ASSESSING SEDIMENT CONNECTIVITY AT THE HILLSLOPE, CHANNEL AND CATCHMENT SCALE

Report to the

Water Research Commission

by

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Executive Summary

Chapter 1. Introduction: context and motivation

Connectivity is being embraced increasingly by hydrologists, geomorphologists and ecologists as a concept that allows integration of landscape structure and function at a number of time and space scales. Connectivity allows the free flow of energy and materials through the system and, as a result, mutual adjustment between system components. It is counterbalanced by storage sites, which allow material to be retained in the system. Ecologists, hydrologists and geomorphologists have all embraced the idea of connectivity as described in the literature review.

The research was conducted in the catchment of Thina River (Tertiary catchment 34), lying in the headwaters of the Mzimvubu catchment, located in the former homeland of the Transkei where subsistence farming has been practiced for many years. A subcatchment of the Thina, the Vuvu, was investigated in detail. Two changes to connectivity are evident in the research area. First erosion dongas and incised cattle tracks are widespread on hillslopes in the area, increasing hillslope-channel coupling and delivery of sediment to the valley floor and channel. Second the main channel shows evidence of incision into the valley floor, resulting in a reduced connectivity between the channel and former flood zones. The research findings presented in this report indicate that there have been two phases of incision, one occurring within a geological time scale of thousands of years and one within the recent past (50 years) pointing to anthropogenically induced causes.

In order to interpret sedimentary features on the valley floor in terms of catchment scale sediment dynamics it was necessary to identify sediment sources and provide a chronology of sediment deposition. Sediment fingerprinting techniques based on mineral magnetism were used to identify sources of sediment deposited in sink areas. Radionuclides (Cs 137 and Pb210) were used to date recent sediment (less than 100 years) deposited on flood benches, while Optically Stimulated Luminescence (OSL) provides a dating tool applicable over a range of time scale from 300 to 100,000 years.

The research has provided insight into the geomorphic processes that influence water related ecosystems through their effect on fluvial structures and the functional relationships between the channel and adjacent valley floor. By disentangling natural processes from human induced change the research has potential to inform the assessment of the geomorphic Reference condition for similar upland rivers that have been subject to incision in the past and will provide guidance to interventions that aim to restore natural ecosystem function. It will thus contribute to the sustainable management of upland catchments that comprise the main water supply areas of the country. By focussing on the dynamics of sediment storage and reworking of stored sediment the research findings will also address the need expressed by Msadala et al. (2010) to incorporate sediment storage into sediment yield models.

The research proposal set out eight aims or objectives as follows.

1. Classify, map and characterize potential sediment sources on hillslopes.
2. Map present-day hillslope-valley floor-channel coupling.
3. Classify, map and characterize valley floor sink zones.
4. Trace sediment sources for sediment in sink zones.
5. Provide a chronology of sedimentation and valley floor incision.
6. Monitor and model present-day hydrological connectivity between channel and valley floor sediment sinks (flood plain and flood benches).
7. Measure suspended sediment load for the two study rivers.
8. Develop a connectivity framework describing sediment erosion, transport and storage processes in the study catchments.

A synthesis of the main findings with respect to the scientific objectives of the project is presented in this report The most relevant results on changes to hillslope-channel and channel-valley fill connectivity are integrated in this synthesis to form a broad perspective of how landscape connectivity has changed in the high rainfall mountainous headwaters of the northern Eastern Cape Province, South Africa. A methodological framework based on methods used in this research is presented as a guide to effective rehabilitation.

Chapter 2. Connectivity concepts and frameworks

Chapter 2 contains a review of international and national literature on connectivity concepts as used by ecologists, hydrologists and geomorphologists. It compares connectivity thinking at the river reach and catchment scale, provides a discussion on the role of sediment stores, considers how spatial scales can be integrated, the importance of the time dimensions, and ways in which spatial and temporal scales can be linked.

A second section examines the drivers of connectivity that are relevant to the Vuvu catchment. A final section considers the application of connectivity frameworks to ecosystem assessment.

Chapter 3. A methodological framework for assessing connectivity at the catchment scale

Chapter three describes the methods used to describe and analyse connectivity in the Vuvu. Selected results are presented in order to illustrate the methods. An important component of any geomorphic assessment is the identification, classification and mapping of key features. In this case erosion sources, sediment pathways and sediment sinks were mapped separately. The sediment sources included fields, sheet erosion, gullies, tracks and roads. They were further characterised according to their relationship to catchment variables such as geology, slope and aspect. The intersection between sources and pathways was analysed in a GIS as a measure of connectivity. The main sinks were identified as flood benches adjacent to the main channel. Sinks were characterised in terms of the particle size distribution of sediment. A sediment chronology was determined using radionuclides and Optical Stimulated Luminescence (OSL).

Hillslope-channel connectivity was assessed firstly by analysing the intersection of sediment sources by pathways and secondly by determining increases in hillslope drainage density caused by gullying relative to that due to the natural stream network.

Channel-valley floor connectivity was assessed by determining the frequency of overbank flooding onto lower and higher flood benches. This involved a combination of transect surveys, flow monitoring, hydraulic modelling and hydrological modelling.

There were few barriers observed that affected longitudinal connectivity; an analysis of longitudinal connectivity was not conducted.

Catchment scale connectivity was integrated using sediment tracing to match sediment sources to sinks. Tracing was applied to both flood benches and suspended sediment sampled during storm events. Environmental magnetism was an effective tracer due to marked differences between the geology of the upper and lower catchment. Elliot Formation mudstones on the lower catchment were found to contribute more sediment per catchment area relative to the Drakensberg Formation basalts in the upper catchment. This was in line with calculations of sediment loss from hillslopes.

Chapter 4. Synthesis of research on connectivity in the Vuvu catchment

A synthesis of the main findings with respect to the scientific objectives of the research is presented in chapter 4. The most relevant results relating to the description of hillslope-channel and channel-valley fill connectivity are integrated to form a broader perspective of how landscape connectivity has changed in the high rainfall mountainous headwaters of the northern Eastern Cape Province, South Africa. In each section the implication of the change in landscape connectivity on sediment dynamics is emphasised and the contribution of the work to the field of geomorphic analysis of river systems and sediment dynamics is highlighted. A conceptual model of altered landscape connectivity is presented, together with research opportunities and management recommendations.

Chapter 5. Application of a connectivity to catchment management

Chapter 5 presents a framework that outlines a recommended approach and associated methods that could be applied in a management context such as catchment rehabilitation. The methods described in this report were used in a research context and it is suggested that methods better related to the management context still need to be developed.

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Dr Christo Marais	Department of the Environment
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Table of contents

List of Tables

List of Figures

1 Introduction: context and motivation

Connectivity is being embraced increasingly by hydrologists, geomorphologists and ecologists as a concept that allows integration of landscape structure and function at a number of time and space scales (Parson et al., 2015). A well connected landscape allows for the free flow of energy and materials through the system and, as a result, mutual adjustment between system components. Connectivity is counterbalanced by storage sites, which allow material to be retained in the system. Connectivity is thus well suited to describe process response systems in catchments and can be used to assess the health of water related ecosystems. The ecologist Ward (1989) introduced the idea of four-dimensional connectivity that acts in the longitudinal, lateral and vertical directions through time. Kondolf et al. (2007) argued that hydrological connectivity is the defining feature of all riverine ecosystems and ascribe river degradation to changes in connectivity and stress the need to restore the natural connectivity regime. Geomorphologists Harvey (2002), Hooke (2003) and Fryirs et al. (2007) embraced connectivity as a way to conceptualise sediment dynamics, stressing the importance of both connectivity and sediment storage. Building on geomorphic concepts of connectivity, Rowntree (2013a) recommends that the Present Ecological State (PES) of a river's geomorphology be evaluated with respect to both increases and decreases in connectivity. Landscape connectivity can also serve as input to sediment and hydrological modelling. Furthermore, the structural understanding of sediment pathways can be used to plan erosion rehabilitation efforts.

Increased connectivity increases the efficiency of water, sediment and nutrient transport. This results in higher sediment loads in rivers and other water bodies and flashier flows during and shortly after rainfall events. These higher energy flows will erode water courses and wetland areas, reducing the capacity of these features to retain water and sediment. Water is no longer retained in the landscape and the slow release of water after rainfall events is decreased. Aquatic ecosystems that are dependent on slow seepage water are likely to decline in ecosystem function and integrity.

Where connectivity along a channel is decreased through reservoir construction, sediment and water transport will be reduced as well as the frequency of overbank flooding. This will have severe consequences for downstream reaches that will not receive the necessary water, sediment and nutrient supplies. For example, reductions in sediment loads could induce channel erosion. Reservoir construction could also have a positive influence on the downstream system by storing some of the sediment and nutrients that have been augmented anthropogenically.

Changes to flow and sediment resulting from changes to connectivity can have a significant effect to both instream and riparian habitat. Increases in coarse sediment load are associated with wider river channels that will have effects on the depth, temperature, sediment composition and diversity of instream habitat. Deposition of fine sediment on the channel bed reduces open habitat between gravels and cobbles (Soulsby et al., 2001). Furthermore, energy thresholds for instream organisms might be crossed more frequently during high flow events. Riparian areas are sensitive to the magnitude and frequency of overbank flooding. On the one hand reductions in overbank flooding are seen as a major cause of floodplain degradation due to infrequent recharge of groundwater, floodplain sediment and lower nutrient inputs (Kondolf et al., 2007). On the other hand increased flooding by high energy flows may cause more frequent channel change in the form of meander cut-offs and avulsions.

The concept of connectivity has only recently featured in geomorphological studies in South Africa, such as the Geomorphological Driver Assessment Index (Rowntree, 2013a), a review of connectivity in South Africa (Rowntree, 2012), and research in KwaZulu-Natal (Miller et al., 2013; Le Roux et al., 2013; Grenfell et al., 2014) and in the Karoo (Foster et al., 2012; Rowntree and Foster, 2012; Rowntree, 2013b; Grenfell et al., 2014) which has begun to address the need for an holistic understanding of sediment transfer processes. There is a need for research on sediment connectivity in other, often contrasting, geographical localities within South Africa. This study aims to apply and develop the connectivity concept in a new geographical locale, the headwaters of the Mzimvubu catchment, where connectivity is thought to have been altered through land use practices.

As river systems and their catchments function as one large interlinked system, changes in connectivity in the high rainfall headwaters will have knock-on effects throughout the system, ranging from the top of the headwaters right through the freshwater system to the marine environment. One such headwater river is the Vuvu, a small tributary of the Thina (tertiary catchment 34), lying in the headwaters of the Mzimvubu (Figure 1.1). The Mzimvubu catchment is located in the former homeland of the Transkei where subsistence farming has been practiced for many years. The catchment makes a significant contribution to the regional surface water resource (as yet subject to limited development) but is also reputed to have high sediment loads resulting from a combination of high rainfall intensities, steep slopes, erodible soils and land use practices conducive to erosion (Blignaut et al., 2010; Watershed Services Project, 2010; Le Roux et al., 2015). The mudstone geology of the lower catchment (Figure 1.2) is notorious for hosting highly erodible soils (Laker, 2000). There is pressure to develop both the land and water resources in the catchment to improve local wellbeing and to augment the national water supply. The Ntabelanga dam is planned for the Tsitsa River, a tributary adjacent to the Thina, as part of a regional development initiative – the Mzimvubu Water Project. Sedimentation is seen as a threat to the lifespan of this dam.

Two subcatchments of the Thina River were initially identified for in-depth research into the relationship between sediment dynamics and water related ecosystems, using connectivity as the conceptual framework for research. However, the complex scope of the research, that adopted a range of approaches to researching connectivity, meant that only one catchment, the Vuvu, was investigated in detail. The location and general topography of the study catchment are shown in Figure 1.1, the catchment geology in Figure 1.2. Two changes to connectivity are evident from field observations in the research area. First, erosion dongas and incised cattle tracks are widespread on hillslopes in the area, increasing hillslope-channel coupling and delivery of sediment to the valley floor and channel. Not all dongas, however, are continuous (i.e. they are disconnected from the main channel) and a number show signs of stabilising. Second, the main channel shows evidence of incision into the valley floor, resulting in reduced connectivity between the channel and lateral flood zones. Wetland soils can be seen as distinct horizons in many channel banks, indicating that previously the river flowed at a higher level and frequent overbank flooding maintained at least localised wetland systems.

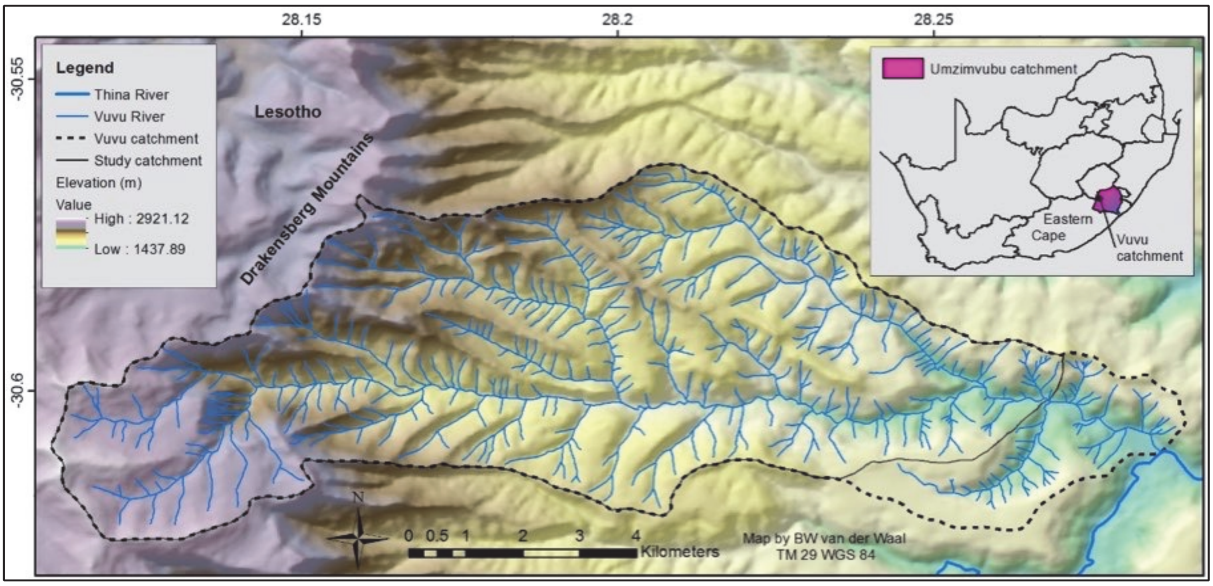

Figure 1.1: The topography and drainage network of the Vuvu catchment. Dashed line indicates catchment boundary, grey line indicates catchment boundary above lowest stage monitoring site. The location of the catchment in relation to South Africa is indicated on the inset map.

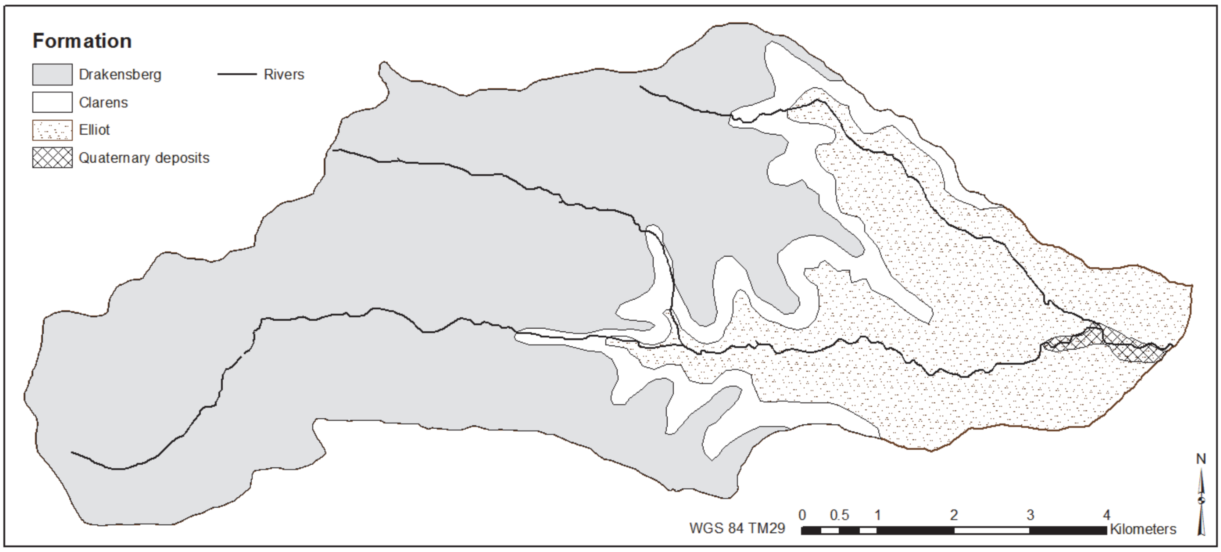

Figure 1.2: The geology of the Vuvu catchment above the lowest stage monitoring site (after .De Decker, 1981)

Incision is likely to be the result of a change in the balance between sediment delivery, valley floor resistance and stream power. The causes and timing of this incision are not known, however. Incision may be a natural process resulting from long term climate variability, accompanied by shifts between erosional and depositional phases on the valley floor, or from breaching of a downstream barrier as postulated by Tooth et al. (2002) for highveld rivers. In either of these cases incision is likely to have taken place prior to human induced disturbance. Incision may also be due to anthropogenically induced changes to catchment hydrology and sediment processes, in which case incision should be a recent phenomenon. The research findings presented in this report have shed further light onto these processes, indicating that there have been two phases of incision, one occurring within a geological time scale of thousands of years and one within the recent past (50 years), pointing to anthropogenically induced causes.

In order to interpret sedimentary features on the valley floor in terms of catchment scale sediment dynamics it was necessary to identify sediment sources and provide a chronology of sediment deposition. Sediment fingerprinting techniques are being used increasingly to identify sources of sediment deposited in sink areas such as wetlands, reservoirs and floodplains (cf Hatfield & Maher, 2009) and have been used successfully in the Karoo of South Africa (Rowntree & Foster 2012) and in the Mkuzi floodplain (Humphries et al., 2010). Similar techniques have been used in a pilot study in the Thina catchment; preliminary results indicate that gully erosion is not necessarily the main source of present day sediment being transported down the river, supporting a gully stabilisation hypothesis (Rowntree et al., 2012, Mzobe 2013). Radionuclides (Cs-137 and Pb-210) have been used to date recent sediment (less than 100 years) deposited in farm dams in the Karoo (Foster et al., 2012), while Optically Stimulated Luminesence (OSL) provides a dating tool applicable over a range of time scale from 300 to 100,000 years. Rodnight et al. (2005) have demonstrated the application of OSL dating to a fluvial feature of the Klip River, South Africa. Facilities for both dating methods and for tracing using environmental magnetism are now available in South Africa (at Rhodes and Witwatersrand Universities) and were used in the research to develop sediment chronologies and to identify links between sediment sources and alluvial sedimentary features.

The research has provided insight into the geomorphic processes that influence water related ecosystems through their effect on fluvial structures and the functional relationships between the channel and adjacent valley floor. By disentangling natural processes from human induced change the research has potential to inform the assessment of the geomorphic Reference Condition for similar upland rivers that have been subject to incision in the past and will provide guidance to interventions that aim to restore natural habitat template and ecosystem function. It will thus contribute to the sustainable management of upland catchments that comprise the main water supply areas of the country. By focusing on the dynamics of sediment storage and reworking of stored sediment, the research findings will also address the need expressed by Msadala et al. (2010) to incorporate sediment storage into sediment yield models.

The research proposal set out eight aims or objectives as follows.

1. Classify, map and characterise potential sediment sources on hillslopes.
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4. Trace sediment sources for sediment in sink zones.
5. Provide a chronology of sedimentation and valley floor incision.
6. Monitor and model present-day hydrological connectivity between channel and valley floor sediment sinks (floodplain and flood benches).
7. Measure suspended sediment load for the two study rivers.
8. Develop a connectivity framework describing sediment erosion, transport and storage processes in the study catchments.

A review of connectivity literature, detailed methodology and a synthesis of the main findings with respect to the scientific objectives of the project are presented in this report. A full description of research methods and findings is presented in the thesis by van der Waal (2014), available on line from the Rhodes University library. The most relevant results on changes to hillslope-channel and channel-valley fill connectivity are integrated in this synthesis to form a broad perspective of how landscape connectivity has changed in the high rainfall mountainous headwaters of the northern Eastern Cape Province, South Africa. In each section the implication of the change in landscape connectivity on sediment dynamics is emphasised and the contribution of the work to the field of geomorphic analysis of river systems and sediment dynamics are highlighted. A conceptual model of altered landscape connectivity is presented, together with suggestions for further research and management recommendations for rehabilitation in the Vuvu. The final chapter presents a framework for applying connectivity within a management context. This framework draws on experience from the Vuvu, which provided an opportunity for in-depth research at a level generally beyond the scope of most management situations. The framework provides a set of guidelines which have not been tested in different management context outside the Vuvu.

2 Connectivity concepts and frameworks

2.1 The evolution of geomorphic thinking around connectivity

Landscape development is influenced by the sediment transfer processes active in the landscape, themselves a reflection of the degree of hydrological and sedimentological connectivity (Harvey, 2002). On a global scale the majority (83%) of continental erosion is currently related to high elevation watersheds (Roy and Lamarre, 2011) due to high energy conditions associated with steep slopes, high drainage densities and erosive rainfall, all conducive to a highly connected landscape (Montgomery and Dietrich, 1988; Roy and Lamarre, 2011). Sediment export is accelerated in many catchments as a result of human activities that further increase connectivity (Womack and Schumm, 1977; Brierley and Murn, 1997; Walling, 1999). The entrained sediment ends up in river systems, leading to the export of valuable soil, highly turbid water, infilling of reservoirs and degradation of river health (Francke et al., 2008; Sandercock and Hooke, 2011; Boardman, 2013). Research effort should be invested in understanding current and past landscape processes in order to conserve land and water for the future (Warner, 2006).

Over the past 150 years various concepts and models were developed to study fluvial landscapes in order to answer basic questions such as 'why does the river look the way it does?' and 'what would it look like in the future?' Grant et al. (2013) gave a history of geomorphic concepts and proposed that concepts and models are mainly based on either physics, encompassing concepts such as hydraulic geometry (Leopold and Maddock, 1953) and frequency/magnitude (Wolman and Miller, 1960), or on form, such as 'the fluvial system' (Schumm, 1977) and channel classification (Rosgen, 1996). Both are useful to study river systems. Both departure points, whether physics or landform based, have their own limitations as discussed in detail by Dollar (2000) and Grant et al. (2013). Furthermore, geomorphologists and hydrologists have addressed some of the land and water problems with a reductionist approach by studying processes at either the hillslope or the river reach scale rather than taking an integrated catchment approach (Michaelides and Wainwright, 2002). It is proposed that connectivity can provide a more holistic framework for researching fluvial landscapes.

Significant earlier work by geomorphologists, e.g. Leopold and Maddock (1953), Chorley (1969); Chorley and Kennedy (1971) and Schumm (1977), did not address connectivity per se, but did so implicitly. Frequently the core question revolved around sediment delivery and sediment budgets, which came with various short comings related to sediment transport processes over various temporal and spatial scales (Parsons et al., 2006; de Vente et al., 2007; Hinderer, 2012; de Vente et al., 2013). These erosional, transport and depositional processes change with changes in scale and is influenced by factors such as land cover, geology, climate, etc. which are variable over time (de Vente et al., 2007). Since the 1990s the concept of connectivity has developed as a unifying approach that allows geomorphologists to explore the internal structure and function of sediment dynamics at a range of spatial and temporal scales (Fryirs, 2013). Structure refers to the spatial layout of the various physical linkages, whereas function refers to the processes responsible for sediment movement. This connectivity concept has enabled an integrated catchment approach that embraces both physics- and form-based concepts. In a recent review of the connectivity concept, Fryirs (2013) identified 'thresholds of stability at various scales' as the main shortcoming for understanding sediment connectivity and its application to predict the accumulated future changes related to environmental change.

As connectivity will be used as a conceptual framework for this study, the key literature related to the connectivity framework and the main factors influencing connectivity, such as magnitude, frequency, vegetation cover, gully development and incision, will be reviewed.

2.2 Concepts and definition

2.2.1 *Introduction*

Connectivity refers to the pathways that link different landscape components at a range of scales from a small area on a hillslope to an entire catchment. Connectivity pathways transfer energy and material between components, which themselves can act as stores, or sinks, for the transferred material. In the context of this project, two types of material are important, water and sediment. Water is the driver of sediment transport whereas the erosion and deposition of sediment results in changing landscape- and, consequently, river morphology.

Two types of connectivity have been identified (Parsons, 2015), functional and structural connectivity. Functional connectivity refers to the process of transfer and is event dependent. It is therefore temporarily variable. Structural connectivity refers to the physical pathways that connect landscape components such as river channels or erosion gullies. Structural connectivity is therefore the spatial expression of connectivity and is independent of events. Geomorphic process, however, will act to change structural connectivity over time. Authors who have recently reviewed connectivity concepts from a geomorphological perspective include Bracken and Croke (2007), Michaelides and Chappell (2009), Lexartza-Artza and Wainwright (2009) and Bracken et al. (2015).

Landscapes can be described as consisting of sediment source, transfer and sink zones (Schumm, 1977; Harvey, 2001). The source zone relates to areas in the catchment that supply sediment to downstream areas through processes for example of surface erosion or mass movement. The catchment surface acts as the main source zone in most environments. Sink zones are the areas where deposition occurs. They may act as temporary stores of sediment, such as channel bars, or more permanent sinks that form long-term landscape features such as alluvial fans or floodplains. All sinks can be reworked and become sediment sources, so the distinction becomes blurred. The extent to which sediment is transferred between sources and sinks depends on the connectivity within the system.

The effective distance between a source and sink depends on the nature of the transfer zone that represents the connectivity link. On a hillslope, mobilised sediment might be deposited within a relatively short distance if the transfer linkage or connection is ineffective. However, where the link is more effective, sediment can be transported to the bottom of the slope or to the river channel where it may be deposited as lateral bars or on the floodplains or transferred lower downstream, depending on the effectiveness of the transfer process (Harvey, 2001). The general trend is that only a small proportion of eroded sediment will make it to the bottom of the catchment as sediment is deposited along slopes and valley bottoms (Walling, 1983). This 'broken process' is the basis of the sediment delivery ratio used to relate catchment sediment yield to hillslope erosion rates.

The following discussion begins with a review of connectivity concepts at different landscape scales from the river reach to the catchment. Connectivity acts to transfer sediment between stores, the dis-connectivity afforded by these stores is therefore an important consideration which is discussed next. This in turn is related to the interplay of stability thresholds and the frequency-magnitude signature of applied energy, which determine the temporal dimension of connectivity.

2.2.2 *Connectivity at the river reach scale*

Ward (1980) recognised hydrological connectivity as being an important driver of river ecosystems. He recognised four dimensions of connectivity – longitudinal, lateral, vertical and temporal. Although water was the main 'material' being transferred between landscape components, the sediment and nutrients carried by that water were also an important consideration.

Longitudinal connectivity refers to the transfer of material down the length of the river channel. At the catchment scale it relates to the connectivity between source zones in the headwaters to sink zones in the lowland floodplains. We normally think of transfers being in the down-river direction, but can they also be in an upstream movement as in fish migration. Natural barriers to sediment movement include rock steps, valley constrictions and alluvial fans (Fryirs et al., 2007). These all slow down sediment transfers and result in upstream accumulation of sediment on the valley floor, forming local sink zones. At the reach scale transverse bars of coarse sediment can also act as natural barriers to sediment movement (Hooke, 2003). Anthropogenic barriers include the extreme example of major dams and smaller barriers such as weirs and causeways.

Lateral connectivity refers to the transfer of water and sediment out of the channel on to the floodplain. It is therefore linked to maintaining the structure and function of the riparian zone. A number of South Africa studies have demonstrated the ecological importance of connectivity between flows and the riparian zone (cf. van Coller et al., 1997; van Coller et al., 2000, Boucher, 2002; Sieben and Reinecke 2008; Reinecke et al., 2015). Lateral connectivity can be measured in terms of the frequency of overbank flooding, which in turn depends on the magnitude-frequency distribution of flows and the channel capacity. Upstream barriers (for example a dam) that reduce the frequency of "bankfull" floods will reduce lateral connectivity, as will channel incision or widening due to bed or bank erosion.

Overbank sediment deposition can also decrease lateral connectivity by increasing the bank height. Aggradation of the channel by sediment deposition can increase lateral connectivity, as can changes to the hydrological processes that cause a shift in the magnitude-frequency relationship towards more frequent larger floods.

Vertical connectivity as described by Ward (1980) refers to the transfer of water and sediment between the channel bed surface and the underlying hyporheic zone, or between surface water and groundwater. Fine sediment and nutrients can filter downwards into a coarse substrate or can be flushed from the surface by winnowing to leave a coarse armour.

Time is the fourth dimension of connectivity. The three dimensions of connectivity recognised by Ward (1980) are all subject to changes in streamflow and therefore have a temporal dimension. This may refer to the short term flow variability reflected by seasonal or shorter term shifts between baseflow conditions and flood events or to regime shifts that change the natural variability. As mentioned previously, connectivity can also be affected by structural changes due to erosion and deposition of sediment, channel incision being an obvious example.

2.2.3 *Connectivity at the catchment scale*

As a river ecologist, Ward (1980) interpreted connectivity in terms of the stream channel. Others, primarily geomorphologists, have taken a wider catchment perspective that incorporates the connectivity within hillslopes, between hillslopes and the channel and within channels (Bracken et al., 2015). Harvey (2000, 2002) made important contributions to the recognition of the importance of hillslope-channel connectivity, termed by Harvey (2000) hillslope-channel coupling. He also recognised the importance of within-hillslope connectivity. Hillslope-channel connectivity enables sediment detached from the soil surface by erosion processes to be transferred to the river channel, rather than being stored further down the hillslope as a result of within-hillslope processes.

Within-hillslope connectivity determines the distance that eroded sediment moves from source down the slope profile and the rate of movement. Factors influencing within-hillslope connectivity include the slope gradient, slope shape and vegetation cover. Clearly, steeper slopes induce higher energy flows and a greater sediment transport capacity. Slope shape will affect whether the transported sediment continues to move downslope (on convex sections) or be deposited (on concave sections). The density and structure of vegetation not only controls the rate of sediment detachment but also exert a strong control on sediment movement. Dickie and Parsons (2012) demonstrate how in dryland areas grassy vegetation tends to from buffers across the contour, serving to trap sediment, whereas woody shrub vegetation has a patchy distribution with clear flow pathways between the shrub clumps. Similar findings are presented by Kakembo et al. (2012).

Hillslope-channel connectivity is determined by the cumulative effects of within-hillslope connectivity if transported sediment is able to reach the bottom of the hillslope and enter the channel. Drainage density is an important variable determining hillslope-channel connectivity as the distance that sediment has to be transported by shallow overland flow is decreased as drainage density increases. Channelised flow is many times more effective in transporting sediment than is sheet flow. Gully erosion adds significantly to the drainage density and is a recognised process enhancing hillslope-channel connectivity (Harvey, 2000).

Hillslope-channel connectivity can be considered to be an extension of longitudinal connectivity as the movement of materials is in the downslope or downstream direction. Vertical connectivity can also operate on hillslopes, epitomised by the infiltration of rainwater into the soil.

2.2.4 *A focus on sediment stores – (dis)connectivity*

A different approach to connectivity was taken by Fryirs and Brierley (2007) who focused on the components that disconnect the landscape. They identified four landscape elements – barriers, buffers, blankets and boosters. The first three elements impede sediment movement and act as sediment stores for periods of tens to thousands of years but can be breached as a result of a hydrological or geomorphic event. Breaching may be temporary, due to changes in functional connectivity during an event, or permanent, due to structural changes caused by an event. Boosters act in the opposite direction, increasing water and sediment flows.

Barriers are described by Fryirs et al. (2007a) as features that delay sediment movement down the channel (Table 2.1). They therefore impact on longitudinal connectivity. Natural barriers include bedrock steps, sediment slugs and woody debris. Resistant dolerite dykes downstream of sandstone valleys are a common form of bedrock steps in upland areas of South Africa (Tooth et al., 2002; Grenfell and Ellery, 2009). Wide, shallow channels can also form barriers as the transport capacity of the flow is reduced relative to that for a deep, narrow channel (Brierley and Murn, 1997, Hooke, 2003). Valley constriction due for example to valley narrowing or an alluvial fan blocking the valley can also be effective as a barrier (cf. Kasai et al., 2005). Dams are the most effective anthropogenic barrier.

Buffers (Table 2.2) are structures or sediment deposits that impede the movement of sediment from hillslopes to the channel and include natural colluvial (hillslope), alluvial and fluvial deposits. Alluvial fans are depositional features that form where steep tributary streams meet a gentler valley floor; river terraces and floodplains serve to detach the river channel from the hillslope. In dryland areas floodouts can form a buffer disrupting longitudinal connectivity. Floodouts form in low gradient dryland channels where a decreasing transport capacity of channel flow causes sediment deposition in a fan-type deposit with multiple diverging channels. Conservation contour banks and artificial embankments are examples of anthropogenic structures that form buffers (Warner, 2006).

Blankets (Table 2.3) are features that disrupt vertical linkages and smother other landforms, temporarily protecting the underlying landforms from being reworked or transported (Fryirs et al., 2007a). Fryirs et al. (2007a) give a detailed explanation of types of blankets and their characteristics (Table 2.4). Blankets can be found in the channel (bed armour) or on the floodplain (sand sheet), varying in size from 0.1-1000 m^2. They vary from thin to thick (1-100 cm) planar sheets covering large areas, but elongated features also exist. Material varies from fines to cobbles that can be stored for a year up to hundreds of years. Blankets normally affect vertical connectivity but can also disrupt lateral channel-valley fill connectivity. This occurs where blankets formed on floodplains increase the height of the banks, effectively enlarging the channel capacity. This causes reduced lateral connectivity as flood flows are contained within the channel.

Boosters are described by Fryirs and Brierley (2007) as features that enhance longitudinal connectivity. Boosters tend to concentrate the flow, increasing the stream power and transport capacity. Natural boosters include gorges. These are common in the course of many South African rivers that drain the eastern seaboard (Rowntree et al., 2000). Gullies and incised channels can be considered as boosters that may have an anthropogenic cause (Brierley and Murn, 1997; Brierley et al., 2006). Channels with constructed levees or flood levees along the banks can also considered to be boosters as the levees restrict overbank flooding and increase flow energy in the channel (Gergel et al., 2002).

Table 2.1 Various forms and characteristics of barriers (modified from Fryirs et al., 2007a).

Form of barrier	Spatial scale (m^2)	Sedimentary character	Sediment cascade effect	Postulated effective timescale of disconnectivity	Cause of breaching
Bedrock step	10^0-10^2	Bedrock	Aids backfilling of valley floor	Permanent over thousands of years	Extreme event
Woody debris	10^1-10^2	n/a	Channel blockage acts to store sediment	Tens to hundreds of years	Channel flows with the capacity to entrain bed material. Decay of wood? Frequent reworking.
Wide, shallow channel cross-section	10^1-10^2	Mixed	Wide channels reduce effective stream power causing sediment accumulation.	Tens to hundreds of years	Channel flows with the capacity to entrain bed material. Frequent reworking.
Sediment slug	10^2-10^3	Sands and gravels cobble?	Impedes sediment transfer along channel	Tend to hundreds of years	Channel flows with the capacity to entrain bed material. Frequent

Form of barrier	Spatial scale (m^2)	Sedimentary character	Sediment cascade effect	Postulated effective timescale of disconnectivity	Cause of breaching
					reworking.
Valley constric-tion	10^2-10^3	Bedrock	Aids backfilling of valley floor	Permanent over thousands of years	Extreme event
Dams and weirs	10^1-10^3	n/a	Blocks sediment conveyance and enhances retention.	Tend to hundreds of years	Extreme event or purposeful removal.

Table 2.2 The various forms and characteristics of buffers (modified from Fryirs et al., 2007a).

Form of buffer	Spatial scale (m^2)	Sedimentary character	Postulated effective timescale of disconnectivity	Cause of breaching
Floodplain pockets	10^1-10^3	Mixed	Thousands of years	Overbank flow stage
Trapped tributary fills	10^2-10^3	Fines	Hundreds to thousands of years	Overbank flow stage
Alluvial fans	10^2-10^3	Mixed	Hundreds to thousands of years	Extreme event
Intact valley fills/floodouts	10^2-10^3	Fines	Thousands of years	Extreme event
Continuous floodplains	10^2-10^3	Mixed	Thousands of years	Extreme event
Terraces	10^2-10^3	Sands and gravels	Thousands of years	Extreme event
Piedmont zones	10^3	Mixed	Thousands of years	Extreme event

Table 2.3 Various forms and characteristics of blankets (modified from Fryirs et al., 2007a).

Form of blanket	Spatial scale (m^2)	Sedimentary character	Sediment cascade effect	Postulated effective timescale of disconnectivity	Cause of breaching
Floodplain sediment sheets	10^1-10^3	Mixed	Changes soil profile and hydrological properties. Sediment sink.	Tens to hundreds of years	Overbank flow events with ability to rework floodplain surfaces. Frequently reworked/ breached.
Fine grained material in interstices of gravels	10^{-1}-10^1	Fines	Changes hydrological properties at a 1 mm to 1 m scale. Sediment store.	Individual event to years	Channel flows up to bankfull with the ability to flush fines. Frequently reworked/ breached
Channel bed armouring	10^1-10^2	Mixed, but tends to be gravels or cobbles	Changes hydrological properties at a 1 mm to 1 m scale. Sediment store.	Years to tens of years	Channel flows with the capacity to entrain and rework surface armour, releasing subsurface sediments. Frequently reworked/ breached

2.2.5 *Integrating spatial scales of connectivity*

Spatial scales of connectivity were considered by Brierley et al. (2006) who combined channel reach and hillslope-channel connectivity in a nested arrangement summarised in Table 2.4. The spatial scales used by Brierley et al. (2006) are: within-landscape, between-landscape, sub-catchment and catchment, where sub-catchment and catchment integrate within- and between-landscape scales. At each spatial scale the various dimensions at play (e.g. lateral, longitudinal) and direction (e.g. from channel to floodplain) are described. At the within-landscape scale the focus is on vertical and lateral connectivity, whereas longitudinal connectivity is introduced at the between-landscape scale and becomes dominant as catchment scale is approached. Each of these linkages can be assessed in terms of its strength through the methods listed in Table 2.4. Controls that are likely to influence the degree of connectivity are also listed, such as slope, shape of the valley bottom, inundation frequency, etc. This detailed framework by Brierley et al. (2006) gives a useful overview of likely pathways and processes that sediment might encounter at various scales within a catchment.

Table 2.4 A summary of the different linkages and their processes, assessment measures and controls at various scales (adapted from Brierley et al., 2006).

Type of linkage/scale	**Processes or features**	**Measures used to assess strength of linkage**	**Controls**
Within landscape compartment			
Landform-scale analyses (colluvial) (lateral linkage)	Hillslope processes along a catena.	Characterise sediment delivery within hillslope compartments through appraisal of the mechanisms, rates and downslope transfer of sediment along the catena. Assess any impediments to downslope sediment transfer in zero and first order systems.	Slope angle and morphology. Underlying geology and rates of sediment generation and reworking.
Landform-scale analyses (alluvial) (lateral linkage)	Formation and reworking of floodplains. Sediment transport and deposition in channels.	Characterise sediment storage and reworking on the valley floor. Appraise the mechanisms and rates of floodplain formation and reworking, and sediment transport capacity of channels.	Valley confinement and slope. Sediment supply and the magnitude-frequency of flows.
Surface–subsurface (vertical linkage)	Surface–subsurface exchange of water, sediment and nutrients. Infiltration and filtering. Maintenance of baseflow.	Characterize sediment and water exchange between surface waters and ground water compartments. Determine the presence, distribution and role of blankets that impede exchange between surface and subsurface compartments and their potential to be reworked.	Bed material texture. Sediment transport regime of the channel. Recurrence of channel flushing flows. Groundwater mechanisms.
Between landscape compartment			
Upstream–downstream (longitudinal linkage)	Transfers of flow through a system affecting the efficiency of supply, transfer and storage of sediments of variable calibre.	Appraise the pattern and role of barriers and boosters (i.e. longitudinal connectivity and continuity within the system). Determine how readily these barriers can be reworked (i.e. the threshold conditions and recurrence interval under which they are likely to be breached)? Estimate the ratio of transport capacity for a given range of events relative to sediment availability (and the character/accessibility of stores) through the examination of the degree of channel bed aggradation or degradation, the distribution of bedrock steps along the longitudinal profile and the degree of channel and valley confinement.	Base level. Sediment transport regime of the system (i.e. sediment supply or sediment transport limited).
Tributary–trunk stream (longitudinal linkage)	Transfers of flow through a system. The supply, transfer and storage of sediments of variable calibre.	Appraise the patterns of tributary (dis)connectivity by examining how often and over what length of river course tributaries are joined or disconnected from the trunk stream. Are buffers absent/present? Examine the impact that tributary contributions have on the trunk stream at the confluence (e.g. aggradation or degradation).	Shape of the catchment (i.e. its elongation ratio). Drainage pattern and density.

Type of linkage/scale	**Processes or features**	**Measures used to assess strength of linkage**	**Controls**
Slope–valley floor (lateral linkage)	Slope denudation and erosion via mass movement, creep, wash, etc. Colluvial footslope deposition and reworking. Deposition and reworking of materials on the valley floor. Channel adjustment on the valley floor.	Appraise how readily sediments transferred downslope are made available to channels. Determine whether buffers are absent/present. Appraise the position of the channel on the valley floor and the nature of the hillslope–channel interface. Interpret the frequency with which impediments to sediment conveyance off hillslopes may be breached.	Confinement of the valley floor. Channel position on the valley floor. The magnitude of flow events along the valley floor.
Channel–floodplain (lateral linkage)	Channel adjustment on the valley floor. Floodplain formation and reworking.	Appraise the character and volume of materials stored on valley floors, and the contemporary flux (i.e. floodplain accretion or reworking). Determine whether the reach operates as a sediment source, transfer or accumulation zone. Determine the channel size and shape, the degree of channel aggradation or degradation relative to floodplain height and the floodplain inundation frequency. Look for evidence of channel migration, avulsion, expansion, contraction.	Bed and bank material texture. Sediment transport regime of the channel relative to the floodplain. The magnitude and inundation frequency of overbank events that drive mechanisms of channel adjustment, and floodplain formation and reworking.
Subcatchment scale			
Valley segment–valley segment	The pattern and sequence of sediment source, transfer and accumulation zones along the valley floor.	Examine the pattern of upstream–downstream connectivity through the subcatchment as a whole. What is the sequence of valley settings (i.e. confined, partly confined or laterally unconfined valleys)? Are these sediment source, transfer or accumulation zones? Appraise the pattern and role of barriers and boosters (i.e. longitudinal connectivity and continuity within the system). Interpret the capacity for downstream propagation of sediment release from primary sediment stores, and their likely off-site impacts. Assess whether this is a transport-limited or a supply-limited system.	Valley confinement, valley slope, valley morphology which are controlled by underlying geology and landscape evolution.
Land system assemblage	Areas of relatively uniform topography measured in terms of relief, landform morphology, valley confinement and geology. Summarize slope–valley floor configuration.	Appraise tributary–trunk, slope–valley floor and channel–floodplain in the subcatchment as a whole. Examine the role of buffers to sediment conveyance.	Hillslope morphology, valley floor confinement, valley slope, valley morphology which are controlled by underlying geology and landscape evolution.

Type of linkage/scale	Processes or features	Measures used to assess strength of linkage	Controls
Catchment scale			
Catchment configuration	Configuration of valley segments and land systems within a catchment to explain across catchment variability in patterns of(dis)connectivity and flux	Measure the effective catchment area. Appraise how subcatchments fit together at the catchment scale through integration of subcatchment-scale relationships. Frame this in terms of how catchment shape, elongation ratio, etc. impact on sediment conveyance, storage, etc. Determine the position of the most downstream blockage that impedes sediment output from the system. Predict the sensitivity of the landscape to change, where change will occur and be propagated from, and likely geomorphic responses.	Subcatchment variability in patterns of valley segments and land systems which are controlled by underlying geology and landscape evolution.

2.2.6 *The time dimension of connectivity – switches, thresholds, frequency-magnitude*

Ward (1989) pointed to time as the fourth dimension of connectivity, recognising that connectivity is event related. Later authors such as Fryirs et al. (2007a) took the temporal aspect of connectivity further by invoking a concept based on landscape switches that responded to events of different magnitude. They saw switches as being represented by barriers, buffers or blankets that disconnect the system. As long as a switch is off it is effective in disconnecting the landscape but if on connectivity is established. Whether or not a switch is on depends on the hydrological magnitude of an event. If it is sufficient to overcome the critical threshold for sediment movement, it is able to breach (or open) the switch. This threshold concept applies well to longitudinal forms of connectivity but may need to be adjusted for lateral connectivity. The threshold is no longer related to sediment transport but whether the flow magnitude is sufficient to physically connect different parts of the channel and floodplain, possibly resulting in sediment deposition rather than entrainment.

Fryirs et al. (2007a) demonstrated how switches can control the effective catchment area depending on the magnitude of the event. As show in Figure 2.1, in a low magnitude event most switches remain off, the catchment is poorly connected and the effective catchment area is small. As the event magnitude increases more switches close to the on position, connectivity increases as does the effective catchment area.

Thresholds are a well-established concept in geomorphology. Schumm (1979) recognised extrinsic and intrinsic thresholds, a distinction that has implications for functional and structural connectivity. An extrinsic threshold refers to the state when a driving force is equal to the resistance to change offered by an object. For example, the threshold stream power for a given particle size is that above which the particle will begin to move. In sediment transport terminology this is termed the critical stream power.

It is a function of flow depth, slope gradient, particle weight and bed roughness. At a larger scale, channel pattern can shift from meandering to braided if the stream power is increased above a certain threshold value (Leopold and Wolman, 1957; Schumm, 1985). Extrinsic thresholds are vulnerable to anthropogenically induced changes to geomorphic drivers such as surface runoff and flood flows or to resistance to erosion imparted by vegetation. In contrast, intrinsic thresholds are a product of geomorphic form and breaching a threshold is the result of internal change in the geomorphic system. Patton and Schumm (1975) showed how the threshold gradient for valley floor incision is related to the valley floor gradient. Over time deposition of sediment on the valley floor steepens the gradient and brings the system closer to the threshold of instability. The same process can be applied to fan evolution (Schumm, 1979). As a geomorphic system approaches the threshold of instability it becomes more sensitive to external drivers such as increased surface runoff, floods or a reduction in vegetation cover. Incision of the valley floor or gullying of hillslopes results in a largely irreversible change in structural connectivity which in turn effect functional connectivity of the system.

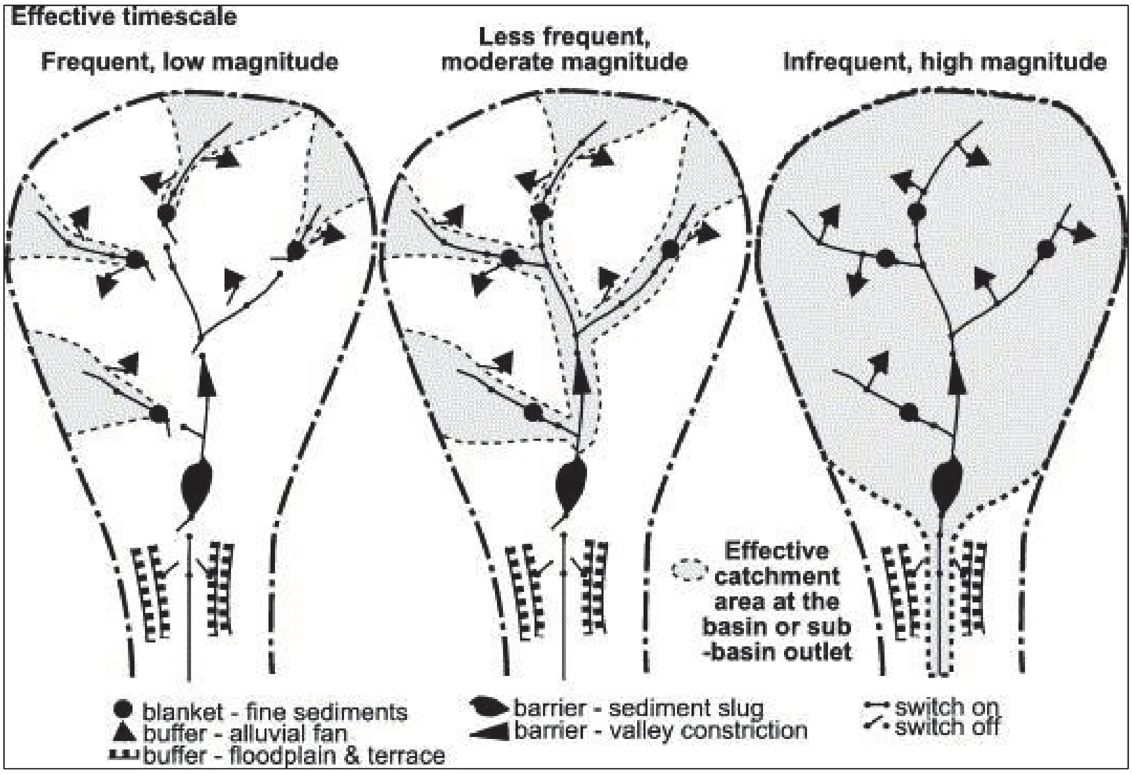

Figure 2.1 Event magnitude and the size of the effective catchment (reproduced from Fryirs et al., 2007a, with permission).

Frequency-magnitude concepts are closely related to threshold concepts. As elucidated by Wolman and Miller (1960) in their seminal paper, the larger the event the greater its force and erosive power, but the less frequently it occurs. They argued that the cumulative effect is greatest for events of moderate magnitude and frequency as illustrated in Figure 2.2. The form of the relationship depends on the threshold for movement (or breaching); as resistance to change increases there is a shift in the required magnitude of event to a lower frequency. It is probably true that functional connectivity is driven primarily by more frequent events of moderate magnitude whereas changes to structural connectivity will be driven by less frequent high magnitude events. For example, overbank flooding is a quasi-annual event in many rivers whereas the creation of a meander cutoff may require a larger flood, but is contingent on the state of intrinsic thresholds.

All buffers go through periods of aggradation, stabilisation and degradation. Alluvial fans are a good example that has been studied in depth by Harvey (2002). Fans aggrade (sediment deposition and slope steepening) during periods of surplus sediment input but can become incised if flow energy exceeds available sediment supply. Shifts in both sediment supply and runoff may be related to long term shifts in global climate (e.g. glacial periods) or to shorter term shifts in the local climate or to anthropogenic disturbance. Thus breaching of a buffer is a response both to intrinsic thresholds (linked to the evolving morphology of the buffer) and to the frequency and magnitude of flow events that provide sufficient energy to transport the available sediment. Breaching will occur more frequently if the buffer is relatively small, as in the case of discontinuous floodplains and narrow terraces, especially when coupled with high energy runoff from the slopes or tributaries (Fryirs et al., 2007b).

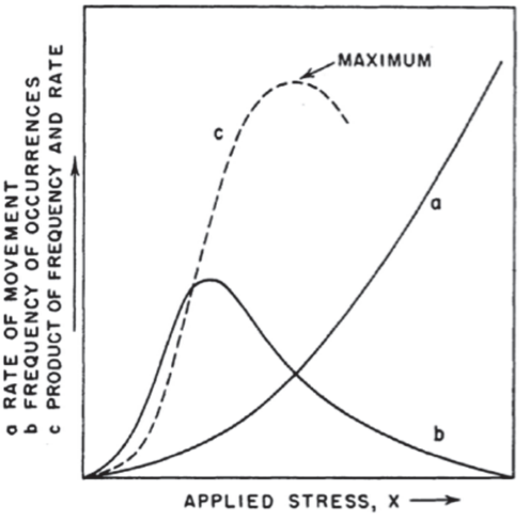

Figure 2.2 The rate of transport, event frequency and applied force (Wolman and Miller, 1960; reproduced with permission).

In a review of landscape change and sensitivity, Brunsden and Thornes (1979) concluded that infrequent events of large magnitude are responsible for causing changes to landscape structure and functional connectivity in systems that are close to their geomorphic threshold. These large scale changes can relax over time to the return to the previous functional state, fashioned by smaller magnitude events of a higher frequency. Brunsden and Thornes (1979), describe the rate and processes involved in the relaxation period as complex and affected by the environment, intrinsic characteristics and the degree of connectivity (diffuse or direct). Schumm (1973) notes that where systems are well connected, effects of large magnitude events will be efficiently propagated, making the system more sensitive to large events. Thus, the effect of a large event and subsequent repercussions will depend on the geomorphological structure and connectivity of the system.

2.2.7 *Linking time and space scales*

It becomes clear from the above discussion that connectivity and the associated dis-connectivity operate at a range of scales in time and space. Schumm and Lichty (1965) were among the first geomorphologists to conceptualise the relationship between time and space scales. Simply stated, small-scale features such as rills on a hillslope or bedforms in a sandbed channel evolve in response to short-term events such as a single storm or flood whereas at the other extreme, the shape and relief of a catchment evolves through geological time in response to long term climate change and tectonic events. Dollar and Rowntree (2003) applied Schumm and Lichty's (1965) ideas to show how time and space scales are related to the geomorphological hierarchy of Rowntree and Wadeson (1999).

These geomorphological relationships between time and space also apply to connectivity. Local connectivity is mainly influenced by shorter term climatic and environmental factors, such as the duration and intensity of rainfall, irregularity of the soil surface and spatial arrangement of the vegetation and land units (Cammeraat, 2002; Harvey, 2002). For larger systems (catchment scale), more long-term factors, e.g. tectonics and erosional history, are the main influences affecting connectivity (Harvey, 2002). Harvey (2002) states that the frequency of the threshold exceeding event, the recovery period and the propagation time are important factors when looking at temporal changes in connectivity. At the within-landscape scale connectivity responds to short term events, such as a single flood (short propagation time) with a one to ten-year recurrence interval, and has a relatively short propagation and recovery time. In larger systems, connectivity changes over longer periods (up to ca. 150 Ka) where propagation time becomes the important controlling factor.

Longitudinal connectivity typically refers to 'down system connectivity' which is the movement of sediment from sources to sinks, but it is important to realise that connectivity can also be propagated in the upstream direction (Harvey, 2002). An example is the upstream migration of a change in base level. Nick points migrate upstream throughout the channel network and onto hillslopes, cutting into colluvium and forming gullies (Harvey, 2001). Harvey (2002) contends that upstream migration of base level change is much slower than its downstream equivalent, being measured in thousands of years rather than decades.

Connectivity also affects the time scale over which change can be propagated through a catchment. In well-connected systems a change in climate and resultant geomorphic response will be synchronous throughout the catchment, assuming that the effective thresholds are crossed (Harvey, 2002). In such a case increased erosion will lead to increased sediment supply to the downstream reaches; similarly, changes in stream base level will be propagated upstream, eroding into colluvium on lower hillslopes. However, where propagation times are slow, as with up-system connectivity, it is likely that different parts of the system will be under different geomorphic regimes (Harvey, 2002; Rommens et al., 2006). In poorly-connected systems, processes in different parts of the catchment could be synchronous or contrasting and asynchronous (Harvey, 2002). Connectivity can follow a complex nonlinear pattern where a specific area switches between source and sink through time depending on environmental, climatic and tectonic influences (Rommens et al., 2006).

2.3 Drivers of hillslope-channel and channel-valley floor connectivity

In the previous section we present an overview of the key concepts and theoretical frameworks informing connectivity. In this section we take an in-depth look at the processes that influence hillslope-channel and channel-valley floor connectivity that are thought to be active in the Vuvu catchment where this study is situated. In the Vuvu catchment, hillslope to channel and channel to valley floor connectivity are thought to be the main pathways that have been affected over time. Longitudinal connectivity was thought not to have changed because base levels (e.g. resistant dolerite dykes) remained relatively stable over the past 100 years and there are no impoundments or other artificial structures across the channel other than bridges. From field evidence it is apparent that hillslope-channel and channel-valley floor connectivity are influenced by a mixture of landscape factors, such as slope, land cover, gullies on slopes and the incision of channels. Trends and effects related to connectivity as a result of changes in these drivers will be discussed below.

2.3.1 *Factors affecting hillslope-channel connectivity*

Harvey (1997) stresses that the key to understanding upland geomorphic processes is to look at hillslope-channel connectivity, especially over varying spatial and temporal scales. Michaelides and Wainwright (2002, p. 1442) defined hillslope-channel connectivity as ‘the effectiveness, direction and speed with which localized changes are transmitted away from the source (hillslope) and propagated throughout the hillslope system to the channel and ultimately to the catchment outlet’. In this section a review of selected factors that influence hillslope-channel connectivity is presented: valley confinement, slope topography, land cover and vegetation, gully systems.

Valley confinement

Valley confinement has a direct influence on hillslope-channel connectivity because it determines how far sediment has to travel from the foot of the hillslope to the channel and the potential for buffering. Confinement tends to decrease downstream as the valley changes from V-shaped valleys in the headwater areas to wide valleys with a floodplain in the lower reaches. As the valley floor widens, buffers on the valley floor become increasingly effective in trapping sediment before it reaches the channel (Brierley and Fryirs, 1999; Fryirs and Brierley, 1999; Fryirs et al., 2007a, 2007; Michaelides et al.; 2010). Buffering is counteracted where tributaries cross the valley floor and connect directly to the main channel but alluvial fans and other depositional features can disconnect the tributary and main channel.

Slope topography and drainage density

Slope gradient and slope length both have a direct effect on connectivity. The available energy for erosion and transport of sediment is directly proportional to the slope gradient. For convex slopes the gradient increases in the downslope direction so the erosion and sediment transport potential also increases. For concave slopes the energy gradient decreases towards the bottom of the slope, encouraging deposition. Many slopes are convex-concave in shape so that the highest energy is found mid-slope.

The length of slope from the drainage divide to a channel affects the volume of runoff and the distance that sediment has to travel to a point where concentrated flow has a much greater transport capacity. All other factors being equal, the volume of surface runoff will increase with slope length but the potential for deposition and transmission losses also increases. Drainage density can be used as a measure of slope length. The higher the drainage density the shorter the distance that runoff and sediment have to travel over the slope surface before entering a channel. The transport capacity and velocity of channelised flow is many times greater than that of overland flow so that more sediment can be carried faster down the channel. Drainage density, measured as the length of channel per unit catchment area, is therefore a good measure of catchment scale connectivity.

Steeper slopes have less surface storage mainly due to the effective drainage of depressions that would act as sinks on gentler slopes (Kirkby et al., 2002). The trend is that steeper catchments have denser drainage networks, which results in the slopes being well connected to the channel. Slope can thus be used as indicator of potential connectivity, as was shown by Fryirs et al. (2007b) who used DEM based slope classifications to identify potential barriers and buffers (less confined, low gradient ($<2^{o}$) areas with large accommodation space). The modelled output agreed with field observations. Another feedback related to slope is vegetation cover. Steeper slopes with thinner soils, low water retention and a poor vegetation cover may have higher erosion and sediment transfer rates (Kirkby et al., 2002).

Gullies are erosional features that act as a sediment source but also extend the natural drainage network and increase drainage density. They are therefore effective connectors between the hillslope and the river channel. Gullies are a conspicuous feature in the Vuvu catchment. Their effect on connectivity will be considered in more detail below.

Land cover and vegetation

Vegetation plays a key role in controlling hillslope processes through its effect on soil protection, infiltration and soil strength. Its effects have been well documented (cf. Brookes, 1994; Cammeraat, 2002; Kirkby et al., 2002; Rommens et al. 2006; Beel et al., 2011). Vegetation cover thus has a direct impact on within-hillslope connectivity as it controls downslope transport and deposition. The main impacts of decreased vegetation cover is increased surface runoff, slope erosion and gully formation, together increasing sediment delivery to the river channel. Conversely, a dense vegetation or ground cover protects soils from erosive rainfall, increases the runoff threshold, reduces overland flow through increased surface roughness and acts as a sediment buffer. Increased vegetation on the wetter, deeper soils in footslope positions often act as an effective buffers, as reported by Fryirs and Brierley (1999).

The spatial layout of vegetation also affects connectivity. Where vegetation cover is transformed to become patchy, buffers are breached and connectivity pathways are established (Cammeraat, 2002;

Kakembo et al., 2009). This allows water and sediment to move freely between patches. Dickie and Parsons (2012) compared within-hillslope connectivity for a cover of grass and woody shrubs in a semi-arid environment. Grass clumps tended to be aligned along the contour, forming buffer strips, whereas woody vegetation formed unconnected clumps with high connectivity between.

Land use has an immediate effect on the protection afforded by vegetation. Cultivation exposes the soil surface to the erosive effects on rainfall; the overall impact over the year will depend on crop type and seasonal growth patterns. Annual crops will on balance have a greater negative impact that perennial crops because of less ground disturbance. Grazing reduces the effective cover, especially if the stock numbers exceed sustainable levels. Grazing can also change the species composition and lead to shifts between grassy and woody vegetation. Fire is often used as a tool to manage the grass sward in South African mountain pastures, as in the Vuvu catchment, and can also be caused by accidental or natural processes (lightening). For the period immediately after a fire there may be zero cover, only growing back after rainfall. Fire also can effect a changes in species composition towards more fire tolerant species.

Marginal agricultural areas, such as characterise the Vuvu catchment, are prone to the phenomenon of the abandonment of cultivated fields due to economic and social shifts that make it no longer worthwhile to cultivate land (Kakembo and Rowntree, 2003). When agricultural land is abandoned (or a landslide has stripped a hillslope) soil can remain bare for several years before being recolonised by vegetation (Harvey, 2001). Sediment yields peak after land abandonment and eventually fall if and when vegetation cover increases, possibly only after several decades (Fryirs and Brierley, 1999; López-Vicente et al., 2013). If erosion strips the topsoil from abandoned cultivated fields they may never recover their original cover and become “erosion hotspots” (Kakembo and Rowntree, 2003).

Gullies as sediment sources and connectors

Gullies are landscape features that not only produce large quantities of sediment but also increase hillslope-channel connectivity. They are significant sediment sources, reworking previous sediment sink zones (de Vente et al., 2006). Wasson (1994) found that gullied basins in Australia produce several times as much sediment compared to ungullied basins, mean annual sediment yield being a linear function of gully density. Gullies can be considered to be a form of booster *sensu* Fryirs and Brierley (2007) (López-Vicente et al., 2013). They often form where existing drainage lines follow shallow linear depressions over the surface of deep valley fill or colluvium. Incision by gully erosion leads to larger, better connected drainage lines that are more efficient in transporting sediment from upslope sources (Croke et al., 2005). Croke et al. (2005) also found that gully development effectively linked other drainage features such as roads and trails to the stream network and increased the drainage density by up to 10%.

Croke et al. (2005) traced runoff on dispersive and gullied pathways in New South Wales, Australia. Runoff travelled two to three times further downslope in gullied pathways. On dispersive pathways fine sediment (<63 μm) stayed in suspension until the runoff infiltrated (Croke et al., 2005). Where gullies are not linked to the drainage network, i.e. discontinuous features, water will be dispersed at the end of the gully and sediment deposited.

Gully initiation, evolution and stabilisation

Although gullies are often seen to be evidence of accelerated erosion due to human activity they can also be a manifestation of a natural cut and fill cycle. Cut and fill processes are constrained by thresholds that may be linked to either intrinsic or extrinsic drivers, or a combination of both (Schumm, 1979; Grenfell and Ellery, 2009). Deposition may increase the slope beyond its stable range, causing incision due to an intrinsic process. Extrinsic drivers include a change in vegetation cover (resistance) or increased stormflow (force). These changes may be related climate (natural change) or land use (anthropogenic change). Lowering the base level through the removal of a barrier or cutting into a foot slope area can also initiate gully formation (Harvey, 2002). This is especially true for dispersive soils prone to tunnelling (Hardie, 2007). Harvey found that gully development was strongest where the feature was directly linked to the stream channel, a situation that also enhances its connectivity role.

Gullies can be continuous, linking directly into the natural drainage network, or discontinuous, draining onto an ungullied hillslope or valley floor. Harvey (2002) found that hillslope gullies formed due to increased runoff are not always directly connected to the main drainage network and can form anywhere on the slope.

Harvey (1992) describes gullies as dynamic, non-equilibrium landforms with progressive changes in process-form relationships that have spatial and temporal limits. His model of gully evolution is depicted in Figure 2.3. Once incision is initiated by a headcut at the foot slope, the gully extends upslope until a barrier prevents further spread or when the gully slope reaches a stability threshold. Gully stabilisation sets in once larger material is deposited along the lower channel, allowing vegetation to be established in the gully floor and on gently sloping areas. The gullies become less efficient in their sediment transfer as they increase in size and vegetation colonise the gully floor (Harvey, 1997). Harvey (1992) found that the large material will be flushed out during larger storms (2-5 year frequency), restoring the efficiency of sediment transport until it fills again. The role of a gully as both source and connector therefore changes through time. A number of authors, however, suggest that, once gullies are fully developed and revegetated, they become stable and hillslope-channel connectivity is reduced (Harvey, 1992; Kasai et al., 2005; Vanacker et al., 2005).

From Figure 2.3 it is evident that the size of the gully is related to its age. Small gullies are thus relatively young, if not spatially or structurally constrained. Large stable gullies were estimated to be 100-175 years old (Harvey, 1992; Kasai et al., 2005). In badly eroded areas, where soils are thin and do not favour vegetation growth, gullies may in certain circumstances provide the only areas for vegetation to become established. Vanacker et al. (2005) studied sediment dynamics in the Ecuadorian Andes where a human population explosion caused a forest to be converted to agricultural land. High sediment yields and the formation of erosional features ensued. Two decades later farming was abandoned, as the population moved to the cities, reducing the farming pressure. Vegetation established itself in the gully networks, effectively disconnecting the landscape units and reducing sediment delivery to the river channel, even though the slopes had not been revegetated. This illustrates the switching role of the gullies, firstly as sediment source and connector and, secondly, as a sediment sink. This has important

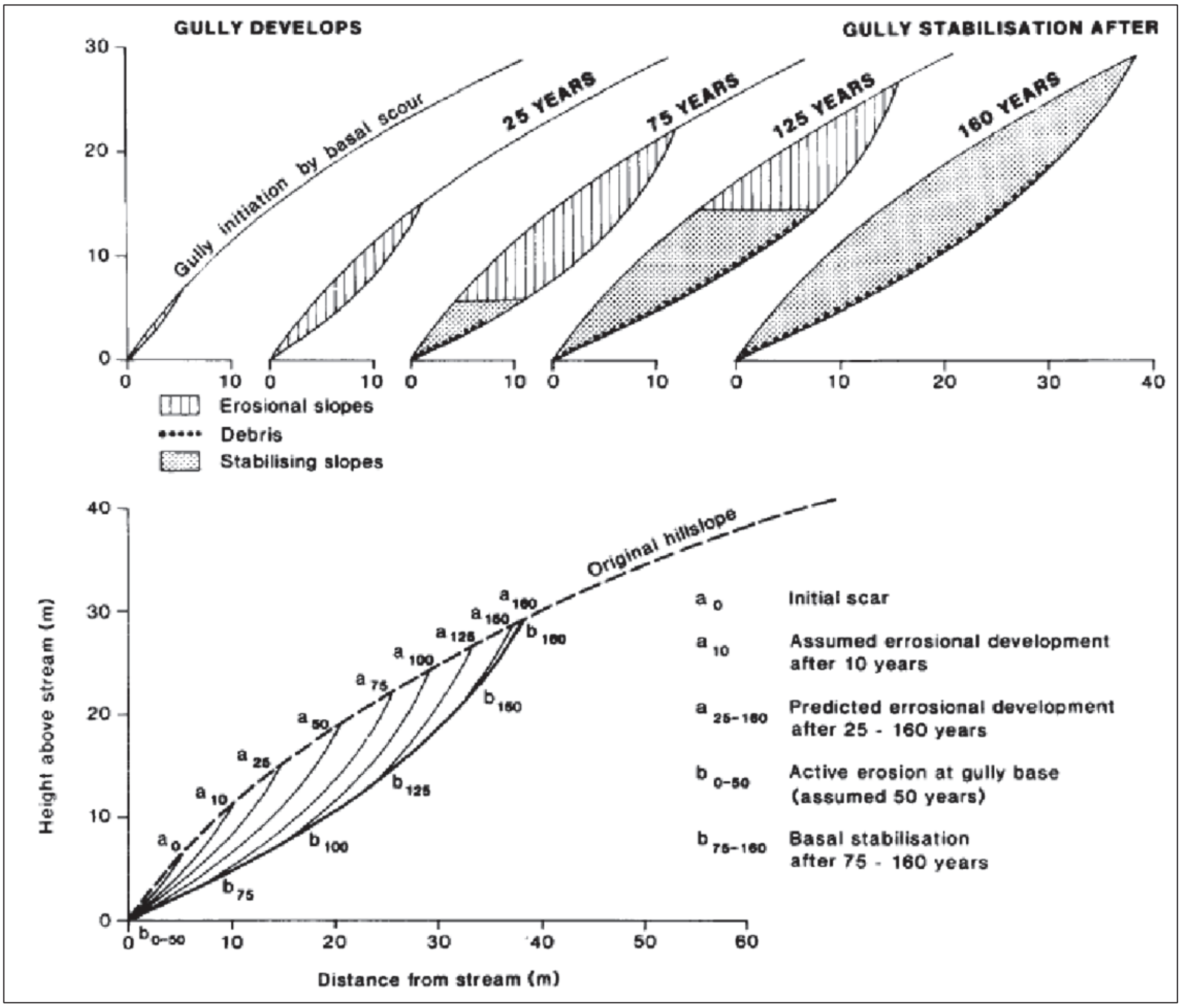

Figure 2.3 Gully development and stabilisation as a result of basal scour (Harvey, 1992; reproduced with permission).

implications for catchment scale rehabilitation of a severely eroded landscape.

2.3.2 *Factors affecting lateral channel-valley floor connectivity*

Incision and floodplain dynamics

The flood pulse is the main river-floodplain driving force that enables channel-valley floor connectivity and maintains the system's dynamic equilibrium (Junk et al., 1989). During a flood new sediment will be transported to a floodplain and some of the sediment in storage will be remobilised and transported downstream (Hooke, 2003). If the system is in equilibrium, the amount of sediment imported and exported will be similar. For the system to remain in this equilibrium state it is thus important that banks are frequently overtopped in order to establish channel-valley floor connectivity and to allow for sediment deposition. During a flood event in a meandering system with cohesive materials (high silt or clay content), the outer bank is eroded, while the inner bank is rebuilt through the formation of lateral or scroll bars (Wolman and Miller, 1960; Page et al., 2003). This continues over time, with the channel slowly migrating across the floodplain. In this equilibrium state the eroded and newly formed bank are at the same elevation (Wolman and Miller, 1960). In a system with coarser material, lateral migration is accomplished through channel avulsion. Poole et al. (2002) found that paleo channels are reactivated through this process, scouring sediment from paleo channels and depositing new sediments in the abandoned channel. Where the system with coarser material is in equilibrium, the active and paleo channels are at the same elevation (Poole et al., 2002).

Channel incision results in a reduction of overbank flooding and a disconnection between the floodplain and the channel. It can increase longitudinal connectivity but decreases lateral connectivity. Incision can result from both anthropogenic influences and geologic, geomorphologic and climatic controls (Schumm, 1999). All these factors can be related to increased or excess transport energy relative to availability of sediment (Simon and Rinaldi, 2006). Valley floor incision can result from a reduction in surface resistance associated with a change in vegetation cover, from a reduction in sediment inputs or an increase in discharge (Schumm, 1999). Anthropogenic factors are believed to be the cause of recent valley floor instability and incision whereas geology, geomorphology and climate act over the long term.

Where channels are incised, the channel capacity is increased relative to the discharge, resulting in reduced inundation of the floodplain (Gergel et al., 2002; Kondolf et al., 2006; Pizzuto, 2011). Hydraulic geometry shows that increased channel capacity will reduce the chances of overbank flooding (Leopold and Maddock, 1953). This will lead to an enlarged channel, containing larger magnitude peak flows, and reducing the frequency of channel-valley floor connectivity and chances to deposit sediment on the valley fill (Simon and Rinaldi, 2006). Where tributaries are not buffered by a floodplain, incision will work its way up the tributary until a barrier prevents upstream propagation of the incision (Fryirs and Brierley, 1999). Incised systems will thus increase sediment transport through drainage features, becoming more efficient conduits and therefore providing less sediment storage capacity on floodplains.

Channel incision is often associated with the development of a suite of terraces and inset floodplains or benches. Following incision the former floodplain becomes a terrace, disconnected from all but the most extreme floods. Lateral migration of the channel at the new bed elevation initially undercuts the terrace, forming high steep banks that are a significant sediment source (Brierley and Murn, 1997; Simon and Rinaldi, 2006), but over time sediment deposition will lead to the formation of a new floodplain (Womack and Schumm, 1977; Bookhagen et al., 2006) in accordance with the new flood regime, re-establishing more frequent channel-valley floor connectivity. If further incision happens, another set of terraces will develop. Terraces are found in most river systems, containing important information on past channel-valley floor connectivity (Womack and Schumm, 1977).

Valley bottoms store sediments until they are reworked (Kasai et al., 2005; Brierley et al., 2006). Stored sediment can form large water aquifers, promoting plant growth. These productive sinks, often swamps (wetlands) with deep soils and anabranching channels, were targeted by early European settlers, for grazing and agriculture (Brierley and Murn, 1997; Brierley and Fryirs, 1998; Walter and Merritts, 2008). Brierley and Murn (1997) suggest that the pre-human disturbance cut and fill phases on valley floors in Australia were more localised or discontinuous. With human disturbance (e.g. agriculture) the cut extent of small channels on valley bottoms was enlarged up to 10 m deep in places and 100 m wide over a few decades, resulting in more continuous cut features, such as incised channels and gully networks (Fryirs and Brierley, 1999). A similar process is described by Womack and Schumm (1977) following the introduction of livestock to Douglas Creek, Colorado, and Rowntree (2013) for the South African Karoo. Other anthropogenic activities such as sediment mining or water storage in reservoirs can reduce the sediment input, effectively changing the sediment equilibrium of the valley fill to such an extent that incision is initiated (Nakamura and Tockner, 2004). In Italy sand mining has resulted in incision of up to 8.5 m deep in cases (Surian et al., 2009). White and Greer (2006), in a study in California, linked incision to the increase in runoff as a result of urbanisation and associated increases in impervious surfaces.

In contrast, where valley bottoms receive increased sediment loads from the slopes, the channels often aggrade following high sediment loads, becoming wider and shallower (Kasai et al., 2005). In the transfer and depositional zone downstream of the Cobargo and Upper Wolumla Creek study sites (NSW), exported sediment choked the downstream system by forming a thick sediment blanket (burying fence posts) on the floodplain, reducing vertical connectivity (Fryirs and Brierley, 1999).

Channel incision can also be linked to longer term natural changes. Alternating wet and dry climatic periods result in cut and fill cycles (Bookhagen et al., 2006) caused by differing amounts of runoff and sediment production. Bookhagen et al. (2006) linked valley infill in the north-western Himalyas to the beginning of a wetter period in the early Holocene when sediment was readily available. Subsequent cut and fill cycles were linked to alternating drier periods with reduced sediment availability and wet periods with increased erosive power. Temme et al. (2008) postulate similar events for headwater streams draining the Drakensberg Escarpment of KwaZulu-Natal.

Incision can also be caused by base level changes (Womack and Schumm, 1977; Maddy, 1997; White and Greer, 2006). In areas near the continental shelf, sea level dropped during colder periods (ice ages), promoting incision into deposited sediments (Maddy, 1997). Further inland, base level change can happen as a result of tectonic movement, breaching of a bedrock barrier or more local changes, such as meander cutoffs (Maddy, 1997; Harvey, 2002, Tooth 2002). Meander cutoffs steepen the channel gradient and lead to incision that migrates upstream, resembling a headcut (Harvey, 2002).

(Prosser et al., 1994) looked at valley cut and fill phases in the south-eastern highlands of Australia. Valleys slowly filled with sediment as densely vegetated meadows trapped sediment. Large aggradational phases lasted several thousands of years, interrupted by gully formation. Phases of gully erosion were evident and were likely to be triggered by thresholds of incision than by changes of sediment supply. Human induced environmental change is largely responsible for the gully formation over the past century.

(Fryirs, 2002) studied landscape controls and river character in the Bega catchment, New South Wales, Australia. River character was determined by antecedent landscape features for rivers directly below the escarpment (in geological time): the amount of cross sectional valley morphology or accommodation space; planform and constriction along valley; catchment area; longitudinal profile and break in slope. Large catchment area increases stream power and the rate of gorge retreat in relation to the rate of valley widening. This results in a narrow elongated valley with limited accommodation space. For valleys with smaller catchments and relatively lower discharges, rates of valley widening were higher than gorge retreat, resulting in wider valleys with a greater accommodation space and the likely accumulation of floodplain sediment.

Tooth (2002) worked on the Klip River, South Africa. He showed that floodplain wetland formation is strongly influenced by rock hardness; harder rock acting as the control on downcutting, and softer rock eroding in a horizontal plain to create accommodation space for a large floodplain with a meandering river channel. The reach on harder rock is characterised by a relatively straight channel and narrow valley fill.

Relating to an even longer time span, (Partridge and Maud, 1987) studied the evolution of the southern African continent since the breakup of Gondwana land (Mesozoic times). Due to various uplift events coupled with river rejuvenation over time, headward erosion has dominated over downward erosion, resulting in steep deep valleys throughout most of southern Africa.

2.3.3 *Application of connectivity frameworks to ecosystem assessment*

Although the above review of literature focused on connectivity from a geomorphological approach, it is directly linked to aquatic ecosystems as habitat and water movement that is crucial to these ecosystems are influenced by connectivity.

The reviewed connectivity frameworks such as that of Brierley et al. (2006) and Fryirs et al. (2007a) follow a holistic approach that assesses pathways and sediment storage areas at a variety of scales, ranging from the plot to catchment scale. It also addresses timescales that the stores can be active for and the influence that large events might have on the effectiveness of storage areas. Harvey (1992) focused more on the function and timescale of pathways at a landscape scale and how that affects the downstream river channel. Hooke (2003) focused on sediment movement and habitat change along a floodplain reach over a decade. All these studies contributed to an understanding of how water and sediment movement is likely to affect habitat and future movement of water and nutrients and what likely pathways there will be for upstream, downstream and lateral movement of organisms.

Connectivity is also relevant input to river health assessments, sediment modelling, hydrological modelling and rehabilitation planning. The Geomorphological Assessment Index (Rowntree 2013) uses catchment wide changes in connectivity to determine the overall ecosystem health of the river system. At a more focused level such as the plot scale, connectivity mapping can be used for rehabilitation planning and as input into sediment modelling.

An application of connectivity concepts to catchment rehabilitation is provided by Herbst et al. (2012) who used grazing exclosures (fenced pens) along channels and complete removal of grazing on third order streams in the interior western United States to assess their effectiveness on river system recovery. The effects of small exclosures (established for 10+ years) on stream habitat were less pronounced than in the catchments where grazing was completely excluded (for four years). Grazed catchments had steeper, actively eroding banks, higher solute loads in the water, bed with increased fine sediment and wider channels. Exclosure plots had better riparian vegetation cover and composition than grazed areas, but continued disturbance through grazing upstream of the exclosure plots prevented recovery of channel habitat. These data suggest that minor catchment-wide reductions in hillslope-channel connectivity (through vegetation recovery) are more effective in channel rehabilitation than major localised reductions in connectivity.

The main challenge of the connectivity concept is that each catchment is unique and will require its own connectivity assessment (Brierley et al., 2006). Assessments are done at various scales, from a 'within landscape' scale up to a catchment scale, to get a holistic understanding of the system. Such a hierarchical range requires a large amount of research resources. Our understanding of thresholds of stability of various landscape units is still limited, especially across spatial scales, making the prediction of likely changes in connectivity challenging (Fryirs, 2013). According to Grant (2013; pers. comm.) the concept of connectivity is useful as a broad concept, but it needs a more rigorous definition and analytical framework for it to become a useful concept for geomorphic work.

2.4 Conclusion

The connectivity concept and framework has been advocated as a valuable, holistic approach to assess sediment dynamics as it addresses both structural and functional changes over time. The concept can be applied over various spatial scales, ranging from the landscape unit to catchment scale. Brierley et al.'s (2006) nested hierarchical framework presents an assessment of landscape connectivity that includes the appraisal of landscape features that could act as buffers, barriers, blankets or boosters at various scales (Fryirs et al., 2007a).

Connectivity focusses on the ease at which material can move from one place to the next. Sediment transport is largely dependent on water movement. Hillslope-channel connectivity can be influenced by drivers that enhance downslope movement such as slope gradient and land cover and those that increase connectivity to the trunk channel such as drainage pathways and valley confinement. Geomorphic systems are disconnected by sediment stores such as barriers, buffers and blankets. Channel-valley floor connectivity can be influenced by flood frequency-magnitude relationships and also by channel incision. Incised channels lead to increased channel capacity, limiting flooding of the valley floor and reduce the associated potential for sediment deposition. Furthermore, all the drivers are affected by the magnitude and frequency of rainfall events, where large infrequent events breach most buffers, barriers and blankets. This influence of event magnitude makes it challenging to assess when linkages become active sediment conductors.

Connectivity is proposed as a framework for a sediment study in the Vuvu catchment of the upper Thina River. By applying connectivity concepts, a catchment-wide understanding of sediment transfer processes can be developed and integrated into a channel reach scale understanding of sediment transfer and deposition. This study will focus on the hillslope-channel connectivity and channel-valley fill connectivity. Hillslope-channel connectivity has been studied in several settings by researchers worldwide and through various models, but channel-valley floor connectivity largely has been neglected in the current literature. This study aims to develop the current understanding of the present-day and historical sediment dynamics in these high altitude, high rainfall catchments at a catchment scale and channel reach scale and improve the channel-valley floor connectivity concept.

3 A methodological framework for assessing connectivity at the catchment and reach scale

This section presents the methods used to describe connectivity in the Vuvu catchment at the hillslope, valley floor and catchment scales. Results are presented in as far as they help to explain the methods used and demonstrate their relevance to the research. Methods are not independent of one another and in a number of cases the application of one method depends on the results of another.

3.1 Identification and characterisation of sediment sources, pathways and sinks

3.1.1 *Characterising the catchment*

The catchment is the basic aerial unit of study so it is important to first capture its key attributes. Catchment data were extracted and manipulated using a GIS (ArcInfo 10.0).

Digital topographic data in the form of shape files were obtained from the Chief Directorate: National Geo-spatial Information, South Africa). This included 20 m contours and river lines captured from 1: 50 000 maps.

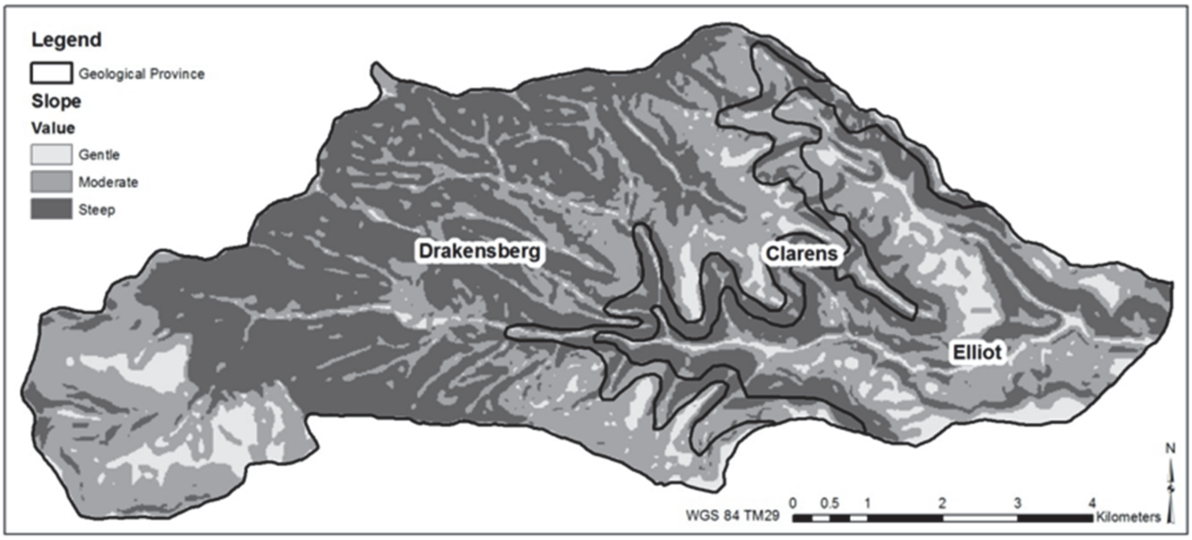

Figure 3.1 Slope map of the Vuvu study catchment created from the 20 m contour DEM .

A 20 m DEM was created using the Interpolate tool applied to the 20 m contour data. This was used to delineate the catchment boundary and to generate a slope and aspect raster data set using the Surface toolset in ArcInfo 10.0. Three slope classes that reflected the stepped nature of the landscape were assigned: gentle (<5°), moderate (5–20°) and steep (>20°). The resulting slope distribution is shown in Figure 3.1. Aspect was categorised by two groups representing north (284–109°) and south (110–283º) facing slopes, reflecting the observed distribution in the catchment.

Geological formations (Figure 1.2) were digitized off a hard copy 1:250 000 geological map (De Decker, 1981). Areas of the catchment, the different geological formations, slope and aspect classes were calculated using a GIS (Arc Map 10.0). The natural river network was assumed to match that provided by the river line shape file.

3.1.2 *Mapping sediment sources*

The methods used to classify, map and characterise sediment sources were based largely on a desktop study capturing data from aerial images using a Geographical Information System (GIS), with field visits to ground truth a selection of the features. Digital colour aerial images from 2009 (0.5 m resolution; acquired from Chief Directorate: National Geo-spatial Information, South Africa) were used

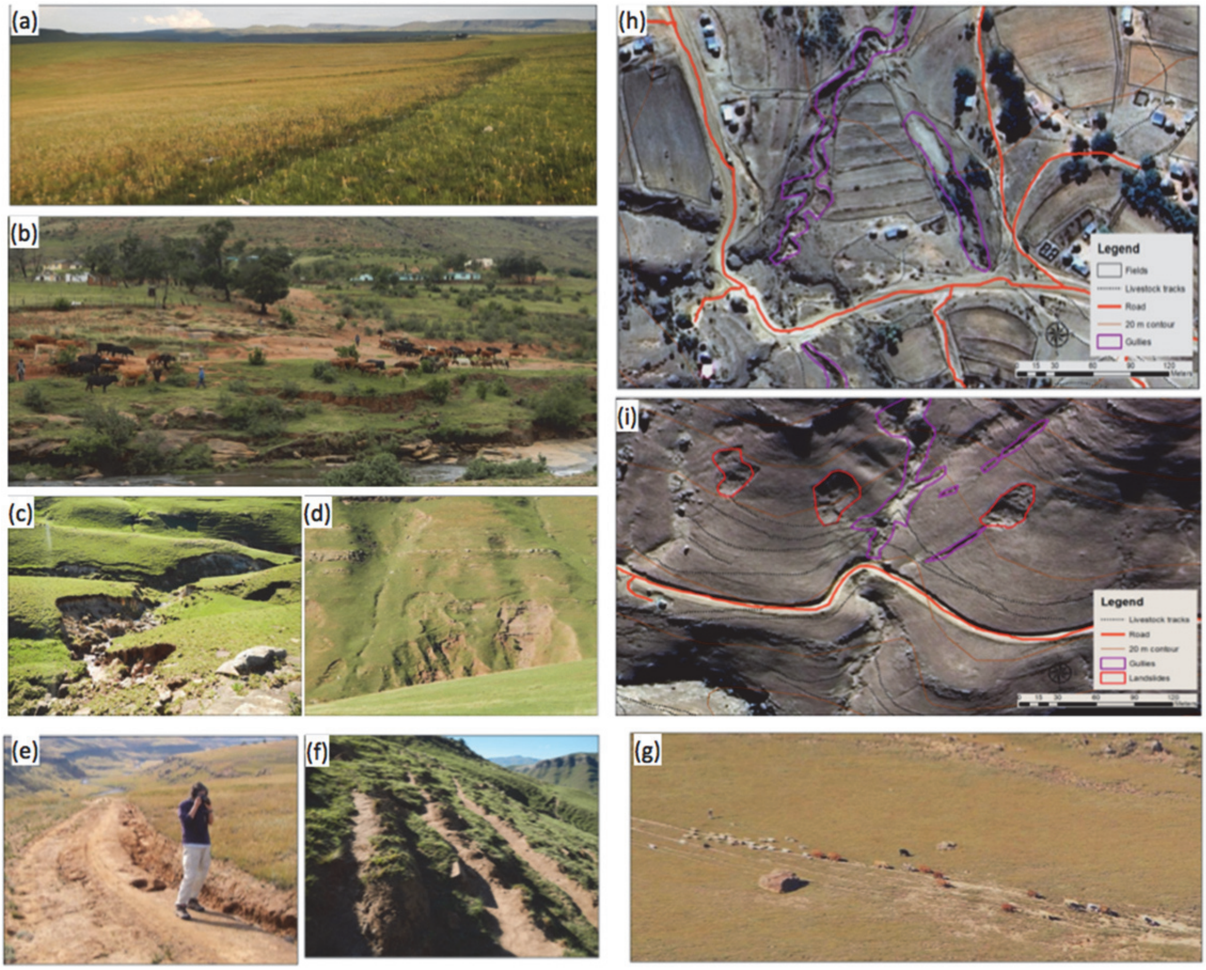

Figure 3.2 (a-d) sediment source types: (a) abandoned field (b) sheet erosion near dip tank (c) gully erosion ((d) landslides (e) roads f-g) livestock tracks (h-i) mapping erosion features, tracks and roads.

in ArcInfo 10.0 to digitize active hillslope sediment sources at a scale of 1:2000 for the entire Vuvu catchment.

Several field visits were conducted (since 2010) before the mapping started, which aided the process of photo interpretation. Geo-tagged land based photos taken during field trips also helped with aerial image interpretation.

The aerial images were colour adjusted to optimise the contrast between the various erosional features. The best results were achieved by using a RGB (Red Green Blue) composite that had a stretch value of 2.5 standard deviations. The brightness was adjusted to negative 10%. Automated extraction of bare areas was attempted as an objective method to identify or verify erosional features. However, the use of GeoEye satellite images (2 m resolution) to calculate Normalised Difference Vegetation Index (NDVI) values as an expression of bare soil and areas with active surface erosion (Kakembo et al., 2006) proved unsuccessful due to similarity between bare soil and rock.

The main sediment sources identified in the study area were agricultural fields, abandoned fields, sheet erosion (not on fields), gullies, landslides, roads (gravel) and livestock tracks (Figures 3.2). Fields were identified as rectangular or trapezoidal areas with linear edges and a clear differentiation in vegetation over the boundary (Figure 3.2a). Abandoned fields were identified as fields that had not been cultivated recently (i.e. with no plough lines visible) and lacked fencing. Areas of sheet erosion were identified as shallow, ill-defined patches with bare soil that often also incorporated areas of badland or rill erosion as defined by Foster et al. (2007) (Figure 3.2b). Gullies were considered large (>2 m or 3 to 4 pixels wide), incised, linear erosional features with steep sidewalls that concentrate flow mainly in a down-slope direction (Figure 3.2c,h). Recent, relatively active landslides (not covered by vegetation) included features with a clear rounded upper rim and lower rock-waste line, where the material was deposited (Figure 3.2d). Dirt roads were easily identifiable as they were larger features (>2 m wide) of a constant width, often following the contour and linking homes to the main dirt road that traverses the lower catchment (Figure 3.2f). Livestock tracks were observed in the field to be narrow (<2 m wide) shallow linear features, mainly following the contours (crossing slopes) or ridge lines (Figure 3e,g). Only sections that were clearly visible were digitized.

Fields, gullies, sheet erosion and landslides were captured as polygons (Figure 3.2h,i), roads and livestock tracks were digitized as line features (Figure 3.2h.i). In order to calculate the area of roads and livestock tracks, lengths were multiplied by the average width of 4.04 m (standard deviation of 1.82 m; n = 24) and 0.79 m (standard deviation of 0.45 m; n = 21) respectively. These averages were based on field and air photo observations for the Vuvu catchment.

A further refinement of the data was required to correct for possible bias arising from shading of steep southwest facing slopes on the aerial photographs. Due to the steep slopes and position of the sun (northeast) at the time of 2009 aerial photography, steep southwest-facing slopes were often shaded, preventing the identification of erosional features (Figure 3.3a). This led to an aspect bias in the analysis. The following process was carried out in order to identify and remove shaded areas from the analysis. The colour images were first converted to greyscale images (255 values). Shaded areas were extracted from the aerial image using a greyscale raster extraction for cell values below 60 (very dark areas). The output was converted to a ‘shaded area’ polygon feature. Shaded areas less than 250 m^2 were removed and polygons with jagged edges were simplified using the bend option of the Simplify tool (reference baseline of 5 m) to preserve the essential shape of the features (Figure 3.3b). The ‘shaded area’ polygon was used to erase any intersecting parts of digitized features in other shapefiles and to correct for area calculation

This ‘shaded area’ shapefile also included areas where black soils were exposed on north-facing slopes. These were removed manually from the ‘shaded area’ shapefile so that the areas with black soils would be retained in the subsequent feature analysis.

Source areas were further categorised in terms of slope, aspect and geology. Slope and aspect data were extracted for source polygons by using the Extract by Mask tool (slope and aspect) and the Intersect tool (geology). A measure of connectivity was assigned to each source polygon based on whether a feature was intersected by a continuous gully or a drainage line. The intersection of fields by other erosion features (in addition to gullies) was also derived.

Statistics that described the topographic character of the catchment, the area of each geological provinces (regions) and the various source types were calculated using ArcInfo 10.0 GIS. Statistics included: area of features, percentage of total area (by catchment or geological province), percentage that was shaded area, slope, aspect, connectedness to the river network, percentage of fields that were

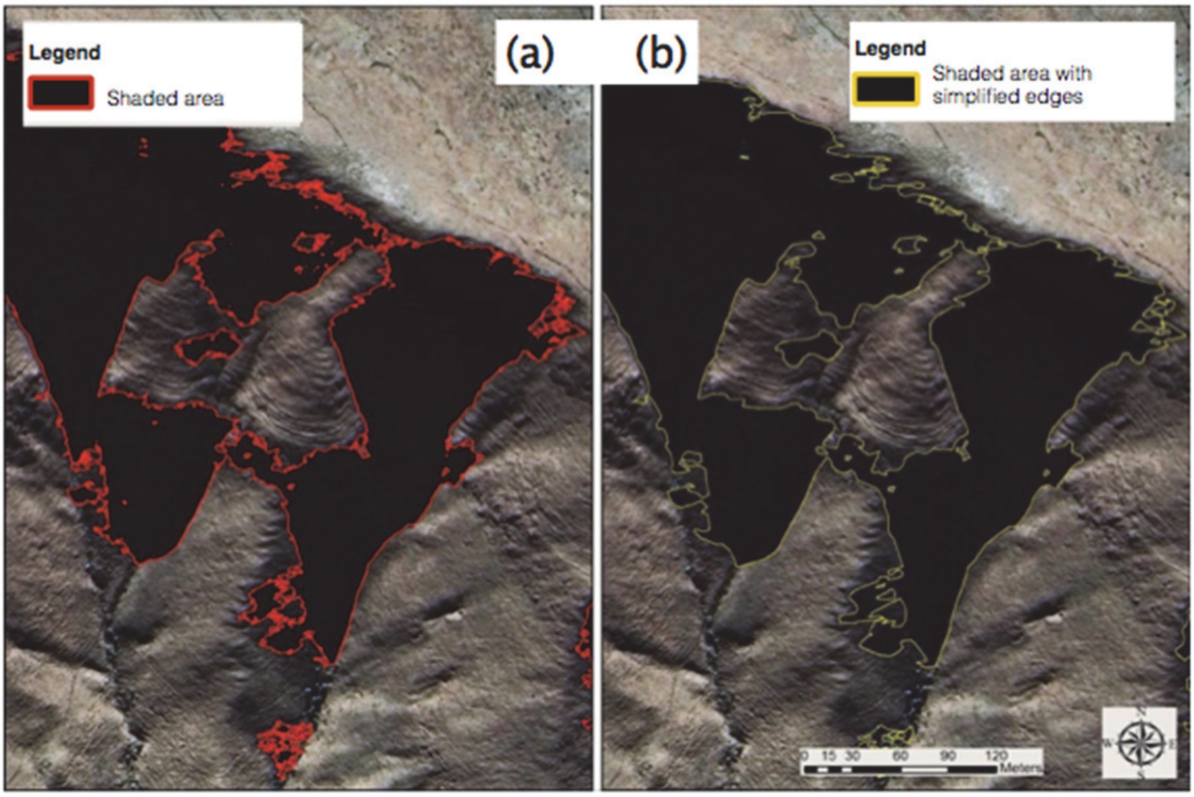

Figure 3.3 2009 colour aerial image showing shaded areas (a) and simplified edges of shaded areas on south-facing slopes (b).

recently cultivated and percentage of features located on fields.

Volumetric estimates of sediment loss were made for each of the source types. A depth reading was taken for each individual feature visited in the field during sediment source sampling (see section 3.6.2) at a point that was thought representative of the average depth of that feature. Based on these field measurements, the average depth for an erosion type, e.g. gully, was calculated. GIS based area data were used in conjunction with the field based depth measurements (gullies, sheet erosion, landslides, roads and livestock tracks) to calculate the approximate volume of soil lost from the various features. The volume contributed by the various features was converted to mass using a bulk density of 1.55 g cm^{-3} (1.55 tonnes m^{-3}) (Flemming and Hay, 1984; Brady and Weil, 2008).

Table 3.1 a) Volumetric estimates and average soil loss for catchment-wide source features. b) Volumetric and soil loss estimates for each of the geological provinces.

(a) Feature	Area (ha)	Depth (m±SD)	Volume (m^3)	Years active	Soil loss (t ha^{-1} y^{-1})
Fields (n = 30)	257.8	0.24 ± 0.08	607 936	50	73
Gully erosion (n = 46)	49.5	1.37 ± 0.90	678 679	50	425
Sheet erosion (n = 36)	106.4	0.58 ± 0.19	618 037	50	180
Landslides (n = 11)	1.3	1.72 ± 0.38	22 968	10	548
Roads (n = 24)	11.8	0.47 ± 0.42	55 554	30	146
Livestock tracks (n = 21)	50.3	0.20 ± 0.10	98 542	50	61
Total for eroded features	**477.1**		2081716		
Total for catchment	**5329**		**2081716**		**12**

(b) Feature	Volume (m^3) Elliot	Clarens	Drakensberg	Soil loss (t ha^{-1} y^{-1}) Elliot	Clarens	Drakensberg
Fields	417 235	5 282	185 419	9.5	0.3	1.7
Gully erosion	235 360	22 417	420 902	5.4	1.3	3.8
Sheet erosion	232 228	32 165	353 644	5.3	1.9	3.2
Landslides	12 370	83	10 515	1.4	0.0	0.5
Dirt roads	55 554	0	0	2.1	0.0	0.0
Livestock tracks	35 116	9 076	56 439	0.8	0.5	0.5
Total volume eroded features	**9 87 863**	**69 023**	**1 026 919**			
Catchment area (m^2)	**1355**	**529**	**3444**	**23**	**4**	**9**

The length of time the source features had existed was estimated based on their extent on the earlier aerial images (1956, 1975) as described in section 3.1.3. Aerial photo evidence indicated that the majority of fields, gullies, sheet erosion and livestock tracks were all initiated at more or less the same time (±50 years ago), whereas roads (±30 years) and landslides (±10 years) were more recent or short-lived features. Landslides were only active for a relatively short period as they were observed to be stabilised by vegetation several years after formation. These data allowed for a sediment loss (t ha^{-1} y^{-1}) to be calculated for each of the features. Results are given in Table 3.1. Gullies, sheet erosion and fields accounted for 91% of an estimated sediment loss of 12 t ha^{-1} y^{-1}. Landslides accounted for the highest sediment loss per unit area but were very localised so their overall contribution was minimal.

Certain of the largest gullies were already well developed by 1956. Historic aerial photographs were used to reconstruct the evolution of gullies in the Vuvu and adjacent Phiri-e-nsto catchments as described below.

Historical change in gully area and current stability

(a)

(b)

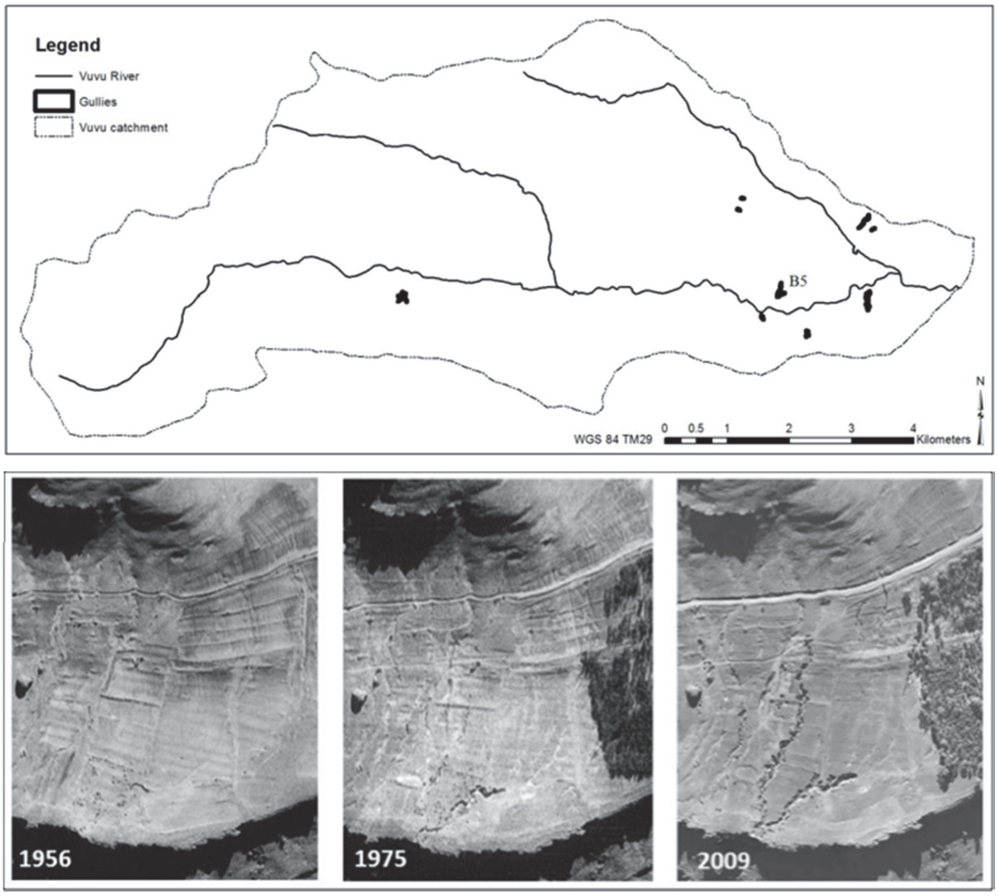

Figure 3.4 (a) Location of sample gullies (b) evolution of gully B5 between 1956 and 2009.

Selected gullies were mapped from aerial photos for 1956 (scale 1:30 000), 1975 (scale 1:50 000) and 2009 (georeferenced ortho photos, 0.5 m resolution). The 1956 and 1975 photos were of a reasonable definition (despite the smaller scale of the 1975 photographs) and allowed for relatively equally spaced temporal succession of the photos. These earlier photos were georeferenced against the 2009 photos using the adjust transformation in ArcInfo. Large boulders and rocky outcrops were used as georeferencing control points as they were commonly found throughout most of the landscape, were easily identifiable and proved to be stable over the 53 year period. Care was taken to use as many control points as possible, especially around the targeted gully features. Between 50-100 control points were used per image, minimising the root mean square error to below 0.01.

Due to the small scale and variation in image quality across the different years, only the larger gullies (2009 length >50 m) could to be digitized accurately (Martínez-Casasnovas, 2003). Nine gullies were identified as being suitable for analysis (Figure 3.4a). The aerial photos for the three dates were used to map the change in gully area over time. An example of gully evolution over this time span is shown in Figure 3.4(b). The data were plotted as a time series and a logarithmic trendline was fitted to predict the potential initiation date of the features (Harvey, 1992) (Figure 3.5). The results were compared with those obtained by Huber (2013) for gullies in the adjacent Phiri-e-ntso catchment.

Further evidence of gully activity was provided by field assessments made of a stratified random selection of gullies sampled for sediment tracing. Gullies showing signs of expansion were categorised as active, those that were well vegetated with minimal signs of expansion as relatively stable.

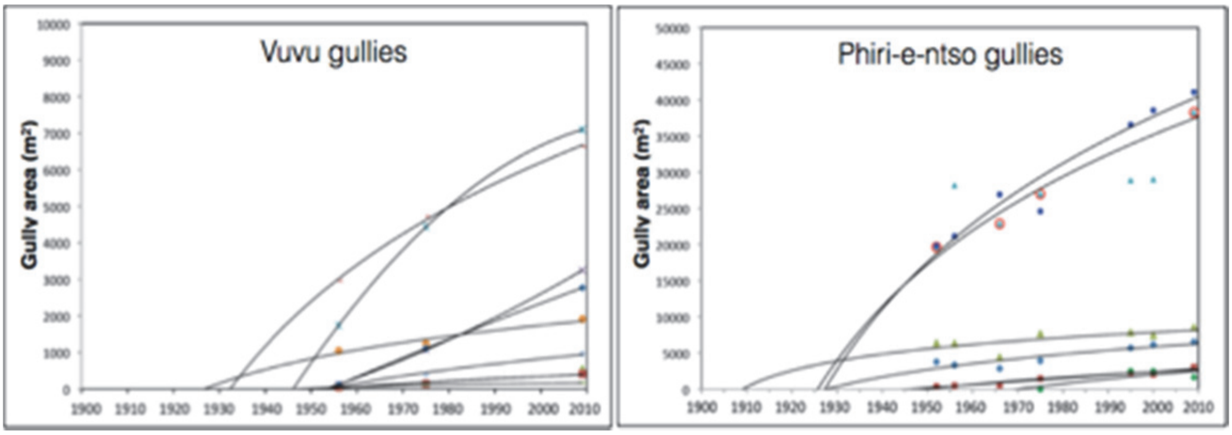

Figure 3.5 Gully evolution in the Vuvu and Phir-e-ntso. Phiri-e-ntso gullies surveyed by Huber (2013)

3.2 Classify, map and characterise valley floor sink features

3.2.1 *Classification of sink features*

Sink features represent sediment deposits that store material transported from the upstream/upslope catchment. The following sink features were identified in the valley floor of the Vuvu: alluvial fans, terraces and flood benches and instream cobble bars (Figure 3.6).

Alluvial fans were defined as sediment deposits with a conical shape that radiates downslope from the point where a tributary stream loses confinement (Bull, 1972). Fans act as buffers that store sediment and reduce hillslope-channel connectivity (Fryirs et al., 2007a).

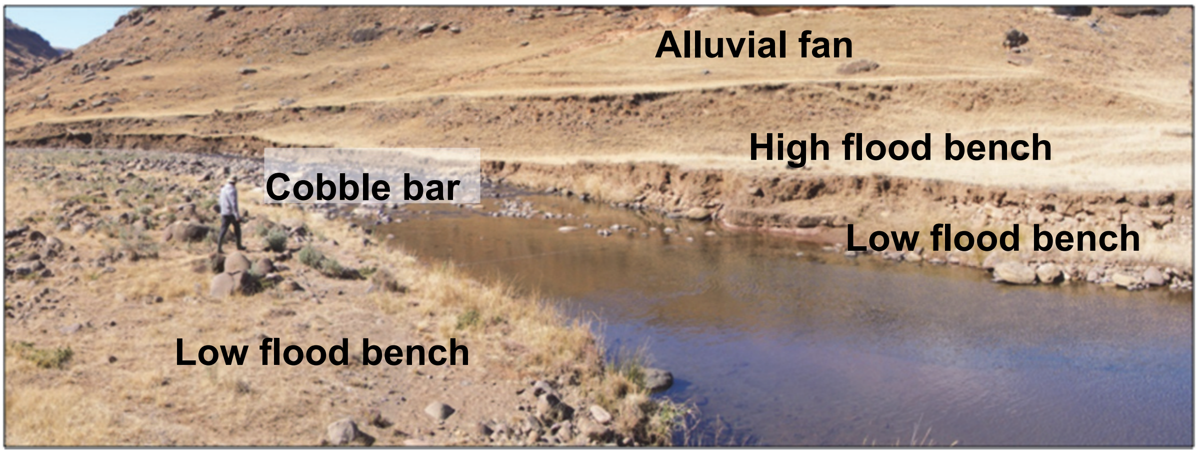

Figure 3.6 Classification of valley floor and margin sink features

Terraces were defined as flat elevated alluvial levels or old flood benches that were no longer thought to be inundated during large floods (Pazzaglia, 2013). Terraces lined the outer parts of the valley fill and were located high above the current water level, being indicative of former flood levels that were abandoned as a result of river incision. Terraces often act as buffers as the level surface of the feature reduces hillslope-channel connectivity.

Flood benches were defined as the relatively flat sediment deposit adjacent to the river channel that is inundated during contemporary floods (Rosgen, 2008). The flood benches have a similar function to floodplains in larger lower gradient systems, but are not continuous and are narrower. Flood benches are seen as buffers that store sediment and increase hillslope-channel but reduce longitudinal connectivity (Fryirs et al., 2007a). Both terraces and flood benches consisted of horizontally layered fluvially deposited sediment. Flood channels were identified on some of the flood benches.

Cobble bars mainly stored gravels, cobbles and boulders that do not form part of the fine sediment load that responds most readily to changes in connectivity. Their role as sediment sinks was not considered further.

3.2.2 *Mapping sink features*

Large scale (1:1 000) geomorphological maps of the Vuvu valley fill sink features were constructed based on the high resolution colour aerial photographs (0.5 m resolution; 2009) and topographic surveys as recommended by Pavlopoulos et al. (2009). An Epoch 35 Differential Global Positioning System (centimetre accuracy) was used to survey valley cross sections and along valley features (terraces, flood channels and main channel), noting clear breaks in slope, landscape features and changes in sediment composition. Fifteen transects were surveyed along a 2 km section of the lower Vuvu valley fill (Figure 3.7). The features were classified according to the survey results, field observations and remote sensing. A detailed map of the valley bottom was drawn by overlaying the surveyed transects and features on a high-resolution aerial image in ArcInfo 10 (Figure 3.8).

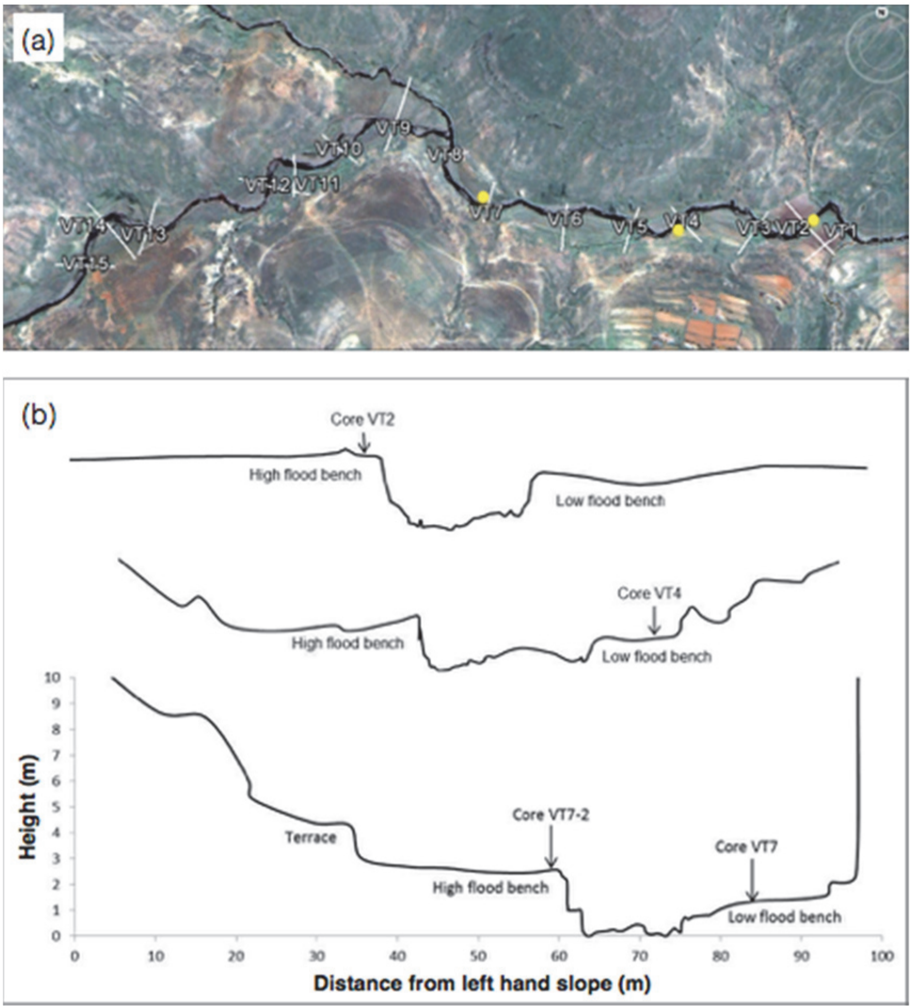

Figure 3.7 (a) Location of transects along the Vuvu valley floor (b) Location of cores on Transects VT2, VT4 and VT7. Core locations also shown as yellow markers on (a).

Evidence such as slope, sediment composition and size of features, together with changes in vegetation, was used to extrapolate field based evidence onto the map.

Flood benches were the most recent main sediment sink in these valley fills. Their total area of flood benches was calculated in the GIS in order to estimate the volume of sediment that has been stored recently on the valley floor.

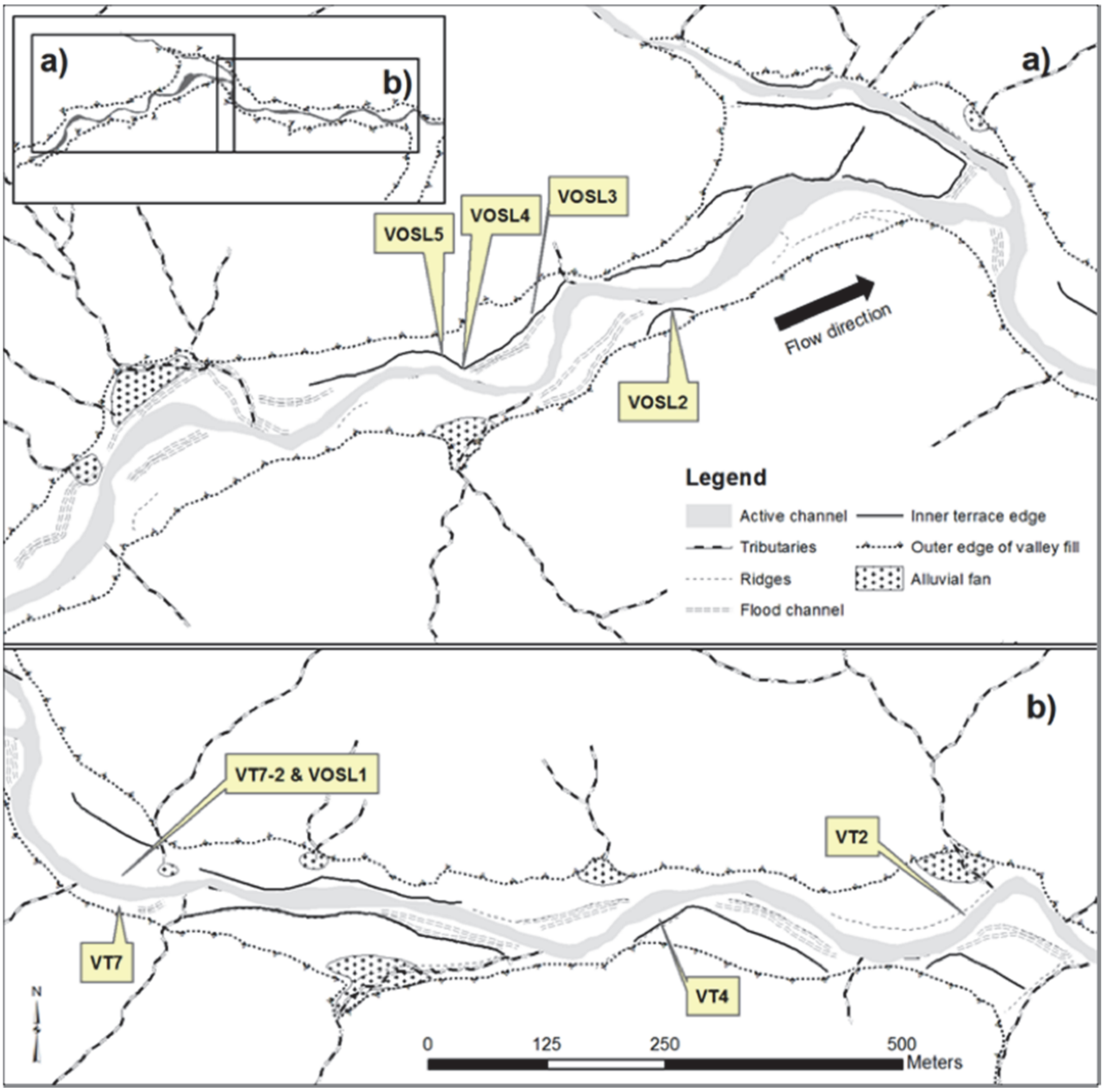

Figure 3.8 Map of valley floor and valley margin sinks.

3.2.3 *Historic mapping*

Recent valley fill and channel dynamics were further assessed using historical aerial images. Aerial images for 1956, 1966 and 1975 were georeferenced to the georectified aerial images for 2009. The active channel along the Vuvu valley fill was digitized for each set of images so that the channel location and shape could be compared between dates. Sections where the river had abandoned a channel or had been straightened were identified from the aerial images (Figure 3.9a). Only two suitable sites could be identified along the Vuvu River. An additional four sites were identified and surveyed along the Phiri-e-Ntso River which had similar hillslope-channel connectivity increases and evidence of incision.

Transects across these straightened channels were surveyed using a differential GPS. It was assumed that the abandoned channel bed, consisting of cobble, would remain stable and fine sediment would slowly accumulate above it, thus preserving the former channel bed elevation. A gouge corer was used to systematically core down to a cobble layer where the abandoned channel had been identified from the aerial images, recording distance along the transect and depth below the surface. The coring data were combined with the surveyed profile to give the buried profile of the abandoned channel in relation

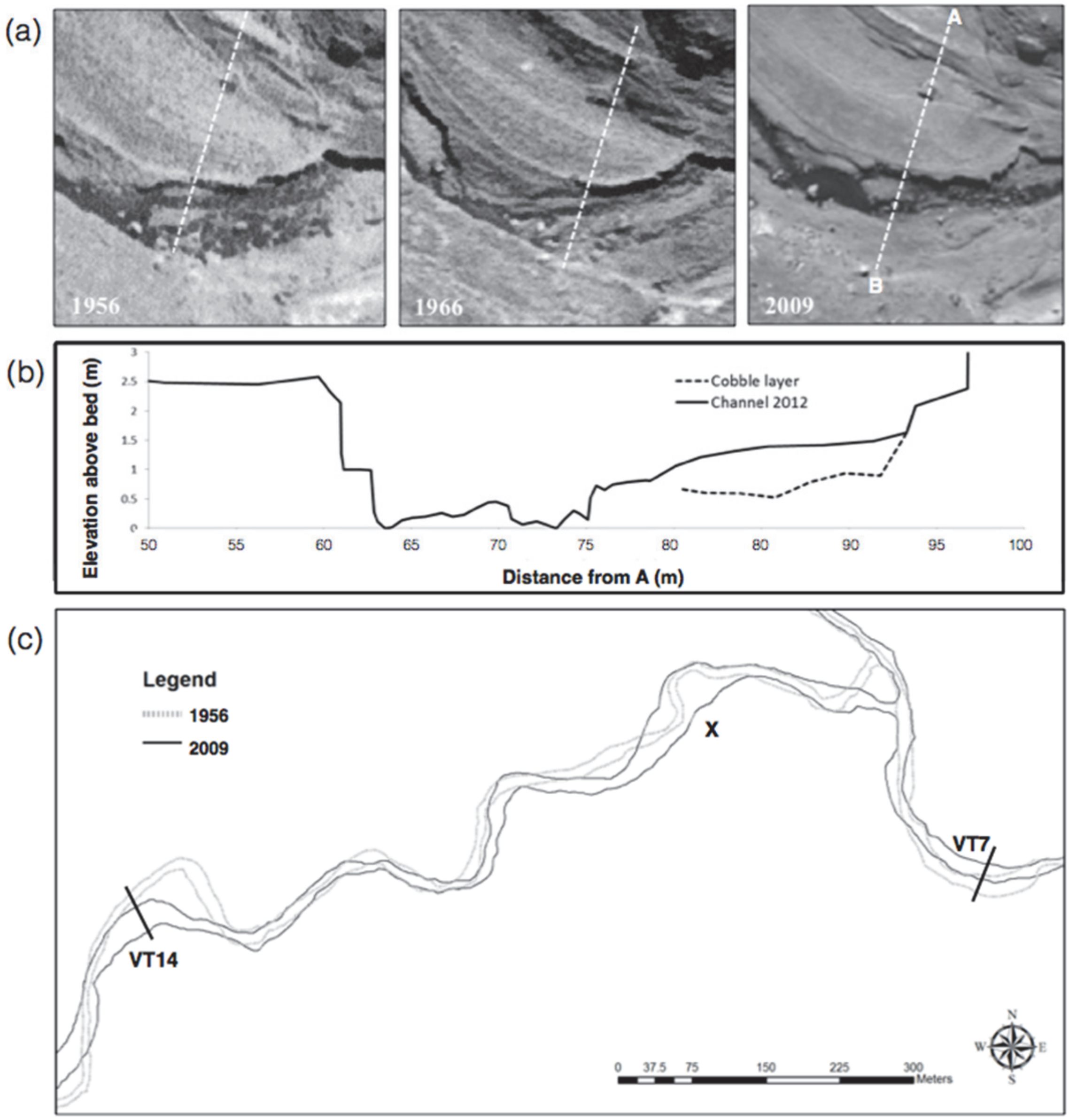

Figure 3.9 (a) Aerial images for VT7 showing the movement of the channel in a northerly direction from 1956 to 2009 and the accumulation of sand on the southern lower flood bench (1966 to 2009). (b) The cross section AB shows the channel profile at VT7 surveyed in 2012 and the depth of the cobble layer in the southern flood bench. (c) The channel has straightened from 1956 to 2009 (cross section VT7 and VT14 indicated). Note the channel widening at VT14 and X.

to the current channel (Figure 3.9b).

The difference in elevation between the active and abandoned channel was calculated based on the average of the five lowest points along each of the six channel profiles (active and abandoned) to determine the degree of incision. Timing of incision was inferred from the photographs, together with evidence from dating (section 3.2.5).

3.2.4 *Characterising sediment sinks*

To determine sediment sink characteristics, and the chronology of recent deposition, four vertical cores were taken from flood benches using an Eijkelkamp percussion corer (nose diameter 4.5 cm), targeting two frequently inundated lower flood benches and two higher lying flood levels that were likely to be inundated less frequently (Figure 3.8). The location of cores was spread along the lower reach of the valley fill (VT2, VT4 and VT7; Figure 3.7). Care was taken to core undisturbed parts of the floodplain where horizontal sediment layering was clearly visible throughout the sequence. Large areas of the valley fill has been ploughed for agriculture, limiting the availability of undisturbed sites suitable for coring. All cores were taken from the upper sandy sequence until a cobble layer was encountered (often visible in the bank). The cores ranged between 60 and 120 cm and were cut into 2 cm slices (30 to 60 samples per core).

In the laboratory, slices were dried for 48 hours at 40^{0}C to preserve their magnetic properties that were to be used in the tracing study (section 3.6). To reduce sample numbers due to time and budget constraints, every second slice was analysed for particle size distribution using a Malvern Mastersizer 3000 (<2 mm fraction). Organic content was calculated using loss on ignition at 450^{0}C over 12 hours. Grade scales for particle size were used as given by Gordon et al. (2004). A sorting index (using the D10, D50 and D90) as given by Andrews (1983) was used to evaluate the degree of sorting of each sample. Results are shown in Figure 3.10. The core samples were also used for establishing a sediment chronology using Cs-137 and Pb-210 dating techniques (Section 3.2.5) and for sediment tracing using magnetic fingerprints (Section 3.6).

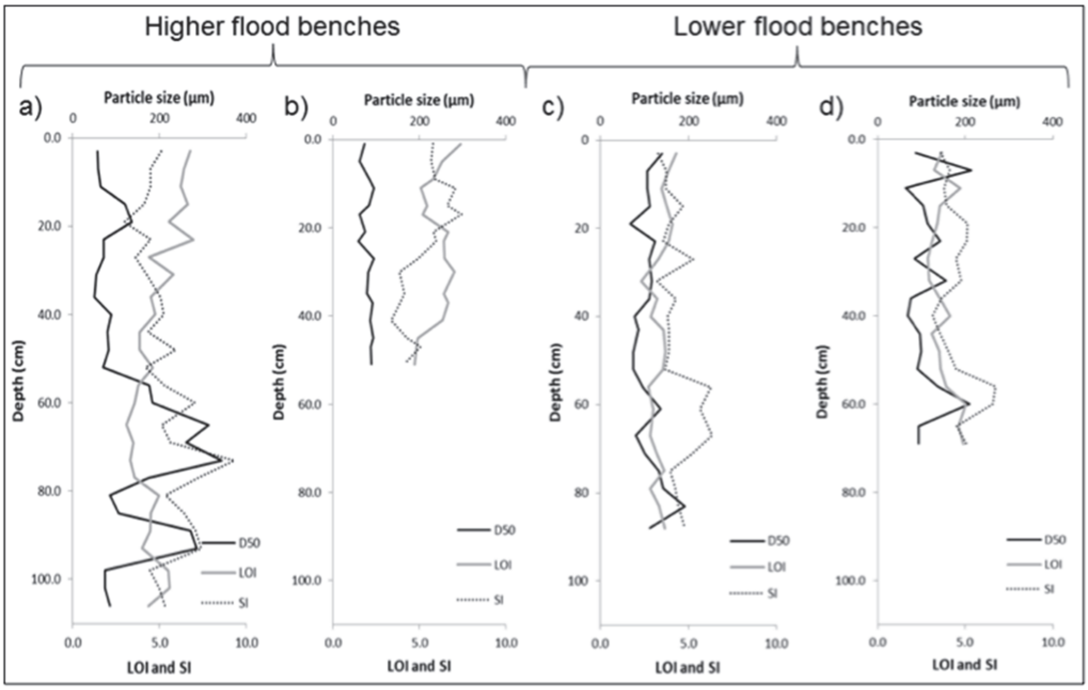

Figure 3.10 Particle size data (D50), loss on ignition (450 ^{0}C) and Sorting Index (SI) data for cores: a) VT2, b) VT7-2, c) VT4 and d) VT7.

Palaeo-channels in exposed river banks and high lying terraces along the valley fill were up to seven meters above the current river level and thus assumed to be much older than the lower flood benches. These features were relicts of former valley fill levels; thus, if dated successfully they would indicate when these features were abandoned or became sediment sinks (Rodnight et al., 2006). OSL dating was used to date these features and proved useful as OSL dating spans a large temporal range and sediment from the Vuvu catchment contains sufficient quarts grains for analysis. As OSL dating was expensive, sample numbers were limited to five samples (2 palaeo-channels, 2 terraces and 1 terrace/high flood bench).

The bottom of sand filled palaeo-channels or the lower section of a sand deposit on a high lying cobble terrace was targeted for OSL sampling (Figure 3.11). Care was taken to sample layers that were clearly sorted and striated, thus being true fluvial deposits. The OSL sampling was done at night (using red light) to prevent white light from bleaching the quartz grains. The vertical face, 15 cm above the cobble layer, was cleaned in order to remove any sediment contaminated by white light (removed a 5 cm deep layer of sediment from the vertical surface). A 30 cm horizontal core of sediment was sampled using an Eijkelkamp percussion corer and the sample was packaged in tough black light-tight packaging. A bulk sample was collected from around the cored hole for gamma analysis, magnetic characterisation, particle sizing and loss on ignition analysis.

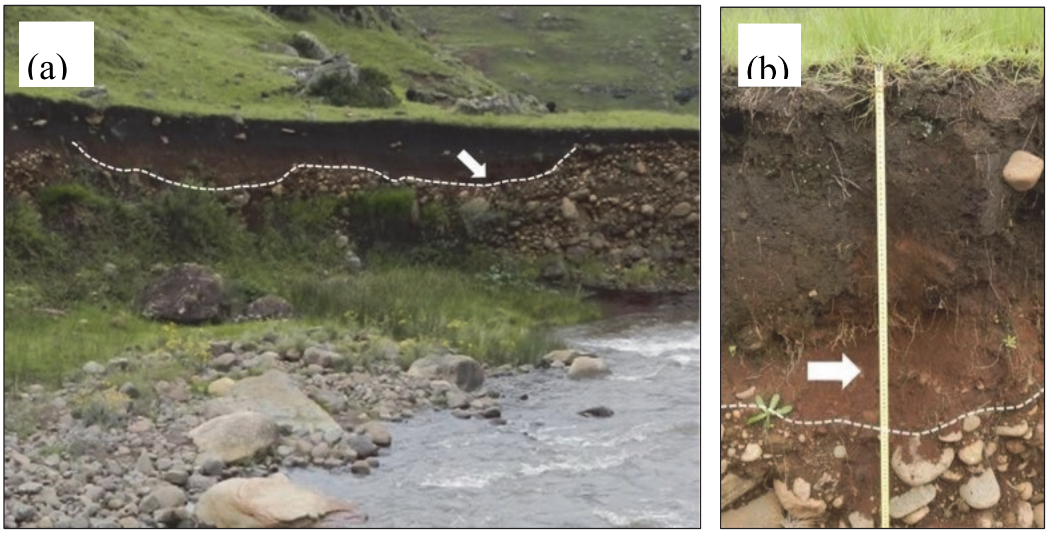

Figure 3.11 The interphase between cobble and sand (dashed line) and the position of OSL samples (arrows) in (a) a palaeo-channel and (b) a terrace.

3.2.5 *Sediment chronology*

The chronology of sediment sequences indicates when the features became active sediment stores and when they were abandoned. The varying rates of sediment accumulation over time can also be assessed. The resultant chronology of floodplain sedimentation was used to calculate the Sediment Accumulation

Rate (SAR) (He and Walling, 1996), test for recent river channel-flood bench connectivity and timing of changes in source material.

Various dating techniques were used to date the valley fill features. Pb-210 in combination with Cs-137 was used to date the more recent flood benches (maximum dating range <88 years) (Saxena et al., 2002; Saint-Laurent et al., 2010; Du and Walling, 2012) and historical aerial images were used to verify flood bench dating and river dynamics. Optically Stimulated Luminescence (OSL) dating (dating range of 300–100 000 years) was used to date paleo-channels and terraces (Olley et al., 1998). OSL dating is based on the bleaching of quartz grains by sunlight and subsequent burial of the grains allows the time of last exposure to be dated (Duller, 2004).

Radio nuclide dating

Pb-210 is a radionuclide that has continuous natural fallout with a half-life of 22.3 years and is detectable for up to 100 years in stable lake environments (Appleby et al., 1986; Du and Walling, 2012). Dating of sediment is based on the decay of Pb-210, assuming that the rate of supply from the atmosphere is constant. Cs-137, on the other hand, is an anthropogenic radionuclide that was first present in the atmosphere during the time of atmospheric thermonuclear testing (late '50s to mid '60s) and only appeared in the Southern Hemisphere around 1958 (Foster et al., 2007). Cs-137 can thus be used as a marker horizon since all sediment containing Cs-137 has been deposited post 1958 (Foster et al., 2005).

Pb-210 dating was first used for dating sediments from lake environments, but recently the method was successfully applied to floodplain environments using the Constant Rate of Supply (CRS) model (Saint-Laurent et al., 2010; Du and Walling, 2012; Manjoro, 2012). Pb-210 can be detected in two forms in sediment – supported and unsupported. Pb-210 dating is based on the activity of the unsupported Pb-210 in a sample that is influenced by the radioactive decay of Pb-210 and the dilution of Pb-210 by sediment contributions. There are two sources of Pb-210 in sediment samples, both related to the U-238 decay series. The first is produced by *in situ* decay of Ra-226 (supported Pb-210), the second by Rn-222 (daughter isotope of Ra-226) that escapes into the atmosphere and forms Pb-210 that is a wet fallout assumed to be uniform through time (unsupported Pb-210). Unlike lake sediment, floodplain sediment is not constantly inundated by water and the sediment particle size is likely to be greater, therefore a proportion of the Rn-222 is expected to escape from the sediment. An emanation coefficient of 0.3 was used to adjust the supported Pb-210 values in order to compensate for the loss of Rn-222 (mother isotope), as recommended by Du and Walling (2012). The unsupported Pb-210 was calculated by subtracting the supported Pb-210 from the total Pb-210. This result was used in the composite CRS model, as this model proves to be reliable in areas with varying sedimentation rates, especially if Cs-137 is used to adjust the CRS age (Appleby, 2001; Du and Walling, 2012). Further details of the method can be found in Appleby (2001) and Du and Walling, (2012).

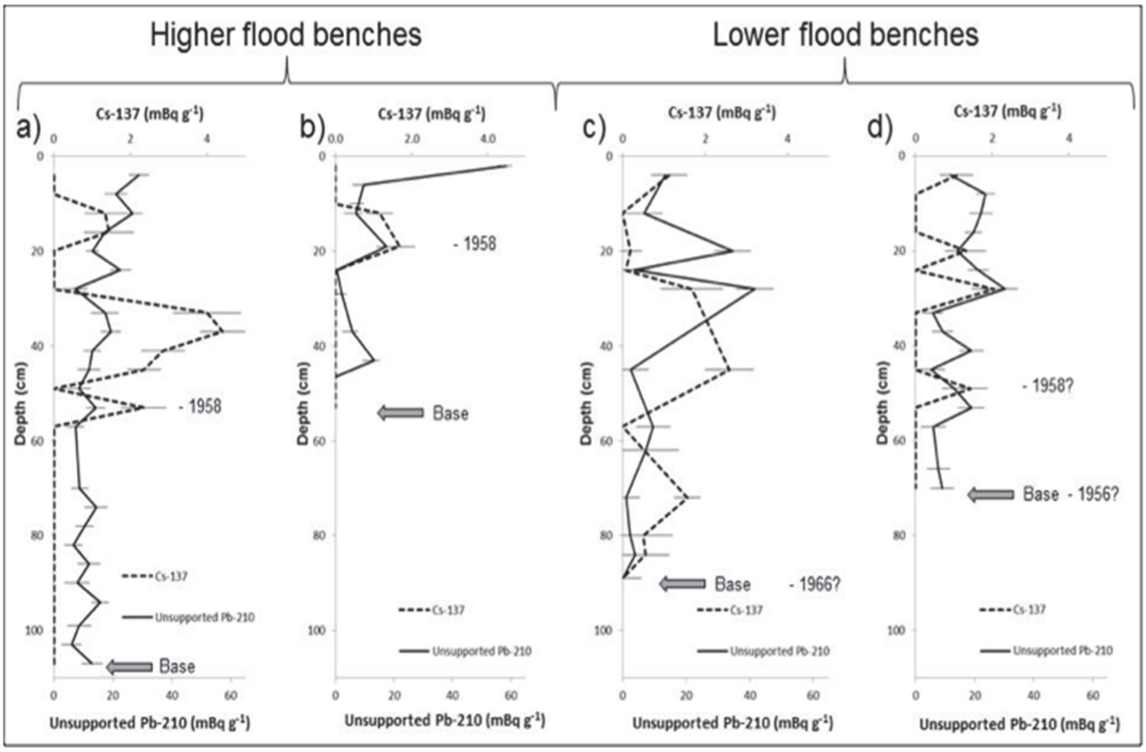

Figure 3.12 Cs-137 and unsupported Pb-210 data for cores: a) VT2, b) VT7-2, c) VT4 and d) VT7.

Pb-210 dating has some shortcomings that might limit its application to the Vuvu sediments. Unsupported Pb-210 delivery is dependent on rainfall, thus drier areas with a higher coefficient of variation will have a varying unsupported Pb-210 input (Appleby, 2008). High spatial and temporal rainfall variability, including wet and dry cycles, could lead to an uneven delivery and distribution of Pb-210. Another shortcoming noted by Appleby (2008) is that in areas with rapid sediment accumulation Pb-210 concentrations are diluted and, if the surface (peak) activity is lower than 100 mBq g^{-1}, could limit the dating horizon to three to four half-lives (e.g. 66–88 years) instead of six half-lives. Peak counts in the Vuvu sediments were in the region of 60 mBq g^{-1}, thus dating was limited to a maximum of 88 years.

Cs-137 was used as an absolute marker in floodplain cores. The first detection of Cs-137 from the bottom of the stratigraphic core was used to indicate 1958, the start of the Cs-137 peak fallout in the southern hemisphere (Foster et al., 2007) while Cs-137 peaks are commonly used to mark a date of 1965, the time of peak fallout. As clear Cs-137 peaks were generally absent from these cores, the first detection of Cs-137 was used as the 1958 marker in the composite Cs-137 and Pb-214 CRS model. Channel shifting identified from historical aerial images was used to verify the Cs-137 marker horizons. Sequential aerial photographs were assessed to determine the earliest date of possible sediment deposition. If a core location was in the channel in an aerial image, the date of the bottom of the core was adjusted to the date of the image, assuming that sediment deposition at the core location started soon after the date of the photo.

Samples taken from the four cores described previously were used for dating. After drying at 40ºC and sieving, the <250 µm fraction was taken for dating as radionuclides are preferentially adsorbed by the finer fractions. Detection of radionuclides was carried out using an Ortec gamma spectrometer. Gamma vials were filled with sediment to the depth (4 cm) of the hyper pure germanium well. Samples were sealed with paraffin wax and left to equilibrate for 21 days before being counted. This is necessary for the accurate detection of unsupported Pb-210 (Foster et al., 2007). A background spectrum was generated by counting an empty vial for 10 000+ seconds. The background was stripped from counted spectra and the resultant spectra were analysed using GammaVision® software. Emissions were counted for 180 000+ seconds to allow for the detection of low radionuclide activity at the 95% level of confidence. Detectible limits for Cs-137, Pb-214 and total Pb-210 were 0.8, 2.2 and 2.5 mBq g^{-1} respectively.

Unsupported Pb-210 and Cs-137 was plotted against depth for the four cores as shown in Figure 3.12.

OSL dating

All OSL samples were screened for the presence of Cs-137 or unsupported Pb-210 before they were sent to the Geo-luminescence Laboratory at WITS University for OSL dating. Samples containing Cs-137 or unsupported Pb-210 were assumed younger than ca. 88 years and were excluded from OSL dating as it falls outside its dating range. One abandoned-channel (1 metre above the current channel) tested positive for unsupported Pb-210 and was omitted from the OSL analysis.

At the Geo-luminescence Laboratory 2 cm of sediment was removed from either end of each core for water content and dosimetry analysis for Thorium, Uranium and Potassium (gamma analysis done by iThemba Labs, South Africa) (Evans, 2014). OSL measurements were done on ca. 30 grains per sample, ranging from 180–212 µm, following the single aliquot regenerative protocol as given by Murray and Wintle (2003). Samples were treated with additional infra-red light before OSL measurement to reduce any contaminating signal from feldspar grains (Evans, 2014). The minimum-age model was applied with a sigma_b of 12% (Cunningham and Walling, 2010). Further details can be found in the OSL dating report by Evans (2014) in Appendix 2.

Results given in Table 3.2 show that the oldest channel infill was dated to approximately 4500 years BP. This was a high level channel, 4 m above the present channel bed. A lower palaeo-channel was shown to be younger, close to 2000 years BP, but the error margin for this sample was high. Two terraces at 1.52 m and 4.6 m were estimated to be between 2000 to 3000 years old. A date of 1400 was derived for a third terrace that was close to the paleo-channel at VOSL5. This much younger date at this higher elevation (4.77 m above the channel bed) seems unrealistic and suggest inclusion of younger material due to some sort of profile disturbance.

Table 3.2 OSL dates (BP) for terraces and paleo-channels (Appendix 2). Sample depth below terrace surface and sample height above the active channel is given.

Sample	Type	Depth below surface (m)	Height above active channel bed (m)	Age in years (std. dev.)
VOSL1	Terrace/flood bench	0.67	1.52	2 270 (490)
VOSL2	Terrace	0.94	4.60	2 990 (720)
VOSL3	Terrace	1.55	4.77	1 400 (750)
VOSL4	Paleo-channel	1.34	1.86	2 100 (1 550)
VOSL5	Paleo-channel	1.40	4.03	4 570 (490)

3.3 Assessing hillslope-channel connectivity

Hillslope-channel connectivity is an expression of the effectiveness of sediment transfers from source areas to the valley floor. As described above (Chapter 3) this depends on slope factors such as gradient, shape and vegetation cover, enhanced by the presence of linear pathways that promote channelised flow and efficient sediment transport. The analysis of connectivity focused on the change in the extent of linear pathways that could be attributed to anthropogenic activity in the catchment. Linear drainage pathways that were identified in the Vuvu catchment included: natural drainage lines, continuous gullies, discontinuous gullies, roads and livestock tracks.

Natural drainage lines are connectivity features present before human influence and provide a reference against which to measure change. They ranged from small, steep, grassy topographic lows to the well-developed main trunk channel. Unchannelled sections of the natural drainage network with dense vegetation cover were captured as part of the drainage network, but were classified as dis-connected as it was assumed that the well vegetated sections will act as sediment buffers. Channelled parts of the natural drainage network were specified as major drainage lines as these lines had the potential to act as a sediment pathway.

Gullies (>2 m or 3 to 4 pixels wide linear features) were digitized as line features and were classified as continuous or discontinuous, based on whether or not the feature was directly linked to the major drainage network (Brierley et al., 2006; Le Roux and Sumner, 2012). Gullies that had more than 20 m of vegetated slope below the outflow of the feature were classified as discontinuous. Field evidence indicated that a vegetated strip of more than 20 m was a successful sediment buffer as sediment build-up on these vegetated areas occurred below the gully outflow.

Where livestock tracks were close together or parallel (<5 m apart), causing water to be functionally be routed in the same direction, only the most prominent track was digitized to prevent duplication. Livestock tracks that occurred within a 5 m radius of a gully were removed (Clip tool) to prevent further functional duplication.

In order to designate slope and aspect values to the linear features, the relevant raster layers (slope and aspect) had to be converted to polygons containing integer values. The slope and aspect data could then be assigned to the individual sections of line features by using the Intersect tool. Geology was treated in the same way. The connectivity of a pathway feature to the drainage network was assigned by intersecting a feature with the continuous gully dataset (5 m tolerance). Lengths of the various line features were calculated for the entire Vuvu catchment and each of the geological provinces. Density was calculated by dividing the length of the features by the area of the catchment and geological province. The increase in drainage density as a result of the anthropogenically induced change was expressed as a change in density (m ha^{-1}) and percentage of the natural drainage network. See Table 3.3 for results.

The above methods were used to quantify increases in hillslope-channel connectivity caused by anthropogenic activity in the catchment. The role of buffers that disconnect the hillslope and channel was assessed more qualitatively from the distribution of alluvial fans and terraces mapped for the valley floor.

Table 3.3 Densities of drainage features for the entire catchment and the various geological provinces.

	Unit	Catchment	Elliot	Clarens	Drakensberg
Area	ha	5328.8	1355.1	529.4	3444.3
% of total			25.4	9.9	64.6
Natural drainage	Length (km)	404.1	114.0	39.0	251.1
	Density (m ha^{-1})	75.8	84.1	73.7	72.9
Cont. gullies	Length (km)	42.3	15.0	3.4	23.9
	Density (m ha^{-1})	7.9	11.0	6.4	6.9
	% of drainage	10.5	13.1	8.7	9.5
Discont. gullies	Length (km)	42.6	15.3	2.8	24.5
	Density (m ha^{-1})	8.0	11.3	5.2	7.1
	% of drainage	10.5	13.5	7.1	9.7
Roads	Length (km)	29.1	29.1	0	0
	Density (m ha^{-1})	0.5	21.5	0	0
	% of drainage	0.7	25.5	0	0
Livestock tracks	Length (km)	637.0	222.3	57.4	357.2
	Density (m ha^{-1})	119.5	164.0	108.5	103.7
	% of drainage	157.6	195.0	147.3	142.2

3.4 Assessing lateral connectivity (channel-valley floor)

3.4.1 *Research approach*

Channel-valley floor connectivity was assessed using a combination of hydraulic analysis and the sediment chronologies. Connectivity between the channel and lateral features is achieved whenever they are overtopped by flows, allowing recharge of water and deposition of sediment and associated nutrients. The frequency at which different levels are inundated is thus an important measure of lateral connectivity. This was determined for the Vuvu by a combination of field monitoring of water levels over a two year period and hydraulic modelling.

Short term (two years) discharge was measured for the Vuvu catchment using rated sections at which the flow stage was monitored using level loggers fixed to the river bed. The record was extended by using rainfall records to model monthly, daily and peak instantaneous flows. The modelling and disaggregation was based on routines developed by Slaughter and Hughes (2014). This allowed for the assessment of flood bench inundation frequency for current conditions and a potential future rehabilitated condition (re-vegetation of bare areas and gullies) in which hillslope-channel connectivity is reduced.

The methods used to monitor shorter term (2 year) and model longer term (73 year) channel-flood

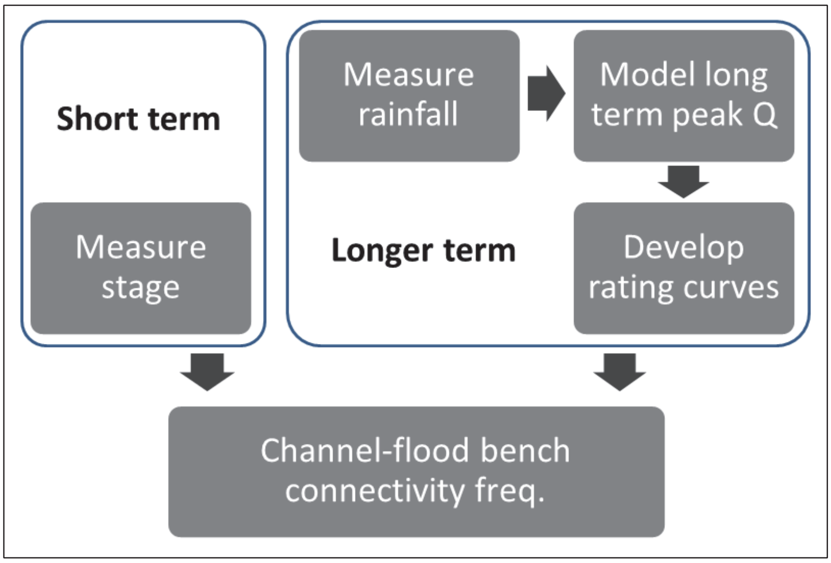

Figure 3.13 The approaches followed to measure the short term and model longer term frequency of channel-flood bench connectivity

bench connectivity are described in this section. An overview of the components involved in the short and longer term approaches to test the channel-flood bench connectivity frequency are presented in Figure 3.13.

3.4.2 *Monitoring flow levels*

A hydraulic monitoring site using a rated section was established at the bottom of the Vuvu valley fill at VT1 (Figure 3.14; 30.59900S, 28.26816E). Guidelines developed by the USGS were followed for site selection and flow measurements (Rantz, 1982). The natural bed shape was used in the hydraulic section, which was located at the top of a riffle where flow was relatively uniform throughout a range of water levels. The hydraulic section was surveyed using an Epoch Differential Global Positioning System (centimetre accuracy).

Repeat discharge measurements were done for nine different stage heights, ranging from 0.31 to 1.06 m, in order to develop a rating curve for each hydraulic section (Whiting, 2003). A portable electromagnetic Flo-Mate 2000® was used to measure flow velocity at 0.6D (60% down the water column) in water less than 0.5 m deep and a combination of 0.2D, 0.6D and 0.8D for water deeper than 0.5 m (Gordon et al., 2004). Flow velocity was measured at more than 20 vertical points across the section.

To monitor water level, a self-logging water level sensor (Solinst Levelogger® with 0.5 cm accuracy) that records stage height at 20-minute intervals was installed at VT1 (installed in December 2012). The sensor was placed in a protective metal casing that was bolted onto a large boulder (Figure 3.15) on the hydraulic transect. Water levels provided by the level logger were to be used to establish a discharge rating curve for the site. Unfortunately the entire boulder and logger at VT1 was washed away during the monitoring period December 2013 to January 2014 causing a loss of data. A new logger was installed at VT1 in January 2014. Water level data were extrapolated from an upstream station.

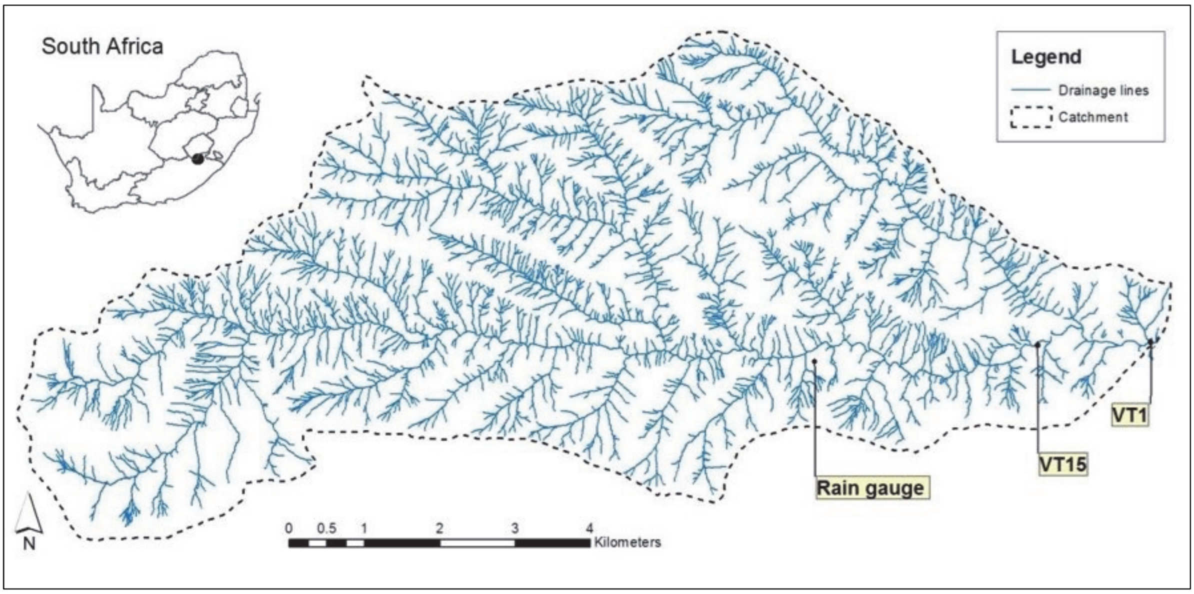

Figure 3.14 The drainage network of the Vuvu catchment and location of the rain gauge and hydraulic monitoring stations.

In addition to the level sensor installed at the hydraulic section VT1, sensors were installed at VT7 and VT15 to measure stage or water level. All loggers were set to record at the same time-steps to prevent unnecessary extrapolation of the data during barometric correction. Unfortunately the logger at VT7 was also ripped off the boulder during December 2012 to March 2013 and was not replaced. Level data from VT15 was used to complete the dataset for VT1. Stage data from the logger at VT15 was used as proxy for VT1 and was adjusted by +20 min as data for recorded flood events indicated a 20 min delay in the flood peak over the 2 km of river between VT15 and VT1. Observed discharge measurements increased from VT15 to VT1 in line with an increase in catchment from 47 km^2 for VT15 to 58 km^2 for VT1. The discharge for VT15 was up-scaled by 23% to match the proportional area increase for VT1.

Figure 3.15 Hydraulic site VT1 and underwater image (bottom left) of the level sensor within a metal casing bolted to a large boulder.

The level readings were corrected for changes in air pressure by using data captured at the same time intervals by an air pressure sensor (Barrologger®) located within 5 km of the water level loggers. These barometrically corrected stage data were converted to instantaneous discharge using rating curves as discussed under hydraulic modelling (Section 3.4.3).

The measured and extrapolated stage data for December 2012 to May 2014 were used to calibrate the relevant hydraulic models and assess the frequency of observed flood bench inundation.

3.4.3 *Hydraulic modelling – extending the rating curve*

In order to extend the discharge-stage relationships to the length of the valley floor, an additional 13 channel sections were surveyed between VT1 and VT15 as described in Section 3.2.2. A rating curve was developed for each of the 15 transects using the hydraulic sub-model (based on the Manning's equation) that is part of the Revised Desktop Model (RDM) (Hughes et al., 2014).

The hydraulic sub-model requires a surveyed channel cross section, minimum and maximum channel slope reading and minimum and maximum channel roughness value (Manning's n). Minimum slope was related to the surface slope of flood water and was calculated based on an average low flow water level over a 500 m (250 m on either side of the hydraulic section) section of surveyed river channel. This procedure assumes that irregularities in the long profile would be drowned out during high discharges. Maximum slope was related to the water surface slope during low flows, thus slope was calculated over a distance stretching from the bottom of a riffle upstream to the bottom of a riffle downstream. The channel roughness values were based on the measured rating curve for VT1 and expert knowledge (Chow, 1959) and ranged from 0.03 to 0.12 (Table 3.5). Slope and roughness were scaled by the hydraulic sub-model over the range of modelled stages.

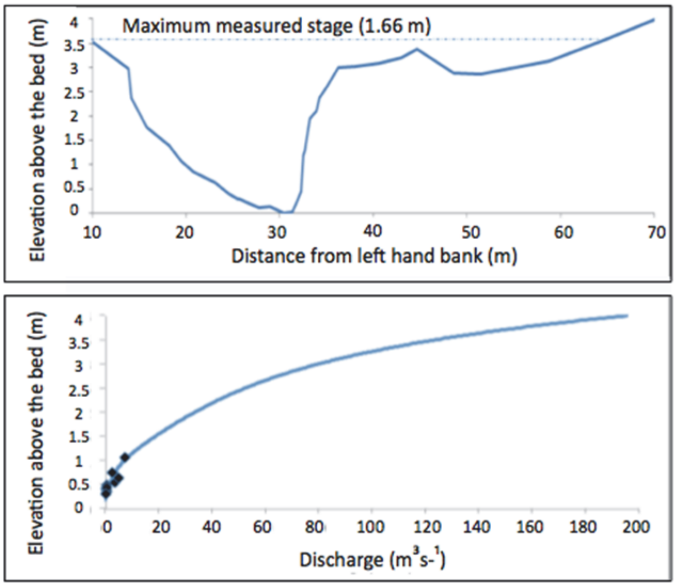

Figure 3.16 The a) channel cross section and b) rating curve for VT1. Markers indicate the measured discharge and stage points on the modelled rating curve.

Table 3.4 Details of hydraulic sections and approach followed to develop rating curves.

Section	Stage record-ed	Roughness (Manning's n)	Slope	Method to develop rating curve
VT1	Yes	0.03-0.12	0.0099-0.0188	Measured discharge at 9 intervals up to 1.06 m or 7.3 m^3 s^{-1}, modelled rating curve up to 4 m based on Manning's equation
VT2	No	0.03-0.12	0.0140-0.0160	Rating curve based on Manning's equation
VT3	No	0.03-0.12	0.0093-0.0160	Rating curve based on Manning's equation
VT4	No	0.03-0.12	0.0080-0.0160	Rating curve based on Manning's equation
VT5	No	0.03-0.12	0.0070-0.0110	Rating curve based on Manning's equation
VT6	No	0.03-0.12	0.0074-0.0118	Rating curve based on Manning's equation
VT7	No	0.03-0.12	0.0161-0.0173	Rating curve based on Manning's equation
VT8	No	0.03-0.12	0.0161-0.0173	Rating curve based on Manning's equation

Section	Stage record-ed	Roughness (Manning's n)	Slope	Method to develop rating curve
VT9	No	0.03-0.12	0.0164-0.0173	Rating curve based on Manning's equation
VT10	No	0.03-0.12	0.0231-0.0173	Rating curve based on Manning's equation
VT11	No	0.03-0.12	0.0091-0.0173	Rating curve based on Manning's equation
VT12	No	0.03-0.12	0.0170-0.0172	Rating curve based on Manning's equation
VT13	No	0.03-0.12	0.0205-0.0265	Rating curve based on Manning's equation
VT14	No	0.03-0.12	0.0265-0.0284	Rating curve based on Manning's equation
VT15	Yes	0.03-0.10	0.0167-0.0260	Rating curve based on Manning's equation

The modelled rating curve for VT1 was fine-tuned based on measured stage and discharge data, adjusting the gradient shape factor and roughness shape factor in the hydraulic sub-model until the modelled curve and measured points matched. A hydraulic model was then developed for the remaining 14 transects using the surveyed transect and gradient data. Gradient and roughness shape factor values, 10 and 5 respectively, were copied from those used for VT1. The channel cross-section and rating curve for VT1 are shown in Figure 3.16. There is considerable uncertainty attached to the stage-discharge relationship at high stages. Estimated values are in line, however, with modelled discharges as described in section 3.4.4.

3.4.4 *Hydrological modelling*

Hydrological modelling was performed to extend the two year measured data set to a 73 year data set derived from rainfall data. The objectives of the modelling were to estimate peak discharge volumes for various event frequencies under present day conditions and to simulate a rehabilitation scenario of a future condition with a decreased hillslope-channel connectivity (drainage efficiency).

Rainfall was measured in the Vuvu catchment (Lundi Village; 30.60871S, 28.22882E, Figure 3.14) using a 150 mm orifice funnel tipping bucket rain gauge and HOBO® pendent event logger. The rain gauge was installed in December 2011 and data were used to model discharge for two river reaches along the Vuvu valley fill (VT15 down to confluence with large tributary and confluence to VT1 in Figure 3.14).

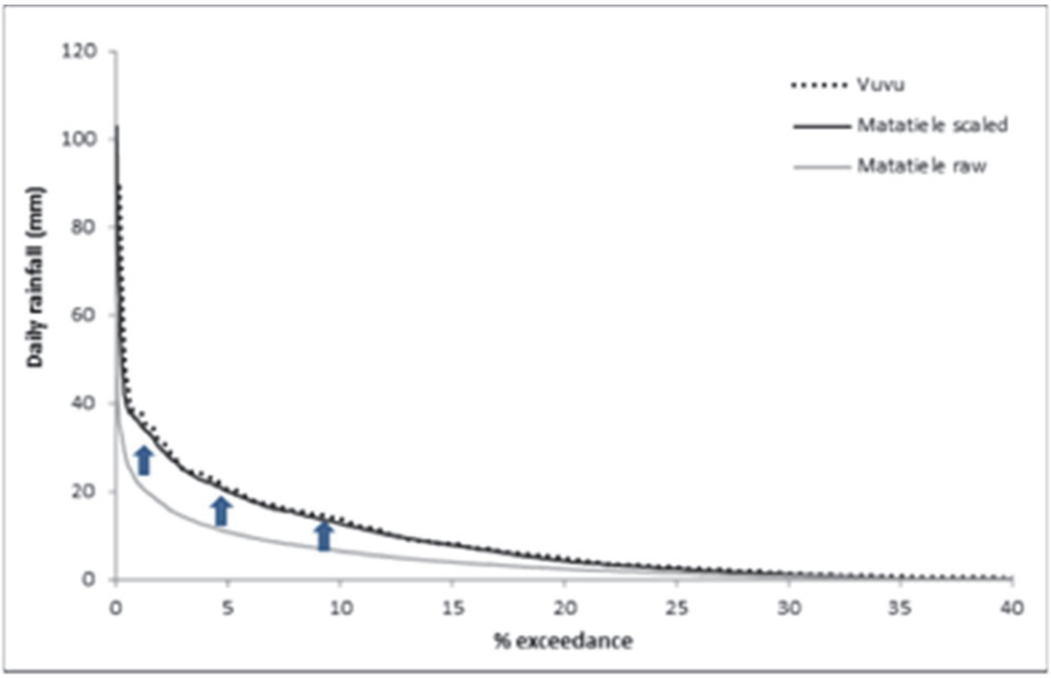

Figure 3.17 Scaling of long-term Matatiele data to match short-term Vuvu data

Daily rainfall data for the Matatiele station (1942–2014; 65 km east-northeast of the Vuvu station) were used to extend the short-term rainfall record available for the Vuvu catchment (2012-2014). Both the

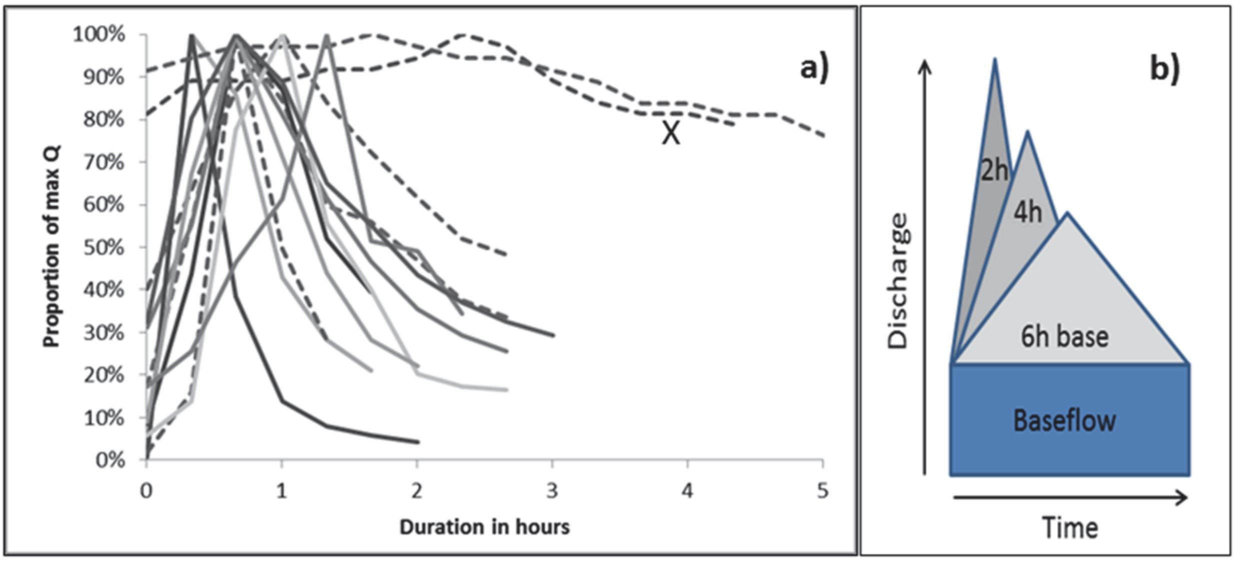

Figure 3.18 (a) Observed flood peaks for the Vuvu River. Flood peaks were standardised against maximum discharge for each event. Events <15 $m^3 s^{-1}$ are indicated with dotted lines. (b) Schematic of flood duration influences on the height of the flood peak.

daily Matatiele and Vuvu rainfall data were sorted from high to low and plotted on the same frequency distribution plot. The daily Matatiele data were manually up-scaled, using a correction factor ranging from 1 to 1.98 depending on the difference between the Matatiele and Vuvu dataset, to match the daily rainfall frequency distribution pattern measured for the Vuvu catchment (Figure 3.17).

The scaled long-term daily rainfall data set for Matatiele was chronologically ordered and converted to monthly rainfall data that was used as input to the monthly Pitman rainfall-runoff model (Hughes, 2013). Parameter values for the model were based on existing regional information (Midgley et al., 1994). Monthly discharge volumes were calculated for catchment areas of 47 and 58 km^2 for VT15 and VT1 respectively. Simulated monthly discharge volumes were disaggregated to mean daily flows using the scaled daily rainfall data for Matatiele and a model developed by Slaughter and Hughes (2015). The lowest threshold discharge observed to inundate the lower flood bench, at VT3, was 5 $m^3 s^{-1}$. Mean daily values greater than this threshold were used in the analysis of peak flows.

The first step in deriving peak flows from the modelled discharge data was to separate the baseflow from the mean daily flow using a digital filtering method (Smakhtin, 2001). In this context, the baseflow is assumed to include the recession flow volume from previous days within an event lasting several days and therefore can be higher than traditional definitions of baseflow that assume an almost constant contribution from baseflow. The mean daily baseflow calculated according to Smakhtin (2001) was deducted from the mean daily flow and the resultant volume was used to determine the peak discharge contributed by stormflow.

Observed flood peaks (Figure 3.18) commonly had a triangular shape, with a steep rising and falling limb, followed by a relatively flat recession limb. Two of the flood peaks (marked X on Figure 3.18a), associated with low intensity rainfall, lacked the steep peak. The mean duration of all floods with a maximum discharge of more than 7 $m^3 s^{-1}$ (stage of 1 m) was 2.98±0.95 hours. A flood hydrograph base ranging from 2 to 4 hours was used to disaggregate the modelled mean daily flow to instantaneous flow so as to account for the total uncertainty introduced by the various steps of scaling the rainfall data (generating and disaggregating monthly flow data).

A correction factor was calculated to compensate for the higher baseflows that result from recession flows following previous wetter periods based on the ratio between mean daily baseflow and mean daily discharge (Equation 3.1). The peak discharge was calculated using Equation 3.2 that consists of two components that are added together, a triangle that represents the flood flow and a base that represents the mean daily baseflow. The triangle height was determined by the volume of water available (daily flow volume minus baseflow volume) and the length of the base of the flood flow triangle. The length of the base of the flood flow triangle was set at 2, 4 and 6 hours to account for uncertainties (Figure 3.18b). The resultant triangle height was added to the height of the mean daily baseflow to produce a total peak discharge (Equation 3.2).

$$\text{Correction factor} = \frac{\text{mean daily baseflow}}{\text{2 x mean dalily Q}} \qquad \text{(Equation 3.1)}$$

$$\text{Peak Q} = \frac{\textit{mean daily}\ \text{Q - mean baseflow}}{\text{2 base x correction factor}} + \text{mean baseflow} \qquad \text{(Equation 3.2)}$$

Base is the length of the flood peak (2, 4 or 6 hours).

A post rehabilitation scenario was introduced where runoff delivery rates were reduced in line with a reduced hillslope-channel connectivity. The disaggregation of the mean daily to instantaneous flow was adjusted so that the base of the peak discharge triangle was two hours wider than for current conditions, that is, four to six hours. It should be noted that this disaggregation process only accounted for the timing of runoff due to a reduction in hillslope-channel connectivity and not for reduced runoff volumes due to an increase in infiltration associated with changes in vegetation cover.

The largest independent peak was selected for each rainfall event, as multiple peak flows (over 2 to 5 days) existed during times of sustained rainfall. The resulting peak daily discharge data were ranked, giving a partial duration discharge-frequency dataset. The Weibull formula was applied to calculate the average recurrence interval (Gordon et al., 2004). Partial duration curves were plotted as given in Figure 3.19. This dataset was used to determine the frequency of channel-flood bench connectivity for the current condition (2 to 4 hour flood base) and a rehabilitated condition (4 to 6 hour flood base).

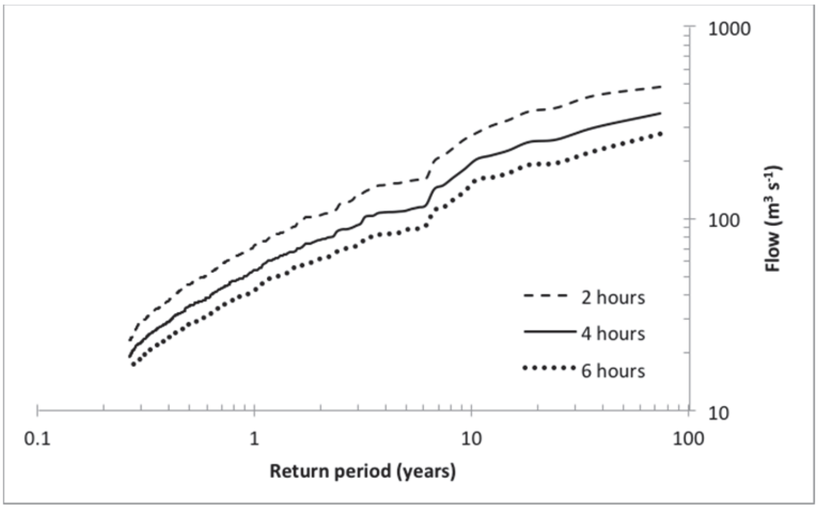

Figure 3.19 Partial duration curves for peak flows modelled using a 2-, 4- and 6-hour hydrograph base.

3.4.5 *Modelling channel-floodbench connectivity*

Connectivity between the channel and active flood benches was evaluated by combining stage and discharge information from the rated sections with the magnitude-frequency data provided by the observed hydrology and hydrological modelling.

Stage threshold levels were determined for inundation of lower and higher flood benches identified on each of the fifteen hydraulic sections. These threshold stage levels were converted to discharge volumes based on the rating curve for the cross section, giving a discharge threshold at which flood bench inundation was initiated.

Inundation frequencies for VT1 were also assessed separately for dry, moderate and wet years (water years starting on 1 October) classified according to a ranking of the total discharge volume for that year. Inundation frequencies were extracted for the ten driest, ten moderate (10 years centred around the median total discharge per year) and ten wettest years. Flood frequencies were limited to 10 years as the data were subsampled.

The difference in inundation frequency for the scenarios of an increased hillslope-channel connectivity (flood duration ranging from 2 to 4 hours) and a reduced hillslope-channel connectivity (flood duration ranging from 4 to 6 hours) was determined using Equation 3.3.

$$\%\ \text{difference} = \left(\frac{A+B}{B+C}\right)*100$$

(Equation 3.3)

where A, B and C are the inundation frequencies for flood peak with a 2 hour base, a 4 hour base and a 6 hour base respectively. Summarised results are indicated in Table 3.5.

Table 3.5 Observed and modelled (average for 73 years) inundation frequencies for the lower and higher flood benches. Average values were given for VT2–VT14.

Section	Feature	Inundation threshold		Average per year or recurrence interval			
		Stage (m)	Q ($m^3 s^{-1}$)	Observed	2 hour	4 hour	6 hour
VT1	Lower flood bench	1.4	16	4.5	4.4	4.2	3.8
	Higher flood bench	3	82	1 in 2	I in 1.2	1 in 2.4	1 in 3.5
VT15	Lower flood bench	1.5	24	1.5	3.7	3.2	2.5
	Higher flood bench	2.9	144	1 in 2	1 in 3.6	1 in 7.3	1 in 10.4
Ave for VT2-VT14	Lower flood bench	1.2	15	-	4.4	3.9	3.8
	Higher flood bench	2.2	76	-	1 in 1.6	1 in 3	1 in 4.3

3.5 Assessing longitudinal connectivity

Longitudinal connectivity was not assessed directly. There were no significant barriers along the length of the channel investigated so natural longitudinal connectivity was considered to be high. Changes to longitudinal connectivity can be associated with changes to lateral connectivity as channel incision and straightening lead to more rapid transmission of water and sediment down the channel. In a sense, there is also a relationship between longitudinal connectivity and hillslope-valley floor connectivity as increases in the drainage density effectively extends the channel network upstream. Thus the conveyance potential for sediment is increased.

3.6 Integrating catchment and valley floor scales using sediment tracing

3.6.1 *Sediment tracing*

Mapping and characterising the various sources, pathways and sinks provides a first indication of how sediment is moving through the landscape. By dating erosional features and sediment sinks the timing of sediment movement can be inferred. Sediment tracing was used as a tool to integrate the information gained about the different scales and locations of connectivity at the catchment scale, confirming the source of the sediment stored in sinks.

Tracing was done in two stages. First the identified sources were sampled and tracer soil properties measured. Second the valley floor sinks were analysed for the same tracer properties. A suitable tracer property depends on it being conservative (i.e. not changing when transported) and linearly additive. A wide range of tracer properties have been used by sediment researchers, including colour, geochemistry and mineral magnetism (Walling, 2005). Mineral magnetism provides a relatively quick, cheap and non-destructive tracer (Oldfield et al., 1979; Walling et al., 1979) that proved effective in the Vuvu catchment. Properties relating to mineral magnetism were measured to derive a set of tracer signatures that could be used to match the sink sediments to source categories according to geological formation. Mineral magnetism can also be used to differentiate topsoils from subsoils. Cs-137 can be used to identify topsoil sources.

Mineral magnetic signatures were effective tracers in the Vuvu because they could differentiate successfully between the igneous basalts and sedimentary sandstones and mudstones. Basalt is associated with magnetite (ferimagnetic, thus high magnetic affinity) and sedimentary rocks with haematite (canted antiferromagnetic, thus low magnetic affinity) (Dearing, 1999; Oldfield, 1999).

The use of mineral magnetism as a tracer requires a number of specific procedures to be followed as listed below.

- Field samples must be collected using a sampler that will not affect the magnetic properties of the soil or sediment. This can be stainless steel, aluminium or plastic.
- Samples must be dried at no more than 40ºC to preserve their magnetic character.
- Results must be corrected for organic content.
- Results are sensitive to particle size.

3.6.2 *Sediment sample collection and processing*

Sediment sources

Sediment sources were classified into three groups based on parent material, e.g. basalt (Drakensberg Formation), sandstone (Clarens Formation) and mudstone (Elliot Formation). Each group consisted of samples collected from gully, sheet erosion features, landslides and hardened roads. Both surface and subsurface samples were collected for all features other than roads (only surface samples). A total of 100 sites were targeted for source sampling. Stratified random sampling was used as it would preserve the ratio of geological and slope proportions in the catchment and allowed for random sampling within each of the groups (Kheir et al., 2007). The largest proportion of samples was thus located on moderate slopes and the Drakensberg Formation respectively as presented in Table 3.6.

All mapped gully, sheet erosion and landslide features were converted to points based on the centroid of each feature and merged to create a single point shapefile from which a random number of sampling points were selected. The selected points were uploaded on Garmin GPSmap devices which were used to navigate to the sites. Five of the higher sites on the Drakensberg Formation could not be reached due to potentially dangerous and challenging terrain.

Table 3.6 The distribution of samples by sampling group used for the random site selection.

	Formation		
	Drakensberg	**Clarens**	**Elliot**
Steep	17	4	14
Moderate	25	5	20
Gentle	7	2	6

A stainless steel corer (2.5 cm inside diameter) was used to collect source samples, as the same depth (10 cm) could be cored for all samples. A vertical surface core was extracted away from the edge of the erosion feature where there was dense grass cover. It was assumed that the grass cover was indicative of a relatively undisturbed surface soil and the sample would therefore represent the surface material that had been eroded from the erosion feature. A horizontal subsurface sample was taken half way to the bottom of a feature. For large features (deeper than 1.5 m), several subsurface samples were extracted at one metre intervals. A total of 200 samples were taken, 93 surface and 107 subsurface.

It is important to target the sediment particle size that is dominant in sinks as differences in particle size between source and sink will alter tracer signatures, introducing error in the fingerprinting (Collins et al., 1997a; Walling, 2013). Reconnaissance field data collected for 10 sink features indicated that the <250 µm fraction was the dominant (>85%) grain size and was thus identified as the fraction used to match sediment to sources (Collins et al., 1997b).

Samples were dried for 48 hours at 40^0C (Yu and Oldfield, 1989) before sieving to extract the <250 µm fraction. Particle size distribution and organic content were determined for subsamples using a Malvern Mastersizer 3000 and muffle furnace (450^0C) respectively.

Sink sediment sinks

The samples selected from the four cores for dating (section 3.2.5) were also used for tracing. Samples were prepared as for the source samples.

3.6.3 *Determination of magnetic signatures*

Methods for determining magnetic signatures followed those described by Maher, (1986), Foster et al. (1998), Dearing (1999), Walden (1999) and Foster et al. (2007). Mass specific magnetic susceptibility and remanence properties were determined for 5-10 g of <250 µm sediment packed into 10 ml pots. The Bartington ® susceptibility meter with an MS2 B dual core sensor was used to measure high and low frequency magnetic susceptibility. The susceptibility readings were corrected for the organic content using the LOI data and expressed as minerogenic low (Xlf) and high (Xhf) frequency magnetic susceptibility. Associated measurement errors for magnetic susceptibility were <2% (Lees, 1997). Frequency dependent susceptibility (Xfd) was calculated based on the Xlf and Xhf. Remanence properties (anhysteretic susceptibility (XARM), saturation remanence (SIRM) and hard isothermal remanence (HIRM)) were measured using the Molspin® rotating magnetometer, Molspin® A.F. demagnetiser and a Molspin® pulse magnetiser (maximum pulse strength of one tesla). Xfd, XARM and ARM are sensitive to small magnetic grains, whereas SIRM, IRM and HIRM are sensitive to large magnetic grains (Table 3.7). Xlf is sensitive to a range of particle sizes. Associated error for remanence signatures were <15% due to the non-linear additivity as a result of grain size interactions (Lees, 1997).

Table 3.7 The properties of mineral magnetic tracers and associated units (Anderson and Rippey, 1988; Walden, 1999; Foster et al., 2007; Yang et al., 2010; Wang et al., 2012).

Magnetic measurement	Unit	Minerals measured	Mineral grain size
Xlf	10^{-6} m^3 kg^{-1}	Diamagnetic, paramagnetic, canted anti-ferromagnetic, ferrimagnetic	Small-large
Xfd	10^{-9} m^3 kg^{-1}	Ultrafine super paramagnetic grains	Small (<0.02 µm)
XARM and ARM	10^{-9} m^3 kg^{-1}	Stable single domain ferrimagnetic minerals	Small (0.02-0.4 µm)
SIRM	10^{-3} Am^2 kg^{-1}	Minerals carrying remanence	Large (<100 µm)
IRM	10^{-3} Am^2 kg^{-1}	Ferrimagnetic minerals	Large (<100 µm)
HIRM	10^{-3} Am^2 kg^{-1}	Antiferromagnetic minerals	Large (<100 µm)

Table 3.8 The presence of C-137 in surface samples

	n	Cs-137 present (%)	lacking Cs-137 (%)
All	28	14	50
Drakensberg	10	6	40
Clarens	2	2	0
Elliot	16	6	63

Cs-137 was used as an independent indicator of surface soil erosion for the different geologies and an indicator of surface soil contributions in sediment cores as Cs-137 adheres strongly to finer particles in surface soils. Cs-137 fallout is assumed to be spatially homogeneous at a relatively small scale (Walling, 2004, 2005). Surface samples lacking Cs-137 would therefore indicate that a significant depth of topsoil had been eroded since 1958 whereas deposited sediment containing Cs-137 would indicate that the sediment was sourced from surface soils after 1958. A selection of surface samples (n = 28) representing the different geological formations was analysed for the presence of Cs-137. The results presented in Table 3.8 indicate that much of the topsoil has been lost from the catchment, with the highest loss from the Elliot formation, where 63% of samples were lacking Cs-137.

3.6.4 *Selecting and verifying the best discriminators for quantitative sediment tracing*

Quantitative and qualitative sediment tracing approaches were tested on the most complete core, VT2. The quantitative approach was based mainly on the work of Lees (1994) and Collins et al. (1997b) that has two stages: 1) to test if tracers can distinguish between the source groups and 2) to compare the composite fingerprint between source samples and sediment samples using a multivariate mixing model. The outcome of the quantitative approach was compared to that of the qualitative approach, using a single tracer, in the hope of simplifying sediment source tracing for other sediment cores and suspended sediment samples.

The tracer signatures of the source samples were interrogated statistically to test if meaningful groups could be identified based on the measured tracers (magnetic susceptibility, magnetic remanence and median particle size). The two null hypotheses, that there was no significant difference for tracers between the various geological provinces and between slope classes, were tested using the two-tailed Kruskal-Wallis H-test. The null hypothesis, that there was no significant difference between the geological provinces, was rejected for all measured tracers as at least one parent material grouping was significantly different from the other groups. The largest difference between geological provinces was between the Xlf values ($H = 142$) and SIRM ($H=140$). The null hypothesis, that there was no difference between slope classes, was only rejected for HIRM for steep and gentle slopes ($H = 6.51$; $n = 180$; $p =0.039$). Magnetic properties were therefore not considered to be differentiated according to slope classes.

Magnetic signatures are not only influenced by parent material but also by biogeochemical processes associated with soil formation (Oldfield, 1991). The nonparametric Mann-Whitney U-test was used to test the null hypotheses that there were no differences for the tracers between: surface and subsurface samples; gully and sheet erosion; north and south-facing slopes, both within the entire catchment and within each respective geological grouping. Null hypotheses were rejected if $p<0.05$. Groupings with less than five cases were not included in the hypothesis testing, but were used in the sediment tracing section. The results of the Mann-Whitney U-tests are summarised in tables 3.9-3.11, which list the variables for which significant differences between groups were detected.

The statistical tests showed that most tracers can be used to distinguish between samples derived from one of two geological groups: the Drakensberg and the Clarens/Elliot Formations. Differences between other groups are less clear. Although differences can be detected within geological provinces for surface/subsurface, erosion type and aspect, the trends would be helpful only if tracing was done within that particular geological province. The detected differences would be less apparent once sediments from other geologies were introduced as within group (i.e. surface/subsurface of particular geology) variance was less than between group (different geologies) variance, making mixtures from various geologies impossible to distinguish in terms of surface/subsurface, feature type and aspect. Sediment tracing was thus limited to igneous and sedimentary sources.

Table 3.9 Significant values determined by the Mann-Whitney U-test for surface and subsurface soils. Mean values and standard deviation are given for the variables. The following variables were included in the analysis: LOI, Xfd%, Xlf, Xfd, ARM, XARM, SIRM, IRM, HIRM, Dx (50).

Variable	p-value	Surface		Subsurface	
		Mean	Std.Dev.	Mean	Std.Dev.
All samples (surface n = 93, subsurface n = 107)					
LOI	0.001	12.4	7.5	9.1	5.5
Xfd	0.031	154.3	161.9	122.2	139.8
Dx (50)	0.000	63.1	32.1	87.0	46.2
Drakensberg (surface n = 41, subsurface n = 46)					
LOI	0.000	18.6	5.6	14.1	4.3
Dx (50)	0.000	70.9	43.1	113.6	54.0
Clarens (surface n = 7, subsurface n = 7)					
No significant results					
Elliot (surface n = 43, subsurface n = 49)					
LOI	0.001	7.2	5.0	4.9	1.5
Xlf	0.015	0.5	0.3	0.4	0.3
Xfd	0.031	53.1	34.5	39.7	35.8
ARM	0.016	0.2	0.3	0.1	0.1
XARM	0.016	6.9	10.5	3.9	3.6
SIRM	0.008	5.5	2.9	4.0	2.4
IRM	0.000	2.8	1.9	1.6	1.7

Table 3.10 Significant values determined by the Mann-Whitney U-test for gully and sheet erosion. Mean values and standard deviation are given for the variables. The following variables were included in the analysis: LOI, Xfd%, Xlf, Xfd, ARM, XARM, SIRM, IRM, HIRM, Dx (50).

		Gully		Sheet erosion	
Variable	p-value	Mean	Std.Dev.	Mean	Std.Dev.
All samples (gully n = 106, sheet n = 73)					
HIRM	0.019	6.7	9.3	10.2	10.5
Drakensberg (gully n = 48, sheet n = 39)					
LOI	0.004	14.7	4.2	18.1	6.2
ARM	0.027	1.7	1.0	1.3	0.5
XARM	0.027	52.8	30.8	42.2	15.7
SIRM	0.004	109.3	72.0	136.2	50.0
HIRM	0.004	13.3	10.5	18.1	8.5
Elliot (gully n = 43, sheet n = 33)					
No significant results					

Table 3.11 Significant values determined by the Mann-Whitney U-test for north and south facing slopes. Mean values and standard deviation are given for the variables. The following variables were included in the analysis: LOI, Xfd%, Xlf, Xfd, ARM, XARM, SIRM, IRM, HIRM, Dx (50).

Variable	p-value	North		South	
		Mean	Std.Dev.	Mean	Std.Dev.
All samples (north n = 116, south n = 67)					
LOI	0.043	10.2	6.4	12.2	7.3
Xfd	0.046	121.1	126.1	172.8	187.8
Dx (50)	0.000	82.1	43.5	65.2	37.7
Drakensberg (north n = 50, south n = 32)					
HIRM	0.023	13.7	9.0	18.3	10.4
Dx (50)	0.004	103.6	52.6	75.3	51.1
Elliot (north n = 53, south n = 30)					
Dx (50)	0.002	65.2	25.6	52.9	12.5

Range tests (Table 3.12) were performed on each tracer by plotting source and sink sediment on a scatterplot in Excel to verify that tracer signatures in the sink sediment falls within the range of signatures found in the potential sediment sources. If sink sediment signatures fell outside the source signature range, it would indicate either that a potential source was missed during sampling or that tracer signatures changed during transport or after deposition, invalidating tracing. The results given in

Table 3.12 indicate that all tracers passed the range test, confirming conservative behaviour of the tracers and that the main sources within the catchment had been sampled.

Due to the selective transport between source and sink, median particle size and organic content were removed from the list of tracers used in source apportionment. Furthermore, Xfd% was removed as it violates a key assumption of the sediment fingerprinting methodology, that the tracers are linearly additive (Lees, 1999)

Table 3.12 Summary of range test results showing that variable values for sinks fall within the source range.

	Source				Sink	
	Igneous		Sedimentary		Sediment	
Variable	Mean	Std. dev.	Mean	Std. dev.	Mean	Std. dev.
Xlf	5.4	2.1	0.5	0.3	1.8	0.9
Xfd	237.6	172.6	50.7	38.8	57.8	49.9
ARM	1.5	0.8	0.2	0.2	0.5	0.7
Xarm	48.0	25.6	5.6	7.4	14.8	20.6
SIRM	121.4	64.2	5.0	2.9	50.0	32.9
IRM	70.7	40.4	2.4	2.1	29.9	19.8
HIRM	15.5	9.9	1.1	0.5	8.8	6.0

3.6.5 *Quantitative sediment tracing approaches*

For the quantitative approach, tracers that could distinguish between source groups were used in a forward stepwise Discriminant Function Analysis (DFA) to identify the composite fingerprint of tracers able to best differentiate between the source groups (Collins et al., 1997b; Foster et al., 2007). Results showed that the best igneous and sedimentary source discrimination was achieved using a composite fingerprint consisting of Xlf, ARM and HIRM. A total of 96% of source samples were correctly classified into their respective groups.

The composite fingerprint of tracers consisting of Xlf, ARM and HIRM was used in a multivariate mixing model to produce a probability density function that would determine the proportional contribution of sediment from each source group and associated uncertainty (Equation 3.4). The probability distribution was based on 3000 iterations per sample using the Monte Carlo algorithm (Collins and Walling, 2007).

$$\sum_{i=1}^{n}\{(C_i-(\sum_{s=1}^{m}P_sS_{si}))/C_i\}^2$$

Equation 3.4

where C_i = concentration of fingerprint property in sediment sample; P_s = the optimised percentage contribution from source category; S_{si} = median concentration of fingerprint property in source category; n = number of fingerprint properties comprising the optimum composite fingerprint; m = number of sediment source categories (Collins et al., 2010). No weightings or correction for particle size was applied.

The results for VT2 showed that sedimentary sources dominated most of the core (Figure 3.20). Sedimentary sources contributed on average 64% of the sediment, with the remainder of the 36% signified by igneous sources. Mean uncertainty for the contributions was 10% with error margins ranging between 3 and 27%. The average goodness of fit for the apportionment was 87%.

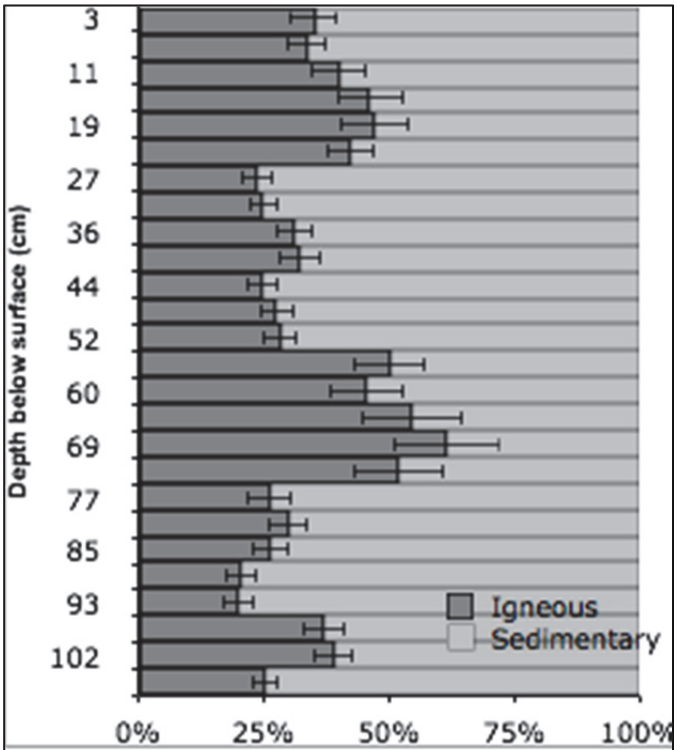

Figure 3.20 Source apportionment for core VT2.

3.6.6 *Qualitative sediment tracing approaches*

For the qualitative approach the tracers that could distinguish between source groups were used in a Principal Component Analysis (PCA) in Statistica 12, a method that optimises the variance for this multi-dimensional dataset (Smith and Blake, 2014). The results are shown in Figure 3.21. As can be seen from Figure 3.21a, factor 1 (eigenvalue of 5.1) explained 71.7% of the variance, with Xlf having the most significant variable loading (Figure 3.18a; R^2 >0.92). Factor 2 (Eigenvalue of 1.2) explained 16.6% of the variance, with Xfd having the highest correlation (R^2 = 0.54). Xlf was therefore chosen as the single variable to trace sediment from igneous and sedimentary sources.

The variable factor loadings were assessed for any meaningful groupings (Figure 3.21b). The flood water, flood bench and terrace samples clustered between the sedimentary and igneous source samples, when considering Factor 1, indicating that these samples were a mixture of these two main source groups. No meaningful grouping was achieved for source groups by Factor 2

As Xlf proved to be the variable explaining the highest variable loading its effectiveness as a single tracer was tested. Median Xlf values of sedimentary (0.4 10^{-6} m^3 kg^{-1}) and igneous sources (5.1 10^{-6} m^3 kg^{-1}) showed large differences between the two geological source groups with minimal overlap between values (Figure 3.21a). The results of the qualitative tracing results for core VT2 were compared to that of the quantitative tracing as seen in Figure 3.22b&c. The trends shown by the two sets of results are very similar. The agreement between the two approaches is confirmed by the strong positive relationship (R^2 = 0.94) between percentage contribution from igneous source and Xlf (Figure 3.23). This was represented by equation 3.5 which gives a zero contribution of igneous sediment at just less than 0.5 10^{-6} m^3 kg^{-1}, in good agreement with a median value for sedimentary sources of 0.4 10^{-6} m^3 kg^{-1}.

$$y = -3.5x^2 + 31.4x - 13.8 \qquad \text{(Equation 3.5)}$$

where x is Xlf (10^{-6} m^3 kg^{-1}) and y is % contribution from an igneous source.

The similar results from both approaches meant that a simpler qualitative approach could be used for further tracing. This was applied to the remaining cores and to suspended sediment sampled during flood events.

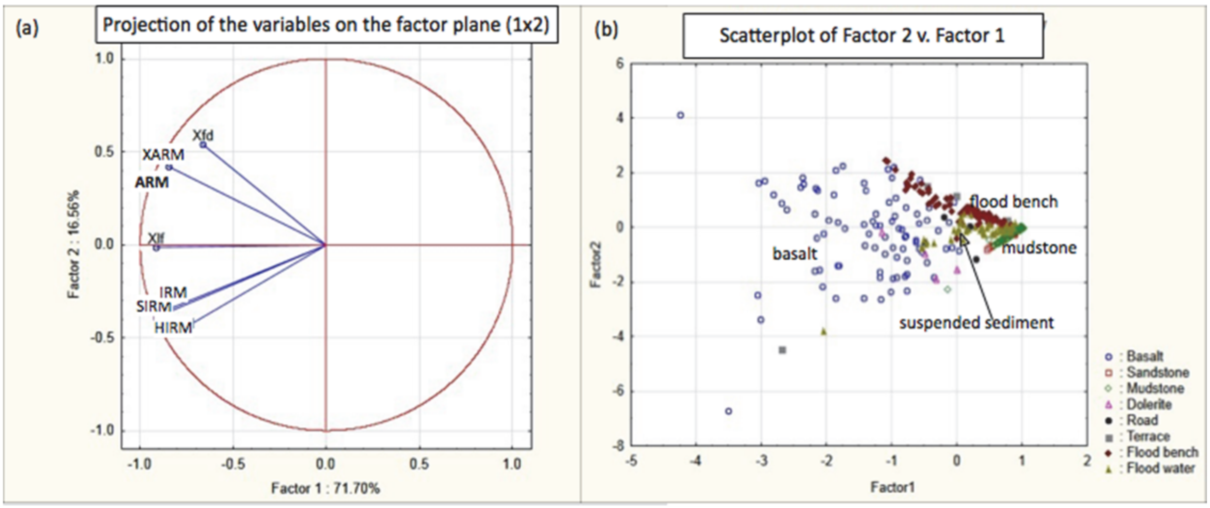

Figure 3.21 (a) Factor loadings for source and sink samples using a Principal Component Analysis (b) Principal Component Analysis factor scores for source, sink and flood water samples.

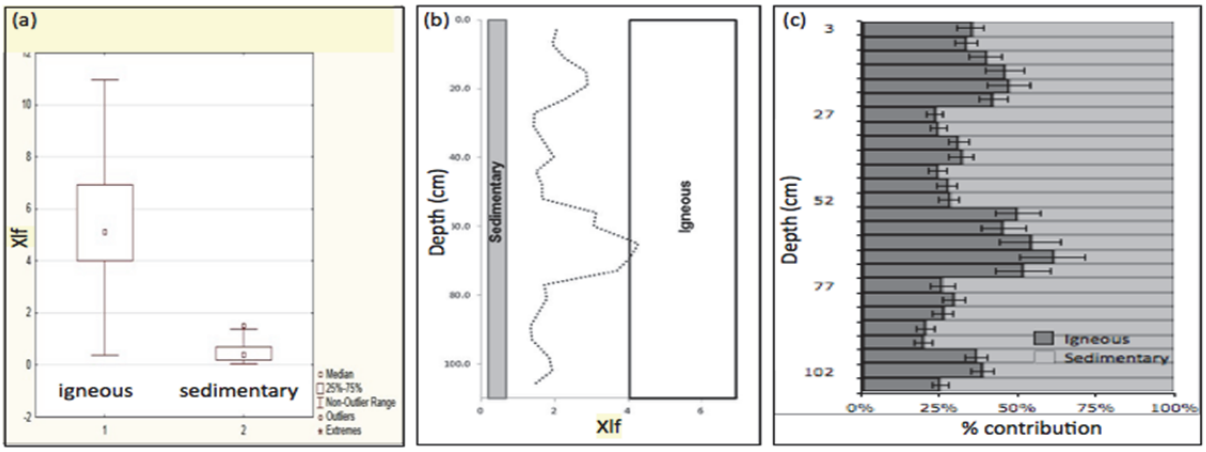

Figure 3.22 (a) Box plots comparing Xlf for two source types. (b) Down core plot of Xlf with quartile ranges indicated for two source types compared to (c) results from mixing model.

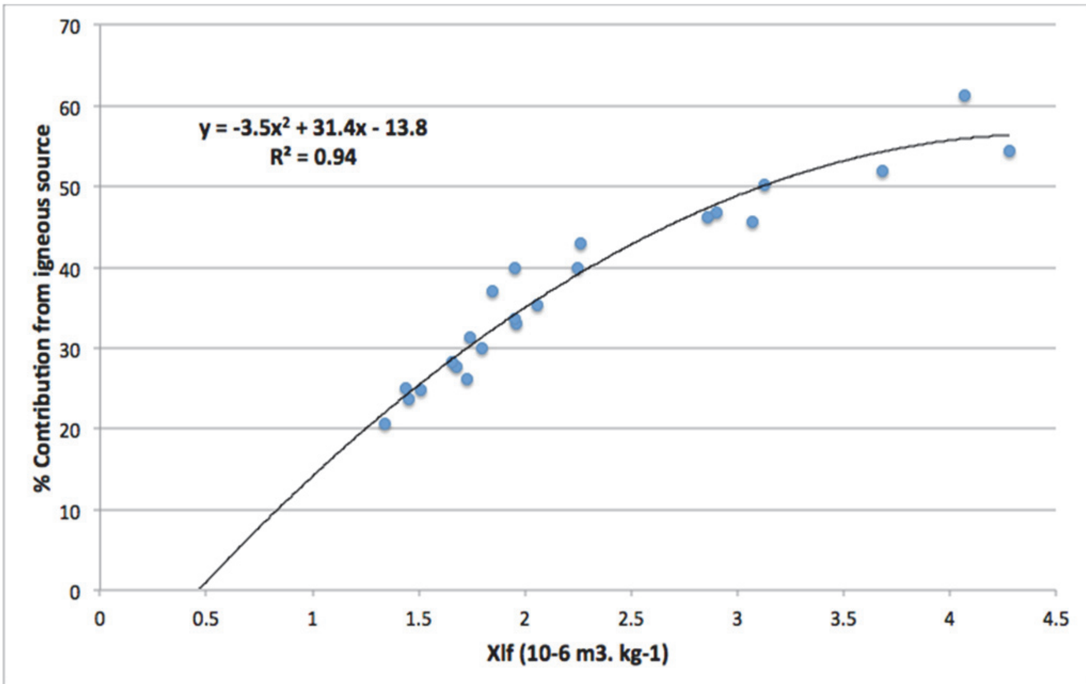

Figure 3.23 Relationship between contribution from igneous source and Xlf (un-mixing model applied to flood bench core data)

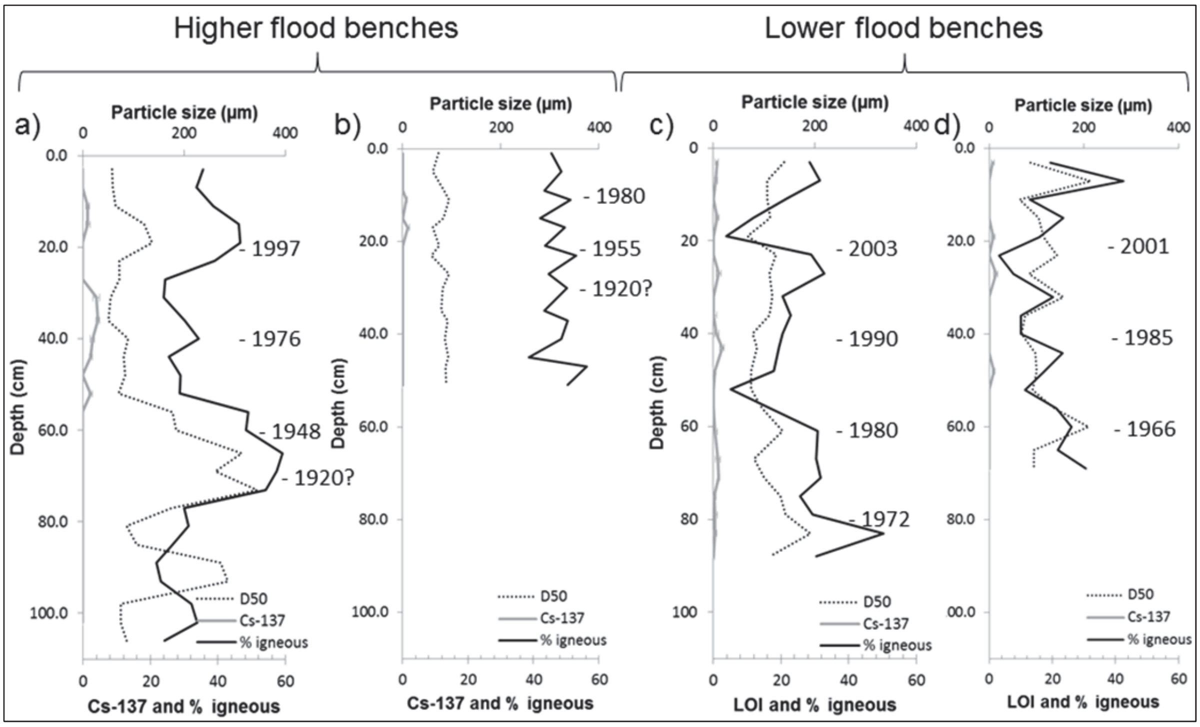

Figure 3.24 Down core median particle size, Cs-137 (mBq g^{-1}) and % igneous sediment for core: a)VT2, b) VT7-2, c) VT4 and d) VT7.

3.6.7 *Floodbench sediment origin*

The percentage igneous contribution calculated using equation 3.5 was plotted against depth for all four flood bench cores, together with Cs-137 and median particle diameter (Figure 3.24). The percentage contribution from the igneous source varied over time, probably in relation to dry and wet periods, but none of the cores show a clear trend that would indicate a systematic shift in sediment source over the past 50-100 years. Although sedimentary sources dominated all cores, higher flood benches tended to have a higher proportion of igneous derived sediment. This sediment was also coarser grained, as is characteristic of basalt soils. This suggests that higher flows are generated from a wider area, increasing connectivity with the upper catchment. This was corroborated by evidence from suspended sediment sampled over two storms in December 2013 and January 2014. It is likely that the upper catchment also generates small floods during isolated storms, but attenuation of these smaller events due to longer travel distances result in more sediment storage in the upper catchment and lower magnitude flood peaks in the lower catchment that possibly do not inundate the lower flood benches. Peaks in igneous contribution, as in 1977 in core VT2, are probably related to wet periods when the frequency of floods generated by the whole catchment would increase.

It was concluded from the tracing results that sediment trapped in the lower benches was dominated by local sedimentary sources. From Table 3.6 it can be seen that Xfd can discriminate between surface (53.1±34.5) and subsurface (39.7±35.8) soils within the Elliot Formation. Xfd values were therefore used to determine top soil contributions to the lower benches. Average Xfd values for VT4 were 20.1±6.5 and for VT7 were 27.2±4.1, indicating that the deposited sediment is more likely to be from subsoil. This may indicate that gullies are the main sediment source or that the widespread loss of topsoils (Table 3.5) leaves only subsoil to be eroded.

The core data in Figure 3.22 shows evidence that the presence of Cs-137 was linked to increased contributions from igneous sources. This tentatively supports the conclusion that surface topsoils continued to be an important source in the upper catchment. 60% of samples from igneous derived soils still contained Cs-137, indicating that topsoil remains a potential source at the present time.

3.6.8 *Terrace sediment origin*

Magnetic signatures were determined for terrace sediments following the methods described above. Terrace sediment was similar to that of the flood benches, being dominated by sedimentary sources (52–73% sedimentary contribution), with greater igneous inputs around 3 000 years ago (48% igneous contribution) (Table 3.13). Xfd values for terrace samples with a smaller contribution from igneous sources (<40%) would suggest that the sediment was sourced from subsoils of the Elliot Formation (refer back to Table 3.9) as Xfd values ranged from 21.9 to 29.4. These results indicate that sediment sources have not changed significantly over a 4000 year period.

Table 3.13 Median particle size, organic content, Xlf,% igneous contribution and Xfd for the terrace samples.

Sample	Age (a)	D50 (μm)	LOI (%)	Xlf	% igneous contribution	Xfd
VOSL 3	1400±750	156	5.8	2.4	41	46.3
VOSL 4	2100±1550	455	5.1	2.0	35	25.6
VOSL 1	2270±490	344	4.5	2.1	36	21.9
VOSL 2	2990±720	87	7.3	2.9	48	51.2
VOSL 5	4570±490	83	6.9	1.6	27	29.4

3.6.9 *Tracing suspended sediment*

Present day sediment dynamics were assessed for a wet season (December 2013–January 2014) by sampling flood peaks and monitoring flood stage. It is well recognised that the bulk of sediment transport takes place during flood events, with a bias towards the rising limb of the hydrograph. It is therefore important to sample during flood events. Continuous recording turbidity meters are commonly used to estimate the variation in suspended sediment during an event but they were not thought suitable for use in the Vuvu because of the high energy flows that would be likely to damage this expensive equipment. Manual sampling was used instead.

Grab water samples were collected by a community member, Motlatsi Mabaleka, living near the river at the bottom of the Vuvu valley near the rated section at VT1. Mr. Mabaleka collected 121 water samples in total during the rising and falling limb of 11 floods. Where possible these were collected at 10 minute intervals through the hydrograph (6 to 13 bottles per event), but only two storms were sampled completely. A >350 ml bottle was filled at a turbulent section of river and the time and date were recorded on the bottle.

In the laboratory bottles and contents were weighed and numbered. The samples were analysed for particle size distribution, sediment concentration and magnetic properties. The particle size distribution was measured using the Malvern 3000 particle sizer. Because of the high sediment concentration of the samples a 10 ml extract of sample was diluted to 500 ml with distilled water. Sediment was re-suspended using a magnetic stirrer before using a pipette to extract the 10 ml sample. This affected the magnetic properties of the sediment because the magnetic grains in the sample stuck to the magnetic stirrer and could not all be recovered. As this would compromise the tracing of sediments, every other sample was excluded from particle size analysis and used solely to measure suspended sediment concentration (57 samples) and mineral magnetic signature (64 samples).

Sediment concentration was determined by vacuum filtration by passing the entire sample through a weighed 90 mm diameter glass fibre disk. The disk plus sediment was dried at 40^{o}C, weighed and packaged in magnetic pots for magnetic analysis. Sediment concentration was determined from the weight of water in the bottle and the weight of sediment on the filter paper. Magnetic susceptibility and magnetic remanence were measured for the packaged suspended sediment. Data were extrapolated linearly to create a dataset with 20 minute intervals for each flow event.

Stage was measured at 20 minute intervals at three stations along the valley fill from December 2012 to May 2014 and converted to discharge as described previously. The total load per twenty minute period was estimated as the product of the concentration and discharge.

The dataset on suspended sediment was used to trace sediment qualitatively and combined with discharge and sediment concentration, was used to interpret source changes during flood events. Only two events, in December 2013 and January 2014, were sampled through both the rising and falling limb of the hydrograph. For these events the contribution of sediment from igneous sources was calculated using equation 3.4. The results are shown in Figure 3.23 and Table 3.10.

Rainfall was measured for the two storms at the station indicated in Figure 3.14. For the December event 22 mm was recorded with a maximum 5-minute intensity of 8 mm. More rainfall was recorded for the January event, 38 mm over a longer period with a maximum 5-minute intensity of 4 mm. The results presented in Figure 3.25 and Table 3.10 show a very different response for the two storms. The December storm had a higher peak discharge and a significant contribution from the Drakensberg igneous source in the upper catchment. Despite the higher recorded rainfall, the January storm had less runoff and carried very little sediment from the upper catchment. This lower intensity event was likely therefore to have been a local storm which did not extend far upstream. Total loads per storm are given in Table 3.14. The December storm carried a load over five times that in January although the peak

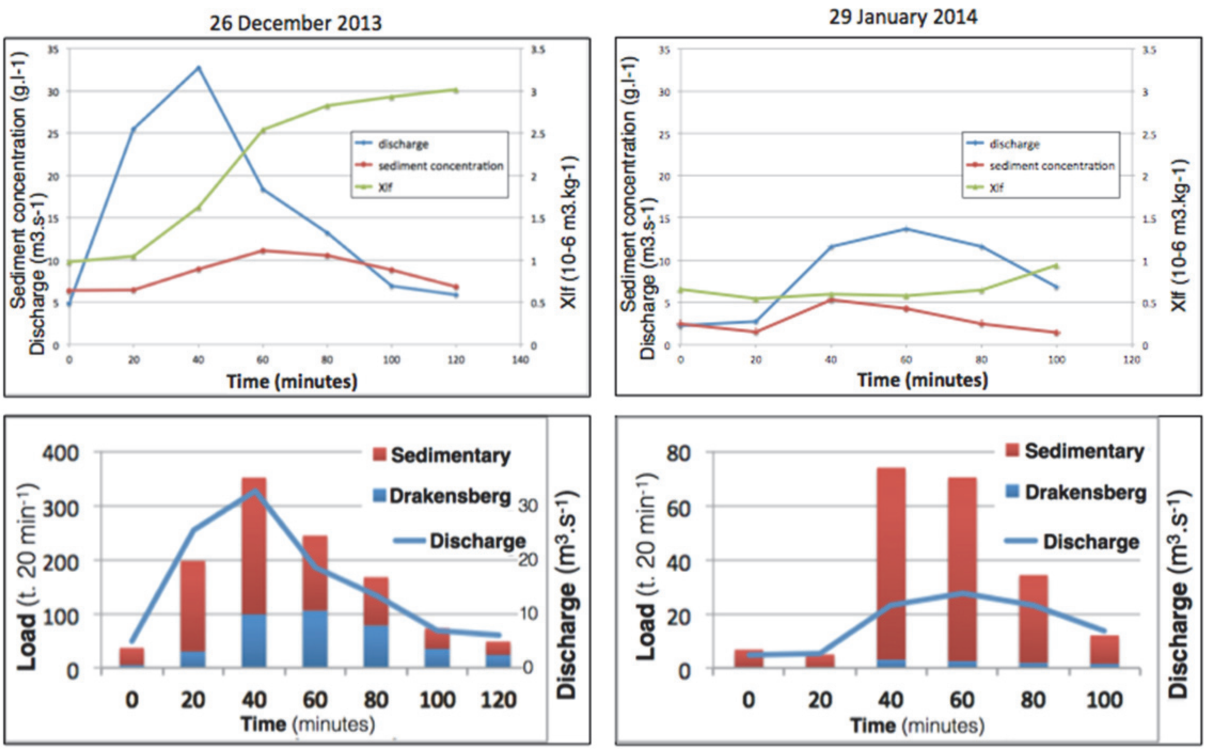

Figure 3.25 Time series of flow, Xlf, sediment concentration, and sediment load through two storm events.

discharge was only approximately double.

Table 3.14 Sediment loads for two storm events

	December		January	
	Total load (tonnes)	**Yield (t.km^{-2})**	**Total load (tonnes)**	**Yield (t.km^{-2})**
Sedimentary	742	37	194	10
Drakensberg	377	10	9	0.25
Catchment	1119	19	202	3.5

A sediment rating curve (concentration against discharge) was plotted for all samples collected for all events (Figure 3.24). The correlation between sediment concentration and discharge for December 2013 (64 samples) was moderately positive (R^2 = 0.3475) and for January 2014 weakly positive (R^2 = 0.105). January concentrations were generally lower, indicating a flushing effect of the storms at the beginning of the wet season. The average suspended sediment concentration for similar flow events also decreased throughout the season as shown by the arrows on Figure 3.26.

There was no correlation between suspended sediment concentration and % contribution from igneous sources (R^2 = 0.014).

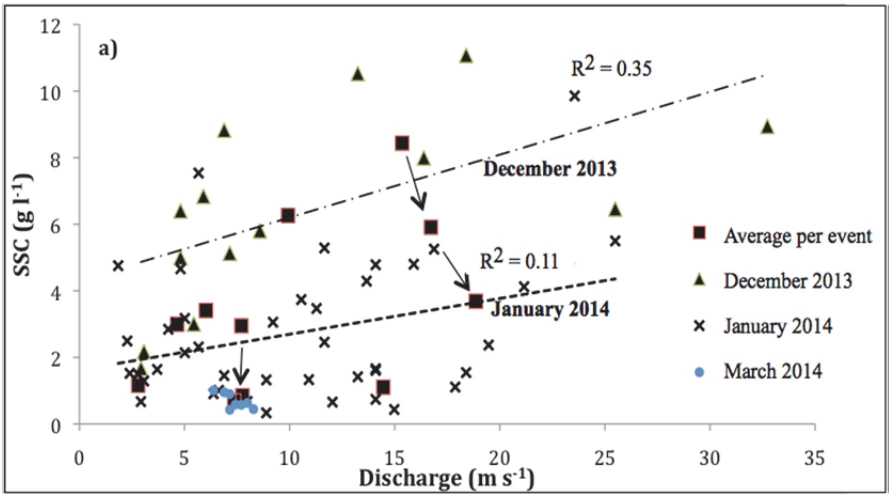

Figure 3.26 Variation of suspended sediment concentration for 11 high flow events in December 2013 to March 2014. Arrows indicate the decrease in average suspended sediment concentration for similar magnitude events through the wet season.

3.7 How accurate is the data? – Sources of measurement error

The wide range of methods used and general lack of detailed data for South Africa made the introduction of error during the research highly likely. A brief overview of possible inaccuracies and approximate estimates of error is given.

Maps and aerial photos are replications of reality and are influenced by scale, geometric transformations and projections. Possible inaccuracies due to photo and map representations and digitizing could be as high as 10%. Sediment volume calculations were based on mapping and field measurements that had standard deviations of ~50% due to the variability of depth and width measurements of the features in the field. Sediment erosion estimates could thus be up to 60% in error.

Rainfall measurement is only representative of the area measured by the raingauge, thus upscaling a single point measurement to catchment scale will introduce error. Scaling of rainfall from the Matatiele area will add further error. The accumulated error associated with the long term rainfall data could be as high as 50%. The hydrological modelling and disaggregation process could introduce a further 50%, making the total error associated with the modelled flow data 100%. Measuring discharge, stage and developing stage-discharge relationships could introduce additional error of 20-50%. Due to the large amount of potential error, a range of flood base duration (i.e. 2-5 and 4-6 hours) was used to account for the likely error introduced by both data and modelling.

Sediment tracing and determining the chronology introduced significant error. The measurement error of laboratory equipment was in the range of 2-10%. Using the data in models introduced further error of 10-30%. Dating and tracing related error could thus be as high as 40%, which excludes the representativeness of the actual field sampling.

The study thus experienced high levels of error associated with data and modelling. Error related to hillslope-channel connectivity is ~50%, sediment tracing and dating error is ~50 and channel-valley fill connectivity modelling error is 50-100%.

4 Synthesis of research on connectivity in the Vuvu catchment

4.1 Introduction

A synthesis of the main findings with respect to the scientific objectives of the research is presented in this chapter. The most relevant results relating to the description of hillslope-channel and channel-valley fill connectivity are integrated to form a broader perspective of how landscape connectivity has changed in the high rainfall mountainous headwaters of the northern Eastern Cape Province, South Africa. In each section the implication of the change in landscape connectivity on sediment dynamics is emphasised and the contribution of the work to the field of geomorphic analysis of river systems and sediment dynamics is highlighted. A conceptual model of altered landscape connectivity is presented, together with research opportunities and management recommendations.

4.2 Summary and general discussion

4.2.1 *Connectivity as a concept and framework for the study of sediment dynamics*

Fluvial geomorphology often is approached from either a purely physical (e.g. Leopold and Maddock, (1953); Wolman and Miller, (1960)) or a purely structurally based approach (e.g. Schumm,1977); Rosgen 1996)) and focuses on a specific reach, ignoring how the reach fits into the larger catchment. The connectivity concept and framework integrates and unifies these approaches to allow geomorphologists to explore the structure and function of fluvial landscapes at a range of spatial and temporal scales (Fryirs, 2013). The connectivity framework is used to anchor the well-developed physics- and structure-based geomorphic approaches in order to study catchment-wide sediment processes. This holistic approach appeared appropriate for the often complex systems encountered in South African rivers (Dollar, 2000). The ideas of various authors (Ward 1989, Harvey 2002, Fryirs et al., 2007) are integrated in Figure 4.1. The central theme relates to the different dimensions of connectivity as proposed by Ward (1989) and Harvey (2002). The routing of sediment through the catchment from hillslopes to channel reach is implied. The diagram also differentiates between factors affecting connectivity and those affecting disconnectivity *sensu* Fryirs et al. (2007). The role of buffers, blankets and barriers in forming sediment sinks and promoting disconnectivity is indicated at appropriate landform scales.

Connectivity is defined as the ease with which material is moved from one landscape unit to the next (Hooke, 2003). Brierley et al. (2006) presented a clustered hierarchical framework that can be used to identify pathways, buffers, barriers, blankets and boosters at a range of scales. This structural and functional view of the catchment and river system enables the researcher to draw conclusions about processes at a range of scales, from channel reach scale to catchment scale, with a holistic understanding of how the links between the landscape units influence the morphology of specific features over time.

In systems where landscape units are poorly connected in terms of pathways, sediment transfer is relatively slow (hundreds to thousands of years) between significant landscape units, with the different units being non synchronous in their sediment delivery processes (Fryirs et al., 2007a). In well-connected systems sediment transfer is rapid (on an event basis) with changes in one part of the catchment often manifesting in other portions of the catchment (Harvey, 2001). The degree of connectivity also is influenced by the magnitude of an event. For smaller events (annual frequency) a barrier or buffer can be effective in disconnecting a sediment pathway (depicted as a switch in the off position), but the pathway becomes activated (switch on or connected) during large magnitude events that occur less frequently (50 year return frequency) (Fryirs et al., 2007a).

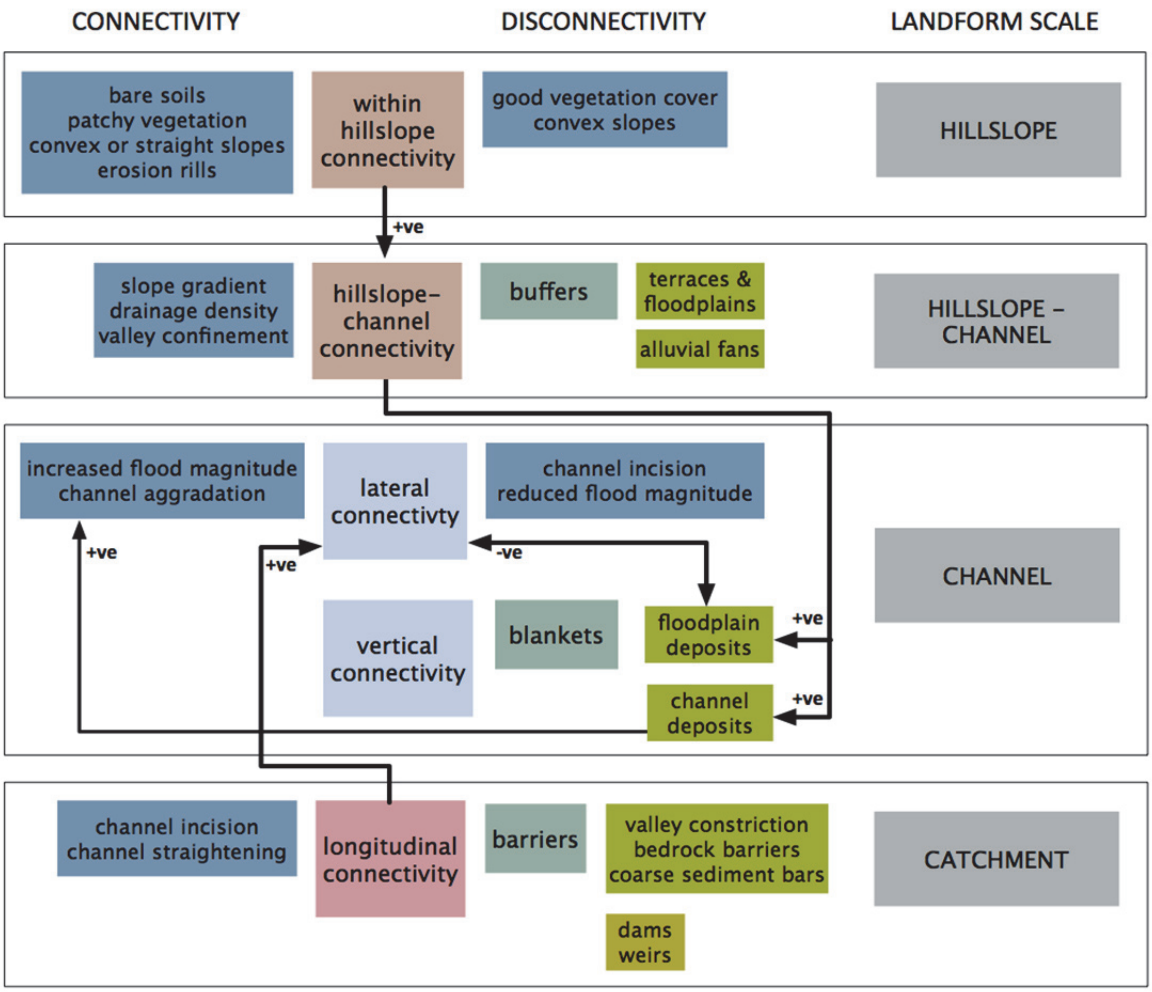

Figure 4.1 A connectivity framework illustrating factors affecting connectivity and disconnectivity at different landscape scales. Arrows indicate relationships between types of connectivity, that can be positive (+ve) or negative (-ve).

The following common themes are drawn from the literature. Firstly, at the catchment scale the focus is on linear pathways downslope and through the catchment (cf. Harvey, 1997, Brierley et al., 2006; Fryirs et al., 2007a). From the literature it is clear that steeper slopes (Kasai et al., 2005; Fryirs et al., 2007a), reduced vegetation cover (Gore, 1994; Cammeraat, 2002; Kirkby et al., 2002; Fryirs et al., 2007a), gully formation (Croke et al., 2005; López-Vicente et al., 2013) and narrow valley fills (Brierley and

Fryirs, 1999; Fryirs et al., 2007a; Fryirs and Brierley, 1999; Michaelides et al., 2010) all contribute to hillslope-channel connectivity and make transport of material to the channel more likely. Secondly, at the channel reach scale the focus is on lateral connectivity between the channel and the adjacent valley fill (cf. Ward, 1989; Kondolf et al., 2006). Channel-valley fill connectivity is decreased by channel incision, making material transfer to buffers less probable if the channel dimensions are enlarged (Gergel et al., 2002; Kondolf, 2006; Pizzuto, 2011). For this study of sediment dynamics in the Vuvu catchment, the main changes in connectivity are addressed at two scales, 1) hillslope-channel connectivity at a catchment scale and 2) channel-valley fill connectivity at a channel reach scale. No published studies were found that encompass in depth both these scales of connectivity. This research therefore adds to the body of connectivity research by integrating these two scales.

Several shortcomings of the connectivity concept have been noted, such as: connectivity is unique in every catchment and assessments are thus resource intensive (Brierley et al., 2006); no universally quantifiable measurement unit has been developed for connectivity, making comparisons among different catchments challenging (Michaelides and Chappell, 2009; Grant, 2013); and magnitude-frequency switches leak, thus not blocking sediment entirely, especially in systems dominated by suspended sediment (Fryirs et al., 2007a). Despite these apparent shortcomings, the connectivity concept proved to be a powerful tool to study catchment-wide sediment transfer processes and structures. Limited work to date has utilised the connectivity concept in South Africa, especially in high rainfall, high altitude catchments, thus the novel application of this holistic approach can be valuable to guide management of this precious high water-yield region and contribute to local and international understanding of connectivity in these catchments.

Figure 4.2 illustrates the methodological framework used to research connectivity in the Vuvu. It can be appreciated that a variety of methods were used to investigate the different types of connectivity but that some of the data was used in various contexts. These methods relied on both a good understanding of geomorphological processes, specialised field and laboratory equipment and high order technical skills to process and interpret data. Details of the methods and examples of results are given in Chapter 3. An interpretation of these results is presented here.

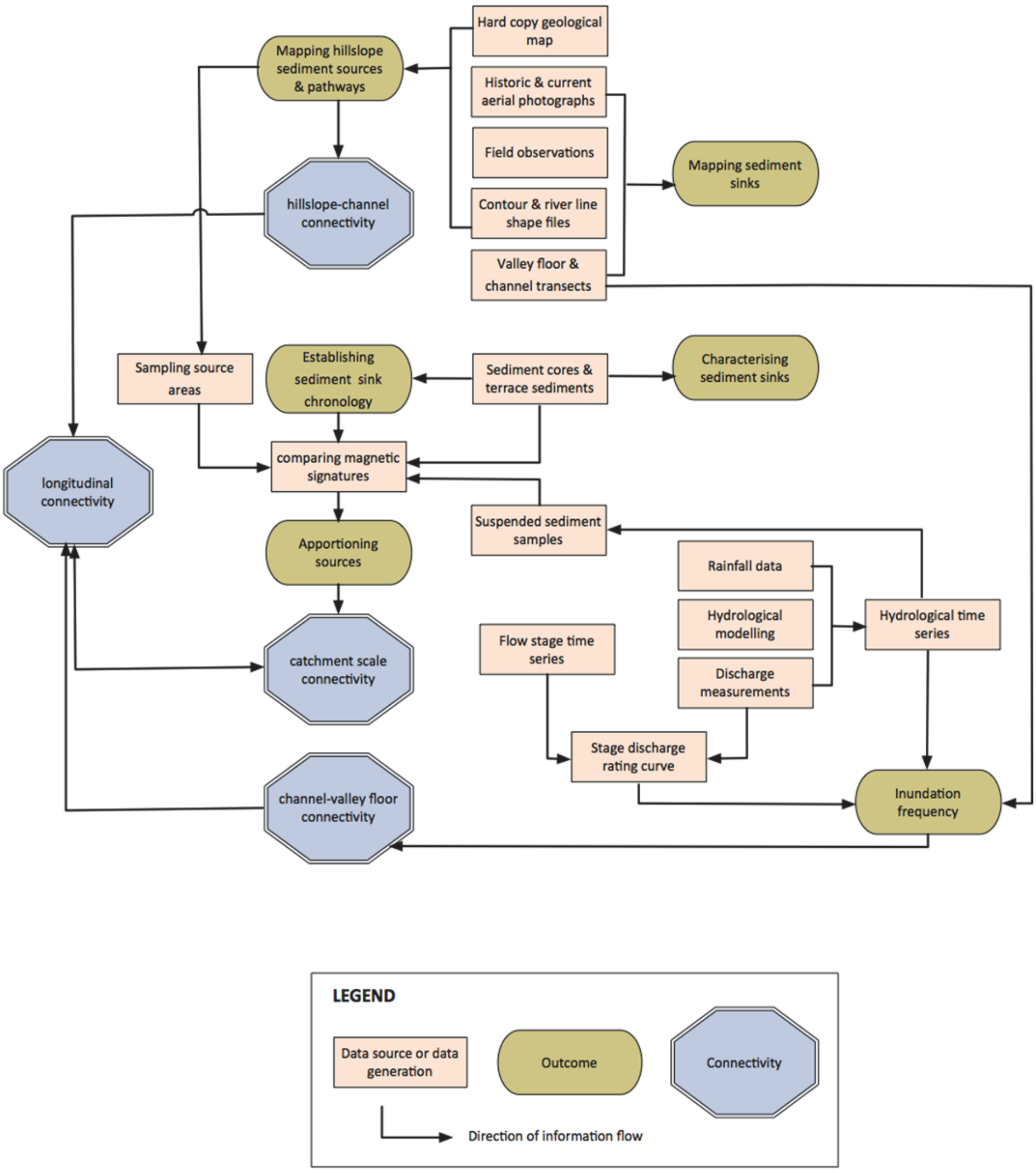

Figure 4.2 Flow chart of methods used in the research

4.2.2 *Hillslope-channel connectivity: present day sediment sources and pathways*

Given the regional setting of the Vuvu catchment in the headwaters of a steep eastern seaboard river draining the Drakensberg Escarpment, it would be expected that drainage density and hillslope-channel connectivity of sediment is high due to the steep topography. The anthropogenic influence on this hillslope-channel connectivity was not well understood and formed the focus of this section of the research. As the connectivity approach is not well developed for quantifying hillslope-channel connectivity, new methods were developed in this study to assess and compare hillslope-channel connectivity within and between various regions in the Vuvu catchment. Field visits, ground based photos and high resolution aerial images proved a useful combination of resources to map and classify potential sediment source areas in the Vuvu catchment. The large extent of gullies, areas of sheet erosion, landslides, roads and cattle tracks made it possible to digitize these features in the mountainous terrain using GIS. The use of historical photos to calculate changes in the area of larger gullies over time proved useful in determining the formation date of these features. Drainage pathways also were assessed and allowed for the differentiation between features that are directly linked to the drainage network from those where sediment transfer is hindered by a vegetated buffer. As no universal measurement unit is available for hillslope-channel connectivity, the density per unit area that often is used for drainage density was adopted. This gave a result that could be compared to that of the existing drainage network and to that of other features that increase hillslope-channel connectivity.

Results from the mapping of source areas showed that more than 9% of the catchment has been exposed to severe erosion, and that 45% of the eroded area is directly connected to the channel, thus having a high sediment yield potential. The Elliot Formation had the highest density of eroded areas due to the erodible nature of the soils (Vetter, 2007; Fey et al., 2010) and the ongoing land use pressures in the lower catchment. Moderate slopes (5–20^0) that were north-facing were most affected by erosion throughout the catchment. Although the Elliot formation was shown to be the most erodible and most active sediment source, the overall greater area of the Drakensberg Formation (65% of catchment area) disproportionately increased contributions from this area.

Table 3.1 gives the estimated soil loss from different erosion features in the catchment. A total volume of approximately two million tonnes of sediment was estimated to have been lost from visible sources identified in the catchment. These included fields, gullies, sheet erosion, landslides, roads and livestock tracks. Erosion from vegetated areas was not assessed but is likely to have contributed to sediment lost from hillslopes as discussed further below. Given that much of the accelerated erosion probably dates from the middle of the last century (c. 50 years ago) the soil loss rate was estimated at 12 t ha^{-1} y^{-1}. Gullies, sheet erosion and fields, covering 8% of the catchment, together contributed 92% of the assessed soil loss. Gullies only covered 1% of the catchment area but contributed the greatest percentage of sediment, 33%, due to their considerable depth. Values were similar to those estimated by Beckedahl and De Villiers (2000) for gully features in other areas of the Transkei. Areas of sheet erosion, covering 2% of the catchment area, contributed 30% of the sediment. Fields covered about 5% of the catchment and were estimated to contribute on average 29% of the sediment. The landslides, gravel roads and livestock tracks covered less than 2% of the catchment and contributed less than 8% collectively, making them less significant sediment sources.

Le Roux et al. (2008) modelled soil loss from the catchment slopes using an adaptation of the Universal Soil Loss Equation. His estimate of 30 t ha^{-1} y^{-1} is significantly higher than that estimated here from the identified erosion sources. If the two sets of estimates are correct, gullies, sheet erosion and fields account for 37% of soil loss, livestock tracks and roads 3% and diffuse erosion from the better vegetated catchment contributes the remaining 60%. However, due to the high connectivity of the mapped erosion features, a higher proportion of eroded soil is likely to reach the stream from these source areas.

The Elliot Formation had the highest sediment loss per area, the Clarens Formation had the lowest. Over the fifty year period the mapped erosion features on the Elliot formation contributed 23 t ha^{-1} y^{-1}, the Drakensberg 9 t ha^{-1} y^{-1} and the Clarens 4 t ha^{-1} y^{-1}. Fields were the main contribution from the Elliot formation, equivalent to the combined contribution from gullies and sheet erosion, which were very similar. Gullies, followed by sheet erosion, were the dominant sediment sources from the Drakensberg formation. Fields contributed less because of their more restricted area in the upper catchment. The contribution from roads on the Elliot Formation was surprisingly high when calculated on a geological province basis (6% of the total sediment loss). Livestock track contributed a similar amount from the Drakensberg formation.

These soil loss data per geological province emphasise the erodible nature of the Elliot Formation. The Elliot formation and Drakensberg Formation have lost similar volumes of soil over the last 50 years (c. 1 000 000 m^3 from each area), despite the Elliot Formation being only 40% of the area of the Drakensberg Formation.

Historical mapping shows that the larger gullies were initiated in the 1920s, whereas the smaller gullies were initiated in the 1950s, similar to that found by Huber (2013) in a neighbouring catchment. These features are mostly human induced as ploughing and grazing were intensified during the early 1900s, leading to increased runoff energy and soil vulnerability. From field assessments it was clear that the majority of the erosion features were still active (63%). Many gullies were still be active (61-83%), but sheet erosion features were mostly (79-86%) stable with vegetation colonising localised areas where sediment is deposited. Gullies that were connected to the natural drainage network tended to be more active than those that are buffered. Erosive features on the Elliot Formation were the most active, mainly due to its erodible nature and continued pressure on the land. Results also showed that gullies remain sediment sources for periods up to 100+ years, where after they stabilize.

The Vuvu catchment had a well-developed natural drainage network as expected for a high relief headwater catchment. Limited natural buffering exists due to the steep nature of the slopes, except for the gentle slopes in valley bottoms and occasionally between the steeper hillslopes (stepped landscape). Hillslope-channel connectivity was significantly increased throughout the Vuvu catchment. Down-slope erosional features, such as gullies, increased the drainage density by 21%, whereas across-slope features (e.g. livestock tracks and roads) increased the drainage density by 178%. The down-slope features would be more efficient in routing water to the channel, but across-slope features play a significant role in intercepting hillslope runoff, concentrating flow and routing it to the drainage network, decreasing the chances for water to infiltrate and sediment deposition along the slope.

Gullies were formed in colluvium on lower slope angles at the base of steeper slopes due to increased runoff contributions from upslope as a result of reduced vegetation cover, hardened surfaces and increased pathways (cf. Cammeraat, 2002). The gentle slopes possibly acted as buffers between the steeper slopes and the river system, storing sediment, but gully development has formed a link between the steeper slopes and the channel, thus effectively overriding the potential for the gentler slopes to act as buffer areas. Continuous gullies were the most important hillslope-channel linkages in terms of sediment delivery as water and sediment are directly discharged into the channel. Buffers below discontinuous gullies reduce the velocity of flows and deposit sediment during low magnitude events, however these buffers will be breached during high magnitude events as described by Croke et al. (2005) and Fryirs et al. (2007a).

The Elliot Formation was the geological province most affected by increases in hillslope-channel connectivity, with increases occurring across the range of slopes. The Drakensberg and Clarens Formations were affected to a lesser degree, with increases in hillslope-channel connectivity mostly occurring on moderate and steep slopes (slopes steeper than 5^0). Hillslope-channel connectivity increases were greatest on north-facing slopes owing to the resilient nature of the moister south-facing slopes that support a greater vegetation cover (Holland and Steyn, 1975; Granger and Schulze, 1977) and the increased pressure on north-facing slopes due to settlement preference and more palatable grasses (Ellery et al., 1995; Mucina et al., 2006).

Landscape connectivity within the Vuvu catchment is naturally high due to limited accommodation space in the generally steep landscape, but anthropogenic influence and accelerated erosion has increased this connectivity over the past 100 years. This means that sediment that is currently mobilized on the slopes is more likely to be transported to the main river, even during the lower intensity rainfall events. The Elliot Formation was the most impacted in terms of erosion and hillslope-channel connectivity; this is a likely function of the erodible nature of its mudstone derived soils and ongoing anthropogenic land use pressures.

4.2.3 *Valley floor sediment sinks: the valley fill character and history*

The Vuvu valley fill is narrow (up to 100 m wide) with a wandering channel pattern (channel up to 30 m wide) that switches from side to side along the valley fill similar to the 'foothill river' classification of Rowntree and Wadeson (1999). The channel consists of a cobble pool-riffle sequence with bedrock outcropping in places and can be classified as a mixed bed river (Rowntree, 2013a). Cobble makes up the majority of the bed, with limited fine sediment stored along the channel bed. Suspended sediment is mostly stored in flood benches, terraces and alluvial fans along the valley fill. The flood benches are narrow (up to 50 m wide) and not continuous, often dissected by poorly defined flood channels. The flood benches and terraces have a cobble base with a sequence of horizontal sand and silt layers up to 1.2 m thick, typical of a river with a mixed load transporting both bed load and suspended load (Schumm, 1977). The cobble base of the terraces is an indication of a previous fill level that formed before 4 500 BP. The source of the cobble is most likely from the upper basalt parts of the catchment as the mudstones of the lower catchment breaks down rapidly to fine grained sediment. The valley fill has limited accommodation space due to the steep topography.

Both higher and lower flood benches are active in storing sediment at the present time as fresh sand and debris deposits were identified at both levels. Particle size varied down the cores that were taken on the flood benches, with median particle size ranging from coarse silt to medium sand, where coarser layers indicate higher energy events (Tooth et al., 2013) and overall variability of the flow regime. The general upwards fining towards the top of the higher benches shows that energy to transport larger particles is waning as the bench builds up vertically. Terraces had a similar sediment composition to that of the benches with all bench and terrace sediment being poorly sorted. This suggests that sediment and energy regimes have not changed significantly over the past 4 500 years.

Channel benches were dated using radionuclides incorporated into the sediments from aerial deposition. Pb-210 dating using an emanation coefficient of 0.3 (Du and Walling, 2012) proved effective, especially when Cs-137 detection and channel position from historical aerial images were used to calibrate the CRS model. Results showed that the lower benches stored sediment for 40-60 years, whereas the higher benches have stored sediment for ~92+ years. The average sediment accumulation rate was ca. 0.9 g cm^{-2} yr^{-1} for the higher flood benches compared to ca. 3.2 g cm^{-2} yr^{-1} for the lower flood benches, showing that the lower benches were more active in receiving, storing and possibly contributing sediment to downstream loads (Erskine and Livingstone, 1999). The increase in sediment accumulation rate over the last ~50 years would suggest that sediment availability has increased, probably due to a combination of accelerated erosion and efficient sediment delivery as a result of increased hillslope-channel connectivity. There is evidence to suggest that the sections with greater sediment accumulation rates were associated with dry periods when vegetation cover is reduced and soils are exposed to erosive rain, resulting in greater sediment availability (López-Bermúdez et al., 1998; van der Waal et al., 2012).

Calculations indicated that the flood benches stored ~2% of the sediment that has been eroded over the past 50 years, making the valley fill an insignificant sediment store, as would be expected for a steep headwater system with limited accommodation space (Rowntree and Wadeson, 1999; Fryirs and Brierley, 2013).

Furthermore, river incision, channel straightening and channel widening over the last 50 years has reduced channel-flood bench connectivity. Erskine (1986) found that river straightening would steepen the river slope and the transport efficiency of the channel, reducing chances of storing sediment on the valley fill. Incision in the Vuvu system was likely a response to increased hillslope-channel connectivity resulting in increased peak discharge (Knighton, 1984; Schumm, 2005), whereas river straightening and widening was the response to an increased coarse sediment load (Knighton, 1984; Erskine, 1986). From the information above one can deduce that channel incision, straightening and widening reduce the buffering capacity of the valley fill.

Terrace dating revealed cut and fill cycles in the Vuvu valley with incision being dominant over the last ~3 000 years. The following scenario is suggested. Warmer and wetter paraglacial conditions during the early Holocene (5 000–10 000 BP) could have redistributed sediment that was produced during the Last Glacial Maximum (Temme et al., 2008) and led to the build-up of sediment in the Vuvu valley fill (up to 4+ m). As vegetation cover increased during the middle to late Holocene, sediment supply was reduced and led to mass valley sediment evacuation (Temme et al., 2008). The findings of the Vuvu valley cut and fill cycles [infill and subsequent degradation during the late Holocene (~3 000 BP)] agree with other studies from South Africa such as the Modder River, Free State (Tooth et al., 2013) and Okhombe valley, KwaZulu-Natal (Temme et al., 2008).

The Vuvu valley fill acts as a buffer for both hillslope-channel and longitudinal connectivity. Terraces and higher flood benches disconnect the slopes and smaller tributaries in the direct vicinity of the valley fill from the channel, whereas flood benches store a small proportion of sediment that is transported downstream. The Vuvu River is in a phase of degradation, reworking old deposits on an ongoing basis, mainly through lateral migration, straightening and incision of the channel.

4.2.4 *Channel-valley fill connectivity*

Intensive summer rainfall in the Vuvu catchment produced steep hydrographs of short duration (3 hours). This is expected for steep, well connected catchments that receive intensive rainfall (Costa, 1987; Taguas et al., 2008). Short term (2 years) discharge was measured for the Vuvu catchment which was extended by disaggregating monthly flows to daily and subsequently peak instantaneous flows. This allowed for the assessment of channel-flood bench inundation frequency for current conditions and a potential future rehabilitated condition (re-vegetation of bare areas and gullies) where hillslope-channel connectivity is reduced.

Simulations indicated that the peak discharge will be reduced in the future as hillslope-channel connectivity is decreased by rehabilitation efforts, similar to results by Jones and Grant (1996) and Schulze and Horan (2007).

Measured and modelled hydraulic results showed that higher and lower flood benches vary significantly in inundation frequency. River level monitoring at two transects showed that the lower benches were inundated 1.5–4.5 times a year and the higher benches 1 in 2 years. The monitoring was done during a moderate to wet period, thus inundation frequencies were higher than expected. Modelled discharge data for 15 transects over a 73 year period produced inundation frequencies of 2.5–4.4 events a year for lower benches and 1 in 1.2 to 1 in 7.3 years for higher benches. The large range of frequencies is due to the differences in inundation threshold (bench level) between the various transects (n=15). Some of the features were elevated due to channel incision or near vertical accrual of sediment, thus increasing their inundation threshold and decreasing their inundation frequency.

The modelled inundation of higher flood benches was less frequent than the 1-2 year frequency expected for bankfull discharge (Wolman and Leopold, 1957; Wolman and Miller, 1960; Leigh, 2010).

This suggests that the higher flood benches were effectively terraces (Erskine and Livingstone, 1999) or that the hydraulic modelling overestimated discharge requirements for inundation, or that the channel has adjusted to the highly variable flows that are characteristic of southern African and Australian rivers (McMahon et al., 1992). Similar results of low inundation frequencies for higher benches were recorded in the literature for South Africa by Dollar (2000) and Heritage et al. (2001), and for Australia by Erskine and Livingstone (1999). These authors related such low inundation frequencies to the highly variable flows that result in a more complex channel composition where an active channel is situated in a much larger macro channel. A very large flood would remove the lower benches, where after the benches are built up again by smaller events, resulting in localised cut and fill cycles (Gupta and Fox, 1974). The effects of a large flood are expected to vary throughout the system, leading to benches at different stages of development, as seen along the Vuvu valley fill. As the Vuvu River has experienced incision over the last 50 years, it is challenging to tease out whether the different flood bench levels are simply due to the incision, or related to the highly variable flows experienced throughout southern Africa. It could also be a combination of incision and variable flows, but identifying the main driver of channel complexity remains debatable with only the current limited observations and data sets.

Wet and dry cycles also play an important role in inundation frequency. In the Vuvu, inundation frequency is increased during wet years (lower benches inundated 7 times a year and higher benches inundated on an annual basis), and decreased in dry years (lower benches inundated once a year and higher benches inundated <1 in 10 years). It was expected that frequent inundation would result in greater sediment accumulation rates. This was contradicted by observations in the sediment history of the Vuvu catchment where dry cycles had greater sediment accumulation rates than wet cycles. This would suggest greater sediment availability during dry periods (reduced vegetation cover). Although average channel-flood bench connectivity was reduced, the greater sediment availability during these dry periods made large contributions to the flood benches during infrequent large events that do inundate the flood benches. This would suggest that hydrological connectivity peaks during wet periods, but that sediment connectivity peaks during infrequent large events over dry periods. This implies that there is a need to separate hydrological and sediment connectivity.

Modelled results for a potential rehabilitated state with reduced hillslope-channel connectivity showed reduced channel-flood bench inundation frequencies as peak flow volumes are reduced. This would reduce the potential to store sediment on the flood benches as sediment deposition is influenced by both sediment concentration and channel-flood bench connectivity. It is likely that the suspended sediment concentration will be reduced due to increased buffering in the catchment as a result of improved vegetation cover and reduced hillslope-channel connectivity. Sediment availability during the short inundation time of benches will thus be limited. Furthermore, reduced channel-flood bench connectivity will be the case until the channel reworks the flood benches either through lateral migration or a large flood, and builds up new benches that are formed and maintained by the post rehabilitation flow regime. These new benches should be inundated more frequently as they are a product of the post rehabilitation flow regime. As the channel adjusts to the post rehabilitation flow and sediment regime a release of valley fill sediment is expected. A reduced hillslope-channel connectivity should cause more sediment to be stored on hillslopes and sediment inout to the river to be reduced. As the channel adjusts to this post rehabilitation flow and sediment regime, a release of valley fill sediment through bank or channel bed erosion is expected. Only once the hillslope-channel and channel-valley fill connectivity have stabilised over the longer term will the sediment yield be significantly reduced. This reduction in sediment yield can possibly take 10-100+ years.

This study focused on fine sediment transfers as these are expected to have shown the largest catchment-wide response to connectivity changes. Coarse sediment may non the less have been affected by the inferred changes in landscape connectivity. Coarse sediment transport is likely to become more efficient with increased hillslope-channel connectivity due to increased runoff volumes, concentrated flow and direct pathways to the river network. Whether more coarse material is made available due to the anthropogenic influences is largely unknown, but it is assumed that the majority of the coarse material resident in the channel originates from the upper catchment's more resistant rocks, thus human influences could be negligible. It is more likely that most of the coarse material presently found in the channel was made available during the last Glacial Maximum (10 000+ BP), where after the increase in rainfall moved the coarse material to the valley fill where a large proportion was deposited. As vegetation stabilised the slopes and the coarse sediment availability declined, the coarse sediment stored in the valley fill started moving downstream. This could be around 5 000 BP as is suggested by the dating of a few terraces in the Vuvu valley. Since then conditions were more stable with smaller fluctuations in coarse sediment availability and transport. The incision of the valley fill, coupled with increased runoff, will possibly have increased the efficiency of coarse sediment transfer along the valley fill. As rehabilitation efforts should reduce both the runoff and transfer of coarse sediment to the river, coarse sediment transport and export will be reduced. Locally sourced coarse sediment from scoured benches and terraces will not be transported as readily and could help form more stable structures such as cobble bars that can initiate the formation of fine grained sediment stores. Due to the confined nature of the valley fill, both fine grained and coarse sediment storage will remain low.

4.2.5 *Integrating catchment scale connectivity*

Sediment tracing using magnetic signatures provided a means of investigating catchment scale connectivity. Igneous (Drakensberg Formation) and sedimentary (Clarens and Elliot Formations) sources could be discriminated effectively using mineral magnetic properties (Oldfield et al., 1979; Foster et al., 1998, 2007). A quantitative and qualitative approach was tested. The quantitative sediment apportionment approach (using mineral magnetic properties in a Discriminant Function Analysis) could differentiate between source groups, based on Xlf, ARM and HIRM values, with relatively small uncertainties (<10%). Apportionment results had relatively low error margins (3-27%). For the qualitative approach Xlf was selected as the best discriminator between igneous and sedimentary samples. A comparison between the two approaches showed the same trends, with sedimentary source sediment being dominant (~64%) in the core (VT2). An equation was developed that could calculate the proportion of igneous material in a sediment sample based on an Xlf value. Increased particle size reduced the certainty levels of the tracing. Surface-subsurface tracing, using Xfd, proved possible where mudstones dominated the sediment sample. Using an additional tracer, Cs-137, which was independent of the magnetic properties, extended the surface-subsurface tracing to more recent samples (post 1958) of sediment from igneous sources.

This qualitative approach could be adopted in catchments with a distinct magnetic difference between the various geologies as it can produce tracing results relatively quickly without requiring elaborate source ascription modelling. Managers and citizen scientists can also use the qualitative approach to determine the general source of sediment as it requires relatively simple equipment and is more easily understood.

Flows were sampled during flood events to establish sediment concentrations and sources by applying the qualitative approach described above. Suspended sediment concentrations were high during summer peak flows (up to 11 g l^{-1} consisting of clay; D50 of 2 µm) and were comparable to concentrations for the larger Mzimvubu River system (Madikizela et al., 2001) of which the Vuvu River forms a part. The difference in particle size between the flood water sampled and bench material (D50 of 2 µm and 110 µm) indicates that the observed floods were relatively small as they did not carry the larger particles in suspension. This was confirmed by the water level readings for the suspended sediment monitoring period that showed that the sampled floods did not inundate the higher benches. It is thus expected that the particle size will increase during larger flood events.

Two flood events were successfully monitored through both the rising and falling limbs of the hydrograph. By assessing sediment loads carried through the two storm events it was evident that the larger proportion of the sediment was derived from the mudstone areas. Only in the larger event during December 2012 did the upper catchment basalts contribute significantly to the load (Figure 3.23). The relative contribution from the upper catchment increased over the recession limb, demonstrating the lag of water moving down the catchment. The total sediment load carried by the December storm was19 t h^{-1} of which 66% came from the Elliot mudstones. In the smaller January storm the mudstones contributed 96% of the yield of 3.5 t h^{-1} (Table 3.14). These results are broadly in line with the estimates of soil loss given in Table 3.1 in which soil loss form the mudstones is estimated at 23 t h^{-1} and from the basalts at 9 t h^{-1}.

Results from the suspended sediment tracing showed that sediment source changed throughout the flood hydrographs and was dependent on rainfall distribution, event intensity and catchment shape. As channel-flood bench connectivity is established during peak flows, clockwise and anticlockwise sediment hysteresis played an important role in the source signal that was stored in the flood bench. Clockwise hysteresis is associated with sediment sourced from the lower parts of the catchment whereas anticlockwise hysteresis is associated with sediment mainly sourced from the distal parts of the catchment. In the Vuvu catchment, for flood events with the same magnitude but opposing hysteresis directions, the event experiencing clockwise hysteresis could leave a stronger sedimentary signature compared to the event with anticlockwise hysteresis that could deposit more igneous sediment on flood benches. These flood hydrographs and linked sediment source tracing results highlighted how variable the Vuvu system is and that the dominance of a source can change over a short time (e.g. within a flood event). This variability has implications for sediment tracing as flows (responsible for overbank links), sediment concentrations and sources differ between and within events. Sediment tracing results should thus be interpreted with care and an understanding that a layer of sediment that is deposited on a flood bench is a mere 'snapshot' or portion of the sediment transported during an event.

A general decrease in sediment concentration was evident towards the end of the wet season as sediment supply is exhausted (Figure 3.24). This is in agreement with a number of other studies from a range of environments (Asselman, 1999; Rovira and Batalla, 2006; Grenfell and Ellery, 2009; Fryirs and Brierley, 2013). Sediment concentrations decreased during the wet season as sediment available for transport is depleted and vegetation provides cover from erosive rainfall (Grenfell and Ellery, 2009). These data on within event and seasonal sediment dynamics suggest that the majority of the sediment movement occurred during short pulses at the beginning of the wet season during catchment-wide high-intensity rainfall. The Vuvu River is thus a supply limited system due to the frequent high energy events and good landscape connectivity.

Higher and lower flood benches stored mostly locally sourced sedimentary sediment, with the higher benches storing finer material with a greater igneous contribution (up to 59% igneous material). This is due to the difference in elevation between the lower and higher flood benches that require different sized flows for inundation (Wolman and Leopold, 1957). Sediment is deposited on the higher benches when the whole catchment is contributing water and sediment (high magnitude), whereas sediment is deposited on the lower benches during more locally derived low magnitude events. Low magnitude events in the upper catchment do not contribute significant amounts of sediment to the lower benches, pointing to both the lower erosion potential of the upper catchment and sediment storage on slopes and along the higher order drainage channels. The sediment from the upper catchment is transported to the lower catchment during high magnitude events, similar to the switch concept by Fryirs et al. (2007a) where switches are on (letting sediment through) during large magnitude events.

Results show that the lower catchment has lost the majority of its surface soil as is reflected by the dominance of subsoil in the lower benches whereas higher benches contained more surface soil from the upper catchment. This confirms the mapping results that pointed to the mudstones of the Elliot Formation as the geological province with the greatest soil loss and highest hillslope-channel connectivity.

Terraces were also dominated by sedimentary subsoil sources. The erodibility of the mudstones, due to the high sodium content and poor structure (Fey et al., 2010), was confirmed by its dominance over the past 4 500 years, suggesting that the recent increase in hillslope-channel connectivity has not changed the proportions of sediment stored in the Vuvu valley fill. It confirms the mudstones as an important suspended sediment source, regardless of land use and degradation, that experienced greater hillslope-channel connectivity over the past 4 500 years relative to the basalt and sandstone areas. This could mean that suspended sediment yield from mudstone areas can remain high despite rehabilitation efforts.

4.2.6 *Conceptual model of sediment connectivity*

A conceptual model of changes in connectivity in the Vuvu catchment is presented in Figure 8.1. The Vuvu catchment is characterised by a high altitude, high rainfall basin. The overall catchment is in a phase of degradation or incision as headward erosion slowly cuts into the Drakensberg Escarpment. Minimal lateral erosion is taking place as can be seen by the generally steep topography. Limited storage space exists due to the steep topography and the well-developed natural drainage network contribute to the good hillslope-channel connectivity. The gentler colluvial slopes of this stepped landscape lends itself to small buffers between the steeper slopes. A narrow valley fill in the lower catchment stores both coarse and fine grained sediment. The coarse grained sediment is more likely to be derived from the harder basalt rock in the upper catchment whereas the fine grained sediment is likely to be a mixture from basalt, sandstone and mudstone derived soils. Catchment-wide high intensity rainfall coupled with erodible mudstones in the lower part of the catchment contribute to high suspended sediment concentrations in the Vuvu River. This high energy system is inherently prone to efficient sediment transfer, but human induced pressures have further increased the sediment transfer potential. Cut and fill cycles are evident on the hillslopes and valley fill as sediment is redistributed and stored in new locations, such as alluvial fans, if not exported from the catchment.

Livestock grazing and trampling, frequent burning, the development and the subsequent abandonment of agricultural fields and the introduction of housing areas and associated road networks have led to the disturbance and reduction in vegetation cover and successive increases in runoff and erosion in the catchment. Gullies formed where slope angles relax and thicker colluvial soil deposits are found. Livestock tracks formed where animals frequently traverse the catchment. Roads link the various homesteads to the main road that traverses the catchment and links the various scattered villages. Gullies, livestock tracks and roads increased the down-slope and across-slope routing of water, limiting water infiltration, and concentrating flows. Increased runoff volumes have resulted in increased energy available to erode soils and transport sediment. Furthermore, the generally fine nature of the eroded sediment and the high energy system made transport in suspension possible, thus limiting both sediment deposition and the effectiveness of existing buffer features on the hillslopes and the valley fill. The increase in hillslope–channel connectivity would increase both fine and coarse grained sediment transport.

The valley fill has limited storage space due to its confined nature. Narrow flood benches were shown to be stores of mostly fine grained sediment with coarse grained sediment or bedrock forming the base of the flood benches. Increases in runoff and hillslope-channel connectivity resulted in larger flood magnitudes and increased sediment concentrations. This increased flow energy enhanced the sediment

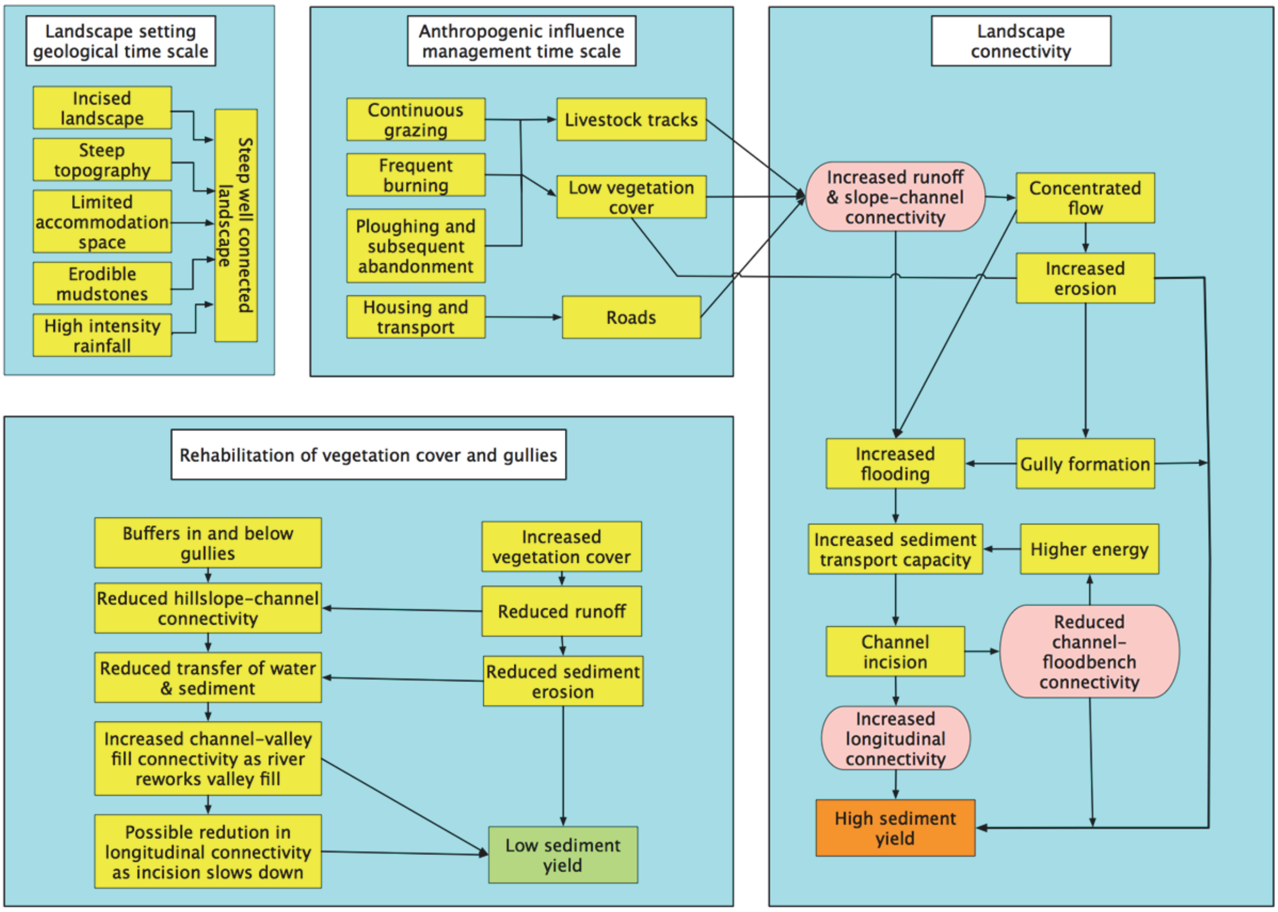

Figure 5.1 A conceptual diagram of how changes in landscape connectivity have altered sediment dynamics in the Vuvu catchment.

entrainment and transport capacity and resulted in channel incision, straightening and widening. This reduced the channel-valley fill connectivity, but due to increased sediment concentrations, sediment deposition on flood benches has increased during the few events that do inundate the flood benches. The overall result is increased down-valley or longitudinal connectivity due to the small storage potential of the narrow flood benches. This reduction in channel-flood bench connectivity and greater flow energy regimes reduced the potential to store sediment in the valley fill, enhancing an already high sediment yield from the Vuvu catchment. This shows that the degraded nature of the catchment reduced the buffering capacity of the landscape, enhancing sediment production and sediment transfer, leading to high sediment yields.

Wet and dry cycles played a role in sediment availability, transfer and deposition. During dry cycles vegetation cover is reduced and soils are exposed to erosive rainfall. Large rainfall events are fewer during dry periods, but when intensive events happen, great quantities of sediment is eroded and transported. This possibly results in high sediment concentrations during the infrequent events that deposit large quantities of sediment on flood benches that are inundated. Wet periods are different in that vegetation cover is greater and soils better protected, leading to low sediment concentrations during the more frequent high flow events and results in less sediment deposition despite the greater channel-valley fill hydrological connectivity. This indicates that sediment connectivity peaks during dry cycles, whereas hydrological connectivity peaks during wet cycles.

It is postulated that rehabilitation of the catchment's vegetation cover and gullies will lead to reduced hillslope-channel connectivity. A better vegetation cover will limit rain drop related soil erosion and the volume and energy available of runoff to erode and transport soils. Buffers around and in gullies will further facilitate sediment deposition and water infiltration. These reductions in hillslope-channel connectivity in turn will reduce flood energy. Incision will slow down with reductions in net sediment export from the valley fill. The river could continue to rework stored valley sediment until a new stable phase is developed as flood benches are rebuilt to the new channel level and supports channel-valley fill connectivity that facilitates greater sediment storage. It is envisaged that rehabilitation will immediately reduce sediment contributions from hillslopes, but that valley fill degradation could continue for another 10-100+ years while a new sediment storage phase is developed on the valley fill. The effects of the catchment-wide rehabilitation is mere speculation and warrants further research.

The Vuvu catchment will remain a non-equilibrium system where sediment export dominates over sediment deposition. This is mainly due to its landscape setting and geological makeup. Localised cut and fill phases were always present in the landscape within larger more general cycles of increased cutting or filling, mainly due to climatic variations. The recent anthropogenic influence has initiated an overall accelerated cut phase on the hillslopes and valley fill, but with the appropriate rehabilitation strategies an catchment-wide fill phase can be initiated with net reductions in sediment yield.

4.2.7 *Connectivity guidelines for rehabilitation in the Vuvu*

The research presented in this report focused on hillslope-channel connectivity and lateral connectivity between the channel and valley fill. Rehabilitation in the catchment has targeted erosion on the hillslopes. The following recommendations could contribute to reduced hillslope-channel connectivity and therefore suspended sediment in the Vuvu River:

1. Within-hillslope connectivity can be reduced by the following interventions that will result in more sediment being stored on the hillslope.

    - Vegetation cover throughout the catchment can be improved by: 1) having strict grazing rules that will allow the veld to rest and recover and 2) reducing the frequency and extent of fires.

    - Contour agriculture lands with well vegetated buffers equally spaced along and directly below fields.

    - Construct non-flammable silt fences at regular intervals of 10-50 m along a hillslope to trap sediment and promote water infiltration.

2. Hillslope-channel connectivity can be reduced by the following interventions that will reduce the movement of sediment along linear pathways and help to stabilise connectivity features.

- Establish vegetation buffers at the base of gullies to trap sediment. This also will help to stabilise gullies by creating a sediment sink that will store water and enhance vegetation growth and sediment trapping efficiency. Sediment trapping should propagate upslope leading to further gully floor stabilisation.

- Construct artificial wetlands using gabion structures on very low angled slopes (<10) to trap sediment.

- The soil along the sharp edges of gullies are mostly dry due to the increased drainage efficiency of the incised feature and rarely supports a good vegetation cover. Replanting along these edges, even if re-sloped and covered by a biomat or mulch before planting is unlikely to restore the necessary soil moisture regime needed for plant proliferation due to the ongoing desiccation of the soil. Consider only using this method for smaller features where the difference between the top and bottom of the feature is less than 0.5 m. The desiccation effect should be less for these smaller features, thus could the replanting be more successful.

- Prevent new across-slope pathway formation and the deterioration of existing pathways by formalising access routes for livestock and reducing up and down catchment movement by establishing dipping stations higher up in the catchment.

- Create runoff diversions, using non-flammable materials, along livestock tracks and roads to channel water onto vegetated slopes in order to disperse runoff, allow for infiltration and sediment trapping.

- Protect seeps, wetlands, vegetated drainage lines from grazing, trampling and fire as dense vegetation growth will aid sediment trapping. Consider grazing these areas only during winter when rainfall is less erosive.

3. Valley floor rehabilitation should target the following in order to optimise sediment deposition and reduce erosion

    - Restore degraded wetlands and fans using appropriate structures in order to optimise sinks and restrict grazing until stability has been achieved. Raising channel base levels will increase lateral connectivity but this can be difficult to achieve in steep gradient high energy systems. A comprehensive guide to wetland rehabilitation is provided by Russell (2009).

5 Application of a connectivity to catchment management

5.1 Introduction

5.1.1 *Application of the connectivity framework*

Connectivity is proposed as a suitable framework for addressing many water and sediment related issues at the catchment scale. It is aimed specifically at groups interested in improving ecosystem services through catchment rehabilitation where an improvement in baseflow and reduction in sediment yield are important considerations. This would include the Department for Water and Sanitation (DWS) and the Department of the Environment (DEA). The Natural Resource Management Programmes of the DEA – Working for Water and Working for Lands – are good examples of potential users. Other user groups could include the World Wildlife Fund through their catchment programmes and various NGOs.

Table 5.1 Qualitative assessment of erosion sources and connectors for subcatchments

Erosion features (list) e.g.	**Rating (Widespread, Common, Local)**	**Connectors/pathways (list) e.g.**	**Rating (Widespread, Common, Local)**	**Is erosion feature connected to the natural channel? (Well, Moderately, Poorly connected)**	**What are the main connectors?**
Cultivated fields		**Natural channels**			
Abandoned fields		Gullies			
Gullies		Roads			
Grazing land		Tracks & footpaths			
Sheet erosion		Drainage pipes			
Landslides					

The framework was initially developed as a research tool that aimed to investigate sediment dynamics in the Vuvu catchment; it has good potential application as a research framework and for model development. There is a clear need for sediment models to take connectivity into account in order to map sediment movement between source areas and final sinks.

Figure 4.1 showed the connectivity pathways through a catchment and demonstrates how sediment moves at different landform scales. Factors increasing both connectivity and disconnectivity are indicated. This figure provides the basis for describing connectivity as a tool for understanding catchment sediment dynamics. Figure 4.2 illustrates the methodological framework used to research connectivity in the Vuvu. As it was developed as a research tool it will be too complex for most management purposes. Full details of methods as used in this research were described in Chapter 3. As noted, high order knowledge and skills were needed to collect, analyse and interpret data, often using specialist equipment that may not be widely available. The methods employed in a particular situation will depend on constraints such as the size of the area, available time and funding, and the level of available expertise. In this chapter we present a skeleton framework that outlines the information that should be collected without detailing the methods used. It is suggested that methods better related to the management context still need to be developed. The effectiveness of simpler method that can be employed by a generalist needs to be tested. In most cases a qualitative assessment may require fewer resources in terms of equipment and time but there is increased reliance on expert judgment based on experience.

5.2 A methodological framework for assessing catchment scale connectivity

5.2.1 *Catchment scale appraisal*

Before starting a formal assessment of the catchment area it is important to familiarise oneself with the area both through a desk top study and a preliminary field visit. The following steps should be followed.

1)1) Study the catchment area using a resource such as Google Earth. This should give a first impression of the relationship between topography, land use and erosion features. Assess access to different areas for the catchment.

1)2) Undertake a field reconnaissance to identify the main connectivity issues in the catchment. The purpose of this activity is to familiarise oneself with the area and to make a first appraisal of problems and possible interventions.

1)3) Make a list of erosion and depositional features – draw up a preliminary classification based on field evidence.

1)4) Ask yourself what scale these operate on: within hillslope, hillslope-channel, channel-valley fill, longitudinal down the length of the main channel?

1)5) Make a preliminary assessment of the drivers of change. Note that these may not be evident from a field visit. These are assessed further under 5.2.3.

1)6) Consider possible types of intervention.

5.2.2 *Assessing hillslope scale connectivity*

Identify and map sediment sources and sediment pathways at the hillslope scale

Sediment sources and pathways of sediment movement can conveniently be mapped together as the techniques are similar. It should be noted that sources and pathways represent different functions, the former supplies sediment, the latter acts to transfer sediment downslope and is therefore a direct expression of connectivity. The following steps are recommended.

1. Undertake a desktop study using remotely sensed images. Recent digital photography at a resolution of can be acquired from the from the NGI in Cape Town. A GIS would normally be used to map and analyse the data.
2. Groundtruthing is important to verify mapping according to the classification of features. If volumetric estimates are required these must be taken in the field.
3. A GIS analysis can be used to identify local drivers of erosion such as geology, slope gradient, aspect and land use using an intersect tool
4. A GIS analysis can be used to estimate the degree of connectivity by linking sediment source areas and pathways using an intersect tool.
5. An analysis of historic aerial photograph is useful to identify when erosion features were initiated and to determine whether or not they have stabilised.
6. GIS based soil loss models are available to map potential erosion hotspots. These models are recognised as being valuable as a means to assess relative soil loss but their use to estimate absolute values is questionable. Moreover the estimates are for soil loss (i.e. hillslope erosion rate), not sediment delivery to the river. They do not take adequate account of connectivity, nor do they normally include gully erosion. The recent report by Le Roux et al. (2015) does take erosion modelling further by including gully erosion in the Mzimvubu catchment.

Assess the drivers of changes to hillslope connectivity and the potential for reversing trends

For rehabilitation to be successful it is important to identify the drivers of change. In some cases these can be addressed directly in order to reverse the degradation process (e.g. land use practices). In other cases addressing the drivers may be beyond the scope of the rehabilitation (egg. weather events). Future practices must take account of the changed system boundaries. Potential interventions can be planned on whether they are addressing the drivers themselves and/or the continued impact if those drivers.

1) Identify drivers

A preliminary assessment of drivers of change can be made during field reconnaissance and groundtruthing activities. Talking to local people can give useful pointers to when and why erosion was initiated. Drivers of change are not always obvious and may be related to both bio-physical and socio-economic conditions. For example social grants can change land use practices as more cash becomes available to households formerly reliant on subsistence crops.

Historic documents can provide insight into land use practices and the reason for change. In the upper Mzimvubu quarantine of livestock in the early 20th century restricted livestock sales and contributed to the build up of stock numbers. (See Hidden Struggles in Rural South Africa). Rainfall records can be interrogated to identify wet and dry periods.

2) Identify possible interventions

Having identified drivers of change we can start to assess the potential for reversing trends. Often it is not sufficient to simply address the driver because the landscape may have crossed an irreversible threshold and created an internal driver. For example overgrazing may cause gully erosion but once a gully exists it becomes its own geomorphic features that increases connectivity and imparts new energy to the landscape. Reducing grazing pressure on its own will not solve the gully erosion and transmission problem. Expert judgment is needed to resolve these complex issues.

Different interventions are required to address soil loss from erosion features and sediment transport through connectors. The former requires a more catchment wide approach using soft engineering structures such as silt fences whereas the latter may require a more spatially targeted approach using hard engineering structures. Key points in the landscape for intervention should be identified. Sites of active or potential deposition should be identified as this is where structures are likely to be most effective. Unstable high energy systems are hard to control and structural interventions can simply cause further damage. There is a wide literature on erosion control methods which can be consulted for practical solutions. Esler et al. (2006) present options applicable to the Karoo, a dryland environment. Russell (2009) presents rehabilitation options for South African wetlands, some of which are applicable to hillslopes.. Details are not be given here.

A rapid, qualitative approach to assessing hillslope connectivity

It is important to determine the scale at which mapping will take place and how detailed it should be. It can be a time consuming exercise if all erosion features and pathways are to be mapped using a GIS. An alternative approach is suggested here but its effectiveness requires further research.

1) Identify sub-catchments for evaluation – their size will depend on scope of the study

2) From the field visit and perusal of aerial photographs, Google Earth, classify erosion features and hillslope connectivity according to Table 5.1. Use a qualitative, visual assessment to identify the main erosion sources and pathways; list and rate them according to their prevalence in the landscape.

3) Assess the connectivity of each erosion source to the natural channel network according to whether or not they are intersected by the different sediment pathways.

An objective method needs to be developed to rank catchments by potential hillslope sediment yield (according to extent of erosion features) and degree of connectivity.

The method described here can guide rehabilitation efforts according to priority sub-catchments and appropriate interventions (targeting erosion features or pathways). More detailed mapping could be carried out in targeted areas.

5.2.3 *Identify and map buffers between hillslopes and valley floor*

Geomorphic features such as alluvial fans and terraces can act as significant buffers that encourage deposition of sediment before it enters the river channel. Incision of channels crossing these features reconnects the hillslopes and channels. Features should be classified according to their type and role as connectors or sinks. A combination of remote sensing and groundtruthing should be used as described in section 5.2.2. A GIS can be used to capture the data.

Historical aerial photographs can be used to identify changes to buffer features such as incised channels or increased deposition and to determine their present stability.

The likely cause of incision should be assessed – is incision due to upslope influences (increased runoff) or downstream influences (fan toe trimming by laterally moving channel). Will any intervention address the incision? It should be understood that alluvial fans are naturally unstable features and channel shifting is a characteristic process. Channels switch in time and space between incision and aggradation depending on the balance between upslope runoff and sediment loads.

Key points for interventions should be identified in the light of findings.

5.2.4 *Assess longitudinal connectivity*

Longitudinal connectivity describes the effectiveness of sediment transport through the channel network. It is normally applied to lower gradient higher order channels that occupy the valley floor rather than to steep first (or possibly second) order tributaries that can be thought of as part of the hillslope connectivity network. This distinction is, however, subjective and the boundary of longitudinal connectivity can be defined by the user. Longitudinal connectivity was not assessed in depth for the Vuvu because a rapid appraisal based on field evidence did not identify any significant connectivity features that would have created sediment sinks within the channel. The following two steps are recommended as a way to assess longitudinal connectivity.

1) Identify natural features that contribute to sediment deposition (barriers) or increased sediment transport (boosters – e.g. gorges). Natural barriers include, in descending order of permanence, valley constrictions, rock steps, alluvial fans, coarse sediment deposits, woody debris dams.
2) Identify anthropogenic features that increase or decrease connectivity. Channel straightening and levees increase connectivity, dams, weirs, causeways and bridges decrease connectivity.

5.2.5 *Determine connectivity between valley floor features*

The research in the Vuvu included a rigorous investigation of lateral connectivity based on long term flow monitoring, hydrological modelling and hydraulic analysis. This is likely to be beyond the scope of most rehabilitation projects. A suggested procedure for a less intensive assessment is given here.

1) Map channels and lateral features on valley floor from aerial photographs.

2) Confirm mapping in the field and assess their role as sediment sinks. Different flood levels should be identified across a river section. Active sediment deposition is evidence of overbank flooding and continued lateral connectivity. If no deposits are evident the flood feature is likely to be inactive, indicating loss of lateral connectivity due channel incision. Another reason for reduced connectivity may be a reduction in the magnitude of floods due to an upstream barrier such as a dam.

3) Determine likely cause of channel incision. Channel incision may be due to natural causes, be anthropogenically induced or be caused by a combination of both. The following causes should be considered.

    a. geomorphic increase in valley floor slope due to long term sediment deposition

    b. increased flood peaks and/or decreased sediment

    c. natural climatic cycles

    d. changes to longitudinal connectivity

        upstream barrier reducing sediment

        loss of downstream barrier – e.g. erosion of a dolerite dyke

4) Identify drivers of change to lateral connectivity

    Source information from aerial photographs, historical documents relating to land use and land use practices, population change, etc. rainfall and flow records.

5) Consider options for rehabilitation

    Different options should be considered depending on whether or not the geomorphic context is a floodplain wetland. Channels that are part of a wetland are characteristically of a low gradient, highly sinuous and dominated by pools. Structures built across a channel can restore these conditions by slowing down flows and enhancing sediment deposition behind the structure. A practical guide to wetland rehabilitation is provided by Russell (2009). If the desired state is a free-flowing river, structural interventions will not help. The incised condition cannot be reversed. If the river is able to shift laterally flood benches will be established over time, restoring a new connectivity regime.

5.2.6 *Catchment scale connectivity using sediment source tracing*

Sediment source tracing can be an effective method to investigate catchment scale connectivity as it is used to match potential sources to sediment sinks (Fryirs and Gore, 2013). Internationally it has been used widely to identify sediment sources in situations where they can be distinguished according to some criteria (Collins and Walling, 2004) and are used increasingly as a management tool (Walling, 2013). In South Africa sediment tracing has been applied successfully in both the Vuvu (Mzobe, 2012;

van der Waal, 2014) and Karoo (Rowntree and Foster, 2012) where there are distinct differences between igneous and sedimentary derived soils that enables the effective use of environmental magnetism to derive signatures. Walden et al. (1999) provide a thorough account of the application of environmental magnetism.

Tracing requires specialised equipment and experienced people and the use of geochemical analysis is expensive. Recent research has investigated the use of colour spectra as a cheaper and less time consuming tracer (Pulley and Rowntree, in prep.)

Methods

1) Collect samples from identified sources. At least ten samples should be taken to characterise each source.

2) Collect samples from sink areas. Samples from cores taken through a flood deposit are commonly used to take samples.

3) Apply the chosen technique to derive the sediment fingerprint. Common alternatives are mineral magnetism and geochemistry. If facilities available mineral magnetism provides a relatively cheap and quick means on deriving signatures. It was used in the Vuvu to identify different areas of the catchment contributing sediment. It was especially useful here because there was coincidence between settlement, land use and geology. Geochemistry is useful in separating land use in agricultural areas (Smith and Blake, 2014), urban areas with heavy metals (Wang et al., 2012) but is expensive and more time consuming in terms of sample preparation and analysis. Full details relating to mineral magnetism were given in section 3.6.

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Appendix 1: Optically Stimulated Luminescence Dating Report, Thina River Project

Compiled by

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Geo-luminescence Laboratory

Optically Stimulated Luminescence Dating Report

THINA RIVER PROJECT

for

Bennie van der Waal

Compiled by

Mary Evans

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2013

Contents

1. Introduction

Luminescence dating emerged as a technique for determining the age of ancient ceramics in the early 1960's and 1970's, through the use of thermoluminescence (TL) or the light emitted by a sample when it is heated. Wintle and Huntley (1979; 1980) presented a workable TL dating method for determining the time of deposition of sediments; first for deep sea sediments, then for a range of aeolian and aquatic clastic sediments. Huntley *et al*. (1985) showed that light could be used to stimulate the dating signal from sedimentary minerals and this work suggested that luminescence dating methods would offer additional practical and methodological advantages to dating sediments. Subsequently the luminescence technique has undergone major developments and significant improvements in instrumentation, measurement, procedures and selection of preferred minerals for dating (see Bøtter-Jensen *et al*., 2003; Murray and Wintle, 2000).

Luminescence dating falls within the category of radiation dosimetric dating techniques which are based on the time-dependent accumulation of radiation damage in minerals (Aitken, 1998; Murray and Wintle, 2000), which is the result of exposure to natural low-levels of ionising radiation. The intensity of the radiation damage is a measure of the total dose or the total amount of energy absorbed from the ionising radiation by the mineral over a certain period of time. In luminescence dating the intensity of the radiation damage is detected as a small amount of light called *luminescence.* This latent luminescence signal can be removed or "zeroed" by exposure to heat or light. Thus for sediment dating the zeroing event or "bleaching" is the exposure to daylight during erosion, transport and deposition of the mineral grains. Once the sediments are buried again and no longer exposed to sunlight, the luminescence signal can start to build up again (Duller, 2004). The latent luminescence signal can also be released under laboratory conditions using heat (thermoluminescence) or light (optically stimulated luminescence) and this signal can be recorded. This luminescence signal is related to the dose the mineral has received since the last zeroing event (or last exposure to sunlight); and if the rate is determined at which the dose was absorbed, it is possible to determine an age for the sediment. However, this age refers to the time that has elapsed between the moment the sediment was deposited and the moment of sampling for analysis (Figure 1). The OSL signal acquired during the previous burial period is reset by sunlight during sediment transport prior to deposition. Quartz or feldspar minerals are commonly used for OSL dating of sediments, but, quartz is the preferred dosimeter as the physical basis of OSL production in quartz is better understood; and feldspar may be subject to phenomena such as anomalous fading (e.g. Bøtter-Jensen *et al.*, 2003).

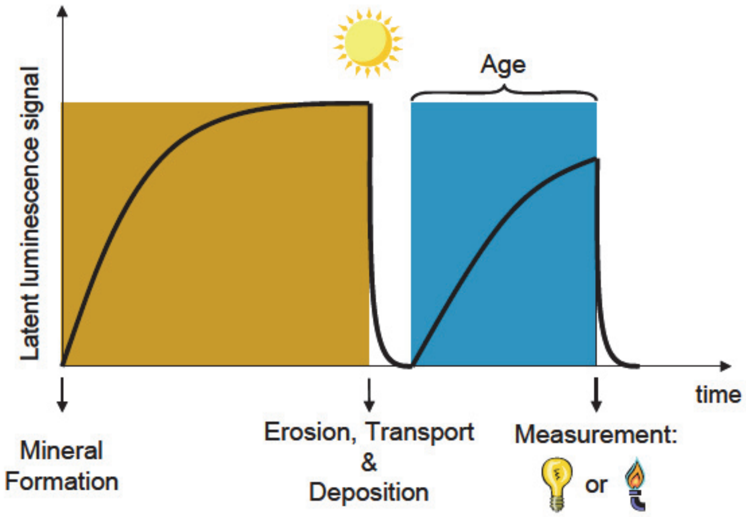

Figure 1 A schematic representation of the event that is being dated in the luminescence dating of sediments where minerals are continuously exposed to a low-level of natural radioactivity, through which they can acquire a latent luminescence signal. During erosion, transport and deposition, the minerals are exposed to sunlight and all the previously accumulated luminescence is removed. Once shielded from the sunlight, the signal starts to build up again, until the moment of measurement in the laboratory. The age that is being determined is consequently the time that has elapsed between these two zeroing events (Duller, 2004)

The main process causing luminescence can be described in terms of the energy level diagram for non-conducting ionic crystalline materials (Figure 2). Aitken (1998) indicated that electrons are associated with discrete ranges of energy called "bands"; where the lowest energy band is the valence band, and the highest energy band is the conduction band. The gap between the two is referred to as the "forbidden zone" which in an ideal crystal, no electron will occupy a position in this zone. However, in a natural crystal defects such as impurities or missing atoms are present and disturb the ordered crystalline structure, which give rise to the presence of energy levels in the forbidden zone. The conduction and valence bands extend throughout the crystal, but the defect states are associated with the defect itself and are referred to as localised energy levels which are significant to the luminescence phenomenon, as they carry the memory of exposure to nuclear radiation. Therefore luminescence requires the existence of lattice defects within the crystal structure (Aitken, 1998).

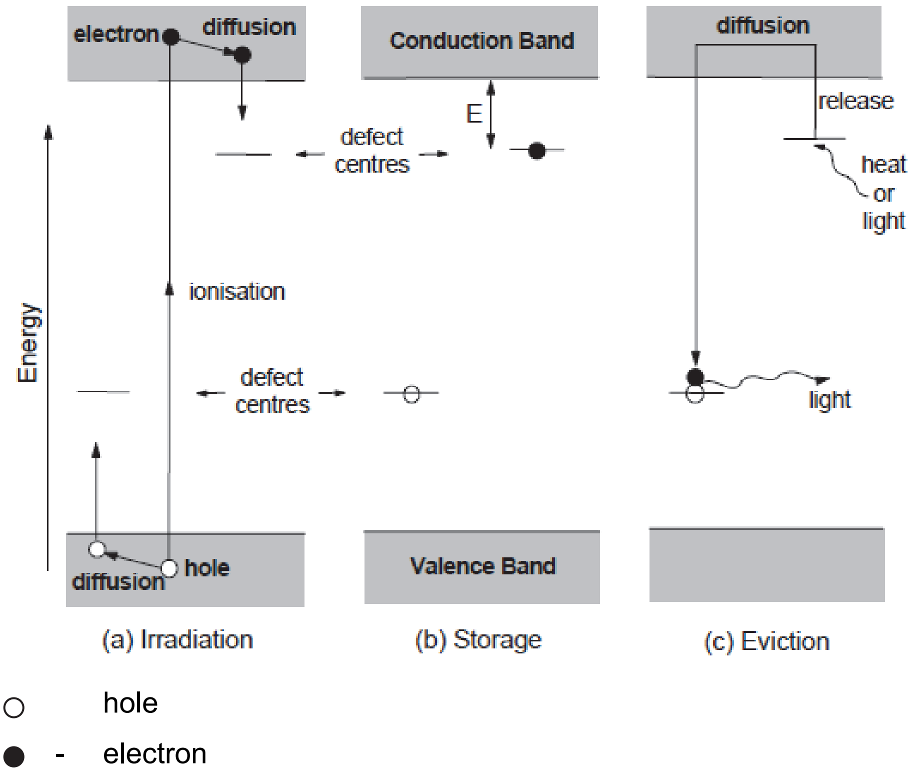

Figure 2 Energy level representation of the luminescence process (modified after Aitken, 1998).

In nature low-level radiation, through its ionising effect can raise an electron from the valence band into the conduction band (Figure 2 a). For every electron created, an electron vacancy (hole) is left behind and both the electron and the hole are free to move through the crystal and in this way the energy of nuclear radiation is taken up. This energy can be released again by recombination and most charges do recombine easily. However, the electron and the hole may be trapped at defect centres. In this instance the nuclear energy is stored temporarily in the crystal lattice and the system is said to be in a metastable situation (Figure 2 b). Energy is required to remove the electrons out of the traps and return the system to a stable situation, where more energy is required to empty deeper traps. By exposing the crystal to heat or light the trapped electrons may absorb enough energy to bridge the barrier to the conduction bands (Figure 2 c), where once excited they can be trapped again, or can recombine with holes in recombination centres (Aitken, 1998; Duller, 2004).

The recombination can result in either the emission of heat or light and the defect sites where radiative (light) recombination occurs called luminescence centres and the resulting light is called TL (if heat is used to release the electrons from the traps) or OSL (if light is used). The amount of light emitted is proportional to the amount of electrons stored in defects and therefore the amount of energy received from irradiation. Since the energy is absorbed at a certain rate, the intensity is related to the time of accumulation, i.e. the longer the material is exposed, the more signal is acquired (Aitken, 1998). The process of stimulation and eviction of the electrons is termed signal bleaching, with stimulation by heat or light resulting in a TL or OSL signal, respectively. If the grain is stimulated sufficiently to evict all the trapped electrons, it is described as being fully bleached. Whilst the TL glow curve contains contributions from traps of various depths, the main source of the OSL signal is thought to be the traps associated with the readily bleachable 325°C TL trap (Aitken, 1998). As OSL is generally very much more rapidly reset than TL, it is more suitable for dating sediments where the bleaching occurs by exposure to light.

The radiation to which a grain is exposed during burial derives from a number of different sources, and consists of alpha and beta particles, and gamma rays. Quartz grains contain very little internal radioactivity, so the majority of the radiation they receive is derived from uranium, thorium, and potassium contained within the surrounding sediment, as well as a small level of cosmic radiation. The radiation flux at a sampling location is termed the environmental dose-rate, and can be obtained either by field or by laboratory measurements. The amount of radiation that a grain has received during burial can be determined by measuring the OSL signal from the natural dose (i.e. that received during burial), and the OSL signals from a series of laboratory irradiations of known dose. The laboratory measurements are used to calibrate the OSL signal derived from the natural dose, and thus determine the laboratory dose that is equivalent to the dose received by the grains in nature; this is termed the equivalent dose (De), with the unit of measurement in Grays (Gy). Since the OSL signal is bleached on exposure to light during sediment transport, the De normally represents the amount of radiation received following deposition and burial after the last transport event. By deriving the burial dose (De) of a sample, and the environmental dose-rate at the sampling location, the age of a sample can be found using the equation:

$$Age(yr) = \frac{Equivalent\ Dose\,(Gy)}{DoseRate\ (Gy.ka^{-1})}$$

where the equivalent dose (in Grays) is the laboratory radiation dose that produces the signal equivalent to the natural luminescence signal for the grains being measured (Duller, 2004). The dose rate (in Grays per thousand years) is the annual dose received by those grains in their depositional environment (Duller, 2004). This annual dose rate refers to the rate at which mineral grains in sediment absorb energy from the surrounding flux of radiation which comes from the naturally occurring radionuclides ^{232}Th, ^{238}U and ^{235}U and their daughters, and ^{40}K and ^{87}Rb as well as cosmic radiation.

Ideally, the OSL signal is derived from a single type of mineral grain such as quartz or potassium feldspar mineral separates. The dating technique can be applied to the age range from present to approximately 300 000 years ago and precision varies from ~3-10% of age for heated materials and ~5-20% for sediments (Wintle *et al.*, 1993).

Initial studies of the application of OSL dating to sediments concentrated on depositional environments where the transport process ensured that sufficient exposure to sunlight to bleach the material had occurred, such as aeolian deposits (e.g. Huntley *et al.*, 1985; Stokes, 1992). In some other depositional settings (e.g. fluvial or colluvial), not every grain receives light exposure of a sufficient strength and/or duration to bleach fully the dose from the previous burial period (Figure 2b). If a residual trapped charge remains in the grains, the sediment is regarded as partially or incompletely bleached. Where partial bleaching is present, careful assessment of the distribution of De values is necessary to obtain the correct age. Simply taking some measure of the average from the De values for a partially bleached sample is not appropriate because the grains with residual trapped charge will cause overestimation of the age (Wallinga, 2002; Kim, 2009).

2. Sample Details

Three samples were submitted from the floodplain deposits of the upper Thina River for optically stimulated luminescence (OSL) dating.

Sample Code	Depth (m)	Altitude (m.a.s.l)	Latitude (S)	Longitude (E)
Thina 1	0.47	30.6	-30	28
Thina 2	1.45	30.6	-30	28
Thina 3	2.43	30.8	-30	28

3. Sample Preparation

Sediment was removed from each sampling tube under controlled, laboratory safe-light conditions. The sediment located within 2 cm of both ends of each tube was removed to isolate any sediment potentially exposed to light during sampling. This material was used to measure the water content and to determine the dosimetry of the sample. The remaining 'bulk' content of each sample was wet sieved to remove any particle sizes smaller than 63 µm. The remaining sediment was treated with 33% hydrochloric acid and 20% hydrogen peroxide to remove any carbonate and organic components. Quartz grains were isolated from any other minerals by heavy liquid separation using sodium polytungstate. After rinsing, drying and sieving, the fine sand (90 - 106 µm and 180-212 µm) fraction was then etched for 40 mins in 40% hydrofluoric acid, in order to remove the outer 10-15 µm layer affected by alpha radiation and degrade each samples' feldspar content. 30% hydrochloric acid was added to remove acid soluble fluorides. Each sample was dried and resieved in preparation for equivalent dose determination.

4. Determination of Equivalent Dose (De)

Single 3 mm aliquots were prepared on stainless steel disks and all luminescence measurements were performed on a Risø TL/OSL Reader Model -DA-15, an automatic measurement system that enables measurement of both thermoluminescence and optically stimulated luminescence of quartz, feldspar and poly-minerals. The reader is programmed through a sequence protocol written on *Sequence Editor (*Risø National Laboratory) which is directed through the MINI-SYS computer attached to the reader. The reader then carries out the measurements fully automated. The system allows up to 48 samples to be individually heated to any temperature between room temperature and 700°C, individually irradiated by radioactive beta or alpha ($^{90}Sr/^{90}Y$) source and optically stimulated using various light sources. The emitted luminescence is measured by a light detection system comprising a photomultiplier tube and suitable detection filters. The sample is placed in a light tight sample chamber which can be programmed to be evacuated (vacuum) or have a nitrogen atmosphere maintained by a nitrogen flow. The standard photomultiplier tube (PMT) in the RisøTL/OSL luminescence reader is bi-alkali EMI 9235QA PMT, which has maximum detection efficiency at approximately 400 nm. To prevent scattered stimulation light from reaching the PMT, 7.5 mm Hoya U-340 detection filter, which has a peak transmission around 340 nm are used.

Optical stimulation is achieved using an array of light emitting diodes (LEDs), which are compact, fast and enables electronic control of the illumination power density. The LEDs are arranged in 7 clusters each containing 7 LEDs (i.e. a total of 49 LEDs). The distance between the diodes and the sample is approximately 20 mm. The Risø TL/OSL luminescence reader is equipped with two stimulation sources: 1) Infrared (IR) LEDs emitting at 875 nm arranged in three clusters each containing seven individual LEDs. The maximum power from the 21 IR LEDs is approximately 135 mW/cm^2 at the sample position; and 2) Blue LEDs emitting at 470 nm arranged in four clusters each containing seven individual LEDs. The total power at the sample position from the 28 LEDs is ~40 mW/cm^2. A green long pass filter (GG-420) is incorporated in front of each blue LED cluster to minimise the amount of directly scattered blue light reaching the detector system.

D_e values were obtained through calibrating the 'natural' optical signal acquired during burial, against 'regenerated' optical signals obtained by administering known amounts of laboratory dose. Specifically, D_e estimates were obtained using a Single-Aliquot Regenerative-dose (SAR) protocol, similar to that proposed by Murray and Wintle (2000).

Up to five different regenerative-doses were given so as to define that linear portion of dose response, bracketing the natural signal, from which D_e were interpolated. A test dose of 1 Gy was used in monitoring sensitivity change. Preheating prior to measurement of natural and regenerated signals was 200ºC for 10 s and 160ºC for 10 s before test dose signal readout.

5. Dose rate Determinations

Dose rate information is presented in the table below. High resolution gamma spectroscopy analysis was performed on material sub-sampled from the 'bulk' samples to determine the average gamma and beta dose contributions, by iThemba Labs, South Africa. Dose rate calculations, following those described by Aitken (1985 in Rodnight, 2006)), incorporated beta-attenuation factors (Mejdahl, 1979), dose rate conversion factors (Adamiec and Aitken, 1998) and the absorption coefficient of present water content (Zimmerman, 1971), with a 10±3% relative uncertainty attached to reflect potential temporal variations in past moisture content. Estimations of cosmic dose followed the calculations of Prescott and Hutton (1994).

6. Luminescence Age

The luminescence age was obtained by dividing the mean D_e value by the mean total dose rate value and is shown in Table 1. The error on luminescence age estimates represents the combined systematic and experimental error associated with both the D_e and dose rate values.

Table 1. Dosimetry and luminescence ages for the Kuiseb samples with dose rate conversions and correction for water content.

Sample	Palaeodose De (Gy) *	Dosimetry			Total wet Beta dose rate ($Gy.ka^{-1}$)	Total wet Gamma dose rate ($Gy.ka^{-1}$)	Cosmic Dose Rate ($Gy.ka^{-1}$)	Total Dose Rate ($Gy.ka^{-1}$)	Age (ka^{-1})
		U-Nat (ppm)	**Th-232 (ppm)**	**K %**					
THINA 1	2.27±0.12	1.95±0.05	9.2±0.3	1.34±0.05	1.24±0.11	0.88±0.07	0.18±0.02	2.30±0.13	**996±78**
THINA 2	1.83±0.10	1.37±0.05	6.8±0.3	1.03±0.04	0.93±0.08	0.65±0.06	0.21±0.02	1.79±0.10	**1 019±81**
THINA 3	0.25±0.08	1.94±0.05	9.1±0.3	1.17±0.05	1.13±0.10	0.84±0.07	0.24±0.02	2.21±0.13	**113±37**

* The palaeodose (De) are calculated using the minimum age model (MAM) of Galbraith *et al*., (1999), with the bootstrap uncertainty estimates of Cunningham and Wallinga (2012).

7. Comment

The palaeodoses were calculated using the minimum age model which is suitable for fluvial environments (Rodnight, 2006). Samples THINA 1 and THINA 2 returned similar dates within the error margin. It should be noted that THINA 2 displayed significant partial bleaching (i.e. the luminescence signal was not completely reset during transportation), and repeated measurements were taken to calculate the De value. Also significant is the low dosimetry (uranium, thorium and potassium) in the THINA 2 sample. However, it had been noted that THINA 1 would possibly have higher water content than the other two samples. If the water content (i.e. the degree of saturation of the sample over the lifetime of the deposit) is increased to 15% for THINA 1 it would return an age of 1 035± 82, which within the error is still similar to THINA 2, but is then the older sequence.

There is no datum for luminescence dates as there is for radiocarbon dates (BP from 1950), therefore the age reported is taken from date of sampling, i.e. AD 2012.

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