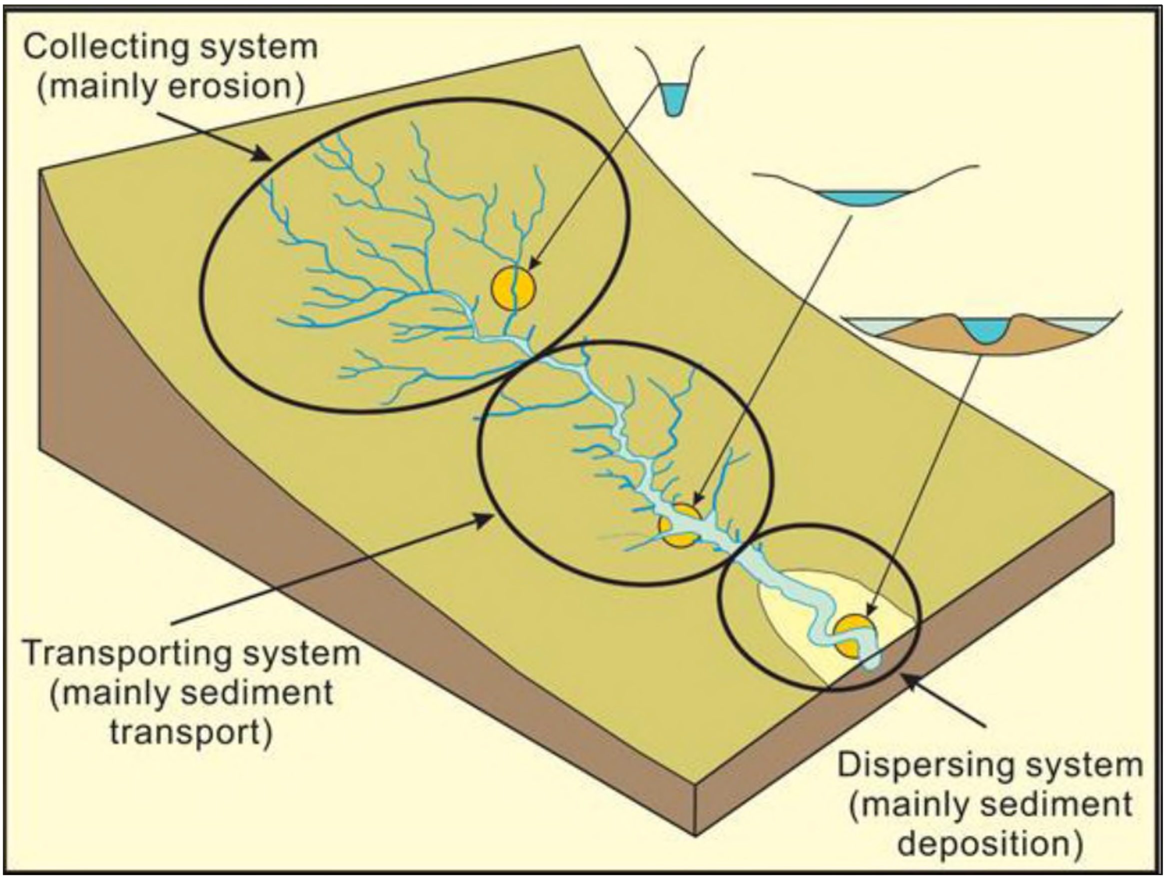

Figure 1: Schematic illustration of the longitudinal profile of a river.

2.2 Spatial variation in sediment distribution during floods

When floodwaters overtop the banks of a stream during a flood, and flow over the levee onto a floodplain, the depth of flow is typically very low such that friction is much greater than is imposed by the bed and banks of a deeper rectangular channel (Ellery *et al.,* 2003). Furthermore, water flowing over the levee of a floodplain typically encounters dense stands of vegetation, which increases roughness and also leads to significant flow reduction (Ellery *et al.,* 2003). Because the velocity and power of water flowing over the levee is much lower than in the stream, large quantities of sediment are deposited on the floodplain. As the floodwaters lose energy on the floodplain, the largest sediment particles settle out first closest to the main stream (Baker *et al.,* 1983; Waugh, 2000). A further reduction in floodwater energy as the water moves further onto the floodplain, reduces the floodwater transport capacity such that medium grained sediment is deposited (Waugh, 2000). Finally, the finest sediment particles are deposited in distal reaches (Waugh, 2000). This sequence of floodwater energy reduction and concomitant sediment deposition results in the characteristic coarse-to-fine variation in sediment size that is observed laterally and longitudinally across a floodplain (Figure 2; Baker *et al.,* 1983; Grenfell *et al.,* 2009).

Additionally, the deposition of coarse to fine material is related to the temporal variation in flow during a single flood event. Typically, individual flood events are associated with an initial pulse of sediment associated with high discharges at the start of an event, followed by the gradual dissipation of floodwater energy, which results in an upward-fining sequence of sedimentary deposition. The base of the individual flood deposit will contain the coarsest material, becoming finer towards the top of the deposit (Baker *et al.,* 1983; Laurent *et al.,* 2010).

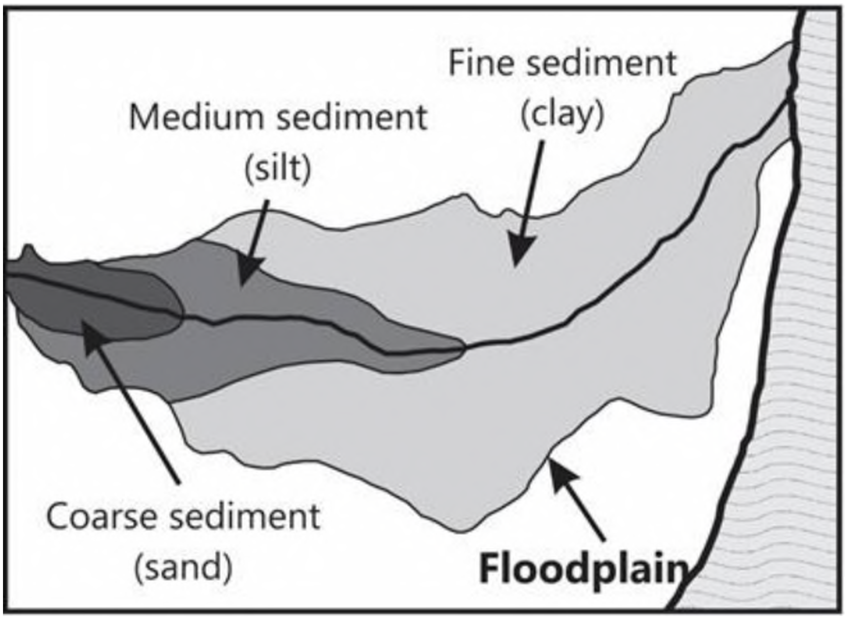

Figure 2: Schematic illustration of the spatial variation in sediment size distribution.

The deposition of sediment adjacent to the main stream causes the build-up of levees adjacent to the stream. This causes the stream to become elevated relative to the floodplain (Ellery *et al.,* 2012). In this way the structure of a floodplain is determined by deposition during flood events (Figure 3).

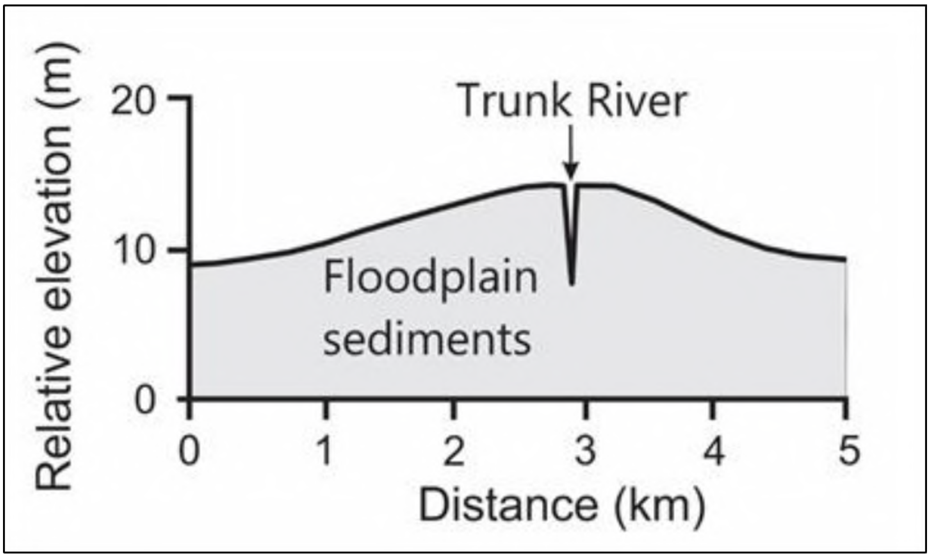

Figure 3: Schematic illustration of levees adjacent to a floodplain stream.

Floodwaters will also transport and deposit sediment that is primarily clastic in nature (Ellery *et al*., 2012). In environments dominated by the deposition of organic material such as peat, flood deposits will be discernible as predominantly clastic deposits in predominantly organic deposits associated with non-flood events (Ellery *et al.,* 2012). This has important implications for the choice of study site within a floodplain; one may wish to core sediment in areas where peat is accumulating but where floodwaters will deposit sediment only during flood events, so as to more easily contrast flood events with non-flood events.

2.3 Floods on the eastern seaboard of southern Africa

Large floods on the eastern seaboard of southern Africa are generally associated with one of two types of meteorological phenomena, namely cut-off lows and tropical cyclones. Notable recently documented floods in the area associated with such systems include the floods of late January – early February 1984 associated with tropical cyclone Demoina, and the floods of September 1987 associated with the passage of a cut-off low system. In both instances large volumes of precipitation caused massive floods. Although both of these meteorological systems produced large floods, there were significant differences in the way these systems behaved, which will be outlined in the following section.

2.3.1 Cut-off lows

Cut-off lows are low pressure systems that become detached or "cut-off" from the main westerly atmospheric circulation current (Barey *et al.,* 2003). Singleton and Reason (2007) have described the variability of these systems over a thirty year period from 1972 to 2002. The characteristics examined include the seasonality, duration, and location of cut-off lows as they occurred in sub-tropical southern Africa. From statistical analysis of records of cut-off low activity over the period of study the authors have shown that cut-off lows occur most frequently in the period from March to May, with April being the month with the most frequent occurrence of these phenomena. The authors note that during the 1980s there was a shift in the most frequent period of cut-off low occurrence from March to May to the period of June to August. It is during this period that there was also a shift in the location where these systems commonly occurred, from the south-western to the north-eastern region of sub-tropical southern Africa.

In terms of their duration, cut-off lows are generally short-lived in sub-tropical areas, lasting on average between one and three days, but occasionally lasting over four days (Prince and Vaughn, 1992; Singleton and Reason, 2007). These systems are fairly extensive and steadily deposit a large amount of rainfall over the period during which they occur, leading to flooding (Baray *et al.,* 2003). Although many instances of flooding associated with these events have occurred in coastal settings, cut-off low systems are also known to track quite far into the interior of the subcontinent: the cut-off low associated with the September 1987 floods in Northern KwaZulu-Natal tracked across the Northern Cape and the North West Province, during which time high amounts of rainfall were deposited across the region. This ability to penetrate inland is in sharp contrast to the other meteorological phenomena associated with floods in the study area, tropical cyclones.

2.3.2 Tropical cyclones

Much of the theoretical background knowledge of tropical cyclones provided for this section is based on work done by Ooyama (1981) and Trenberth (1991). In essence, tropical cyclones are mesoscale low pressure systems characterised by the cyclonic movement of clouds and intense thunderstorms. These systems form over, and derive energy from, warm ocean water during the summer months (December to February in the southern hemisphere; Trenberth, 1991). As suggested by the name, tropical cyclones form in the tropical regions of the globe and move away from the equator towards the sub-tropics (Ooyama, 1981). In the southern hemisphere tropical cyclones moving across the Indian Ocean affect Mauritius, Madagascar and the east coast of Mozambique.

Tropical cyclones generally dissipate rapidly as they encounter land due to the relative lack of warm water and evaporation required by these systems (Ooyama, 1981). This means that rainfall and associated flood waters will be restricted to coastal areas. In addition, the high quantities of rainfall associated with these systems will be deposited in a fairly short space of time, from a few hours to a few days depending on the system.

The floodwaters associated with cut-off lows and tropical cyclones will entrain, transport and deposit sediment according to the conditions and processes outlined in previous sections. As this study focuses on an environment that is predominantly depositional in nature, a review of the different methods for analysis of flood sedimentary signatures is necessary and follows in the next section.

2.4 Analysis of characteristics of flood deposit

Various sediment properties have been used to characterise flood deposits. This section will review these properties and describe how they can be used to shed light on the nature of large flood events. The analytical methods examined include analysis of the physical properties of sediment associated with flood deposits, such as particle size, as well as examples of sediment source tracers such as environmental magnetism, mineralogy, organic content and radionuclides. Lastly, radionuclide dating as a means of dating flood sediments will be described. These analytical techniques have been chosen due to their prevalence in the literature as useful tools for understanding sediment transport and deposition dynamics. When used in conjunction with one another, a broad picture of large flood characteristics in terms of magnitude and frequency emerge, helping to advance knowledge of large flood dynamics.

2.4.1 Physical properties of flood deposits

The high energy of floodwaters allows for the transport and eventual deposition of a greater amount of sediment than is deposited on a floodplain during periods of normal flow, i.e. when the river is not in flood (Waugh, 2000). The high energy associated with flood waters also facilitates the transport of larger sediment particles than would be transported by lesser floodwaters. Additionally, sediment associated with flood deposits accumulates at a faster rate than during normal flow periods (Du and Walling, 2012). These factors will be reflected in the physical properties of the observed sedimentary deposit in terms of particle size and organic content, which will be reviewed in the following sections.

2.4.1.1. Particle size distribution

The sedimentary deposits associated with large flood events will be coarse in nature, especially in areas more proximal to the main stream of the river, than deposits associated with much smaller flood deposits (Laurent *et al.,* 2010; Wang *et al.,* 2010). It follows then that analysis of the particle size distribution of floodplain sedimentary deposits can be used to identify flood events and to differentiate large flood events from relatively smaller flood events (Walling and Woodward, 2000; Grangeon *et al.,* 2012;). This is true even in areas where the deposited particle size is fine; flood events will introduce larger particles throughout the floodplain relative to periods of normal flow (Walling and Woodward, 2000). The analysis of particle size distribution is a well-accepted method of investigating the dynamics of flood sedimentary deposition (Walling and Woodward, 2000; Walling *et al.,* 2004; Grangeon *et al.,* 2012; Pavanelli and Selli, 2013).

2.4.1.2 Organic matter content

Organic sediment may accumulate in permanently flooded backswamp environments of floodplains. This requires low energy conditions such that organic litter falling into the standing water body is not transported elsewhere. However, floodwaters are associated with high energy conditions and the transport and deposition of mainly clastic material (Waugh, 2000). The rapid deposition of clastic sediment in such backwater environments, associated with flood sedimentation, will produce a layer of clastic sediment in an otherwise organic sequence (Thoms *et al.,* 2000). For this reason, in backswamp environments in the vicinity of floodplain margin or tributary valley lakes (Grenfell *et al.,* 2010), one would associate lower organic matter content with a flood deposit compared to deposits in periods of normal flow (Reineck and Singh, 1980). Organic matter content can thus serve as a useful indicator of flood events in the sedimentary record (Reineck and Singh, 1980, Thoms *et al.,* 2000).

2.4.2 Sediment tracers

The use of sediment tracers as a means of investigating sediment dynamics is well established (Manning and Owens, 1977; Walden, 1999; Pulley, 2014). Sediment tracers are properties that can be used to link a sediment sample to its source, and have the potential to shed light on the extent of a flood event by discriminating between different geologies and land uses of source material (Walden, 1999; Pulley, 2014). Provided that bedrock in the catchment of a depositional system is spatially variable, one is able to infer how far into the catchment a flood has penetrated. This is crucial in understanding the likely nature of the climatic event that produced a large flood event.

2.4.2.1 Analysis of mineralogical properties

Provided that there is a diverse suite of lithologies present in a catchment, which produce a range of weathered products, the identification of major minerals or mineral groups in eroded products provides a useful means of tracing the parent rocks (Manning and Owens, 1977; Wadsworth and Baird, 1989; Ontao, 2008). Geomorphological studies utilising mineral assemblage identification are not as numerous are their geological counterparts, but are available in the literature (Drake, 1997; Criado *et al.,* 2008). The principle method of tracing parent rocks material via mineral assemblage is by means of X-ray diffraction (XRD) analysis. The identification of the average bulk minerogenic composition of a sample has been shown to be suitable for differentiating between different parent materials in a number of different environments (Manning and Owens, 1977; Drake, 1997).

The use of XRD analysis in this study will require an assessment of the geology of the catchment. Once it has been determined which rock types are prevalent in different parts of the catchment, it is possible to determine the type of minerals likely to be present as a product of weathering. The contributions of weathered minerals in the sedimentary record should therefore enable the location of the site of erosion to be identified.

2.4.2.2 Analysis of magnetic properties

The environmental magnetic signatures of sediment are the magnetic values of the sediment and are controlled by the mineralogical make-up of the sediment. The mineralogical make-up of the sediment itself is primarily controlled by the chemical and mineralogical characteristics of parent material that has weathered to produce the sediment. It is for this reason that environmental magnetism is able to serve as a useful sediment source tracer in a number of different environments, including fluvial and lacustrine environments (Dearing *et al.,* 1986; Oldfield, 1999; Pulley, 2014). Crucially, the measurement of a suite of magnetic signatures is non-destructive and, when compared with a number of other sediment source tracers, it can be done at relatively low cost as it is less time consuming than other techniques (Walden, 1999). For these reasons there are numerous studies that make use of environmental magnetic signatures as a sediment source tracer (Oldfield, 1999; Pulley, 2014).

Environmental magnetism has been shown to be effective at differentiating between different parent lithologies (Owens *et al.,* 1999), as well as between surface and sub-surface source material (Dearing, 1999). This kind of sediment tracing, especially when used in conjunction with other tracers such as X-ray diffraction should prove useful in tracking how far into the catchment a flood has penetrated or where in the catchment the rainfall fell.

2.4.3 Radionuclide dating

Radionuclides, specifically the class of radionuclides called fallout radionuclides, have been used extensively in studies utilising sediment source tracing. Fallout radionuclides are deposited as fallout from the atmosphere onto the surface of the earth. Fallout radionuclides differ from lithogenic radionuclides, which are present in rock and form due to the natural process of radioactive decay in rocks and soil (Appleby, 2008). Fallout radionuclides have been shown to be effective when utilised in conjunction with other sediment source tracers (Du and Walling, 2012; Pulley, 2014). The most commonly used fallout radionuclides for sediment source tracing as well as dating are ^{210}Pb and ^{137}Cs (Pulley, 2014). These fallout radionuclides have been shown to be effective sediment tracers in a number of environments (Foster, 2006; Appleby, 2008; Du and Walling, 2012; Pulley, 2014).

The fallout radionuclide ^{210}Pb is derived from the decay series of Radon (^{222}Rn) gas, such that ^{210}Pb thus formed is deposited in trace quantities on the surface of the Earth. ^{210}Pb fallout to the earth's surface is essentially constant at a given point on the surface of the earth (Appleby, 2008). At this point it is strongly adsorbed to mineral soil particles. When using ^{210}Pb to date sediments it is important to note that the total radionuclide activity is defined by two components, the supported and unsupported ^{210}Pb. The supported ^{210}Pb fraction is derived from the decay of Radium (^{226}Ra), a naturally occurring element in the

Uranium decay series. The unsupported ^{210}Pb fraction is derived from atmospheric fallout of ^{210}Pb.

^{210}Pb is continually added to the surface of the earth and adsorbed to clay particles while simultaneously undergoing decay with a half-life of 22 years. However, once such a grain is deposited in a sedimentary sequence, it is no longer exposed to fallout nuclides such that the decay of unsupported lead is related to the time since deposition. Thus, the unsupported ^{210}Pb activity of a flood deposit can be used to calculate the time that has elapsed since deposition. This is achieved by measuring the current unsupported ^{210}Pb (C_{uns}) activity and comparing that with the estimated initial unsupported ^{210}Pb activity (C_{uns}). The elapsed time (t) is then calculated according to the formula:

$$\mathbf{C_{uns}(t) = C_{uns}(0)e^{-\lambda t}}$$

Equation 1: Calculation of the age of a sedimentary deposit based on the current unsupported ^{210}Pb activity ($C_{uns}(t)$) based on the estimated initial unsupported ^{210}Pb activity ($C_{uns}(0)$) and the decay rate (λt) (Appleby, 2008).

The fallout radionuclide ^{137}Cs is derived from atmospheric fallout resulting from thermal nuclear testing that occurred in the northern hemisphere during the 1950s and 1960s, reaching a peak in fallout in 1963 in the southern hemisphere, which is slightly later than in the northern hemisphere (Aalto and Nittrouer, 2003). ^{137}Cs dating is useful in providing a chronological marker (the 1963 global fallout peak) around which flood sedimentary signatures can be placed due to the radionuclide adhering strongly to sediment particles (Taylor *et al.,* 2012).

One distinct disadvantage of using ^{137}Cs as a dating tool is that due to peaks in ^{137}Cs activity being linked to the ^{137}Cs fallout maximum of 1963, ^{137}Cs serves as a solid marker of only four decades of deposition (Aalto and Nittrouer, 2003). Another disadvantage is the variable distribution of ^{137}Cs as the majority of fallout of ^{137}Cs occurred in the northern hemisphere, with some areas in the southern hemisphere receiving negligible amounts of fallout (Aalto and Nittrouer, 2003). Studies by Humphries *et al. (*2010) as well as Aalto and Nittrouer (2003) have however proven successful in their attempts to utilise ^{137}Cs in studies looking at sedimentation rates in southern hemisphere settings.

2.5 Reconstructing flood histories

Several studies have attempted to reconstruct flood histories in a number of different settings. For studies looking at floods that occurred during the past two centuries, where rainfall and flow records exist to correlate the occurrence of floods, analysis of the physical and magnetic properties of flood sediments have proven useful (Lintern *et al.,* 2016; Wittenberg *et al.,* 2007). Lintern *et al. (*2016) explored the use of sediment cores in reconstructing the flood history of two floodplain lakes on the Yarra River catchment in Melbourne, Australia. The authors have demonstrated the use of particle size and magnetic analysis of sediment cores from floodplain lake deposits to reconstruct the hydrological activity of an urbanised river catchment. The study also highlighted some of the shortcomings of these analytical techniques in reconstructing flood history, particularly in an area that experiences multiple large floods during the course of a year.

The presence of layers of coarse particles in a sedimentary sequence dominated by fine particles indicates a likely flood deposit related to a discrete flood event. However, where multiple flood events occur in a single year, the individual deposits may agglomerate into a large deposit. Thus, particle size analysis may underestimate the number of discrete flood events that have occurred over time. Additionally, depending on factors such as parent material and the source of the flood, small flood events may not produce the characteristic laminations in the sedimentary record that one would expect of a larger flood. As such, particle size may not be the most suitable means of reconstructing a flood record containing numerous small flood events. Other means of distinguishing between discrete events, such as utilising sediment tracers as well as hydrological records may be necessary to overcome these limitations.

Radionuclide dating has been utilised in a number of studies looking at sedimentation on river floodplains as well as various lacustrine, estuarine and marine environments (Appleby, 2008; Aalto and Nittrouer, 2003). The method has proven reliable in establishing chronological records in historically deposited sediments. Use of atmospheric fallout radionuclide dating has also proven to be a useful and reliable geochronological marker (Humphries *et al.,* 2010; Lintern *et al.,* 2016), even in the southern hemisphere where fallout of ^{137}Cs was not as marked as in the northern hemisphere. Most studies utilising radionuclide dating have however taken place in the northern hemisphere.

Mineral magnetic signatures have also proven to be useful in studies investigating sedimentation rates. The magnetic properties of flood deposited sediments have been utilised together with radionuclide dating and organic matter content to characterise flood deposits and reconstruct historical flood records (Lintern *et al.,* 2016). Fluctuations in magnetic susceptibility have commonly been utilised to identify flood deposits as well as tracing the source of deposited material.

Chapter 3: Study Area

3.1 The Mfolozi River catchment

3.1.1 Physiographic characteristics

The catchment of the Mfolozi River is situated in the northern region of the province of KwaZulu-Natal (KZN) in South Africa. The catchment covers an area of just over 11,000 km^2, extending from the coast inland to the town of Vryheid, on the highveld of northern KZN. The catchment encompasses a range of physiographic features including mountains, wetlands and the coastal plain.

3.1.2 Geology

The upper reaches of the catchment of the Mfolozi River are underlain by sedimentary rocks of the Karoo Supergroup (Figure 4; Begg, 1988). These sediments were deposited in the Karoo Sea over a period from about 300 to 180 million years BP. The lowermost sequence is the Dwyka Group tillite that occurs in the central and southern region of the upper catchment. The Dwyka Group is overlain by shale and sandstone of the Ecca and Beaufort Groups, which occur in much of the remaining upper part of the catchment, with minor lithologies of more ancient sequences of Cape Supergroup (Natal Group sandstone) and Natal Metamorphic Province granite and gneiss in the southern part of the upper catchment.

The middle to lower-middle reaches of the catchment are underlain by various sedimentary and igneous rocks of the Karoo Supergroup, which are in sequences oriented perpendicular to the course of the Mfolozi River, and include sedimentary lithologies of the Beaufort Group (shale and sandstone) and basic to acidic rocks of the Lebombo Group (basalt and rhyolite respectively). The volcanic rocks of the Lebombo Group were extruded co-incident with the breakup of Gondwanaland about 180 million years BP. These rocks are relatively resistant to weathering and erosion and form a prominent mountain range (Lebombo Mountains) that lies to the west of the coastal plain of Maputaland.

The coastal plain itself comprises rocks of the Zululand Group (Tertiary) in the west, comprising silt-, sand-and limestone. The eastern coastal plain comprises unconsolidated Quaternary sediment, which is sandy in nature and of marine and aeolian origin.

Southern Africa has experienced two major uplift events that have impacted on the fluvial processes of the region. The first uplift event occurred approximately 20 million years ago and raised the eastern seaboard by approximately 250 m (McCarthy and Rubridge, 2005). The second uplift event occurred approximately 5 million years ago and raised the eastern seaboard by a further 900 m (McCarthy and Rubridge, 2005). The high elevation of the region relative to sea level means that the region is in experiencing catchment scale erosion.

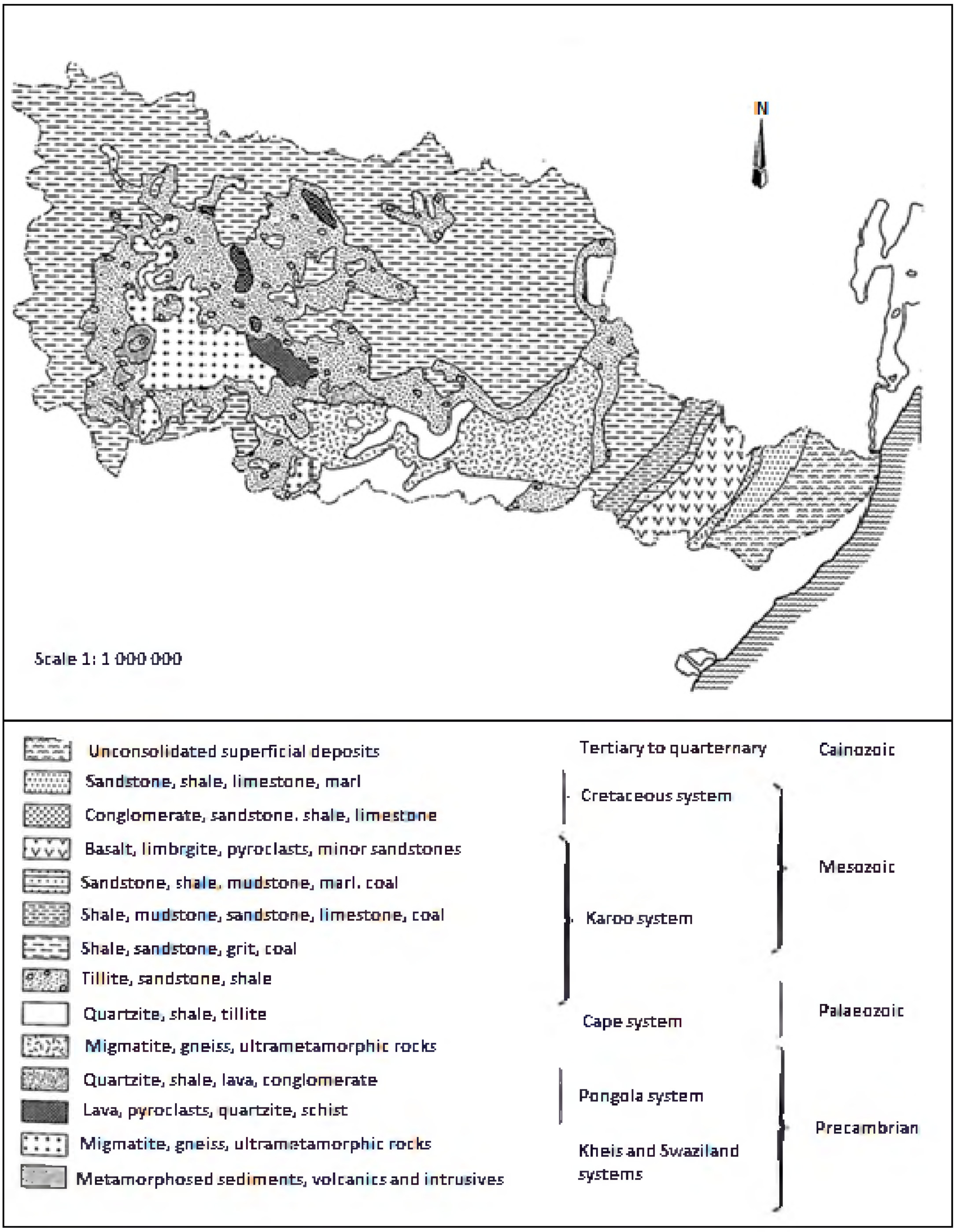

Figure 4: Geological map of the Mfolozi River catchment (Begg, 1988).

3.1.3 Climate

The climate of northern KwaZulu-Natal is characterised by subtropical conditions of warm temperatures throughout the year. Precipitation mostly occurs during the summer months of November to April, and is generally associated with coastal low pressure cells and infrequent tropical cyclones (Tyson, 1986). Winter rainfall accounts for approximately 20% of the mean annual rainfall in the region and is associated with the passage of cold fronts as well as coastal low pressure systems (Tyson, 1986). There is a systematic east-to-west decrease in rainfall across the catchment, with coastal regions of the floodplain averaging 1090 mm/year and declining steadily towards the upper reaches of the catchment to an average of 645 mm/year (Schulze, 1997).

3.1.4 Drainage

The Mfolozi River catchment is drained by the two main tributaries, the Black Mfolozi and the White Mfolozi. The Black Mfolozi is the main northern tributary of the Mfolozi River, arising at an altitude of 1 500 m above sea level (Grenfell and Ellery, 2009). The White Mfolozi is the main southern tributary of the Mfolozi River and arises at an altitude of 1 620 m above sea level (Grenfell and Ellery, 2009). The two main tributaries converge 50 km west of the coast where the Mfolozi drains into the Indian Ocean.

3.1.5 Land use and socio-economic characteristics

The Mfolozi-Hhluhluwe Nature Reserve falls within the Mfolozi River catchment, which is a protected area that makes up a large fraction of the middle catchment. As such a large portion of the catchment comprises natural vegetation. A second very extensive land use in the Mfolozi catchment comprises agriculture in the form of subsistence farming, as well as commercial forestry operations (Grenfell and Ellery, 2009). There are two urban centres in the catchment; Vryheid in the upper reaches of the catchment, which is a coal-mining centre, and Mtubatuba in the lower reaches of the catchment, which relies on commercial activity associated with sugar cane and timber production and processing.

3.2 The Mfolozi River floodplain

3.2.1 Physiographic characteristics

The Mfolozi River floodplain is situated on the Maputaland coastal plain of Northern KwaZulu-Natal approximately 200 km north of Durban. The floodplain is one of the largest in South Africa, extending longitudinally a length of approximately 30 km from the foothills of the Lebombo Mountains in the west to the entry of the Mfolozi River into the sea south of Lake St Lucia (Grenfell *et al.,* 2009).

There are three lakes situated on the Mfolozi floodplain periphery: Lake Futululu and Lake Teza are blocked valley lakes situated on the northern and southern edges of the floodplain respectively. Lake St Lucia, the largest estuarine lake in Africa, is situated on the north-eastern edge of the floodplain (Grenfell *et al.,* 2009).

3.2.2 Fluvial Characteristics

The Mfolozi River flows along the northern region of the floodplain, periodically overtopping its banks and inundating the floodplain. A second river, the Msunduze, flows along the southern part of the floodplain and joins the main stream of the Mfolozi River near its mouth. Due to the seasonal nature of rainfall and flooding in the region, the floodplain is dominated by clastic deposition with very few areas suitable for the formation of peat. However, extensive peat deposits occur on the lower reaches of blocked tributary valley lakes such as Lake Futululu and Lake Teza (Grenfell *et al.,* 2009), which are likely to be long-term sinks for organic sediment (Ellery *et al*., 2013).

3.2.3 Flood history

The Mfolozi floodplain has experienced several large flood events over the past century. One of the largest on record occurred in late January 1984 when Cyclone Demoina made landfall over the northern KwaZulu-Natal region. In some areas of the catchment rainfall exceeded 700 mm over the course of a few days, causing widespread flooding as well as damage to infrastructure as the Mfolozi and Msunduze rivers overtopped their banks and inundated the floodplain to a depth of approximately 2.5 m (van Heerden and Swart, 1986). Sediment deposition mainly took place on the floodplain, allowing seaward flowing waters to severely erode sediment at the mouth of the Mfolozi River and St Lucia estuary. Scouring of the St Lucia estuary to depth of approximately 6 m took place, while the extensive erosion of the river bank on the southern edge of the of the floodplain by approximately 300 m occurred (Forbes and Cyrus, 1992). To date, Cyclone Demoina is the only tropical cyclone to have made landfall over South Africa.

Other instances of large flood events have been caused by high rainfall associated with cut-off lows, such as in late September 1987. Rainfall in the catchment peaked at 366 mm on the 29th September, resulting in flooding along some reaches of the river. Several more flood events have occurred in the region over recorded history, most of which have been caused by runoff from seasonal rainfall.

3.2.4 Land use

Land use on the Mfolozi floodplain is predominantly agriculture (Grenfell and Ellery, 2009). The upper two thirds of the floodplain have been converted to sugar cane cultivation, while the lower third of the floodplain falls within the Isimangaliso Wetland Park, a World Heritage Site. Illegal subsistence farming on the floodplain within the Isimangaliso Wetland Park is the predominant form of land use on the lower third of the floodplain.

Chapter 4: Methods

4.1. Objective 1: To determine a history of flood events for the Mfolozi River catchment.

Historical flood data for the Mfolozi River was provided by UCOSP. The data was in the form of peak discharge for a flood event and highlighted the occurrence of a number floods over the period from 1911 to 2013. Flow was recorded at a gauging station located in the lower reaches of the Mfolozi River but in the middle reaches of the floodplain (Figure 5). Floods occurring after the year 2000 were calibrated to flow measurements from data obtained from the Department of Water Affairs (DWA).

While this flood data provides a clear record of flood occurrences in the lower reaches over the past century, it provides little insight into the degree of penetration of the identified flood events into the interior of the catchment. As such, flow data from flow stations in the upper to middle reaches of the catchment were extracted from the DWA website and compared with the flood data from UCOSP to determine how far into the catchment different events penetrated (Figure 5).

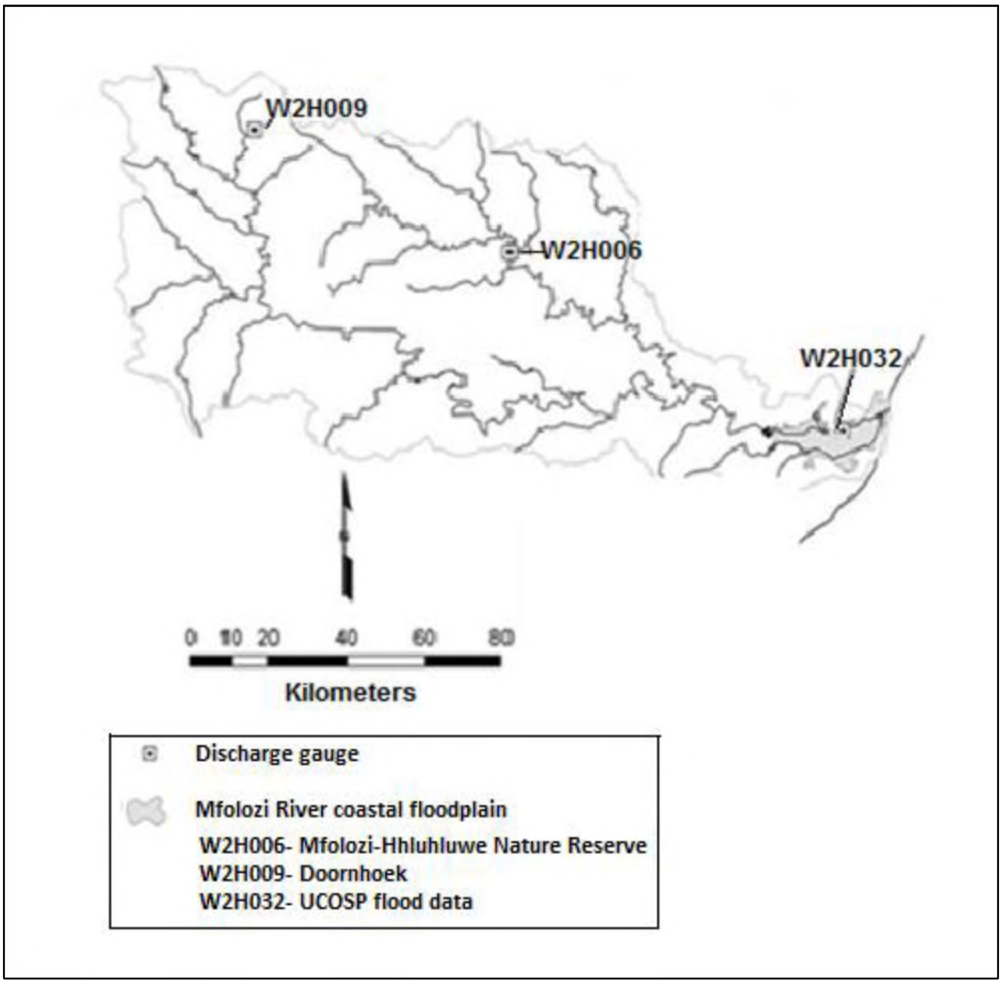

Figure 5: Map of the Mfolozi River catchment showing the location of selected flow stations.

4.2 Objective 2: identifying the signature of flood events in the sedimentary record

4.2.1 Sediment sampling

Two sediment cores were retrieved from the study area using a vibrocorer and a Russian peat corer. The first sediment core was retrieved on the southern edge of Lake Futululu, a blocked-valley lake on the northern edge of the Mfolozi River floodplain, approximately 1km away from the Mfolozi River (Figure 6). The second sediment core was retrieved on the northern edge of South Lake, situated on the southern edge of the Mfolozi floodplain. The location of the second core was approximately 7km away from the trunk stream (Figure 6). The core samples were then subsampled at 2 mm intervals and labelled according to depth.

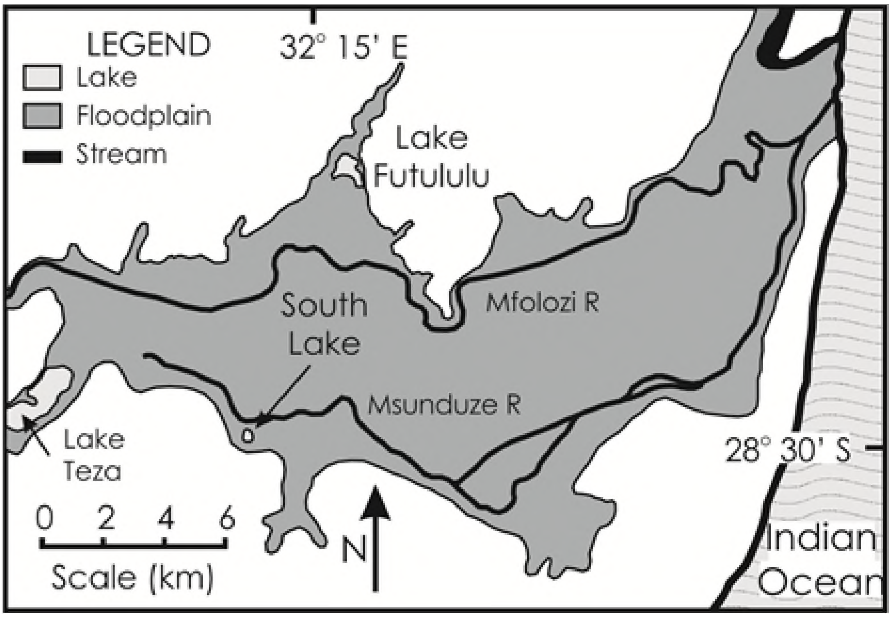

Figure 6: Map of the Mfolozi floodplain. Modified after Grenfell *et al.,* (2010).

4.2.2 Analysis of physical properties

4.2.2.1 Particle size analysis

Several methods exist for determining particle size distribution. These include sieving through a graded set of sieves, sedimentation techniques such as pipette and hydrometer based analytical techniques (Plumb, 1981). In addition to being time consuming and requiring manual calibration of instruments, such analytical techniques require strict control of the temperature of the sediment mixture as well as a low concentration of sediment in the mixture to avoid particle interaction (Di Stefano *et al.,* 2010). Another technique for analysis of particle size distribution is laser granulometry. Laser diffraction determines particle size by measuring the scattering of light as a laser beam is passed through a dispersed granular sample. Because the angle of light scattering varies with particle size, measurement of the angular variation of light as it passes through the sample allows for the determination of particle size distribution (Buurman *et al.,* 1997).

Laser granulometry as a method for deriving particle size data has gained increasing acceptance over the past two decades. Initial reluctance to the method centred on a number of factors including the acceptance of sedimentation methods as the standard for particle size analysis of sediment (Buurman *et al.,* 1997). In addition, the high cost of laser granulometry equipment has meant that sedimentation methods for studies looking at particle size are still widely in use today. Laser granulometry has also been proven to underestimate the clay-size fractions of the observed sediment due to the two dimensional nature of analysis (the method assumes a spherical particle) (Buurman *et al.,* 1997; Di Stefano *et al.,* 2010). The laser granulometry technique does however, possess some important advantages. Firstly, the technique has the advantage of being less time consuming than sedimentation techniques (measurement of samples takes less than five minutes) as well as being able to measure a wide range of particle sizes without the need for large sample sizes. Secondly, the technique also requires no manual calibration of the instruments. Thirdly, apart from the underestimation of the clay-size particle fraction, laser granulometry has been shown to be an on par with sedimentation techniques in terms of accuracy of sand and silt size particle determination (Di Stefano *et al.,* 2010). Due to the advantages of the technique, and its availability at Rhodes University, laser granulometry was selected to determine particle size. A sample from every depth interval in both cores was subjected to analysis.

Prior to analysis organic matter was removed from each sample by adding 5ml of 30% hydrogen peroxide to a test tube containing approximately 0.2g of sediment following the methods of Di Stefano *et al.,* (2010). This is because organic matter can bind to sediment particles, leading to an overestimation of the particle size. The samples were then left for a minimum of 24 hours at room temperature. The samples were then heated for 4 hours at a temperature of 70°C, after which bubbling of the sample mixture had ceased. Immediately prior to analysis (approximately 2 minutes) 5 ml of 3% sodium hexametaphosphate solution was added to each sample to further disperse the sediment samples. The prepared samples were added to a glass beaker containing 500ml of tap water and analysed using a Malvern Hydro 3000 unit. Each sample was subjected to two minutes of ultrasonic dispersion immediately prior to analysis. Each sample was then measured for 60 seconds at 3-12% obscuration.

4.2.2.2 Determination of the organic matter content of sediments

The determination of the organic matter content of sediment is useful as it reflects the rate of clastic sediment accumulation in a subaqueous environment flooded to a shallow depth. Rapid deposition of clastic sediment prevents organic matter accumulation from vegetation growth on the floodplain (Ellery *et al.,* 2012). Amongst the quantitative methods, loss on ignition (LOI) is a widely used method for determination of organic content. A disadvantage of the LOI method is that an overestimation of the organic content may occur due to the loss of structural water in clay particles as well as loss of carbonates upon heating. Schumacher (2002) noted that a possible method of countering the effect of structural water loss is the pre-treatment of the sample with hydrochloric acid (HCl). This pre-treatment itself can present a challenge by dissolving organic matter, leading to an underestimation of the organic content of the sample (Schumacher, 2002).

An alternative quantitative method is the digestion of organic matter via hydrogen peroxide. Concentrated hydrogen peroxide is used to destroy the organic matter within a sample by oxidation. Hydrogen peroxide is continuously added to a weighed sample until the frothing of the sample has ceased. The sample is then dried at 105 degrees Celsius before being allowed to cool off in a desiccator and weighed. The percentage of organic matter of the sample is calculated as the difference in weight between the initial and final weights, divided by the initial weight, multiplied by 100%. This method has the disadvantage of being highly dependent on the type of sediment being analysed as the oxidation process is a not a complete oxidation of the sample and the degree of oxidation, and thus the final result, will vary according to the nature of the material being oxidised (Schumacher, 2002). As such this method may not be appropriate for a study where the exact nature of the sediment being looked at in unknown. It is for this reason that the LOI method was selected for the determination of organic matter.

The loss on ignition method was used to determine the organic content of sediment samples collected in this study (Heiri *et al.,* 2001). As with particle size analysis, samples from every depth interval in both cores was selected. Clean ceramic crucibles used for LOI were heated in an oven to 105°C for two hours. This was done to ensure that the crucibles were free of any residual moisture. The crucible was weighed. A sample weighing approximately 2g was added to a crucible and placed in an oven to dry at 105 °C. The dried sample and crucible were then weighed and placed inside a muffle furnace. The muffle furnace was heated to 450 °C s and samples were left in the furnace for 4 hours. The samples were then removed and placed in a desiccator for 5 to 10 minutes to cool. The percentage LOI was then calculated as the difference in weight between the initial dry weight and the final weight after combustion, divided by the initial weight. The result is multiplied by 100 to make it a percentage.

4.2.3 Environmental tracers

4.2.3.1 Mineral magnetic signatures

The utilisation of mineral magnetic signatures as a means of tracing the source of deposited sediments is well established in the literature. The measurement of environmental magnetic signatures for this study followed the protocols set out by Lees (1997) and represent the most commonly used techniques for determination of environmental magnetic signatures in sediment tracing (table 1). Approximately 10 g of each of the prepared samples from the collected sediment cores was tightly packed into 10 ml sample pots to a depth of 2 cm. The samples were then subjected to the various magnetic susceptibility as well as magnetic remanence methods listed in Table 1.

Magnetic susceptibility measurements are useful in determining the content of magnetic minerals in a sample (Dearing, 1999). A high magnetic susceptibility measurement is reflective of a sample containing a high proportion of magnetic minerals such as magnetite and hematite. Low frequency magnetic susceptibility (X_{lf}) is the most common measurement of environmental magnetic susceptibility and involves the measurement of a sample placed into a magnetic field (Dearing, 1999). Susceptibility measurements essentially measure the response of the sample to the externally applied field, thereby giving an indication of its mineral makeup.

Magnetic remanence measurements involve the measurement of a sample that has been placed within a magnetic field and the ability of that sample to retain the magnetism when the field is removed (Walden, 1999). Anhysteretic remanent magnetisation (ARM) is a common magnetic measurement and targets fine, single domain grains in the range of 0.002 to 0.4um in diameter (Walden, 1999). This method involves the exposure of a sample to slowly decreasing alternating field whilst the sample is in the presence of a small constant biasing magnetic field. A simple calculation to normalise this measurement to field strength gives the susceptibility of anhysteretic remanent magnetisation (X_{arm}) of a sample. Another common measurement of magnetic remanence is Saturated Isothermal Remanence Magnetisation (SIRM). This measurement involves immersing a sample in a high (1T) "saturating" magnetic field and measuring the magnetic remanence of the sample thereafter (Walden, 1999). The SIRM measurement targets all grains capable of carrying a remanence, such as iron and magnetite, and is therefore a widely applicable method for remanence measurement (Walden, 1999).

Table 1: Environmental magnetism measurements (Dearing, 1999; Walden, 1999).

Type of measurements	Instrument/calculation	Targeted minerals	Unit
Susceptibility measurements			
Low Frequency Susceptibility (χ_{lf})	Bartinton MS2B Dual frequency sensor (LF setting)	All minerals: Diamagnetic, paramagnetic, canted antiferromagnetic, ferrimagnetic. Determined by magnetic mineral type.	10^{-6} m^3 kg^{-1}
Remanence measurements			
Anhysteretic Remanence Magnetisation (ARM)	Molspin alternating field demagnetiser then Rotating Magnetometer	Highly sensitive to stable single domain ferrimagnetic minerals.	10^{-9} m^3 kg^{-1}
Susceptibility of ARM (χ_{arm})	ARM * 3.14 * 10	Highly sensitive to stable single domain ferrimagnetic minerals	10^{-6} m^3 kg^{-1}
Saturation Isothermal Remanent Magnetisation (SIRM)	Molspin pulse magnetiser then Rotating Magnetometer	Minerals capable of carrying a remanence, i.e. Ferromagnetic or ferrimagnetic	10^{-3} Am^2 kg^{-1}

The mineral magnetic signatures of the sediment are a useful tool for discriminating between the different types of geology within the catchment, such as sedimentary and igneous rocks, thus allowing one to trace where the in the catchment the source material is located.

The catchment of the Mfolozi River floodplain is underlain by various rocks of the Karoo Supergroup. The magnetic signatures of the main lithologies in the catchment have been measured by Pulley and Rowntree (2016), Miller *et al.* (unpublished data) and Pulley (unpublished data) and are outlined in Table 2. One of the most striking differences between the different rock groups is that igneous rocks tend to be more magnetic than sedimentary and metamorphic rocks. Very high magnetic values therefore probably indicate igneous source material (Table 2).

Among the sedimentary rocks sandstone tends to be more magnetic in nature than mudstone, shale and quartzite (Table 2). It should therefore be possible to discriminate between different sedimentary rock sources within the catchment. Lastly, the metamorphic rock gneiss tends to be the least magnetic of the different source rocks found within the catchment (Table 2). Gneiss tends to have a similar magnetic susceptibility value to sandstone. The two rock types are more easily distinguished from one another using Xarm; sandstone is almost four times as magnetic with regards to this particular parameter than gneiss (Table 2). It should also be noted that within the different geologies, surface materials will exhibit higher magnetic signatures than subsurface materials.

Table 2: Magnetic signatures of the major rock groups within the Mfolozi River Catchment.

Rock type		Exposure	Magnetic susceptibility (10^{-6} m^3 kg^{-1})	Xarm (10^{-6} m^3 kg^{-1})	SIRM (10^{-3} Am^2 kg^{-1})	Particle Size (µm)
Igneous	Basalt	Surface	5.16	57.83	98.54	<32
		Subsurface	4.52	51.85	92.24	<32
	Dolerite	Surface	6.81	44.59	58.56	<32
		Subsurface	11.53	51.25	89.72	<32
Sedimentary	Quartzite	Surface	0.43	5.25	11.63	17.5
		Subsurface	0.21	2.52	6.13	17.5
	Sandstone	Surface	1.65	17.97	17.42	<32
		Subsurface	1.15	12.47	10.39	<32
	Mudstone	Surface	0.84	10.49	10.97	<32
		Subsurface	0.74	10.17	10.50	<32
	Shale	Surface	0,63	7.00	9.89	<32
Metamorphic	Gneiss	Surface	1.105	4.60	10.17	<32

Mineral magnetics have been shown to be influenced by particle size (Thompson and Morton, 1979). As the relationship between particle size and magnetics is not a linear one, applying a simple correction factor for the effects of particle size is not always possible. Maher (1998) recommended site specific analysis of particle size effects on mineral magnetic signatures. Pulley and Rowntree (2016) investigated the relationship between particle size and magnetic susceptibility in Karoo sediments derived from dolerite and shale (Figure (7). The magnetic susceptibility of doleritic sediment is highly influenced by particle size, particularly in the 200-400µm particle size range (Figure 7). The magnetic susceptibility of shale derived sediments is influenced less by particle size. Shale derived sediments returned consistently low magnetic susceptibility values above 100µm (Figure 7).

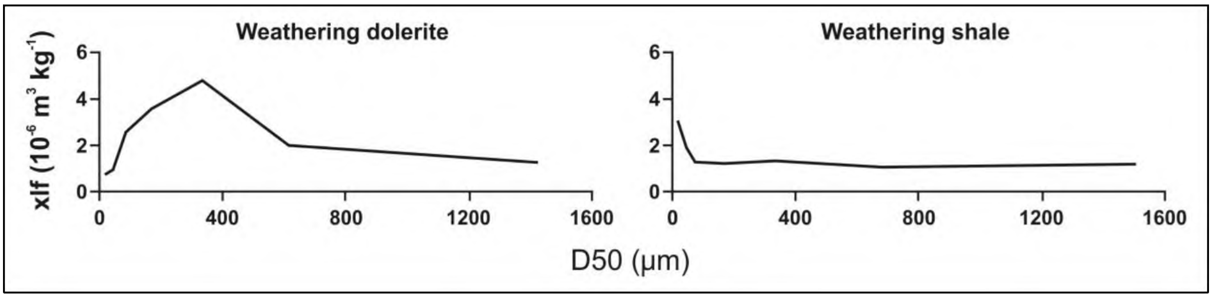

Figure 7: Variation in magnetic susceptibility with particle size of igneous (Dolerite) and sedimentary (Shale) rocks. Modified after Pulley and Rowntree (2016).

Comparing the known magnetic values of the sediment sources within the catchment with those identified in the core samples should provide some insight into the sources of the sampled sediment and the extent of the eroding flood event.

4.2.3.2 Sediment mineralogical properties

The mineralogical properties of sedimentary material have been utilised for source tracing in various geological and geomorphological studies (Manning and Owens, 1977; Drake, 1997, Criado *et al.,* 2008). X-ray diffraction is a commonly used analytical tool in mineral identification. A disadvantage of the process is that it is time consuming given that individual samples require up to 45 minutes of analysis in a high-resolution powder x-ray diffractometer. When coupled with the high cost of analysis (up to R150/ sample, depending on the institution), the number of samples that can be analysed is often quite limited.

There are advantages to using XRD for mineral identification rather than less advanced methods of mineral identification, such as thin section analysis using a polarising microscope. One such advantage is that the utilisation of XRD requires minimal sample preparation where selected samples are crushed to form a fine powder for analysis (Moor and Reynolds, 1997). Analysis of the data derived from XRD measurements also requires the use of a database of mineral spectra. Access to such databases and the analytical programs that compare the measured XRD spectra of a sample to database spectra for expected minerals are readily available (Laetsch and Downs, 2006).

Due to the availability and advantages of the using XRD for sediment source tracing, the XRD method was selected for use in this study. Sediment samples from flood deposits were sent for XRD analysis in the Chemistry Department at Rhodes University. Samples were gently crushed to form a fine powder before being placed into a high-resolution powder x-ray diffractometer. The XRD spectra derived from analysis of the samples were then analysed using the CrystalSleuth analytical program that utilises database spectra for expected minerals from the RRUFF Project website for Raman spectra and XRD data for minerals. The interpretation of the XRD Spectra was undertaken by a specialist in the Geology Department.

Table 3 lists the most common rocks and their associated rock-forming minerals within the catchment of the Mfolozi River. Quartz is a ubiquitous mineral, found in all the major rock groups (igneous, sedimentary and metamorphic). As such it is not in itself indicative of any particular rock type, unless it is the only mineral present (in which case the rock is sandstone or quartzite). Other minerals such as pyroxene, olivine and ilmenite are indicative of igneous rocks and/or their metamorphic products. Clay minerals are found in the finest grained sedimentary rocks and also in the weathered products of basic and ultrabasic volcanic rocks. In this context however, given the extensive distribution of fine-grained sedimentary rocks in the Karoo Supergroup in the catchment of the Mfolozi River, their abundance identifies a sample as being derived from shale or very fine grained mudstone. A comparison between the observed bulk compositions of the measured samples with the possible rock forming minerals may be useful in tracing the source of the sediment.

Table 3: Common minerals for the main rocks types in the Mfolozi River catchment.

Rock type		Common minerals
Igneous	Basalt	Calcic plagioclase feldspar
		Pyroxene
		Olivine
		Ulvospinel
		Ilmenite
		Magnetite
	Dolerite	Quartz
		Olivine
		Hornblende
		Biotite
Sedimentary	Quartzite	Quartz
	Sandstone	Quartz
		Feldspar
	Mudstone	Quartz
		Clay minerals kaolin-serpentine, Kaolinite, Clauconite, Vermiculite
	Shale	Quartz
		Calcite
Metamorphic	Gneiss	Quartz
		Hornblende
		Biotite
		Muscovite
		Sodium feldspar
		Potassium feldspar

4.2.3.3 Radionuclide dating

Work utilising environmental radionuclides in the study of sediment source tracing and the rates of sediment accumulation has traditionally focused on a class of environmental radionuclides known as fallout radionuclides. These radionuclides are deposited on the surface of the earth as fallout from the atmosphere. The radionuclides chosen for this study were Caesium (^{137}Cs) and Lead (^{210}Pb), the most commonly used and reliable radionuclides utilised in the dating of sediment.

In the case of ^{210}Pb the total radionuclide activity is defined by supported and unsupported ^{210}Pb components. The supported ^{210}Pb fraction is derived from the decay of Radium (^{222}Ra), a naturally occurring element in the Uranium decay series. The unsupported ^{210}Pb fraction is derived from atmospheric fallout of ^{210}Pb, considered to be constant over time at a given point on the surface of the earth, though this may vary spatially due to factors such as rainfall (Appleby, 2008). A fraction of the total fallout from the atmosphere settles in surface soils to which it adheres strongly. Soil erosion in the catchment transports such sediment in, which may be deposited in floodplain environments, after which no additional fallout ^{210}Pb is added to the sample. Given this the date of burial of the sediment can be calculated given that the half-life of ^{210}Pb is known. The unsupported ^{210}Pb activity of a flood deposit is used to calculate the time that has elapsed since deposition using a standard formula (Equation 1).

The radionuclide ^{137}Cs was produced as fallout from weapons testing in the northern hemisphere during the early to mid- 1950s to early 1960s. Further fallout occurred as a result of the nuclear accident at Chernobyl in 1986, but was mostly limited to the region of continental Europe (Volchok and Chieco, 1986). Due to most of the ^{137}Cs fallout occurring in the northern hemisphere (Figure 8), work utilising ^{137}Cs for studies looking at sediment movement have mostly been limited to the northern hemisphere, with very few such studies taking place in Southern Africa (Humphries *et al.,* 2010).

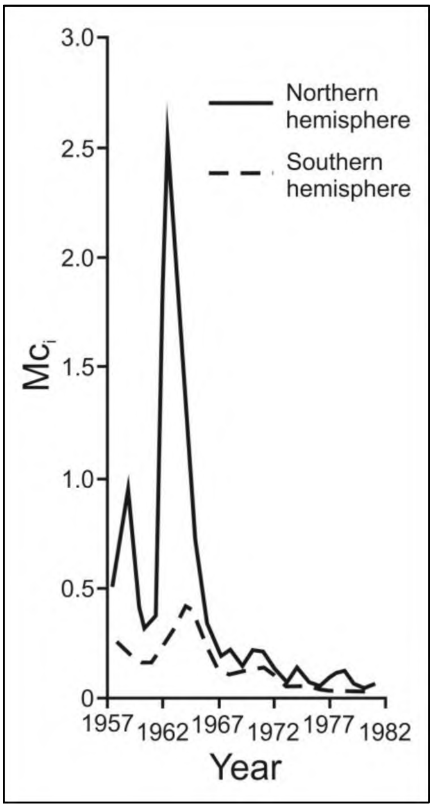

Figure 8: Model of Caesium fallout in the Northern and Southern Hemispheres. Modified after Ritchie and McHenry (1990).

Humphries *et al.,* 2010 demonstrated the use of ^{210}Pb and ^{137}Cs in the determination of sediment accumulation rates in a Southern African wetland, the Mkuze River floodplain, which is located on the Maputaland coastal plain, with ^{210}Pb and ^{137}Cs proving to be within the realms of analytical detection limits. The radionuclide ^{137}Cs is useful in that it provides a distinct chronological marker, such that its presence signifies the 1950-1960s, when fallout of ^{137}Cs occurred.

Radionuclides can emit alpha and beta particles as well as gamma rays. For this study the measurement of gamma rays was chosen as it does not present the kinds of practical challenges associated with the measurement of beta particles. Sediment samples of approximately 3 g were weighed and packed to a depth of 4 cm in clean PTFE sample pots. The pots were then sealed using rubber turnover caps and sealed with paraffin wax. The samples were left for 21 days to allow for the equilibration of the ^{210}Pb. Measurements were made using High-Purity Germanium (HPGe) gamma detectors. Total ^{210}Pb was measured at 46.5 keV and ^{137}Cs was measured at 661 keV using gamma ray spectrometry.

Chapter 5: Results

5.1 Introduction

This chapter begins by exploring the flood history of the Mfolozi River. This is to determine how often floods have occurred over the recorded time period as well as which parts of the catchment were affected by different floods. It then explores the various sedimentary features to determine the signatures left behind by flood events in the sedimentary record.

5.2 Objective 1: A history of flood events for the Mfolozi River catchment.

Flood data from the Mfolozi River floodplain as measured at W2H032 indicates several large floods over a period of just over a century (Figure 9). Notably large events (discharge greater than 5 000 $m^3.s^{-1}$) were recorded in 1957, 1963, 1984, 1987 and 1989. The Cyclone Demoina event produced the highest discharges of any flood event in the record such that peak discharge during the event was measured at 15 500 $m^3.s^{-1}$. The 1987 flood with a peak discharge of 6 200 $m^3.s^{-1}$ was a result of rainfall caused by a cut-off low. Several smaller events were also recorded subsequent to 1987, with three events (in 1989, and two in 1996) producing flow rates of over 4 000 $m^3.s^{-1}$.

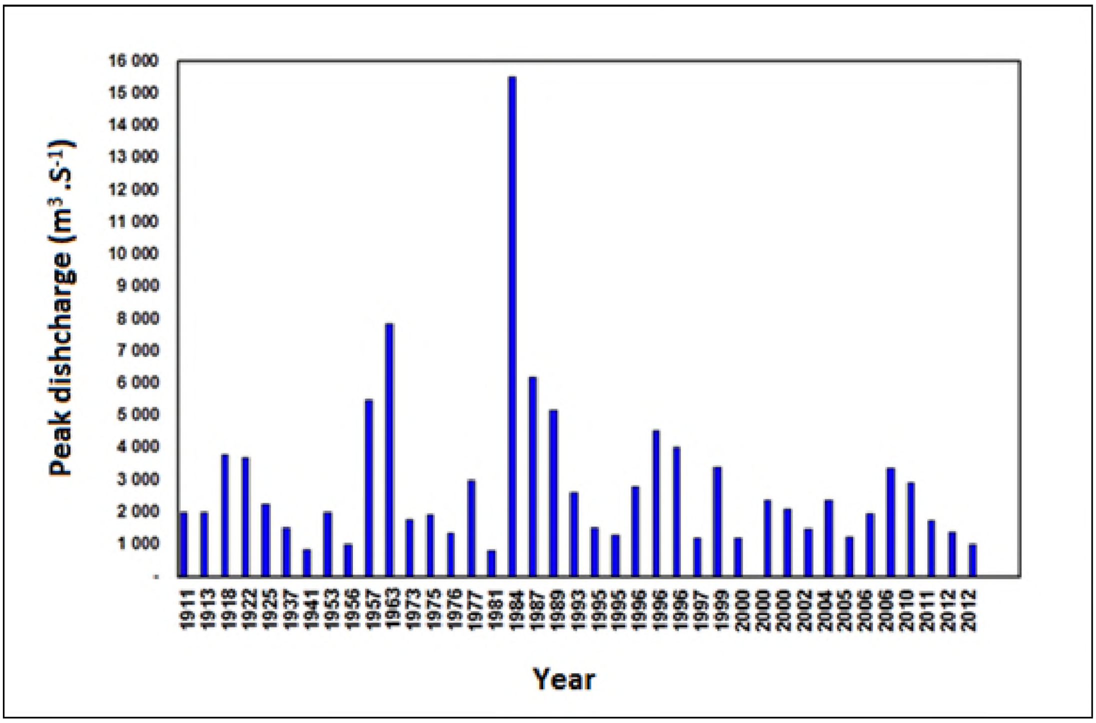

Figure 9: Historical flood data from the Mfolozi River measured at W2H032 in the central reach of the Mfolozi Floodplain. Flood data was provided by UCOSP.

Several flood events were recorded over the period from 1963 to 2015 at the gauging station on the upper Black Mfolozi River (W2H006), the largest of which occurred in 1977 with a peak daily average flow rate of 556.4 $m^3.s^{-1}$ (Figure 10). Many flood events over the period of record registered daily average flow rates above 200 $m^3.s^{-1}$. The daily average flow at this station coincident with the Cyclone Demoina event of 1984 was 354.3 $m^3.s^{-1}$. The cut-off low event of 1987 registered an even higher discharge of 483.2 $m^3.s^{-1}$. From Figure 8 it is evident that most of the flood events recorded at the W2H032 flow station on the Mfolozi floodplain were also recorded at the W2H006 station further upstream.

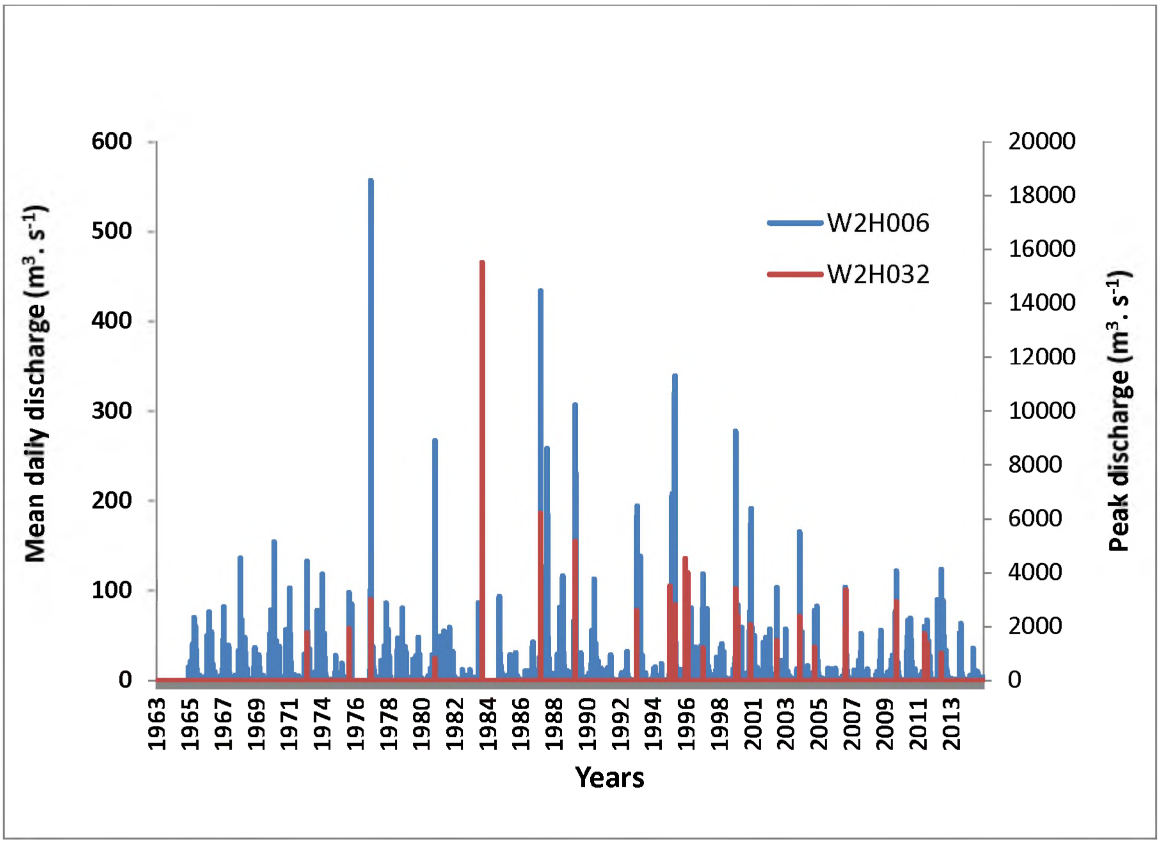

Figure 10: Historical average daily flows from the upper Black Mfolozi River gauging station (W2H006) plotted with peak discharge for the Mfolozi Floodplain (W2H032).

A complete history of flow could not be obtained from the gauging station on the upper reaches of the White Mfolozi River (W2H009) as the gauging equipment was destroyed at several points in the recoding history. At certain points along the record several months' worth of data could not be recorded. For this reason the interval of dates reported on the x-axis of Figure 11 is not uniform. The highest mean daily discharge recorded at (W2H009) was 629 $m^3.s^{-1}$, which was coincident with the Cyclone Demoina flood. Discharge coincident with floodwaters from the 1987 cut-off low as recorded on the Mfolozi Floodplain (W2H032) at 6 000 $m^3.s^{-1}$, peaked at 124.7 $m^3.s^{-1}$ at W2H009. Flood events were also recorded in 1996 and 2006 at gauging station W2H009 with values of 129.7 and 92.0 $m^3.s^{-1}$ respectively. These were both associated with cut-off low weather systems, and corresponded with peak flows on the Mfolozi Floodplain (W2H032) of 2 800 and 3 359 $m^3.s^{-1}$ respectively. A recent flood event was also recorded at the station on the upper White Mfolozi River (W2H009) in 2013, with a daily average flow of 255 $m^3.s^{-1}$. The 2013 flood occurred on January 17 and peaked at 89.0 $m^3.s^{-1}$ at the W2H006 station further downstream.

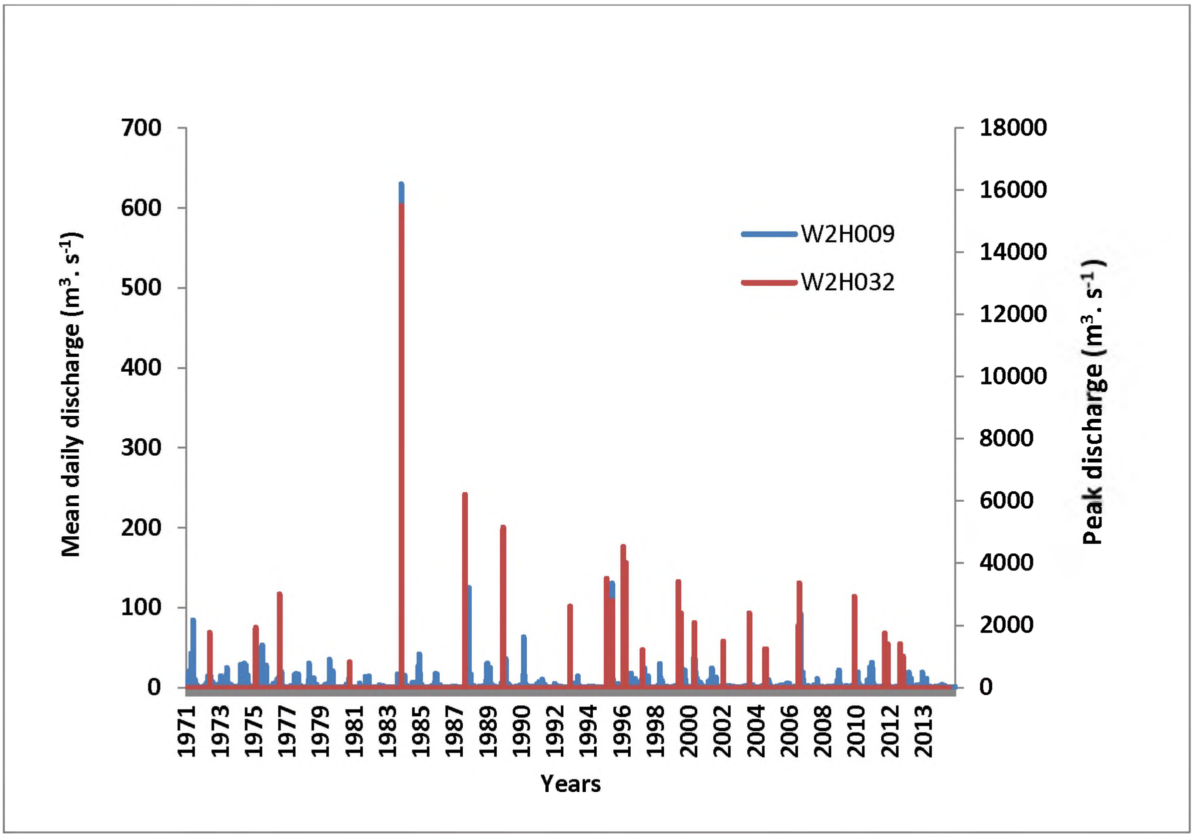

Figure 11: Historical average daily flows from the upper White Mfolozi River gauging station (W2H009) plotted with peak discharge for the Mfolozi Floodplain (W2H032).

5.3 Objective 2: The signature of flood events in the sedimentary record

This section examines a range of physical, geochemical and mineralogical features or signatures, of sediment associated with flood events recorded in the sedimentary record. These signatures are potentially useful in helping to distinguish between large and small flood events as well as floods that originate from coastal and inland rainfall events. This section begins by examining variation in particle size and organic matter content, which indicate flood event magnitude in the sedimentary record. Finally, the mineral magnetic properties, mineralogical analysis and radionuclide profiles are presented. These have been used as sediment tracers to provide some insight as to the source of the identified flood events and their deposited sediments.

5.3.1 Particle size distribution

Variation in median particle size (D50) values with depth is shown for the two sediment cores retrieved in this study in Figure 12. The D50 values for the Lake Futululu core (Figure 12a), which was taken closer to the main stream of the river than the South Lake core, were generally coarser and more variable than in the South Lake core (Figure 12b). Several peaks in D50 values are apparent in the Lake Futululu core, with a few sequences of high values present over a considerable depth of approximately 0.3 m. Most of the measured D50 values of the Futululu core fall between 20 µm and 90 µm, with the highest measured value being 128 µm (Figure 12a).

The D50 values for sediment from the South Lake core were on average much finer than the sediment from the Lake Futululu core. Most of the measured values were below 30 µm, with only a few of the measured samples returning values higher than 50 µm. There were fewer peaks in particle size values present in the South Lake core. However, below 1.5 m in depth the measured D50 values became more variable. The coarsest material in the core is found from a depth of approximately 2.5 m onwards, with a particularly notable peak near the bottom of the core at just over approximately 3.2 m. This sediment was the coarsest material measured in either of the cores. Overall there would appear to be very little similarity between the two cores, with the Futululu core returning far more variable values than the South Lake core, which returned consistently fine D50 values.

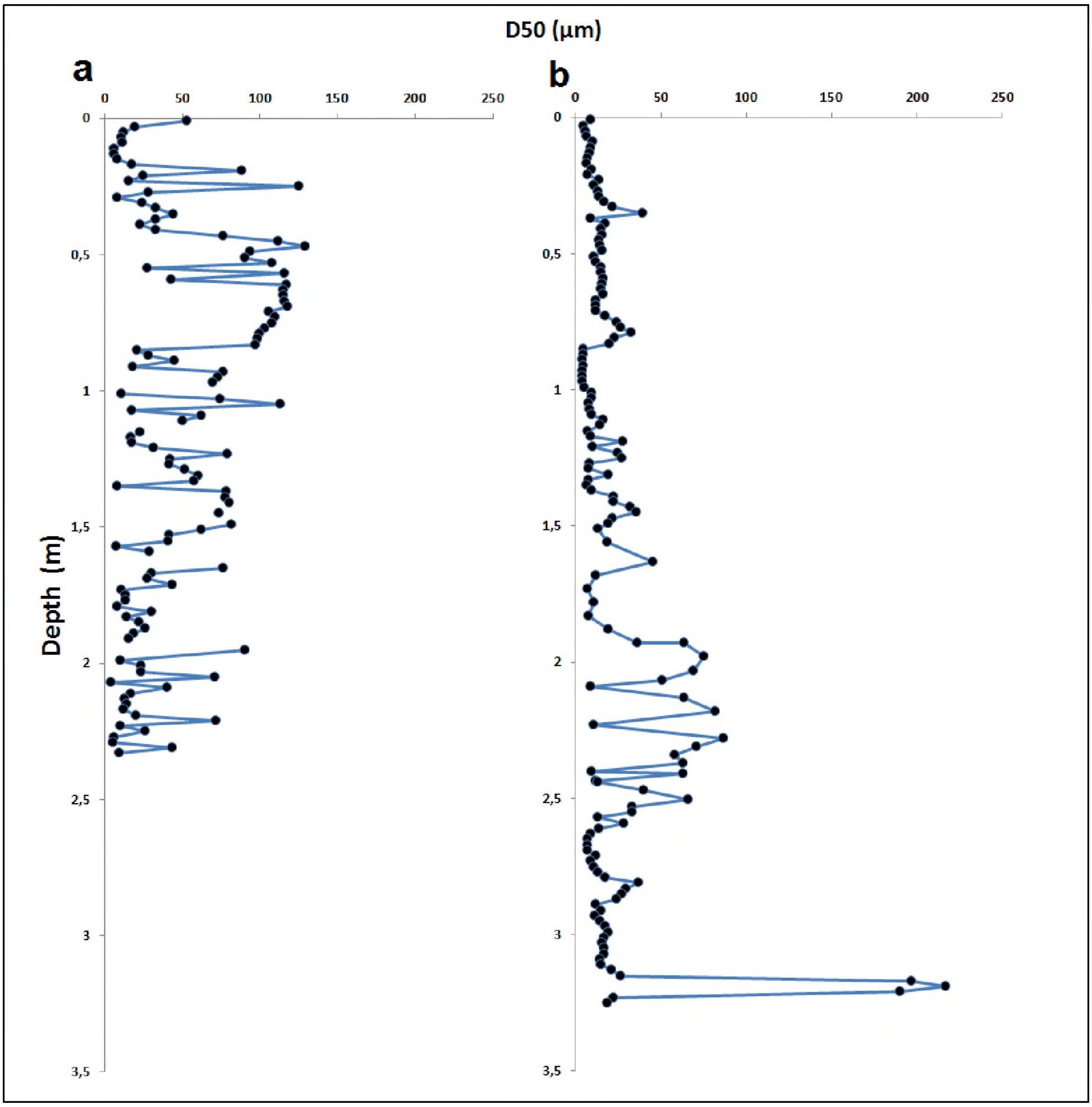

Figure 12: Variation in median particle size values (D50) with depth of the Lake Futululu (a) and South Lake (b) cores.

5.3.2 Organic matter content

The Lake Futululu core samples generally contained very little organic material, with most samples containing less than 1% organic matter (Figure 13a). A few samples returned LOI values of close to 5%, with 2 samples containing just over 5% organic matter at the soil surface and at about 2.0 m depth. Additionally, the organic matter content seemed to decrease fairly systematically from the soil surface to a depth of about 0.5 m and then increase fairly systematically from 0.5 m depth to the base of the core. The low organic content of samples suggests on-going clastic sediment input from the trunk stream at this site, which is within 1 km of the main channel.

The South Lake core contained far more organic matter (Figure 13b) than the Lake Futululu core. The samples from the middle sections of the core in particular contained high amounts of organic material, with many samples containing more than 10 % organic matter and several containing more than 20 % organic matter. This suggests an environment where there is limited clastic sediment input due to flood events, allowing for the accumulation of organic matter that is produced in situ as illustrated by organic macro-remains of plants growing on site at depth within the core. Below 2.8 m the samples returned implausibly high values and as such were removed from the dataset.

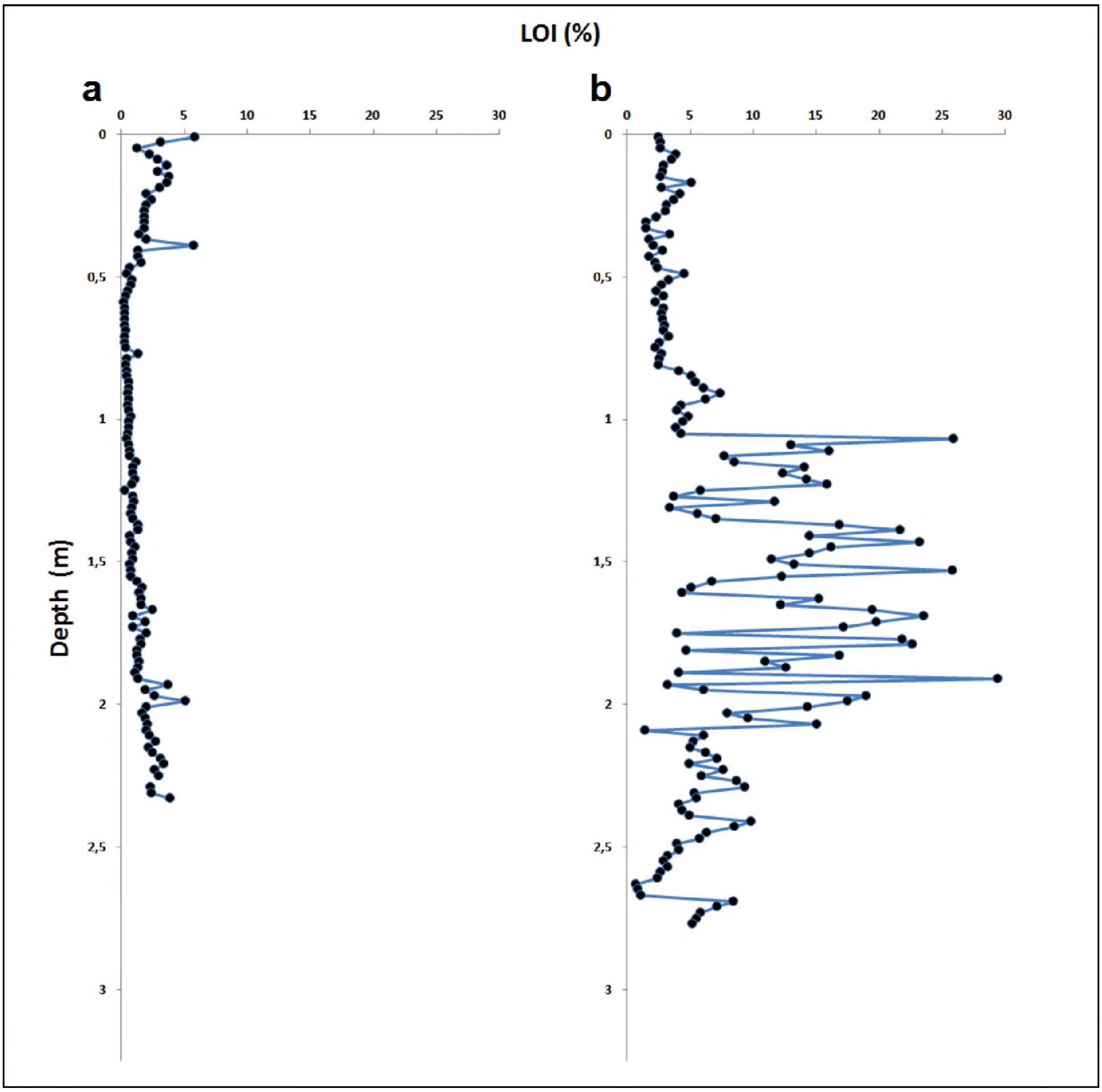

Figure 13: Organic matter content with depth for Lake Futululu (a) and South Lake (b) cores.

5.3.3 Mineral magnetic properties

This section examines how certain magnetic signatures vary with depth. The primary aim of this section is to establish the magnetic signatures of the sediment that can be used to identify its source material. The variation of the magnetic values with depth will also indicate whether or not source tracing using magnetics is reliable across a range of depths in environments with a high water table. This is an important consideration as certain magnetic signatures can be affected by factors such as dissolution where they experience prolonged saturation due to the presence of a high water table.

Variation of low frequency magnetic susceptibility (X_{lf}) with depth of the two measured sediment cores is shown in Figure 14. The X_{lf} values for the Lake Futululu core sediments were highly variable, with a gradual trend of increasing values with depth (Figure 14a). Most values ranged between 0.1 and 0.5 x 10^{-6} $m^3.kg^{-1}$, with the graph taking on a highly irregular profile. The majority of the X_{lf} values for the Lake Futululu core were very low, with some of the values within the range one might expect for sediment derived from mudstone and shale, while several other values were within the range one might expect for sediment derived from quartzite.

The graph of X_{lf} values for the South Lake core sediments were variable within the uppermost meter of the core, with some of the high values (up to 0.8 x $10^{-6}m^3.kg^{-1}$) being greater than any of the values recorded in the Lake Futululu core (Figure 14b). These values are low and do not suggest the presence of highly magnetic mineral grains. At depths greater than 1 m, X_{lf} values decreased and remained below 0.2 x 10^{-6} $m^3.kg^{-1}$. Values for X_{lf} were below detection limits at a depth greater than 3 m, possibly indicating dissolution of many magnetic mineral grains (Figure 14b).

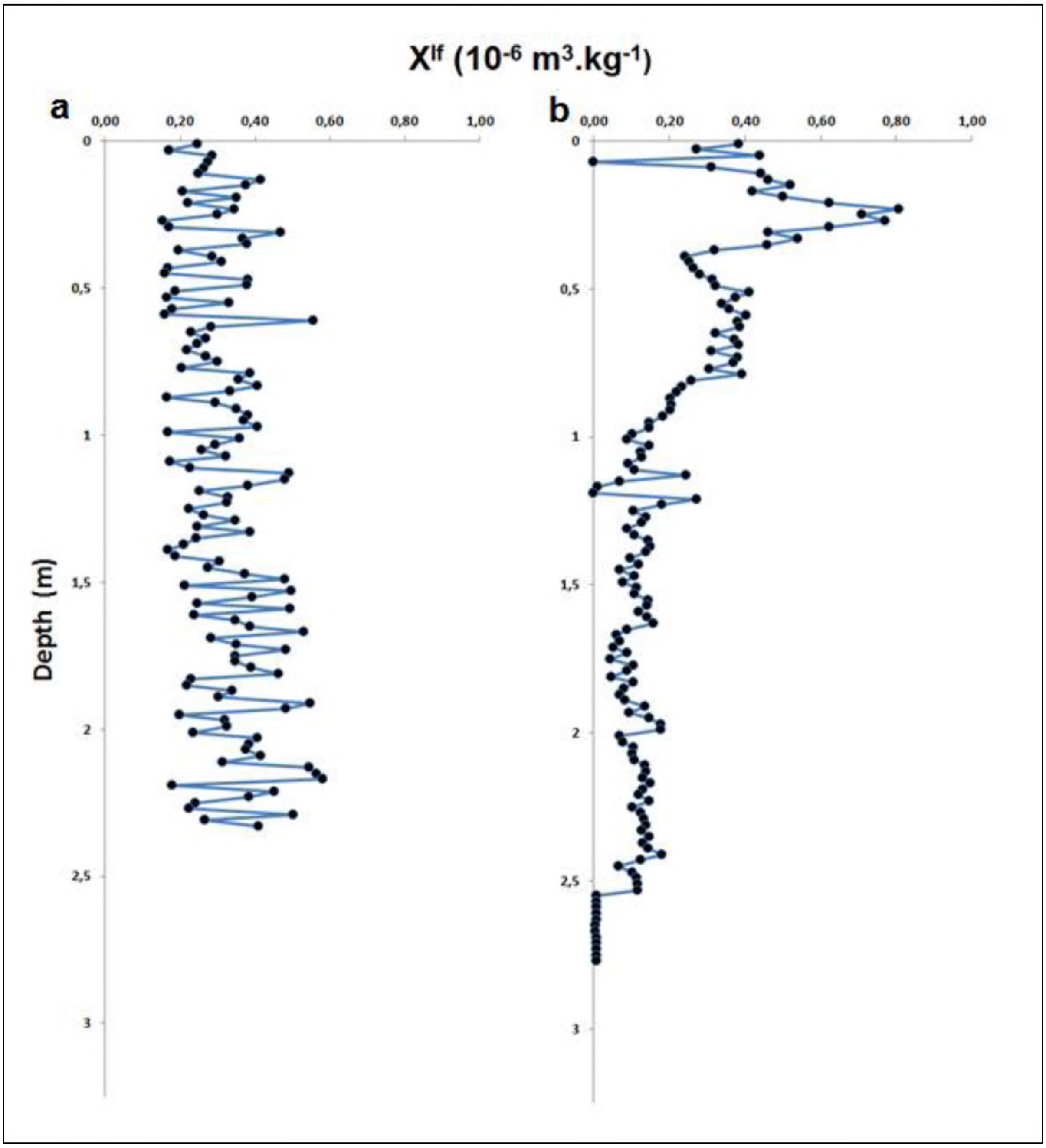

Figure 14: Variation in Low frequency magnetic susceptibility with depth for the Lake Futululu (a) and South Lake (b) cores.

Variation in anhysteretic remanent magnetisation (X_{arm}) values with depth for the two sedimentary cores is shown in Figure 15. X_{arm} values for the Lake Futululu core were highly variable. The highest measured X_{arm} value was recorded within the uppermost 0.02 m of the core at just over 15 x 10^{-6} $m^3.kg^{-1}$, while at a depth greater than 0.9 m values were generally very low (Figure 15a). The majority of the remaining values were about 5 x 10^{-6} $m^3.kg^{-1}$. Overall there was no systematic variation in X_{arm} values with depth for the Lake Futululu core.

The uppermost meter of sediment from the South Lake core returned several X_{arm} values that were higher than those measured from the Lake Futululu core, with several samples returning measured values of over 15 x 10^{-6} $m^3.kg^{-1}$ (Figure 15b). The high values in the uppermost meter of sediment stand in contrast to the values from the remaining two and a half meters of sediment which are characterised by very low values (Figure 15b).

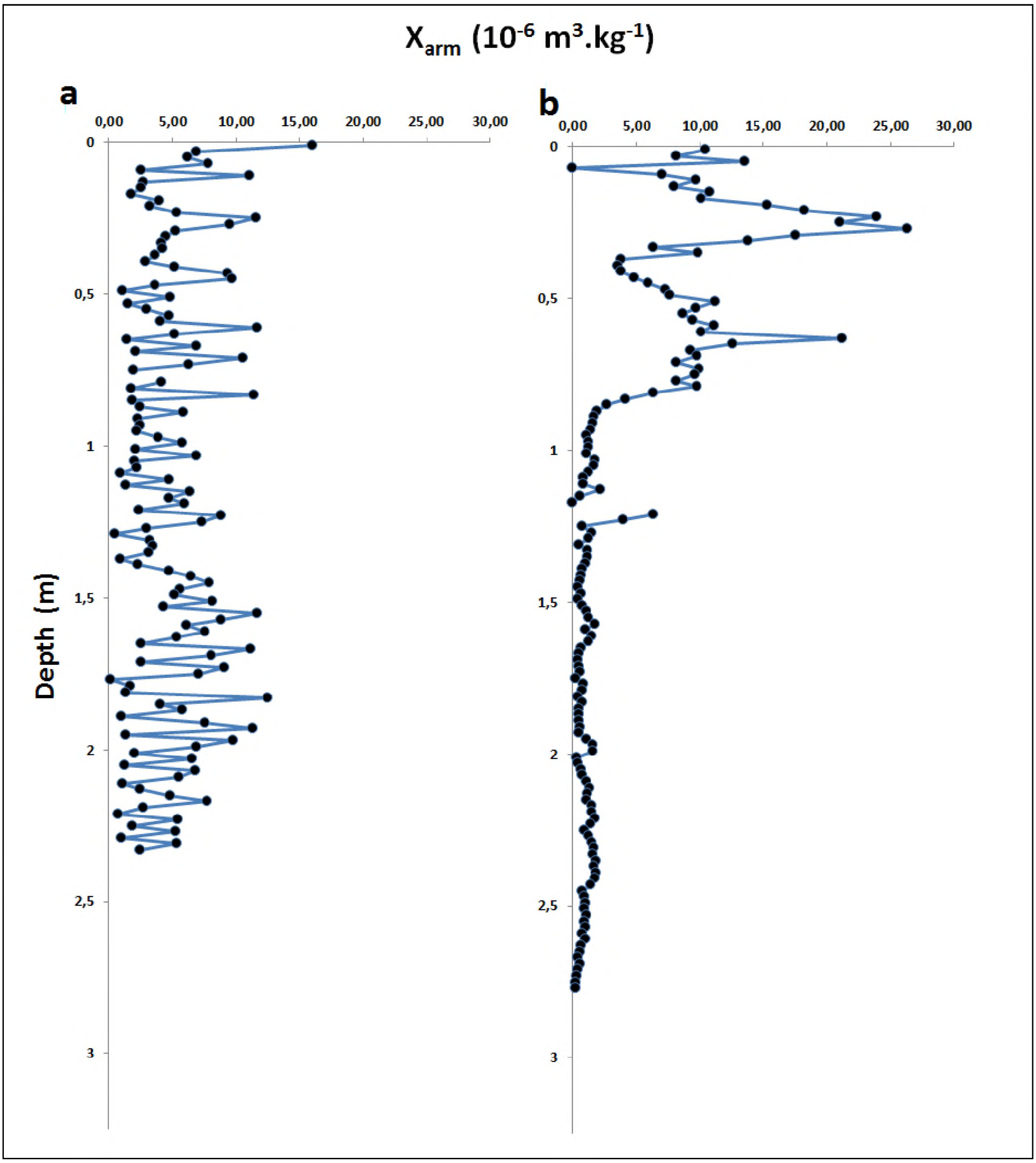

Figure 15: Xarm magnetic values for the Lake Futululu (a) and South Lake (b) sedimentary cores.

Variation in Saturated Isothermal Remanence Magnetisation (SIRM) values with depth for the two sediment cores is shown in Figure 16. The Lake Futululu sediments produced variable but generally low SIRM values that were all below 5 x 10^{-3} $Am^2.kg^{-1}$ (Figure 16a). The values for the South Lake sediments were generally very low, although there were a small number of higher SIRM values (Figure 16b). Overall, SIRM values for the two cores were generally well below the values one might expect for the kind of igneous lithologies found within the eastern part of the catchment.

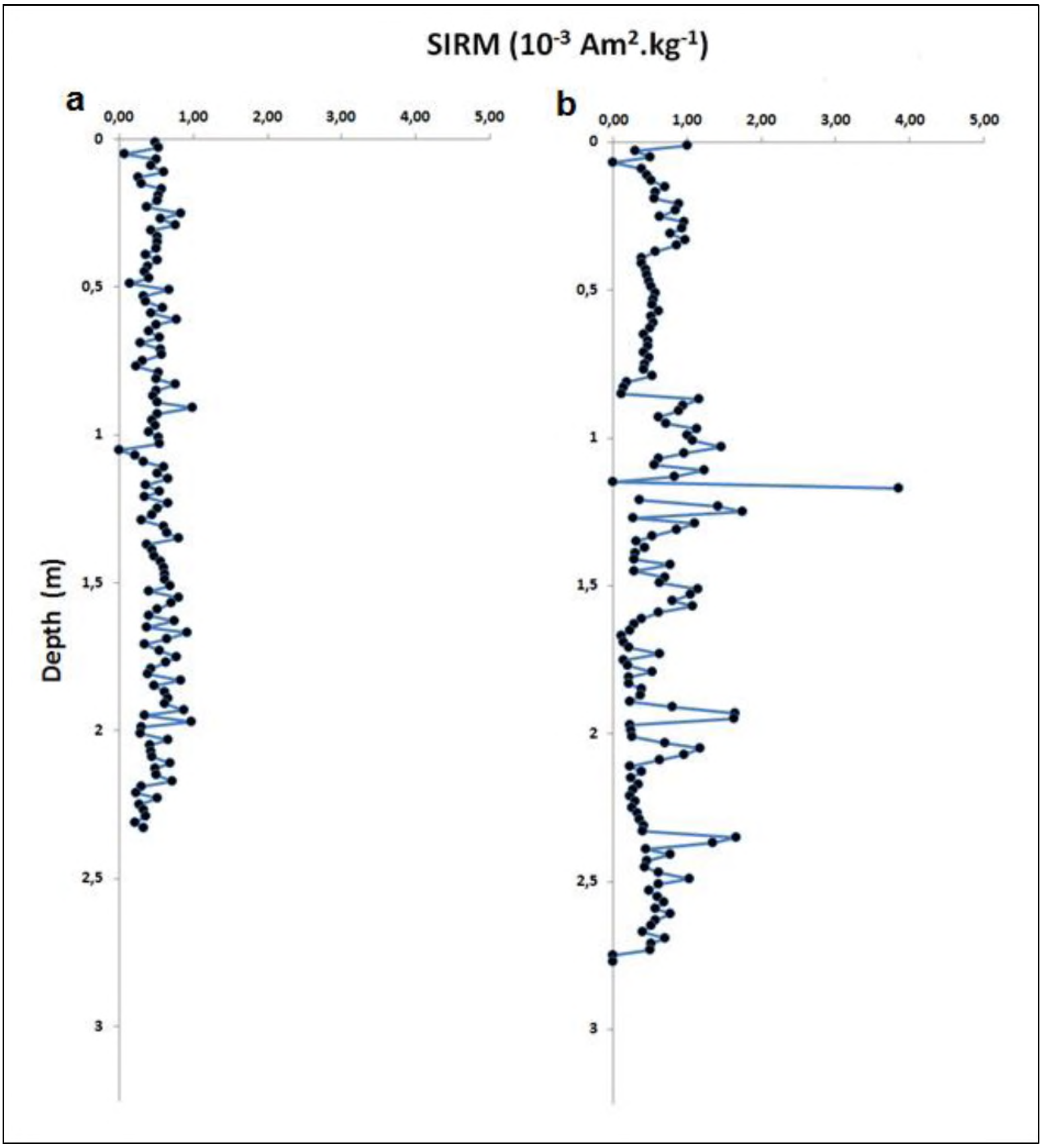

Figure 16: Variation with depth of saturated isothermal remanence magnetism values for the Lake Futululu (a) and South Lake (b) sediment cores.

5.3.4 Mineralogy

This section examines the bulk mineral assemblage of samples taken from both of the sedimentary cores. For both cores, samples were selected from depths with the coarsest sediment particles, as these were the most likely to be associated with flood deposits.

Variation in mineralogical composition with depth for the Lake Futululu core samples indicated that the sample was made up mostly of quartz, with orthoclase feldspar and rutile making up the remaining mineral assemblage (Table 4). The observed bulk mineral composition is indicative of material derived from sedimentary rocks such as quartzite, sandstone, shale and mudstone.

The mineralogy of the South Lake samples did not display much variation: samples were comprised of mostly quartz, as well as the common rock forming mineral orthoclase feldspar (Table 4). Most of the samples also contained vermiculite, which is relatively common in shale and mudstone.

Table 4: Variation in sample mineralogy with depth from the Lake Futululu and South Lake cores. For each sample minerals are presented in order of their abundance.

Lake Futululu		**South Lake**	
Sample depth (m)	**Minerals**	**Sample depth (m)**	**Minerals**
0.28-0.30	Quartz Orthoclase Rutile	0-0.02	Quartz Orthoclase Vermiculite
0.32-0.34	Quartz	0.12-0.14	Quartz Orthoclase
0.66-0.68	Quartz Orthoclase Rutile	0.18-0.2	Quartz Orthoclase Vermiculite
1.36-1.38	Quartz Orthoclase Rutile	0.34-0.36	Quartz
1.7-1.72	Quartz	0.78-0.8	Quartz Orthoclase Vermiculite
1.76-1.78	Quartz Orthoclase Rutile	1.62-1.64	Quartz Orthoclase Vermiculite
1.9-1.92	Quartz Rutile	1.98-2	Quartz Orthoclase Vermiculite
2.1-2.12	Quartz Rutile	2.26-2.28	Quartz Orthoclase Vermiculite
2.3-2.32	Quartz	3.18-3.2	Quartz Orthoclase Vermiculite

5.3.5 Radionuclide dating

This section outlines the results of radionuclide testing that was done on samples from both cores to establish a chronological sequence of flood events in the catchment. The targeted radionuclides were ^{210}Pb and ^{137}Cs. A peak in the ^{137}Cs concentration in particular would establish a chronological marker in the sediment, which would allow placement of the different flood events around the 1960's ^{137}Cs fallout peak.

No ^{137}Cs was detected in any of the samples from either of the two cores. ^{210}Pb levels were also below the limit of detection by the equipment in both cores. The lack of ^{137}Cs in particular suggests that the sediment in both of the cores was deposited either prior to the late 1960’s, or after the late 1960's (after which ^{137}Cs fallout declined, particularly in the southern hemisphere).

Chapter 6: Discussion

6.1 Introduction

The aim of this study was to construct a record of major flood events on the Mfolozi River floodplain over the last century and determine their source using hydrological records and sediment source tracing techniques. This chapter discusses the main findings of this study. It explores the implications of the results of the study in the context of the literature to determine whether or not the aim and objectives of the study have been met.

6.2. Objective 1: To determine a history of flood events for the Mfolozi River catchment

This section discusses the results of the flood record analysis undertaken using hydrological data. The hydrology of the catchment is an important consideration when attempting to characterise historical flood events. The frequency with which large flood events occur as well as their degree of penetration into the catchment provides a useful context for interpretation of sedimentary flood signatures.

Historical flood data provided by UCOSP provides evidence that high magnitude flood events do occur within the catchment of the Mfolozi River. Since recording began in 1911, 39 different flood events have occurred, each with a peak daily average discharge of over 800 $m^3.s^{-1}$. In the past 30 years, the Cyclone Demoina and cut-off low events generated the highest flows recorded in the catchment. Whilst the discharge data from the stations further upstream also reflect these events, they serve to highlight the differences in the degree of penetration of the two types of weather systems.

The ratio of mean daily flows at flow stations in the upper reaches of the catchment co-incident with peak discharge for large flood events recorded on the Mfolozi Floodplain is shown in Figure 17. In most instances, the ratio for W2H006 (upper Black Mfolozi River) is higher than for the upper White Mfolozi River (W2H009) further west in the catchment. This is to be expected given than the W2H006 station is the closer of the two stations to the floodplain and therefore has the greatest tributary contribution. Ratios for the W2H006 station were generally much less than 0.15, with discharge for only two floods having a ratio greater than 0.20 (1981 and 2000).

Ratios for the W2H009 station were generally very low, with only the 1984 flood and the first of three floods in 1995 having a ratio higher than 0.03. Ratios for several of the floods that occurred after the year 2000 were negligible. Surprisingly, discharge coincident with Cyclone Demoina was higher at the W2H009 station than at the W2H006 station further east, an anomaly considering the coastal nature of the event.

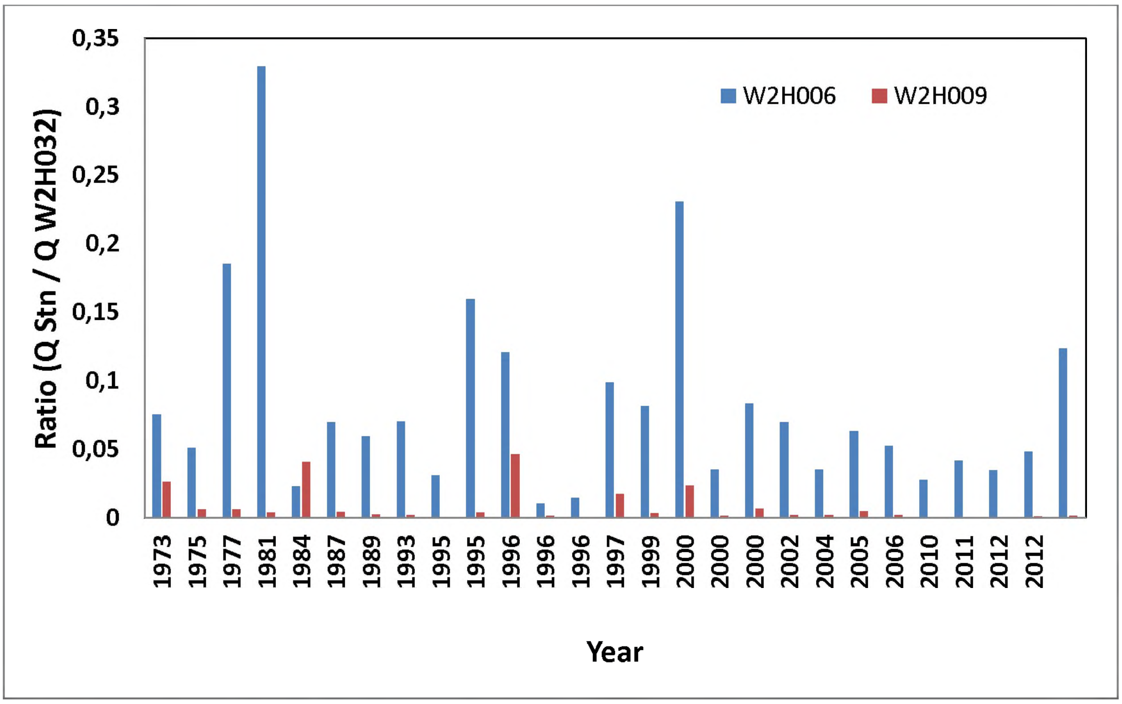

Figure 17: The ratio of discharge at W2H006 and W2H009 gauging stations to discharge at station W2H032 on the Mfolozi Floodplain for individual flood events.

Flood data from UCOSP highlighted several smaller flood events that occurred in the region throughout the last decade of the previous century and into the first decade of the 21st century. Barring a few instances of equipment failures, these floods were reflected at the flow stations in the upper reaches of the catchment. For the March 1996 flood, the W2H006 station returned one of the highest ratios for any flood recorded at that station, while the ratio for discharge coincident with the floods of November 1997, December 1999 and January 2000 were also higher than average. The increased ratios coincident for these floods for the W2H009 station suggest that these floods were concentrated in the upper to middle reaches of the catchment.

Additionally, several instances of flood-producing weather events are reflected in the stations in the upper catchment, particularly at W2H006, which were not reflected as particularly large flood events in the UCOSP flood record. These are likely localised flood events, reflecting runoff from sub-catchments in the upper reaches of the Mfolozi catchment that do not result in regional floods.

6.3 Objective 2: Signatures of flood events in the sedimentary record

6.3.1 Introduction

This section discusses the results of the analysis of the features of flood sedimentary deposits. Different sedimentary features were analysed to identify the signatures left behind by flood events. This is useful as it allows one to determine the size of the event, as well as the likely part of the catchment where rainfall that contributed to the generation of the flood was distributed. This is useful in linking sedimentary features to climatic data for the observed period.

6.3.2 Particle size

Analysis of particle size values is a straightforward method of identifying flood events in the sedimentary record. The high energies associated with floodwaters allow for the transportation of larger particles relative to periods of normal flow (Baker *et al.,* 1983). This coarse sediment is immediately identifiable as peaks in the profile of particle size variation with depth, relative to the particle size values associated smaller flood events. Particle size will also vary according to the location on the floodplain relative to the main stream of the river; coarser sediment will be deposited first as floodwater energies recede, and finer sediment will be deposited further away from the main stream (Baker *et al.,* 1983). The fining of deposited sediment with distance from the main stream of the river was a feature of the results of this study.

The location of the two cores relative to the main stream of the river played a critical role in influencing particle size. The Lake Futululu core, the closest to the main stream of the river, was located in a position where one would expect the deposition of coarse sediment by a given flood event compared to the South Lake, which is much further away from the trunk stream. The proximity of the Lake Futululu core to the main stream of the river means that a high magnitude event such as Cyclone Demoina would have deposited a large amount of coarse material onto that area of the floodplain. The particle size results from the Lake Futululu core show a clear relationship of particle size with the flood record, and it seems possible that the consistently coarse-grained sequence at a depth from about 0.6 m to 0.8 m is a single flood event and possibly represents Cyclone Demoina (I; Figure 18). This would mean that there are 7 or 8 clearly identifiable flood events in the uppermost 0.6 m, which may feasibly be related to floods in 1987, 1989, 1996, 1999, 2000, 2004, 2006 and 2010 (H to B with decreasing depth respectively in Figure 18). Additionally, several earlier flood deposits were identified (S to J with increasing depth in Figure 18), which may feasibly be related to floods in 1911, 1913, 1922, 1925, 1941, 1953, 1957, 1963, 1977 and 1981 respectively. Additional flood deposits were identified from approximately 1.8 m to 2.3 m depth, but these could not be assigned depths. The results would seem to confirm that the sedimentary record does house a history of flood events extending beyond the period of historical data capture.

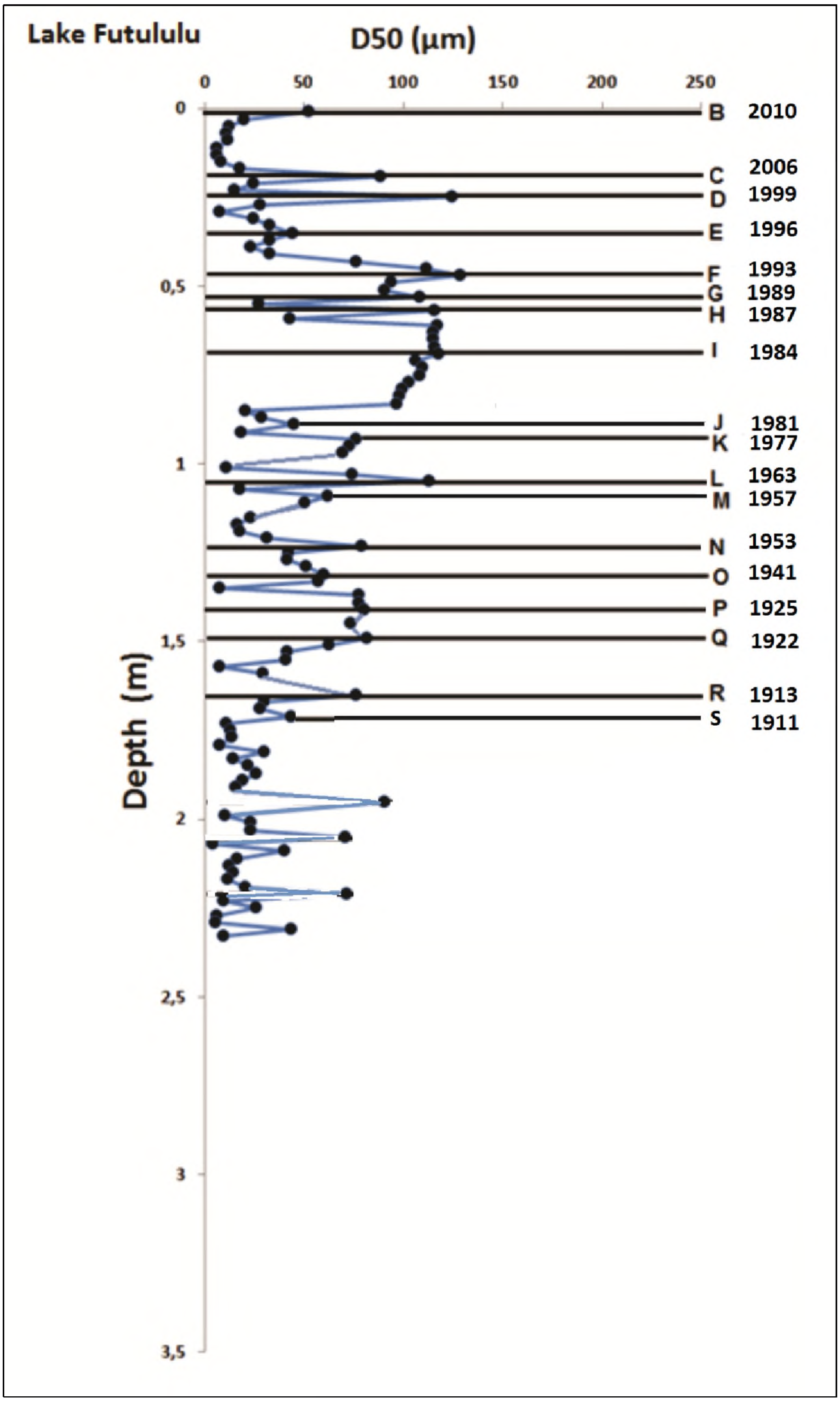

Figure 18: Variation in median particle size with depth with identified flood deposits (B – S) marked at the particle size peak in the Lake Futululu core.

The South Lake core was situated in a position where one would expect much finer average particle sizes, with increases in particle size values reflecting large flood events capable of transporting coarse sediment further away from the main stream of the river. Nevertheless, the lower average particle size of the South Lake sediment did allow distinct flood events to be readily identifiable. The results of median particle size analysis of the South Lake sediments suggests the presence of at least 14 distinct flood deposits in the observed sedimentary record as indicated by the letters B to Q in Figure 19.

Flood deposits B to H are likely the products of relatively small flood events given that each flood deposit has a maximum median particle size value below 50 µm and may feasibly be related with floods in 2010, 2006, 1999, 1996, 1993, 1989 and 1987. Flood deposits I and K are deposits with much larger particle size sediment represented. They are thus likely to be the results of higher magnitude flood events, possibly 1984 and 1977 respectively. Five earlier flood deposits were identified in the core, possibly reflecting floods in 1963, 1957, 1953, 1947 and 1922 (K - Q respectively in Figure 19). Flood deposit Q is the deepest of the identified flood deposits and is characterised by the highest median particle size value found in either core (217 µm).

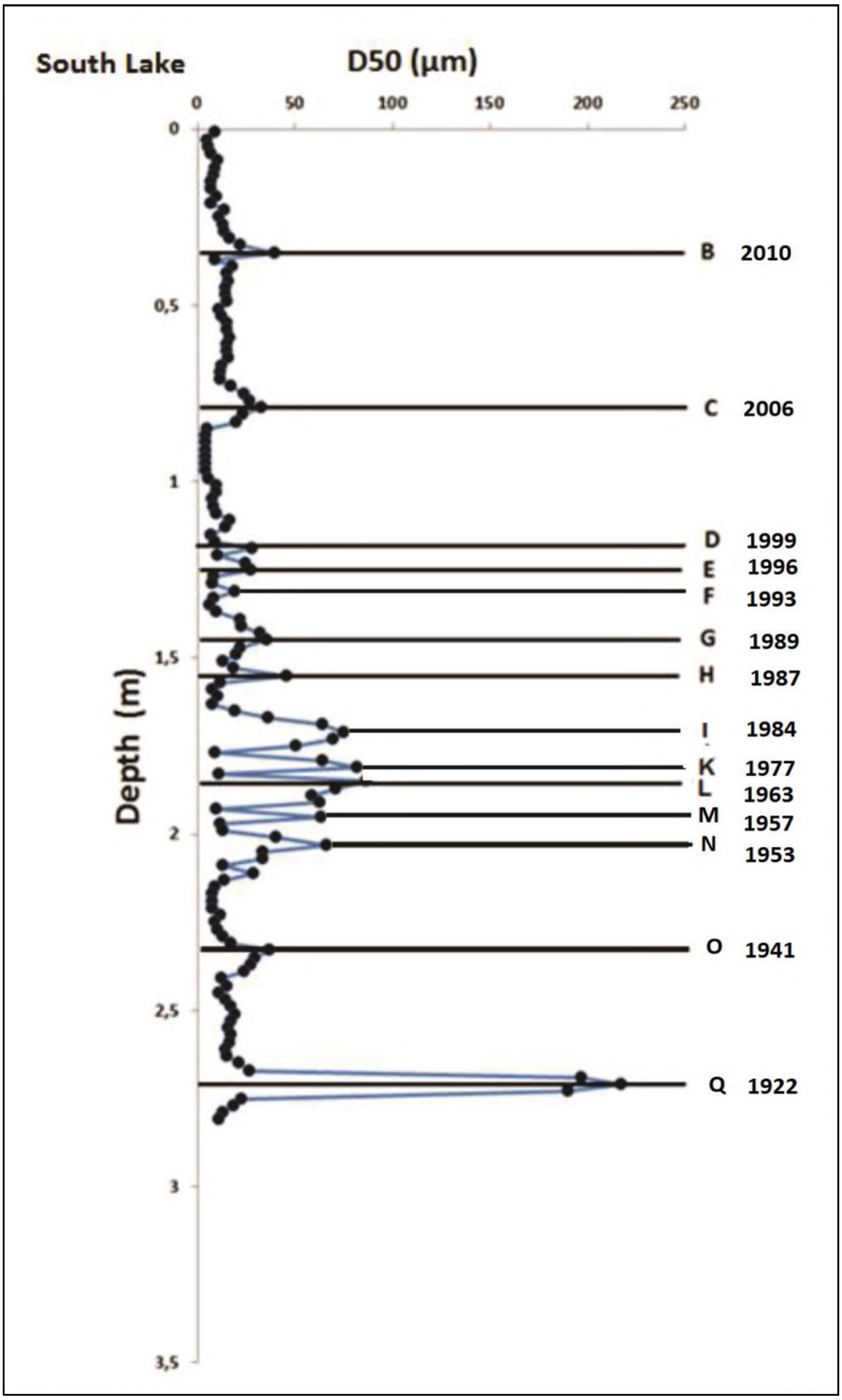

Figure 19: Variation in median particle size with depth with identified flood deposits (B – Q) marked at the particle size peak in the South Lake core.

6.3.3 Deposition rates in relation to proximity to the primary floodplain channel

There is a fairly consistent relationship between the age of the flood and the depth of the core for the Lake Futululu sediments (Figure 20). The Cyclone Demoina event is associated with the deposition of a particularly large sedimentary deposit in this core (approximately 0.25 m thick). It is for this reason that there is a break in the lines of best fit for the relationship between the age of the identified flood events and depth within the Lake Futululu core com-incident with the 1984 event. The correlation co-efficient (R^2-value) of 0.974 before the Demoina event suggests an aggradation rate of 0.011 $m.a^{-1}$, which is twice the published rate of aggradation on the Mkuze Floodplain about 50 km north of the Mfolozi Floodplain Humphries *et al.,* 2010; Figure 20). A sedimentation rate of 0.011 $m.a^{-1}$, is approximately an order of magnitude higher than for the Futululu peat deposits along the tributary valley north of the lake (Grenfell *et al.,* 2010).

Subsequent to the Demoina event, the R^2 value of 0.975 suggests an aggradation rate of 0.02 $m.a^{-1}$, an increase by a factor of two and much higher than published figures for the Mfolozi and other floodplains in the region which are likely to have experienced the kinds of flood-producing weather phenomena that led to flooding of the Mfolozi floodplain.

Grenfell *et al*., (2010) report an aggradation rate of 0.0013 $m.a^{-1}$ for the Futululu drainage line over the last 6 500 years, but careful scrutiny of the data reveals that sediment shallower than 1.7 m is “modern” (post 1950). These authors allude to a radical increase in sedimentation rate in the last several decades but do not suggest what such an increase might amount to or why it may have occurred. The location of the core dated by Grenfell *et al*., (2010) examined peat accumulation in the tributary valley upstream of Lake Futululu, where aggradation is viewed to be a passive response to aggradation on the floodplain surface, which acts as a local base level for the Futululu tributary. As such it might be expected that the rate of aggradation in the tributary is related to but lower than, the aggradation rate of the floodplain (Grenfell *et al*., 2010).

Published rates of aggradation in other floodplain systems in the region indicate rates of aggradation between 0.0020 and 0.0050 $m.a^{-1}$ for the Mkuze Floodplain (Humphries *et al*., 2010). Turner and Plater (2004) reported similar aggradation rates of 0.0050 $m.a^{-1}$ for the for the Mdlanzi swamp, north of the Mkuze River system. The 0.0050 $m.a^{-1}$ rate was calculated using radiocarbon dating and is similar to figures reported by Smuts (1992).

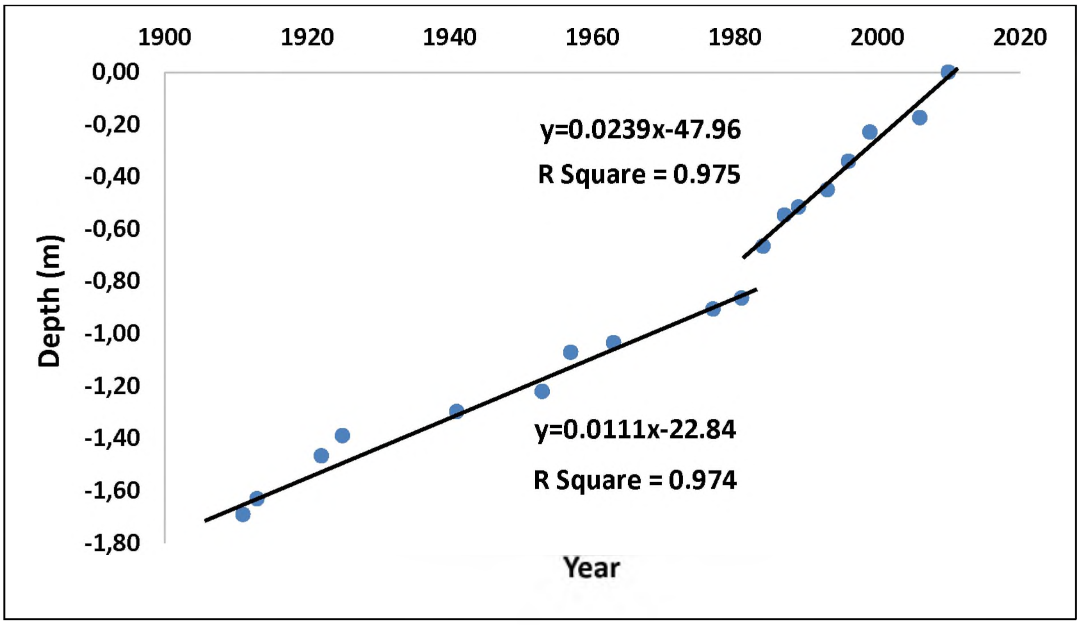

Figure 20: Relationship between flood deposits and depth as identified in the Lake Futululu core.

Based on analysis of the South Lake sediments it is likely that the depositional feature at a depth of 1.6 m represents the flood deposits of Cyclone Demoina (Figure 21). Once again, if this is the Cyclone Demoina flood, it is of interest to consider rates of aggradation Indicated by the South Lake core. If the flood deposit of Cyclone Demoina terminated in 1984 at a depth of 1.6 m, it suggests an aggradation rate prior to the Demoina flood of 0.011 $m.a^{-1}$, and of 0.051 $m.a^{-1}$, after the Demoina event (Figure 21). This latter does seem remarkably high compared to rates of aggradation in this and other floodplain systems in the region – as described above.

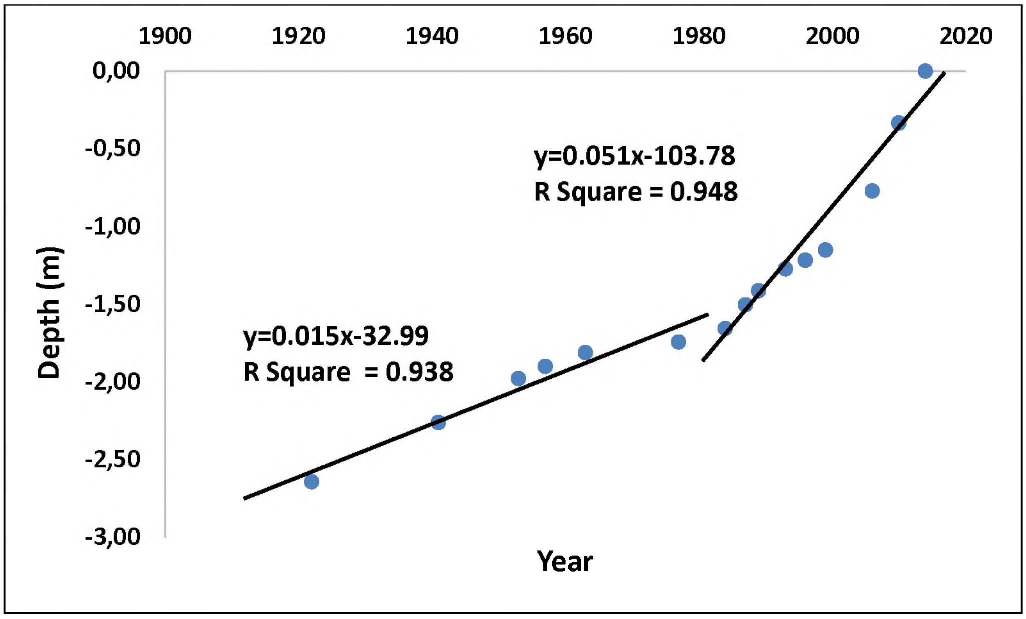

Figure 21: Relationship between age of flood deposits and depth as identified in the South Lake core.

The contrasting results from the two cores, particularly in respect of aggradation rates, seems to contrast with the assertion that aggradation rates close to the main floodplain stream should be higher than for locations further away. However, Grenfell *et al.* (2009) describe the location of the most extensive, coarse and thick deposits associated with Cyclone Demoina (Figure 22). During the Cyclone Demoina floods the Mfolozi River avulsed southwards and flowed into the Msunduse River, with deposits in excess of 2 to 3 m thick in the region of the avulsion. Given extensive damage to infrastructure and sugar cane, the Umfolozi Co-operative of Sugar Producers (UCOSP) redirected flow back into the former Mfolozi River course. However, the preferential flow of the Mfolozi towards the southern floodplain suggests that this region of the floodplain is at a lower elevation than the northern region of the floodplain, which is borne out by floodplain cross-sections presented by Grenfell *et al.,* (2009) as shown in Figure 23.

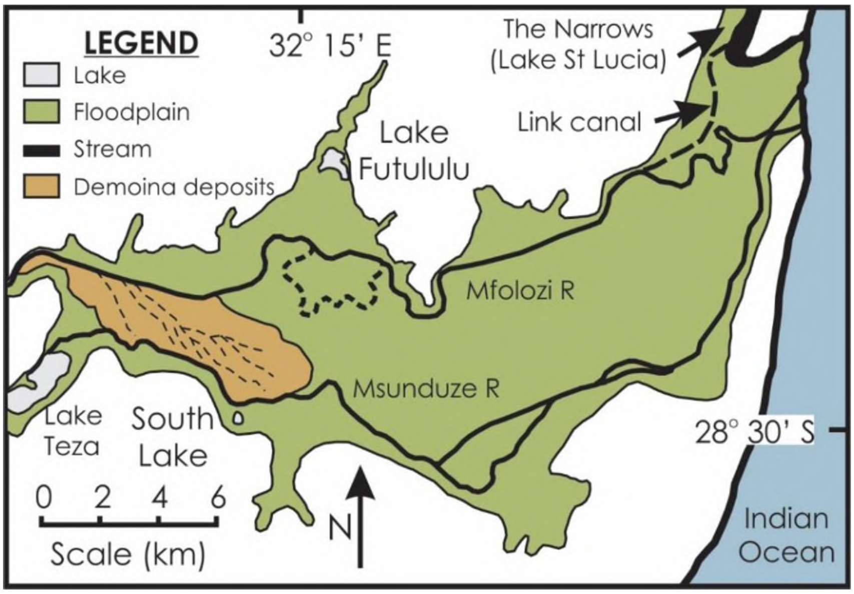

Figure 22: Map of the Mfolozi River floodplain illustrating the most extensive sedimentary deposits associated with Cyclone Demoina (modified after Grenfell *et al*., (2009)).

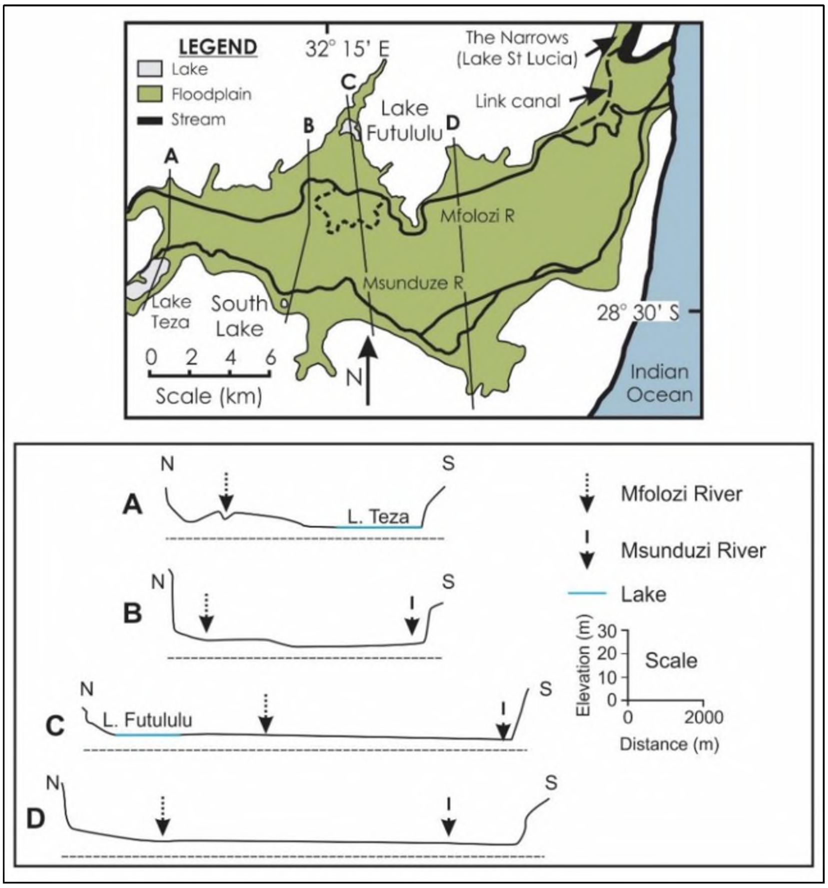

Figure 23: Cross sections illustrating the elevation of the Mfolozi River floodplain from its northern to southern edges (modified after Grenfell *et al*., (2009)). The dashed line below each cross-section simply shows the horizontal.

The claim that proximity to the primary floodplain is likely to influence particle size and variation in sedimentation rate seems simplistic given the results of this study. Local slope and the direction of a future avulsion are likely to be major factors influencing the distribution of sediment on floodplain systems, such that remote sites may receive larger quantities of sediment than proximal ones. The assumption that proximal sites may yield more insight into flood dynamics than distal ones may therefore be more complex than the distance of a site from the trunk stream.

The increased sedimentation rates on the Mfolozi floodplain over the upper 1-2 m of sedimentation are likely a reflection of the widespread increase in soil erosion that has been a feature of the region for over a century. This increase in erosion has largely been attributed to extensive stock farming coinciding with European settlement of the region (Key-Bright and Boardman, 2006). Decker *et al*. (2011) reported that short term soil erosion rates in the Karoo region are higher than long term rates of soil production. The Mfolozi River is thus situated in a region predominated by erosion (Martin, 1987). Heavy grazing pressure is a feature of the Mfolozi River catchment outside the borders of protected areas and has likely contributed to increased erosion rates in the catchment and subsequent sedimentation on the floodplain (Key-Bright and Boardman, 2006). The increased sedimentation rates subsequent to Cyclone Demoina also likely reflect the increased sediment availability in the catchment as a result of the large quantities of sediment generated and deposited by the event along the valley upstream of the Mfolozi Floodplain. It is likely that not all of the sediment generated by the floods was transported to the floodplain, leaving a large amount of available sediment to be transported by subsequent floods.

Based on this analysis and in the absence of any dating of sediments, the chronology of flood events proposed from this study is presented as Table 5. There were 19 individual flood events indicated in the sedimentary record that correspond to the flood record provided by UCOSP. While not all the events are reflected at both cores, the sedimentary record nonetheless serves as a valuable source of historical flood data in the catchment owing to the presence of readily identifiable flood deposits in the record.

Table 5: Proposed flood event date, depth and flood peak label as identified in the Lake Futululu and South Lake cores

Futululu	**South Lake**	
Year	Year	Letter
	2014	A
2010	2010	B
2006	2006	C
1999	1999	D
1996	1996	E
1993	1993	F
1989	1989	G
1987	1987	H
1984	1984	I
1981		J
1977	1977	K
1963	1963	L
1957	1957	M
1953	1953	N
1941	1941	O
1925		P
1922	1922	Q
1913		R
1911		S

6.3.4 Mineral magnetic properties

Mineral magnetic signatures have been used in a variety of studies utilising sediment source tracing. Magnetic signatures have been shown to be reliable at differentiating between different sediment source types by geology. Pulley *et al.,* (2015) demonstrated the conservatism of mineral magnetic signatures in deposited sediments of the semi-arid Karoo region of South Africa, where many of the rock types which underlie the catchment of the Mfolozi River are present.

The mineral magnetic measurements of the sediment from the Lake Futululu core indicted sediment derived from sedimentary rocks. The values of the various parameters tended to plot within a large group, with no values that could be considered to immediately identify a sample as being derived from a different source. In the case of the Lake Futululu core, the most useful measurements proved to be X_{lf} as well as $X_{arm.}$ Both of these measurements strongly indicated the presence of weakly magnetic material such as that derived from quartzite, and specifically subsurface quartzite. The catchment of the Mfolozi River is underlain by quartzite towards the middle and lower reaches. The predominance of quartzitic material suggests that the depositing flood events were confined to the coastal regions of the catchment in terms of penetration into the catchment, where the largest quartzitic outcrops are concentrated in the catchment, rather than an event that started or penetrated deep into the interior of the region such as Cyclone Demoina and subsequent smaller storms.

The mineral magnetic measurements of the sediment from the South Lake core highlighted the effects of dissolution on magnetic grains, particularly on magnetic susceptibility and X_{arm} results. Below the level of the water table it was clear that dissolution of the magnetic grains had taken place, thus the only reliable results from these measurements corresponded with sediment up to a meter deep. SIRM results were less affected by dissolution and provided more reliable data for the entire core. The magnetic measurements of the South Lake core sediment suggested sedimentary rock was likely the source of the material in the core. The values did not indicate the presence of any material likely to have been derived from the weathering of igneous rocks.

Focusing more on the samples that were not affected by dissolution, there was greater variation in the type of sedimentary rock present than in the Lake Futululu core. Magnetic measurements indicated the presence of sandstone, mudstone and shale in higher quantities than the Lake Futululu core. Most of the magnetic values were quite low compared to database values, suggesting that the sediment was from subsurface sources. This is supported by the lack of ^{137}Cs in either core.

6.3.5 Correlation between magnetic signatures

This section discusses the correlation between different parameters related to mineral magnetics, primarily particle size, with the measures of environmental magnetism utilised as part of this study. This is because magnetic properties are influenced by particle size. Pulley and Rowntree (2016) have explored the relationship between particle size and different magnetic properties of Karoo sediments. The results of that study form the database for sediment source tracing for this section; multiple magnetic database values, corresponding to different particle size fractions, are provided as a basis of comparison for this study

The biplot of low frequency magnetic susceptibility and median particle size reveals that for both the Lake Futululu and South Lake cores, samples were generally similar to values for material weathered from sedimentary rock. The spread of Xlf values for both the Lake Futululu and South Lake cores plotted in a range between 0.10 and 1.00 x 10^{-6} $m^3.kg^{-3}$. The Lake Futululu values were within the range that would be expected for material derived from quartzite and shale (Figure 24). The South Lake sediment values also plotted within the range one would expect for material derived from quartzite and shale (Figure 25). A few samples were similar to values for subsurface sandstone, suggesting a sediment source in the upper reaches of the catchment where sandstone rocks predominate in the catchment (Figure 25).

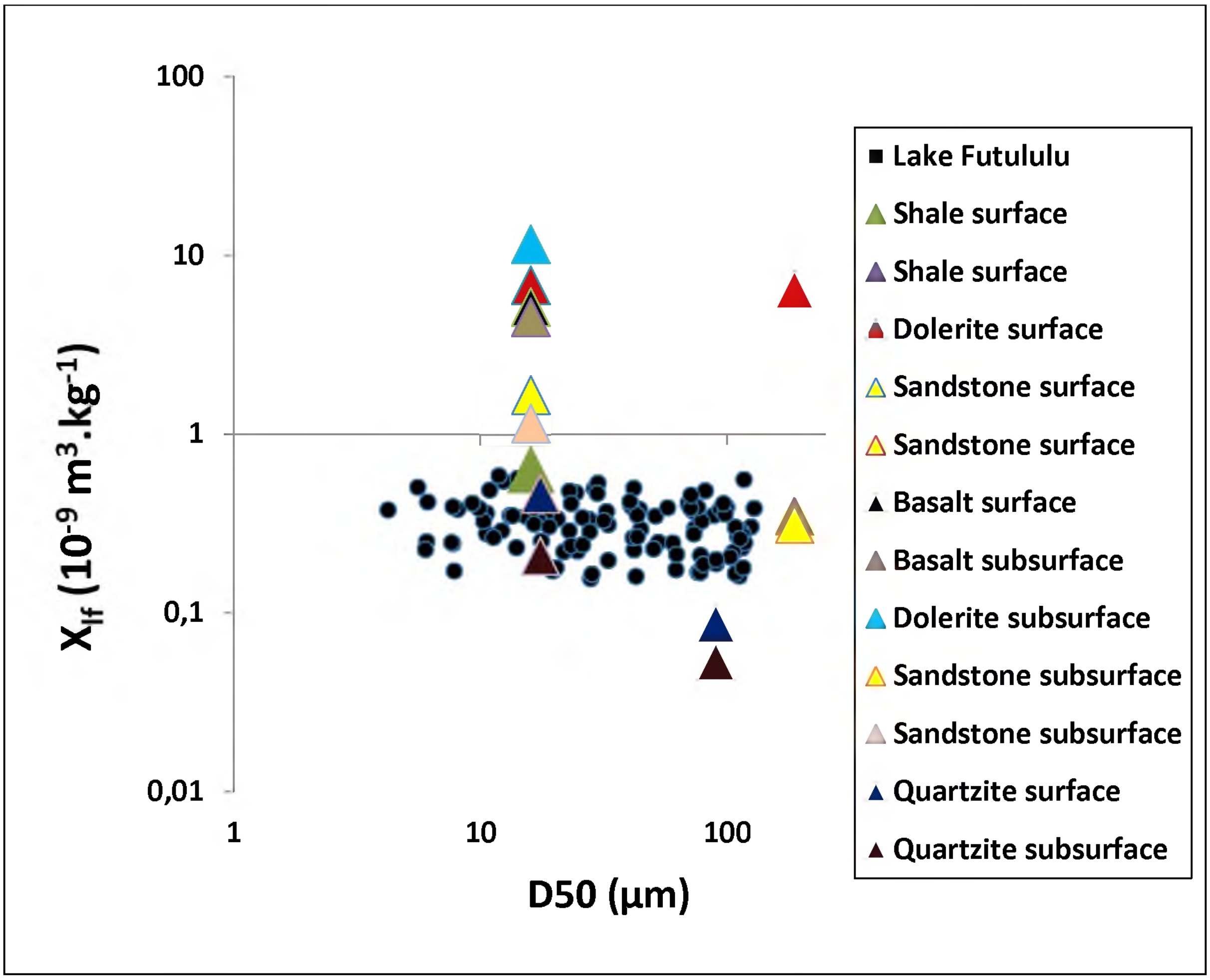

Figure 24: Variation in low frequency magnetic susceptibility with particle size of the Lake Futululu core with values for possible source material.

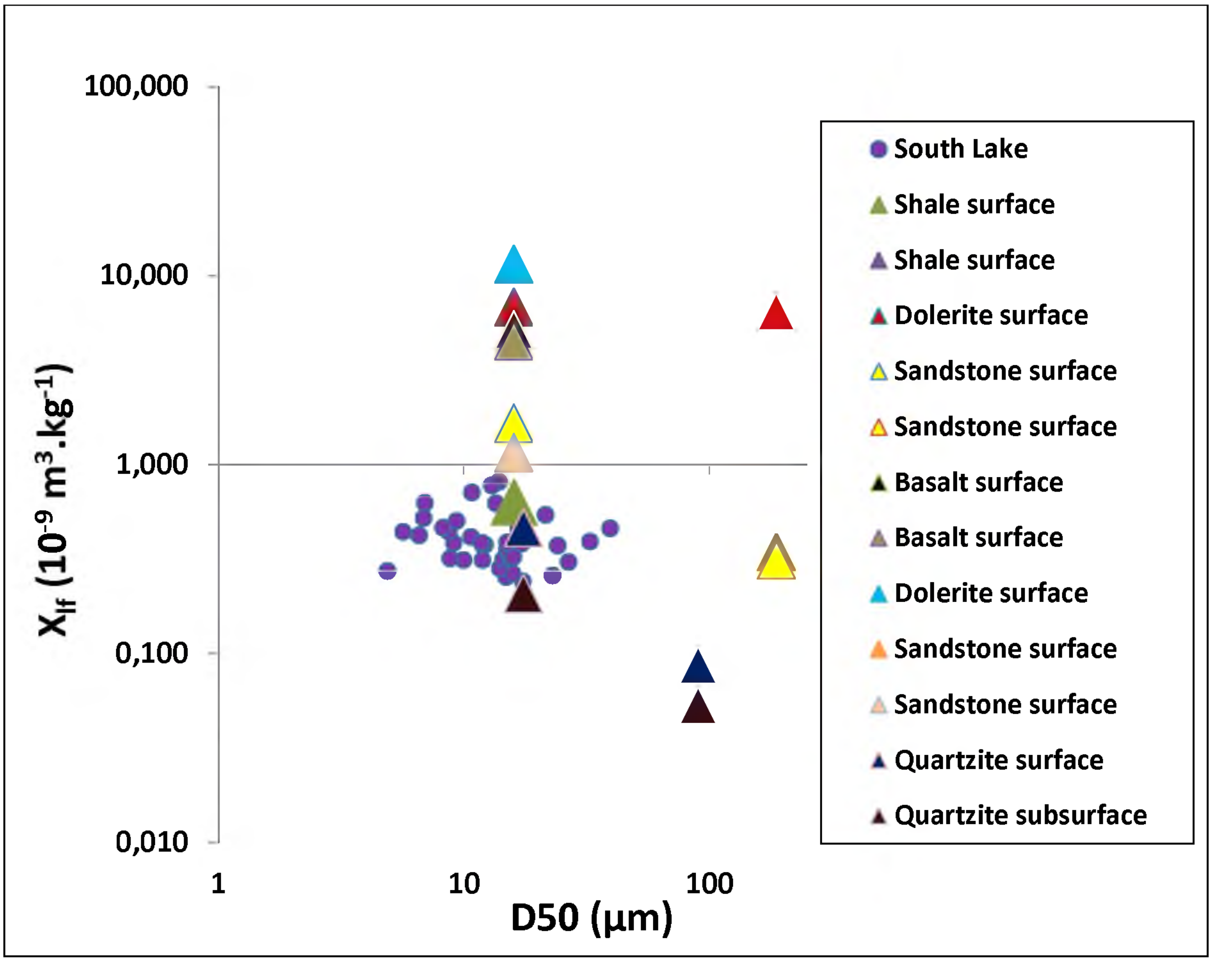

Figure 25: Variation in low frequency magnetic susceptibility with particle size of the South Lake core with values for possible source material.

The biplot of SIRM and median particle size values of the Lake Futululu sediments revealed no consistent relationship between the two parameters. The values of the Lake Futululu core were mostly evenly spread out, with no consistent grouping of SIRM values relative to the various particle size fractions. There were however some elevated SIRM values in the coarser sediment. These values were consistent with the values one would expect for material derived from sedimentary rocks, particularly subsurface quartzite (Figure 26).

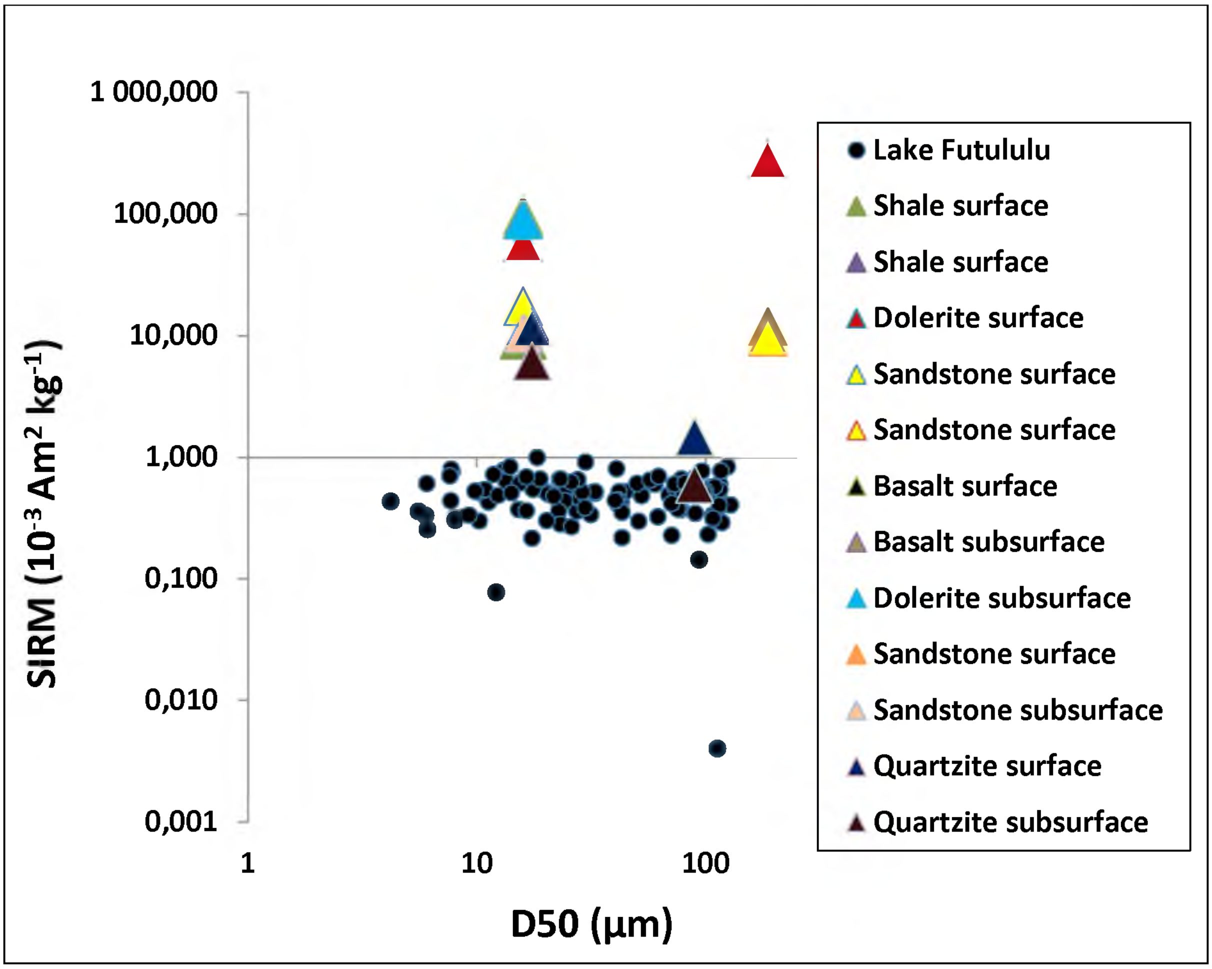

Figure 26: Variation in SIRM values with particle size of the Lake Futululu core with values for possible source material.

In the South Lake core elevated SIRM values were also observed in the coarsest sediment. The values plotted outside the range of any of the expected source material though, making it difficult to link particle size with SIRM values (Figure 27). This is likely due to the fine particle size of the core sediment compared to the particle size of the source samples.

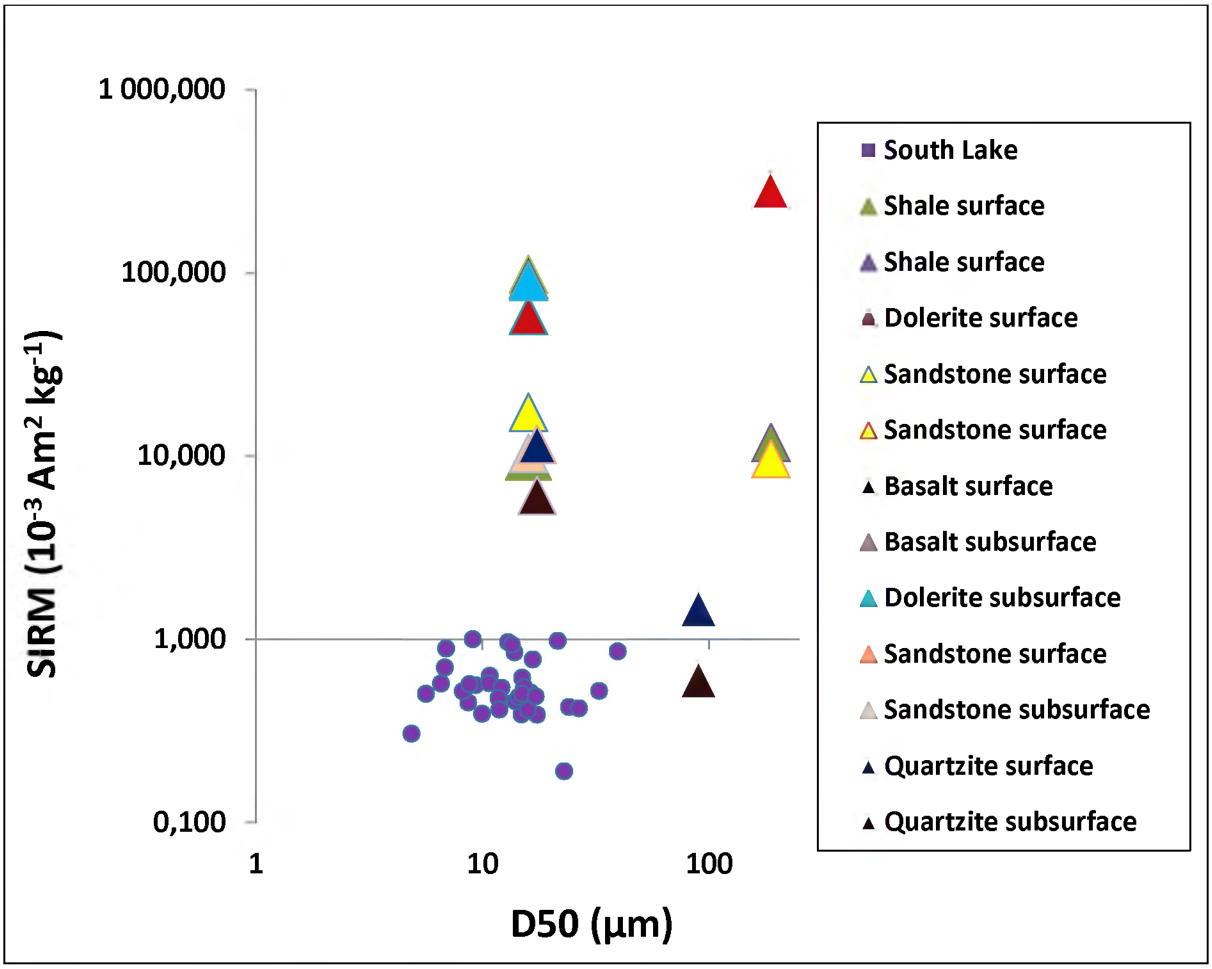

Figure 27: Variation in SIRM values with particle size of the South Lake core with values for possible source material.

The parameters X_{lf} and X_{arm} are both strongly affected by the fine-grained magnetite concentration of the sediment (Pulley and Rowntree, 2016). As such one would expect a strong correlation between the two parameters. The measured samples from the Lake Futululu core however displayed no consistent relationship between X_{lf} and X_{arm} (Figure 28). The values were evenly spread out, with no distinct relationship between variables. Most of the values plotted in the range one would expect for sedimentary material such as quartzite, shale and sandstone. The presence of material eroded from quartzite and shale suggests a source in the middle reaches of the catchment, whereas the material derived from sandstone suggests that some of the material in the core was eroded from the upper reaches of the catchment.

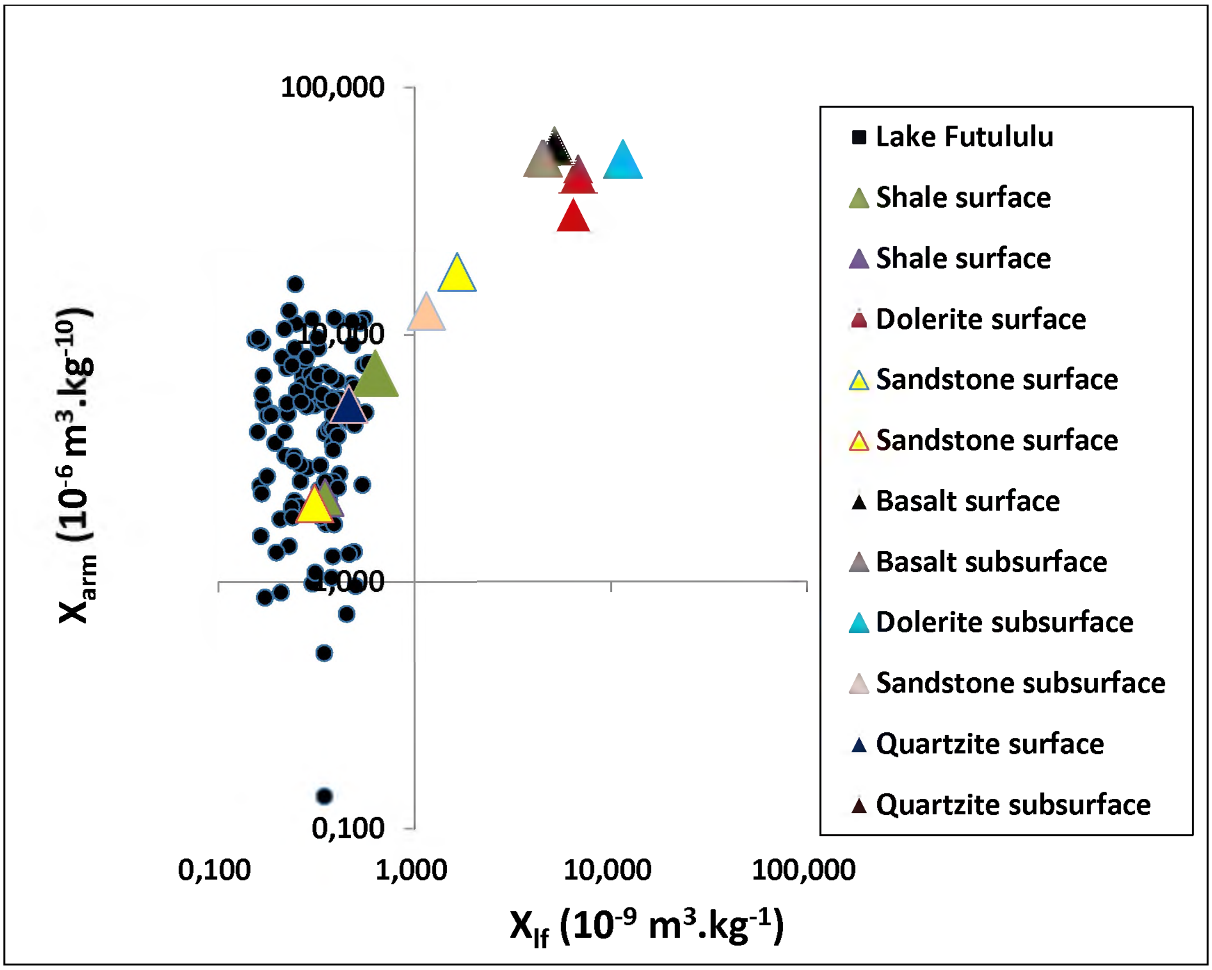

Figure 28: Relationship between X_{lf} and X_{arm} in the Lake Futululu core samples with values for possible source material.

The South Lake samples displayed a strong relationship between X_{lf} and X_{arm} (Figure 29). There was a near linear relationship of the two parameters; the samples with the lowest X_{lf} values also returned the lowest X_{arm} values, with the highest X_{lf} values returning the highest X_{arm} values. The reasonably strong relationship between the two parameters in the South Lake core stands in sharp contrast to the lack of any significant relationship between the same parameters in the Lake Futululu core. The South Lake samples all plotted outside the range one would expect for sedimentary material, particularly quartzite and shale (Figure 28). This is likely due to the high X_{arm} values in relation to X_{lf} for the core sediments.

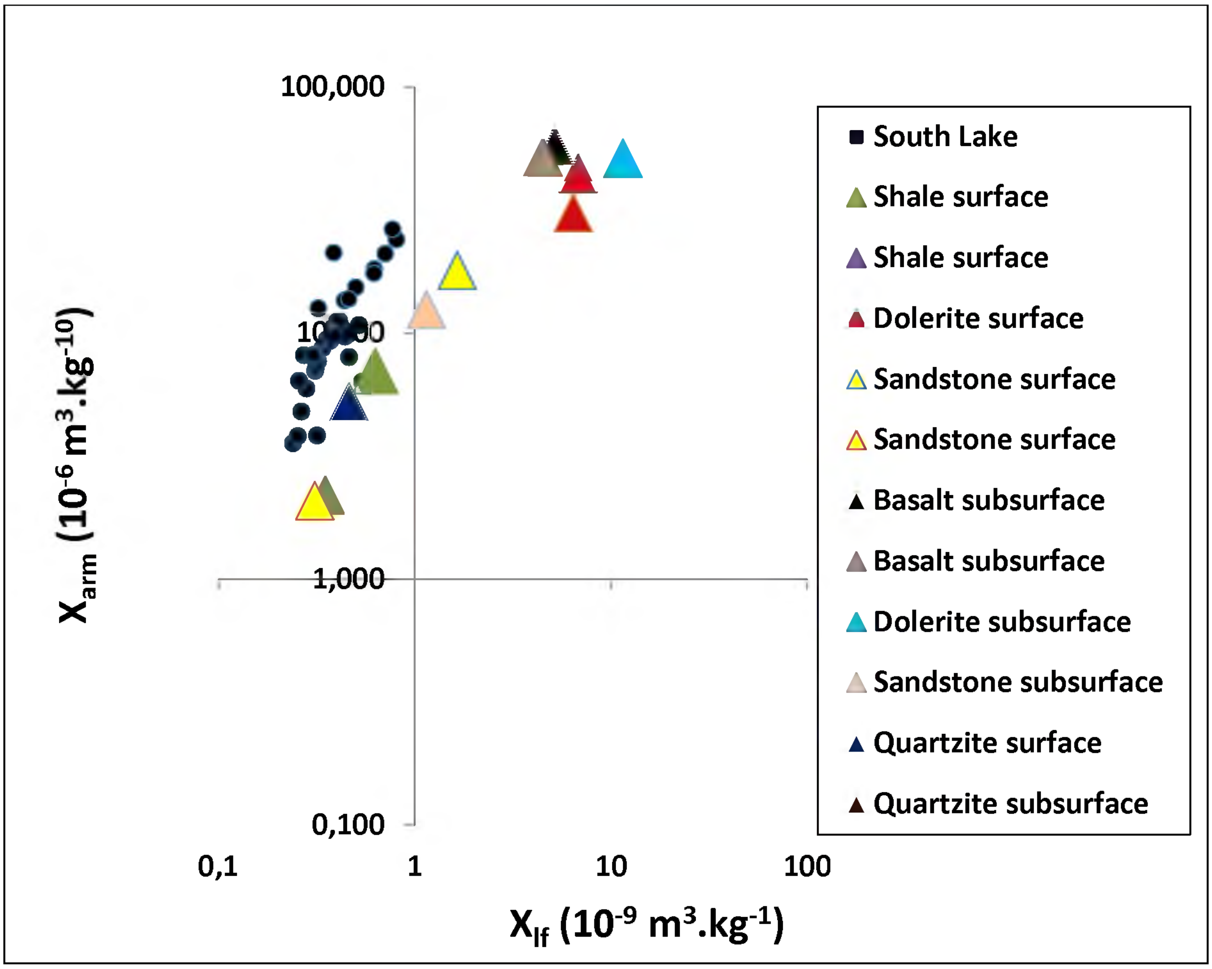

Figure 29: Relationship between X_{lf} and X_{arm} in the South Lake core samples with values for possible source material.

6.3.6 Mineralogy

For the Lake Futululu core the bulk mineral composition of the samples indicated quartzite was the dominant source rock, with traces of mudstone also present. This would suggest the depositing the flood events were concentrated around the middle to lower reaches of the catchment. This seemingly correlates with mineral magnetic signatures that also place the source of the sediment in the Lake Futululu core towards to the middle to lower reaches of the catchment.

Mineralogical analysis of samples from the South Lake core also suggested a sedimentary source rock for the bulk of the sediment in the core. Quartz was a dominant mineral in the samples from the South Lake core. However, the presence of the clay mineral vermiculite as well as the presence of orthoclase feldspar suggests that mudstone, shale and sandstone have also contributed to the sediment in the core. This would seemingly confirm some of the information provided by mineral magnetic measurements, which indicated the aforementioned sedimentary rocks as sources for the sediment in the core.

6.3.7 Deconstructing methods and results

This study utilised various analytical techniques to investigate the signatures of flood events in the sedimentary record. Each of these techniques offered advantages as well as drawbacks. Ultimately, the usefulness of sedimentary signatures varied between techniques.

The most straightforward analytical methods proved to be one of the most useful: analysis of the physical features of the sediment (particle size and organic matter content) proved useful in identifying flood events in the sedimentary record. However, effectiveness of this analysis was limited by the location and maximum depth of the core samples. The Lake Futululu core did not offer a high resolution indicator of flood events given that the post 1960 flood record was compressed into only the upper 1 m of the sedimentary core. However, the South Lake core seemed to offer a clear indication between depth in the core and the timing and magnitude of flood events. However, the depth of the core proved a limitation in respect of obtaining a record of flood events over even a period of 100 years.

The sediment tracing techniques were generally of limited success in tracing the source rocks of the sediment in the cores. Analysis of the mineral magnetic signatures of the sediment proved most useful as a sediment tracer, being able to differentiate between potential source rocks as well as providing additional information about the likely exposure of the rocks (surface or subsurface). This study also highlighted the importance of selecting the right magnetic measurements for analysis. Certain parameters proved limited in their usefulness due to the chemically unstable nature of the target minerals in flooded environments. Dissolution of the ARM carrying magnetic grains was a feature of the South Lake core, which effectively limited magnetic analysis to measurements of X_{lf} and SIRM. Future research utilising environmental magnetism for sediment tracing may have to consider the position of the water table and associated dissolution of certain magnetic grains when selecting magnetic measurements and the associated sampling locations.

Mineralogical analysis also proved useful as a sediment tracer. This technique is perhaps even more useful in differentiating between different types of parent material than environmental magnetism, as it is less affected by rapid mineral dissolution. This would help to avoid a high co-linearity, leading to artificial correlation of the results. This technique was perhaps limited by the nature of the sediment under analysis. The bulk of the material contained quartz, a ubiquitous mineral that hardly points to a unique rock type. But when combined with the presence (and absence) of other, more definitive rock forming minerals, this method proved a useful means of sediment source tracing. Though it was not specifically dealt with in this study, it is possible that having a mixture of markedly different magnetic minerals in a sample can mask the overall magnetic signature of the observed sediment. AS it happened with this study, most of the observed sediment samples did point definitively to one or another specific lithology.

Lastly, the fallout radionuclides proved unsuitable for sediment tracing in this environment. The very absence of any Caesium in either of the two cores did indicate that the sediment was predominantly sourced from the subsurface source material. While a few studies have demonstrated the usefulness of fallout radionuclides for work looking at sediment tracing and sediment accumulation rates, it should be stressed that fallout rates of radionuclides such as Caesium were much lower in the southern that the northern hemisphere as the majority of nuclear testing that formed this radionuclide took place in the northern hemisphere. Overall, this analytical technique proved the least useful as a sediment source tracer.

Chapter 7: Conclusion

The aim of this project was to construct a record of major flood events on the Mfolozi River floodplain over the last century and determine their source using hydrological records. To that end, various literature sources were consulted to design a project capable of achieving this aim. The results of project and the implications of these results have been outlined in previous sections of this thesis. This chapter examines the key findings of this project within the context of published literature. The design of the project is critically examined before the remaining gaps in knowledge are explored and recommendations for future research are highlighted.

7.1 Key Findings

The analysis of hydrological records from the Mfolozi River catchment suggested that large floods are a reoccurring feature in the region; 39 large flood events have occurred in the region over the past century. Additionally, analysis of discharge data from different flow gauging stations around the catchment provided information about the penetration of recent flood events in the catchment. A key finding of this study was that there were differences in the ratio of discharge in the upper reaches of the catchment to discharge on the Mfolozi floodplain that allows one to distinguish between coastal and inland flood events.

The analysis of flood signatures in the sedimentary record of the Mfolozi River floodplain suggested that flood events can be traced using a variety of analytical techniques focusing on physical as well as mineralogical attributes of the sediment. Particle size and organic matter were found to be useful when identifying individual flood deposits, particularly in the South Lake core which was further from the trunk Mfolozi River than the Lake Futululu core. Sediment tracing also proved to be useful in this study, allowing flood deposits to be traced to certain parts of the catchment. This made it possible to infer the penetration of the of the flood event, allowing for a link to be made between the flood signatures in the sedimentary record and the record of flood activity in the catchment provided by UCOSP and the DWA.

From a sedimentary perspective there were two findings relating to unsuccessful sediment tracing techniques. The first was that certain mineral magnetic measurements are significantly affected by dissolution below the water table. This limited the range of magnetic measurements that could be reliably used to draw conclusions. The second finding was the unsuitability of the environmental radionuclides for this particular study. This was due to the predominantly subsurface nature of the observed sediment. Radionuclides have been used in a numerous studies looking at a variety of environments. Unfortunately radionuclide dating proved to be less useful in this particular study, possibly also due to dissolution of the relevant radionuclides or the very recent nature of the deposits examined.

Ultimately this study did achieve the stated aim. However, there are certain areas where future projects may be able to improve on the experimental design so as to expand on the work that has been done as part of this project such that remaining gaps in knowledge can be resolved.

7.2 Remaining gaps in knowledge: Recommendations for future research

From a hydrological perspective, there remain gaps in the knowledge pertaining to where in the catchment the rainfall that produced each flood likely fell. As outlined in previous sections, a contributing factor to the difficulty in reconciling rainfall and discharge data was difference in recording methods employed by the South African Weather Bureau in recording rainfall and those employed by the DWA in recording and calculating discharge. It is recommended that future research endeavour to more deeply explore the relationship between the two parameters, keeping in mind that there remain significant gaps in the recording history of the two parameters due to such factors as equipment failure. Resolving such issues presents further challenges; however without a clear understanding of the relationship between these parameters the task of narrowing the source of a given flood event to a specific area of the catchment using hydrological analysis is potentially compromised.

From a sedimentary perspective, a major gap in the knowledge at present is the long term record of flood events in the sedimentary record. Due to large flood events such as Cyclone Demoina and the large volume of sediment associated with such events, future research may have to very carefully consider the location of sediment coring on the floodplain. Sediment cores retrieved at a distance even greater than that of the South Lake core relative to the main stream of the river may reveal a much longer term record of flood deposits, making the task of matching the sedimentary record to the hydrological record of floods much more practical and reliable. Deeper sediment cores may also allow for longer term flood records to be accessed, although one has to consider the position of the water table and the effect this may have on certain minerals if sediment tracing via environmental magnetism is to be employed. This study has noted the effects of dissolution on mineral magnetic grains below the water table. Future research should plan for the effects of dissolution by perhaps utilising more measurements of environmental magnetism that are not as easily affected by dissolution. Finally, while radionuclides have been demonstrated as being reliable in a variety of environments, this particular study has highlighted the limitations of such a tool when dealing with sediment derived from predominantly subsurface sources. Future research may have to employ robust experimental designs that allow for other methods of source tracing to be utilised in the event that radionuclide levels are below the minimum levels of detection. This is especially true in the southern hemisphere due to the generally low levels of fallout compared to the northern hemisphere.

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