GEOMORPHOLOGICAL CONNECTIVITY AND SENSITIVITY EXAMINED IN A RECENTLY DEGRADED GRAVEL-BED STREAM: IMPLICATIONS FOR RIVER-FLOODPLAIN REHABILITATION

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ABSTRACT

The study of river complexity and sensitivity to future human land-use activities and climate change is a fast growing field within the discipline of fluvial geomorphology. Associated with this is a need to improve river rehabilitation and catchment management approach, design and effectiveness. This study aimed to investigate drivers of the recent geomorphological sensitivity of the Baviaanskloof River-floodplain, an upland system in South Africa, by integrating the concepts of geomorphological connectivity and Panarchy. The understanding generated was used to evaluate the approach of the State agency, Working for Wetlands (WfWet), to river-floodplain rehabilitation in the catchment.

The concepts of geomorphological connectivity and Panarchy provide useful frameworks for understanding interactions between geomorphological processes and structure across scales of space and time. Geomorphological connectivity explains the degree to which water and sediment is linked in a river landscape, determined by the distribution of erosional and depositional landforms (Brierley et al. 2006; Fryirs et al. 2007a; Fryirs et al. 2007b). Panarchy attempts to explain lagged response to disturbances, non-linear interactions, and sudden shifts in system state, and has been applied largely to ecological systems. Panarchy theory, when combined with the concept of geomorphological connectivity, provides a guiding framework for understanding river complexity in greater depth.

The first results chapter of this study investigated river long-term and recent geomorphological history, towards understanding the nature and timing of river geomorphological cycling between erosion and deposition. Optically Stimulated Luminescence dating of alluvial fan and floodplain sedimentary units was conducted, for analysis of river-floodplain long-term history (100s to 1 000s of years). Interviews with 11 local landowners, combined with analysis of historic aerial imagery and river-floodplain topographic surveys, provided a means of describing recent (last few decades) geomorphological dynamics. The results indicated that the Baviaanskloof is naturally a cut-and-fill landscape over scales of several hundred to thousands of years, characterized by the alternation between phases of high fluvial energy and alluvial fan expansion, and low energy conditions associated with floodplain accretion. Recent and widespread river-floodplain degradation was compressed into a short period of approximately 30 years, suggesting that

one or more drivers have pushed the system beyond a threshold, resulting in increased water and sediment connectivity.

The second results chapter investigated the role of human land-use activities and flooding frequency and magnitude, as drivers of recent river-floodplain degradation. Human impacts were investigated by describing land-use activities for the preceding 80 years, and relating these activities to changes in river-floodplain form and behavior. Temporal trends in flood events of different frequency and magnitude were investigated by analyzing rainfall data, integrated with landowner reports of flood-inducing rainfall magnitudes. The findings indicated that human land-use activities have been an important driver of recent river-floodplain degradation, through the enhancement of water and sediment connectivity across spatial scales of the catchment. Episodic and high magnitude floods synergized with human driven increased connectivity, precipitating stream power and geomorphological threshold breaches, resulting in a shift in river behaviour.

The third results chapter investigated the influence of tributary-junction streams and fans on the geomorphological form, behavior and sensitivity of the Baviaanskloof River. Local-scale topographic impacts of tributary fans and streams were described using topographic surveys and geomorphological mapping techniques. Tributary streams form a major control on the behaviour of the river, by influencing the degree of coarse sediment connectivity with the main channel. Although tributary fans buffer the river from disturbances occurring in the wider catchment, they initiate topographic variations along the floodplain, influencing local-scale patterns of deposition and erosion along the river. The main river responds to water and sediment inputs from tributary junction streams by locally adjusting longitudinal slope, maintaining an overall constant slope of 0.0066 m/m. The response of the Baviaanskloof River to tributary junction fans and streams is however variable, and is fashioned by complex interactions between geomorphological and anthropogenic factors.

The final two chapters of the thesis evaluate the findings of the study within the context of river-floodplain rehabilitation approaches in South Africa, and within the theoretical, philosophical and methodological context of the research. The first of these two chapters evaluates the approach of the WfWet programme to river-floodplain rehabilitation in the Baviaanskloof. The chapter indicates that the present practice of WfWet is to reinstate a

pre-degradation state, which is not suited to the Baviaanskloof River-floodplain, since the river-floodplain has passed a geomorphological threshold, resulting in a new set of interacting processes and landforms. The author presents a conceptual model illustrating the existence of geomorphological adaptive cycles interacting across spatial and temporal scales, thereby attempting to explain a river Panarchy specific to the Baviaanskloof. From this conceptual model, a hierarchical rehabilitation framework, targeting geomorphological processes and structure situated at different spatial and temporal scales of the landscape is suggested. The final chapter discusses the implications of integrating the concepts of geomorphological connectivity and river Panarchy theory in studies of river complexity and sensitivity to geomorphological change. The author suggests that there is scope for further investigation of the application of the two concepts within the discipline of fluvial geomorphology, particularly with regard to developing quantitative approaches to measuring and describing connectivity and Panarchy.

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DEDICATION

This thesis is dedicated to the long-suffering rivers of the Eastern Cape, South Africa, for the beauty and pleasures they offer, and the impacts they endure.

CHAPTER 1: INTRODUCTION

"No man ever steps in the same river twice, for it is not the same river and he is not the same man" (*Heraclitus*, Greek Philosopher, 500 BCE).

1.1. From reductionism to complexity thinking in fluvial geomorphology

Geomorphology is a system science concerned with the complex interactions of geomorphological processes and landforms across different scales of space and time (Schumm 1977; de Boer 1992; Thorndycraft et al. 2008; Murray et al. 2009; Slaymaker 2009; Church 2010; Wohl 2014). Before the mid-20th Century fluvial landscapes were viewed as a number of interacting components governed by physical laws and linear relations between observed geomorphological processes, fluxes of water and sediment, and landform development (Preston et al. 2011). Rivers were predominantly studied at a single spatial and temporal scale limiting an understanding of the complexity of these systems (Murray et al. 2009).

Although the reductionist approach described above is still present within the discipline, there has been a recent shift toward complex systems thinking and applied geomorphology (Church 2010; Wynn 2015). The complexity paradigm suggests that geomorphological behaviour and change may not always be explained by simple laws or linear relations between contemporary processes, disturbances and landform development and change. Non-linear interactions and lags in response to disturbances are common in river systems and may result due to the influence of an array of processes and landforms that are both old and modern responses to disturbance events (Orme 2013; Rhoads 2013). Preston et al. (2011) describe this approach as 'constructivist' such that landscapes are understood as the synthesis of the interaction of many components and disturbance responses across space and time. To understand how a landscape behaves one needs to understand the interactions between the components and the history of the landscape. This shift in thinking is largely a result of philosophical inquiry within the discipline of geomorphology, and methodological developments that have improved investigation of processes and landform interactions across space and time (Thorndycraft et al. 2008; Church 2010; Orme 2013).

As a branch of geomorphology, fluvial geomorphology has shown similar advances to that described above with increasing recognition of the complexity of river systems (Church

2010). This complexity means that river behavior may often be explained by non-linear interactions between fluvial processes and landforms across spatial and temporal scales. These interactions give rise to self-organization, varying levels of resilience to perturbations or to threshold breaches at different scales and points in time, and sudden changes in river behaviour and state (Rhoads 2013). This complexity means that rivers may show variable response to similar frequency and magnitude disturbance events, or may exhibit threshold breaches in the absence of externally induced perturbations (Anderson and Calver 1977; Schumm 1979; Renwick 1992; Lane and Richards 1997; Preston et al. 2011). For example, changes in hillslope runoff and erosion may or may not translate to a proportional change in discharge and sediment delivery along a main stem (trunk) stream. A trunk stream may experience an abrupt shift in geomorphological process and form in the absence of external perturbations that disrupt discharge and sediment delivery to the channel network. However, the difficulty in measuring the multitude of interacting processes and variables at different spatial and temporal scales of river landscapes, and the difficulty of transferring findings at one particular scale to others, hampers the ability to fully investigate and account for the complexity of rivers as geomorphological systems (Slaymaker 2006; Slaymaker 2009).

Classical geomorphological theories such as river regime (equilibrium) and thresholds have long formed the basis for interpreting river process, form and change (Leopold and Langbein 1962; Langbein and Leopold 1964; Schumm and Litchy 1965; Schumm 1973; Schumm 1977). In this regard, rivers have been interpreted as open systems attempting to balance available discharge and sediment load with channel morphology, such that there is just enough energy for sediment transport. Thresholds (stream power or slope) determine the critical point at which this ‘equilibrium’ state is disturbed, following which a river adjusts available energy through processes of erosion and deposition that alter channel morphology and concomitant flow energy (Schumm and Litchy 1965, Schumm 1999). The merits of these classic theories is that they are able to predict river behaviour and change at the local-scale (river reach), but they do not capture complex interactions and geomorphological behaviour across scales.

In recent years, there has been a shift towards understanding river behaviour and change within the framework of complexity theory (Phillips 1992; Phillips 1999; Phillips 2003;

Murray et al. 2009; Phillips 2015; Temme et al. 2015). It is now more accepted that river systems are characterized by non-linear interactions between process and form across space and time (Phillips 2015). These interactions mean that ongoing change at relatively small scales (e.g. continuous deposition at the river reach scale) may initiate sudden change at larger scales as thresholds are crossed (e.g. channel reach-wide degradation). At the same time, slow yet ongoing geomorphological change at large spatial and temporal scales may hinder or enhance processes operating at smaller scales (Murray et al. 2009). As a result, rivers can behave in a predictable and organized manner or in an unpredictable and chaotic manner, even when no external forces stimulate change in system conditions (Schumm 1973; Slaymaker 2009).

The aforementioned properties of complex systems have been reasoned within the conceptual framing of Panarchy and adaptive cycles, applied mostly to understanding resilience and change in ecological and social-ecological systems (Holling 2001; Gunderson and Holling 2002; Walker et al. 2004; Gunderson 2008; Garmestani et al. 2009; Allen and Holling 2010; Allen et al. 2014). The concept of Panarchy suggests that complex systems are characterized by a multitude of interacting components and processes across spatial and temporal scales (Holling 2001; Garmestani et al. 2009; Allen et al. 2014). As explained by Gunderson (2008), at each spatial and temporal scale of a system exist adaptive cycles, which are the mechanisms by which a system is able to organize internal structure. Each adaptive cycle consists of a sequence of phases characterized by slow change and stability, punctuated by shorter phases of rapid change in structure, as a result of breaching of thresholds and growth of a new internal structure. If a perturbation is large enough to result in multiple threshold breaches at different scales of the hierarchy of adaptive cycles there may be a shift toward a new system state. The adaptive cycle and the interaction of these across scales determines the resilience of a system to perturbations of differing magnitude, and whether a threshold breach at one spatial scale is transferred up or down the hierarchy (Gunderson 2008). The adaptive cycle is a conceptual model that has the potential to aid an understanding of the mechanisms by which river systems are able to self-organize, yet indicate sudden and unpredictable geomorphological change. In fluvial geomorphology, there has been little investigation of the multitude of interacting variables and geomorphological processes at large, intermediate and small scales of space and time, using the concept of the adaptive cycle within the framework of Panarchy.

One of the concepts receiving increasing attention in fluvial geomorphology is 'connectivity' which is often interchangeably also referred to as 'coupling'. Broadly defined, connectivity relates to the degree to which water and available sediment are transferred through a river system and is determined by the nature and spatial arrangement of landforms that either impede or enhance water and sediment transfer (Harvey 2002a; Fryirs et al. 2007a). Connectivity is often described separately in either hydrological or geomorphologic terms. In this study the author has chosen to investigate the influence of geomorphological connectivity on contemporary river behavior and geomorphological sensitivity, and explore how connectivity may be integrated with the concept of the adaptive cycle within Panarchy theory, in developing this understanding. River geomorphological sensitivity has been defined in several ways based upon the founding definition of geomorphological sensitivity provided by Brunsden and Thornes (1979: 476) "…the likelihood that a given change in the controls of a system will produce a sensible, recognisable and persistent response". Authors such as Downs and Gregory (1993), Werrity and Leys (2001) and Brierley and Fryirs (2005) adapted this early definition to the fluvial geomorphological system. Brierley and Fryirs (2005) describe river geomorphological sensitivity as a measure of how sensitively a channel responds to disturbance events. If a channel responds readily and recurrently it is considered sensitive and if responses are negligible and infrequent, the river is considered to be resilient to geomorphological change. In this study geomorphological resilience is distinguished from geomorphological sensitivity as the ability of a river to recover quickly to a former condition, relative to the time taken to respond to a perturbation (Snyder 2012).

The degree of connectivity of water and sediment between landforms and zones of a river landscape determines the sensitivity of different parts of the catchment and different channel reaches to disturbances (Brunsden 2001; Harvey 2002a; Hooke 2003; Brierley et al. 2006; Bracken and Croke 2007; Fryirs et al. 2007a; Harvey 2007a; Fryirs et al. 2009). A river system characterised by a high degree of connectivity (i.e. when nearly all available sediment is transported through the system) will operate close to erosional and depositional thresholds. As a result, the system may be more sensitive to external disturbances such as floods (Harvey 2002a; Hooke 2003; Harvey 2007a; Reid and Brierley

2015). Alternatively, a system displaying low connectivity may show high levels of resilience where depositional landforms buffer against changes in flow and sediment delivery (Thomas 2001; Fryirs et al. 2007a). For example, a disturbance response at the hillslope scale (i.e. runoff and erosion) may be buffered by low-sloping tributary streams and alluvial fans such that little geomorphological response occurs along a trunk stream.

Some authors distinguish between connectivity and coupling indicating that whilst connectivity refers to ease of sediment transfer through a system or parts of a system, coupling refers to the degree of linkage of different landforms and zones the river system (Harvey 2002a; Preston et al. 2011). The latter relates to the degree to which water and sediment is transmitted between these different landforms and zones. For example, a high degree of hillslope to channel coupling is usually determined by a high degree of transmittance of water and associated sediment from hillslope to stream channels.

Only a few studies have applied the concept of geomorphological connectivity to understanding river sensitivity in relation to planning rehabilitation and catchment management strategies that are appropriate to the particular context (Brierley et al. 1999; Brierley and Fryirs 2000; Brierley et al. 2006; Kondolf et al. 2006; Baartman et al. 2013; Fryirs and Gore 2013; van der Waal 2014). Furthermore, the concept has not been applied to understanding changes in connectivity in a fluvial system over long time scales in relation to changes in climate and associated geomorphological responses of erosion and deposition. This kind of knowledge together with an understanding of the connectivity of processes and fluvial landforms across scales will facilitate the prediction of sensitive areas and the range of stream responses to different disturbances (Murray et al. 2009).

Humans are now considered a major agent of geomorphological instability and change in river landscapes (Church 2010). The growing global water crisis resulting from the Anthropocene has stimulated renewed investigation of the interplay between human activities and river geomorphological process, form and change (Wohl 2014). This shift in focus requires renewed investigation of river restoration and catchment management approaches (Slaymaker 2009; Wohl 2014), with an appreciation of river complexity and inherent connectivity of humans with these landscapes. Understanding the most sensitive parts of a catchment to geomorphological change, and the mechanisms by which this change occurs is essential for strategic and effective river recovery (Fryirs and Brierley

2009). Channel reconstruction can sometimes be unnecessary and inappropriate where a stream type has the flow and sediment regime necessary for self-recovery toward a near-pristine or human desired ecological state (Kondolf et al. 2001; Pasternack 2013). River restoration is often based on experience and intuition rather than a thorough understanding of the geomorphological processes that drive river dynamics (Downs and Kondolf 2002). There is also a strong tendency to adopt a form-based or structural approach to the restoration of degraded or incised streams (Simon et al. 2007) inferring a desirable stable channel form and behaviour from a past state (Rosgen 1997; Wohl et al. 2005). This approach discounts the fact that the degraded reach may have moved beyond this reference state and may be controlled by a different set of interacting processes and drivers of geomorphological form and dynamics (Fryirs and Brierley 2009). Simon and Thorne (1996) suggest that the form-based approach to restoration produces a 'snapshot in time', implying a static and stable endpoint in a dynamic system that may be inherently unstable through time.

With an increasing appreciation of the interplay of geomorphological processes across scales in river landscapes, it is now more effective and desirable to promote fluvial geomorphological processes at different scales of a catchment that aid self-recovery of functioning (Simon et al. 2007). Such a process-based approach requires a shift away from managing the local scale to managing the catchment scale, and the connectivity of processes and environmental variables that determine how resilient a river is to perturbations (Hughes et al. 2005; Fryirs and Brierley 2009; Beechie et al. 2010). Associated with the process-based approach is the issue of designing rehabilitation strategies that accommodate the variability and unpredictability of rivers (Kondolf et al. 2001; Hughes et al. 2005). There is often uncertainty in predicting river geomorphological trajectories making it difficult to predict restoration outcomes and trajectories (Downs and Kondolf 2002; Hughes et al. 2005). Hence there is a need for experimentation, monitoring and evaluation of process-based approaches to river rehabilitation based on a thorough understanding of the geomorphological structure and history of a targeted catchment.

1.2 South African river research and conservation management

The South African landscape hosts a dense drainage network comprising rivers which flow within humid, semi-arid and arid regions. Rivers flow across a wide range of topographic settings from the interior, high-lying plateau region, to mountain belts and the coastal escarpment, to the low-lying coastal plains. The diversity of fluvial environments has led to an array of river types with contrasting geomorphological character. The majority of South African rivers are classed as dryland systems in which flow is non-perennial, yet many of these systems host wetlands, particularly within valley-bottom and floodplain settings (Ferrar et al. 1988; Uys and O'Keeffe 1997; Ellery et al. 2009). It has been predicted that a large proportion of South Africa's wetlands have been lost from the landscape due to human-induced impacts, and that >50% of South Africa's main rivers are in a degraded state resulting in diminished ecosystem services (Kotze et al. 1995; Roux et al. 2006; Nel et al. 2007; Russell et al. 2010; Nel and Driver 2012). River and wetland degradation has been attributed to a number of factors, including impacts of European settlement and associated land-use, urbanization and increasing demand for water resources from all sectors of the economy.

The most common direct threat to river and wetland integrity in South Africa is erosion in the form of channel incision, erosional head cuts and erosional gullies (Kotze et al. 2009a). These features are often attributed to poor land-use management and the South African farmer is often branded as the culprit. Yet, the natural erosion of rivers and wetlands in South Africa has been demonstrated in several studies. These studies have indicated that erosion can occur naturally in wetlands due to the breaching of one or more natural barriers that previously inhibited vertical incision along a rivers course, or the breaching of geomorphological thresholds (Tooth et al. 2004; McCarthy et al. 2007; Tooth and McCarthy 2007; Joubert and Ellery 2013). As a result of naturally induced erosion, wetlands may be lost from a particular landscape setting over time in association with the formation of a wetland elsewhere, at appropriate hydro-geomorphological settings (Ellery et al. 2009). Since the South African landscape has inherited a long-term trajectory of river erosion from ancient tectonic uplift events, it is not surprising that erosion is a common process in rivers and wetlands of the region (Ellery et al. 2009).

Much of the focus of water resource management in South Africa since the early 1970s to the 2000s has been aimed at conserving pristine to near-pristine ecosystems and managing the potential impacts of urban development. South Africa has some of the most progressive legislation relating to freshwater conservation management including the National Water

Act of 1998 and the National Environmental Management: Biodiversity Act of 2004. Since the 1970s several freshwater conservation strategies have been developed for South Africa (O'Keeffe et al. 1986; Newson 1996; McLoughlin et al. 2011; Roux and Nel 2013). These were developed along with a rigorous freshwater research programme, and the River Health Programme (RHP) which serves to monitor changes in ecological integrity of a range of river types across South Africa. Much of the attention of river research and conservation planning in the past has been toward biological and physical (flow, chemical and nutrient fluxes) attributes of rivers. This ecological focus is evident for example in a report on 'The conservation of South African rivers' published in 1986 by the Council for Scientific and Industrial Research and edited by J. O'Keeffe. Little attention has been given to the underlying geomorphological processes and forms that control the ecological functioning and sensitivity of rivers and riverine wetlands. More recently, there has been focus on the geomorphological and hydrological processes occurring at different zones of a river catchment for understanding the underlying drivers of aquatic ecosystem functioning and dynamics (Rowntree and Wadeson 1998; Wadeson and Rowntree 2005; van der Waal et al. 2015). This new focus has demonstrated a shift toward understanding the underlying drivers of river and wetland functioning and dynamics in South Africa with particular attention to geomorphological process and form relations.

1.2.1 Wetland conservation management and rehabilitation

In response to wetland erosion and ecological degradation in South Africa, the State developed a comprehensive wetland rehabilitation programme, "Working for Wetlands" (WfWet), which has as its primary focus the rehabilitation of gullies in fluvially-coupled wetlands. The standard aim of the programme is to halt channel erosion and attempt to restore a former 'pristine' condition at the local scale (i.e. river reach scale). The approach aims at a geomorphological (and hydrological) end-point that is based on a previous more pristine condition. This disregards the dynamic nature of rivers and wetlands and their propensity for changes in geomorphological (and hydrological) behaviour over time. Given the inherent natural dynamics of these systems, the WfWet rehabilitation interventions do not always achieve a desired outcome, nor is the sustainability of a particular intervention certain. In some cases, millions of South African Rand (ZAR) has been wasted within a year of implementation, due to failure of instream engineered structures. Since 2004, the programme has implemented rehabilitation at over 1 000 wetlands across the country, amounting to more than 820 million ZAR creating more than 20 000 jobs (DEA 2016). Although the level of job creation is massive benefit to the country, there needs to be a concerted effort to revise rehabilitation approaches such that project failures and associated wastage of financial resources is kept to a minimum.

In their manual on methods for wetland rehabilitation in South Africa, Russell et al. (2010: 19) define wetland rehabilitation as follows:

"*..the process of assisting in: (1) the recovery of a degraded wetland's health and ecosystem service-delivery by reinstating the natural ecological driving forces or (2) halting the decline in health of a wetland that is in the process of degrading, so as to maintain its health and ecosystem service-delivery*."

Russell et al. (2010: 19) clearly state that rehabilitation in South Africa should not aim toward a static endpoint as is common to many restoration projects across the globe. This statement signifies a shift toward process-based rehabilitation thinking in South Africa, although the shift in practice in this regard has not taken place on a widespread scale. In most cases, the WfWet programme still employs a generic, geomorphological form-based approach to rehabilitation. A civil engineering approach is commonly employed through design of weir-like structures across an incised channel or gully. However, 'soft' interventions such as using vegetation to prevent erosion, or re-shaping an erosional head cut or gully, are less commonly adopted, but are increasingly being considered in wetland rehabilitation practice (Russell et al. 2010). There has been a mix of successes and failures in the WfWet programme, the details of which are not thoroughly documented for individual sites. The development of a series of integrated tools for wetland assessment and management in 2009, the Wetland Management Series (WMS), has substantially improved the scientific basis for decision making around riverine wetland rehabilitation. The series offers greater consideration of the biophysical processes that drive wetland functioning and dynamics. The Management Tools in the WMS guide several aspects of wetland assessment and conservation management in South Africa, including: rapid assessment of the interaction of biotic (vegetation), hydrological and geomorphological processes that are fundamental determinants of wetland ecosystem service delivery and health, guidelines for when rehabilitation intervention is legally required, and guidelines on how and where to implement process-based rehabilitation, evaluation and monitoring for different types of systems (Ellery et al. 2009; Russell et al. 2010; Sieben et al. 2011; Roux and Nel 2013). The WMS tools were produced recently and still need to be tested across a wide-range of systems in South Africa such that they can be refined for specific assessment of the range of types of rivers and wetlands the country contains.

In South Africa, most wetlands are linked to rivers and their formation and functioning is largely controlled by fluvial geomorphological processes which interact with local hydrology (Ellery et al. 2009). Yet, it is still common practice for most wetland rehabilitation projects in South Africa to focus at the scale of the degraded wetland and not the scale of the catchment where drivers of degradation often operate (Sieben et al. 2011; Riddell et al. 2012). Although these local-scale interventions may have short-term (several years) impacts, they may not achieve long-term (over several decades) ecological and social benefits. The consideration of the fluvial geomorphological origin and evolution of wetlands is a critical component of any rehabilitation project (Ellery et al. 2009), including investigation of contemporary geomorphological processes and future change. However, this knowledge base is largely lacking in South Africa such that rehabilitation of rivers and riverine wetlands is still focused on form-based outcomes.

1.2.2 An overview of the history of fluvial geomorphological research in South Africa

The study of fluvial geomorphological process and form in South Africa has only recently taken shape and has focused at controls on floodplain and valley-bottom wetland formation and degradation (Tooth et al. 2002; Tooth et al. 2004; Grenfell et al. 2009a; Grenfell et al. 2009b; Tooth et al. 2009; Grenfell et al. 2010; Ellery et al. 2012; Joubert and Ellery 2013). A handful of studies have applied the concept of connectivity to investigate present-day sediment pathways, and the influence of human land-use on sediment sources and fluxes. These include studies by, Foster et al. (2007), Boardman et al. (2010), Foster et al. (2012), Rowntree and Foster (2012), and van der Waal (2014). Many of the latter studies have been located in the semi-arid to arid Karoo interior of South Africa in relatively low-relief settings, investigating the development of erosional gullies over time, the influence on sediment pathways, and the relation between gully formation and land-use activities. Grenfell et al. (2014) investigated channel behaviour in two climatically-contrasting fluvial settings (semi-arid vs. humid) in South Africa indicating that climate and associated variations in flow and sediment regime exert a strong control on river behaviour and floodplain form. A few studies have investigated palaeo-fluvial environments during the Holocene in South Africa, including, Damm and Hagedorn (2010), Grenfell et al. (2012), and Tooth et al. (2014).

One of the earliest appearances of the concept of connectivity in South African fluvial literature was in the form of the 'river continuum concept' (Vannote et al. 1980) devised for early conservation planning. The river continuum concept highlights the importance of longitudinal linkages of sediments, nutrients and biota between different river zones, such as between uplands and lowlands, for maintenance of river functioning and biodiversity (Day et al. 1986; Ferrar et al. 1988). Following these early studies, geomorphology began to feature more in planning the conservation management of South African rivers. Newson (1996) discussed the role of fluvial geomorphology in river management in South Africa, highlighting the need to integrate knowledge of geomorphological processes for different types of rivers. Following the implementation of the RHP, a number of geomorphological tools were developed for aiding assessment of instream flow requirements, the impacts of impoundments and water transfer schemes on aquatic ecological condition, and for assessing a geomorphological reference condition to aid monitoring of the impacts of different land- and water-use activities. Rowntree and Wadeson (1999) developed a hierarchical geomorphological classification system for South African rivers which recognized the nested hierarchical nature of river catchments and hydrological and geomorphological process occurring across scales. The framework was devised to assist conservation management efforts that are sensitive to processes occurring at different spatial scales of a catchment. This framework indicates a shift away from river management that targets a single scale. Rowntree and Wadeson (1998) and Wadeson and Rowntree (2005) developed and revised the first geomorphological tool for designing instream flow requirements for South African rivers, as part of the ecological reserve determination required by the National Water Act (1998). More recently Du Preez and Rowntree (2006) developed a geomorphological reference condition assessment tool for guiding river rehabilitation, and Rowntree et al. (2013) developed a geomorphological assessment index that guides assessment of the geomorphological drivers of change on the ecological status of South African rivers.

The aforementioned geomorphological tools have been useful in providing a template for understanding the physical structure and processes that define the healthy ecological functioning of South African rivers, for application to rehabilitation planning and catchment management. The concept of connectivity has also begun to feature in studies investigating hydrological and geomorphological dynamics across spatial and temporal scales of river catchments, and the implications of this knowledge for managing and rehabilitating degraded systems (Bobbins 2011; van der Waal 2014; Glenday 2015; Smith-Adao 2016). The concept has also featured in river assessment tools guiding the RHP but has yet to feature substantially in wetland assessment, management and rehabilitation approaches adopted under the WfWet programme. The application of connectivity concept could enhance the geomorphological assessment tools that have already been devised under the aforementioned programmes, promoting more effective development and implementation of catchment-scale, process-based rehabilitation initiatives in South Africa.

1.3 Aim and objectives

In view of the knowledge gaps outlined above, this study aims to investigate drivers of recent geomorphological sensitivity and associated degradation in a gravel-bed mountain stream in South Africa, using geomorphological connectivity as a guiding concept, drawing on the conceptual framework of Panarchy. The findings will be used to evaluate river-floodplain rehabilitation interventions that have been employed by Working for Wetlands (WfWet), and consider the broader-scale implications of the particular rehabilitation interventions.

Based on the above aim, the objectives are to:

1. Investigate the geomorphological history and pre-history of the Baviaanskloof River-floodplain, including medium to long-term (hundreds to thousands of years) geomorphological adaptive cycles of erosion and deposition, and the nature of recent river-floodplain geomorphological dynamics.
2. Identify the major drivers of recent geomorphological change, including environmental, anthropogenic and geomorphological drivers.

3. Define present-day channel-floodplain process, form [1] and sensitivity to geomorphological change within the context of tributary junction stream (dis)connectivity.
4. Develop a conceptual model using the framework of Panarchy and adaptive cycles, to illustrate the interplay between different drivers of geomorphological change, sediment connectivity, and river sensitivity, across spatial and temporal scales of the study reach.
5. Using the knowledge generated above, evaluate river-floodplain rehabilitation interventions that have been employed by WfWet and offer recommendations toward better rehabilitation practice.

The above aim and objectives were encouraged by Rowntree (2012) in her book chapter found in Holmes and Meadows (2012): Southern African Geomorphology: Recent trends and new directions. In her chapter on fluvial geomorphology, Rowntree (2012) uses the Baviaanskloof as a case example to propose the application of the concept of geomorphological connectivity to planning effective, catchment-scale rehabilitation. The latter was one of the first appearances of the concept of geomorphological connectivity in South African fluvial literature, and has led to the development of a school of associated research, based largely at Rhodes University. This school takes a strong applied stance, investigating how the concept of connectivity can be used to guide process-based and catchment-scale river rehabilitation in South Africa. The present research relates to four other studies that have recently been conducted in South African river systems, each adopting the concept of connectivity (geomorphologic and hydrological) to explain fluvial dynamics. Three of these studies have been conducted in the Baviaanskloof catchment as described below:

- Bobbins (2011), investigated alluvial fan geomorphologic form and process, describing slope thresholds for fan entrenchment and the interaction of tributary junction fans with the main stream. Bobbins (2011) used the findings of her study to

[1] Channel and floodplain form in this study refers to the cross-sectional shape of the channel and floodplain and the shape and arrangement of geomorphologic features in planimetric view (Fuller et al. 2013).

propose an alluvial fan rehabilitation framework for the upper-middle reaches of the Baviaanskloof, indicating that those fans that are entrenched due to human interference should be prioritized for rehabilitation.

- Smith-Adao (2016), investigated the interaction of valley floor morphology and confinement and riparian vegetation with river-floodplain hydrogeomorphology along the upper-middle reaches of the Baviaanskloof floodplain. Smith-Adao (2016) applied her findings to provide recommendations for strategic river-floodplain rehabilitation efforts that consider the interaction between riparian and in-channel vegetation with river-floodplain hydrogeomorphology.
- Glenday (2015) from the University of California, modeled the hydraulics and hydrology of the Baviaanskloof catchment using extensive data on stream flow, groundwater, surface runoff and soil moisture to develop a framework of hydrological connectivity for the Baviaanskloof that would guide the modeling process. Glenday (2015) used the aforementioned data set to model different future scenarios for the catchment including: continued degradation, hillslope vegetation rehabilitation, and alluvial fan and channel-floodplain rehabilitation. The results of the study are critical to understanding the hydrological trade-offs that exist between different types of rehabilitation focused at different scales of the Baviaanskloof catchment.
- Van der Waal (2014), investigated sediment connectivity in the Thina catchment, a high lying mountain system in Eastern South Africa. Van der Waal (2014) describes sediment sources, transfers and sinks, providing insight into catchment areas that should be prioritized for future rehabilitation interventions.

The present study therefore continues within the theme of connectivity and applied fluvial geomorphologic research described above.

1.4 The use of critical realism to investigate river dynamics and sensitivity

Slaymaker (2009) states that a positivist epistemological approach has dominated river geomorphology and suggests a need to shift toward the approach of critical realism. The latter approach makes use of qualitative data and interpretation to provide a more holistic understanding of the complex set of interacting processes and landforms influencing the behaviour of a specific geomorphologic system. Couper (2015: 79) describes critical realism as "...combining empirical evidence and abstraction to reveal the structure and mechanisms that result in events". Critical realism views reality as a single form that cannot be fully known but can be studied and partially known, to gain a more in-depth understanding of the world and how it works. This philosophy appreciates that knowledge is influenced by human values and perceptions, even within the realm of positivism and the practice of rigorous and so called objective scientific method. Hence, there may be different descriptions of reality based upon the influence of personal value judgements and experience of individual scientists, making it difficult to accept any one version of reality as 'the truth' (Urban 2013).

Critical realism is well-suited to fluvial geomorphology which is a relatively young discipline, in which standard laws and theories are still being developed, and where the complexity of geomorphological systems cannot be fully measured and known (Favis-Mortlock 2013). Thus, qualitative conceptual models that employ logical reasoning in describing process-form interactions and geomorphological dynamics across space and time are necessary for understanding rivers as complex social-ecological systems (Rhoads 2013). The critical realist approach is often adopted in fluvial geomorphological investigations, but is not often acknowledged as an overarching philosophy. The application of the connectivity concept in recent fluvial geomorphological, as applied by Fryirs et al. (2007a) and Fryirs et al. (2007b), is an example of the use of critical realism within the discipline of fluvial geomorphology. Although connectivity can be quantitatively measured, it is often described in qualitative terms and inferred from observed geomorphological processes and forms. However, Urban (2013) argues that the discipline of geomorphology should not lose the positivist approach, since it provides a basis for rational and rigorous study of geomorphological systems, and attempts at best to be relatively non-biased.

The present research therefore adopts a critical realist stance, understanding that geomorphological systems are characterized by long-term processes that are often hidden, and a multitude of variables interacting within and across space and time, that are difficult to measure in their entirety (Bracken and Wainwright 2006; Slaymaker 2009; Preston et al. 2011; Favis-Mortlock 2013). The author also appreciates that this philosophical stance means that the version of 'reality' synthesized from the findings of this research has been influenced by the personal values and perceptive lense of the author.

Aspects of positivism are incorporated into the present study through empirical investigation involving the systematic observation and measurement of geomorphological processes and forms. Abduction is the main form of reasoning employed to infer general relationships between measured and observed geomorphological forms and processes, and to identify the role of different environmental variables and humans in influencing geomorphological process, form and change. To gain a fuller understanding of the complexity of the Baviaanskloof River-floodplain, conceptual tools such as connectivity and Panarchy have been used to provide a logical theoretical framework for describing complexity. The role of human agency in adding to system complexity is also investigated (Wikgren 2005).

1.5 Methodology: a process-form and applied approach

The present study uses a process-form approach with a strong applied component. Quantitative measurement of contemporary river-floodplain process and form is combined with qualitative geomorphological tools for studying system processes and change. The qualitative tool applied most widely in this study is that of 'reading the landscape', as described by Fryirs and Brierley (2012). The technique of 'reading the landscape' includes geomorphological mapping of landforms indicating sediment sources, transfers and sinks, observation of the nature of fluvial processes (flow regime and sediment transport processes), measurement of morphology of different landforms and rates of erosion and deposition, and assessment of the role of human activities in altering fluvial process and form. Existing theory relating to process-form relationships is applied in efforts to understand the contemporary and historical structure of the system, and the mechanisms by which the river-floodplain has evolved through time. This knowledge is applied in evaluating river rehabilitation and catchment management strategies that have been implemented along the study reach, within a process-based conceptual framework.

1.6 Thesis structure

This thesis comprises 8 chapters that address different components of the Doctoral research. The first 3 chapters provide the context for the research describing the thematic domain within the discipline of fluvial geomorphology. The rationale and objectives of the research is provided in Chapter 1, the theoretical and conceptual context is provided in

Chapter 2, and the geographic, social and pragmatic setting of the study is provided in Chapter 3. Chapters 4-7 form an integrative series of results and answers to the main objectives of the study. Each chapter contains a short literature review, description of methods used, the results of investigation, and a discussion of the implications of the findings. Chapter 7 of the results series is unique, in that it is largely a discussion chapter, which collates the findings of the previous results chapters, toward evaluating the approach of WfWet to rehabilitation in the Baviaanskloof. The final chapter of the thesis (Chapter 8) provides an overview of the theoretical, methodological and philosophical implications of the research within the discipline of fluvial geomorphology. Chapter 8 also discusses the practical implications of the findings of the research for improving river and wetland rehabilitation in South Africa.

CHAPTER 2: GUIDING CONCEPTS FOR INVESTIGATING FLUVIAL GEOMORPHOLOGICAL DYNAMICS AND SENSITIVITY WITHIN AN APPLIED CONTEXT

2.1 River equilibrium, dis-equilibrium or non-equilibrium?

Traditionally rivers have been viewed as operating close to an equilibrium condition over relatively short time frames (decades to centuries), whereby variables of slope and channel geometry are adjusted to changes in discharge and sediment load to minimize energy expenditure during sediment transport (Schumm 2005). There has been a wealth of debate and review of equilibrium theory within the discipline of geomorphology but there exists no widely accepted framework for defining and measuring equilibrium at different space and time scales (Knighton 1984; Bracken and Wainwright 2006; Hugget 2007). Since equilibria have been defined from catchment to the river reach scale (Table 2.1), it is critical to specify the temporal and spatial scale of any geomorphological investigation (Schumm and Litchy 1965; Schumm 1977).

Table 2.1 summarizes the most common types of equilibrium defined in fluvial geomorphology, with reference to different spatial and temporal scales. Traditional equilibrium perspectives suggest that parts of a river system, such as a single landform or a river reach, may approximate an equilibrium state, (alternatively termed “static” and “steady” state), over a few days to 1 000s of years. An entire river system or components thereof, may attempt to maintain an average condition that gradually changes over short to long time periods (10 to 10^5 years), termed dynamic equilibrium or quasi-equilibrium. For example, over hundreds of thousands of years a river attempts to adjust its longitudinal profile such that there is no net sediment erosion or deposition along its entire length. The equilibrium condition, notionally characterised by the balance between available fluvial energy and sediment delivered to the channel network, is continually changing and is thus dynamic. However, this dynamic equilibrium condition is usually never reached as internal variability and external disturbances disrupt the equilibrium trajectory of rivers (Bracken and Wainwright 2006). River systems may therefore experience relatively abrupt changes in overall equilibrium state, termed metastable equilibrium, as shocks to the system result in a new physical structure and process boundary conditions, to which the system will begin to adjust over tens of thousands of years (Table 2.1). It is increasingly the view that rivers show disequilibrium or non-equilibrium characteristics over several hundred to thousands of years (de Boer 2001; Bracken and Wainwright 2006), due to positive feedback processes that reinforce adjustment responses. An example of a positive feedback process includes continued or increased bed erosion, due to an initial increase in channel gradient as the river begins to down-cut toward a concave or adjusted longitudinal slope profile (Phillips 1999; Pratt-Sitaula et al. 2004; Molin and Corti 2015).

Table 2.1: Traditional forms of equilibrium defined in the discipline of fluvial geomorphology

	Time (in years) & spatial scale	**Type**	**Definition**
Increasing time and spatial scale ↑	10^2 to 10^5 Sub-catchment to catchment	Dynamic metastable equilibrium	Sudden changes in equilibrium state due to breaching of threshold, processes maintain balance around new state (Schumm 1977; Renwick 1992).
	10 to 10^5 Landforms to river reaches to sub-catchments	Dynamic equilibrium	Processes maintain balance around a variable average condition or geomorphological form, or balance between sediment inputs and outputs; Schumm and Litchy (1965); Schumm (1977); Renwick (1992).
	$>10^3$ Catchment to sub-catchment	Non-equilibrium	Absence of equilibrium even over long time spans (Tooth and Nanson 2000)
	10^2 to 10^3 Reach to catchment-scale	Quasi-equilibrium	Adjustment around a mean condition or channel form that defines minimum energy expenditure and uniform distribution in energy expenditure (Langbein and Leopold 1964).
	10 to 10^2 Landform to catchment scale	Disequilibrium	Form and process changing continually in attempt to regain equilibrium (Bracken and Wainwright 2006).
	10 to 10^2 Landform to river reach	Steady state	No change in average form with time, processes maintain balance as variables such as discharge and sediment load fluctuate (Schumm 1977).
	0.01 to 0.1 Landform	Static equilibrium	No change in inputs or outputs, processes or forms (Schumm 1977).

Few quantitative accounts of river equilibrium or stability are documented in the literature, such that some authors have questioned the validity of the theory (Bracken and Wainwright 2006), and the degree to which rivers exhibit equilibrium conditions (Rhoads 2013). Despite uncertainties in defining equilibrium in fluvial geomorphology, the theory is still widely used to explain river behaviour and change over relatively short time periods (several years to decades). Bracken and Wainwright (2006: 176) suggest a 'fuller' definition of geomorphological equilibrium which attempts to incorporate the complexity of these systems: "*…a matrix of eventualities incorporating relationships which have stable process and stable form; stable process and unstable form; unstable process and stable form; and unstable process and unstable form. Whether a particular landscape falls within this matrix is a function of the dominant landscape-forming processes, the historical trajectory of environmental drivers of those processes (dominantly tectonics, climate and vegetation) and any specific contingencies (e.g. extreme events and increasingly human activity)*". One may therefore deem it necessary to speak of relative geomorphological stability and instability conditions in river landscapes, specifying the spatial and temporal scale of investigation.

The concept of equilibrium and associated relative channel stability relates to the geomorphological sensitivity of a river to disturbing forces such as tectonic events or floods that promote changes in fluvial conditions of discharge, sediment supply, and base-level. Geomorphological sensitivity is defined as the propensity of a system for morphological change induced by one or more disturbances (Brunsden 2001). Sensitivity relates to the capacity of the system or parts of the systems to absorb changes in system inputs or variables (Brunsden and Thornes 1979; Brunsden 2001). The terms sensitivity and resilience can be used interchangeably. For instance, Reid and Brierley (2015) define resilience in fluvial geomorphological terms as the ability of a river channel to absorb and resist the energy of a disturbing force, by indicating little geomorphological change. Reid and Brierley (2015) suggest that river sensitivity is reflected by the ease with which geomorphological adjustment takes place following a disturbance of particular frequency of occurrence and magnitude. A system that is able to absorb shocks by indicating little overall morphological change following a disturbance would thus be considered resilient or of low geomorphological sensitivity, for the particular frequency and magnitude of disturbance event. The nature and rate of channel adjustment following a disturbing force defines the degree of sensitivity of a river channel to geomorphological change (Reid and Brierley 2015). Herein, proximity to thresholds is an important determinant of sensitivity since a system (or parts thereof) that lie far from erosional or depositional thresholds have a higher capacity to absorb shocks than a system that lies close to these thresholds (Brierley and Fryirs 2005). The rate at which erosional or depositional thresholds are approached may be influenced by the degree of water and sediment connectivity (Brierley et al. 2006; Faulkner 2008). Hence the degree of water and sediment connectivity in a river landscape is one of the underlying determinants of river sensitivity, as it influences the extent and pattern of propagation of disturbance responses in the form of sediment erosion and deposition (Harvey 2002a; Fryirs et al. 2007a; Fryirs et al. 2007b; Harvey 2007a).

Geomorphological sensitivity is dependent on a number of factors both internal and external to a fluvial geomorphological system:

- The degree of exposure to disturbance events that induce threshold shifts and the magnitude-frequency of formative (change inducing) events (Brunsden 2001).
- Proximity of a landform or an entire catchment to thresholds between erosion and deposition (Brunsden 2001).
- The degree and spatial pattern of water and sediment connectivity in a river landscape, which determines the spatial extent or capacity for change (Brunsden and Thornes 1979; Brunsden 2001; Harvey 2001; Brierley and Fryirs 2005; Harvey 2007a). For example, degree of slope-channel coupling is an important determinant of sensitivity of the channel network to high intensity rainfall events and human land-use activities occurring on the hillslopes of a catchment (Harvey 1997; Harvey 2001; Chiverrell et al. 2009; García-Ruiz et al. 2010).
- Temporal and spatial characteristics of resisting and disturbing forces (Brunsden 2001): resisting forces occur in several different forms, for example strength resistance is a function of the properties of individual landforms, relating for example to soil cohesiveness; morphological resistance may include for example physical barriers such as gently sloping floodplains or river channels and confined valley reaches that hinder coupling and have a degree of absorbing capacity (Brunsden and Thornes 1979; Fryirs et al. 2007a). The nature of resisting forces and

magnitude-frequency of disturbing forces will determine potential for geomorphological change.

- The prevailing flow and sediment regime, which influences the ability of a river channel or catchment to recover and re-establish some kind of internal equilibrium (Knighton 1984; Harvey 2007a). Systems that recover slowly from disturbance effects relative to the frequency of the formative disturbance are generally viewed as sensitive (Harvey 2007a).
- The complexity of the system is a function of the variety of interacting processes, variables and landforms over different scales. Each landform or zone of a river catchment (e.g. upper-slopes vs. foothills) has differing degrees of geomorphological sensitivity, which cumulatively provides the framework defining the resilience of the system to disturbing forces. Here, the history of disturbance events may be important where a past extreme event has promoted long-term diffusive geomorphological adjustment, creating structural and process conditions that may compliment or counteract the forces of smaller events (Brunsden 2001).

River sensitivity is not static but changes through time with the continual internal adjustment and morphological evolution of a river landscape, which results in alternation of connectivity between landforms of parts of a catchment. For example, a decrease in hillslope-channel connectivity over time, as gully systems stabilize or as vegetation cover increases, may decrease sensitivity of the downstream channel network where hillslope sediment storage buffers against disturbances such as high-magnitude storm events (Brunsden 2001; Fryirs et al. 2007a; Fryirs et al. 2007b). River sensitivity thus reflects the interplay of numerous system components with environmental drivers and with time, such that the concept requires consideration of river landscape complexity.

2.2 A complex-adaptive systems approach

The perception of rivers as complex geomorphological systems with the inherent ability to self-regulate and self-organize internal structure and processes has long been presented within the fluvial geomorphologic literature (Schumm and Litchy 1965; Schumm 1973; Schumm 1981; Chorley et al. 1984; Phillips 1992; Phillips 1999; Ryan et al. 2007; Phillips and Jerolmack 2016). Rivers are able to regulate fluvial process and available fluvial energy in response to changes in environmental conditions that induce changes in water and sediment fluxes. This self-regulation is afforded by positive and negative feedbacks, typically mediated by erosion and deposition that alter channel morphology. The self-regulatory response of rivers to changing inputs of water and sediment means that they are able to enter periods of relative stability, characterised by slow geomorphological change despite fluctuations in climate and runoff (Leopold and Langbein 1962; Tooth and Nanson 2000). Self-organization is related to self-regulation, and involves the structuring of a fluvial landscape into interdependent landforms in the absence of externally induced perturbations that may induce geomorphological change (Phillips 1999; Favis-Mortlock 2013). In fluvial geomorphology, self-organization may be exhibited by the internal production of landform patterns such as pool-riffle sequences, point bars, channel bends, and tributary stream alluvial fans, that aid establishment of a condition of relative stability (Phillips and Jerolmack 2016). The self-organizing capacity of a river is fashioned by the interaction of a range of geomorphological processes and landforms across scales of space and time. The ability of river systems to self-regulate and self-organize determines the resilience of a particular system to disturbances.

Investigation of the interaction of multiple (dis)equilibrium processes and landforms across scales of space and time has not been exhaustive and has only recently received renewed attention within the discipline of fluvial geomorphology. The emerging theory of complex adaptive systems, applied traditionally within the discipline of ecology, is now being applied to understand the self-regulatory capacity of rivers and their sometimes unpredictable behaviour (Phillips 1992; Phillips 1999; Favis-Mortlock 2013). Complexity theory was applied to geomorphological systems in the early 1980s in the form of non-linear dynamical systems (NDS) theory (Phillips 1992). This theory suggests that geomorphological systems typically exhibit complex, and often unpredictable geomorphological behaviour and landform patterns (Phillips 1992; Rhoads 2013). This complexity is a result of the interaction of many components of the system over historic and present time, and across different spatial scales, such that the present structure and behaviour of a geomorphological system is not just a function of the present-day observed processes or recent disturbances to the system (Favis-Mortlock 2013). The NDS theory appreciates that geomorphological systems are characterised by energy dissipation through self-organizing structures and processes, which may include for example, changes in bed form during and after a flood event that result in energy dissipation.

As geomorphological systems, rivers have been shown to possess some of the fundamental aspects of complex-adaptive landscapes as discussed by several authors and described below:

- *Open energy and resource gradients*: Energy and resource gradients are thermodynamically open in that they are in constant feedback with the surrounding environment which determines fluctuations in water and sediment inputs (Knighton 1984).
- *Non-linearity and chaos* producing unpredictable response or system outputs, e.g. different sediment yields from the same sized flood (Phillips 1999; Van De Wiel and Coulthard 2010).
- *Self-organisation:* Fluvial landscapes naturally evolve towards critical limits or thresholds between stability (mostly sediment transport) and instability (mostly sediment erosion and deposition) under prevailing conditions. This natural evolution results in spatial patterns of landforms that emerge locally in a system linked to non-linear interactions and feedbacks (Phillips 1999; Ryan et al. 2007). An example of a self-organizing structure is stone cells that form during low flows in certain gravel-bed streams, resulting in increased bed stability (Church et al. 1998).
- *Internal resilience*: Due to the self-organizing property of geomorphological systems, a disturbance may occur with very little observed change in the system properties (Murray et al. 2009; Hooke 2015).
- *Hierarchy of scales and interactions*: Interactions of processes and landforms across a range of spatial and temporal scales influences the structure of the system (Phillips 1999; Ryan et al. 2007). An example is the interaction of catchment scale geology with hillslope and floodplain soil properties, which influence characteristics of hillslope runoff and resistance of the channel boundary to erosion. These broader scale influences translate to a characteristic set of channel processes and forms.
- *Multiple states and transitions*: Abrupt transitions in system behaviour or mean state are underpinned by thresholds of the landscape; as a result the system shifts between multiple stable states over time scales of several thousand to tens of

thousands of years, forced either by external or internal threshold disturbances (Favis-Mortlock 2013).

The above characteristics described for complex geomorphological systems are key features of complex adaptive systems, described within the conceptual framework of adaptive cycles and Panarchy (Holling and Gunderson 2002; Gunderson 2008). The concept of Panarchy attempts to explain cross-scale interactions of processes and structure in natural and social systems, which results in organized processes and features, yet sometimes unpredictable change in system behavior or state (Holling 2001; Holling and Gunderson 2002; Gunderson 2008). Each scale range of a particular system's Panarchy contains the adaptive cycle (described in following paragraphs). The interaction of these adaptive cycles determines the capacity of a system to self-regulate and when and how a system will respond to a particular perturbation.

The adaptive cycle is considered in the context of two axes (Figure 2.1): the connectedness of internal controlling variables and processes (x-axis), and the internal potential for change toward an alternative future stable state (y-axis). Here, connectedness relates to the interaction between processes and variables that result in the ability of a system to self-regulate internal condition, through positive and negative feedback loops and the development of structures that maintain the functioning and resilience of the system (Holling and Gunderson 2002). These regulatory mechanisms allow the system to withstand changes in the external environment, to a threshold point. The concept of connectedness here is different to the concept of connectivity in fluvial geomorphology. An example of connectedness and self-regulation offered by Holling and Gunderson (2002) is a woodland in which vegetation forms a striped pattern on a hillslope due to the interaction of tree growth with water, soil nutrients and topography. As the trees intercept water moving downslope, the water becomes available to the plant roots causing preferential plant growth, whilst limiting plant growth further downslope. A 'line' of enhanced plant growth forms as the trees are able to grow along and upslope where water is intercepted. The occurrence of these feedback loops occur across different areas of the hillslope resulting in alternating vegetated and bare soil areas and the 'striped' pattern observed. As the connectedness of controlling variables and processes increases so does the rigidity of the system, making the system less flexible to adjust to perturbations which disrupt processes and structure, thus increasing vulnerability to a change in state (Gunderson 2000). Thus, connectedness increases the self-regulatory capacity of the system, but it also increases the potential for a change in state.

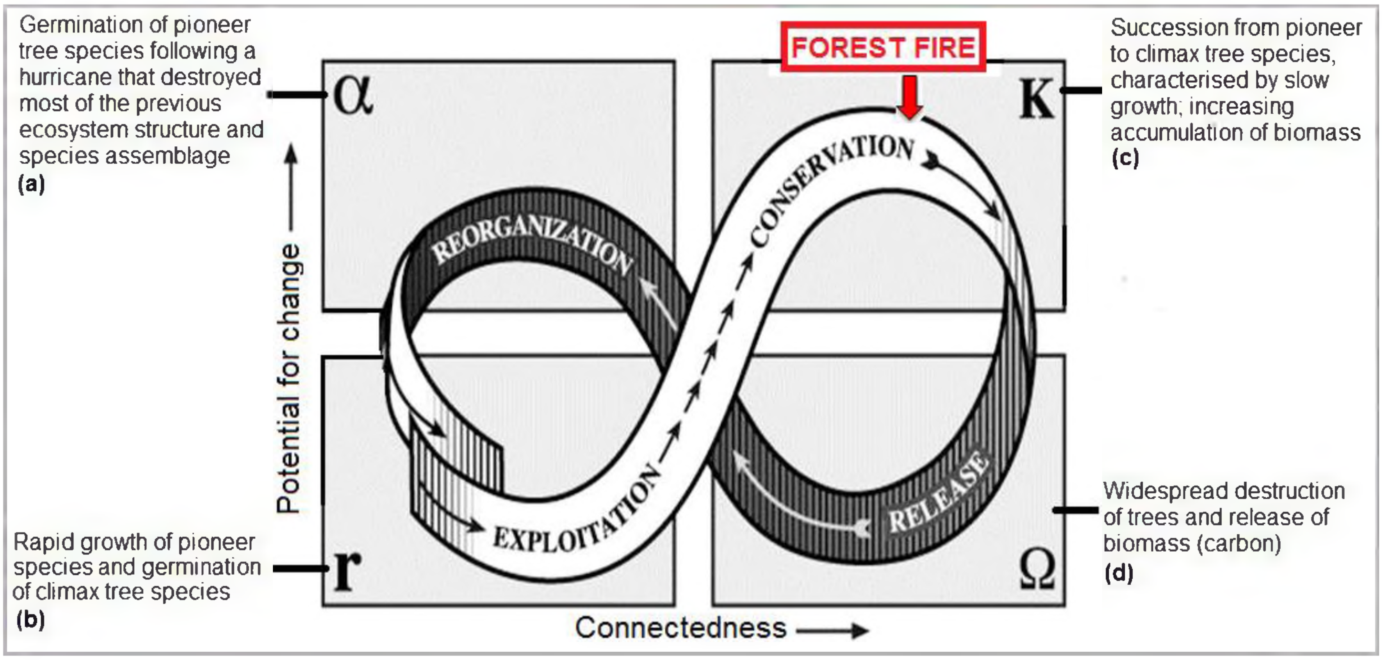


Figure 2.1: An example of an adaptive cycle indicating phase changes between rapid growth ('r'), slow change and accumulation of resources ('K'), collapse ('Ω'), and reorganization ('α'), at the forest patch scale (adapted from the Resilience Alliance 2015).

Within the two axes of an adaptive cycle exist four phases as described by Gunderson (2008):

1) The exploitation or growth phase when the system is rapidly changing in a predictable way following collapse and reorganization, using and accumulating available resources and increasing structural complexity **(r)**.

2) The conservation phase when structural complexity is very high and components of the system (variables and processes) become highly connected **(K)**. It is during the latter phase, that a system is most vulnerable to change due to external perturbations or as internal thresholds are approached and breached (Holling 2001).

3) The destruction or release phase results from a perturbation and breaching of a threshold, resulting in collapse of structure and release of accumulated resources such that a change in system structure and state occurs **(Ω)**.

4) The reorganization phase when the system adjusts to new conditions by reorganizing available resources for the next exploitation phase **(α)**. Whether a change in state occurs throughout the entire system or at an individual scale range of the system during the phase of collapse depends on the magnitude of the disturbing force at a particular scale range, how well the effects of the disturbance are transferred to other scales and how sensitive the other scales are to change (Holling 2001).

The example in Figure 2.1 illustrates an adaptive cycle for a vegetation Panarchy at the scale of an entire forest patch following two perturbations: a hurricane, and a widespread fire. In this example, a hurricane results in widespread break-down of vegetation structure and climax species composition associated with the **Ω**-phase. The example begins at '**a**' in Figure 2.1, the **α**-phase, indicating germination of pioneer trees species and mobilization of soil nutrients following the destruction caused by the hurricane. This reorganization phase is followed by the exploitation phase involving rapid growth and utilization of resources such as biomass and soil nutrients by pioneer trees, such that a new vegetation structure begins to form ('**b**'- **r**-phase, Figure 2.1). The growth of pioneer trees and associated structuring of soil and nutrients creates necessary conditions for the germination of climax tree species resulting in a shift into the conservation phase ('**c**'- **K**-phase, Figure 2.1). The **K**-phase is characterized by slower vegetation growth as climax species begin to dominate the vegetation community structure. Thus phase results in increasing structural complexity, such as a community of densely packed trees, an understorey of shrubs and herbs, and interspecific interactions that vary from mutually beneficial (mutualism) to mutually harmful (competition). Gradually there is an increasing accumulation of biomass and self-sustaining interactions between different tree species, water, soil nutrients and light. At this point the vegetation community becomes 'over-connected' and is at highest risk to a threshold breach associated either with continued evolution of the structure and competitive interactions of the climax tree community, or an external perturbation that drives the community beyond a structural threshold. In this example, a severe forest fire occurs at the 'over-connected' point in the K-phase ('FOREST FIRE', Figure 2.1), utilizing the accumulated biomass and resulting in widespread loss of climax trees. The structure of the forest patch collapses and carbon and nutrients are released. The ecosystem has thus shifted into the **Ω**-phase (**'d'**, Figure 2.1), a phase of 'creative destruction' where structure is broken down but there is increased opportunity for the development of a new assemblage of species. Depending on surviving propagules and recruitment from neighbouring areas, a different forest community and state may emerge.

Adaptive cycles operate at each hierarchical scale of a system and are in constant feedback with processes and structures of adaptive cycles occurring at other hierarchical scales (Holling 2001; Figure 2.2). For example, a vegetation Panarchy may contain adaptive cycles occurring at the leaf, tree, patch, forest and biome level in increasing order of time and space (Figure 2.2a, Gunderson 2008). Similarly, an atmospheric Panarchy may contain adaptive cycles occurring at the wind gusts, storms, droughts/hurricanes and ENSO (El Niño Southern Oscillation) levels (Figure 2.2a). Relatively slow processes occurring at large scales, such as vegetation succession at the forest scale (Figure 2.2b), may constrain or influence processes occurring at smaller scales by influencing for example, the growth rate of an individual tree ('remember', Figure 2.2b). Alternatively, processes of change occurring at small scales, such as a leaf fungal infection which causes leaf death, may cause abrupt change at larger scales, such as death of an entire forest patch ('revolt', Figure 2.2b; Gunderson 2008).

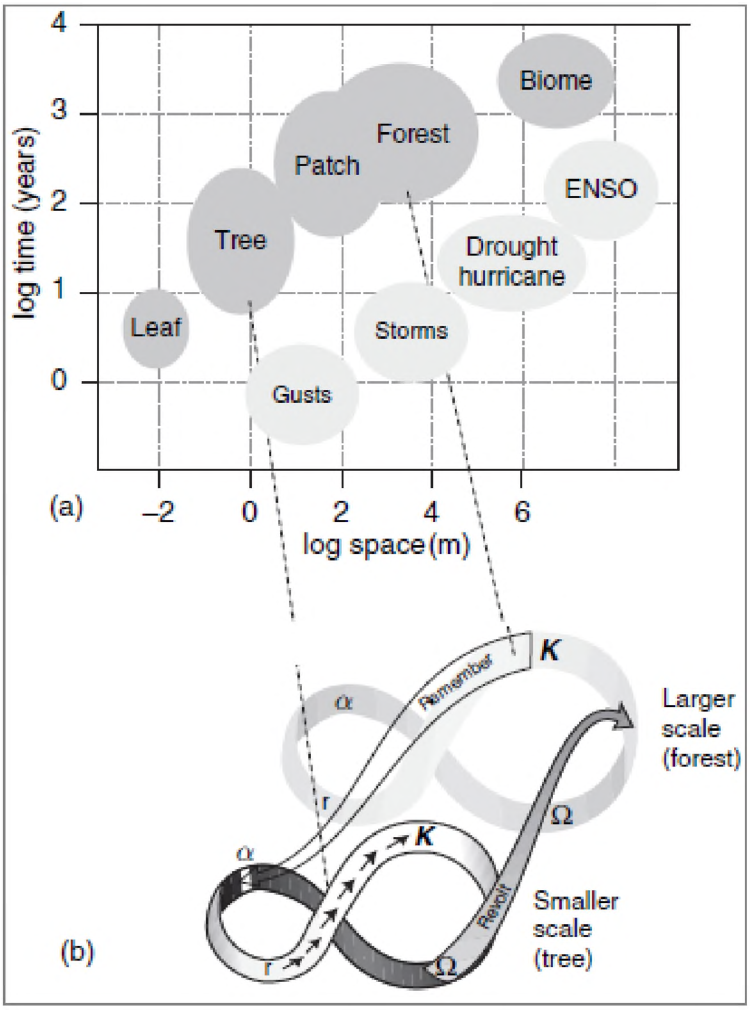


Figure 2.2: An example of spatial and temporal hierarchies of vegetation and atmospheric Panarchies (a); an example of the cross-scale interaction ('revolt' and 'remember') of adaptive cycles occurring at two scale ranges of the vegetation Panarchy (forest patch and the tree), is indicated (b) (Gunderson 2008: 2635).

Adaptive cycles described in the framework of Panarchy may be likened to the cycling between erosion, deposition and relative geomorphological stability or instability, at different spatial and temporal scales of a fluvial system. These cycles represent adjustment toward an internal state (either stable or unstable), defined by the approximate balance between available transport energy and available sediment load (Schumm 1977; Lane and Richards 1997). However, it is proposed here that the adaptive cycle, is quite different to that proposed for ecological systems. The interactions between landforms, geomorphological processes and water and sediment connectivity bring about a unique series of changes in geomorphological structure, processes and relative stability, at different scale ranges of the fluvial geomorphological Panarchy. Processes of erosion and deposition alter the geomorphological structure of a river system by modifying channel and floodplain morphology, patterns of erosional and depositional landforms and associated connectivity of water and sediment, and the geomorphological sensitivity of the fluvial landscape to change.

Figure 2.3 illustrates a Panarchy tailored to fit a river landscape illustrating geomorphological adjustment cycles that exist and interact across different spatial and temporal scales. These adaptive cycles may exist for example at the catchment scale, hillslope to tributary channel scale, and the trunk channel reach scale. Geomorphological adaptive cycles at the hillslope to tributary channel scale may include for example, phases of heightened hillslope runoff, soil erosion associated with gully formation, and tributary channel deposition, followed by phases of gully filling and soil development, and relative gully and channel stability. These cycles may operate over hundreds to thousands of years in association with long-term climatic variations. At the channel reach scale (defined as several kilometers of homogenous channel and valley geomorphological form), adaptive cycles may occur over several years to decades and may include for example phases of channel degradation followed by phases of channel aggradation. These phases of degradation and aggradation may be influenced by moderate or large flood events or thresholds that are breached at higher levels of the system hierarchy. The adaptive cycles within a fluvial geomorphological system are thus characterised by switches between processes of predominantly erosion, transport or deposition and associated changes in geomorphological structure at a particular scale range. These phase changes are associated with changes in the degree of water and sediment connectivity, changes in relative geomorphological stability, and changes in the complexity of interacting landforms and geomorphological processes, with biotic components of the system.

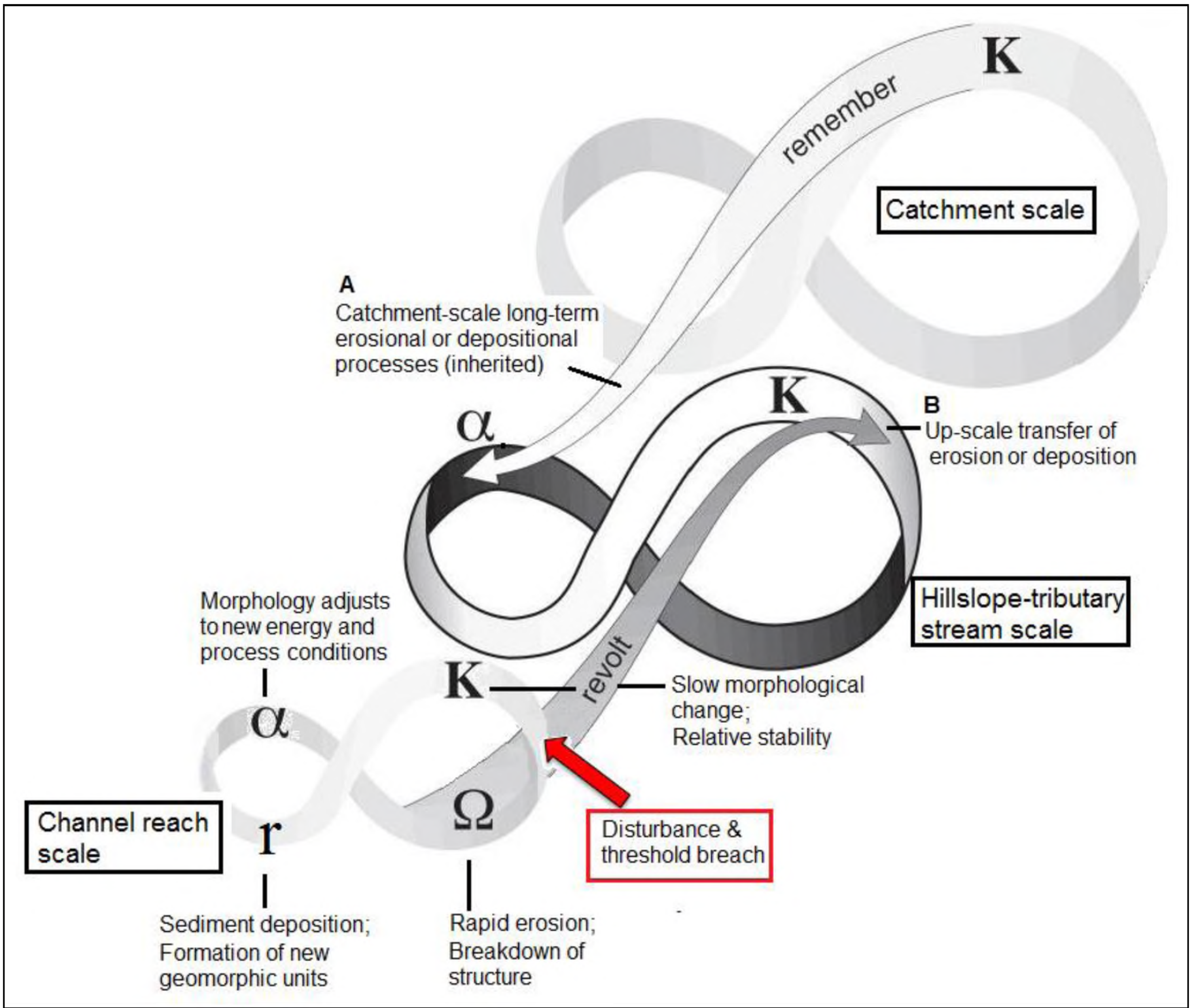


Figure 2.3: An example of a fluvial geomorphological Panarchy indicating adaptive cycles at nested hierarchies, from the catchment scale to the channel reach scale, and the nature of an adaptive cycle that is possible at the channel reach scale (adapted from Holling 2001). 'Revolt' and 'Remember' interactions between adaptive cycles at different spatial-temporal scales are described using examples, in the main text.

Figure 2.3 illustrates what a fluvial geomorphological adaptive cycle could look like at the channel reach scale, and how this adaptive cycle could interact with adaptive cycles occurring at the hillslope to sub-catchment (tributary stream) scale, to entire catchment scale. The example represents a channel reach in which a geomorphological threshold has recently been breached due to an external disturbance ('1', Figure 2.3), such as a large flood. The channel enters a phase of geomorphological restructuring ('**α**', Figure 2.3) associated with redistribution of sediment and adjustment of channel morphology, such that erosional energy that is available is used to do geomorphological work. The channel is unstable as structure (landforms) is being broken down, as the channel adjusts rapidly to the effects of the perturbation. Connectedness is low as there is a low diversity of geomorphological landforms, such as depositional bars or pools and riffles, interacting with water, sediment and adjacent geomorphological features within the channel zone. The channel thus has a relatively simple geomorphological form ('X', Figure 2.3). The rate of adjustment begins to slow during the alpha-phase, but the channel continues to adjust through processes of erosion and deposition to the new channel morphology, sediment load and fluvial energy conditions ('**α**', figure 2.3). During the exploitation phase ('**r**', Figure 2.3), erosional energy has been substantially reduced following channel adjustment such that available sediment is deposited, and depositional features begin to form within the channel zone. The channel begins to stabilize and geomorphological complexity increases indicating a shift toward the conservation phase ('**K**', Figure 2.3). During the **K**-phase sediment transport becomes important, although depositional landforms such as point bars, riffles or sediment slugs continue to gradually develop, forming buffers to geomorphological change within the channel zone. The river and surrounding floodplain thus becomes more complex in geomorphological structure (inset b, Figure 2.3), and channel stability and resilience to external perturbations increases. Connectedness increases as a diverse range of fluvial landforms interact through water and sediment movement, between different landforms in the channel zone, and between the channel and floodplain. However, during the latter part of the **K**-phase as gradual sediment deposition creates relief along the channel, slope thresholds are approached resulting in increasing sensitivity to geomorphological change. If a large flood event occurs a threshold will be breached and the channel will enter the destruction phase of the adaptive cycle **(Ω)**, leading to channel avulsion**.** During destruction**,** rapid structural breakdown of the channel occurs, such that a new phase of channel development is initiated and the complex, interconnected array of landforms that previously existed is lost. The channel enters a new state with different form, energy conditions and available water and sediment.

The cross-scale interaction of adaptive cycles in a fluvial landscape influences the geomorphological processes, forms and sensitivity to change at individual scale ranges. These cross-scale interactions may occur from larger scales to small scales ('remember', Figure 2.3), and from smaller scales to larger scales ('revolt', Figure 2.3). For example, long-term landscape erosion or sedimentation that is inherited from previous tectonic or eustatic events may influence the nature and rate of adjustment processes occurring at the tributary catchment and channel reach scales (‘A’, Figure 2.3). Similarly, threshold breaches and structural change at the channel reach scale may be transferred to the hillslope and tributary stream scales (‘B’, Figure 2.3). The interplay between geomorphological cycles occurring at different spatial and temporal scales of a catchment is not always linear or easily predictable since a range of factors determine the strength of interactions between different scales. For example, Pratt-Sitaula et al. (2004) studied the nature of long-term phases of erosion and alluviation driven by climate and tectonics in a Himalayan mountain catchment. The study indicated that the timing of maximum hillslope erosion did not correlate with the timing of maximum channel incision. In this study, hillslope erosion initiated sediment deposition on the valley floor and it was only when this sediment supply slowed or was exhausted, that a phase of heightened river erosion occurred. Hence, there may be considerable time lags between the onsets of large-scale erosional or aggradation phases and the onset of corresponding phases at the river reach scale.

The concept of Panarchy has not been widely used to frame cross-scale process-form interactions in fluvial geomorphology. Slaymaker (2006) investigates scaling relations in sediment budgets for rivers within the framework of Panarchy, indicating that it is difficult to transfer findings at one spatial scale to other scales. For example, a sediment budget calculated at the sub-catchment scale does not translate to the overall catchment sediment budget when multiplied by the sum of all subcatchments within comprising the broader catchment (Slaymaker 2006). Slaymaker (2009) speaks of climatically induced long-term cycling between erosion and deposition in river systems and refers to these cycles as ‘adaptive cycles’ but does not provide further discussion on the potential for application of adaptive cycles in fluvial geomorphology.

The complexity of river systems means that they may indicate levels of organization and self-regulation but may change unpredictably (Knighton 1984; Ryan et al. 2007; Thorndycraft et al. 2008), such that similar landforms and fluvial systems may respond very differently to the same type and magnitude of disturbance (Schumm 1973). It thus becomes difficult to accurately predict river response to different types of disturbing forces without a thorough understanding of river geomorphological and disturbance history, the connectivity of processes and landforms across different scales, and the thresholds that exist at different scales (Phillips 1999; Fryirs and Brierley 2009).

2.3 Geomorphological connectivity for understanding complex interactions and river sensitivity

2.3.1 Geomorphological connectivity defined

'Connectivity' was first widely applied in the discipline of landscape ecology to explain links between ecological processes and patterns (Moilanen and Nieminen 2002; Bélisle 2005; Kindlmann and Burel 2008). 'Landscape connectivity' refers to the degree to which the landscape facilitates or impedes movement of biota among resource patches (Bélisle 2005). For example a grassland-forest patch mosaic may contain a number of fragmented forest patches separated by grassland. If these patches are far apart the movement of biota such as birds, millipedes or tree seeds between forest patches will be more unlikely than if the patches are close together. The author has already provided a definition of 'connectivity' and 'coupling' applied within the discipline of fluvial geomorphology, in Chapter 1. These terms broadly refer to how easily available water and sediment is transferred between landforms and parts of a river system (Harvey 2002a; Fryirs et al. 2007a). These linkages do not only imply material linkages of water and sediment, but imply linkages between geomorphological processes occurring at different parts of a river landscape. In the present study the concept of geomorphological connectivity is referred to as the degree of linkage of sediment through different parts of a river landscape, influencing the degree to which different landforms and parts of the landscape are coupled in terms of the transfer of geomorphological response between these components.

There is currently no consensus on the definition or measurement of connectivity in fluvial geomorphology. The concept is often defined and measured from a range of perspectives including studies of hydrological (water) connectivity (Burt and Pinay 2005; Bracken and Croke 2007; Lane et al. 2009; Bracken et al. 2013), studies of ecological connectivity (Townsend 1989; Stanford and Ward 1993; Poole 2002; Burcher et al. 2007), and studies of sediment (geomorphological) connectivity (Fryirs and Brierley 2001; Rommens et al. 2006; Godfrey et al. 2008; Boardman et al. 2010; Foster et al. 2012; Cavalli et al. 2013; Fryirs and Gore 2013; Heckmann and Schwanghart 2013; Bracken et al. 2015). The concept began to feature in the discipline of aquatic science during the late 1980s to early 1990s (Wohl 2014), during which time an understanding of the linkages of water and nutrients in different dimensions, including upstream-downstream or channel-floodplain, were essential to understanding the ecological dynamics of rivers (Ward 1989; Stanford and Ward 1993; Ward and Stanford 1995; Poole 2002). Following these early studies, the concept was used to investigate river sensitivity to contemporary environmental change and anthropogenic impacts (Harvey 1997; Brierley et al. 1999; Fryirs and Brierley 2001; Harvey 2001; Werrity and Leys 2001; Harvey 2002a), and more recently to understanding the timescales over which different parts of a river system become connected and thus increasingly sensitive to disturbance events (Fryirs et al. 2007b; Hoffman 2015).

Fryirs et al. (2007a) provide a framework for describing connectivity in river landscapes by classifying different landforms that impede the transfer of water and sediment as 'barriers', 'buffers' and 'blankets', and landforms that enable connectivity as 'enhancers' (Table 2.2). Barriers may include, for example, sediment slugs that form across a channel, slowing water flow and trapping sediment that is being transferred from upstream channel reaches. Another example is a low-sloping, wide-channel reach that does not possess sufficient sediment transport capacity, thus preventing efficient upstream-downstream linkages of sediment. Buffers are those features that impede lateral inputs of water and sediment to a channel, including for example, alluvial fans or wide floodplains that trap sediment and disperse water across a wide area. Blankets impede vertical connectivity of water and nutrient, for example a clay layer on a floodplain surface may impede infiltration of flood water into the alluvial aquifer. Features that enhance water and sediment connectivity may include, for example, a steep channel with high stream power, or an incised channel that effectively channelizes storm flows, resulting in high capacity for sediment transport. These buffers, barriers, blankets and enhancers of connectivity have been compared to 'switches' that are able to 'turn off' or disconnect, and 'switch on' or connect sediment delivery to different parts of a catchment (Brierley et al. 2006). Brierley et al. (2006) present a useful illustration of these 'switches' and their effect on catchment-scale sediment (dis)connectivity, as illustrated in Figure 2.4. In the illustration, landforms such as alluvial fans and sediment slugs 'switch-off' sediment transfer between tributary catchments and the trunk stream, and between different trunk stream reaches, whilst an incising channel 'switches-on' sediment connectivity between different stream reaches by enhancing sediment transport capacity. Enhancers of connectivity such as incising channel reaches are generally termed features of instability as they tend to enhance water and sediment delivery to downstream channel reaches. These features increase the vulnerability of the downstream channel reaches to geomorphological change (Brunsden 2001; Fryirs et al. 2007a), by disrupting local equilibrium conditions and inducing channel adjustment. Sediment impediments decrease the potential area that can deliver sediment to a downstream channel component ('effective catchment area', Figure 2.4), thus explaining the ability of these features to 'buffer' parts of a system by reducing the exposure of the buffered parts of the system to disturbing forces of particular frequency and magnitude.

Table 2.2: Examples of buffers, barriers, blankets and enhancers of water and sediment connectivity in river landscapes (adapted from Fryirs et al. 2007a).

Type of impediment	**Landform examples**	**Effect on continuity of water and sediment**
Barrier	Bedrock steps	Promote backfilling of valleys
	Sediment slugs	A plug to sediment transfer along channels
	Channel capacity (width/depth ratio)	May impede sediment movement along channel.
	Valley constriction	Restricts sediment transfer along a valley
Buffer	Alluvial fans	Impede sediment transfer between tributary and trunk channel
	Floodplain pockets	Impede sediment transfer between tributary and trunk channel
	Floodplain terraces and channel levees	Impede sediment transfer from trunk to floodplain
Blanket	Clay layer within floodplain alluvium	Clay is impermeable to water thus impedes vertical movement of water in a floodplain
Enhancer	Incising or incised river channel	Enhances upstream-downstream and tributary and trunk connectivity
	Canalized river channel	Enhances upstream-downstream connectivity; enhances tributary-trunk connectivity for canalized tributary streams

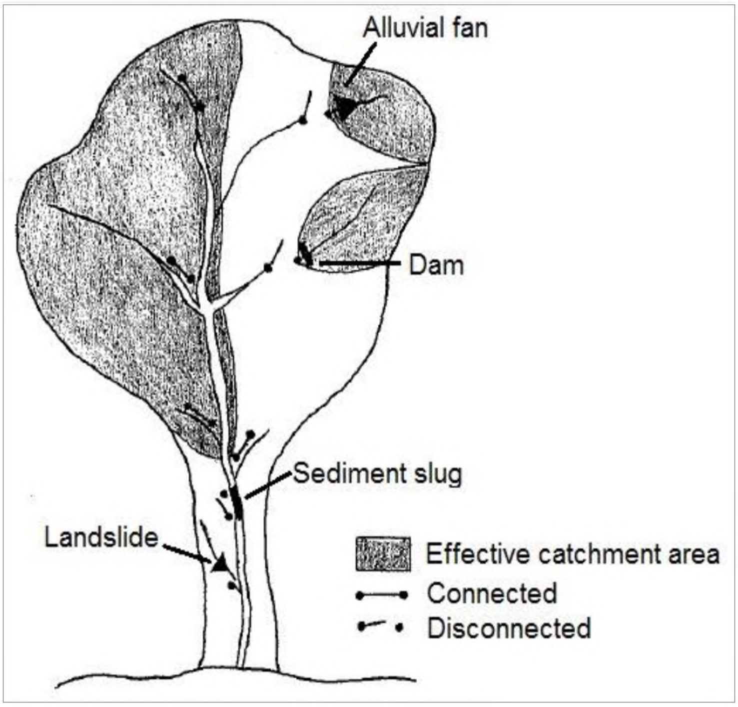


Figure 2.4: Conceptual illustration of catchment scale (dis)connectivity indicating different barriers, buffers and enhancers of water and sediment connectivity (re-drawn from Brierley et al. 2006: 170).

Whilst impediments to connectivity, such as alluvial fans or channel bars act as 'off-switches', they tend to increase the resilience and stability of parts of a river system to disturbing forces (Brunsden 2001; Fryirs et al. 2007b; Hoffman 2015). This relative resilience is dependent upon the interaction of the frequency and magnitude of a disturbing force, with the morphological resistance of a particular landform acting as a buffer, barrier or blanket. For example, if a small flood event occurs and a channel reach has enough structural resistance in the form of low channel slope, and a sediment slug across the channel which disperses the energy of the flood flows, then it is likely that the flood will induce little geomorphological change. However, if a moderate or large flood event were to occur, the sediment slug may not be able to resist the power of the flood force, resulting in erosion of the slug and increased sediment connectivity. Thus over time, disconnected and relatively resistant parts of a catchment may become connected with downstream components if a threshold breaching event occurs, making the downstream channel network more sensitive to the effects of disturbances occurring in the wider catchment area (Fryirs et al. 2007b; Fryirs and Brierley 2009; Reid and Brierley 2015).

Hooke (2003) indicates the importance of coarse sediment connectivity in influencing the relative resistance of gravel-bed rivers to geomorphological change, and identifies varying degrees of coarse-sediment connectivity for these types of streams, based largely on observation and field mapping of (dis)connectivity landforms. The connectivity classes defined by Hooke (2003: 86) include:

- *Unconnected*: reaches operate almost independently of each other as sediment budgets are localised (a single reach of a few 10s to 100s of meters); this condition may exist when a channel reach lacks competence to transport sediments downstream.
- *Disconnected*: lack of transfer between different reaches due to barriers that have been constructed (e.g. dams, weirs), which prevent sediment throughput during the lifetime of the structure. Lack of propagation of channel morphological change into a channel reach over a 20 year period or more indicates a lack of connectivity.
- *Partially (or episodically) connected*: sediment connected or transported between reaches only during extreme episodic events. In this case the event needs to be bankfull size or more such that gravels are transported.
- *Potentially connected*: potential transfer of sediment between reaches but a lack of sediment supply to the channel means no connectivity.
- *Connected system*: coarse sediment moves easily and frequently through the system, between reaches, during normal floods (0.5-5 year events).

2.3.2 Connectivity in relation to river sensitivity

In the discipline of geomorphology, connectivity was first applied to understanding the geomorphological sensitivity of landscapes, by relating the degree of linkage of different geomorphological processes and landforms, to the ease with which a disturbance response propagates through a given landscape (Brunsden and Thornes 1979; Brunsden 2001; Thomas 2001; Usher 2001). In this regard, if different components of a landscape, such as mountain peaks, hillslopes and valley floors, are highly connected in terms of geomorphological processes and sediment movement, then the landscape should be sensitive to geomorphological change, such that the effects of a disturbance will propagate easily through the landscape to the valley floor (Hoffman 2015). Degree of connectivity is thus one of the determinants of the sensitivity of a geomorphological system to change. In the last few decades, connectivity or coupling has featured in a range of fluvial geomorphological studies, including descriptive studies that define types and degrees of connectivity (Hooke 2003; Kondolf et al. 2006; Wang et al. 2008), to the study of connectivity of processes and landforms across different spatial and temporal scales (Harvey 2002a), and connectivity in relation to geomorphological change and sensitivity (Thomas 2001; Usher 2001; Hooke 2006; Harvey 2007a). Others have considered the application of connectivity theory to conservation management of river landscapes influenced by human land-use (Brierley et al. 1999; Brierley et al. 2006; Fryirs and Gore 2013). There are few cases where water and sediment connectivity has been understood across scales of space and time in a fluvial system with evaluation of the implications for river rehabilitation and catchment management (Gilvear 1999; Brierley and Fryirs 2000; Kondolf et al. 2006).

Connectivity can be studied and described at different hierarchical scales from the catchment level down to the river reach or sub-reach scale, and at different time scales of 10 to 10^{4-6} years (Fryirs et al. 2007a; Hoffman 2015). Thus, aspects of time and space are important when investigating and describing connectivity (Harvey 2002a; Brierley et al. 2006; Bracken et al. 2015). Brierley et al. (2006) and Bracken et al. (2015) discuss sediment connectivity from a hierarchical perspective, suggesting that processes and material transfers at the catchment scale influence processes and transfers at smaller spatial scales and vice versa. Geomorphological connectivity may thus be related to the concept of Panarchy, since the degree of sediment connectivity determines the degree to which geomorphological processes and threshold breaches characterizing geomorphological adaptive cycles, interact across spatial and temporal scales of a river landscape. The concept of connectivity thus facilitates an understanding of system complexity and the process controls on channel behavior, since erosion cycles inherited from millennia ago may influence contemporary river process (Hoffman 2015).

2.3.3 Measures of geomorphological connectivity

Bracken and Croke (2007), suggest that a proposed connectivity framework for the whole or part of a catchment needs to be supported by a quantitative variable that can be measured and estimated in the field. This kind of quantitative investigation requires extensive sediment tracing exercises, which can be costly and time consuming. Thus, connectivity is often described qualitatively. Common qualitative approaches include:

- Sensitivity mapping: mapping the occurrence intervals of formative events like floods, fires and land-use change, and mapping the location, type and propagation of geomorphological response to these disturbances (Brunsden 2001; Harvey 2001; Harvey 2007b).
- Morphological mapping: mapping the size and distribution of different landforms that form partial or full breaks in connectivity of sediment, or enhance transfers of sediment (Fryirs and Brierley 1999; Hooke 2003; Fryirs et al. 2007a; Fryirs et al. 2007b; Jain and Tandon 2010).
- Mapping river styles: classify river planform pattern according to the river styles framework devised by Brierley and Fryirs (2000) for the Bega catchment in Australia. The river styles framework distinguishes different channel forms determined largely by dominant geomorphological processes and channel and valley morphology, and relates this to degree of sediment connectivity with the wider catchment, and associated sensitivity to geomorphological change.
- Visible evidence: observed changes in channel morphology and depositional landforms during flood events that indicate movement of coarse and fine sediment (Hooke 2003; Kasai et al. 2005; Kasai 2006).
- Sediment source-sink tracing: use of radioactive isotopes to trace sediment source to sink pathways for different parts of a catchment (Grenfell et al. 2012; Rowntree and Foster 2012).

Quantitative approaches to measuring connectivity include:

- Estimating the competence and capacity of a channel reach using a range of indicators such as stream power and critical shear stress.
- Sediment flux and budget measurements that may include the use of pebble tracers for bed load fluxes (Hooke 2003), and the use of sediment models and fine sediment tracers (radioactive isotopes) to estimate fine sediment fluxes (Kasai et al. 2005; Hooke 2006; Rommens et al. 2006; Fryirs et al. 2007b; Godfrey et al. 2008).

- A geomorphological connectivity index that estimates potential connectivity between different parts of a catchment based on local topography (Borselli et al. 2008; Cavalli et al. 2013).
- Numerical models that indicate spatial variations in sediment sources, pathways and sinks, and hence degree of sediment connectivity (Heckmann and Schwanghart 2013).

Many of the aforementioned quantitative approaches require substantial technological skill, time and financial investment into top-of-the-range technologies, thus limiting wide-range application (Bracken and Croke 2007). The range of definitions and methods of measuring connectivity have made it difficult to compare findings across different river systems. Furthermore, there is still much room for developing the methodology of measuring sediment connectivity that includes controls other than hydrology or geomorphological and topographic influences (Bracken et al. 2015). These controls could include for example, the influence of vegetation structure and cover or soil structure and type on the ease with which sediment is released, transferred and stored within a fluvial system. Despite these pitfalls, there is still much scope for investigating the application of the concept for understanding river process, form and change across a range of rivers types (Wohl 2014).

Although connectivity is not the only determinant of geomorphological sensitivity (Brunsden 2001; Reid and Brierley 2015), it is a relatively easy concept to apply when attempting to understand the structural resilience of different parts of a river landscape, and the potential for future geomorphological change. The concept thus has multiple areas of application including:

1) Understanding the parts of a catchment that are well-connected to upstream areas, and thus vulnerable to the effects of perturbations that influence water and sediment inputs and available fluvial energy. These areas should be targeted for strategic catchment management since they are particularly sensitive to geomorphological change (Brierley et al. 2006).
2) Understanding the timescales over which a catchment or parts of a catchment are relatively sensitive or resilient to geomorphological change, such that the natural dynamics of the system can be understood (Fryirs et al. 2007b; Hoffman 2015). For example, if alluvial fans form natural buffers in the upper-reaches of a catchment for

periods of several decades, then these features should be conserved if sustained river resilience is desired.

3) Understanding how humans or climate change may influence timescales of connectivity by altering water and sediment inputs and channel stability (Hoffman 2015), and estimating the impacts of these drivers on river geomorphological behaviour, such that changes can be predicted and managed.

2.4 Toward process-based river rehabilitation

The above concepts of adaptive cycles, Panarchy and geomorphological connectivity are useful for guiding river rehabilitation and catchment management approaches, in that they start to appreciate the geomorphological complexity of rivers. Yet, the discipline of river restoration has traditionally aimed at reinstating a pre-degradation channel form (geometry, shape and arrangement of habitats) and ecological condition at the channel reach scale, focusing mainly on conservation of endangered stream biota (Kondolf 1998; Roni et al. 2002; Shields et al. 2003a; Caruso 2006; Beechie et al. 2010). This form-based approach aims at a stable physical and ecological endpoint, which is inappropriate considering that rivers are inherently complex and dynamic, with multiple scales of interacting drivers and processes that determine channel response (Simon and Thorne 1996; Wohl et al. 2005; Fryirs and Brierley 2009; Beechie et al. 2010; Rosgen 2011).

Interventions associated with the form-based approach include, for example, attempting to reconnect an incised channel to a former floodplain using channel engineering approaches (Bravard et al. 1999), or reconnecting fish habitats that have been isolated by human activities (Roni et al. 2002). Weirs (gabion or cement), bank stabilization (using cement, rocks or gabions), artificial log jams, and creation of artificial channels are some of the common measures used to create a desired stable channel form and habitat endpoint (King et al. 2003). These approaches thus reduce heterogeneity in geomorphological and ecological structure that is often necessary for the healthy functioning of a river-floodplain (Fryirs and Brierley 2009), and may sometimes be unnecessary where a stream is capable of self-recovery (Kondolf et al. 2001). It is thus not surprising that form-based or structural approaches to river restoration often fail to achieve improved and sustainable ecological condition and functioning (Mika et al. 2010). Furthermore, the varied use of terminology in the discipline hampers ability for learning and comparison within and between different restoration projects (King et al. 2003; Grenfell et al. 2007; Khatami 2012).

'Restoration', which is generally defined as the return to a structural and functional pre-disturbance state, is the most widely adopted definition in the field of river ecological recovery (Bradshaw 1997; Khatami 2012). However, this definition is rarely achieved given that it is extremely difficult to reconstruct the previous set of conditions, processes and drivers that characterised the pre-degradation ecosystem (Fryirs and Brierley 2009).

The term 'restoration' in the field of fluvial geomorphology and ecology has been defined in varying ways including:

1) "The return of a degraded ecosystem to a close approximation of its remaining natural potential", (Shields et al. 2003a: 575).
2) "Assisting the establishment of improved hydrological, geomorphological, and ecological processes in a degraded watershed system and replacing lost, damaged, or compromised elements of the natural system", (Wohl et al. 2005: 2).
3) "A process of river repair that strives to promote recovery toward a pre-disturbance state (near-intact condition). Reversible geomorphological change has occurred following human disturbance", (Brierley and Fryirs 2008: 9).
4) "Establishment of physical, chemical and biological functions that are self-regulating and emulate the natural stable form within the constraints imposed by the larger landscape", (Rosgen 2011: 70).

Rehabilitation is distinguished from restoration as rehabilitation attempts to re-instating natural processes that allow a system to self-regulate internal processes and structure toward an improved ecological condition. However, the term 'rehabilitation' has also taken on a variety of definitions:

1) "Re-establishment of processes and replacement of elements rather than treating the symptoms", (Wohl et al. 2005: 2).
2) "…a partial return of former function", (Shields et al. 2003b: 442).
3) "An intentional activity that enhances/assists the recovery of an ecosystem that has been degraded, damaged, or destroyed through manipulation of its structure and function. Management activities aim to promote the recovery of ecosystem

processes so as to regain normal/expected function and self-sufficiency without necessarily aiming to recover all indigenous biota", (Brierley and Fryirs 2008: 9).

In this study the term rehabilitation is adopted and defined within the context of water and sediment connectivity, including a consideration of the social aspect of river rehabilitation, as: "the promotion of geomorphological processes and (dis)connectivity of these processes across different scales, assisting the self-recovery of a degraded river floodplain towards an improved functional state, that is sympathetic to local ecological and social needs and desires".

The above definition closely aligns with a process-based approach to river rehabilitation. The process-based approach as an effective alternative to the form-based approach has been widely endorsed in the fluvial geomorphology and ecology literature in recent decades (Kondolf 1998; Wohl et al. 2005; Kondolf et al. 2006; Fryirs and Brierley 2009; Beechie et al. 2010; Pasternack 2013). Process-based rehabilitation aims to foster geomorphological, hydrological and ecological processes that allow a system to recover toward improved ecological functioning (Beechie et al. 2010). This approach focusses at different hierarchical scales of the catchment, considering how drivers of change and processes at larger scales interact with processes at smaller scales of the catchment (Brierley and Fryirs 2009; Fryirs and Brierley 2009). By fostering natural river recovery, process-based rehabilitation is more sustainable in the long-term and likely to be more cost-effective, than engineered structures such as cement weirs that are often barriers to natural recovery processes (Kondolf et al. 2006). Despite acknowledgement of the importance of a process-based approach to river rehabilitation in the literature, it is still common practice to attempt to restore a particular channel condition and geomorphological form in isolation of drivers of change occurring at broader spatial scales (Florsheim et al. 2008; Beechie et al. 2010).

Beechie et al. (2010) propose four basic principles that should guide process-based rehabilitation:

1) Identify and address the root causes of degradation instead of addressing the symptoms.
2) Interventions should align with the physical and biological potential of a particular river reach. This potential is linked to the physiographic and climatic setting and the processes that operate across different scales to determine the range of habitats and

processes that could exist at the local scale. This requires historical analysis of former conditions, understanding processes and controls that determine river type and condition, and identification of anthropogenic factors that limit rehabilitation.

3) The scale of rehabilitation should align with the scale of the drivers of degradation. For example, if gravel has been removed from a channel reach by humans then focus rehabilitation efforts at the channel reach scale, since the driver of degradation occurs at this scale, as well as the resulting impacts. Alternatively, if fine sediment delivery from the catchment has changed due to human activities, then, where possible, adjust catchment land-use activities to achieve a more natural sediment balance.
4) The expected ecological outcomes should be clearly outlined through an attempt to quantitatively predict the range of expected channel conditions that could follow rehabilitation.

The process-based approach therefore requires an assessment of river and catchment history, including land-use and land cover changes, the history of natural disturbances and associated channel condition, behaviour and change (Gilvear 1999; Brierley and Fryirs 2005). This historical perspective facilitates prediction of the possible future geomorphological and ecological pathways of different channel reaches, such that appropriate rehabilitation interventions can be planned (Brierley and Fryirs 2008), and the impacts of future land-use and climate change can be predicted (Large and Petts 1996; Kondolf 1998; Campana et al. 2014). A catchment scale approach to rehabilitation of a single river reach is therefore a fundamental consideration since it is often human disturbance responses, or the nature of geomorphological processes at the catchment or sub-catchment scale, that drive channel behaviour and change at the reach scale (Bravard et al. 1999; Wohl et al. 2005; Florsheim et al. 2008; Fryirs and Brierley 2009; Beechie et al. 2010).

The geomorphological process-based approach to river rehabilitation should be participatory, integrating social-cultural values and desires of the particular context into rehabilitation planning in an attempt to, as far as possible, align the social desires and needs with the need for river recovery (Gregory 2006; Pahl-Wostl 2006; Gregory and Brierley 2010; Le Lay et al. 2013). Furthermore, ongoing monitoring and evaluation of the hydrological, geomorphological and ecological outcomes of rehabilitation efforts facilitates adaptive management, and is an essential component of any geomorphological process-based rehabilitation programme (Downs and Kondolf 2002; Beechie et al. 2010; Brierley et al. 2010). This kind of monitoring should investigate how changes in geomorphological structure and hydrological regime brought about by rehabilitation efforts, influence stream and riparian biota and land-use practices, adjusting the rehabilitation approach were possible (Brierley et al. 2010). This integrative approach to process-based river rehabilitation is however challenging, working at the catchment-scale is costly and takes time (Hillman and Brierley 2005), the stakeholder engagement process may be undermined by political tensions and monitoring and evaluation processes require several years of commitment to a single site.

2.4.1 Examples of process-based rehabilitation frameworks

The river-styles framework (RSF)

Brierley and Fryirs (2000) first demonstrated the application of the RSF for guiding process-based rehabilitation and management efforts in the upper-Bega River catchment in Australia. Following this initial study, the RSF has been widely used in river rehabilitation and catchment management projects across Australia, and has also been applied in other landscapes such as North America, New Zealand and India (Reid et al. 2008; Brierley et al. 2011; O'Brien and Wheaton 2014; Kasprak et al. 2016). The approach has not to the knowledge of the author been applied to rehabilitation projects in South Africa. According to the webpage created for the RSF, www.riverstyles.com, the concept involves a four-stage assessment of river character and behavior (Stage 1), river evolution and geomorphic condition (Stage 2), river recovery potential (Stage 3), and the implications of information gained from stages 1-3 for catchment management (Stage 4). The framework may therefore be used to understand the geomorphic diversity and behavior of different parts of a river catchment, the potential for natural river recovery, and for directing management decisions that are sensitive to the processes and controls on a particular fluvial system.

The RSF webpage summarizes each of the four assessment stages as follows (University of Auckland 2017):

Stage 1 defines river character and behaviour for different parts of a catchment based upon valley confinement and channel planform (e.g. confined valley with single-thread channel and occasional floodplain pockets vs. laterally unconfined valley with wandering river), the nature and arrangement of geomorphological landforms such as floodplain pockets, channel bars, bedrock channel reaches, pool-riffle sequences, and bed material texture size (Figure 2.5). Figure 2.6 is an example of a river styles classification for Bega River catchment in New South Wales, Australia. The river styles are identified for different landscape units including for example, uplands and escarpment units containing the Steep headwater style, the rounded foothills unit containing the Confined valley with ocassional floodplain pockets style amongst others, and the lowland plain unit containing the Low sinuosity sand bed style. The river styles identified indicate adjustment to varying antecedent controls, such as valley width and slope, floodplain alluvium and related cohesiveness of sediments, different dominant geomorphological processes, and differences in geomorphological sensitivity to human disturbances. The approach is hierarchical, defining landscape units such as uplands or the base of an escarpment, within which characteristic river styles are found, including for example headwater styles in upland areas or cut-and-fill styles in lowland areas. The geomorphological units, such as point bars, flood-outs or floodplain terraces that comprise each river style reflect the operation of particular fluvial processes (Brierley and Fryirs 2005). The downstream pattern of river styles in a particular sub-catchment influences the connectivity of sediment and water and hence the sensitivity of different parts of a catchment to disturbances. The river styles framework thus provides clues as to dominant geomorphological processes influencing river behaviour, and potential for natural river recovery, as well as how a channel reach may respond to different types of management and rehabilitation interventions (Brierley and Fryirs 2005).

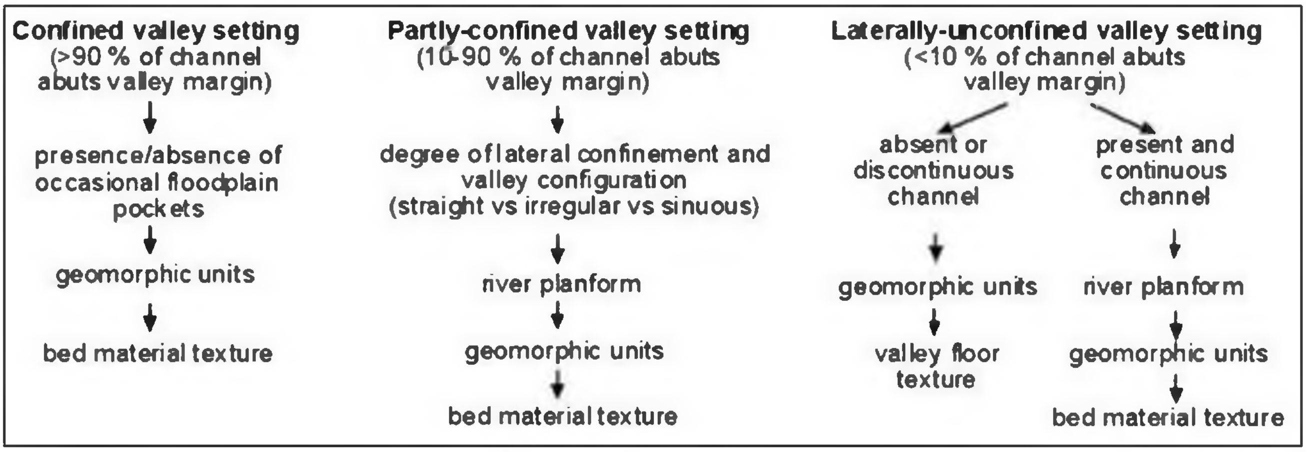


Figure 2.5: Procedural tree for classifying river styles (Brierley and Fryirs 2005: 264)

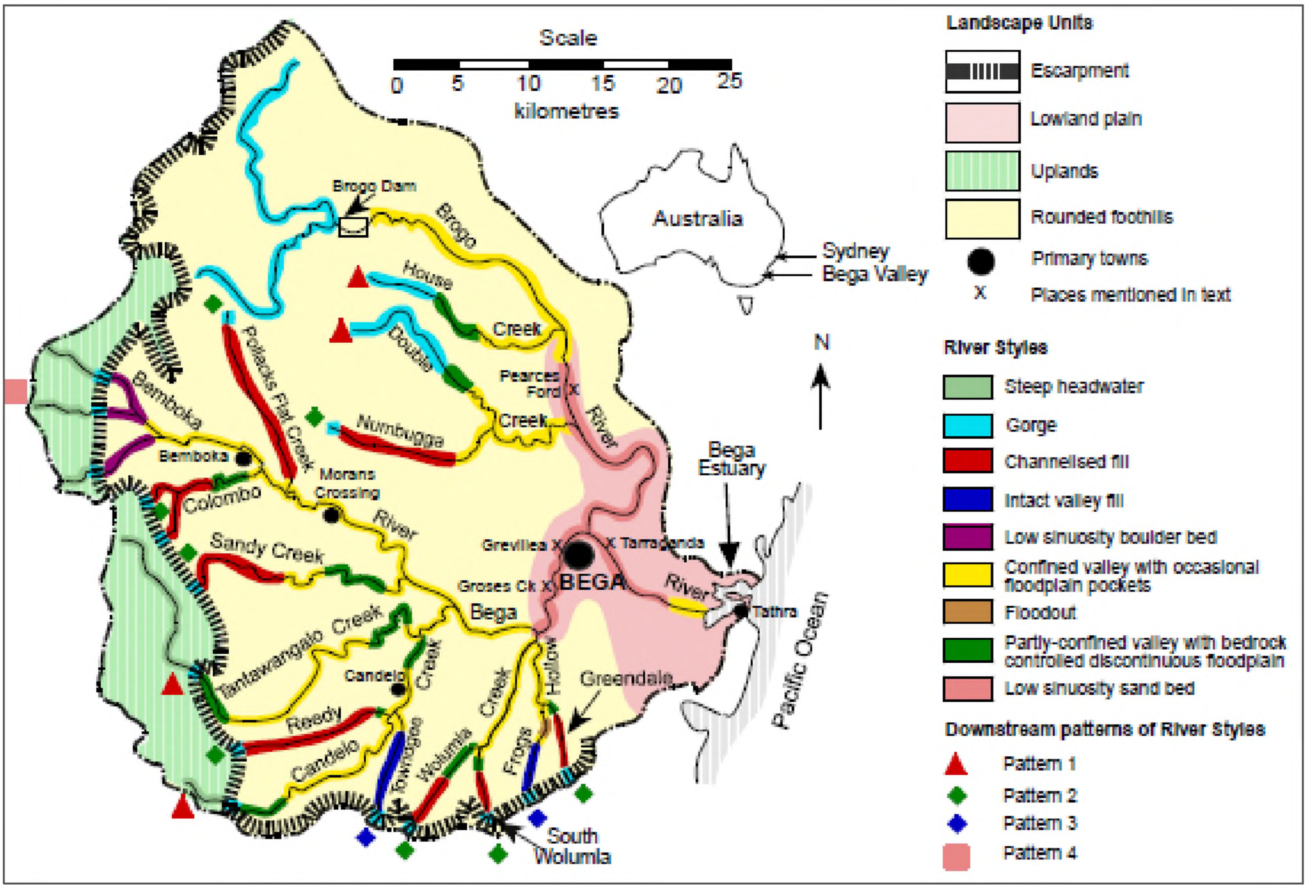


Figure 2.6: The river styles identified for Bega River Catchment in New South Wales, Australia (Fryirs and Brierley 2005: 74).

Stage 2 involves 1) assessing river condition by investigating how a particular river style adjusts within its valley setting and whether the types of adjustments are expected for that style, 2) the evolutionary history of a river to determine if irreversible change has occurred and what the reference condition is.

Stage 3 investigates the potential geomorphological trajectory and potential for natural river recovery for each reach of each river style that has been identified. This assessment involves ergodic reason, using different river sites representing different stages of geomorphological adjustment to infer future change of each river reach and whether the reach will be able to recover along an expected evolutionary pathway with little human influence (Fryirs and Brierley 2005). These evolutionary pathways are described by Fryirs and Brierley (2005) as follows (Figure 2.7):

- Intact condition: when there has been very little to no human impact on river process and form;
- Restored pathway: when a reach has experienced reversible change in river style but the reach operates under new catchment boundary conditions and therefore may evolve toward a restored condition;
- Creation pathway: when impact on geomorphological condition is irreversible but the river reach is resilient to change and there is potential for evolution toward a new geomorphological condition;
- Degraded pathway: when impact on river style and catchment boundary conditions has been severe such that the river continues along a degradation pathway.

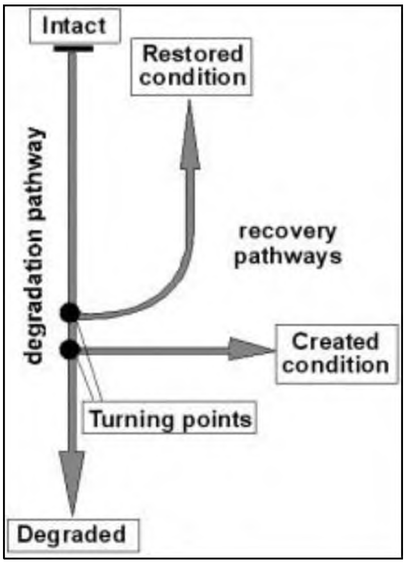


Figure 2.7: Conceptual diagram of potential geomorphological trajectories used to assess natural river recovery for the River Styles Framework (Auckland University 2017).

Stage 4 uses information from the above three stages to prioritise river styles for management interventions based upon river condition and potential for geomorphological recovery. Rehabilitation is prioritized as follows (Auckland University 2017):

1) Those reaches that are most intact and have highest potential for natural recovery are prioritized for conservation efforts and enhanced recovery efforts respectively.
2) Tackle strategic reaches: highly degraded styles receive lowest prioritization and are only rehabilitated if they have some recovery potential.
3) Tackle more difficult areas- with lower rehabilitation potential if above priorities have been addressed.

Monitoring and auditing improvement in river geomorphological condition for improving catchment management is an important component of Stage 4.

Connectivity-based frameworks

The concept of connectivity (water, sediment and biota) is gradually being incorporated into rehabilitation and catchment management as a framework for understanding the structural mechanisms determining river sensitivity to land-use impacts (Gilvear 1999; Brierley et al. 2006; Kondolf et al. 2006; Fryirs and Gore 2013), and as a framework to guide the recovery of more natural flow and sediment regimes in disturbed catchments (Jansson et al. 2007; Fryirs et al. 2009). Understanding connectivity of water and sediment beyond the scale of a targeted rehabilitation reach provides the broader-scale controls on how a river behaves, the potential for a degraded river to recover with little human-intervention, and how a river channel may morphologically evolve in the future (Fryirs and Brierley 2009). Fryirs et al. (2009) found that channel degradation and recovery responses following European settlement in the Hunter catchment in Australia was variable, and dependent on connectivity with the wider catchment. River reaches that were disconnected from the wider catchment showed a longer response time lag for the onset of channel degradation and recovery. Hence, these reaches were less sensitive to geomorphological change but were less resilient to the geomorphological effects of perturbations. River reaches that were well-connected to the wider catchment were relatively sensitive to geomorphological change but were able to recover more quickly, given sediment availability, thereby indicating greater geomorphological resilience following a degradation phase. Riparian vegetation recovery and reduced flooding magnitudes were also important determinants of channel recovery, highlighting the complex interplay between sediment connectivity, flood frequency and magnitude, and the stabilizing effect of riparian vegetation (Fryirs et al. 2009).

Kondolf et al. (2006) present a model that illustrates how changes in three dimensional water and sediment connectivity (lateral, longitudinal and vertical dimensions), can determine river degradation and rehabilitation trajectories (Figure 2.8). The conceptual model describes a river naturally characterised by a high degree of longitudinal, lateral and vertical connectivity and high flow variability (Point 1, Figure 2.8). The system evolves from point 1 to point 2 following the introduction of revetments (hard structures that stabilize banks) by humans, resulting in reduced lateral and vertical connectivity, whilst natural flow variability at this point remains relatively similar to the former condition. The system then evolves toward point 3, as a result of impoundment in the catchment which resulted in decreased longitudinal connectivity and flow variability. The system thus begins to degrade ecologically, as natural fluvial processes are inhibited. Rehabilitation efforts, including the removal of channel revetments, resulted in improved lateral and vertical connectivity and increased flow variability at point 4, although the system did not regain the pre-degradation condition, since impoundments were still present in the catchment. The conceptual model thus illustrates the importance of considering the role of human activities in altering natural levels of water and sediment connectivity and associated flow variability, for planning the type and scale of river rehabilitation efforts.

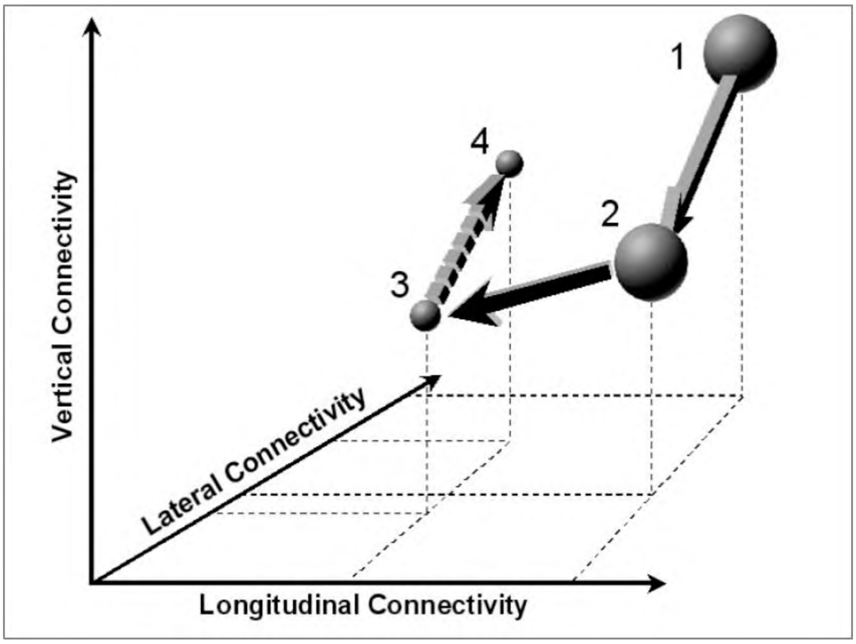


Figure 2.8: An example of a three-dimensional connectivity-based conceptual model of river degradation and rehabilitation developed for the Pike River in Sweden by Kondolf et al. (2006: 10). The size of the dots indicate relative variability in annual flow associated with different connectivity scenarios (large dots = high flow variability and smaller dots = lower flow variability).

Fryirs et al. (2007a) present a different model of connectivity to that described above. The model indicated in Figure 2.9, compares connectivity characteristics in two contrasting fluvial landscapes: 1) a high-energy mountain catchment in New Zealand (the Weraamaia), and 2) a lowland catchment in Australia (the Bega catchment). Fryirs et al. (2007a) suggest that this context-specific and catchment-scale understanding of the nature and influences on sediment connectivity, provides a foundation for understanding river sensitivity or resilience to disturbing forces necessary for effective catchment management. The authors suggest that high-relief catchments ('a', 'b', Figure 2.9) are characterised by ongoing connectivity, with frequent and often high volumes of coarse sediment delivered to the channel network from surrounding hillslopes during high-magnitude storm events. These high-relief landscapes have larger areas contributing sediment to the channel network ('effective catchment area', Figure 2.9), due to more effective water and sediment transfers than in low-relief landscapes. In the low relief setting, the formation of buffers and barriers and associated sediment storage is more common ('c' and 'd', Figure 2.9). Thus, it would be expected that high-relief landscapes are more sensitive to geomorphological change, such that management practices that protect natural buffers and barriers at different scales of a catchment is important. In low-relief landscapes the presence of channel zones devoid of buffers and barriers may be important in maintaining flow and sediment through-put to lowland plains.

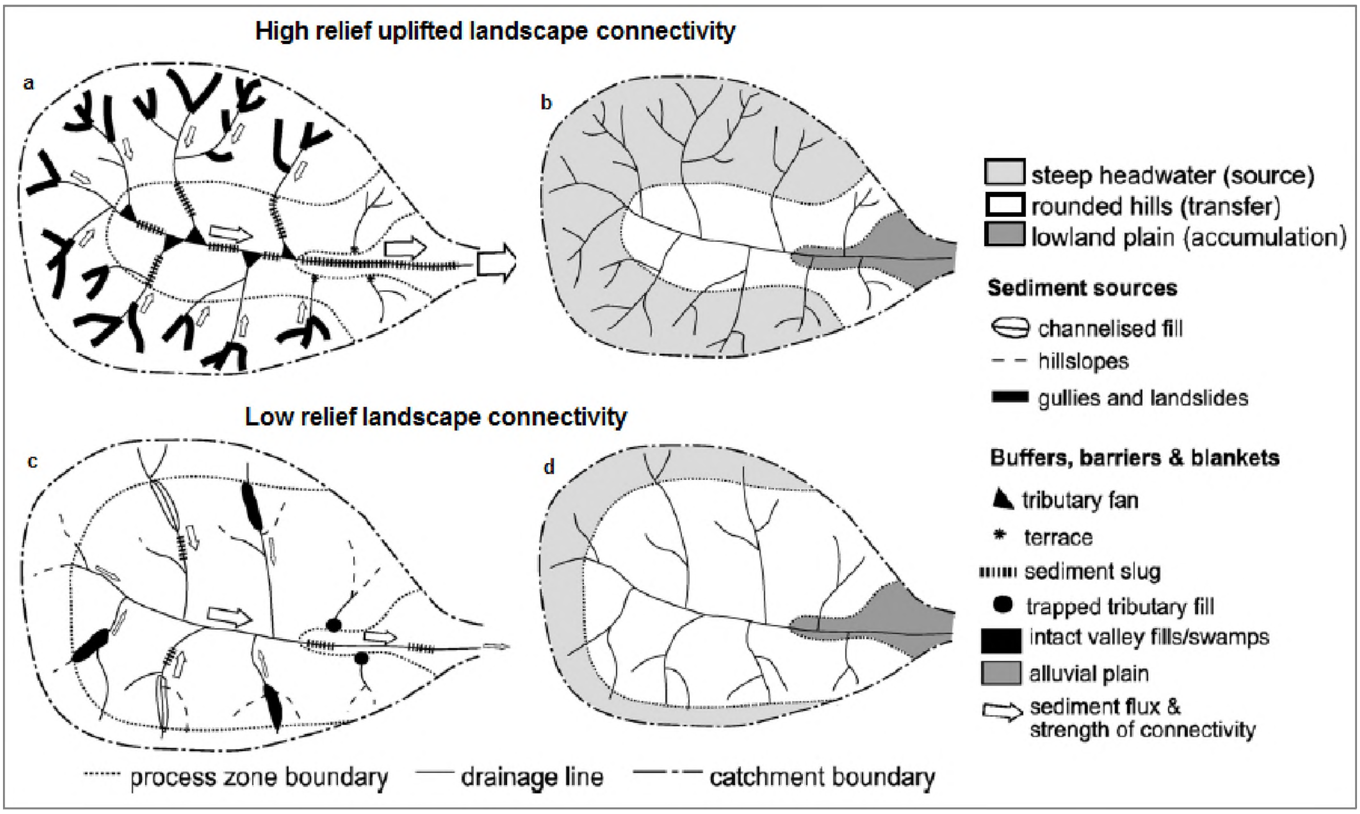


Figure 2.9: Conceptual model of Fryirs et al. (2007a: 61) indicating differences in connectivity and related effective catchment area between a high-relief uplifted landscape (a and b), and a low-relief landscape (c and d).

The above described conceptual frameworks of connectivity and river styles are interlinked. The RSF considers water and sediment connectivity as important aspects of river recovery but does not map catchment (dis)connectivity landforms in detail. When the RSF and connectivity frameworks are combined, they form a powerful tool for effective process-based catchment management and river rehabilitation interventions. The two concepts highlight the importance of applying varied rehabilitation and management interventions to different types of rivers with different sets of interacting processes and landforms, and different potential for geomorphological change and recovery following perturbations (Brierley and Fryirs 2005).

2.4.2 The importance of social stewardship and adaptive management in river rehabilitation

Hillman et al. (2008) indicate that degree of social connection to a river landscape is a fundamental determinant of the success and sustainability of any rehabilitation project. Social connectivity is defined by Hillman et al. (2008) as the degree to which local communities are linked to a river landscape such that a strong sense of place-identity is created. A sense of place-identity engenders environmental stewardship and is thus crucial to the sustainability of any rehabilitation project (Piégay et al. 2006). Gregory and Brierley (2010) highlight the importance of community participation and capacity development in any river rehabilitation project, using 'vision statements' as a tool. A vision statement is a statement of the desired vision or future for a particular catchment, which is co-generated by local stakeholders. A vision statement created in this sense should thus guide rehabilitation interventions that align social values, needs and desires with that of conservation needs and the ecological potential of a particular site. This approach incorporates ecological knowledge and experience held by local communities, thereby promoting social ownership of a rehabilitation project (Spink et al. 2010). The process of stakeholder engagement to foster a greater sense of environmental stewardship can however be lengthy and requires continual engagement and diffusion of tensions between stakeholders. Yet, if successful, stakeholder by-in provides the cornerstone for effective catchment management and river rehabilitation.

Effective and sustainable river rehabilitation incorporating a process-based approach, and social stewardship, should be considered within the context of adaptive management (cite Palmer et al. 2005; 2007 and Berhhardt 2005. Adaptive management involves monitoring and learning from rehabilitation and management outcomes, and then innovatively adjusting the management and rehabilitation programme to improve outcomes for ecological and social facets of the system (Downs and Kondolf 2002; Wohl et al. 2005). Adaptive management therefore calls for flexible rehabilitation interventions that can be altered relatively easily with changes in the structure of the system. This approach also calls for practitioners who are flexible in their approach to rehabilitation rather than adopting a generic approach with which they are familiar. The adaptive management approach requires two important components: 1) assessment and incorporation of social needs and values into rehabilitation objectives and design; 2) post-project appraisal that involves physical and ecological monitoring of channel-floodplain response to rehabilitation intervention, and assessment of whether the desired ecological and social outcomes are being met (Kondolf 1998; Downs and Kondolf 2002). The latter criteria are more easily written than fulfilled, and require careful consideration and planning, and sufficient and ongoing funding.

2.5 Summary

This chapter has provided an overview of several conceptual frameworks that, when integrated, guide investigation of the complexity and sensitivity of rivers as geomorphological systems to different types and magnitudes of perturbations. This knowledge basis may then effectively guide a process-based approach to river rehabilitation, deemed to be most effective and sustainable for ensuring river recovery. There are no studies known by the author that have attempted to integrate the concepts of Panarchy and connectivity to understand river geomorphological dynamics and sensitivity, and to guide the development of a process-based framework of river rehabilitation. Panarchy provides the framework for understanding the interaction of geomorphological structure and processes, comprising geomorphological adaptive cycles occurring at different spatial and temporal hierarchies of a river landscape. These cross-scale interactions determine complex response, including for example, lagged and non-linear responses to disturbing forces at different spatial scales, and sudden chaotic geomorphological change due to threshold breaches at one or more scales of the landscape. Geomorphological (dis)connectivity is a fundamental feature of river landscapes influencing the degree to which processes and landforms are linked, and the degree to which a geomorphological response at one spatial-temporal scale is transferred to other scales of a river system. The author suggests that this eclectic conceptual framework provides the basis for informing rehabilitation that fosters the recovery of geomorphological processes important for enhancing the natural resilience of a river to perturbations.

CHAPTER 3: CHARACTERISTICS OF THE STUDY AREA

3.1 Introduction

The Baviaanskloof catchment is situated in the western-most region of the Eastern Cape Province of South Africa, and is of a moderate size of ~1207 km^2. The catchment lies <50 km north of the Indian Ocean and about 95 km north-west of the metropolitan area of Nelson Mandela Bay, otherwise known as Port Elizabeth (Figure 3.1). The main river valley is positioned between two parallel mountain ranges, the Kouga and the Baviaanskloof Mountains to the south and north respectively, and is approximately 75 km long (Crane 2006). The Baviaanskloof River rises at an elevation of 700 masl in the Kouga mountains, flowing to an elevation of <160 masl at its confluence with the Kouga River (Ilgner et al. 2003), which then drains into the Kouga Dam (Figure 3.1).

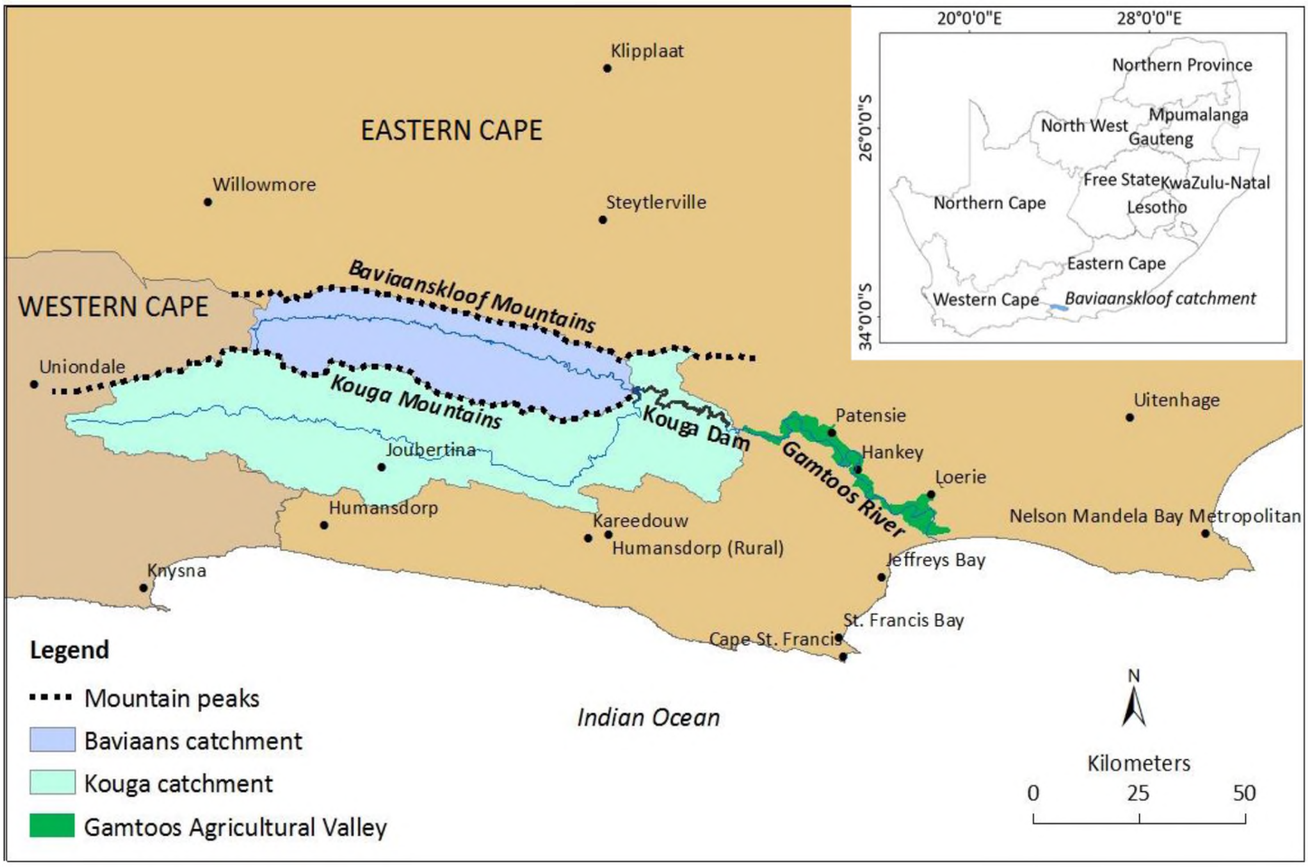


Figure 3.1: The location of the Baviaanskloof catchment, and the adjacent Kouga catchment, indicating the Kouga dam into which the two catchments drain.

The Baviaanskloof is a diverse landscape, hosting a number of South Africa's Biomes within a topographically diverse setting. The area has a rich cultural history and was once inhabited by the native San-bushman of South Africa. The high floral diversity and species richness of the catchment and surrounds means that the area has received attention from a conservation perspective. In 2002 plans were made by local government and non-government agencies to expand the Baviaanskloof Conservation Area into a Mega-Reserve (BMR) within a size of >400 000 ha (BMR-PMU 2004). This initiative was encouraged by the exceptionally high biodiversity and cultural heritage value of the catchment and surrounds, which has been recognized on an international-scale, resulting in the declaration of the Baviaanskloof Mega Reserve area as a World Heritage Site in 2004 (Boshoff 2005).

The Baviaanskloof is not only important from a biodiversity and cultural perspective, but is also valuable from a national and regional water security perspective. On a national-scale, the Baviaanskloof forms a strategic water resource area. The upper-middle reaches of the Baviaanskloof and adjacent Kouga catchment fall within the Kougaberg Strategic Water Source Area defined by DWA & SANBI under the National Freshwater Ecosystem Priority Areas Assessment (NFEPA) of 2010/2011 (Nel et al. 2013). The 'Strategic Water Source Areas' are defined as those areas that supply >50% of the country's mean annual runoff (Nel et al. 2013). At a regional scale, the Baviaanskloof forms part of the Algoa Strategic Water Supply System (ASWSS) identified under the DWA, Algoa Water Reconciliation Strategy (DWA 2011). The Baviaanskloof falls within the western most section of the ASWSS, together with the Kouga and Kromme Rivers to the south, and the Loerie and Gamtoos Rivers to the south-east. The catchments of the ASWSS are considered extremely important for securing water for agricultural, urban and industrial use within the Algoa region, which has experienced a steady increase in urban and industrial demands for water since the 1960s (DWA 2011). These increases have not been met with increased water supply infrastructure development, such that Nelson Mandela Metropolitan is often faced with water restrictions (van der Burg 2008; DWA 2011). The purpose of this chapter is to describe important biophysical, social and institutional characteristics of the Baviaanskloof River landscape, in order to set the context of the present study.

3.2 Physiography of the Baviaanskloof catchment

3.2.1 Geology and topography

The Baviaanskloof catchment and Mega-Reserve fall in the eastern sector of the Cape Fold Mountain Belt region, comprising the Cape Supergroup rocks which extend for about 1 300 km along the southern coastline of Africa (Figure 3.2; Booth and Shone 2002). The Cape fold belt is associated with a fascinating geomorphological history due to major geological events that occurred during the inclusion and break-away of the African continent from the supercontinent Gondwanaland (McCarthy and Rubidge 2005). The rocks were deformed during the Permian–Triassic period to form the Cape Fold Belt which extends along the southern and western coastal region of South Africa today (McCarthy and Rubidge 2005). This event resulted in the formation of an inland basin and sea ('Karoo foreland basin', Figure 3.2). During the breakup of Gondwana and associated rifting events, numerous normal faults developed within the Cape Supergroup rocks, including the fault along which the Baviaanskloof River flows ('Baviaanskloof', Figure 3.2).

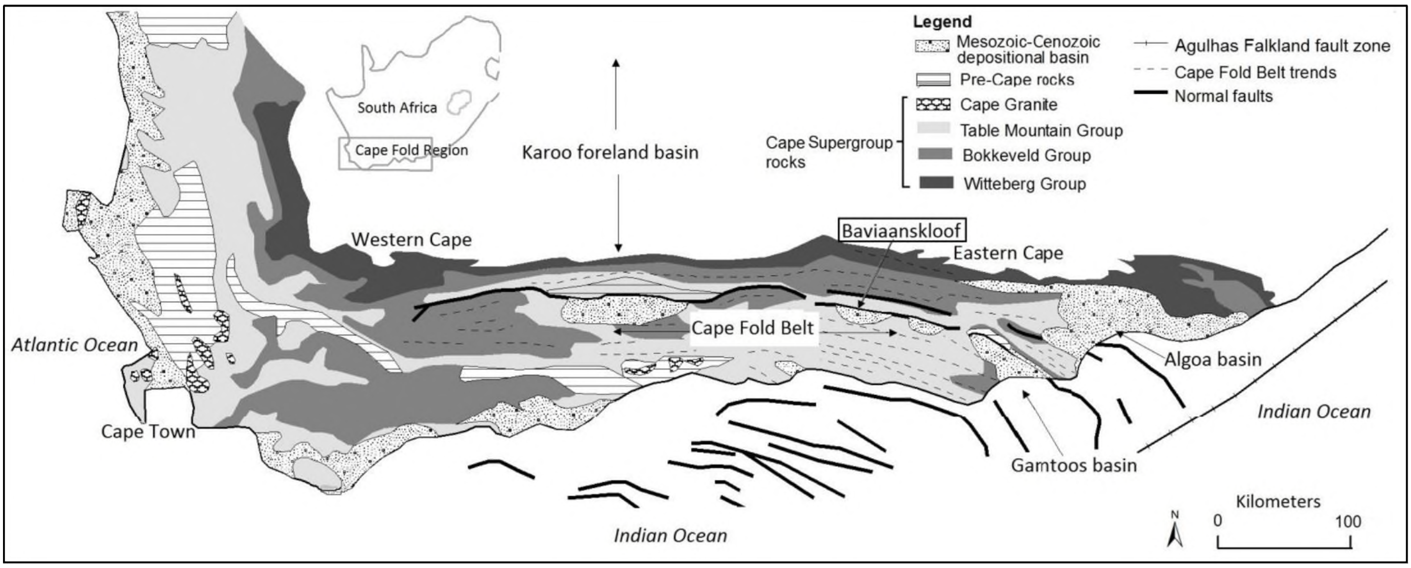


Figure 3.2: Geological map of the southern region of South Africa showing the depositional margin of the Cape Supergroup rocks and the normal fault along which the Baviaanskloof River flows (re-drawn from Paton 2006: 869).

The Baviaanskloof catchment comprises the Table Mountain Group (TMG) of the Cape Supergroup rocks (Figure 3.3). The following rock formations of the TMG outcrop along the Baviaanskloof River valley: Nardouw quartzitic and feldspathic sandstone (430 to 410 MYA), Cedarberg shale (440 MYA), Penninsula quartzitic sandstone (460 MYA), and Sardinia quartzitic sandstone (480 MYA), from youngest to oldest respectively (Figure 3.3, Toerien and Hill 1991). Minor outcrops of younger Bokkeveld shale (Bokkeveld Group; 380 MYA) and Enon Conglomerate (Uitenhage Group; 150 MYA) rocks outcrop along the lower-foothills of the Kouga Mountains (Figure 3.3). The quartzitic nature of the TMG sandstones that occur throughout the study area evolved during intensive folding and metamorphosis of the original TMG sandstone. These metamorphosed rocks are more resistant to erosion than surrounding feldspathic sandstones, Bokkeveld shales and Enon conglomerate, except for the fracture and fault zones which represent relative zones of weakness that are more easily eroded (Rust and Illenberger 1989). The location of several block faults is indicated ('Block', Figure 3.3), including a relatively large fault along which the modern day Baviaanskloof river flows from west to east, and smaller north to south trending faults.

The TMG rocks are recognized as a major aquifer and potential water supplement system throughout the Cape Region (Jia 2007). It is thus not surprising that the mountains of the Baviaanskloof catchment host numerous springs that flow almost on a continual basis.

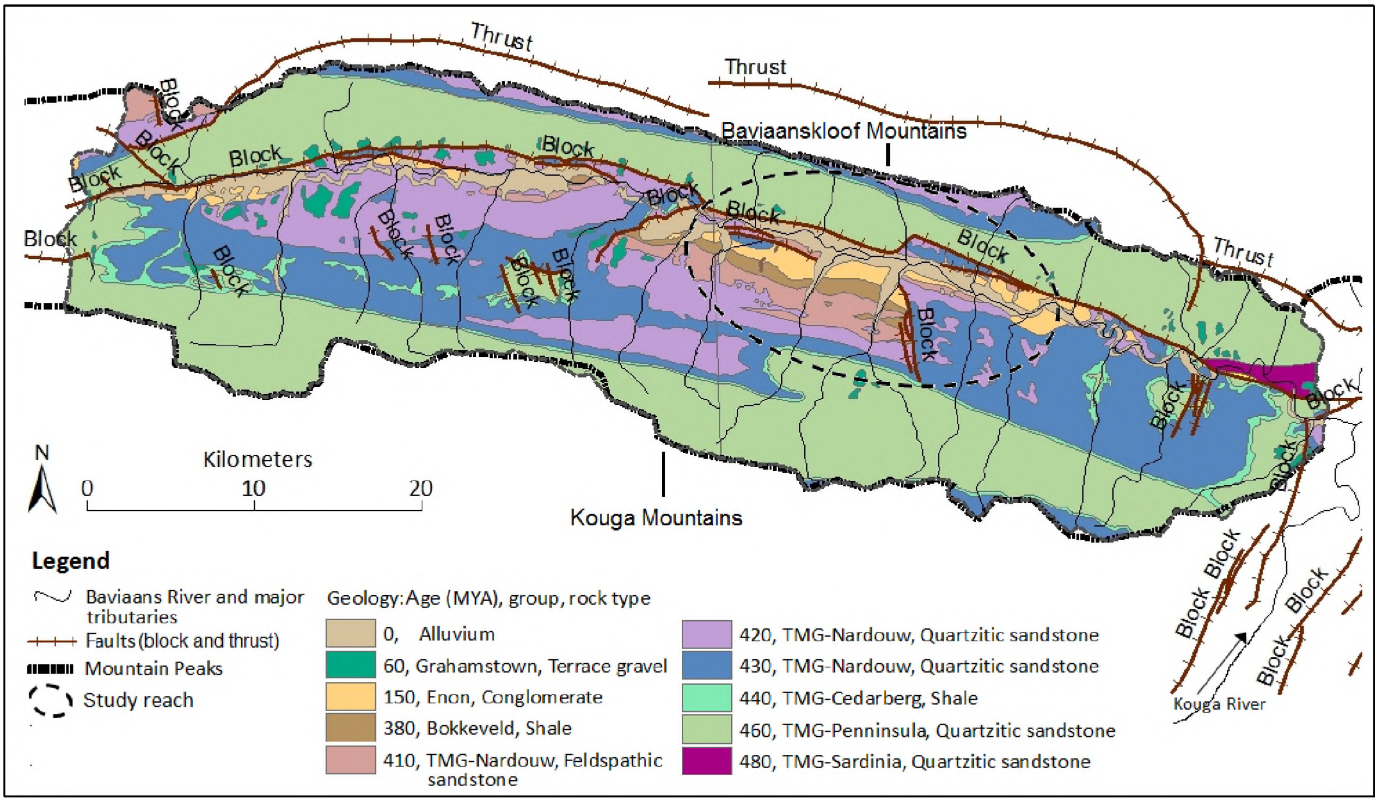


Figure 3.3: Geological map of the Baviaanskloof catchment indicating geological units that outcrop along the river valley. The location of the study reach is indicated by the broken circle (adapted from the South African Geological Survey, Port Elizabeth: shapefiles of 1: 250 000 geological map sheet 3324).

As a result of the lithological diversity and the geomorphological history of the Baviaanskloof valley, the topography is characterized by steep mountain slopes, narrow gorges, and a gently sloping valley floor. The Baviaanskloof has been described as "…rugged- that of a rejuvenated maturely dissected mountain land", (de Villiers 1941: 152). Variations in rock resistance to erosion across and along the valley, has resulted in this rugged topography, as indicated by cross-sectional profiles of the valley in Figure 3.4. As indicated in Figure 3.4, the northern lying Baviaanskloof Mountains are relatively steep (a southwards dip of about 60°), whilst the southern lying Kouga Mountains are more gently sloping (Rust and Illenberger 1989; Booth et al. 2004). The study reach is a ~25.5 km length of river which drains an area of ~987.7 km^2 situated along the middle-reaches of the Baviaanskloof floodplain (Figure 3.4). The upper-limit of the reach lies at an elevation of ~500 masl and the lower-limit at ~340 masl. The reach has a relatively wide valley (>500 m) which is bounded at the upper- and lower-limits by two relatively narrow valley sections (<200 m width).

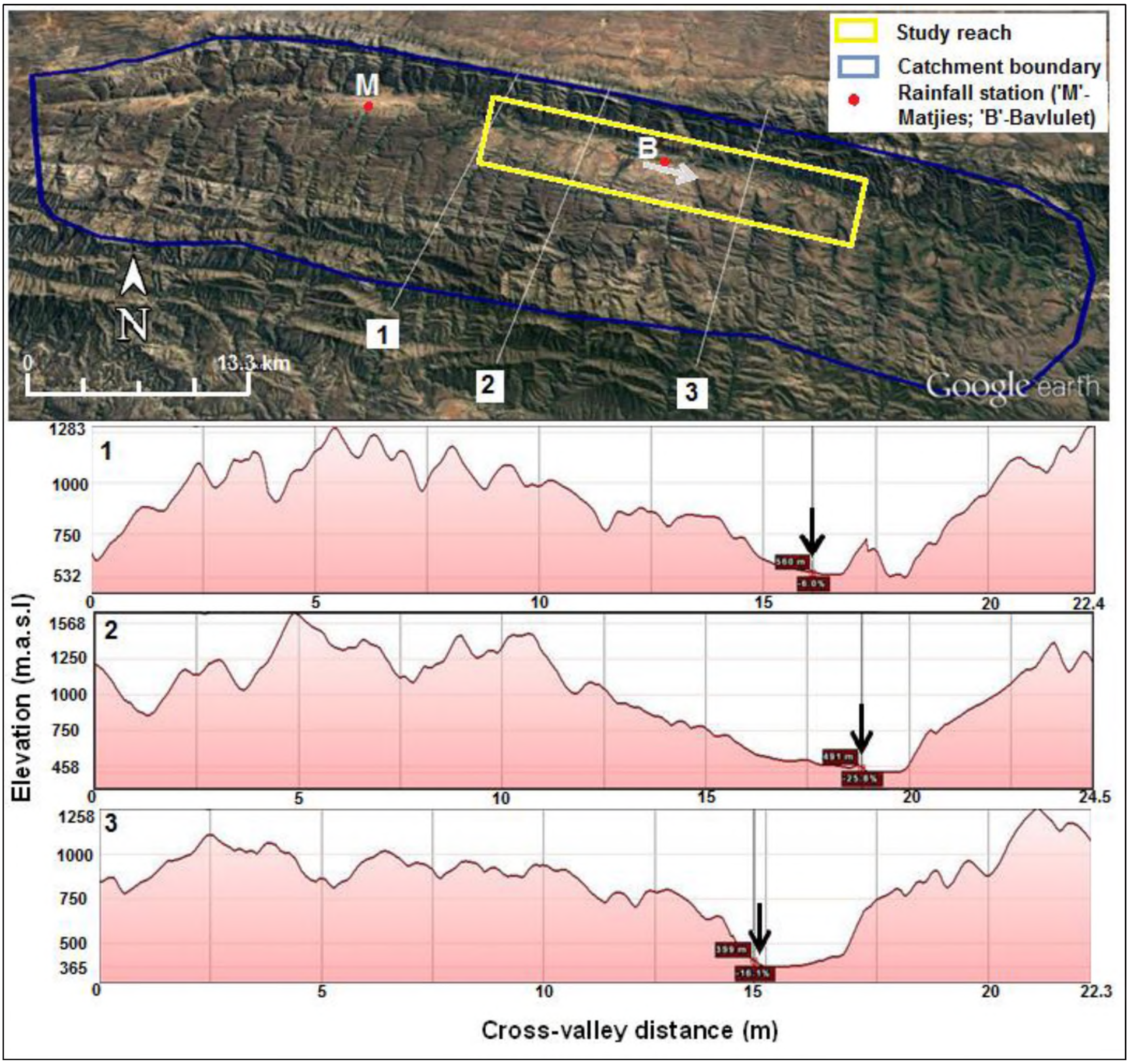


Figure 3.4: Topographic profiles of the Baviaanskloof River valley at three sections along the study reach. The location of the cross-sections (1, 2 and 3) is indicated on the aerial photograph. The grey arrow in the aerial photograph indicates the direction of flow of the Baviaanskloof River; the black arrows in the cross sections indicate the location of the present-day river channel (adapted from Google Earth Professional, 2016).

3.2.2 Climate and rainfall characteristics

The BMR falls within the eastern most region of the Mediterranean climatic zone of South Africa, which experiences a relatively even distribution of rainfall during the year, with slightly higher rainfall during summer months (Teague et al. 1989). On average the climate is semi-arid with low annual rainfall of ~300 mm/annum (Jansen 2008). This is substantially lower than the Kouga catchment which lies immediately to the south of the Baviaanskloof and receives an average of approximately 500 mm rain per annum. The weather and climate of the Baviaanskloof is generally accepted to be highly variable in time and space (Boshoff 2008; Powell 2009), thus diverging somewhat from a Mediterranean classification. Jansen (2008), who based his determination of the annual average rainfall estimates on a weighted average analysis of 8 rainfall stations distributed from east to west across the Baviaanskloof catchment, states that annual rainfall can vary between <100 mm and >700 mm over a >10 year period.

Knight (2012) reported an annual average evaporation value of 1694 mm for the middle-reaches of the valley, which is more than five-fold the average annual rainfall along these reaches. The catchment experiences intense and sporadic rainfall events associated with either cyclonic or orographic rainfall (Jansen 2008). The rainfall is not only variable in time but in space, with reports of differences in rainfall along the valley and between the northern Baviaanskloof and southern Kouga mountain ranges (Jansen 2008; Smith-Adao 2016). Jansen (2008) modeled spatial variations in annual average rainfall for the Baviaanskloof and Kouga catchments using Thiessen polygons to interpolate rainfall from available rainfall data (Figure 3.5). The results indicated higher rainfall on average for the Kouga catchment and Kouga mountain range than for the Baviaanskloof catchment and Baviaanskloof mountain range to the north.

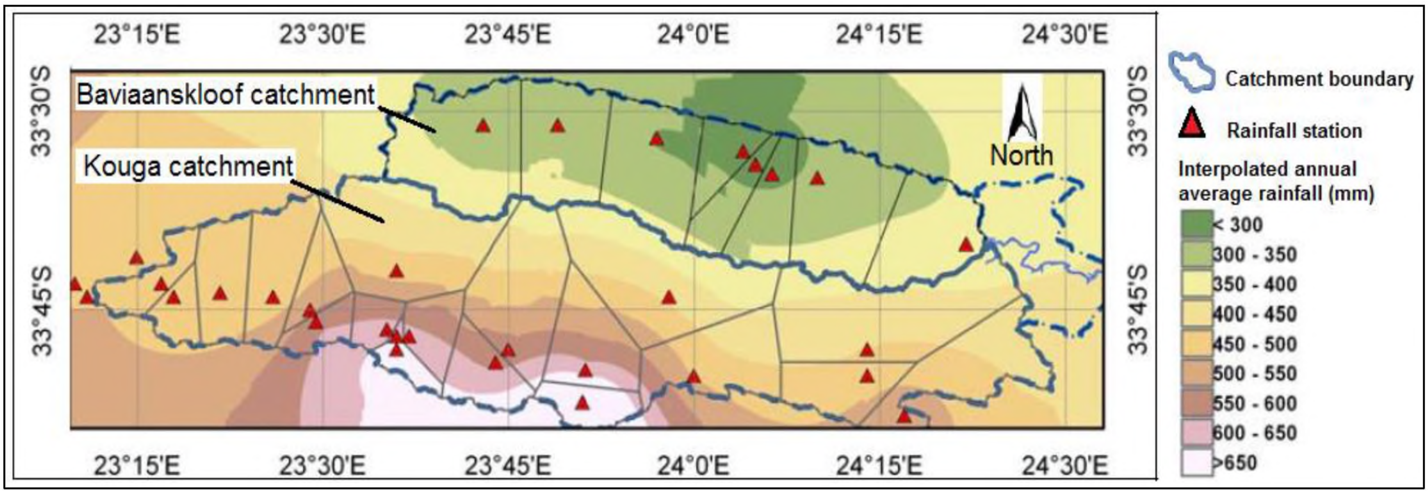


Figure 3.5: Interpolated annual average rainfall for the Baviaanskloof and Kouga catchments (adapted from Jansen 2008: 43).

In the present study, rainfall data for two stations situated along the upper- and middle-reaches of the catchment were analyzed, supporting the above accounts of rainfall variability in time and space. The rainfall station along the upper-reaches was named 'Matjies' in this thesis, whilst the station along the middle-reaches of the study reach was named 'Bavlulet' ('M'-Matjies and 'B'-Bavlulet, Figure 3.6). The analysis of data from the two rainfall stations indicated an annual average rainfall of ~400 mm/annum along the upper-reaches of the floodplain, where the rain station is situated closest to the southern, Kouga Mountains, and an annual average of ~295 mm for the middle-reaches of the floodplain, in which the study reach is located. The rainfall series for the two stations indicates a cyclic variation between relatively wet and relatively dry rainfall periods between 1950 and 2012 (Figure 3.6). These wet and dry periods appear to span between 3-4 or 6-8 years in length producing rainfall oscillations of 6-8 years or 12-16 years.

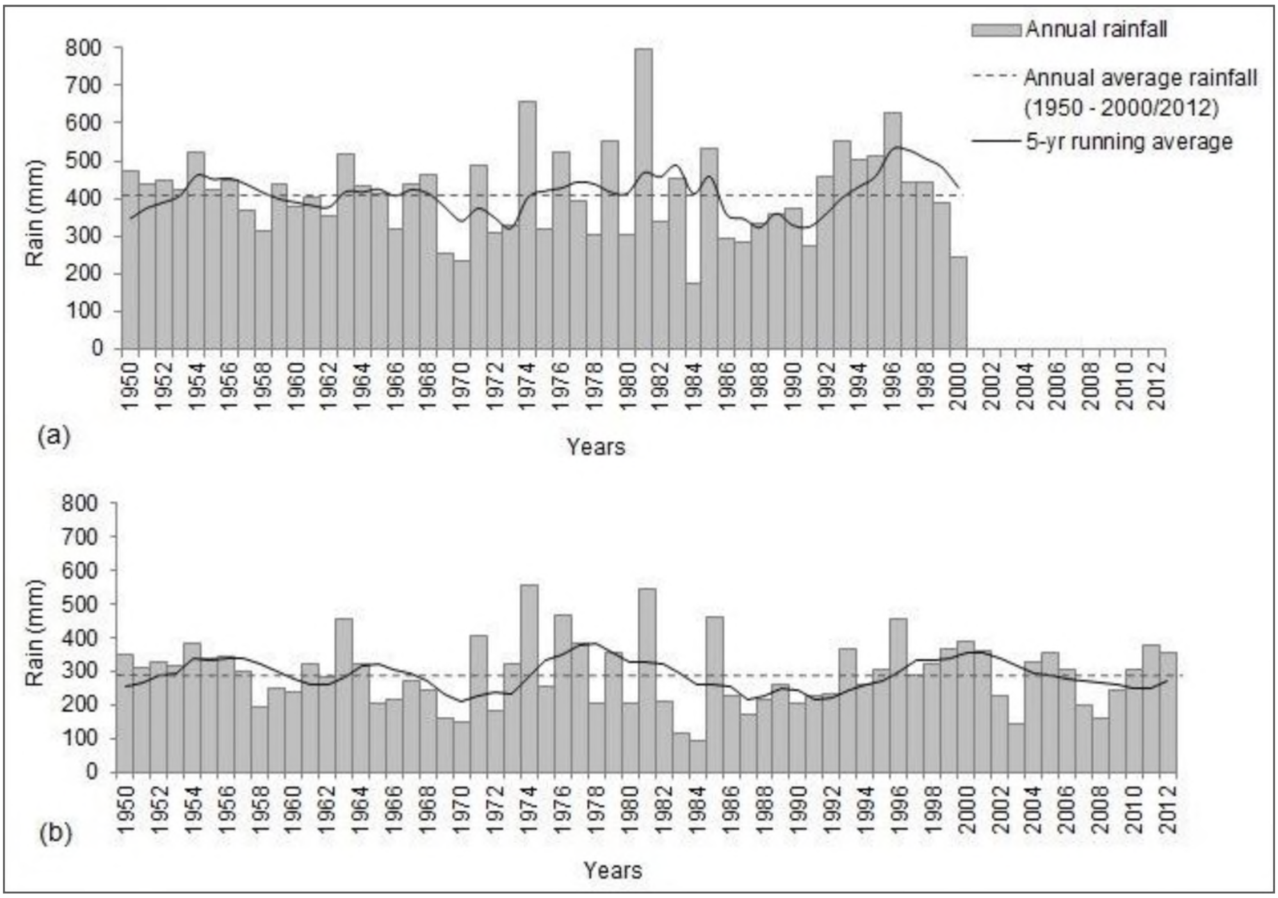


Figure 3.6: Annual rainfall and 5-year running annual average for rainfall stations 'Matjies' (a) situated in the upper-reaches, and station 'Bavlulet' (b) situated in the middle-reaches of the Baviaanskloof floodplain. The annual average for the period of analysis is indicated by the dotted line. The rainfall data was made available from the Agricultural Research Council (ARC) of South Africa.

Average temperatures are also variable with considerable daily and seasonal fluctuations. Average daily minimum temperatures are 5°C for winter and 16°C in summer, but have been recorded as low as -3°C (ECPB 2007; Hattingh 2011). Average daily maximum temperatures are 20°C in winter (June/July) and 32°C in summer (Jansen 2008; Hattingh 2011), although temperatures as high as 45-48°C have been recorded during berg wind conditions that occur throughout the year (Jansen 2008). These winds appear to be more common during autumn and winter months, reducing local humidity (Jansen 2008).

3.2.3 Hydrology

The Baviaanskloof and adjacent Kouga are tertiary catchments of the primary Gamtoos River catchment, which is the fourth largest of all Cape river catchments (Heinecken et al. 1981). Jansen (2008) modeled mean annual discharge for the two catchments indicating that on average the Baviaanskloof contributes a much smaller water yield to the Kouga dam (<30% of the inflow/annum) than that of the Kouga River (>70% of the inflow/annum). These differences are largely due to the greater average annual rainfall in the Kouga compared to the Baviaanskloof catchment.

The steep sloping nature of the Baviaanskloof catchment combined with the variable rainfall regime of the area means that the Baviaanskloof River is characterised by 'flashy' flows of variable magnitude. Flood events usually occur during the rainy season during relatively wet years, delivering coarse gravel to the channel from the surrounding mountainous catchment (Plate 3.1). Along relatively narrow valley reaches the river flows perennially for most of the time where groundwater appears at the surface due to the confining influence of valley side-walls. In contrast, along wide valley reaches the river is non-perennial as base-flows may only last for several months or weeks of the year following one or more flood events, but the stream may be dry for months between flood events. Where the stream is sufficiently deep to dissect the groundwater, water may be present for longer periods, than where the channel is shallow (Plates 3.2a and b). The intermittent nature of water flow in the Baviaanskloof River reflects the variability of rainfall in the catchment.

Plate 3.1: Large boulders are commonly encountered along the bed of the Baviaanskloof River along most of the upper- to middle-reaches, including the study reach.

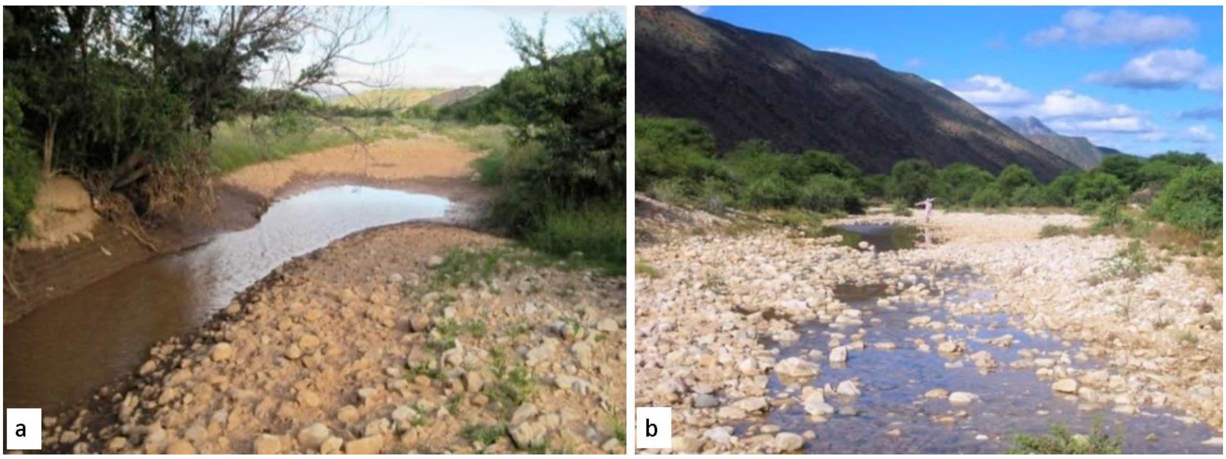


Plate 3.2: An example of a 'pool' which remains after flow cessation along the main channel following a flow event in January 2011 (a); and low flow conditions along the middle of the study reach (b)

There is no long-term stream flow and discharge data for the Baviaanskloof catchment however, there have been a few studies that have modeled the hydrology and hydraulics of the catchment in recent years. In her study, Glenday (2015) modelled variations in stream flow and discharge for the catchment from groundwater, stream flow, surface runoff and soil data collected throughout the upper-middle reaches of the catchment over a 2 year period. The results of the study indicated significant seasonal and inter-annual variations, and spatial variations, in stream flow and discharge for the study reach. This variability in stream flow was explained by the spatially and temporally variable nature of rainfall magnitude and frequency together with the variable nature of runoff, groundwater recharge and groundwater flow rate for different zones of the study reach (Glenday 2015). For the period December 2011 to December 2013, Glenday (2015) recorded a stream flow range of 0.06 m^3/s to 51 m^3/s for the upper-reaches of the study reach, and a flow range of 0 m^3/s to 58 m^3/s for the middle of the study reach. Glenday (2015) modeled an annual average discharge of ~28-31 Mm^3 for the Baviaanskloof catchment in its present (2011-2013) ecological and geomorphological state. These values are considerably lower than the annual average discharge modeled by Jansen (2008), who obtained a discharge value of ~45.7 Mm^3/annum for the Baviaanskloof, based on available DWA inflow and outflow data for the Kouga dam.

Given the climatic setting of the Baviaanskloof and the observed and measured high variability of flow and discharge for the river, one may class the Baviaanskloof as an intermittent aseasonal flowing river based upon the classification of Uys and O'Keeffe (1997) for South African temporary rivers. According to Uys and O'Keeffe (1997: 528) intermittent aseasonal rivers "exhibit intermittent, unpredictable and highly variable flow within and between years in a five-year period".

According to the NFEPAs assessment of 2011, the Baviaanskloof falls within a moderate groundwater recharge area, indicating that up three times more recharge occurs in the area compared to the primary Gamtoos catchment within which the Baviaanskloof falls (Nel et al. 2011). Jansen (2008) uses DWA data to estimate that 8-13% of the annual rainfall is recharged to groundwater in the Baviaanskloof (Jansen 2008), some of which would potentially be lost to the deep mountain aquifer system of the TMG rocks. Based on overall water balance estimates for the Kouga Dam, Jansen (2008) predicts that annual average base flows for the Baviaanskloof River are around 4 Mm^3, which includes a mix of shallow alluvial aquifer and deep mountain aquifer water reserves.

Glenday (2015) indicates that a considerable proportion of annual river flow is contributed by groundwater reserves of the TMG mountain aquifer and the floodplain-alluvial aquifer. The floodplain aquifer is able to hold relatively large amounts of water due to the coarse (cobbles, boulders, sand) and deep (>40 m in some places) nature of the valley fill sediments (Glenday 2015; Smith-Adao 2016). Glenday (2015) monitored floodplain groundwater levels along the study reach indicating that they fluctuate, albeit in a lagged response, to rainfall events occurring in the surrounding catchment. Glenday (2015) also indicated localized variations in groundwater levels that were attributed to differences in recharge rates and groundwater flow rates. The spatially and temporally variable nature of groundwater levels along the study reach initiate spatially and temporally variable river base-flows. During dry rainfall months the river may be completely dry along wide floodplain reaches.

3.2.4 Vegetation characteristics

The BMR includes several globally recognized biodiversity hot spots and as a result the area has exceptionally high floral species richness and endemism, and associated high levels of faunal diversity and endemism (Euston-Brown 2006; Boshoff 2008). The Baviaanskloof Mega-Reserve area contains vegetation types representative of 8 of South Africa's 9 recognized biomes (Mucina et al. 2007), including forest, grassland, savanna, fynbos, thicket, succulent karoo and nama-karoo and coastal vegetation types (Euston-Brown 2006). The Baviaanskloof catchment incorporates the first five of the aforementioned (Figure 3.7; Boshoff 2005). The variety of vegetation types yielded by the BMR reflects the topographic ruggedness of the region, spatial variations in rainfall and hydrology, and variations in lithology and associated soil types. Fynbos and grassy-fynbos occurs on the higher lying plateaus and mountain tops where rainfall is highest and the soils are thin and sandy; Albany subtropical thicket occurs on the lower- to upper-hillslopes, where rainfall decreases and where soils become deeper and more silty; grassland is rare and is found on a few planed surfaces in the foothills; savanna occurs on the valley-bottom on alluvial soils where rainfall and low but where groundwater levels are highest; and forest is found in the narrow gorges of tributary streams where soils are constantly moist and fed by perennial groundwater springs (Euston-Brown 2006). The most dominant vegetation types occurring within the catchment are fynbos, subtropical thicket and savanna. The latter two are the most extensive throughout the study reach of this research (broken circle, Figure 3.7), and have been considerably transformed by agricultural activities (Powell et al. 2011).

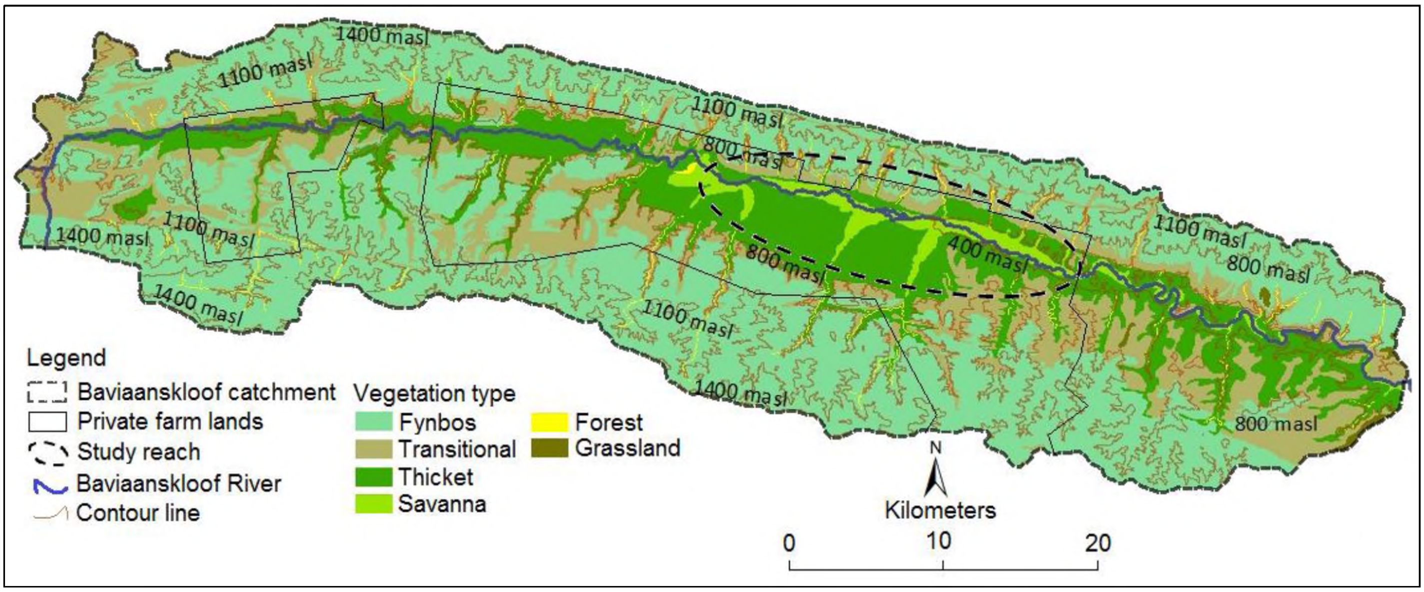


Figure 3.7: The distribution of vegetation classes for the Baviaanskloof catchment as mapped by Euston-Brown (2006).

3.3 Social and cultural context

3.3.1 Cultural history

The Baviaanskloof hosts a rich and diverse array of archaeological remains relating to occupation of the area by pre-historic humans which, besides the high biodiversity of the area, provided yet another reason for the declaration of the BMR as a World Heritage Site (Boshoff et al. 2000; Boshoff 2005). Around 100 rock art and stone-age tool sites have been recorded for the BMR, relating to San-hunter-gatherer occupation from ~100 000 to ~2 000 years ago (Binneman 1989; Boshoff 2005). Some of the rock art has been dated to the last 12 000 years, and a few archaeological sites are believed to contain some of the most well-preserved plant remains in southern Africa (Binneman 1989). There is also evidence of occupation by Khoekhoen (KhoiKhoi) pastoralist people who migrated into the area from the northern region of southern Africa and mixed with the San from ~2 000 years ago to around the mid-19th Century. European settlement during the mid-19th Century resulted in forced removals of the San and Khoi-San peoples from the Baviaanskloof and surrounding region (Boshoff 2005). Today the catchment contains a mix of cultural and ethnic groups ranging from farmers of European descent to communities of mixed Khoi-San and European descent.

3.3.2 Land tenure and land-use

The majority of the Baviaanskloof catchment is managed as conservation land by the Statutory Agency, Eastern Cape Parks and Tourism Agency (ECPTA), as the Baviaanskloof Nature Reserve (Boshoff 2008). The nature reserve comprises around 200 000 ha in the eastern most section of the Baviaanskloof and Kouga Mountains, through which the lower-reaches of the Baviaanskloof River flows (ECPB 2007; Stokhof de Jong 2013). Private land ownership forms the next largest land-use, consisting of a mix of commercial farmland, free-hold titles and three relatively small communities, collectively situated along the upper-middle reaches of the catchment, including the study reach of the present research (Powell et al. 2011; Stokhof de Jong 2013). In 2009 the ECPTA owned approximately 62% (75 871 ha) of the catchment, of which about 36.2% (44 304 ha) was under commercial farmer and free-hold title ownership, and approximately 1.8% (2 204 ha) fell under community ownership (Powell and Mander 2009). Although this portioning of land ownership has not changed drastically to the present, land-use is slowly shifting away from commercial farming to nature-based tourism activities and conservation (Crane 2006; Stokhof de Jong 2013). Over the last 2-3 years, several private landowners have signed stewardship agreements with ECPTA, increasing the proportion of land under cooperative conservation management. The people and associated economic activities of the western private lands rely heavily on the ecosystem services provided by the Baviaanskloof catchment for sustained productivity and livelihoods, with water and soil security and biodiversity being of most importance (de la Flor Tejero 2008; De Paoli 2008).

At present <1 000 people live in the western private lands of the Baviaanskloof (Stokhof de Jong 2013). There are 23 separate landowners including community trust holdings, engaged in a mix of activities including pastoral and crop farming, game farming and nature-based tourism activities (hiking and horse trails, 4x4 vehicle trails, and accommodation), and nature-based living (Stokhof de Jong 2013). Free-range Mohair and sheep farming is the most dominant of all commercial farming and livelihood activities (Powell et al. 2011; Stokhof de Jong 2013). Grazing of livestock commonly takes place along the lower- to middle-hillslopes of free-hold title land (Powell and Mander 2009), although overgrazing and associated declining veld quality has resulted in expansion of grazing toward the upper-hillslopes and mountain tops over the last 20 years (Stokhof de Jong 2013). Nature-based tourism and game farming combined is the next most important land-use activity (Powell and Mander 2009; Stokhof de Jong 2013). The aforementioned activities have been growing slowly over the last 40 years, along with declining productivity of agricultural lands and the relatively high costs of transporting agricultural goods out of the valley (Crane 2006; Stokhof de Jong 2013). The smallest commercial activity is crop farming, comprising mostly fodder, some vegetable seeds and some maize, tobacco and other small crops (Stokhof de Jong 2013). As with many other catchments in the Eastern Cape (e.g. Rowntree and Dollar 2008), the aforementioned activities have resulted in extensive transformation of land along the western private lands section of the catchment (the upper-middle reaches).

3.3.3 Recent initiatives toward integrative catchment rehabilitation

The Baviaanskloof catchment has faced increasing environmental, institutional and socio-economic pressure over the last few decades (Boshoff 2005; Crane 2006). These pressures are briefly described by Boshoff (2005):

- Overgrazing of large tracts of subtropical thicket on hillslopes throughout the western Baviaanskloof due to overstocking with goats and sheep.
- Increasing extension of grazing lands into the mountains and associated development of poorly designed roads that promote soil erosion and more efficient water runoff.
- Increasing demands for catchment surface and groundwater resources for irrigating crops.
- Frequent burning on an annual to biannual basis to provide grazing for livestock.
- Lack of institutional capacity of State agencies such as ECPTA and South African Department of Environmental Affairs to adequately manage and encourage synergistic relationships with local communities and landowners around conservation initiatives.
- The development of private nature-based initiatives that don’t always align with the conservation management objectives of the BMR.

The above pressures have impacted on a number of ecosystem services including carbon sequestration, maintenance of biodiversity, sustained and regular supply of potable water, and the ability of the river-floodplain to attenuate flood flows and diminish flooding damage locally and downstream (De Paoli 2008; van der Burg 2008; Sommeijer 2010; van Luijk et al. 2013). As a result, the high conservation and water security value of the Baviaanskloof has been compromised. The formation of the Baviaanskloof Megareserve Project and declaration as a World Heritage Site provided the framework for the implementation of an integrated catchment rehabilitation and conservation management strategy for the Baviaanskloof, which has been planned and implemented over the last 10 years. This process has involved discussion and collaboration between multiple stakeholders including government and non-government agencies, research institutions, and local landowners, resulting in a complex set of networks and interactions amongst the various stakeholders.

The Baviaanskloof formed one of the first pilot projects of the South African Government led Subtropical Thicket Restoration Project (STRP) between 2004 and 2008, which constituted one of the first 'big' ecosystem rehabilitation research and implementation projects in the Baviaanskloof (Powell 2009). In the Baviaanskloof it has been estimated that approximately 12 336 ha of the subtropical thicket has been degraded (Powell et al. 2011). Most of this degraded area comprises 'severely' degraded Thicket vegetation, defined as having <20% of the dominant, keystone species, *Portulacaria afra* (spekboom) remaining (Powell et al. 2011). Overgrazing by goats is the primary means by which subtropical thicket has been degraded in the Eastern Cape as well as the western Baviaanskloof (Mills et al. 2007; Powell 2009). The Baviaanskloof thus formed a suitable pilot project for the STRP research trials which took place on degraded Thicket sites in the Baviaanskloof Nature Reserve (Powell 2009), downstream of the study reach. The aim of the project was to investigate the practical and financial feasibility of using the dominant plant species of the main thicket type found in the Baviaanskloof catchment, *Portulacaria afra*, as a means of improving the functioning and provisioning of ecosystem services of Thicket. The project also investigated the potential of forming a Payment for Ecosystem Services Scheme around carbon sequestration, given the relatively high rate (~2.4 tons/ha/annum) at which spekboom is able to sequester carbon (Mills et al. 2007; Powell et al. 2009). The project suggested that the use of spekboom for thicket rehabilitation is an ecologically viable option in the long-term (decades) due to the ability of the plant to survive harsh climatic conditions and create habitat for recruitment of other thicket species (Powell 2009).

Following from the STRP pilot project, an integrated catchment restoration project (ICRP) was initiated at the end of 2008 by the non-government organization LivingLands, in collaboration with several national government and research agencies. The overarching vision of LivingLands is to foster “collaborations on living landscapes” by facilitating open and transparent sharing of knowledge, beneficial partnerships, and social learning towards achieving more sustainable social-ecological systems (LivingLands 2014). This organization has been fundamental in coordinating improved land management and catchment rehabilitation activities in the Baviaanskloof by stimulating and coordinating research and knowledge sharing, developing trust amongst various stakeholders, and initiating integrated and collaborative processes around various ecosystem restoration projects in the Baviaanskloof. The ICRP has involved the interaction of a number of government and non-government agencies, research institutes and local landowners. This institutional framing has resulted in a wealth of scientific knowledge generation, interactions between different experts and knowledge bearers.

The Baviaanskloof ICRP initially involved the identification of target areas for restoration based on discussions between ECPTA, local farmers, restoration implementers (Working for Wetlands, Gamtoos Irrigation Board) and local scientists. Following from this, several restoration strategies have been implemented in the catchment over the last few years focused on improving degraded ecosystem services. LivingLands obtained funding from the ‘Water for Food and Ecosystems Project’, a Dutch Government funded programme administered through Wageningen University (De Paoli 2008), to fund student research, stakeholder workshops and some of the restoration in the catchment. The range of restoration projects implemented by various government and non-government agencies so far include:

1) Thicket vegetation rehabilitation (spekboom planting) that has taken place on several hectares on farms along the study reach of this research, under the STRP and LivingLands: Elemental Equity Project.

2) Alluvial fan rehabilitation administered by LivingLands has involved reinstatement of more natural, dispersive flows along a few of the tributary streams along the study reach that were formerly channelized by human engineering interventions.
3) Floodplain wetland rehabilitation administered by the DEA Working for Wetlands Programme (WfWet). This project is still ongoing and is aimed at halting erosion along the main river and gullied hillslopes, and reinstating a former relatively large area of floodplain wetland that existed a few decades ago along parts of the main river floodplain.

Thicket and floodplain wetland rehabilitation activities are still ongoing in the catchment and LivingLands has recently secured enough funding for the re-planting of vegetation on 1 000 ha of hillslope area along the study reach (Four Returns 2016).

The present research evaluates the work of the DEA WfWet programme in the context of other rehabilitation activities that have been active within the catchment, and based on knowledge generated during this study.

CHAPTER 4: LONG-TERM AND RECENT RIVER HISTORY: EVIDENCE FOR GEOMORPHOLOGICAL ADAPTIVE CYCLES

4.1 Introduction

From a process-based river rehabilitation perspective, understanding river history and pre-history provides the framework for predicting the potential geomorphological behavioural regime of a river, its sensitivity to geomorphological change, and the most important drivers of recent river dynamics, such that these can be managed appropriately (Brierley et al. 2006; Fryirs and Brierley 2009; Stinchcomb et al. 2012). Harvey (2002a) introduces the concept of effective timescales of coupling in fluvial landscapes determined by disturbance events that drive geomorphological instability and change, operating at different spatial-temporal scales. Here, 'effective timescales of coupling' refers to the time period over which different spatial scales of a catchment become well-connected, related to the frequency and magnitude of disturbing forces and the geomorphological sensitivity of the system to these disturbances. Entire catchments may be dominated by relatively high connectivity over thousands of years, related to landscape incision that has been induced by base-level fall or by a major tectonic uplift event. At smaller scales, parts of a catchment, such as channel reaches and hillslopes and channels, may become well-connected every 10-15 years, associated with flood events that breach erosional thresholds (Harvey 2002a).

Long-term geomorphological adjustment cycles occurring over several thousand to tens of thousands of years are being documented in greater detail in river landscapes due to the development of more accurate sediment dating techniques in recent years (Macklin et al. 2010; Macklin et al. 2015). The switching between long-term geomorphological phases of erosion and deposition associated with large-scale changes in environmental conditions is usually well-preserved in floodplain and alluvial fan sedimentary fills (Harvey 1984; Stock 2013). These long-term geomorphological cycles are commonly driven by long-term climate change associated with glacial and interglacial periods, and large-scale tectonic events (Pratt-Sitaula et al. 2004; Meetei et al. 2007; Lespez et al. 2011; Madritsch et al. 2012; Fontana et al. 2014). Short-term geomorphological adjustment cycles occurring over several decades to hundreds of years may be induced by decadal to century scale rainfall variations, intensified human land-use activities that alter discharge and sediment regime, and breaching geomorphological thresholds, as a result of natural fluvial geomorphological evolution toward these thresholds (Lespez et al. 2011; Broothearts et al. 2014; Macklin et al. 2015). Several studies have indicated that human land-use activities have exerted a strong control on the recent (last few hundred to thousand years) adjustment phases in river landscapes in the form of increased catchment erosion and associated floodplain sedimentation, often followed by floodplain incision (Hoffman et al. 2009; Piccarreta et al. 2011; Stinchcomb et al. 2012; Macklin et al. 2014; Kirchner et al. 2015). Humans thus form an important driving agent of more rapid cycling between erosion and deposition in disturbed catchments.

The long-term geomorphological history of a river landscape influences contemporary river process and form by, for example, determining the sedimentary characteristics of alluvial valley fill and associated propensity for river erosion, the pattern and abundance of buffering features such as alluvial fans and wide floodplains, and the slope of the floodplain. This inherited structure provides the basis for contemporary fluvial geomorphological processes and geomorphological sensitivity (Murray et al. 2009). Hence, it is useful to understand the nature and controls of long-term geomorphological cycles in river landscapes and how these have influenced contemporary processes and sensitivity to geomorphological change, particularly within the context of managing river sensitivity, reinstating important river processes, and predicting future channel behaviour.

The study of Holocene river dynamics has focused at systems in the northern Hemisphere, indicating the close link between Holocene climate change and associated switching between erosional and aggradational river phases, which may be punctuated by periods of relative geomorphological stability (Kirchner et al. 2015). Climate change in upland catchments can have profound impacts on the interaction between the trunk stream and tributary streams and fans (Harvey 2012). These climatic changes may induce switching between phases dominated by tributary stream cutting or fan sedimentation and phases of trunk stream cutting or floodplain sedimentation (Fryirs and Gore 2014). Harvey et al. (2005) provide an overview of alluvial fan research indicating that fans respond more sensitively to climate change occurring on timescales of 10^2 to 10^4 years. Fans may enter adaptive geomorphological phases of either fan expansion or reduced fan activity and entrenchment, as tributary catchments respond to changes in sediment supply and discharge from the surrounding hillslopes, initiated by changes in rainfall regime and vegetation cover. The fans, if large enough, may then interact with a trunk stream by controlling longitudinal valley slope and trunk stream confinement, initiating geomorphological responses of incision and/or aggradation along the trunk channel (McCarthy et al. 2011). Alternatively, long-term sedimentation along a trunk stream may result in sediment accumulation along a tributary stream as it responds to a rise in local base-level resulting in tributary stream 'blockage' by sediment deposition (Grenfell et al. 2008; Fryirs and Gore 2014). The interaction between fluvial processes occurring along one or more tributary streams and a trunk stream is thus a key determinant of the respective sensitivity of trunk and tributary channels to geomorphological change.

The geomorphological history of the southern African landscape means rivers are rejuvenated and thus on a long-term path of incision (Partridge and Maud 2000). This phase of incision was initiated millions of years ago during multiple uplift events of the southern African landscape (McCarthy and Rubidge 2005). Within this millennial scale geomorphological adaptive phase, are smaller scale adaptive cycles driven by climatic variations between relatively cool and dry, and relatively warm and wet climatic periods that have characterised the southern African climate over the last approximately 200 000 years (Partridge 1997). These long-term climatic cycles are suggested to have occurred on scales of 10^2 to 10^4 years (Partridge 1997; Norström et al. 2009; Chase et al. 2012). There have only been a few studies that have investigated the relation between long-term climate cycles and fluvial geomorphologic cycles of erosion and deposition (Damm and Hagedorn 2010; Tooth et al. 2014). Keen-Zebert et al. (2013) investigated dynamics in two floodplain wetland systems in the eastern interior of South Africa using geo-chronological investigation. This study indicated that fluctuations in fluvial energy and geomorphology during the Holocene was driven mostly by changes in local base-level due to erosion through resistant lithologies that traverse a river's course, rather than the influence of climate change. The study also documented that the floodplain wetland had undergone prolonged periods of relative stability until the resistant lithological barrier was breached, resulting in relatively rapid wetland incision and channel instability. Hence, South African rivers may be relatively resistant to the disturbing effects of climate shifts where they are controlled by local geological structure. These studies suggest both geological and climatic controls on the nature and timing of long-term fluvial geomorphological adaptive cycles which determine the structure and functioning of river floodplains and wetlands in the South African landscape.

The aim of this chapter is to identify and describe the overall nature of long-term fluvial geomorphological cycles evident within palaeo-sediments of the Baviaanskloof valley floor, and compare these to recent fluvial geomorphological adjustment along the study reach.

In line with the above aim, the objectives of this chapter are to:

1) Describe and compare the nature and timing of Holocene fluvial geomorphological cycles evident in palaeo-floodplain and alluvial fan sedimentary units along the study reach based on chronostratigraphic evidence.
2) Identify and describe the nature and timing of recent channel adjustment along the study reach from analysis of historical aerial imagery and information gained from landowner oral histories.
3) Investigate how the geomorphological evolution of the river floodplain during the Holocene has influenced the nature of recent channel adjustment and sensitivity to geomorphological change.

4.2 Methods

4.2.1 Identifying long-term geomorphological adaptive cycles

During the course of the research, a funding opportunity arose to conduct limited geochronological investigation of fluvial and alluvial fan sedimentary units of the Baviaanskloof floodplain. This exercise would provide insight into the nature and timing of contrasting Holocene fluvial environments for the study reach. As a result of the funding provided, two floodplain sedimentary units were dated using Optically Stimulated Luminescence (OSL) dating. Samples were collected from sedimentary deposits at two erosion banks along the middle of the study reach (Figure 4.1). The first site 'SKOSL' was a bank exposing a mix of alluvial fan and floodplain deposits and the second site 'JOSL' contained a mix of floodplain sands and silts alternating with dark organic horizons. Three samples were collected at approximately 0.2-0.4 m, 1.0-1.5 m and 1.7-1.9 m depths for each site. The samples were collected in the dark using a standard sediment corer, and were carefully stored in light impenetrable black plastic.

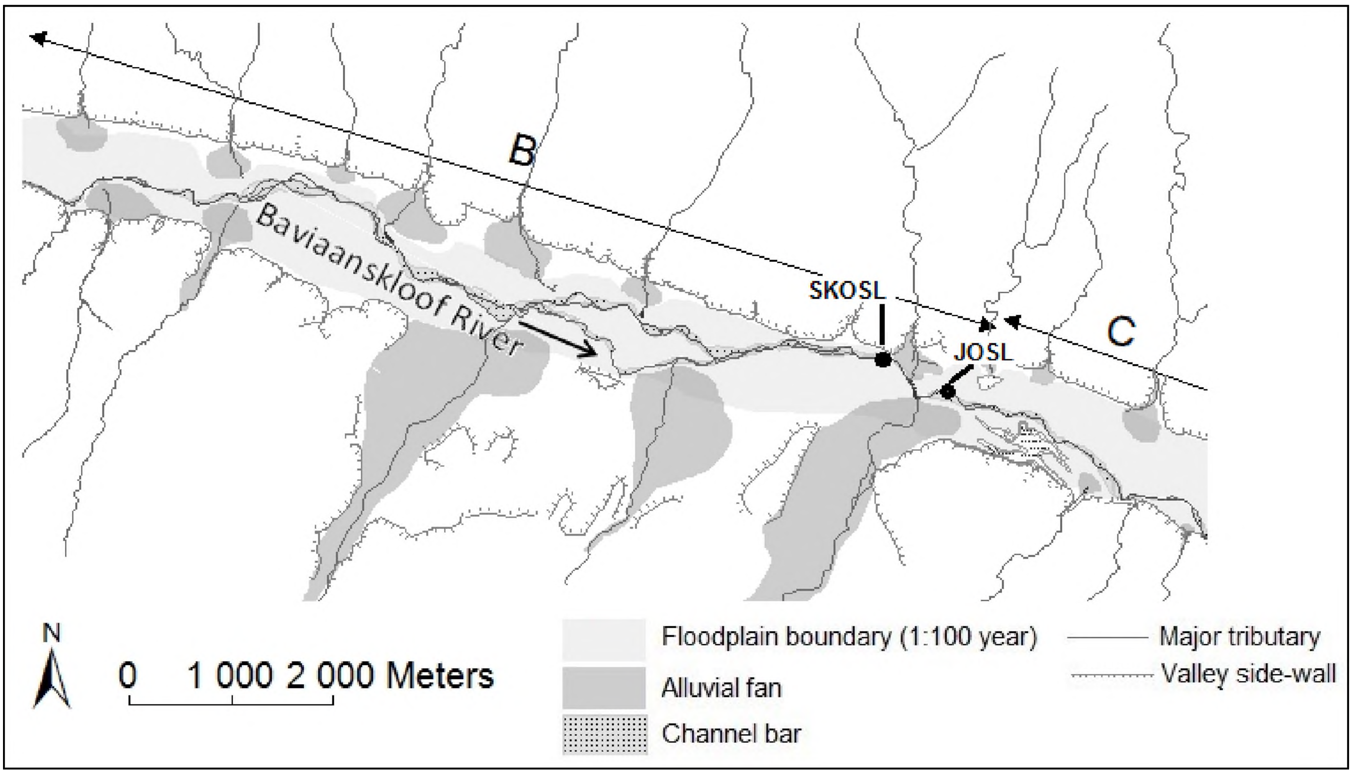


Figure 4.1: Map indicating the location of OSL sample sites 'SKOSL' and 'JOSL' along sub-reach B of the study reach.

The OSL dating technique measures time that has passed since burial of a quartz or feldspar rich sedimentary grain. According to Murray and Olley (2002) luminescence dating relies on the build-up of electrons and associated energy within a mineral grain as a result of exposure to natural levels of ionising radiation from the surrounding environment (i.e. ^{232}Th, ^{238}U and ^{235}U and their daughters, and ^{40}K and ^{87}Rb as well as cosmic radiation). The radiation damage accumulates in a predictable manner and can be detected as a light or luminescence 'signal' when grains are exposed to white light or to temperatures of a few hundred degrees Celsius (Murray and Olley 2002; Wallinga 2002). On exposure to heat or light the 'clock is zeroed' and the amount of luminescence or heat energy released by a mineral grain on exposure is proportional to time of exposure to environmental radiation following deposition. Hence, the age of deposition can be estimated.

The OSL dating technique has been suggested as relatively accurate in comparison to other dating techniques such as carbon dating, with few systematic errors for ages dating back as far as 350 000 years (Murray and Olley 2002). The OSL dating for the present study was performed by the Geo-luminescence Laboratory of the School of Geosciences, University of

Witwatersrand, South Africa. The Single Aliquot Regenerative dose (SAR) procedure was employed for measurement of OSL ages (Murray and Wintle 2003). The age of a particular mineral grain was determined as the ratio of the equivalent/environmental radiation dose (Gy) and the radiation dose rate ($Gy.ka^{-1}$), as indicated in the equation below (Evans and Cunningham 2013).

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

The equivalent dose method approximates the amount of radiation received by the grains in their natural environment. The dose rate is the annual flux of radiation delivered to grains in the natural environment. The error on the age of each sample combines estimates of systematic and experimental error associated with equivalent/environmental dose and dose rate measurements (Evans and Cunningham 2013).

The sediment samples from the present study were sent to iThemba laboratory in South Africa for estimation of the isotopic abundances of the parent radionuclides using gamma spectrometry (Evans and Cunningham 2013). From these isotopic abundances, the dose rates to quartz grains were calculated using the latest conversion factors. The cosmic radiation rates to the samples were determined as a function of the altitude, latitude/longitude, and depth each sample. From all of the above the total dose rate per sample was calculated and used to determine the approximate age of each sample. The OSL derived sedimentary deposit ages for the Baviaanskloof were reported by Evans and Cunningham (2013) as an age before the sample collection date, which was 2012. The dates were later converted to an age before present (BP), since this is standard practice for reporting sedimentary ages, particularly for carbon dating techniques (van der Plicht and Hogg 2006). This conversion of ages allowed the author to compare the results of the present study with the relevant South African literature on Holocene climate conditions, reported using radio-isotopic dating techniques.

4.2.2 Describing recent channel adjustment

Changes in channel morphology

Recent channel morphodynamics, indicating recent river adjustment processes, was investigated by analyzing a sequence of aerial photography for the study reach spanning the last 60 years. The aerial imagery was obtained from the South African National Geospatial Information Service (NGI) for the years 1956, 1960, 1972, 1986, 2003 and 2009. These dates spanned the youngest and oldest imagery for the study reach at the time of data analysis. Georectification was performed for the 1960, 1972 and 1986 imagery in ArcGIS (version 10.1) since these images had not been orthorectified and indicated the most obvious change in channel planform throughout the photographic series. Channel and floodplain form in the 1956 imagery was fairly similar to the 1960 imagery and the clarity of the 1956 imagery was relatively poor. Hence, the 1960 was included in the analysis. At least 50 'hard' control points were selected for image rectification including road junctions, buildings, distinctive mountain features (spurs and rock outcrops) and dams. The center of emergent canopy species that are slow growing (>100 years old), and could easily be matched between years, were also used as hard control points during rectification. The 'adjust' method of image transformation was applied as this gives more spatial accuracy on the local scale (ESRI ArcGIS Help, ArcMap version 10.1). The transformed images were then rectified using 'Nearest neighbour (for discrete data) resample type' and using the same projection as the 2009 imagery (Transverse Mercator, WGS1984, with a central meridian of 23 degrees). Scale differences between the various images were thus dealt with in this manner. Although there were seasonal differences between imagery of different years and inaccuracies brought about by local distortions during rectification, these factors did not present a major obstacle to the relative comparison of river geomorphology between different years.

Changes in channel planform over the 60 year period was quantitatively depicted by measuring a number of indices such as channel anabranching intensity and sinuosity of the thalweg channel between years in which considerable planform changes were obvious. Total sinuosity (length of all channel anabranches divided by reach length) has been used extensively in braided river research (Ashmore 2013). In this study sinuosity was measured along the length of the widest channel (Bridge 1993; Friend and Sinha 1993) to include reaches that were non-braided. A braiding index (B), which indicates the intensity of channel bifurcation (Howard et al. 1970; Ashmore 1991a; Thorne 1997) was measured by calculating the mean number of trunk channel divisions for each of the channel sub-reaches defined in this study. This method of calculating braiding intensity is commonly used

(Ashmore 2013) and has been described as the most accurate for depicting channel braiding (Bridge 1993).

The characterization of channel pattern between different years for the study reach was based upon the method described by Beechie et al. (2006), who distinguished four channel pattern types for forested mountain river catchments in the northwest USA. Beechie et al. (2006) based their classification on a range of major channel types that have been distinguished in classical literature (Leopold and Wolman 1957; Church 2002). The four channel pattern types are described below:

1) **Straight**: primarily single-thread channel with sinuosity <1.5
2) **Meandering**: primarily single thread with sinuosity >1.5
3) **Island braided/Wandering**: multiple channels, mainly separated by vegetated islands
4) **Braided**: multiple channels mainly separated by non-vegetated gravel bars

However this study included a 5th pattern type:

5) **Anabranching:** multiple channels that are separated by semi-permanent vegetated islands that are more than 3 times channel width at average discharge condition (Schumm 1985; Knighton and Nanson 1993).

Type 3 - island braided channels form a transitional channel type between meandering and braided channels, and are characterised by islands that are relatively permanent features, yet are smaller than the islands that define anabranching channels (Schumm 1985; Knighton and Nanson 1993).

Mapping the degree of channel degradation

The occurrence and degree of channel-floodplain degradation was described from field observations, including for example a lack of recent debris deposits on the floodplain; failing or under-cut banks; and nick points on the channel bed, and from flooding depth measurements during storm flow events at different channel sites. In the present study, a degraded channel was distinguished from an incised channel. Channel degradation is associated with deepening and widening of a channel by bed and bank erosion. Degradation may eventually lead to an incised channel, representing an eroded channel flanked by one or more abandoned floodplain surfaces (Schumm 1999; Schumm 2005).

Since river channels follow an evolutionary path from degrading to incised and then to channel recovery (Schumm 2005), three broad classes of channel-floodplain state were defined in the present study; 1) 'degrading': channel reaches that are in the initial stages of degradation, such that the floodplain is still inundated on an annual basis, but flooding frequency may be insufficient to maintain temporary, seasonal or permanent floodplain wetland conditions into the future; 2) 'degraded': when channel deepening has resulted in a considerable decline in floodplain inundation frequency such that the floodplain wetland ecosystem has been lost. In South Africa, a flooding frequency sufficient to inundate an area for more than 6 weeks of the year is necessary for the existence of at least, a temporary floodplain wetland (DWAF 2005); 3) 'incised': when the present-day channel is confined within an abandoned floodplain surface inundated only by rare, extreme events. The first two classes of degradation were mapped in this study as an indication of the extent of present-day active degradation processes. To map the degrading and degraded classes, a total of 86 channel cross-sectional morphology surveys were conducted at approximately 300 to 1 000 m intervals along the trunk stream (Figure 4.2). Due to time constraints an approximate method was used to record bankfull and degradation width and depth at just below 10% of the channel survey sites. The method involved stretching a rope across the channel and using a staff to measure channel depth. Figure 4.3 illustrates the general method used to distinguish bankfull width and depth from degraded channel width and depth. It was not uncommon to encounter channel banks of unequal height where the trunk channel has eroded through alluvial fan deposits on either the left or right side of the floodplain ('Heightened bank', Figure 4.3). Bankfull depth was therefore recorded from the bank with the lowest bank height to the present-day (2011-2012) channel thalweg. In such cases the channel reach was classified as degraded if bank height of the lowest bank was deep enough to prevent flooding inundation during annual or inter-annual flood events.

In some cases active channel banks were difficult to distinguish due to the complex nature of channel morphology. In this case the elevation of the tallest channel bar was used as a proxy for bankfull water levels (Copeland et al. 2000).

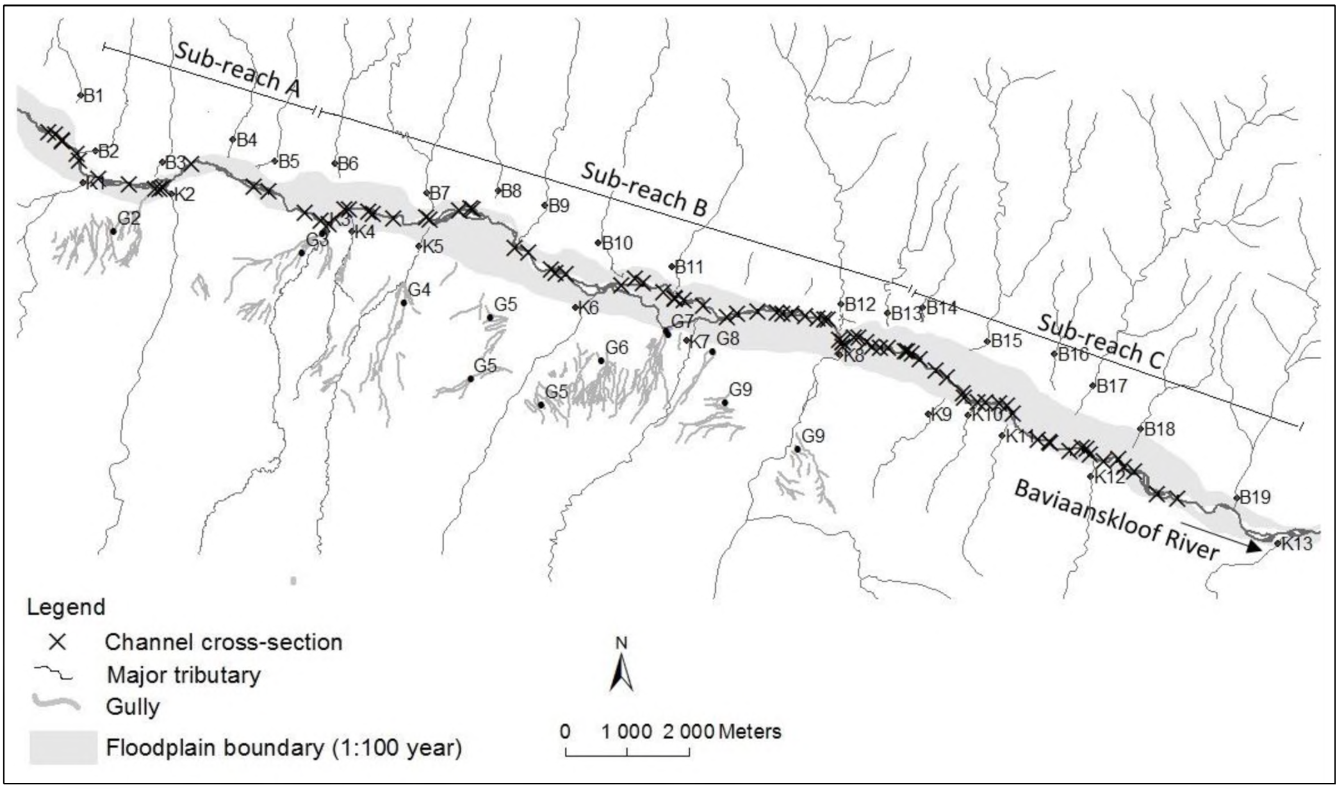


Figure 4.2: The study reach indicating the extent of sub-reaches A-C and the location of surveyed channel cross sections. Northern and southern tributaries are labelled B1-B19 and K1-13 respectively; hillslope gullies are labelled as G1-9.

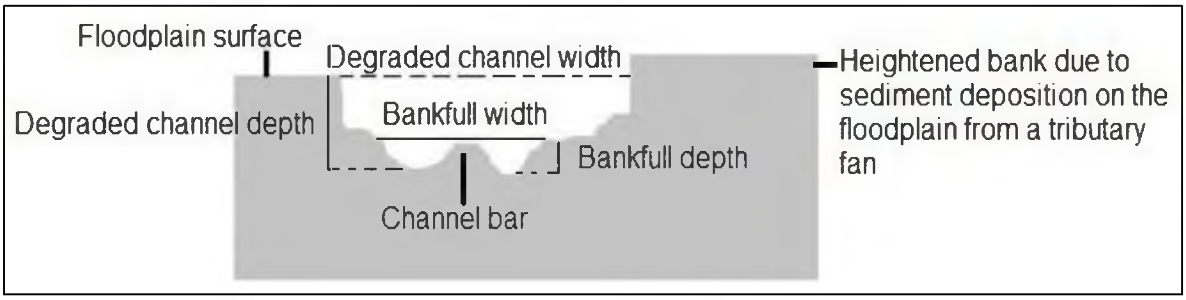


Figure 4.3: Schematic diagram illustrating the method used to measure bankfull and degraded channel width and depth (adapted from Beechie et al. 2008: 788).

To assist identification and mapping of channel degradation levels, flooding depth was measured at 10 sites along a ~2 km stretch of the study reach during a flood event. The particular flood event resulted in floodplain inundation along a number of relatively shallow channel reaches but not along deeply eroded channel reaches and was therefore assumed to be a small to moderate sized flood event. Flooding depth was measured as height from channel thalweg at the 10 sites along a relatively degraded reach. Measurements were conducted for relatively wide and narrow channel sites to account for the influence of channel geometry on flooding depth. This exercise provided a basis upon which to classify channel degradation along the study reach by assuming that channel reaches with similar channel geometry to those at which flooding depth was measured, were of the same degradation class identified at the measured sites.

Rates of channel adjustment

Channel erosion monitoring was conducted over a 2.5-yr period between January 2011 and August 2013 along the trunk stream to investigate whether channel degradation is still a dominant process, and whether the channel is beginning to recover. Erosion monitoring was conducted at two river sub-reaches separated by several kilometers, along the middle of the study reach. Each monitoring sub-reach ranged between 800 and 1000 m in length. The first sub-reach coded 'DEM' was positioned in the middle of the study reach where trunk channel degradation levels were relatively low and where the river was not influenced by major tributaries connecting directly to the trunk channel. The second sub-reach coded 'JEM' was situated several kilometers downstream of DEM and was selected based on relatively high levels of channel degradation. Sub-reach JEM was directly influenced by two major tributary streams and a large furrow that connect to the trunk channel from opposite sides of the floodplain. The latter sub-reach was also selected for river-floodplain rehabilitation by the WfWet programme.

Between six and seven fixed channel cross-section sites were surveyed intermittently during the 2.5-year period at sub-reaches DEM and JEM. The first survey was conducted in January 2011 with three more surveys conducted in November 2011, August 2012 and August 2013. Each cross section was surveyed at 1 m intervals between two fixed points (metal stakes) on the left bank and right bank of the active channel using a dumpy level and staff. Distance across the channel was indicated by stretching a piece of rope marked at 1 m intervals across the channel. Channel cross-section profiles were plotted for each of the three time intervals such that visual comparisons could be made and changes in channel width and bed elevation could be calculated. For the latter calculations, each time interval survey was made relative to the same fixed point, for example the left bank metal stake, such that deviations in mean bed elevation from the first channel survey could be calculated. The net change in channel bed elevation for each cross section over the entire monitoring period was also calculated, using the first survey as the reference. The channel morphological changes were analyzed for three sub-periods of the entire monitoring period, each period defined by different frequency and magnitude flood events. The results thus indicated whether on average the trunk channel bed had degraded or aggraded over the monitoring period. These changes could then be assessed with regards to the frequency and magnitude of floods that occurred during each sub-period analyzed.

The above visual analysis of channel morphodynamics was supplemented by oral accounts of the historical character of the river-floodplain from interviews with local landowners. In these interviews the respondents were asked a range of questions relating to the history of the river floodplain in terms of channel (main stream and tributaries) and floodplain morphological and hydrological characteristics, to indicate the nature of recent geomorphological adjustment.

4.3 Results

4.3.1 Evidence for pre-historic cut-and-fill cycles

Two floodplain terrace surfaces occurring tens to hundreds of meters away from the present-day active channel zone were clearly identified throughout the study reach (T1 and T2, Figure 4.4), indicating past phases of floodplain filling and cutting. Numerous abandoned channels were also encountered on the floodplain indicating that the trunk stream has historically been laterally dynamic. This dynamism has been somewhat controlled by the extension of alluvial fans across the floodplain which create topography and hence limit the extent to which the trunk can shift across the valley floor (e.g. JXA, GXA, ZXA, Figure 4.4).

The OSL age estimates determined for sediment samples collected from contemporary river erosion banks SKOSL and JOSL are indicated in Figure 4.5a and b. The ages are given in years before present (BP). Site SKOSL was directly adjacent to an alluvial fan that extends across the floodplain toward the trunk channel. The erosion bank at this site contained sandy-silty deposits with angular pebbles indicating the distal reach deposits of the alluvial fans. These alluvial fan units alternated with floodplain units, allowing age estimates of the differing fluvial environments (Figure 4.5a). Site JOSL was situated downstream of SKOSL and contained relatively high-energy palaeo-floodplain units indicated by sandy deposits alternating with relatively low-energy palaeo-floodplain wetland units, characterised by silty deposits rich in organic matter ranging from decomposed to relatively intact plant matter (Figure 4.5b).

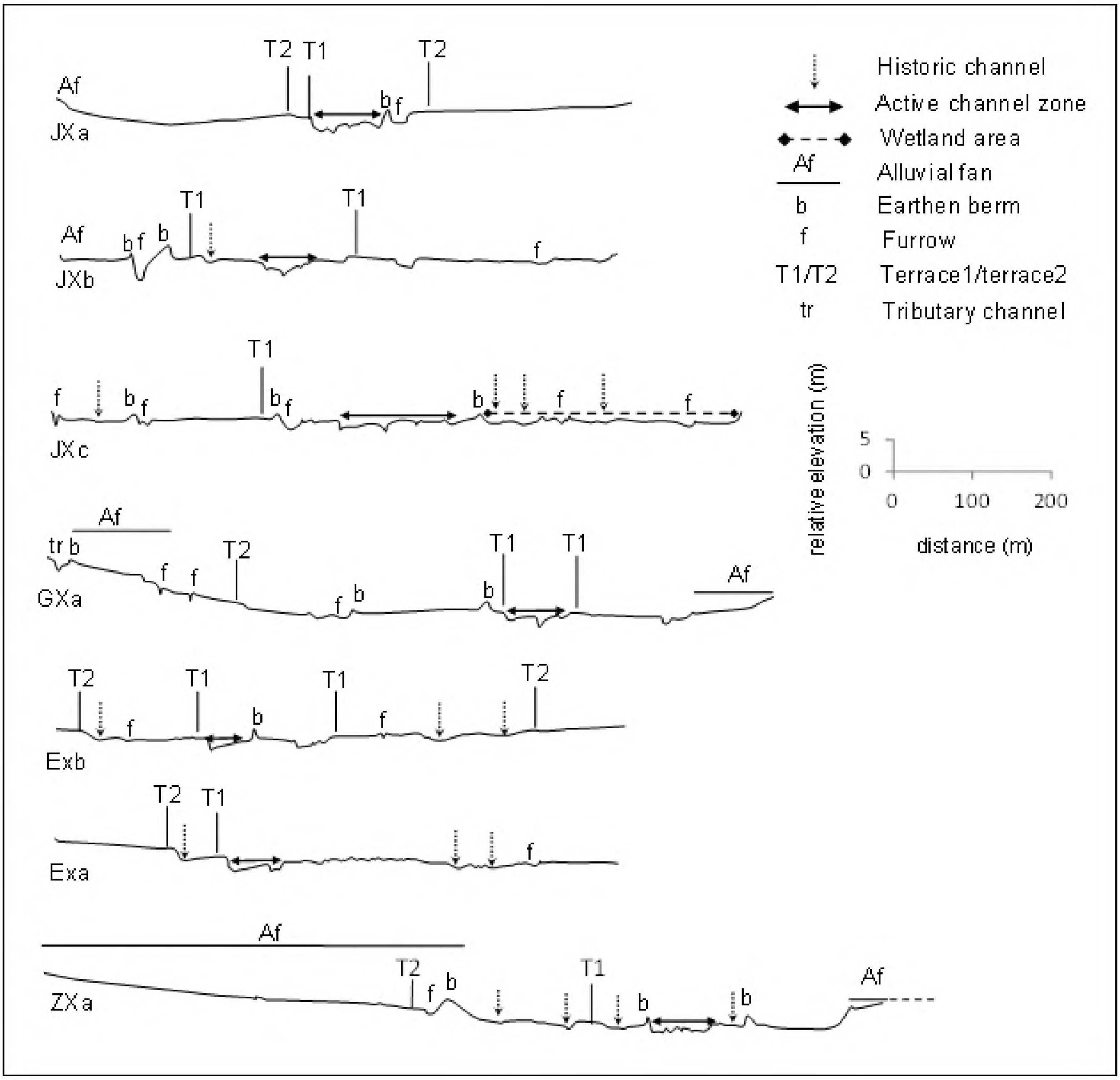


Figure 4.4: Floodplain cross-sectional morphology for several sites along the middle- to lower-reaches of the study reach indicating various human and geomorphological features.

The palaeo-floodplain sedimentary deposits at a depth of 0.4 m at site SKOSL (SKOSL3, Figure 4.5a) delivered an approximate age of 268 BP ± 70 years. This unit is underlain by palaeo-alluvial fan sedimentary deposits that delivered an approximate age of 2 288 BP ± 210 years (SKOSL2, Figure 4.5a). Both of these sedimentary units contained low-moderate abundance of iron mottling suggesting that at time of deposition the sediments were seasonally saturated. The sample taken at a depth of 1.75 m at site SKOSL contained organic matter and delivered an age of approximately 5 188 BP ± 370 years (SKOSL1, Figure 4.5a). The organic content of this unit suggests that conditions were wet enough to support the growth of hydrophytic vegetation. At site JOSL floodplain deposits at a depth of 0.17 m (JOSL3, Figure 4.5b) yielded an OSL date of approximately 178 BP ± 100 years. This date is similar to the sample taken near the top of the bank at site SKOSL. The palaeo-floodplain wetland deposits situated at a depth of 1.35 m at site JOSL delivered an approximate age of 1 658 BP ± 130 years. This unit was very dark in colour and contained undecomposed fragments of plant matter, suggesting high organic content and permanently saturated anaerobic floodplain conditions. The sample taken at 1.8 m depth at site JOSL represented a palaeo-floodplain wetland unit and unexpectedly delivered a younger age than overlying sediment deposits, dating approximately 648 BP ± 50 years (JOSL1, Figure 4.5b).

The anomaly of a young age for the sample taken at 1.8 m depth at site JOSL could be associated with several factors including, sampling error or environmental factors that cause mixing of young and old sediments, or partial bleaching of sediments which erases some of the luminescence signal. Partial bleaching of mineral grains associated with the underground peat fire that occurred in the floodplain during the 1960s is suggested to have been unlikely (M Evans, pers. comm., 2013). The photo in Figure 4.5b shows long root systems that have been exposed by bank erosion. It is possible that relatively young sedimentary material situated near the top of the erosion bank moved downwards along an abandoned root channel, mixing with older sedimentary material near the bottom of the erosion bank, where sample JOSL1 was removed (K Rowntree, pers. comm., July 2016). It is unlikely that material would move upwards along a root channel such that the older date in the middle of the profile (JOSL2, Figure 4.5b) should be accurate (K Rowntree, pers. comm., July 2016).

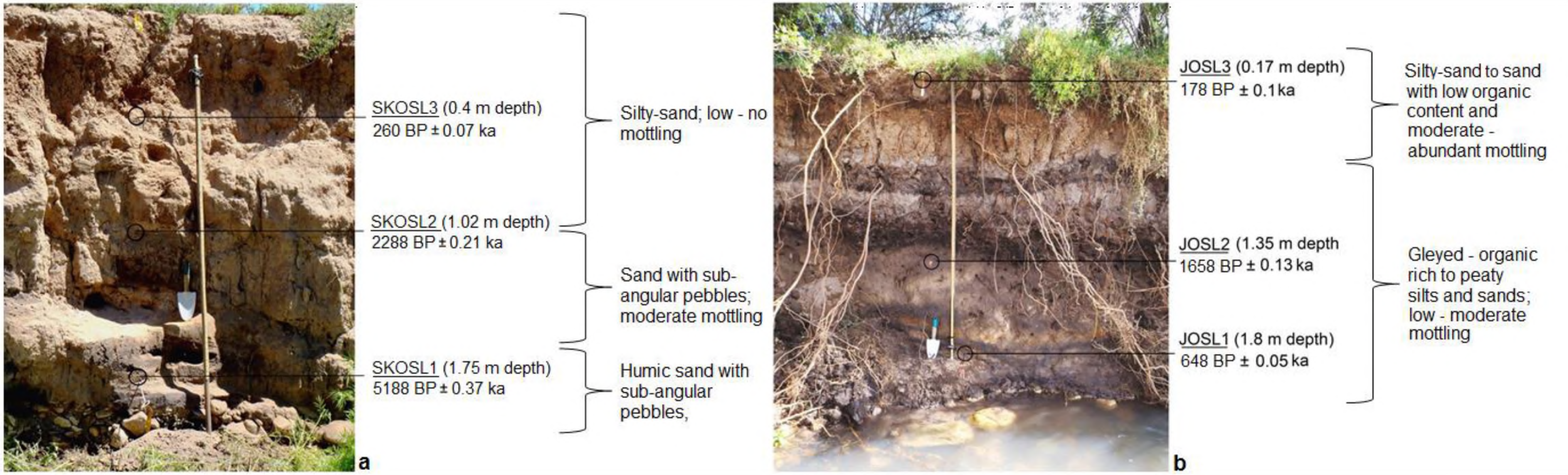


Figure 4.5: Optically Stimulated Luminescence (OSL) age estimates at erosion bank site 'SKOSL' (a) and 'JOSL' (b).

Using the OSL age estimates presented above, average sedimentation rates for the time periods represented between OSL dates at each site were calculated (Table 4.1). Sedimentation rates for the most recently deposited materials ('youngest', Table 4.1) at each site were calculated using OSL age estimates for the shallow-most OSL sediment sample, and estimated time of cessation of floodplain inundation due to channel incision at the sites. The timing of cessation of frequent floodplain inundation was estimated to be at the year 1990, thus this date was used to calculate the depositional period of the youngest sediment deposits at sites SKOSL and JOSL. Overall, calculated average sedimentation rates for the two sites indicated a gradual decline in sedimentation rate with age of sedimentary deposits. The youngest sediment deposits at site SKOSL yielded the highest average sedimentation rate of ~1.3 $mm.yr^{-1}$ ('SKOSL3 to top of bank', Table 4.1), with average sedimentation rates declining to ~0.31 $mm.yr^{-1}$ for middle-aged sediment deposits at this site ('SKOSL2 to SKOSL3', Table 4.1). Site JOSL yielded very similar average sedimentation rates for the youngest and middle-aged sediment deposits, calculated at ~0.78 $mm.yr^{-1}$ ('JOSL3 to top of bank', Table 4.1) and 0.8 $mm.yr^{-1}$ ('JOSL2 to JOSL3', Table 4.1) respectively. The oldest sedimentary deposits at site SKOSL yielded the lowest average sedimentation rate of ~0.25 $mm.yr^{-1}$. The average sedimentation rate for the oldest deposits at site JOSL was not calculated due to the anomalous young age delivered for the bottom-most sample JOSL1.

Table 4.1: Average sedimentation rates for deposits occurring at different depths of channel erosion bank sites SKOSL and JOSL, based on OSL age estimates.

Sample code	**Age (relative)**	**Thickness of unit (mm)**	**Depositional period of unit (years)**	**Average sedimentation rate ($mm.yr^{-1}$)**
SKOSL3 to top of bank	Youngest	400	308	1.3
SKOSL2 to SKOSL3	Middle	620	2 028	0.31
JOSL3 to top of bank	Youngest	170	218	0.78
JOSL2 to JOSL3	Middle	1180	1 480	0.80
SKOSL1 to SKOSL2	Oldest	730	2 900	0.25

The wetland units identified at sites SKOSL and JOSL were not restricted to these sites. Hydromorphic (wetland) soil horizons were encountered at different depths within channel erosion banks along the study reach (Plate 4.1). The varying abundance of mottling of the palaeo-wetland soils suggests temporal variations in degree of wetness of the floodplain historically. The presence of light grey to gleyed soils (Chromas <1) indicated the existence of permanent wetland areas (Plate 4.1a), and the presence of soils with abundant red-orange mottling within a matrix of low chromas of <2 suggested previous seasonal wetland areas (Plate 4.1b). These different hydromorphic soils were encountered at varying locations throughout the study reach at varying depths. For example, along the middle of the study reach relatively thin (<0.5 m deep) organic rich to peaty layers alternate with highly mottled sandy-silty layers, suggesting temporal variations between permanent and seasonal floodplain wetland conditions. Local landowners state that in the past (a few decades ago) the floodplain was inundated more frequently than at present due to the shallow nature of the trunk channel. Lateral (channel-floodplain) connectivity was thus much higher than at present such that flooding frequency and duration of soil saturation (>3 months of the year) was sufficient to sustain floodplain wetlands. At present, the existence of permanent floodplain wetlands is limited to a relatively small area on the southern side of the floodplain along the middle of the study reach. Several ash layers were encountered in erosion banks indicating organic rich palaeo-wetland sedimentary horizons. The ash layers were reported to be the remains of a subsurface peat fire that burned along these floodplain reaches during a drought period in the 1960s (P Kruger, pers. comm., n.d.).

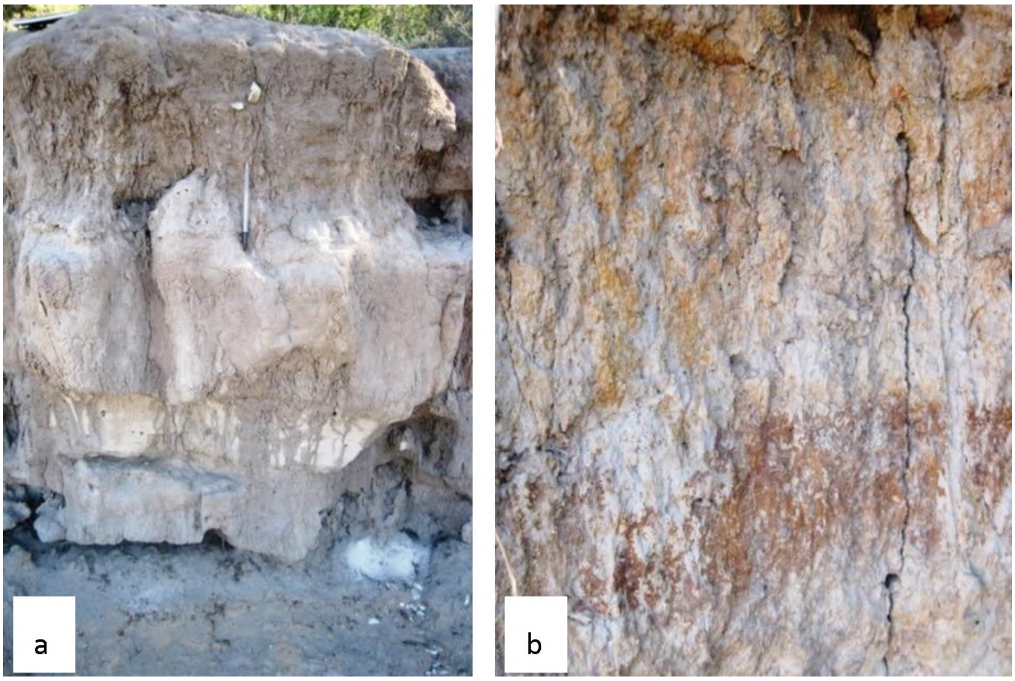


Plate 4.1: Examples of hydromorphic soils encountered along the study reach; a channel erosion bank with gleyed soils of chroma <1 toward the middle of the profile, and grey-brown soils of chroma <2 toward the top of the profile (a); low chroma soils (<2) with abundant mottling in the upper 1 m of a channel erosion bank (b).

4.3.2 Recent river history

Oral histories of river-floodplain form

Interviews with local landowners provided an interesting account of the historical hydrological and geomorphological character of the river, floodplain, and surrounding tributary catchments as well as a description of general vegetation structure along the study reach (Table 4.2). One of the respondents had lived in the valley from birth such that the individual could re-count river-floodplain conditions during the 1950s, when they were in their early 20 years of age. This respondent therefore provided a more than 40 year account of changes in the general structure and hydrological characteristics of the Baviaanskloof River and floodplain. The information gained from the aforementioned account and several other oral histories, suggests that in the 1950s there was more water available in the valley, riparian and hillslope vegetation cover was higher, and the trunk channel flowed regularly and for longer periods of time than in recent years (Table 4.2). The channel was reported to be much narrower (±15 m wide) than at present-day (on average >40 m wide), and there were more channel divisions, particularly along the middle of the study reach (sub-reach B). Lateral connectivity between the trunk channel and floodplain was reported to be much higher in the past. These hydrological and geomorphological conditions were conducive to the existence of permanent to seasonal floodplain wetlands, which reportedly contained numerous permanent springs and the reed, *Phragmites australis* commonly occurs in seasonal to permanent wetland environments in South Africa. The aforementioned conditions are at present largely absent from the study reach since floodplain inundation is less frequent.

Table 4.2: A summary of the local-landowner narrative on present-day (2013) versus pre-degradation (1950s and 1960s) characteristics of the Baviaanskloof river and floodplain.

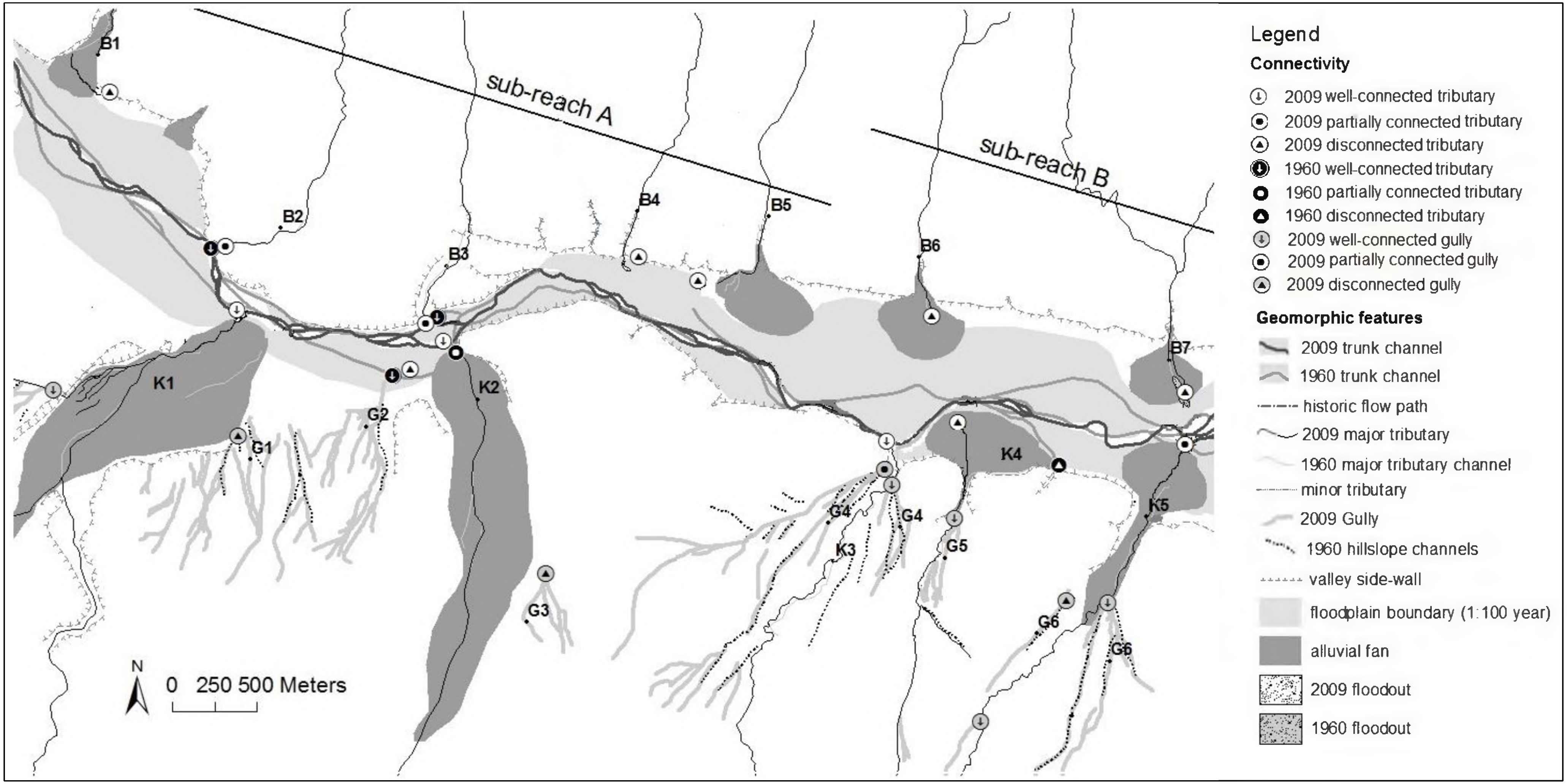
River-floodplain character	**Historical (1950s – 1960s)**	**Present-day (2013)**
Flow regime	River flowed almost all year round	Flows once or twice a year
Channel morphology	Multiple, narrow (on average ±15 m wide) channels dividing flow	Mostly wide (on average >40 m), 'single' channel (braided channel)
Floodplain character	Fine sediment accumulation; seasonal to permanent floodplain wetlands and floodplain springs	Limited (<1 ha) seasonal-permanent wetland exists; no springs; isolated pockets of sediment accretion
Impacts of floods	Channel avulsions in places; extensive floodplain inundation; large floods would remove stands of trees or reeds	Channel widening, deepening; limited inundation; undermining of bank vegetation
Catchment and riparian vegetation	Denser hillslope and riparian vegetation and greener in appearance	Vegetation less dense and not as green

Flood events in the 1970s and 1980s were reported to have driven channel widening and deepening, along with reduction of a once multi-thread channel to a single-thread channel along many reaches. Channel adjustment was particularly noticeable along the middle of the study reach where permanent-seasonal wetlands once occurred. A local farmer noted that despite the regular occurrence of small to moderate flood events, a particularly large flood in 1984 initiated deepening of the trunk channel by about 2 m in a single event. The drop in local water table resulting from channel deepening resulted in uncharacteristic drying of human made drains in the floodplain. According to the local farmer channel degradation and drying of the floodplain continued at a relatively rapid rate between 1984 and 1996. Large floods reported to have occurred in the 1960s, 1980s and 1990s were noted to be powerful enough to remove large stands of riparian vegetation, including reeds (*Phragmites australis*), trees (dominated by tree *Vachellia karroo*, formerly *Acacia karoo)* and various shrubs. A few respondents noted that riparian woody species density is slowly recovering (during 2012/2013) to a similar density that existed prior to the damaging flood events of the 1980s and 1990s.

Visual evidence for recent channel adjustment

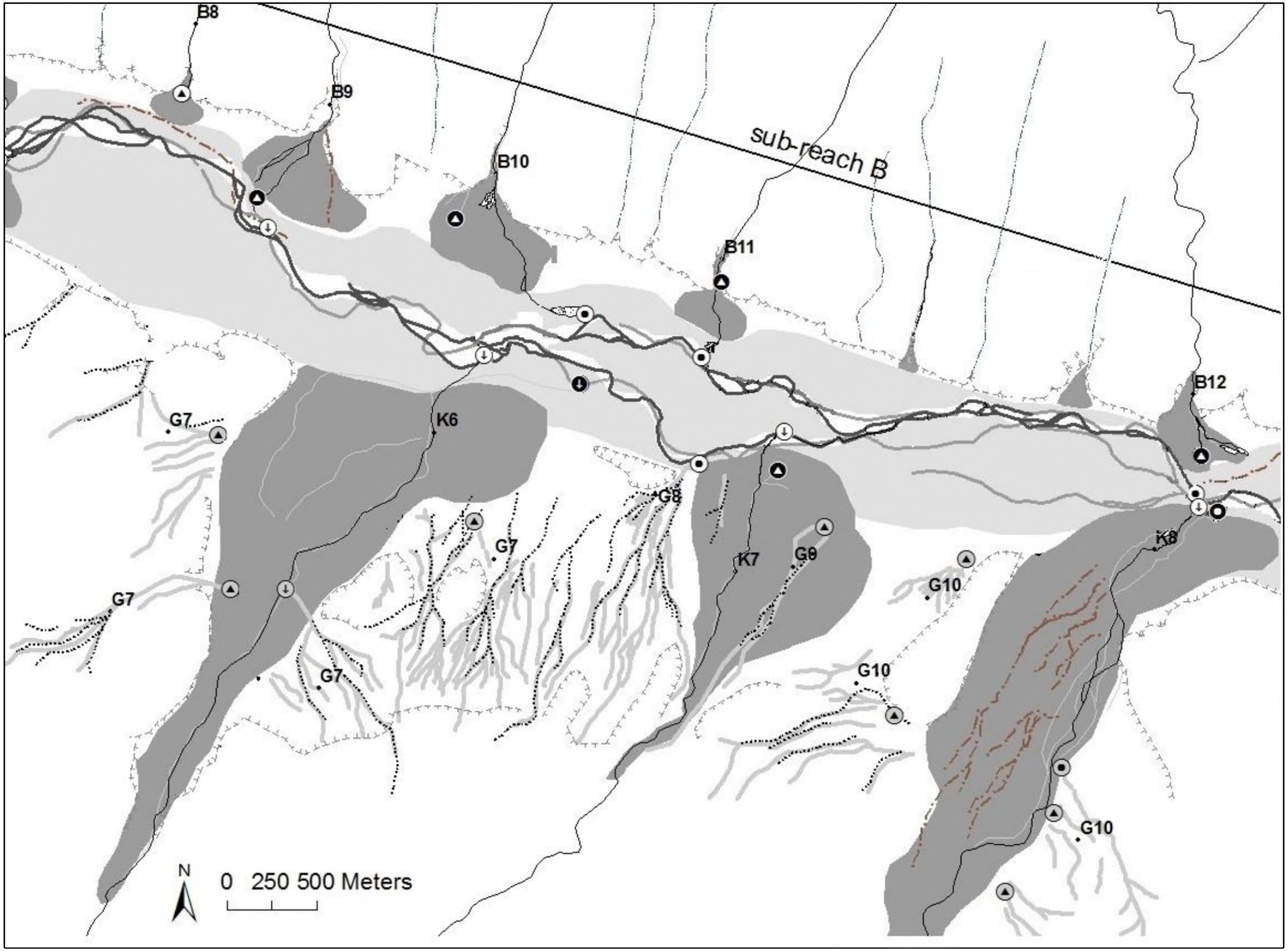
It is clear from historical aerial imagery that the trunk channel and several major tributary streams were morphologically dynamic between 1960 and 2009 (approximately 50-year period), including changes in channel pattern and width and avulsions (Figure 4.6a-c). These changes were accompanied in some cases by changes in tributary-trunk stream connectivity. Trunk channel and tributary stream avulsions occurred for all sub-reaches of the study reach between 1960 and 2009. The degree of connectivity of several tributaries also changed over the same period. For example, B2 and B3 indicated a decrease in connectivity over the period (Figure 4.6a), whilst tributaries K2 and B9 (Figure 4.6a) B10, B11, B12, K7, K8 (Figure 4.6b), K10 and K13 (Figure 4.6c) increased in connectivity with the trunk stream over the period. Tributary-trunk connectivity therefore increased in general between 1960 and 2009. Overall the trunk channel morphed from a mixed single-thread to anabranching style, to a mixed braided to anabranching-braided style. In some areas the channel clearly morphed from a multi-thread to a single-thread stream, for example in the vicinity of K5 (Figure 4.6a), and in the vicinity of K8 and B12 (Figure 4.6b and c). The aerial photographic analysis also indicated the development of an extensive gully network between 1960 and 2009 on the southern foothills of the study reach. Many of these system became partially or well-connected to the trunk stream over the period.

Considerable channel widening also occurred between 1960 and 2009. In 1960 average trunk channel width was 29 m increasing to 45 m in 2009 (Figure 4.7). The highest proportion of channel widening occurred between 1960 and 1986. By 1986 the trunk had widened by more than 200% for sub-reaches A and B ('A' and 'B', Figure 4.7) and by 141% for sub-reach C ('C', Figure 4.7). However, by 2009 the trunk channel had contracted by more than 40% for all sub-reaches.



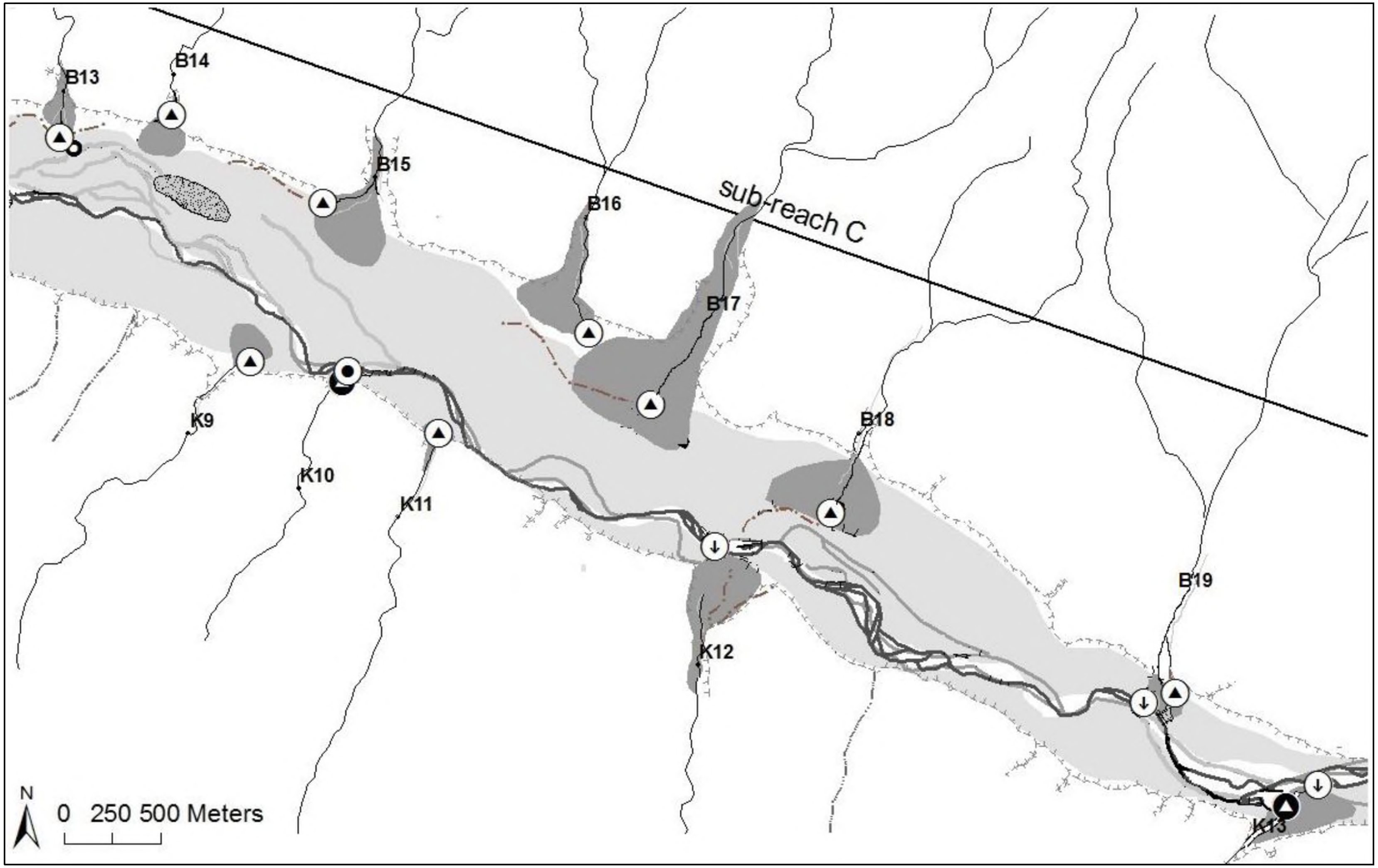
sub-reach A
sub-reach B
B1
B2
B3
B4
B5
B6
B7
K1
K2
K3
K4
K5
G1
G2
G3
G4
G4
G5
G6
G6
N
0 250 500 Meters
Legend
Connectivity
2009 well-connected tributary
2009 partially connected tributary
2009 disconnected tributary
1960 well-connected tributary
1960 partially connected tributary
1960 disconnected tributary
2009 well-connected gully
2009 partially connected gully
2009 disconnected gully
Geomorphic features
2009 trunk channel
1960 trunk channel
historic flow path
2009 major tributary
1960 major tributary channel
minor tributary
2009 Gully
1960 hillslope channels
valley side-wall
floodplain boundary (1:100 year)
alluvial fan
2009 floodout
1960 floodout

(a)



B8
B9
B10
sub-reach B
B11
B12
G7
K6
G8
K7
G9
G10
K8
N
0 250 500 Meters

(b)



(c)

Figure 4.6: Changes in channel planform and tributary-trunk connectivity for the Baviaanskloof River and tributary stream for the upper (a), middle (b), and lower (c) parts of the study reach between 1960 and 2009. Trunk channel flow is from north-west to south-east.

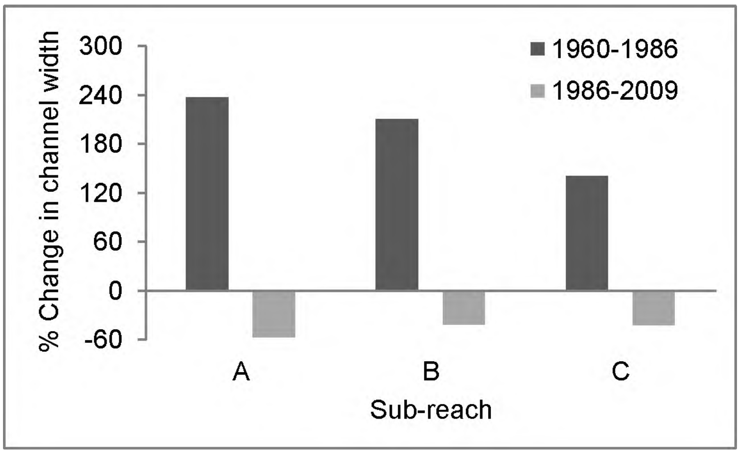


Figure 4.7: Changes in channel width for sub-reaches A-C between 1960 and 1986 and between 1986 and 2009.

Despite considerable channel widening and lateral dynamism of the trunk channel between 1960 and 2009, the channel kept a remarkably uniform sinuosity of between 1.1 and 1.2 for all sub-reaches (Table 4.3). The braiding intensity (average number anabranches) also remained relatively uniform over the ~50 year period (Table 4.3). Anabranching intensity was lowest for the 1986 channel, increasing again in 2009.

Table 4.3: Planform characteristics of the trunk channel for 1960, 1986 and 2009.

		Sinuosity			**Braiding intensity**			**Average channel width (m)**		
		Sub-reach								
Year	**Channel pattern**	**A**	**B**	**C**	**A**	**B**	**C**	**A**	**B**	**C**
1960	single-thread - anabranching	1.2	1.2	1.1	1.3	1.5	2	27	28	32
1986	mostly braided with some anabranching	1.2	1.2	1.2	1.2	1.4	1.3	91	87	77
2009	mostly braided with some anabranching	1.2	1.2	1.2	1.5	1.6	1.6	39	51	44

4.3.3 Patterns and extent of trunk and tributary stream degradation

The results of measured flooding depths during a flood event in 2012 indicate that on average, wide channels experience a lower flooding depth than narrow channel reaches (Table 4.4; Figure 4.8). The flood event was defined as a moderate sized event, since local landowners suggested that the event was larger than annual to biannual flood events but not large enough to cause floodplain wide inundation characteristic of large floods. The flooding depth for relatively wide channels measuring between 40-63 m in depth was ~1.7 m and for relatively narrow channels measuring between 12-36 m in width was ~2.1 m. The channel sites EM-J9 and EM-J7 appear to have an unusually large flooding depth given that these two sites have a larger channel width than upstream channel sites EM- J1 & EM-J2 (Table 4.4). This may be due to additional inflows of flood water from a large tributary which connects to the trunk stream just a few hundred meters upstream of EM- J9 and EM-J7. In most cases the flooding level associated with the moderate flood event was below the elevation of identified incised floodplain surfaces for each of the 10 channel sites. Using this flooding data, criteria for identifying channel degradation was defined as any channel bank above a height of 1.7 m and 2.1 m for relatively wide and narrow channel reaches respectively.

Table 4.4: Flood levels recorded for the 10 channel sites along the middle of the study reach during a moderate flood event in 2012.

Channel site code	Channel bed feature	Bankfull width (m)	Height of floodplain surface (m)	Flooding depth (m)
EM-J1	Pool	12	2.3	2.0
EM-J2	Pool	12	2.0	2.0
EM-J9	Riffle	25	3.0	2.3
EM-J7	pool	36	2.2	2.2
Average		**21**	**2.4**	**2.1**
EM-J10	Riffle	40	2.3	1.8
XS57	?	44	2.4	1.8
XS65	?	51	1.8	1.8
EM-J8	Riffle	56	2.2	1.8
XS61	Pool?	60	2.1	1.8
XS62	Pool?	63	2.1	1.4
Average		**52**	**2.2**	**1.7**

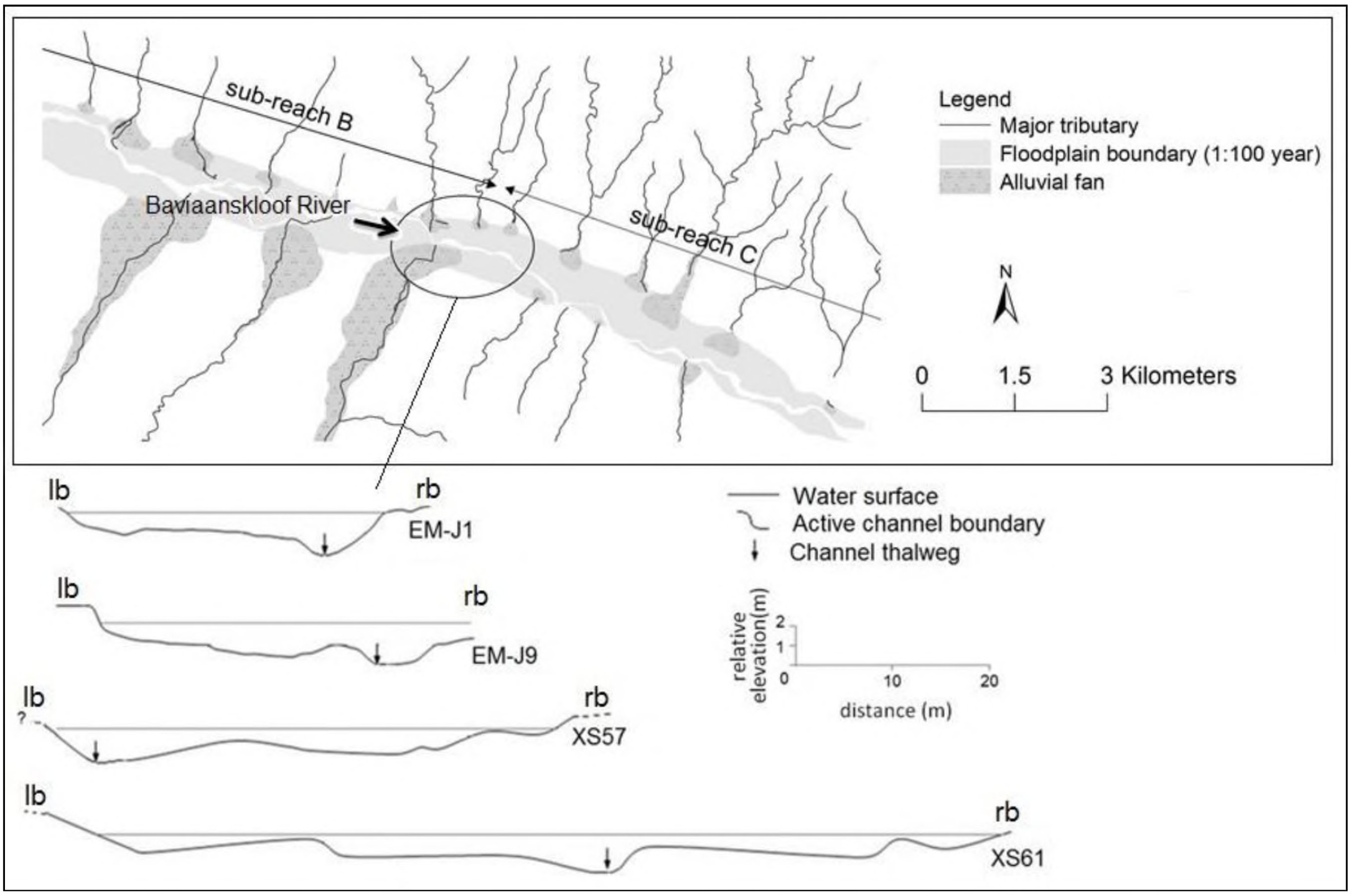


Figure 4.8: Examples of flooding levels for different channel morphologies along the middle of the study reach (circled) recorded for a moderate flood event. The profiles are plotted between active channel banks and the small arrows indicate the position of the channel thalweg. Flow direction of the Baviaanskloof River is indicated by the arrow.

Using the above results and channel cross-sectional surveys the pattern of trunk channel degradation was mapped along the study reach as illustrated in Figure 4.9. Trunk channel degradation is common throughout the study reach. Sub-reaches B and C were measured to have the highest levels of degradation with 87% and 83% respectively of total channel length. Sub-reach A has a lower proportion of degraded channel length as 68% of the trunk channel along this reach is degrading-degraded. Degradation of the floodplain by trunk channel erosion appears to have progressed over a relatively short time span of ~30 years, according to oral histories presented in section 4.3.2. Many degraded and degrading channel reaches had failing channel banks (Plate 4.2a and b) indicating that channel deepening has been accompanied by active channel widening. Along several reaches the channel had degraded to a paleao-gravel layer which appears to provide armouring against further channel deepening and widening (Plate 4.3a and b).

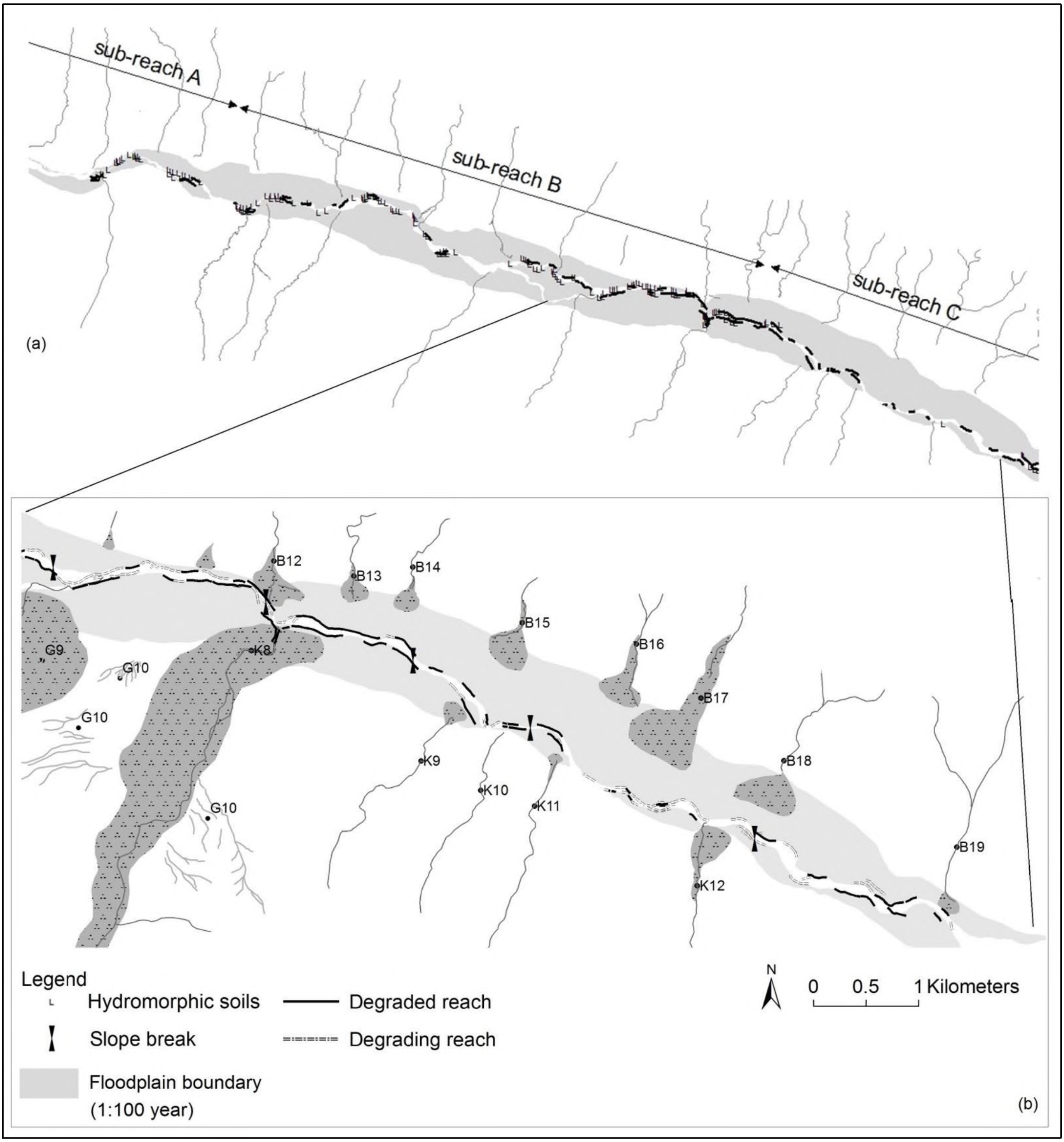


Figure 4.9: The distribution of hydromorphic soils in channel erosion banks along the study reach (a), showing degrading and degraded channel reaches (b).

Plate 4.2: Examples of bank failure (a) and undercutting (b) commonly observed throughout the study reach.

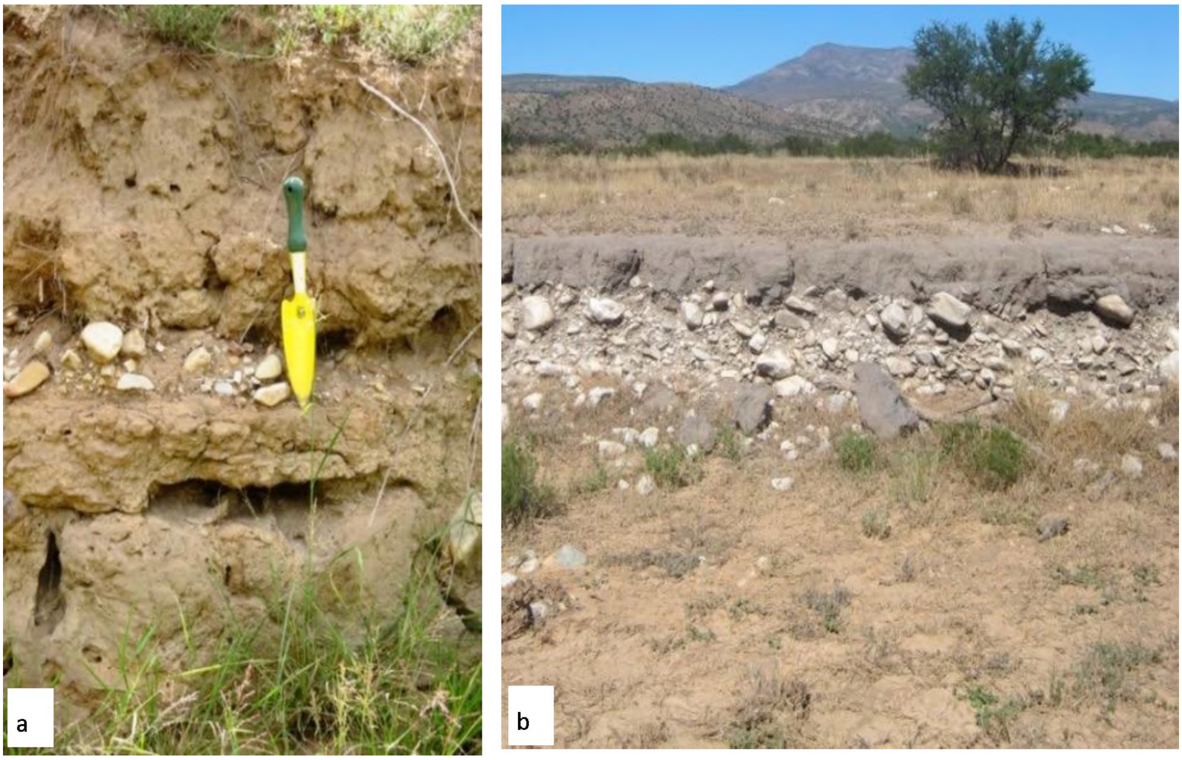


Plate 4.3: A thin lens of palaeo-channel gravel in an erosion bank through which the Baviaanksloof River has been able to erode (a); a relatively thick layer of palaeo-channel deposits in a channel erosion bank which is at present-day not degraded (b).

Most of the tributary alluvial fans along the study reach have been dissected by their respective tributary streams. Table 4.5 indicates the zone of fan dissection for some of the tributary streams investigated during the present study. Those tributaries that were connected to the trunk channel (K7, K8 and K12, Table 4.5) ranged from dissection across the entire fan surface to dissection along the lower-reaches of the fan surface (middle-distal reaches). The disconnected tributaries, representing those that at present do not deliver sediment or surface flows to the trunk channel were dissected along either the distal reaches or proximal-middle reaches (B12 and B15, Table 4.5). The larger fans that abut on the active channel zone were observed to have been recently toe-trimmed by the trunk channel. In some cases this has produced deeply incised erosion banks flanking the present-day channel (Plate 4.4).

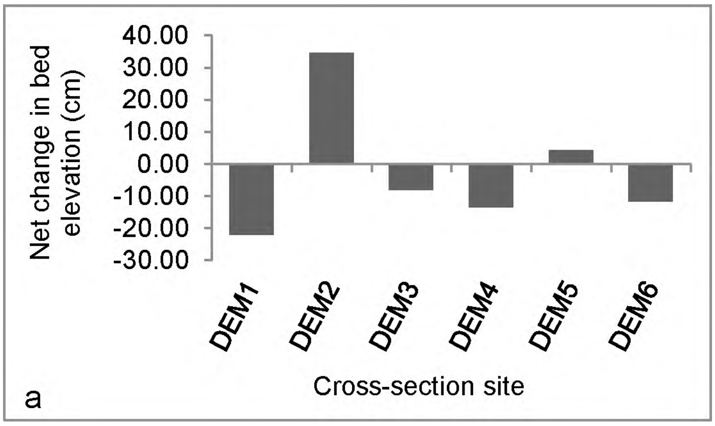
Table 4.5: Characteristics of tributary fan dissection for different tributary-trunk connectivity scenarios.

Tributary/ fan code	**Zone of fan dissection**	**Tributary-trunk connectivity**
K7	Proximal, middle, distal	Connected
K8	Middle-distal	Connected
K12	Middle-distal	Connected
B12	Distal	Disconnected
B15	Proximal-middle	Disconnected

Plate 4.4: A deeply eroded toe of an alluvial fan that impinges on the left bank of the trunk channel producing an incised bank of approximately 6 m deep.

4.3.4 Rates of trunk channel degradation

Figure 4.10a and b indicate net changes in elevation of the trunk channel bed at channel erosion monitoring sites DEM and JEM for the 2.5-yr monitoring period. Both sites indicated net channel bed aggradation or degradation (lowering) of no greater than 40 cm, with site JEM indicating slightly higher levels of bed degradation (average of 18 cm) over the monitoring period than site DEM (average of 14 cm degradation). Sub-reach DEM indicated a mostly degrading to stabilizing channel, as degradation occurred at four of the six channel sites, whilst only 2 sites, indicated aggrdation. Monitoring sub-reach JEM indicated higher levels of channel bed lowering in correspondence with the influence of a connecting furrow and large tributary that join the main channel just upstream of sites JEM4 to JEM8. The monitoring sites upstream of the connecting furrow and tributary stream indicated net channel bed aggradation over the monitoring period (Figure 4.10b, JEM1 to JEM3).



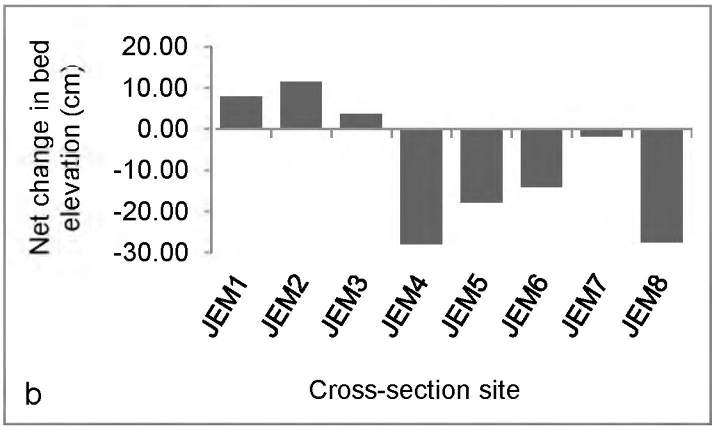


Figure 4.10: Net change in bed elevation for channel cross sections at site DEM (a) and JEM (b), between January 2011 and August 2013. The cross sections are arranged from upstream to downstream starting from sites DEM1 and JEM1.

Figure 4.11a and b indicate the average deviation of the trunk channel bed over three time periods recorded during the 2.5 year monitoring period to distinguish the influence of different magnitude-frequency flood events. During time period 1 (February 2011 to November 2011), four near bankfull events occurred, whilst during time period 2 (December 2011 to August 2012) a moderate flood and three small floods (over-bank flow) occurred. During time period 3 (September 2012 to August 2013), one near bankfull and one small flood event occurred. At sub-reach DEM (Figure 4.11a), the highest levels of change in channel bed elevation were experienced during time periods 2 and 3 consistent with the occurrence of several small floods and a moderate flood event. Relatively low levels of deviation occurred during time period 1 when a few near bankfull events occurred. In contrast, at sub-reach JEM (Figure 4.11b), the highest levels of bed degradation were not consistent with time period 2 when the largest sized flood event occurred. At both monitoring sub-reaches DEM and JEM, some channel sites switched between dominantly bed degradation to dominantly bed aggradation over the monitoring period (e.g. DEM2 and 6, Figure 4.11a; JEM2 and 7, Figure 4.11b).

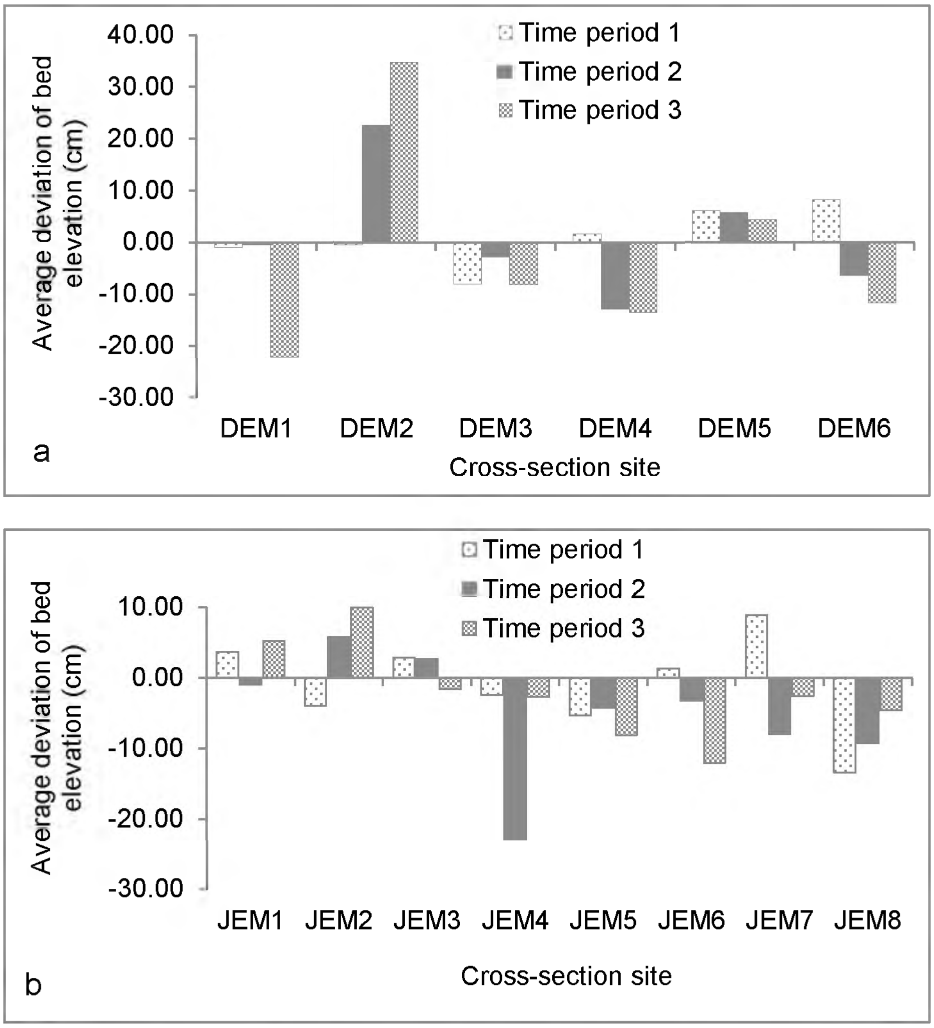


Figure 4.11: Average deviations of trunk channel bed elevation over time, from the first channel surveys conducted in January 2011. Deviations from the January 2011 survey were calculated for three time periods at monitoring sites DEM (a) and JEM (b). Time period 1 = February 2011 to November 2011; Time period 2 = December 2011 to August 2012; Time period 3 = September 2012 to August 2013.

4.4 Discussion

4.4.1 Evidence for Holocene fluvial adaptive cycles

The sedimentary units at two erosion banks along the middle of the study reach (SKOSL and JOSL) clearly indicated long-term (over thousands to hundreds of years) oscillation between relatively high-energy and low-energy fluvial environments evidenced by alternating relatively coarse and fine sediment deposits. These long-term oscillations represent long-term geomorphological adaptive cycles controlled by oscillations in regional climate (Dollar 1998; Norström et al. 2009). At erosion site SKOSL, alternating floodplain and alluvial fan sediment deposits match alternating relatively moist and dry climates identified for the Cape region of South Africa during the mid-late Holocene (Scott 1993; Meadows et al. 1996; Tyson et al. 2000; Meadows and Baxter 2001; Chase et al. 2012; Truc et al. 2013; Weldeab et al. 2013). The ages delivered from alluvial fan deposits at site SKOSL dated approximately 5 188 and 2 288 BP correspond with relatively moist climatic periods identified for the Cape region of South Africa (Chase et al. 2012). The upper-most palaeo-floodplain sedimentary units at sites SKOSL and JOSL dating approximately 270 BP and 178 BP respectively, correspond with the timing of the later-part of the Little Ice Age (LIA) identified for southern Africa, between 650-150 BP (Tyson and Lindsay 1992; Tyson et al. 2000). Conditions during the LIA are suggested to have been relatively cool, with relatively moist or dry conditions depending on location along the east-west rainfall seasonality gradient (Meadows et al. 1996; Tyson et al. 2000). The Baviaanskloof is located within the transitional zone between the eastern summer rainfall zone and the western Mediterranean climatic zone of South Africa, making it difficult to surmise the climatic conditions during the LIA for the area. The preference of a fine-grained floodplain environment rather than alluvial fan expansion and coarse sediment deposition during the latter climatic period, suggests that conditions were relatively moist with low-magnitude, high-frequency rainfall events promoting fine sediment delivery and floodplain accretion (Lane et al. 2008).

The organic rich to peaty sediment layers found within the floodplain sedimentary unit at JOSL indicate a high groundwater table and anaerobic conditions (Kirchner et al. 2015) during the late Holocene suggesting that the floodplain was permanently flooded in association with a relatively wet climate. The age of this palaeo-wetland deposit of ~1 700 BP closely fits a relatively warm climatic period identified by Tyson and Lindsay (1992) for

South Africa. This period would have been characterised by low-magnitude flood events allowing for the growth of hydrophytic vegetation, fine sediment accretion and peat formation. It is therefore suggested that during warm and moist climatic periods fluvial energy is diminished and floodplain accretion and wetland conditions dominate along the middle-reaches of the Baviaanskloof. Alternatively, during cool and dry climatic periods, fluvial energy in general increases along with catchment erosion and coarse sediment delivery to the floodplain. These conditions are most likely initiated by a switch to high-magnitude, low-frequency storm and associated flood events. During these periods, coarse sediment delivery to the valley floor and alluvial fan progradation would be relatively high, followed by channel switching and channel degradation associated with heightened storm discharges and breaching of stream power thresholds of erosion.

The present-day system indicates similar traits to that described above, such that delivery of coarse sediment to the valley floor evidenced by fan channel switching in recent years has been followed by breaching of erosional thresholds and channel degradation. It is questionable however, whether the incisional nature of present-day tributaries and the trunk stream channel has been solely driven by a switch in climate regime given the short-time period over which these changes occurred.

The average sedimentation rates calculated for mid-late Holocene sedimentary deposits at the two erosion banks were relatively low ranging between 0.25-1.3 $mm.yr^{-1}$. The average sedimentation rates calculated for contemporary deposits dated for the last 200 to 300 years at the alluvial fan site were four times higher than calculated for underlying mid-late Holocene deposits at the same site. This contemporary sedimentation rate was also two times higher than the sedimentation rate calculated for corresponding contemporary deposits at floodplain site JOSL. These results suggest that in recent years, alluvial fan sedimentation rates have been heightened relative to pre-historic periods. Heightened sedimentation may be linked to human land-use activities in the catchment over the last ~200 years, which have increased sediment delivery to the channel network. This finding is not uncommon for river catchments that have been influenced by European settlement around the world (Brierley et al. 1999; Kasai et al. 2005; Fryirs and Gore 2013; Kirchner et al. 2015). However, the increased sedimentation rate experienced on the alluvial fan at site SKOSL does not appear to have translated to heightened floodplain sedimentation rates in the last 200-300 years for the study reach, most probably because of the buffering role providing by multiple alluvial fans along this reach. It is difficult to determine the extent to which alluvial fans have buffered the river and floodplain against the influence of human land-use activities over the last few centuaries in the catchment, given the limited geo-chronological exercise (only two sites dated) that was undertaken in this study.

It is apparent however from the sedimentary evidence and OSL dating results of this study, that the Baviaanskloof River and surrounding tributaries have undergone multiple phases of cutting (degradation) and channel-floodplain filling (aggradation), indicating that the landscape naturally experiences cut-and-fill geomorphological adaptive cycles. The switching between these phases is largely determined by degree of connectivity between hillslopes and channels, which in turn reflects climatic regime and vegetation cover on hillslopes (Chiverrell et al. 2009). The nature of sedimentary fill inherited from the above discussed pre-historic fluvial adjustment cycles of erosion and deposition during the mid- to late-Holocene has influenced the degree to which the trunk stream has degraded along different reaches. In this regard, palaeogravel layers have increased the resistance of some channel reaches to morphological change. The inherited sedimentary structure of the floodplain has contributed to the complexity of channel response along the study reach (Brunsden 2001; Fryirs and Brierley 2009).

4.4.2 Natural or anthropogenically inducecd river degradation?

It is clear that in recent decades the study reach has indicated abrupt changes in hydrology, channel morphology and fluvial geomorphological process. It is suggested that widespread channel degradation along the study reach over the last ~30 years is unexpected given contemporary climatic regime and recent fluvial history. The contemporary climate is relatively warm on a global and regional scale due to a recent (last several years) shift toward strong El Niño and anthropogenic climate change (IPCC 2013). Thus it should be expected that floodplain accretion and decreased alluvial fan activity should be the overall dominant condition for the Baviaanskloof River at present and into the future, controlled by a long-term warm and wet climatic phase. However, a long-term fluvial adaptive cycle may be interjected by short-term erosional or depositional cycles that are driven by short-term climate variations, human land-use or a sudden tectonic event. The recent (~30 years ago) existence of seasonal to permanent floodplain wetlands along the study reach prior to channel degradation confirms the existence of a floodplain accretion phase. However, the overall degradation state of the Baviaanskloof River and tributary streams along the study reach suggests a recent breach in one or more thresholds of erosion (Piégay and Schumm 2003; Simon and Rinaldi 2006), resulting in a change in floodplain conditions. Channel degradation under natural conditions would have proceeded over a longer time span than the ~30 year period accounted in oral histories for the Baviaanskloof, suggesting that high-magnitude disturbing force/s have driven and compressed recent degradation (Simon and Rinaldi 2006). Increased floodplain sedimentation rate over the last ~200 years corresponds with the timing of European settlement and modern agricultural practices in the Baviaanskloof valley (Boshoff 2005). It is therefore suggested that human land-use activities over the last few decades has been an important factor driving recent channel degradation along the study reach. The reports by local landowners of rapid and deep channel degradation during flood events in the early 1980s to 1990s suggests that flood events have also been an important control on recent degradation. Channel monitoring surveys and observations suggest that levels of channel adjustment have slowed over the last few years and that the channel is beginning to recover.

The observed patterns of trenching of alluvial fans by tributary streams fit the findings of Bobbins (2011) in her study of alluvial fan morphology in the Baviaanskloof. Bobbins (2011) found that nearly all tributary fans along the study reach are entrenched in the distal-middle or proximal reaches. The widespread nature of fan trenching is suggested to be a result of two controls: a) historical toe trimming of fans by the trunk which would have shortened and steepened the fan profile, initiating stream degradation; b) trunk channel degradation which causes a lowering of the base-level of tributary streams (Harvey 2012) and hence channel degradation. The aforementioned controls on fan trenching are common in dryland settings (Harvey 2002b). Fan trenching along the proximal to medial reaches of presently disconnected tributaries may be a result of the breaching of geomorphological (slope) or stream power thresholds of erosion (Schumm 1979; Harvey 2012).

4.5 Conclusion

Geo-chronological investigation of floodplain and alluvial fan sedimentary units along the middle-reaches of the Baviaanskloof floodplain indicate that the river and surrounding tributary fans have undergone natural cut-and-fill geomorphological adaptive cycles spanning several hundred to thousands of years, driven by natural climate variations during the Holocene. These cut-and-fill phases were characterised by fluctuation between relatively high-energy and low-energy fluvial conditions. It is suggested that the high-energy phases would have been dominated by river incision and high levels of coarse sediment delivery to the floodplain resulting in alluvial fan expansion, during relatively cool and dry climatic periods (glacial periods). These fluvial incisional phases alternated with quieter conditions characterised by lower magnitude flow events, fine sediment deposition and the formation of floodplain wetland environments, during relatively warm and wet periods (interglacial periods). The trunk stream and surrounding tributary catchments recently entered a short-term (a few decades long) cutting phase which was approached as a widespread erosional threshold was breached. As a result, the river and surrounding tributary fans entered a phase of channel instability and morphological change analogous to the creative destruction phase of an adaptive geomorphological cycle depicted within the concept of Panarchy. However, channel response has not been uniform throughout the study reach reflecting the complex response of the river to perturbation. This chapter has indicated that the presence of palaeo-gravel layers exposed on the channel bed and banks of various degrading channel reaches provide relative armouring of the channel to erosion, increasing resistance to the effects of small to moderate flood events. The heightened rate of floodplain sedimentation over the last ~200-300 years suggests that human land-use activities have influenced the onset of recent channel adjustment through changes in water and sediment delivery to the channel network.

APPENDIX 4A: CHANNEL CROSS-SECTION DATA FOR THE STUDY REACH

Table 4.6: Bankfull width and depth measurements for classifying levels of channel degradation for the study reach

code	**bankfull depth (m)** used lowest bank height	**bankfull width (m)**	**incision depth (m)** from lowest bank where two incision banks present	**incision width (m)**	**bankfull w/d**	**incision w/d**	**I = incised**	**incision side**
XS3	1.45	27	2.155	40	18.6	18.6	I	both
XS5	1.01	40	2.19	50	39.6	22.8	I	both
XS7	1.02	14.5	?	?	14.2	?	incising	incising
XS8	1.05	42	2.2	?	40.0	?	I	left
XS9	0.845	20	?	?	23.6686		?	
XS10	1.71	42	1.8	?	24.6	?	I	right
XS13/C8	1.3	15.8	2.15	17.6			I	
XS14	1.585	80	2	90	50.5	45.0	I	both
XS15/C9	0.96	12	2	31.5			No	
XS17	1.555	35	2.23	50	22.5	22.4	I	both
XS18/C10	1.06	22.8	1.8	34			No	
XS20	1.66	50	2.32	54.5	30.1	23.5	I	both
C21	0.7	14.75	2.3	47.4			I	
XS21/C11	0.88	10.8	2.28	25.2			I	
XS22	1.22	41	1.765	?	33.6	?	I	left
XS26	?	?	2.2	16	?	?	I	right
XS27	?	?	2.5	12	?	?	I	right
XS28/C13	0.59	21.8	1.79	25.9			No	
XS35/C17	0.6	62	1.8	89.62			I	
XS38	1.42	55	?	?	38.7	?	INCISING-CUTBANK	both
XS39/C19	0.4	27.5	1.47	51.13			No	
XS40	0.88	112	2.135	116	127.3	54.3	I	both
XS41/C20	1.2	39.2	1.95	81			No	
XS42	1.12	22	2.395	62			I	both
XS43	1.425	96	?	?	67.4	?	incising?	both?
XS45/C22	0.5	24	1.25	95			No	
XS46	1.5	78	2.255	?	52.0	?	I	right/both ?
XS47	1.575	52	2.63	?	33.0	?	I	right
XS48	1.255	10	2.465	44.5	8.0	18.1	I	both
XS49	1.675	30	5	?	17.9	?	I	left
XS50/C23	0.7	17.3	6.1	26.5				
XS51	0.85	46	?	?	54.1	?	?	

code	bankfull depth (m) used lowest bank height	bankfull width (m)	incision depth (m) from lowest bank where two incision banks present	incision width (m)	bankfull w/d	incision w/d	I = incised	incision side
XS52							I	right
XS52A/C25	1.55	55	4.81	95			I	
XS53	2.23	49	3.64	110			I	
XS56	1.495	15	2.29	59	10.0	25.8	I	both
XS57	1.45	45.5	2.38	?	31.4		I	right/both ?
XS58	1.555	48	1.85	51	30.9	27.6	I	both
XS59	1.075	19	2.19	?	17.7	?	I	right/both ?
XS61	1.7	60	2.08	100	35.3	48.1	I	both
XS65	1.38	51	1.8	?	37.0	?	I	left/both?
XS66	1.235	57	?	?	46.2	?	no?	
XS68	1.525	58	?	?	38.0	?	incising	left
XS69/C30	0.93	21.2	1.85	55.5			No	
XS70	1	24.5	2.345	35	24.5	14.9	I	both
XS71	1.2	31	2.3	?	25.8		I	
XS72	1.645	33	3.015	?	20.1	?	I	left
XS73/C31	0.73	25	2.5	55.8			I	
XS74	1.72	48	2.19	49	27.9	22.4	I	both
XS76	1.73	47	2.3	?	27.2	?	I	rigth/both ?
XS77	1.98	11	3.565	?	5.6	?	I	left/both?
XS78	1.545	33	?	?	21.4	?	?	
XS82	1.73	42	2.035	?	24.3	?	I	rigth/both ?
XS84	1.1	87	?	?	79.1	?	no?	
XS85	?	?	2.035	59	?	29.0	I	both
XS86	1.395	47	1.91	?	33.7	?	I	left/both?
XS88	1.49	85	1.865	?	57.0	?	I	left/both?
XS89	1.295	62	1.4	87	47.9	62.1	I	both

CHAPTER 5: DRIVERS OF RECENT CHANNEL DYNAMICS AND GEOMORPHOLOGICAL SENSITIVITY

5.1 Introduction

For catchment management purposes it is often difficult to pin-down the cause of a particular river geomorphological response since: 1) a river response may persist long after an initial disturbance and may therefore be confused with recent channel response (Brunsden 2001; James and Lecce 2013); 2) rivers may experience sudden geomorphological change in the absence of extreme external events that force change, due to long-term (>10^2 years) adjustment and internal thresholds that are breached as the system evolves (Schumm 1973, Schumm 1979; Church 2002; Van De Wiel and Coulthard 2010); 3) the effect of disturbances at the local scale are influenced by landscape or catchment-scale long-term adjustment phases that either synergies or counteract processes at the local-scale (Phillips 1999; Ryan et al. 2007; Downs et al. 2013). For gravel-bed rivers, the return interval between phases of degradation and aggradation may be determined by degree of coarse sediment connectivity (Harvey 1997; Bravard 2010), which may be influenced by the interplay of floods and human land-use activities with internal geomorphological structure and thresholds.

The impact of European settlement on fluvial process and form has been widely studied across a range of river environments with a wealth of evidence for human induced channel degradation, planform change and hillslope gullying. Much of the research focus has been at the impacts of human land-use on channel-floodplain form in Mediterranean, British, North American and Australian River systems (Simon and Hupp 1987; Brooks and Brierley 1997; Simon and Rinaldi 2000; Surian and Rinaldi 2003; Simon and Rinaldi 2006; Hoyle et al. 2008). Channel incision and widening or narrowing along a trunk stream is a common response observed in these systems. Common land-use activities that induce the aforementioned channel morphodynamics include gravel-mining, stream flow channelization and dams (Simon 1992; Landon et al. 1998; Simon and Rinaldi 2000; Surian and Rinaldi 2003; Wishart et al. 2008; Zawiejska and Wyżga 2010; Comiti et al. 2011; Draut et al. 2011; Ziliani and Surian 2012), and removal of vegetation or afforestation within the surrounding catchment (Prosser and Slade 1994; Beguería et al. 2006; Hooke 2006; García-Ruiz et al. 2010).

Not many fluvial studies have investigated human and/or flooding impacts on channel behaviour within the context of sediment connectivity and river sensitivity. However there is growing interest in the investigation of the role of sediment connectivity in determining river sensitivity to human and climatic disturbances (Brierley et al. 1999; Harvey 2002a; Hooke 2003; Hooke 2006; Vanacker et al. 2005; Fryirs et al. 2007b; Callow and Smettem 2009; Chiverrell et al. 2009; Fryirs et al. 2009; Downs et al. 2013). Many of these studies have demonstrated how human land-use activities modify water and sediment connectivity and channel geometry (slope, width and depth), thereby altering fluvial energy by disturbing sediment supply relative to transport capacity. This disturbance often results in channel adjustment and instability. In most cases, human land-use activities increase water and sediment connectivity, making rivers increasingly sensitive to geomorphological change induced by flood events (Hoyle et al. 2008; Bravard 2010). However, in some cases human activities may not be the primary control on the initiation and pattern of degradation in catchments that have been occupied since European settlement (Rowntree et al. 2004).

The timing and nature of channel response to perturbations can be highly variable (Fryirs et al. 2009), depending on the internal sensitivity of different river reaches to change and the nature and magnitude of perturbations (Schumm 2005; Harvey 2007b; Hoyle et al. 2008; Fryirs et al. 2009; Downs et al. 2013). Several studies have indicated the resilience of rivers to human impacts such as little net channel morphological change (Brooks et al. 2003; Wishart et al. 2008) and long-time lags (several decades) between the onset of human activities and channel response (Fryirs et al. 2009; Kemp et al. 2015). This internal resilience is a result of the low degree of water and sediment connectivity (Brunsden and Thornes 1979; Brunsden 2001; Thomas 2001; Harvey 2007b), and a relatively low geomorphological propensity of different channel reaches to degradation- which is determined by the interplay between valley width, channel geometry (width and depth), closeness to slope thresholds and degree of channel boundary resistance (Brooks et al. 2003; Simon and Rinaldi 2006; Beechie et al. 2008; Fryirs et al. 2009; Zawiejska and Wyżga 2010). Fryirs et al. (2009) discuss controls on the variability of river sensitivity for the Hunter catchment in Australia, indicating that antecedent controls such as valley confinement and the nature of floodplain alluvium combined with patterns of water and sediment connectivity were strong controls on the relative sensitivity of different parts of the stream channel to morphological change.

Several studies in South Africa have investigated the impacts of human land-use and rainfall regime on sediment connectivity and river-floodplain process and form. In the semi-arid interior of South Africa changes in fine sediment sources and increased catchment sediment yields over the last few decades have been linked to the impacts of European settlement and increasing frequency of one-day rain events (Keay-Bright and Boardman 2007; Keay-Bright and Boardman 2009; Boardman et al. 2010; Foster et al. 2012; Mighall et al. 2012). In these studies the development of hillslope gullies or 'badlands' has been a key determinant of increased sediment connectivity and sediment yield for the dryland catchments investigated. Grenfell et al. (2012) indicated that episodic gully formation has been common throughout the Holocene in the semi-arid interior of South Africa, indicating that these fluvial features form naturally in dryland catchments and are not always linked to poor land-use management. Tooth et al. (2009) linked catchment and riparian vegetation removal and floodplain drainage to increased avulsion rates and fluvial erosion for a large floodplain wetland in the humid east of South Africa.

A number of studies have indicated the control of sediment buffers and barriers such as flood outs, alluvial fans and resistant lithology across the course of a river, on valley-bottom and floodplain wetland formation (Tooth et al. 2002; Grenfell et al. 2008; Grenfell et al. 2009a; McCarthy et al. 2011). The aforementioned studies have been important in highlighting the interplay between the long-term trajectory of incision in South Africa's rivers with local geological controls, such that wide and low-sloping valleys form along a river's course, reducing water and sediment connectivity, and promoting the formation of floodplain or valley-bottom wetlands. In South Africa there is still much room for investigation of the interplay between river-floodplain process, form and sensitivity to geomorphological change within the context of different controls on water and sediment connectivity. This kind of research is particularly important in dryland gravel-bed streams, which have not received much attention to date in South Africa and which are particularly sensitive to the impacts of high-magnitude flood events and human land-use activities that alter coarse sediment connectivity.

Recent degradation of the Baviaanskloof River along the upper-middle reaches of the floodplain has altered hydrological and sedimentological connectivity, thereby impacting on floodplain structure and functioning. At first glance river degradation appears to be linked to human-related land use activities such as floodplain agriculture and river engineering. However, critical hydrological and geomorphological controls involving slope and stream power thresholds associated with feedbacks between processes of erosion and deposition also could have formed an important control on recent river sensitivity (Schumm 1979; Church 2002).

This chapter aims to investigate the influence of human land-use activities and flooding regime on coarse sediment connectivity and associated geomorphological sensitivity of the Baviaanskloof River and immediate surrounding catchment over the last ~60 years.

To address the above aim the objectives are to:

1) Describe trends and patterns of flood-inducing rainfall events over the last 60-80 years for the study reach, using local daily rainfall data supported by landowner oral accounts of the relationship between rainfall magnitude-duration and the occurrence of floods of different sizes;
2) Describe the timing, nature and pattern of land-use and land-cover changes, as well as channel-floodplain engineering, for the study reach over the last 80-100 years using historic aerial photography and oral histories provided by local landowners.

The influence human land-use activities and flood-inducing rainfall events will be discussed using the information developed from the above two objectives, in relation to coarse sediment connectivity and geomorphological sensitivity.

5.2 Methods

5.2.1 Flood events and coarse sediment connectivity

The hydrological regime strongly controls sediment connectivity and thus the aim was to identify the pattern and timing of flow events that initiate bed load sediment transfer (connectivity). Given that there is no long term gauged flow data for the Baviaanskloof, a variety of information sources were used to broadly describe hydrological regime for the study reach, including:

1) Various published and unpublished conservation management and research reports relating to the hydrology and climate of the Baviaanskoof and the downstream Gamtoos River Valley.
2) Oral accounts of short (seasonal to inter-annual) and long-term (several years to decades) rainfall and oral histories of flooding characteristics provided by 10 landowners who had lived in the catchment for more than 10 years, and a former ecological manager of the area.
3) Personal observations of flow regime and characteristics of flood events during the 4-year period of field visits.

The main questions relating to hydrological regime, posed to the respondents (n=11) interviewed in the study were:

1) "Can you remember big floods or drought years?"
2) "How much rain needs to fall and for how long, in order to result in a flood event or high (near-bankfull) flows?"
3) "How much rainfall is required for tributary streams to flow and reach the river?"
4) "How long does it take the river to rise after a flood-inducing rainfall event and for how long does the river flow?"
5) "How long does it take the river flow to drop to below bankfull following a flood flow"?
6) "Does water always flow in the tributary streams and along the main river?"

Patterns and trends in small to moderate and large flood events over the last approximately 60 years were inferred from information obtained through oral histories and other secondary data sources. Small to moderate floods were grouped into one category as it was difficult to distinguish between the two types of events based on oral histories, given the highly variable nature of the local climate and the timing of flood-inducing rain events. It was assumed, however, that small to moderate floods occur more frequently than 1 in 10 years, since it was reported in a study by van der Burg (2008), that floods occur every few years with larger events every approximately 10 years. Large floods were classed as those events that cause widespread flooding of the valley floor and damage to infrastructure (e.g. roads, furrows, buildings), but recede relatively quickly (within a few weeks). Extreme floods were defined as those events that occur approximately every 50 to 100 years and result in flooding of the entire valley floor.

The data obtained from oral histories and other secondary sources was used to devise categories of flood-inducing rainfall for relatively dry versus wet antecedent climatic conditions. Dry antecedent conditions were defined as a preceding year or several years that were below the calculated average annual rainfall. Alternatively, wet antecedent conditions were defined as preceding years with above average annual rainfall. The information was used to plot and analyze trends in flood-inducing rainfall events over the last 60 years using two rainfall stations: 'Matjies' situated along the upper-reaches of the catchment about 8 km upstream of the study reach; and rainfall station 'Bavlulet' situated along the middle of the study reach. Rainfall station 'Matjies' was analyzed for the period 1950-2000 (when the data terminated) and rainfall station 'Bavlulet' was analyzed for the period 1950-2012.

Although the interviews with local people provided sufficient information to analyze rainfall data for the timing of flood events, the analysis only provided an approximation of flooding patterns and trends. There are several reasons for this:

1) It was difficult to capture the effects of rainfall intensity on flooding initiation. For example if rain is soft then a relatively long rainfall duration is required to induce a flood event and the amount required to induce flooding will vary according to antecedent conditions. Alternatively, if rainfall is hard much less rain falling over a short period would potentially induce a flood if antecedent conditions had been relatively wet. The rainfall data only provided daily event resolution making it difficult to determine the influence of rainfall magnitude-duration on flood event occurrence.
2) The influence of spatial variations in rainfall on the occurrence of floods could also not be captured from the rain data. The rainfall stations analysed were situated on the valley floor and thus did not account for flood-inducing snow and rain events that occur on mountain peaks surrounding the floodplain.

The rainfall dataset of Lynch (2004) was used for the above analyses. Lynch (2004) developed a raster database of daily, monthly and annual rainfall for the whole of southern Africa for the period 1900-2001. In the study by Lynch (2004), all available climatic data from appropriate government organizations such as the Agricultural Research Council of South Africa (ARC), the South African Weather Services (SWS), and landowners' daily rainfall records, were combined. The data was cleaned for observed faulty values (e.g. values that looked unnaturally high) and missing values were filled-in using several algorithms and regression techniques (e.g. Geographically Weighted Regression Technique). These methods made use of data from closest weather stations to interpolate the missing value/s in any one dataset (Lynch 2004). Daily rainfall data for the study reach was also obtained from the ARC and SWS, however the Lynch (2004) dataset was preferred for the period 1950-2001 since it had been carefully 'cleaned' for dubious values and therefore presented a fuller and more reliable dataset. Recent rainfall data obtained from the ARC for the period 2002-2012 was added to the Lynch (2004) dataset to provide a full record of rainfall for the study reach. Missing values in the ARC rainfall records were patched and obtained with permission from Glenday (2015). Glenday (2015) patched the data by working out a rainfall difference ratio between the two spatially closest stations during periods when both stations had data, and using the ratio to calculate an estimation of rainfall for a station that had missing data (J Glenday, pers. comm., November 2014).

A minor pebble tracing experiment was conducted to investigate coarse sediment movement during a small flood event that occurred in the field work period. Thirty pebble-sized stones were painted with yellow road paint and deployed at a riffle section at the middle of the study reach, during the peak of the small flood event. Only six pebbles were retrieved, one of which was lost between transport and storage at Rhodes University. The distance of transport of each of the pebbles was measured along the thalweg of the river channel, from the deployment site to the point of retrieval of the particular pebble. The bed feature on which a pebble was retrieved was noted. The size (length and breadth) of each pebble was measured following field work, in the laboratory.

5.2.2 Describing the nature and timing of human land-use impacts

The nature, pattern and timing of human land-use activities over the last 80-100 years for the study reach were described using information from interviews with 10 local landowners and a former catchment manager; from available documentation (e.g. conservation plans, research reports); and from visual analysis of digitized versions of 1: 50 000 topographic maps of the study area. This exercise included describing changes in types and intensities of agricultural activities, veld management (burning regimes) and river-floodplain engineering activities. River-floodplain engineering interventions were mapped in the field by recording the location of earthen berms, floodplain drains, and any other human-made features that were encountered during surveys and walks through the floodplain. This exercise was not systematic or intensive, mainly due to time constraints, and because digitized features were available from CD-NGI GIS shapefiles. There were, however, no shape files available for earthen berms and it was difficult to visibly distinguish these features on the aerial photography as they are a similar visual tone to that of the surrounding floodplain. Mapping changes in relative abundances of berms through time was therefore not possible. The results therefore underestimated the actual abundance of earthen berms throughout the floodplain but provided an idea of their relative influence on flood flows.

The above human land-use activities were related to the nature and timing of changes in channel planform and sediment connectivity, including tributary-trunk and hillslope-channel connectivity, in recent years. Rectified aerial imagery for the study reach was analyzed to identify the nature and timing of channel morphological changes, and changes in degree of connectivity of tributaries with the trunk stream. In the latter regard, tributaries were defined either as connected, if the tributary stream visually joined the trunk channel, or disconnected if the tributary stream did not reach the trunk channel.

The results of the above two activities were integrated and evaluated within the present literature on fluvial geomorphology and connectivity in relation to river sensitivity and dynamics. A conceptual model indicating the role of flood magnitude-frequency and human land-use activities in influencing coarse sediment connectivity and relative channel stability along the study reach was developed.

5.3 Results

5.3.1 Human influences on catchment and river-floodplain structure and sediment connectivity

Land management and land-cover changes

Table 5.1 summarizes the nature and timing of important land-use and land management changes that have influenced the vegetation structure and cover along the upper-middle reaches of the Baviaanskloof catchment since early European settlement. Major changes in land-use have included cultivation of the floodplain, a major shift towards pastoral farming and associated overstocking of goats and sheep along the valley, and changes in burning frequencies on mountain tops. All of the aforementioned activities have visibly and reportedly influenced the structure and cover of hillslope, mountain top and floodplain vegetation.

Vegetation cover on hillslopes diminished from a natural canopy cover of ~70% (Mills et al. 2005) prior to overstocking with goats and sheep, to an average canopy cover of <30% throughout the study reach, with most severe reductions in canopy cover on the foothills of the southern side of the valley (Draaijer 2010). Although stocking densities were not obtained by the author during literature search, overstocking was reported to have occurred in the catchment between the 1940s and 1990s, by various local landowners. Towards the early 1990s stocking densities were reportedly reduced and many agricultural fields were abandoned due to a decreased demand for wool, mohair and cash crops (ECPB 2007). Reduced agriculture over the last couple of decades (Knight 2012) together with small-scale ecological rehabilitation interventions from the early 2000s onwards has resulted in observed and reported minor improvements in vegetation cover in localized areas of hillslopes and the floodplain.

The timing of land cover changes described above often coincided with the formation of several hillslope gully systems on the southern side of the valley. Analysis of aerial imagery suggests that the gullies were shallow, discontinuous hillslope channels during the 1960s, when stocking and browsing of hillslope vegetation was already high. By 1986 these minor hillslope channels had expanded into relatively wide and deep gully networks, coinciding with the timing of intensive stocking of the valley with Angora goats due to the boom in the Mohair market. Between 1986 and 2009 the morphology of the gullies appears to have remained relatively stable. The gullies today exist as deeply entrenched features of the landscape, but appear to be relatively stable as indicated by vegetation growth on the gully be and on gently sloping banks (Plate 5.1).

Table 5.1: Land-use and land management changes reported to have considerably altered the structure of the river and floodplain along the upper-middle reaches (J Buckle, pers. comm., August 2013).

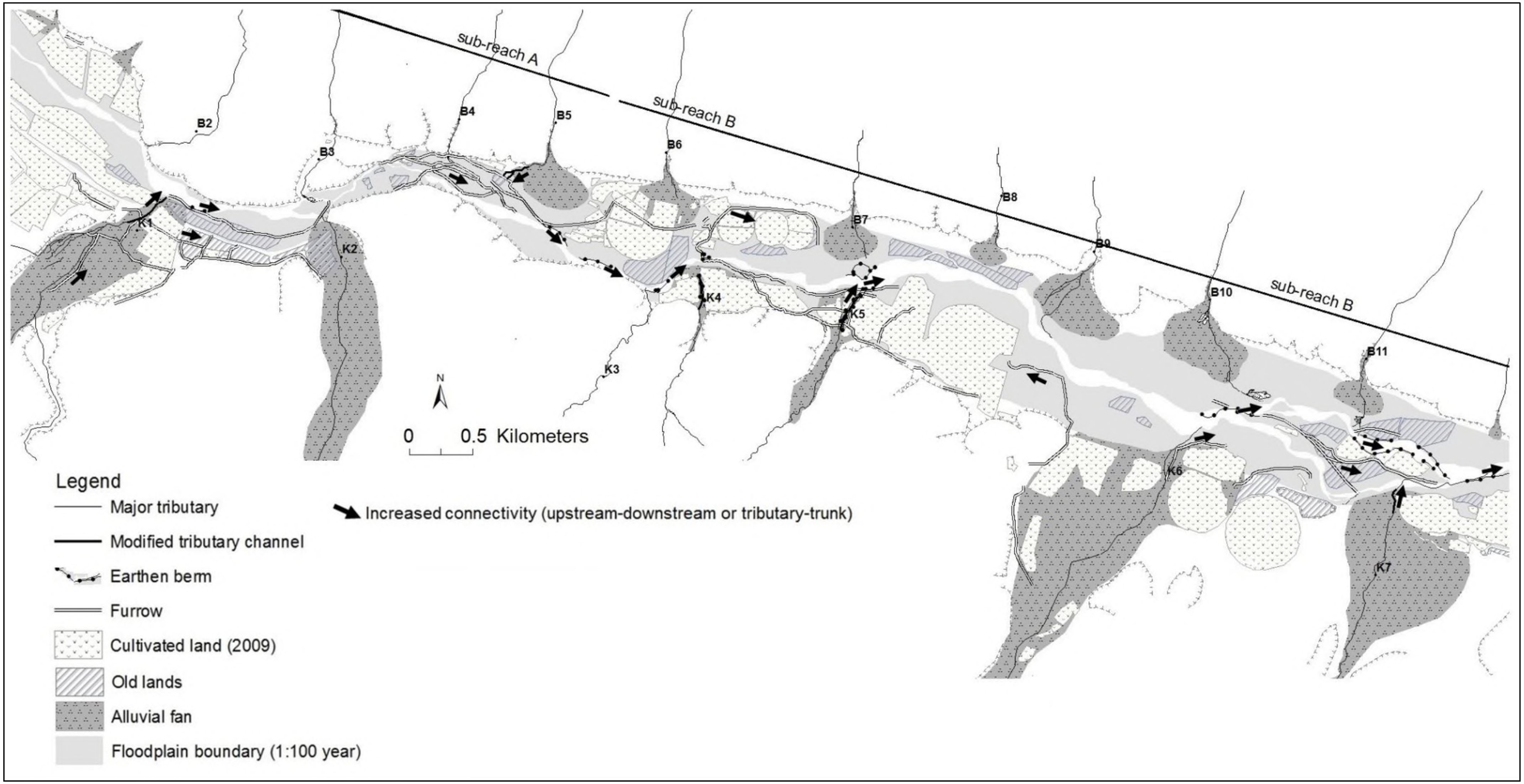
Timing	**Description**	**Reported or observed impacts**
1920s	Major production of vegetable seed on the floodplain.	Decreased woody vegetation cover in riparian zone.
1933-44	Removal of vast stands of the alien plant, *Opuntia* ('Prickly pear') along upper-middle reaches of catchment.	Decreased hillslope vegetation cover.
1960s	Occurrence of an underground peat fire.	Destruction of organic sediment and conversion to ash.
1966 - 1988	Boom in the Angora goat-Mohair wool industry.	Major decrease in woody vegetation cover on hillslopes, particularly on the southern side of the river valley.
1982-1986	Intensive stream flow channelization and introduction of center pivot irrigation.	Channelization of trunk and tributary stream flow; increased water use from floodplain aquifer and tributary springs.
1987-1990	Removal of small stands of the alien plant *Oleander* from the floodplain.	Slight decrease in presence of woody trees within the riparian zone.
1988	Change in mountain veld burning policy by the local statutory agency– return to natural burning regime.	Improved grass and shrub land vegetation cover on mountain tops and upper-slopes.
1991	Localized removal of channelizing berms along tributary and trunk channel; Reduction in stocking densities; Some abandonment of cultivated areas.	Slight improvement in floodplain and alluvial fan infiltration; Reduced water abstraction; Gradual improvement in woody and herbaceous vegetation cover on hillslopes.

Plate 5.1: An example of a deeply entrenched, relatively stable hillslope gully located on the southern foothills of the study reach.

Channel and floodplain engineering

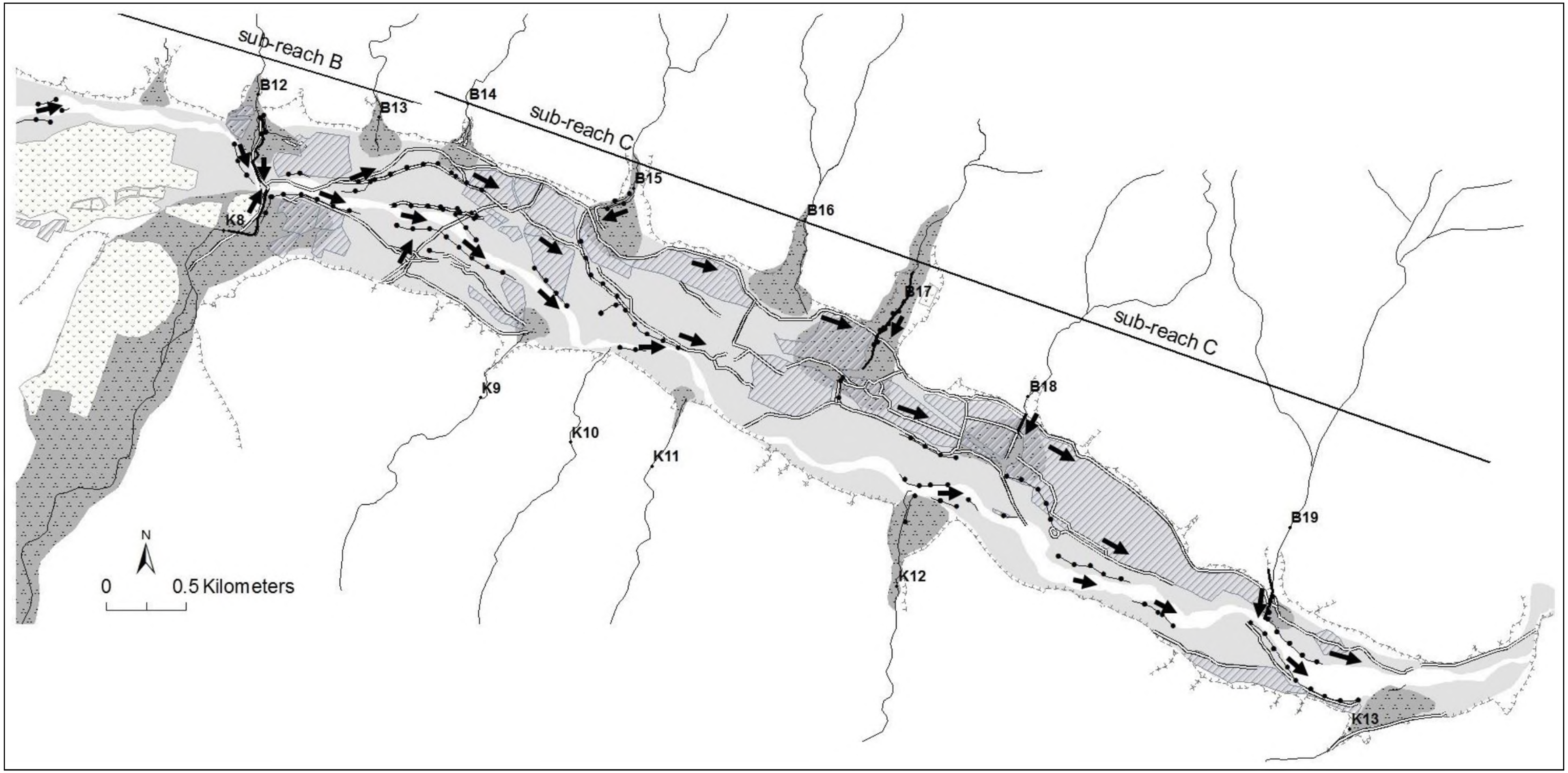
Human engineering of stream flows and floodplain hydrology has been extensive throughout the study reach. Activities have included channelization, diversion of stream flows and construction of an artificial drainage network throughout the floodplain (Figure 5.1a and b). The method used by local landowners to channelize stream flows has largely been through the construction of earthen berms, which take the form of high boulder-cobble levees on either side of the trunk or a tributary stream (Plate 5.2). These earthen berms are usually built using gravel extracted from the adjacent trunk or tributary stream bed, thereby deepening the bed. The berms are commonly built within 50 m of the active channel bank so as to confine overbank flows to the channel, increasing the power of flood flows. Stream flow diversions have also been effected by the erection of earthen berms across the course of a tributary to divert flow either away or toward the trunk stream. The extensive drainage network throughout the floodplain was built to transfer water to cultivated areas for irrigation purposes, and to drain wetland areas that were too wet for agriculture. Analysis of aerial imagery indicated that this drainage system kept much the same pattern and network density between 1960 and 2009.

The arrows in Figures 5.1a and b indicate the inferred influence of drains and stream flow channelization (earthen berms and diversions) on the degree of tributary-trunk and upstream-downstream water and sediment connectivity. It is assumed that where an increase in upstream-downstream connectivity has occurred due to the presence of channelizing features, an associated decrease in lateral connectivity has occurred. For example, where earthen berms flank the trunk channel an increase in upstream–downstream connectivity would be effected, at the same time decreasing connectivity between the trunk and surrounding floodplain. It is clear from Figure 5.1a and b that human interventions, particularly channelizing features, have substantially increased tributary-trunk and upstream-downstream connectivity for all sub-reaches of the study reach. Channelization of the distal reaches of tributary streams has been common throughout the study reach (‘modified tributary channel’, Figure 5.1a), effecting an overall increase in tributary-trunk connectivity and an associated decrease in connectivity between a tributary stream and alluvial fan. These effects are indicated for example for tributaries K1, K5, K7 (Figure 5.1a) and tributaries K8, K12, B12, B19 (Figure 5.1b). In some cases localized infiltration into an alluvial fan surface has been diminished through channelizing features that divert tributary stream flow into a drain, which then transfers the water down-valley (B5, B11, Figure 5.1a; B15, B17, B18, Figure 5.1b).



sub-reach A
sub-reach B
sub-reach B
B2
B3
B4
B5
B6
B7
B8
B9
B10
B11
K1
K2
K3
K4
K5
K6
K7
N
0 0.5 Kilometers
Legend
Major tributary
Modified tributary channel
Earthen berm
Furrow
Cultivated land (2009)
Old lands
Alluvial fan
Floodplain boundary (1:100 year)
Increased connectivity (upstream-downstream or tributary-trunk)

(a)



(b)

Figure 5.1: Human river-floodplain interventions and associated influence on tributary-trunk and upstream-downstream connectivity for the upper-middle reaches of the study reach (a), and the middle-lower reaches of the study reach (b). The arrows indicate an increase in water and sediment connectivity in the upstream-downstream and tributary-trunk dimensions.

Plate 5.2: Examples of earthen berms, indicated by the arrows, that are common throughout the study reach.

Interviews with local landowners indicated that stream channel and floodplain engineering interventions were most intensively employed during the early 1980s when the South African government subsidized local farmers to increase agricultural productivity (P Kruger, pers. comm., 2012). This was also the period in which greatest channel widening and deepening occurred along the study reach as indicated by historical aerial imagery, and as reported by local farmers. It was reported that the rapid nature of morphological change during this period was encouraged by the occurrence of a flood event in 1984, during which several earthen berms were washed away. This event caused the channel to widen considerably during the early to mid-1980s. The berms destroyed by the flood were subsequently re-built.

Severe degradation noted along the middle of the study reach may be incidental with relatively high levels of channelization that occurred along this reach from the early 1970s onwards. Enhanced storm discharges along this reach would have been compounded by the effect of two major tributaries that became connected to the trunk from opposite sides of the valley in the early 1970s (Chapter 4, Figure 4.6), in the region where deep channel erosion and substantial widening has taken place. These findings demonstrate the importance of increased tributary connectivity and stream flow channelization in enhancing the erosional power of the trunk channel and hence the sensitivity of the river-floodplain to erosion during flood events.

The presence of an extensive artificial drainage system throughout the floodplain together with degradation of the trunk channel and tributary streams, as indicated in Chapter 4, has reduced flooding attenuation and river base flows. Desiccation and eventual loss of floodplain wetland was reported in the early 1980s when the trunk channel began to rapidly deepen. These observations suggest that degradation along the trunk formed a major drain directing local groundwater and flood flows away from the floodplain, which would have been enhanced by human drainage of the floodplain. The entrenchment of many of the alluvial fans which followed trunk channel degradation would have reduced water retention within alluvial fan aquifers, further reducing groundwater levels. These impacts translated to reduced river base flows since flood flows were no longer effectively attenuated by the floodplain and alluvial fans.

There are relatively few human-made features that have decreased water and sediment connectivity along the study reach. Numerous small farm dams have been built, mostly in gullies on the southern side of the valley ('Dam or reservoir', Figure 5.2). An erosion wall was also built across the lower-reaches of several gully catchments on foothills of the southern side of the valley, presumably to control erosion and sedimentation of agricultural fields on the valley floor. Most of the dams visible in the 2009 imagery were also visible in the 1960 aerial imagery with only minor increases in the abundance of small dams over the period. The erosion control wall shown in Figure 5.2 first appeared in the 1986 aerial imagery. These dis-connectivity features would have locally reduced hillslope-channel sediment and water connectivity, but would have had no major effect on decreasing hillslope erosion and coarse sediment connectivity along the study reach.

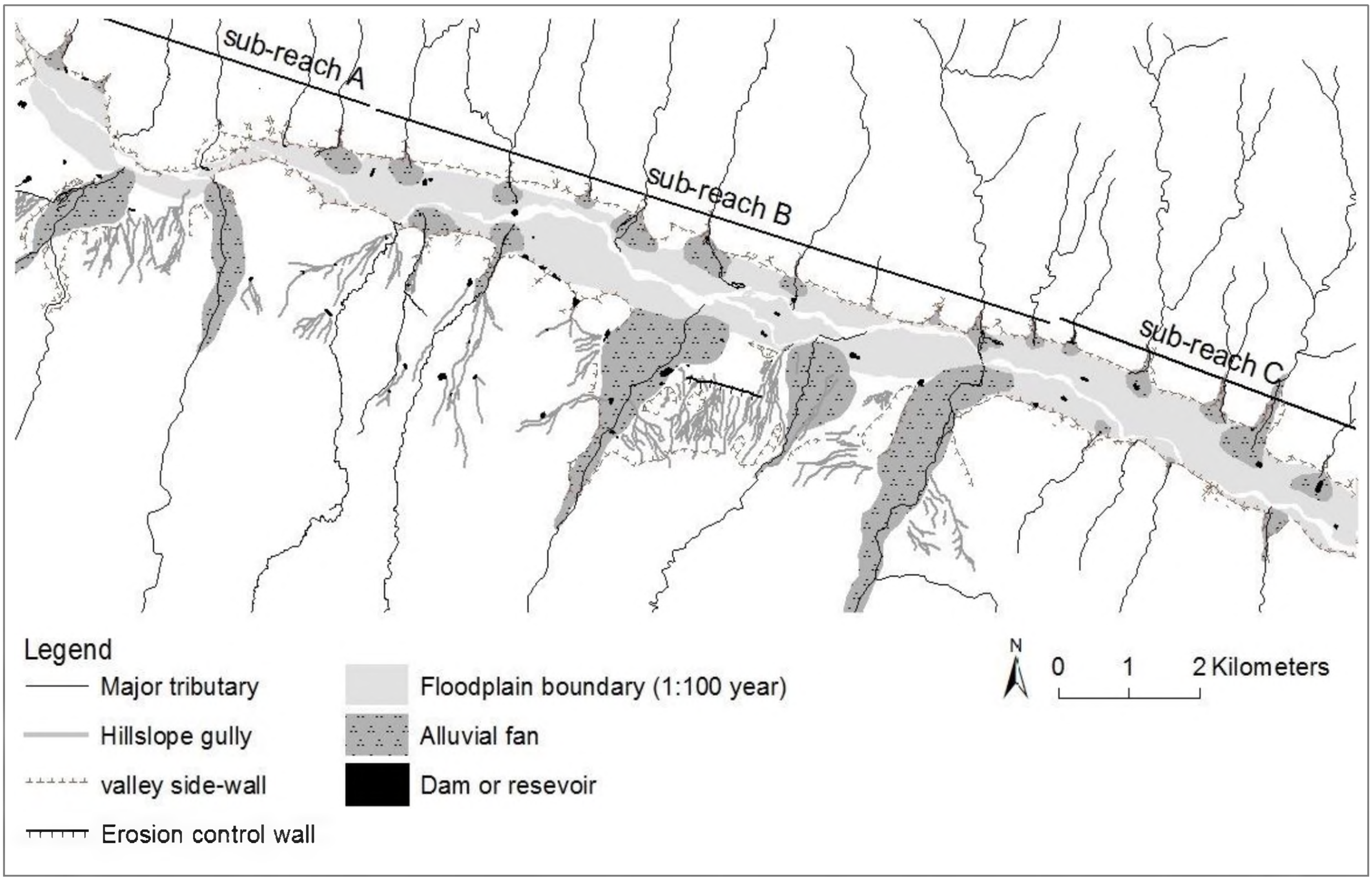


Figure 5.2: The distribution of artificial impoundments and an erosion wall that have decreased hillslope-tributary (and gully) and hillslope-valley floor connectivity.

Figure 5.3 indicates some of the major changes in trunk channel planform and tributary-trunk connectivity in relation to human engineering along the middle of the study reach where most severe channel-floodplain degradation was observed during field surveys. In 1960 the trunk channel and the two large tributary channels indicated at '2' and '4' in Figure 5.3 were narrow and poorly defined. By 1972 the trunk channel, indicated at '1', '3', and '5', as well as tributary streams indicated at '2' and '4', had widened considerably and the two tributaries became well-connected to the trunk. At the same time the trunk channel downstream of '3' and '5' evolved from a multi-thread to single-thread channel. Both of these reductions in channel bifurcation and the observed increase in tributary-trunk connectivity were a result of human interventions. For example, at location '3' the channel anabranch was infilled with coarse rubble and sand to allow for cultivation on the floodplain, as indicated from interviews with a local farmer. Thus flow was concentrated within the northern channel anabranch. Both tributaries were channelized using earthen berms to reduce flooding damage to the surrounding cultivated land, thereby increasing the connectivity of these streams to the trunk channel. In 1986 the trunk and the two large tributaries had visibly widened more than previous years, but by 2009 the trunk channel along with the two tributaries had visibly contracted.

The increases in tributary-trunk connectivity indicated above were not isolated to the middle of the study reach, but were common throughout the study reach. Analysis of aerial imagery indicated that tributary-trunk connectivity increased between 1960 and 2009. Out of 33 tributaries in the study reach, 14 were visibly connected in 1960, 21 were connected in 1986 and 17 were connected in 2009.

It is notable that at point ‘5’ on Figure 5.3 in the 1960 image, the trunk channel abruptly switches from a relatively confined braided channel where it flows between two confining tributary fans entering the floodplain from either side of the valley at location ‘4’, to several narrow channel anabranches that are dispersed across the floodplain as the trunk exits the confining zone. These anabranches flood-out shortly downstream of ‘5’. This zone of flow dispersion and flood-out is the area in which the peaty and organic rich wetland sediments were encountered in erosion banks along the study reach and the area described by local landowners as being the ‘wettest’ part of the valley floor in the recent history of the floodplain, previously containing permanent floodplain wetlands and springs. The flood-out zone was therefore an important control on the existence of these permanent wetlands and floodplain springs.

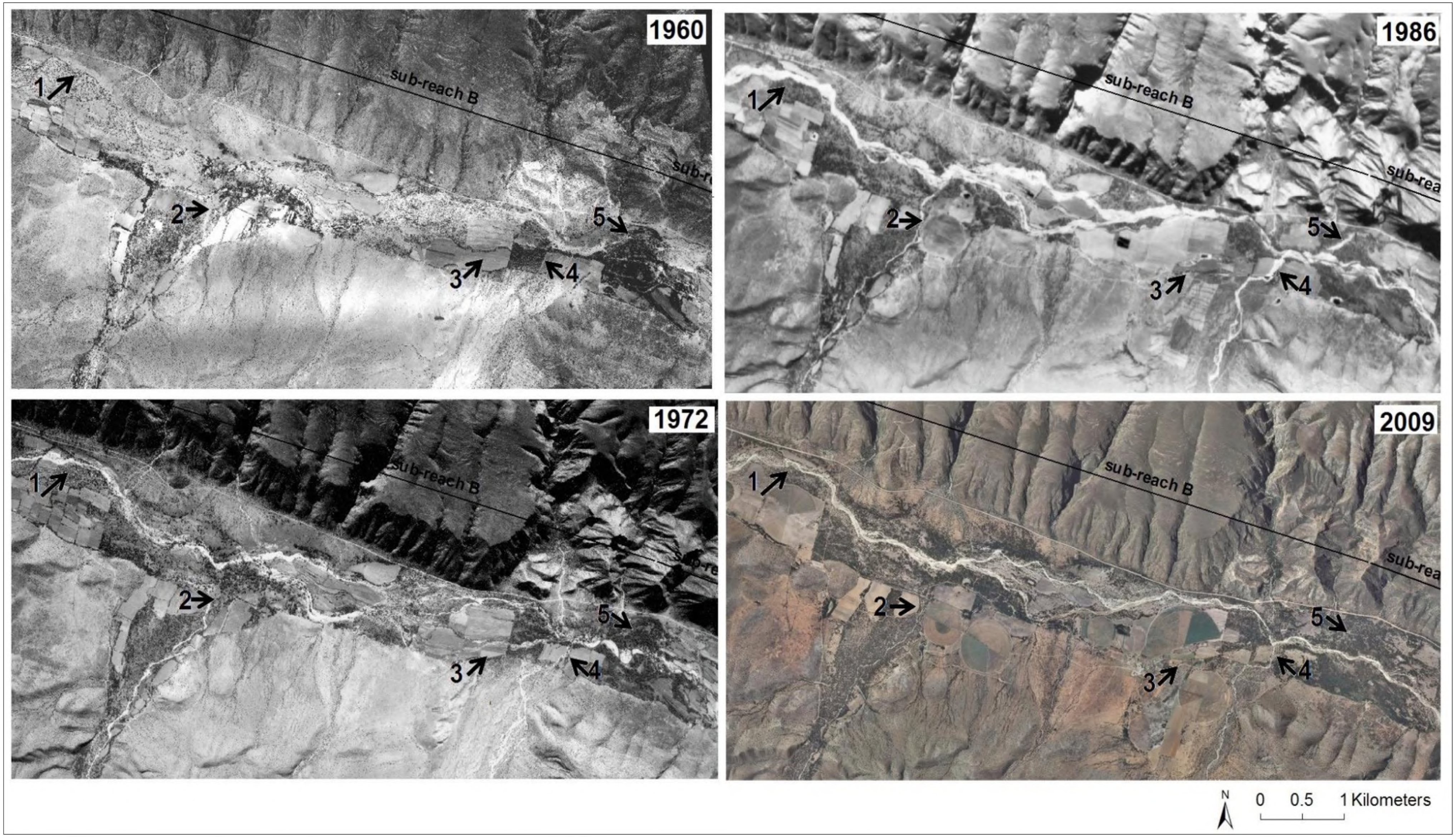


Figure 5.3: Sequential changes in channel planform and connectivity along the most notably degraded reach of the study reach. The photos are arranged in chronological order from 1960 to 2009. Specific locations of channel form change are indicated by the arrows and numbers for comparison between different years. Trunk channel flow direction is from north-west to south-east.

5.3.2 Flooding regime and coarse sediment connectivity

Climate and rainfall characteristics associated with small to moderate floods

Interviews with local farmers indicated that there are considerable differences in rainfall amount and intensity between upper- and lower-reaches of the catchment and between the mountain ranges on the northern and southern side of the river valley. Local landowners situated in the upper-reaches of the catchment reported to receive between 10 and 20 mm more rainfall during a single storm event than landowners situated approximately 20 km down-valley, along the lower-reaches of the study reach. Local farmers also reported that in general, the mountains on the southern side of the river valley (Kouga Mountains) receive higher single-event rainfall occurrences than the mountains on the northern side of the valley (Baviaanskloof Mountains).

Local landowner accounts of rainfall characteristics associated with small to moderate flood events along the study reach are presented in Table 5.2. Antecedent weather conditions are an important control on whether a flood event is initiated both upstream of and along the study reach. Local landowners noted that bankfull events usually occur when a relatively large rainfall or snow event is preceded by several months or weeks of relatively high rainfall, and that antecedent periods of high rainfall result in larger floods and longer sustained river flow for a given rainfall event size (P Kruger, pers. comm., November 2014). Similar rainfall and antecedent weather conditions are required to induce a small to moderate flood upstream of the study reach (Table 5.2, 'Upper-reaches') and along the study reach (Table 5.2, 'Middle-reaches'). However, the study reach requires a higher depth of rain on a single day for a small to moderate flood to occur, than the upper reaches. If antecedent conditions have been relatively wet then between 20 and 50 mm of hard rain falling over a few minutes or hours is necessary to induce a small to moderate flood. For antecedent dry conditions, greater than 50 or 60 mm of rain falling over several days to a couple of weeks is necessary for flooding along the upper- and middle-reaches respectively. The above flood-inducing rainfall and antecedent weather characteristics were confirmed during field observation of a moderate flood event that occurred in 2012. During the latter event approximately 61 mm of a total of 68 mm of rain fell over a few hours. Antecedent conditions for this event were wet and flooding along non-degraded reaches occurred within a few tens of meters from the trunk channel.

Table 5.2: Characteristics of rainfall required to initiate small to moderate and large flood events for different antecedent weather conditions and rain duration.

Rainfall (mm)	Antecedent conditions	Duration of rainfall event	River-floodplain reach
±20–50	Relatively wet	± 30 minutes - several hours	Upper-reaches
±50–100	Relatively wet - dry	a few days - couple of weeks	Upper-reaches
±30 –50	Relatively wet	a few hours	Middle-reaches (study reach)
±60-125	Relatively dry	a few hours to weeks	Middle-reaches (study reach)

Using the information presented in Table 5.2, various flood-inducing rainfall parameters were devised for antecedent wet and dry conditions for both the upper- and middle-reaches of the floodplain. It is suggested that rainfall events greater than 30 mm on a single day would induce a small to moderate flood for periods with antecedent wet conditions, and that single events of greater than 50 mm, for the upper-reaches, or 60 mm for the middle-reaches of the floodplain, would induce a flood during periods with antecedent dry conditions. For several day rainfall events, greater than 100 mm and 120 mm of rainfall is required for flooding along the upper- and middle-reaches of the floodplain respectively. In addition, a small to moderate flood was suggested to occur during antecedent dry periods if a relatively large rainfall event (>70 or 80 mm) was preceded by several events of greater than 50 mm rainfall depth.

Rainfall characteristics necessary for inducing large flood events were inferred by analyzing rainfall data for years in which exceptional flood events were reported by local landowners. A large flood event was defined by landowners as inducing extensive flooding (more than 50 m on either side of the trunk channel along non-degraded reaches) and damage to floodplain infrastructure and cultivated lands. Large events were recounted for the Baviaanskloof in 1971, 1972, 1976, 1981, 1996, 2006, 2007, and 2009. However, some of these 'large flood' years did not match years in which one or more exceptionally high rainfall events (>120 mm) occurred. The discrepancy between large flood years reported by local landowners and the rainfall data may be a result of poor memory or the subjective nature of personal accounts of floods.

Despite this mismatch there were several large flood years with exceptionally high-magnitude rainfall events within the rainfall record. These events were characterised as follows:

1) For years with antecedent wet conditions: two or more moderate sized rainfall events (>50 mm) followed by a large event of >130 mm, or a large event of >130 mm followed by two or more events of >50 mm.;
2) For years with antecedent dry conditions: two or more events of >70 mm followed by a large event of >130 mm;
3) Or, a very large event of >200 mm of rain falling over approximately 1 month for a year preceeded by wet weather conditions.

The above conditions provided the criteria for documenting the timing of large flood events between 1950 and 2000/2012 for rainfall stations 'Matjies' and 'Bavlulet', occurring upstream of the study reach, and in the middle of the study reach respectively.

Flood-inducing rainfall frequencies

Using the rainfall criteria presented above, the frequency of small to moderate flood-inducing rainfall events was plotted for the upper- and middle-reaches of the Baviaanskloof floodplain (Figure 5.4). The analysis indicated that small to moderate flood-inducing rainfall events occur at most every year to two years and at least once in every 10 years. The annual to biannual events are defined in this study as small floods, whereas events occurring every approximately five to ten years are reportedly larger than annual events and are thus defined as a moderate flood. According to Figure 5.4, the frequency of small to moderate flood-inducing rainfall events varied between the upper- and middle-reaches of the floodplain over the period of analysis. There is no indication of an increasing or decreasing trend in the frequency of small to moderate floods rather, but flood frequencies vary in a cyclic manner. These flood cycles are characterized by alternating phases of relatively high flood frequency and phases of relatively low flood frequency. Rainfall station 'Matjies' in the upper-reaches experienced 54 small to moderate flood-inducing rainfall events between 1950 and 2000 whereas the study reach ('Bavlulet') only experienced 31 events of this magnitude over the same period of time. The timing (month and year) and magnitude of most of the flood-inducing rainfall events were similar between the two rainfall stations. However, 14% of years between 1950 and 2000 produced flood-inducing rainfall events that were isolated to one of either of the rainfall stations, reflecting the spatially variable nature of rainfall along the river valley. The data in Figure 5.4 thus underestimates the number of floods experienced along the study reach since a flood initiated along the upper-reaches of the floodplain is often transmitted down-valley to the study reach.

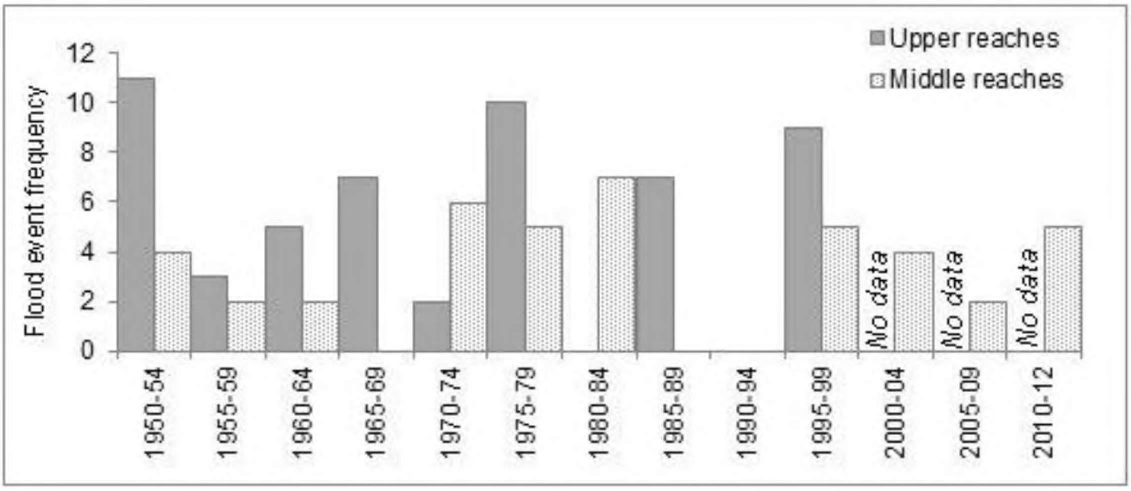


Figure 5.4: Frequencies of small to moderate flood-inducing rainfall events plotted at 5-year intervals for rainfall stations 'Matjies' and 'Bavlulet', situated in the upper- and middle-reaches of the Baviaanskloof floodplain respectively.

Approximately a third of local landowners interviewed reported a general increase in the frequency of what they considered 'high intensity' rain events over the last decade or more (from about 2004 to 2013). Rainfall station 'Bavlulet' indicated an increasing frequency of one-day rainfall events ≥20 mm in magnitude from 1990 to 2009, when the data was plotted at 10-year intervals ('Middle-reaches', Figure 5.5). Rainfall station 'Matjies' along the upper-reaches of the floodplain did not indicate an increase in frequency of one-day rainfall events ≥20 mm in magnitude, between 1990 and 1999, although this may be due to the fact that the rainfall record ceases at the station after 1999 ('no data', Figure 5.5).

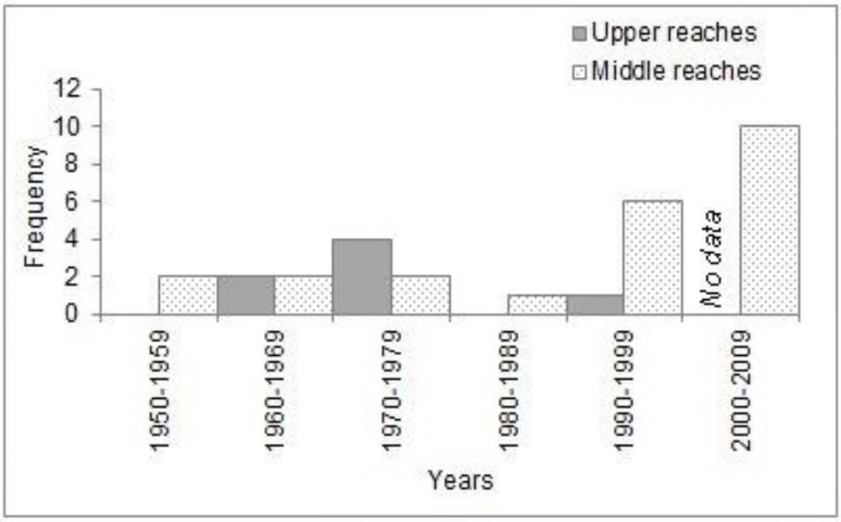


Figure 5.5: Frequency of ≥20 mm one-day rainfall events recorded for rainfall stations situated along the upper ('Matjies) and middle ('Bavlulet') reaches of the Baviaanskloof floodplain.

Overall, the results indicate that the upper-reaches of the floodplain experienced a higher number of one-day flood-inducing rainfall events than the study reach (middle-reaches), whereas the study reach experienced a higher frequency of one-day events ≥20 mm, over the period of analysis.

Using the rain duration and climate criteria for defining a large flood, a total of seven large-flood-inducing rainfall events were recorded for the two rainfall stations combined between 1950 and 2000/2012 (Table 5.3). Rainfall station 'Matjies' indicated five of the total of seven large flood-inducing rain events. The timing and duration of the rainfall events was variable as some events were relatively short and intense with between 140 and 160 mm of rain falling over one to one-and-half weeks. Other events were characterised by a high amount of rain falling almost continuously over several weeks. The occurrence of large floods appears highly variable with events occurring as frequently as once in every 3-5 years or once in 19-20 years. Both stations indicate a large flood-inducing rainfall event in 1974, indicating widespread rain and flooding throughout the river valley. The timing of this large flood corresponds with reports of major floods throughout the Eastern Cape in 1974 (eWISA 2016).

Table 5.3: The timing and magnitude of large-flood inducing rainfall events recorded for rainfall stations 'Matjies and 'Bavlulet' between 1950 and 2000/2012.

Year	Rainfall (mm)	Duration (days)
Upper-reaches ('Matjies')		
1955	143	20
1974	160	7
1977	137	6
1986	148	9
1996	207	28
Middle-reaches ('Bavlulet')		
1954	186	19
1974	140	15

Implications for coarse sediment movement

Moderate and large flood events are powerful enough to induce transport of considerable amounts of coarse sediment along the bed of tributary streams and the trunk channel. Bed load transport during flood events in the Baviaanskloof, is accompanied by a loud 'rumbling' sound as cobbles and boulders collide with one another. During the waning phase of floods, bed load sediments are deposited and temporarily stored in various landforms including, tributary junction fans, channel flood-outs or debris cones; lateral, medial and point bars, and riffle zones. Debris cones, cobble bars and riffle zones, are commonly encountered at the junction or shortly downstream of the junction of a tributary with the trunk stream, indicating coarse sediment connectivity between tributaries that join the trunk channel. The morphology of channel bed depositional features is readily altered during moderate (1 in 3-5 year frequency) or large flood events (1 in 10 year frequency or less), such that these depositional features form temporary sediment stores.

The degraded nature of tributaries and the trunk channel means that coarse sediment is transferred as 'waves' through the study reach during flood events. The episodic nature of coarse sediment connectivity means that trunk channel adjustment is episodic and occurs during flood events when water and sediment connectivity is high, but is reduced to a minimum during base-flow periods. Coarse sediment connectivity is thus temporally and spatially variable inducing a variable array of erosional and depositional landforms, trunk channel morphology, and process. These include for example pool-riffle sequences every few 10s of meters along the channel, medial and lateral channel bars every few 100 m, and sedimentation and erosion zones identified from the longitudinal profile of the river every few 1000 m. The results of the minor pebble tracing experiment indicated that cobble-sized bedload particles can move as much as 415 m along the channel during a small flood event (Table 5.4). The pebbles were of variable size, with the smallest pebbles being transported furtherest ('P5' and 'P6', Table 5.4). The pebbles were retrieved on the channel bed at a downstream riffle section and a lateral channel bar.

Table 5.4: Transport distances of pebbles of varying size class (according to the Udden-Wentworth system) during a small flood event in the Baviaanskloof.

Pebble code	**Distance transported (m)**	**Length and breadth measurement (cm)**
P3	113	8.5 x 7.4
P2	114	10.17 x 10
P1	126	11.6 x 6.2
P5	233	7 x 5.7
P6	415	6.5 x 4.5

Based on the above observations, it is suggested that coarse sediment is temporarily connected during flood wave sediment transport, and then stored over varying temporal and spatial scales along the trunk channel.

5.4 Discussion

The results of the present analysis have indicated that episodic floods, anthropic river-floodplain engineering, and catchment land-cover changes, seem to have been important factors driving recent changes in water and sediment connectivity and relative channel stability of the Baviaanskloof River. Increasing hillslope-channel, tributary-trunk, and upstream-downstream water and sediment connectivity along the study reach since the 1960s has increased the sensitivity of the trunk stream to flood events. As indicated in Chapter 4, the observed and documented channel dynamics between 1960 and 2009, included channel widening and deepening. The present analysis has indicated that the channel shifted from a relatively stable, anabranching planform to a relatively unstable, wide, and braided form. At the same time, the floodplain evolved from a relatively low-energy system with extensive wetlands to a relatively high-energy system in which wetlands are largely absent.

5.4.1 Interpreting drivers of recent channel dynamics and sensitivity

It is difficult to infer the relative role and synergistic interaction between human influences and flood events, in driving recent changes in geomorphological behavior of the Baviaanskloof River-floodplain. Figure 5.6 is a timeline indicating some of the major human influences and flood events within the catchment, together with the timing of changes in character and form of the river-floodplain, between 1926 and 2016. The author suggests that there was a succession of events and interventions that led to enhanced sensitivity and geomorphological change of the Baviaanskloof River and floodplain. The first event was a large flood which occurred in 1966 (Figure 5.6). This event appears to have coincided with observed widening of the trunk channel. Leading up to this large flood, were several decades of continued overgrazing in the catchment and engineering of the river and floodplain (channelization and drainage), in association with pastoral farming and cultivation of vegetable seeds. These human influences would have enhanced water and sediment connectivity and prepared a more sensitive river to the effects of the large flood. Following the large flood in 1966, were several other large floods occurring at roughly 10 year intervals. These events occurred during the period of intensive hillslope overgrazing and river-floodplain engineering reported for the 1970s to about the early 1990s (Figure 5.6). During this period of heightened large flood occurrence and human influences, the trunk channel continued to widen and become unstable. However, the river only began to deepen rapidly in the early 1980s, during intensive channelization of river flows. It therefore appears that human river-floodplain engineering and decreased hillslope vegetation cover prepared a more sensitive river to the effects of large floods, with each flood inducing further instability and channel change. Channel widening and switch to braiding was the first response of the trunk to the synergistic effects of large floods and human influences, followed by rapid channel deepening in response to enhanced storm flows resulting from human-induced stream flow channelization.

A more detailed discussion of the effect of each of the drivers on river-floodplain process and form, including large floods, decreased hillslope vegetation cover, and river-floodplain engineering, is discussed below.

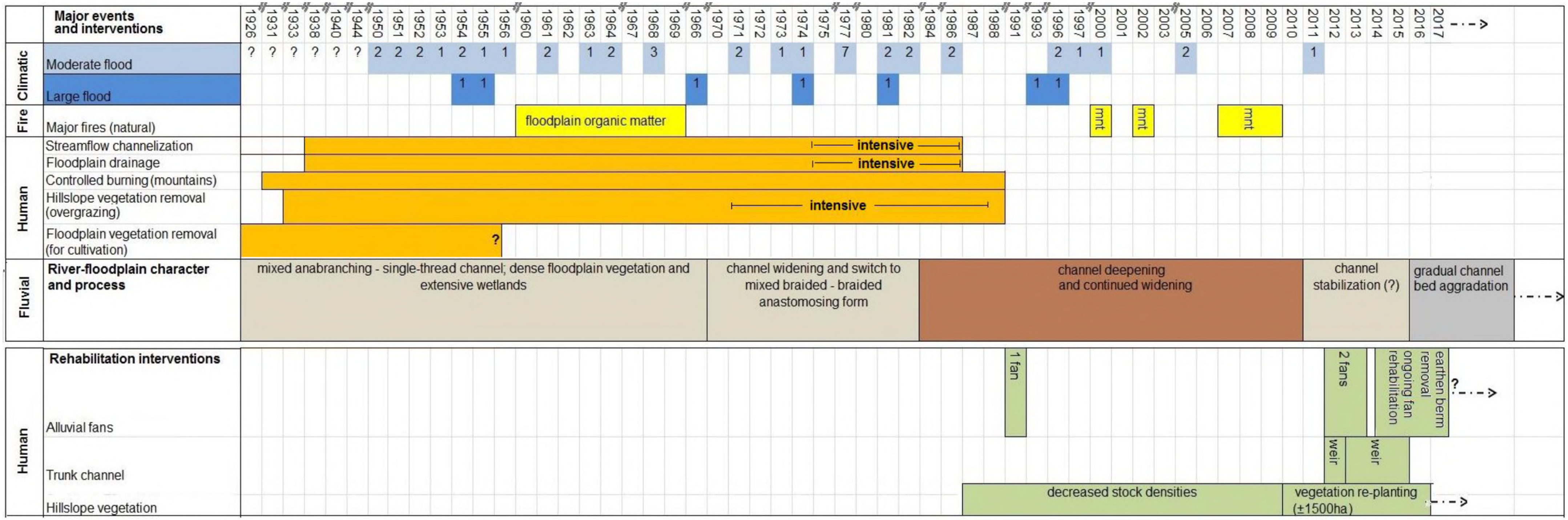


Figure 5.6: Timeline of documented land-use and flood events, and changes in river-floodplain geomorphological form.

Vegetation degradation

Degradation of hillslope subtropical thicket vegetation along the study reach is suggested to have had a considerable impact on hillslope runoff and erosion. If hillslope-channel and tributary-trunk connectivity are high, then changes in runoff and erosion on hillslopes should translate to changes in discharge and sediment flux to the trunk channel (Fryirs et al. 2007b; Bracken et al. 2013). There is much evidence for the initiation of channel instability following catchment and riparian vegetation removal that alters flow and sediment regime (Brooks and Brierley 1997; Simon and Rinaldi 2000, Kasai et al. 2005; Simon and Rinaldi 2006; Vanacker et al. 2005; Hooke 2006; Hoyle et al. 2008; García-Ruiz et al. 2010). The general consensus is that vegetation removal increases landscape sensitivity to the effects of high-intensity rain events, resulting in heightened storm discharges and sediment fluxes, and associated channel instability (Overeem et al. 2013). Studies conducted in high-energy mountain catchments like the Baviaanskloof have indicated that a trunk stream responds to vegetation removal in the wider catchment through channel incision, widening and a switch to channel braiding (Brooks and Brierley 1997; Hooke 2006). These impacts are clearly evident in the Baviaanskloof along the study reach, suggesting that human-induced removal and modification of catchment and riparian vegetation has had indirect impacts on river sensitivity to storm events.

The vegetation on the hillslopes of the study reach usually forms a dense, canopy layer where it is in pristine to near-pristine condition (Mills et al. 2007). The once-thick canopy cover has been transformed to scattered trees and shrubs on hillslopes such that most of the hillslope vegetation along the study reach has been classed as moderately to severely degraded (Euston-Brown 2006; Vlok 2010; Plate 5.3). Vegetation degradation has been attributed to overgrazing, largely in the form of browsing by goats and sheep. Overgrazing has been preferential to the southern side of the valley (north-facing slopes), partially because the hills are lower sloping and easily accessible by goats and sheep, and historically these slopes contained the highest density of the palatable thicket species, *Portulacaria afra* or 'spekboom' (Powell et al. 2011). It is suggested that most of the hillslope vegetation degradation in the Baviaanskloof occurred between 1960 and 1988 when stocking densities were highest due to a peak in the market for mohair (Angora goat) and sheep wool (J Buckle, pers. comm., August 2013). The vegetation cover on the left of the dotted line in

Plate 5.3 more closely resembles vegetation cover that would have existed along the study reach prior to intensive overgrazing during the 1970s and 1980s.

Plate 5.3: Degraded subtropical thicket vegetation on the southern side of the valley. Different grazing pressures are visible on either side of the fence line indicated by the yellow dotted line (Photos by B Robb 2012).

The loss of canopy cover on hillslopes surrounding the study reach has had a considerable impact on hillslope runoff and erosion (van Luijk et al. 2013). In their study, van Luijk et al. (2013) investigated the effect of vegetation degradation on rain splash intensity, soil erosion, infiltration and runoff, at two hillslope sites along the study reach, reflecting different levels of vegetation degradation. Van Luijk et al. (2013) measured each of the aforementioned variables for 23 rainfall events at a hillslope fence line separating severely degraded (>50% canopy cover lost) and semi-intact thicket vegetation. The results of the study indicated that rain splash intensity, runoff, and soil erosion were higher, while infiltration was lower, for the degraded vegetation site compared to the semi-intact site. These changes were largely due to reduced rainfall interception by a dense woody vegetation cover, increasing the impact intensity of rain drops at ground level. The study indicated that rainfall interception below the common canopy species 'spekboom' on the relatively intact thicket site was 115-650 times higher than on the degraded site where 'spekboom' was absent. These findings suggest that following severe losses in canopy cover along the study reach, hillslope runoff and erosion would have considerably increased. The degree to which these effects propagate to the trunk channel as increased discharge and sediment delivery is dependent upon the degree of hillslope-channel and tributary-trunk connectivity (Harvey 2002a; Brierley et al. 2006; Fryirs et al. 2007a; Chiverrell et al. 2009). In the Baviaanskloof, there is evidence that high hillslope runoff and sediment erosion is easily transferred to the trunk channel as indicated by dark brown colour of river water during the initial stages of a flood event (Plate 5.4). Interviews with local landowners confirmed that most flood events, whether small or large, are accompanied by sediment laden water that is brown or black in colour (Plate 5.5). Viscous black flood waters are rare but usually associated with an intense storm that follows burning of fynbos vegetation on the mountain slopes of either the Baviaanskloof or Kouga mountains. All of the aforementioned observations indicate high levels of hillslope-channel and tributary-trunk sediment connectivity along the study reach.

Plate 5.4: Sediment laden flood waters during a small flood event in 2012 for a site situated in the middle of the study reach (photos by Hestelle Van Rensburg).

Plate 5.5: Charcoal and ash laden river water at the same site as Plate 5.4 during a flood event in 2009. The flood event occurred soon after a mountain fire (photos by Hestelle Van Rensburg).

The development of numerous hillslope gullies and increasing tributary-trunk connectivity from the early 1970s onwards would have enhanced the delivery of runoff and sediment eroded from hillslopes to the trunk channel during storm events. Observations during flood events confirm that during moderate to large floods substantial amounts of coarse sediment is delivered to the trunk channel via connecting tributaries. The minor hillslope channels apparent in 1960 aerial imagery developed relatively rapidly into deep gully systems over subsequent years, most likely driven by intensive grazing pressure and relatively rapid vegetation degradation. These findings are not uncommon for semi-arid catchments in South Africa impacted by human land-use activities, particularly livestock grazing (Boardman et al. 2003; Boardman et al. 2010; Foster et al. 2012).

The influence of controlled burning of mountain fynbos vegetation on runoff and erosion is uncertain. Between 1923 and 1988 the Department of Forestry employed controlled block burns on mountain peaks surrounding the study reach every 1-2 years (J Buckle, pers. comm., August 2013). Fynbos vegetation is highly dependent upon natural burning cycles for its development, regeneration and species composition, and generally requires about 4-6 years between burns to regenerate and accumulate sufficient fuel for another burn (Teague et al. 1989). Natural burning cycles can take place at return intervals anywhere between 6 and 40 years (Teague et al. 1989). A study by Vlok and Yeaton (2000) indicates that frequent burning of mountain fynbos can result in an increase in understorey species that sprout rapidly following a burn. These sprouting species grow quickly and establish a relatively dense cover below taller, mature species (Vlok and Yeaton 2000). The increase in understorey species following frequent burns may increase rainfall interception and thereby reduce runoff, but these effects have not been studied for fynbos in the Baviaanskloof. It is therefore difficult to draw conclusions as to the overall effect of controlled burning on runoff and sediment fluxes for the study reach.

River-floodplain engineering

Channelizing features such as earthen berms, channel diversions and straightening are effective in increasing stream power relative to a former condition (Simon 1992; Simon 1994; Landon et al. 1998; Simon and Rinaldi 2000). As indicated from the present analysis, most of the trunk channel and lower-reaches of tributary streams have been channelized. River-floodplain engineering would have occurred from the onset of European agricultural activities in the valley (early 1920s), however it was during the early 1980s that flow channelization and floodplain drainage was most intense. The results of this analysis indicated increases in tributary-trunk connectivity between 1970 and the early 1980s which may partially be attributed to flow channelization and diversions along the lower-reaches of tributary streams. Stream flow channelization along most of the study reach would have considerably increased stream power during storm flows (Simon 1994; Simon and Rinaldi 2000; Surian and Rinaldi 2003), enhancing the effects of reduced vegetation cover on hillslopes. The correlation between the timing of intensive stream flow channelization and the onset of channel degradation during floods events occurring in the early 1980s supports the suggestion that a threshold of erosion was exceeded along the study reach resulting in widespread trunk channel degradation. The relatively rapid onset of degradation along tributary streams, in response to degradation and lowering of the trunk channel bed, would have further increased connectivity and power of storm flows delivered to the trunk channel. The trunk channel was able to dissipate the excess energy through widening, which increases hydraulic roughness, and deepening, which over time reduces slope along the bed and thus flow velocity (Simon 1992, Simon 1994; Schumm 2005). This response indicates an attempt to alter the relationship between discharge, available sediment load and channel slope, so there is enough energy to transport the available sediment.

Floods and rainfall patterns and trends

It is well known that rainfall over southern Africa is highly variable both spatially and temporally. Inter-annual to decadal scale oscillations between relatively wet and dry climatic conditions has been attributed to variations in sunspot activity and the effect of El Niño Southern Oscillation events (Mason and Jury 1997; Kane 2009). The temporal variability of rainfall over the Baviaanskloof means that the hydrology of the catchment is highly variable, inducing temporal variations in sediment connectivity. The frequency of small to moderate and large floods inferred from rainfall analyses indicates that sediment connectivity is intermittent and may only be induced once every two to three years during a small to moderate flood event (Bertoldi et al. 2010). It is also clear from this analysis that moderate and large flood events have been important drivers of recent channel dynamics, since the timing of major channel planform changes followed the timing of large floods and periods of relatively high flood event frequency.

Smith-Adao (2016) analyzed rainfall data using a modeling approach to infer flooding magnitude-frequency for the Baviaanskloof, during her PhD research. Smith-Adao (2016) suggested that moderate floods occur once in every 3 years and large events occur once every 10 years. These findings closely following the findings of the present research, which is interesting since the present research applied a qualitative approach to infer flooding magnitude-frequency, in contrast to Smith-Adao's (2016) quantitative approach.

Although there were no clear trends in the frequency of flood-inducing rain events for the upper-middle-reaches of the Baviaanskloof floodplain between 1950 and 2012, the results of this analysis indicated an increasing frequency of >20 mm one-day rain events from the 1990s onwards for the study reach. During the project period, La Niña conditions were experienced over southern Africa, persisting until 2014 following which strong El Niño conditions have been experienced on a global and regional scale (Cole and Gray 2015). El Niño events usually result in warm and dry conditions over South Africa, and La Niña events are generally associated with cool and moist conditions and above average rainfall (SAWS 2016). The climatic effects of El Niño and La Niña however may vary locally. Localized impacts of above average rainfall associated with La Niña during the study period, may explain the increase in one-day rain events >20 mm in magnitude observed for the study reach.

There is similar evidence for changing frequency of one-day rain events elsewhere in South Africa. Boardman et al. (2010) indicated an increasing frequency of >25 mm one-day events for a semi-arid catchment several hundred kilometers inland of the Baviaanskloof. Boardman et al. (2010) used radioactive isotopes to date sedimentary deposits in small farm dams in the Karoo and to trace the source of the sediment deposits. The results of the study indicated that the timing of increased fine sediment flux within the catchment during the previous 100 years matched the timing of increased frequency of one-day rain events and land cultivation. Since the Baviaanskloof is also a semi-arid catchment with degraded vegetation it is likely that the increasing frequency of one-day rain events has been important in driving increases in water and fine sediment connectivity for the study reach over the last few decades, thereby increasing the likelihood of enhanced river sensitivity to geomorphological change.

A change in flooding regime has implications for coarse sediment movement and relative channel stability. In the Baviaanskloof, an increase in flooding regime would be expected to result in an increase in coarse sediment connectivity and a decrease in relative channel stability. The spacing of pools and riffles, channel bars and sedimentation and erosion zones along the trunk channel roughly indicate the path length of coarse sediments during flood events of varying magnitude and frequency (Pyrce and Ashmore 2003; Lane et al. 2007). However, path length may vary according to a number of factors including magnitude of flow events that are able to entrain bed particles, local channel morphology and associated transport capacity and competence, and particle mobility related to degree of bed armouring or imbrication (Hooke 2003). Particle path length for small gravel-bed systems has been recorded at a range of 100-1 000 m for small to moderate sized flood events (Schneider et al. 2014). The Baviaanskloof is a medium-sized system, such that one would expect particle lengths to be greater than 1 000 m for small to moderate flood events. However, particle path length is dependent on a number of factors including channel morphology (with, slope, depth, planform and bed morphology) and stream power (Schneider et al. 2014). The largest transport distance of a pebble-sized particle during a small flood event in this study was 415 m from a riffle to a lateral bar. It is therefore suggested that during small floods coarse sediment is connected at the local scale between pools and riffles and between riffles and channel bars. During moderate floods, coarse sediment may be connected between multiple pool-riffle sequences and channel bars. It is suggested that during large floods, coarse sediment may be connected over a few hundred to thousand meters, resulting in the large-scale sedimentation and erosion zones identified in the longitudinal profile of the Baviaanskloof River. Sediment may be stored in these features over varying time periods, depending on the magnitude and frequency of flood events that induce transport over different distances.

5.4.2 The interplay between coarse sediment connectivity and recent channel instability

The interaction of multiple drivers of river change, including hillslope and riparian vegetation removal, river engineering, flood events and relative geomorphological sensitivity to erosion of different channel reaches, has determined recent channel dynamics along the middle-reaches of the Baviaanskloof floodplain. The findings of this analysis suggest that human land-use activities and high-magnitude flood events have been key drivers of recent channel-floodplain sensitivity and associated geomorphological degradation along the study reach. Increased water and sediment connectivity has been the primary means by which the aforementioned drivers have effected channel-floodplain erosion. These shifts in channel-floodplain form appear to have occurred relatively abruptly over a ~20 year period between the early 1970s and 1980s, mirroring the abrupt changes that are often observed in complex systems as critical thresholds are reached (Schumm 1973, Schumm 1979; Thomas 2001; Ryan et al. 2007). By the late 1990s to early 2000s the channel had begun to contract, indicating the onset of a phase of recovery. There was a time-lag between the onset of European settlement, and associated land-use activities, and the onset of relative channel instability. Although human modifications to river-floodplain structure would have occurred soon after the onset of agricultural activities along the river valley, it was only some 50 years or so later, by the early 1970s, that considerable changes in channel morphology and stability were noted. This time-lag in the onset of noticeable channel morphological change coincides with the onset of heightened livestock densities and intensive river floodplain engineering during the 1970s, continuing into the 1980s. During this period episodic flood events became more effective in driving channel change, as storm runoff was efficiently channelized by human made features. In the Hunter catchment in New South Wales, Australia, Fryirs et al. (2009) indicated a 70 year time lag between catchment land-use disturbance and channel morphological change. The authors suggested that the river took several years to move towards geomorphological thresholds of change, which were breached during successive flood events. The lag in channel response in the Baviaanskloof reflects the internal resistance of the system to geomorphological change prior to the 1970s, which is suggested to have been determined largely by a low degree of coarse sediment connectivity.

There has thus been a clear link between coarse sediment connectivity and relative trunk channel stability for the Baviaanskloof River along the study reach. Figure 5.7 is a conceptual model indicating the interaction between degree of coarse sediment connectivity and relative channel stability in the context of external drivers of geomorphological change identified in this study. Between the 1920s and early 1960s the channel-floodplain system would have been a relatively low-energy environment, dominated by overbank accumulation of relatively fine sediments and slow, dispersive flows. During this period hillslope-channel, tributary-trunk and upstream-downstream connectivity was lower than subsequently, allowing for greater channel stability and resistance to flood disturbances. Although episodic flood events would have occurred between the 1920s and 1960s the channel-floodplain maintained a relatively constant state. However, the influence of human induced modifications to catchment and channel-floodplain form during this period would have predisposed the channel to the effects of flood events in subsequent years. These modifications included:

- Human streamflow and floodplain engineering activities that served to increase stream power during storm flows (Simon 1992; Simon 1994; Landon et al. 1998; Simon and Rinaldi 2000; Surian and Rinaldi 2003).
- Removal of relatively dense woody riparian vegetation to make space for floodplain cultivation would have reduced the resistance of channel banks and the immediate floodplain to geomorphologically effective floods supporting channel degradation and the shift toward channel braiding (Rowntree and Dollar 1996; Brooks and Brierley 1997; Fryirs and Brierley 1999; Simon and Rinaldi 2000; Brooks et al. 2003; Burge 2006; Tal and Paola 2007; Ashmore 2013; Yu et al. 2014).
- Changes in floodplain sediment cohesiveness: ash layers created by underground peat fires during the 1960s may have decreased the resistance of channel banks along sub-reach B explaining why the trunk is most degraded (up to 6 m deep) along this reach.

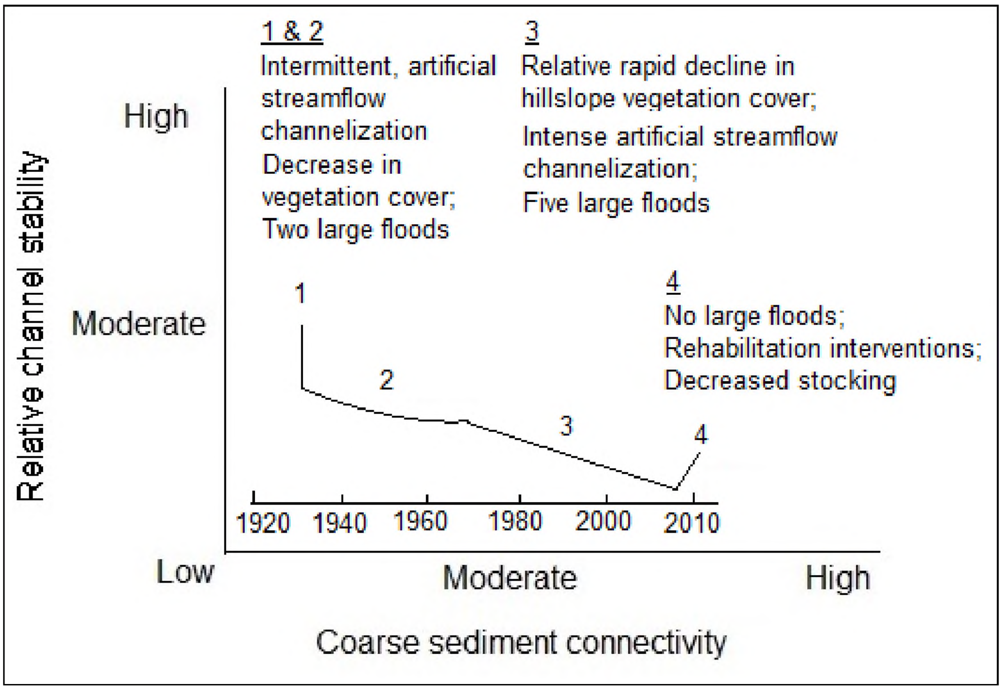


Figure 5.7: Conceptual model illustrating changes in the relationship between coarse sediment connectivity and relative channel stability in response to multiple disturbing forces between the 1920s and early 2000s.

The non-uniform nature of trunk channel degradation reflects the complexity of the sub-system represented by the study reach (Simon 1994). This complexity may be explained by downstream variations in the sensitivity of the trunk to erosion. This sensitivity is controlled by a number of factors including:

- Antecedent controls (Hoyle et al. 2008) in the form of relative resistance of bank materials inherited from past fluvial processes and catchment lithology.
- Potential for geomorphological change of a channel reach determined by closeness to geomorphological thresholds.
- The relative degree of human influence on stream power (flow channelization) at different sites.
- The superimposition of hillslope and tributary stream processes and forms upon trunk channel processes.

Recent channel degradation along the study reach has limited the buffering role that alluvial fan and the floodplain used to offer. The aforementioned factors together with the higher-energy nature of the river-floodplain at present mean that the study reach is unlikely to favour the formation of floodplain wetlands.

The Baviaanskloof has indicated some similarity in the nature of channel response to that reported in several other studies of the impacts of European settlement and episodic flood events (Brooks and Brierley 1997; Cohen and Brierley 2000; Fryirs and Brierley 2001; Harvey 2001; Brooks et al. 2003; Simon and Rinaldi 2006; Godfrey et al. 2008; Hoyle et al. 2008; García-Ruiz et al. 2010). In these studies, channel widening, deepening and a shift to channel braiding has commonly been observed, in response to human land-use impacts and/or large flood events that drive a river beyond one or more thresholds. Degree of coarse sediment connectivity was suggested to be an important determinant of the increased sensitivity of a particular river to geomorphological change, aligning with the results of the present analysis.

5.5 Conclusion

In his overview of geomorphological instability and change, Harvey (2007b), indicated that semi-arid fluvial systems operate close to thresholds of erosion and deposition and are therefore intrinsically unstable. Although the Baviaanskloof River-floodplain along the study reach has indicated this characteristic, the system does appear to enter phases of relative geomorphological stability characterised by floodplain accretion, wetland formation, and stable channel form over a range of time-scales. This stability is promoted by low levels of coarse sediment connectivity together with the buffering role provided by dense woody vegetation cover, non-entrenched alluvial fans and a wide accretionary floodplain, hosting a shallow single-thread to anabranching channel. These factors were essential determinants of the resilience of the study reach to flood events prior to the onset of widespread channel degradation. Intensive human land-use activities over the last approximately 60-70 years reduced the geomorphological complexity and buffering capacity of the study reach, thereby increasing the sensitivity of the trunk channel to high-magnitude flood events. However, there was a ~70 year time lag between European settlement, and the start of agricultural activities along the valley, and the onset of channel degradation, reflecting the inherent internal resistance of the Baviaanskloof to disturbances. The breaching of geomorphological and stream power thresholds of erosion resulted in sudden and relatively short-lived channel degradation between the early 1970s and the early 1990s. Following this period the channel began to stabilize.

APPENDIX 5A: RAINFALL DATA ANALYSIS FOR STATIONS BAVLULET AND MATJIES IN THE BAVIAANSKLOOF CATCHMENT

Table 5.5: Rainfall data for station Bavlulet

year	1 day event (mm)	several day event (mm)	date	Antecedent wet/dry	flood size	notes
1951		90	11-12 Jan	wet	S-M	
1951		73	24-26 July	wet	S-M	
1952		98	16-3 Feb-Mar	wet	S-M	
1953		90	16-22 Oct	wet	S-M	
1954		186	13 Mar - 2 Apr	wet	L	2 days break without rain
1955		115	17-23 Feb	wet	S-M	
1955		76	28-5NOv/Dec	wet	S-M	2 day break without rain
1963		104.8	27 March - 13 April	dry	S-M	2 days no rain in the series
1964		63	12-13 August	wet	S-M	2 days no rain in the series
1971		103	14 Mar - 7 April	dry	S-M	2 days without rain
		117.9	17-25 August	dry	S-M	
1973		104	17 Mar - 8 Apr	dry	S-M	2 DAYS NO RAIN
1974		140	15-29 Jan	wet	L	2 days no rain twice in the series
		66	24-2 march-april	wet	S-M	
		116	22-24 Aug	wet	S-M	
		60	22-3 dec-jan	wet	S-M	
1977		65	28-13 jan-feb	wet	S-M	2 DAYS NO RAIN
		70	17-20 Feb	wet	S-M	
	31			wet	S-M	
1979		71	18-23 July	wet	S-M	
		60	11-12 June		S-M	
1981		116	22-26 March	dry	S-M	
		84	26-30 May		S-M	
		73	21-31 Aug		S-M	
		77	14-17 Oct		S-M	
1982		61	26-30 April	wet	S-M	
		94	1-7 December	dry	S-M	
		120.5	21-24 September	dry	S-M	
1996		85.5	18-23 October	wet	S-M	
		79	16-21 Nov		S-M	
		75	27-29 Dec		S-M	
1998		62	14-15 December	wet	S-M	
1999		69	20-30 july	wet	S-M	
2000		99.6	27 February - 2 March	wet	S-M	
	37			wet	S-M	
2001	34			wet	S-M	
2002		61.5	14-18 August	wet	S-M	

2005		90	12-15 November	wet	S-M	
		86	16-22 feb	wet	S-M	
year	**1 day event (mm)**	**several day event (mm)**	**date**	**Antecedent wet/dry**	**flood size**	**notes**
2011	32			wet	S-M	
		65	7-9 June	wet	S-M	
		69	23-25 July	wet	S-M	
		99	15-22 October	wet	S-M	
2012						

Table 5.6: Rainfall data for station Matjies

Year	date	rain (mm)	notes	antecedent conditions	flood events
1950	4-7 July	109		dry	S-M
1950	8-10 Oct	43		dry	
1950	4-11 Nov	125	2 days no rain	dry	S-M
1951	11-12 Jan	74		wet	S-M
1951	24-25 July	107		wet	S-M
1952	17-22 Feb	66		wet	S-M
1952	5-13 Aug	63	2 days no rain	wet	S-M
1952	21-24 Aug	40		wet	
1952	10-18 Sep	82		wet	S-M
1952	13-19 Dec	44		wet	
1953	21-1 Jun-July	44	2 days no rain	wet	
1953	15-23 Oct	104		wet	S-M
1954	11-15 March	42		wet	
1954	29-02 Apr-May	88		wet	S-M
1954	16-27 July	58.2		wet	S-M
1954	25-29 Aug	115		wet	S-M
1955	17-9 Feb-Mar	143		wet	L
1955	28-5 Nov-Dec	74.6		wet	S-M
1956	23-25 May	51		wet	S-M
1956	15-23 Sep	81		wet	S-M
1956	16-21 Dec	44		wet	
1958	26-31 May	61		dry	
1959	11-13 Jan	54		dry	
1959	28-3 Apr-May	44		dry	
1959	10-18 Jul	50		dry	

Year	date	rain (mm)	notes	antecedent conditions	flood events
1959	29-31 Aug	47		dry	
1960	3-5 Jan	49		wet	
1960	16-Jan		24	wet	
1961	9-30 Mar	136		dry	S-M
1961	29-9 July-Aug	42		dry	
1962	20-22 Aug	96		dry	
1962	15-23 Nov	44		dry	
1963	1-22 mar	52		dry	
	27-13 mar-apr	113		dry	S-M
	7-15 dec	56		dry	
1964	11-13 Aug	83		wet	S-M
	14-21	76		wet	S-M
	5-7 Nov	46		wet	
1965	29-2 Sep-Oct	43		wet	
	30-13 Oct-Nov	60		wet	S-M
	16-17 Dec	40		wet	
1966	21-Jan		22	wet	
1967	8-28 Apr	140		dry	S-M
	25-1 May	72		dry	S-M
1968	26-4 June	51		wet	S-M
	8-20 June	107		wet	S-M
	30-3 Aug-Sep	81		wet	S-M
1969	15-19 June	40		wet	
	17-1 oct-nov	56		wet	S-M
1970	4-8 dec	61		dry	
1971	1-10 Apr	70		dry	
	29-31 July	59		dry	
	18-25 Aug	118		dry	S-M
1972	2-6 Feb	78		wet	S-M
1973	17-22 Mar	43		dry	
	06-Nov		24.3	dry	
1974	15-29 Jan	115		dry	S-M
	21-5 feb-mar	57		dry	
	13-26 mar	62		dry	
	3-8 may	59		dry	
	18-24 aug	160		dry	L
1975	15-Mar		21	wet	
	06-Jun		21	wet	
1975-76	27-11 Dec-Jan	55		dry	

Year	date	rain (mm)	notes	antecedent conditions	flood events
1976	18-22 Mar	47		dry	
1977	28-2 Jan-Feb	114		wet	S-M
	9-16 may	70		wet	S-M
1978	1-2 nov	42		dry	
1979	02-May		20	dry	
	6-10 may	58		dry	
	22-4 may-june	48		dry	
	9-12 june	103		dry	S-M
	18-24 july	79		dry	S-M
	16-22 aug	70		dry	
1981	23-5 jan-feb	69		dry	
	20-22 mar	131		dry	S-M
	24-1 apr-may	56		dry	
	25-30 may	137		dry	L
	12-1 aug-sept	132		dry	S-M
	14-17 oct	96		dry	S-M
1982	15-19 apr	42		wet	
	26-30 apr	106		wet	S-M
1983	9-17 july	69		dry	
	21-27 july	140		dry	S-M
1985	5-12 feb	45		dry	
	12-15 oct	45		dry	
	28-9 nov	47		dry	
	20-10 nov-dec	74		dry	S-M
	18-24 dec	63		dry	
1986	1-15 oct	63		wet	S-M
1987	14-22 apr	51		dry	
	19-2 sep-oct	83		dry	S-M
1988	1-7 apr	50		dry	
	15-29 dec	58		dry	
1989	9-23 apr	51		dry	
	1-9 oct	53		dry	
	14-18 nov	85		dry	S-M
1991	28-30 oct	47		dry	
1992	27-2 feb-mar	51		dry	
	22-24 july	55		dry	
	7-10 aug	59		dry	
	6-20 oct	76		dry	S-M
	8-16 nov	47		dry	
1993	11-13 june	57		wet	

Year	date	rain (mm)	notes	antecedent conditions	flood events
	21-29 sept	148		wet	L
	2-9 dec	44		wet	
1994	28-7 mar	45		wet	
	19-23 apr	77		wet	S-M
	23-27 dec	57		wet	S-M
1995	17-30 mar	43		wet	
	20-22 aug	42		wet	
	13-26 dec	64		wet	S-M
1996	18-23 oct	98		wet	S-M
	5-2 nov-dec	207		wet	L
	26-31 dec	92		wet	S-M
1997	14-19 mar	54		wet	S-M
	29-9 mar-apr	87		wet	S-M
	23-27 may	55		wet	S-M
1998	20-Feb		22	wet	
	24-1 mar-apr	48		wet	
	5-14 may	46		wet	
	21-24 aug	50		wet	
	13-21 dec	53		wet	S-M
1999	27-6 feb	42		wet	
	26-1 july-aug	52		wet	S-M
	26-3 sep-oct	40		wet	
1999-2000	21-7 dec-jan	77		dry	
2000	23-28 jan	40		dry	
	10-19 feb	52		dry	
	1-17 mar	43		dry	
	23-4 apr	46		dry	

CHAPTER 6: TRIBUTARY-TRUNK STREAM RELATIONS: IMPLICATIONS FOR RIVER SENSITIVITY

6.1 Introduction

One of the distinguishing features of the Baviaanskloof River-floodplain is the numerous alluvial fans that have formed where tributaries exit the surrounding steep mountain catchment onto the gently sloping valley floor. Nearly all tributaries along the study reach have formed fans of variable size. Tributary fans are effective buffers of sediment connectivity between mountain hillslopes (uplands), the valley floor and a trunk stream, where they form temporary stores of sediment received from discontinuous tributary streams (Harvey 2002a; Fryirs et al. 2007a; Fryirs et al. 2007b; Harvey 2012). However, the buffering role of tributary fans may be altered by fan entrenchment or truncation, which is often linked to processes occurring along a trunk stream (Harvey 2012). Increasing tributary-trunk connectivity and associated delivery of coarse sediment and water to the trunk channel can result in considerable changes in trunk channel process and form, commonly through channel deepening, widening and/or braiding (Chew and Ashmore 2001; Fryirs et al. 2007a; Fryirs et al. 2007b; Bravard 2010; Farraj and Harvey 2010). The aforementioned channel adjustments reflect the enhanced geomorphological sensitivity of the receiving trunk channel reach, due to increased coarse sediment delivery from the wider catchment. The nature and rate of channel adjustment to coarse sediment delivery can be variable for different rivers, reflecting the influence of local channel controls such as riparian vegetation structure and cover, bed or bank armouring, and proximity to local geomorphological thresholds (Hooke 2003; Anders et al. 2005; Beechie et al. 2006; Harvey 2007b; Lane et al. 2007; Bravard 2010). Few studies have investigated the influence of coarse sediment connectivity on river sensitivity in upland river catchments dominated by bed load. In her conceptual paper, Hooke (2003), indicates that coarse sediment connectivity is a fundamental driver of channel morphology and sensitivity to geomorphological change. The concept of coarse sediment connectivity thus provides a useful framework for understanding river sensitivity and dynamics in upland gravel-bed streams.

The impacts of tributary junctions and tributary junction fans on trunk stream process and morphology has been demonstrated for several upland fluvial systems in the northern hemisphere, but not across a wide range of fluvial environments. Some of the commonly documented morphological impacts of tributary junction streams and fans on a trunk stream include:

- Increased trunk channel slope downstream of a tributary confluence due to sediment accumulation across the trunk and associated channel bed aggradation (Ashmore 1991a; Bravard 2010).
- Marked increases in trunk channel width associated with increased discharge within the vicinity of a tributary junction (Harvey 2007b; Farraj and Harvey 2010).
- Introduction of a series of localised sedimentation zones downstream of tributary junctions and associated discontinuous braiding and channel instability (Ashmore 1991b; Harvey 2007b; Bravard 2010; Farraj and Harvey 2010).
- A local rise in base level where a tributary fan extends across the entire valley floor and blocks the trunk channel, in which case the trunk channel may attempt to cut through the fan deposit where it has sufficient capacity (Lane et al. 2008).

The caliber and volume of sediment delivery to a trunk channel from a connecting tributary, relative to the transport capacity of the receiving channel reach, determines the influence of a connecting tributary on trunk channel morphology (Rice 1998; Church 2006). If more sediment is delivered than the capacity of the trunk to transport the sediment, then bed deposition on the trunk will occur upstream of the impinging tributary fan. If transport capacity is higher than the volume and caliber of sediment supplied, then the trunk may adjust through channel widening and deepening and the available sediment will be transferred to downstream reaches. However, the latter is not the only determinant of trunk channel response. A receiving stream may exhibit a delayed response to increased water and coarse sediment inputs, where riparian and instream vegetation stabilizes the channel or where bed and bank sediments are resistant to erosion (Fryirs and Brierley 2001; Harvey 2002a; Farraj and Harvey 2010). Similarly, if the receiving reach is competent enough to transport most of the sediment supplied from a tributary junction to downstream reaches, then there may be little morphological adjustment within the vicinity of the receiving reach.

The interaction between tributary stream junctions and a trunk stream may be reciprocal, as tributary streams generally respond to erosional or depositional processes along a trunk stream (Harvey 2002b; Grenfell et al. 2008). Degradation along a trunk stream may initiate degradation along a tributary, as the tributary adjusts to a lowered base-level (Harvey 2002b; Harvey 2012). This situation may result in tributary fan entrenchment and enhanced tributary-trunk connectivity. Alternatively, aggradation along a trunk channel that occurs at a higher rate than aggradation along a tributary stream junction, may result in blockage of the tributary by the trunk, inducing flood-out formation along the tributary (Grenfell et al. 2009a). The response of tributaries to trunk processes in dryland catchments may be relatively rapid (years) or there may be a considerable lag time in response (hundreds to a thousand years).

The nature of interactions between tributary and trunk streams is thus diverse and complicated by local controls on sensitivity to geomorphological change, and the relative nature of hydrological and geomorphological processes occurring along tributary streams compared to the trunk stream.

The Baviaanskloof River-floodplain receives considerable amounts of coarse sediment via tributary streams and tributary fans that impinge on the floodplain every few hundred to thousand meters. The channel bed of these tributary streams is characterised by coarse angular grains of mostly pebbles and cobbles, with some boulders indicating high competence and capacity to transfer the coarse sediment from the surrounding mountains during flood events (Plate 6.1). Historically this coarse sediment would have been stored on alluvial fans that formed where streams exit the mountains and enter the valley floor. However, recent fan entrenchment and enhanced tributary-trunk connectivity has diminished the buffering role these fans used to offer along the study reach. Limited understanding of the impacts of tributary-trunk (dis)connectivity on river process, form and sensitivity to change in dryland, gravel-bed streams such as the Baviaanskloof, poses a problem for effectively predicting and managing the impacts of human land-use activities and climate change on these types of systems.

Plate 6.1: The coarse nature of sediment on tributary stream beds.

This chapter aims to investigate the influence of coarse sediment (dis)connectivity on channel-floodplain process, form and sensitivity to erosion, focusing on the influence of tributary-junction fans and streams on the trunk stream at the reach (several thousand meters) to sub-reach scale (several hundred meters). Three main objectives that underpin the overall aim will be addressed:

1) Describe the influence of tributary catchment size and slope, and flooding regime, on patterns of tributary-trunk (dis)connectivity and coarse sediment supply to the trunk channel.
2) Investigate downstream variations in present-day geomorphological form and process of the trunk channel and relate this to pattern and regime of coarse sediment supplied by connecting tributary streams.
3) Determine if there is a relationship between tributary stream (dis)connectivity and sensitivity of the trunk channel to geomorphological change.

The knowledge produced from the above investigation forms an essential component of understanding controls on river sensitivity and geomorphological dynamics for developing a process-based rehabilitation plan for the Baviaanskloof.

6.2 Methods

6.2.1 Patterns and degree of tributary-trunk connectivity

The method used to identify and describe the degree of coarse sediment connectivity was largely qualitative and relied on previous studies including Hooke's (2003) coarse sediment connectivity model for two European gravel-bed systems, as well as the classification system for different (dis)connectivity landforms provided by Fryirs et al. (2007a). Both Hooke (2003) and Fryirs et al. (2007a) infer sediment connectivity based upon the pattern and type of geomorphological features within a catchment that are known to either enhance or impede water and sediment fluxes. Both studies focus at different spatial and temporal scales and at different types of rivers: Hooke (2003) infers coarse sediment connectivity at the channel-reach scale for a gravel-bed stream based upon channel morphology and the presence or absence of bed features such as channel bars that indicate competence for temporary transfer of coarse sediment during floods. Fryirs et al. (2007a) infer sediment connectivity for a mixed-load stream based upon the pattern of geomorphological features in a catchment that act as barriers, buffers, blankets or enhancers of water and sediment connectivity. Hooke (2003: 85) defines three levels of coarse sediment connectivity:

1) Unconnected: Local sources and stores/sinks separated by incompetent reaches;
2) Partially connected: Transfer only occurs during extreme flood events;
3) Connected: Coarse sediment is transferred during 'normal' flood events;
4) Potentially connected: Channel reach has competence to transport coarse sediment but there is a lack of supply;
5) Disconnected: Formerly connected but transfer along reach is now obstructed (e.g. by dams).

Fryirs et al. (2007a) infer two degrees of connectivity:

1) Connected: When a landform or part of a catchment receives available water and sediment from the upstream catchment area;
2) Dis-connected: When buffers, barriers or blankets limit sediment and water conveyance to a particular landform or part of catchment.

The time period for which different landforms or parts of a catchment are either connected or disconnected is dependent on the magnitude-frequency of disturbance events that are able to maintain sediment conveyance or breach impediments to sediment conveyance (Fryirs et al. 2007a).

The present study focusses at coarse sediment connectivity but adopts the approach of Fryirs et al. (2007a), to infer patterns and degree of coarse sediment connectivity for the study reach, drawing from the approach of Hooke (2003). Coarse sediment connectivity in the present study was described in terms of tributary-trunk connectivity and general patterns of upstream-downstream connectivity along the trunk channel, since these are the main conduits of coarse sediment. The 2009 digital orthorectified aerial imagery with topographic references 3323DB Studtis and 3324CA Zandvlakte, were used to map geomorphological features such as alluvial fans, channel bars and stream channels, in order to identify the degree of tributary-trunk and upstream-downstream connectivity.

Three classes of tributary-trunk connectivity were defined in the present study (Figure 6.1), as follows:

1) Disconnected: when a channel reach does not receive coarse sediment from a source. For example, a disconnected tributary-trunk situation would occur when a tributary stream does not reach the trunk channel due to loss of confinement on a fan or floodplain surface that traps sediment. A trunk channel reach may also be disconnected from bed load sediment supplied from upstream eroding reaches due to the presence of a human-made weir or dam.
2) Partially connected: when a channel reach only receives a limited portion of bed load sediment being supplied from upstream or from lateral inputs due to the presence of one or more geomorphological or human-made features that partially impede water and sediment movement. This situation may include, barriers such as small dams that occur in part of a tributary catchment, and thus partially impede water and sediment transfers; a tributary stream that loses considerable competence through diminished channel width and depth before reaching the trunk stream resulting in only partial transfer of coarse sediment to the trunk stream during floods.
3) Well-connected: when a channel reach receives most of the bed load sediment being supplied from upstream or lateral inputs during flood events. For example, a well-connected tributary channel is one that has dissected an alluvial fan such that bed

load and fine sediment is readily supplied to the trunk channel. Effective transfers of sediment to the trunk channel are usually indicated by debris cones or cobble bars that form at the junction of or shortly downstream of the tributary junction. Alternatively, actively degrading trunk channel reaches usually have excess transport energy and will thus effectively transmit coarse sediment supplied from upstream to downstream channel reaches during floods.

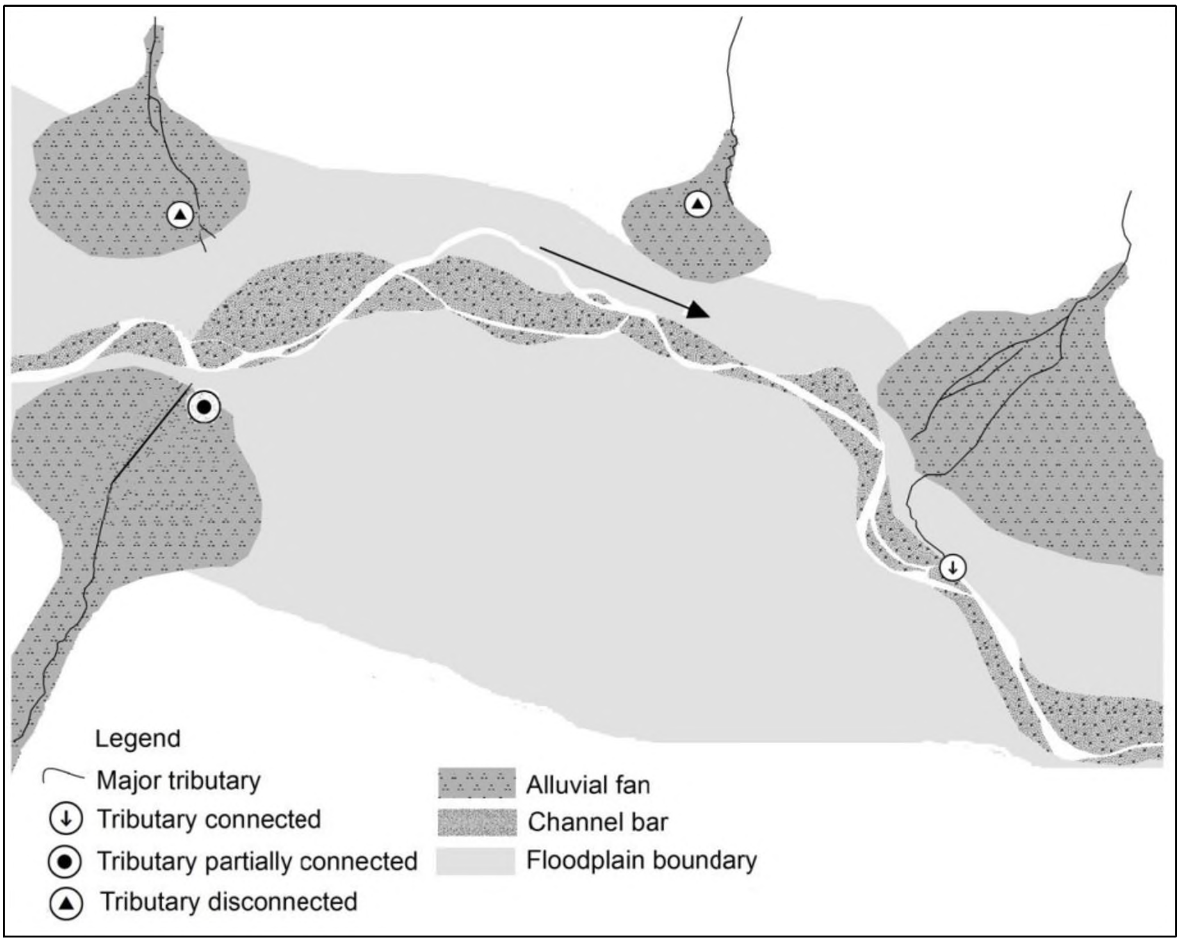


Figure 6.1: Examples of the degrees of tributary-trunk connectivity defined in the present study. Flow direction is indicated by the arrow.

The catchment area and average channel slope of each tributary stream was measured using the orthorectified 2009 aerial imagery and spatially referenced 20 m contours in ArcGIS (version 10.1). The catchment of each tributary stream was digitized using ArcGIS and the catchment area of each tributary was measured using the measuring tool for polygon features. Average channel gradient of each tributary stream was calculated by digitizing the main stem stream and measuring the distance along the digitized feature.

Change in elevation along each tributary stream was calculated using the spatially referenced 20 m contours in order to calculate average slope

The above variables were plotted on a scatter graph to determine the relationship between tributary catchment size and channel slope, and degree of tributary-trunk connectivity. An independent T-test was performed to determine whether there was a significant difference (significant at $p<0.05$) in catchment size and average tributary channel slope between tributaries on the southern vs. northern side of the river valley.

6.2.2 Tributary junction impacts on trunk stream process, form and sensitivity

Downstream variations in the geomorphological form of the trunk channel, indicated by variations in channel width, sinuosity and braiding intensity, thalweg slope, and river style was described in relation to the pattern of connecting tributary streams and other controls including valley width and slope. Channel width, sinuosity and braiding intensity was measured using the same approach described in Chapter 4. The slope along the trunk channel thalweg and left and right bank surfaces were surveyed every 300 to 500 m along the length of the study reach using dumpy level and staff surveying techniques (accuracy in the elevation plane of ~0.05 m per km).. The location of connecting tributary streams was superimposed onto the longitudinal profile by measuring the distance of each connecting tributary along the length of the trunk stream in ArcGIS, from the 2009 orthorectified aerial imagery. Downstream breaks in trunk channel thalweg and floodplain slope, indicating changes in geomorphological process and form, were visually identified as distinct points of deviation from the uniformity of the plotted longitudinal profiles. Changes in trunk channel sinuosity, width and bankfull depth were measured for 400 m reaches upstream and downstream of tributaries that were classed as well-connected, to identify impacts of tributary junctions on trunk channel geometry and behaviour. Trunk channel width was measured at approximately 80 m intervals along these 400 m zones upstream and downstream of the point of a tributary junction, in ArcGIS, using the orthorectified 2009 aerial imagery. The edge of the channel was delineated where the riparian tree line began. Changes in bankfull depth within the 400 m zone were calculated from channel cross-sectional surveys conducted for the entire study reach.

Slope thresholds of erosion at the reach (over several kilometers) and sub-reach (over several 100 m) scales of the trunk channel were identified by relating the slope of the left and right floodplain surface to levels of degradation along the trunk channel. If the trunk channel was degraded (using criteria identified in Chapter 4), then the threshold slope of degradation was inferred from the slope of the left and right bank surface adjacent to the degraded or degrading channel reach.

Downstream changes planform morphology and geomorphological behavior of the river-floodplain were described by adapting the approach of the River Styles Framework described by Brierley and Fryirs (2005). Major changes in river style were related to changes in valley width, slope and frequency of tributary stream junctions (number of streams connecting per km of channel length), and observed behavior of the trunk stream during small to moderate flood events.

6.3 Results

6.3.1 Characteristics of tributary-trunk connectivity

There are differences in the size, slope and degree of connectivity of tributary streams ($n = 32$) originating on the north compared to the south side of the trunk river valley. The southern tributary catchments are significantly larger and lower sloping than the northern tributary catchments ($P=0.0023$ and <0.0001 respectively; Table 6.1). The larger southern tributaries have produced relatively large fans, with significantly greater fan length than the northern fans ($P=0.023$, Table 6.1). Many of these southern fans extend across the floodplain impinging upon the trunk stream. In contrast, most of the smaller northern fans are small and do not reach the trunk stream.

Table 6.1: Mean catchment area, channel slope, and fan length for tributaries on the northern and southern sides of the Baviaanskloof River valley, for the study reach. Standard deviations and significance values for a T-test comparing catchment size and channel slope between the northern and southern tributary streams are indicated.

Tributaries	Mean catchment area (km^2)	Mean channel slope (m/m)	Mean fan length (m)
Northern (n=19)	4.5 (SD = 3.4)	0.18 (SD = 0.04)	406
Southern (n=13)	24.6 (SD = 26.3)	0.08 (SD = 0.04)	1382
***P*-value from a T-test**	0.0023	<0.0001	0.023

Tributary streams originating on the southern side of the river valley have an overall higher degree of connectivity with the trunk stream than tributaries originating on the northern side of the river valley (Figure 6.2a). In general there is a negative relationship between tributary catchment size and channel bed slope, and this relationship influences the degree of connectivity of tributaries with the trunk stream (Figure 6.2b). In general, small catchments, equating to relatively low discharge and high channel slope, are disconnected and the well-connected tributaries have large catchment areas, equating to higher discharges and gently sloping channels. However, there are several tributaries that deviate from the aforementioned general trend, including tributaries with relatively small catchment areas that are well-connected. The two tributaries reported as outliers in Figure 6.2b, are well-connected to the trunk channel because the channel has truncated the toe of these small alluvial fans, lowering the base-level. Several of the larger tributaries that are presently well-connected to the trunk channel have been artificially channelized, to promote flow from the tributary into the trunk stream, thereby protecting infrastructure on the fan ('connectivity artificially enhanced', Figure 6.2b). Hence, factors other than catchment size and associated discharge, such as human land-use, or position of the trunk stream in relation to a tributary stream on the valley floor, influence degree of tributary-trunk connectivity.

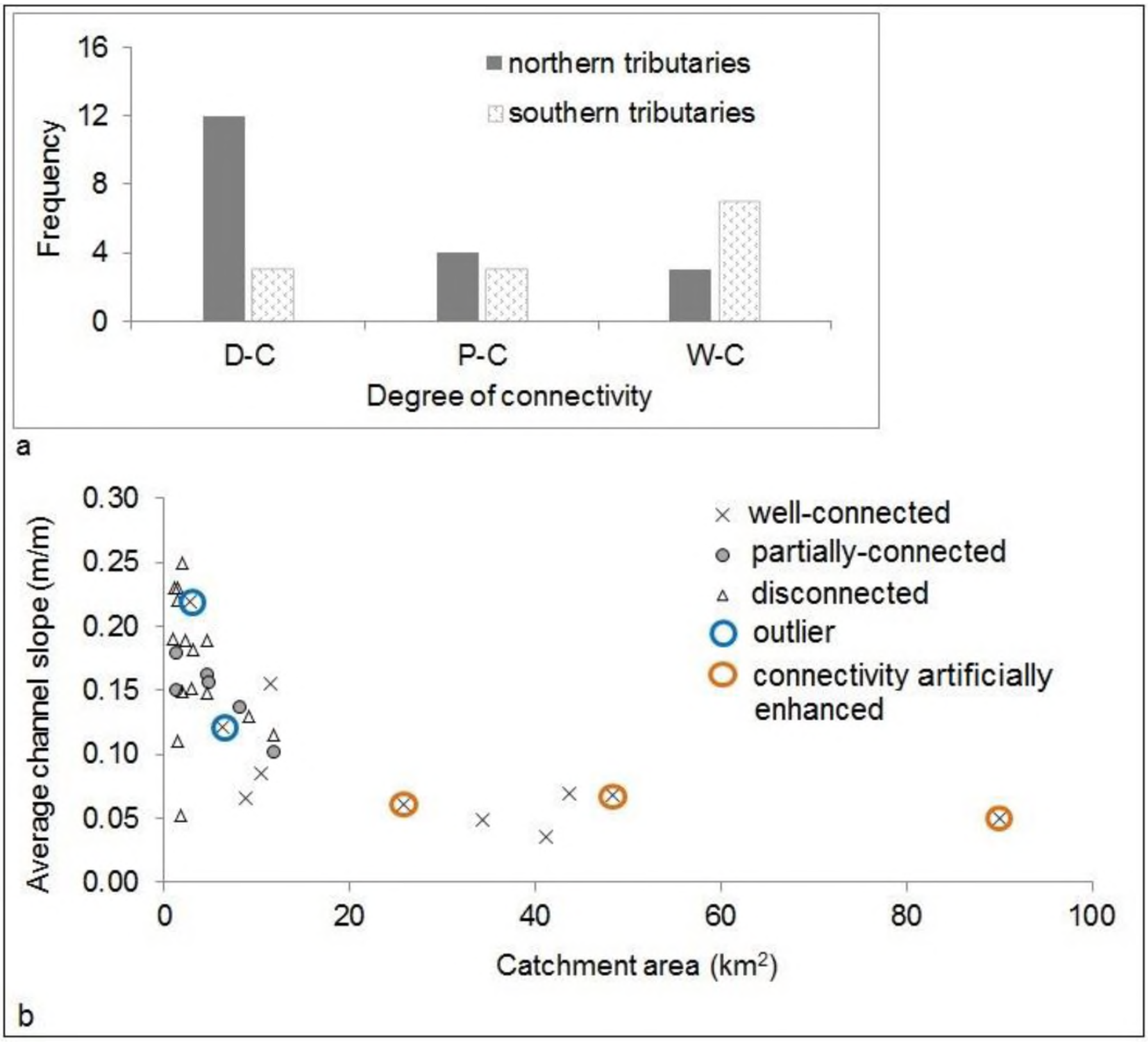


Figure 6.2: The frequency of disconnected (D-C), partially connected (P-C), and well-connected (W-C) tributary-trunk confluences for the northern versus southern tributaries (a); and the relationship between catchment area (discharge), average channel slope, and degree of tributary-trunk connectivity (b).

6.3.2 Downstream variations in channel-floodplain form and process in relation to tributary connectivity

Channel planform characteristics

Over most of the study reach the trunk channel maintains a braided channel pattern with channel bifurcations occurring at channel bars consisting of coarse bed load material. The most distinct deviation from this pattern exists along sub-reach B, where the channel divides around a relatively large and stable sediment island (Figure 6.3), and thereby displays a braided-anastomosing channel pattern (Bridge 2003). Common channel bed features include pool-riffle sequences which span several tens of meters along the channel bed, channel bars of varying size, and erosional head cuts. Head cuts form either at the distal end of a relatively steep riffle section, or at a channel bar where flow converges. Channel bars are unstable features that are morphologically altered during small to moderate or large flood events.

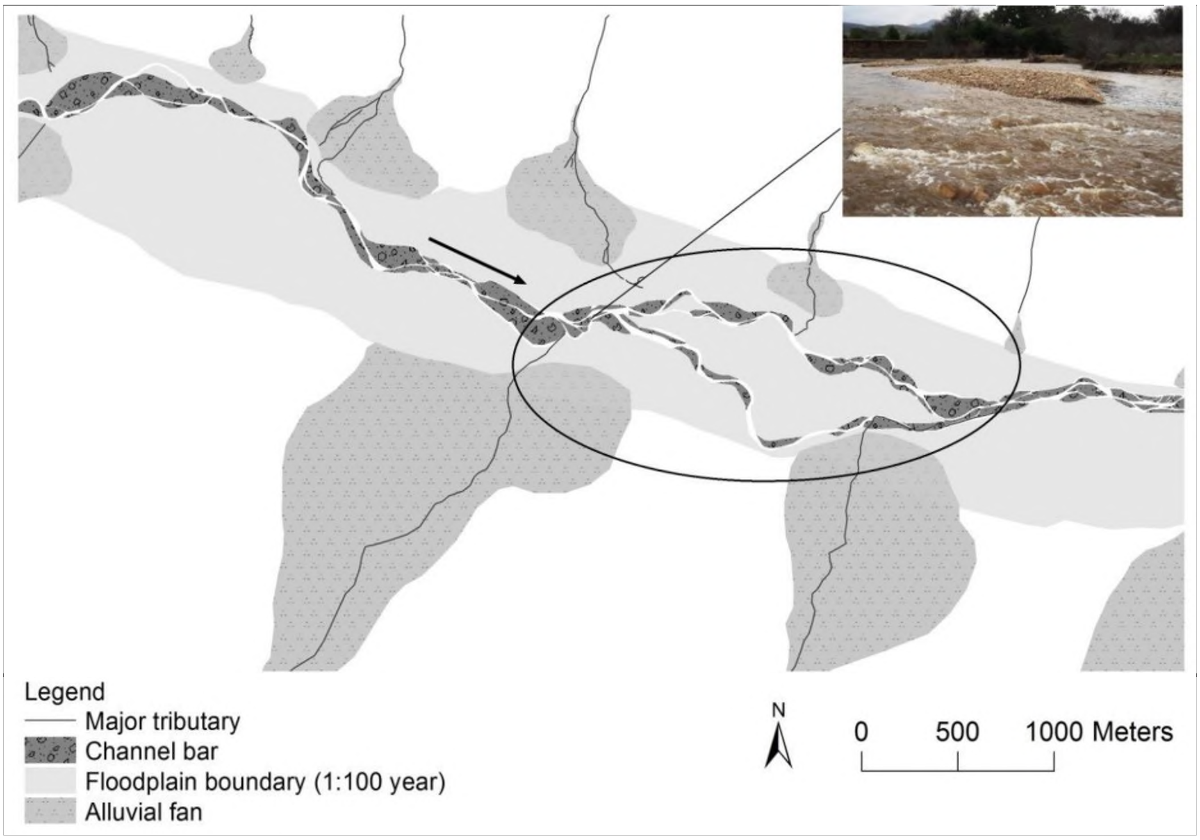


Figure 6.3: The braided-anastomosing channel planform (circled) of the Baviaanskloof River. Flow direction is indicated by the arrow.

Distinct downstream variations in valley and trunk channel morphology occur at the sub-reach scale, from sub-reach A at the upper-part of the study reach to sub-reach C at the lower-end of the study reach (Table 6.2). Channel thalweg slope decreases progressively downstream from sub-reach A, with a slope of 0.0072 m/m, to sub-reach B, with a slope of 0.0069 m/m, to sub-reach C, with a thalweg slope of 0.0060 m/m. Thalweg slopes along sub-reach B and C are lower than the average floodplain slopes for these sub-reaches respectively. Along sub-reach A, the channel has the same slope as the surrounding floodplain. Thalweg channel sinuosity increases consistently downstream ranging between 1.2 and 1.3, indicating an overall 6% increase in thalweg sinuosity between sub-reach A and sub-reach C (Table 6.2). Sub-reach B, which is the most unconfined valley reach, has the highest average floodplain slope (0.0078 m/m) and braiding intensity (*B:* ~1.8) of all the sub-reaches. This sub-reach, together with sub-reach A, have a higher frequency of connecting (partially and well-connected) tributary streams than sub-reach C.

Table 6.2: Valley and trunk channel morphological characteristics for sub-reaches A to C.

Valley sub-reach	Average valley floor width (m)	Average floodplain slope (m/m)	Thalweg channel slope (m/m)	Thalweg channel sinuosity *(SI)*	Braiding Index (*B*)	Connecting tributaries (frequency/km channel)	Average catchment area of connecting tributaries
A	580	0.0072	0.0072	1.2	1.7	0.8	
B	1 263	0.0078	0.0069	1.25	1.8	0.8	
C	745	0.0064	0.006	1.27	1.6	0.5	

Adapting the approach of Brierley and Fryirs (2000) to defining river styles, three distinct river styles were defined for the study reach. The spatial extent and pattern of the river styles identified conform to the three valley morphological sub-reaches characterized in Table 6.2 above. The identified river styles are described below with photographic examples.

1) ***Transfer style (valley sub-reach A):***

This style occurs mainly along sub-reach A at the upper-end of the study reach and is dominated by a single thread, narrow and straight channel that is relatively stable, flowing through a narrow valley reach (Figure 6.4). The channel is relatively steeply sloping (average of 0.0072 m/m) and is largely a conduit of sediment to downstream channel reaches during floods, downstream of which sediment is stored in channel bars and on the floodplain. The transfer style has fewest human-made features that influence water and sediment connectivity and space for river adjustment, and represents one of the most stable sub-reaches along the study reach.

Figure 6.4: Example of a transfer river style along the upper-end of the study reach. The arrow indicates direction of flow for the trunk stream.

2) Cut-and-fill style (valley sub-reach B):

The cut-and-fill style consists of a wide and relatively deep channel, inset within a wider incised channel boundary with a continuous floodplain (Figure 6.5). The trunk stream has recently cut into intact floodplain swamps, adjusting from a once relatively stable and narrow single-thread to anabranching pattern, with a vertically accreting floodplain, to a wide, braided channel dominated by lateral sediment accretion and relative channel instability. Numerous tributaries join the trunk stream from the north and south side of the river valley, increasing the sensitivity of this style to morphological change. The trunks stream is more gently sloping than the transfer river style, with an average slope of 0.0069 m/m. The terraces indicated in floodplain cross-sectional profiles presented in Chapter 5 suggest historic phases of river-floodplain cutting and filling. These cut-and-fill phases are supported with evidence of relatively coarse (high energy) and fine-grained (low energy) sedimentary units in exposed erosion vertical sections. Although the channel appears to be situated in an unconfined floodplain, the existence of human made earthen levees on either side of the channel, as indicated in Chapter 5 (see Figure 5.2), partially limits the ease with which lateral adjustments may occur. During small to moderate floods stream flows are thus confined to the active channel zone. Floodplain accretion for this river style is limited by both a deepened channel and channelizing levees. Coarse sediment is stored mostly along the active channel zone in lateral and mid-channel bars and on the channel bed in riffles and sediment zones, while fine sediments appear to be transmitted downstream. This river style is the most unstable and sensitive of the three styles identified for the study reach, and has a relatively high frequency of connecting tributary streams of large catchment size.

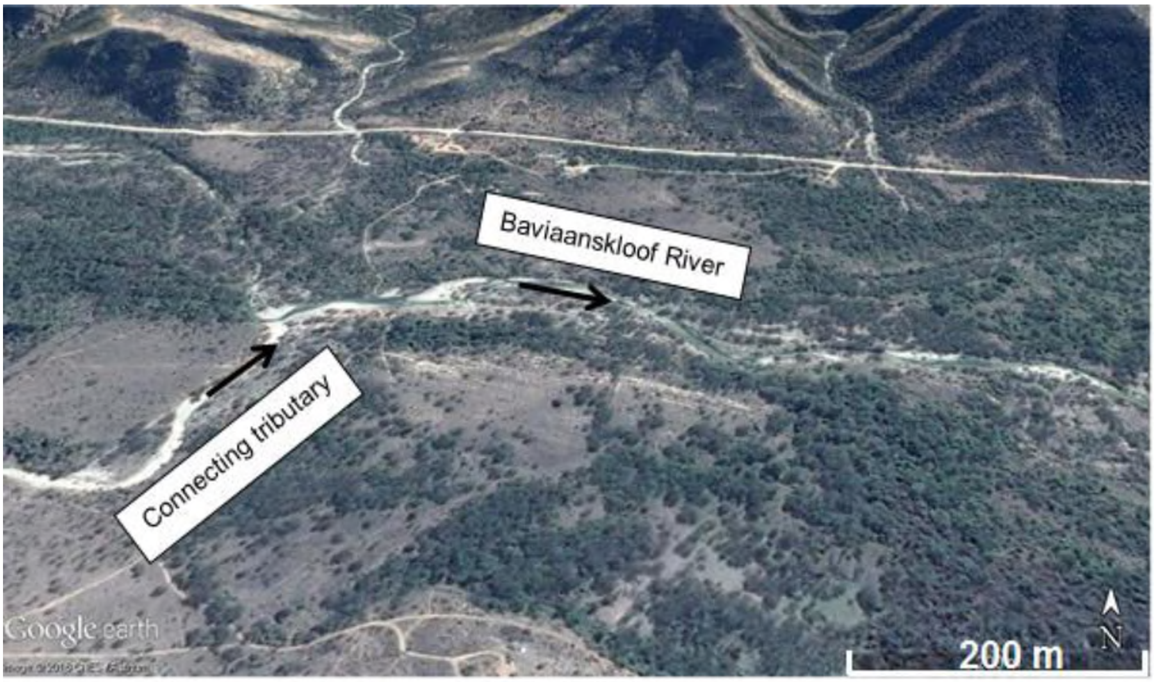


Figure 6.5: Example of a cut-and-fill river style along the middle of the study reach. The arrows indicate direction of flow of the trunk stream and a connecting major tributary.

3) ***Floodplain accumulation style (valley sub-reach C)***:

In this style the channel is braided and laterally dynamic and lies within a largely unconfined floodplain setting (Figure 6.6). Earthen levees have limited the lateral connectivity of the channel in some places. However, the presence of lateral channel bars, levees and abandoned channels on the floodplain indicate that the channel is dynamic, storing sediments largely through lateral accretion processes as the channel migrates and avulses across the valley floor. The floodplain is more frequently flooded than the cut-and-fill style due to lower levels of channel degradation and less intensive human channelization. The trunk stream has the lowest average slope, of 0.006 m/m. This style has a lower frequency of connecting tributary streams than the upstream cut-and-fill and transfer river styles. The floodplain accumulation river is an important river zone for receiving and storing some of the sediments that have eroded from the upstream cut-and-fill style.

Figure 6.6: An example of a floodplain accumulation style along the lower-end of the study reach. Flow direction is indicated by the arrow.

Variations in longitudinal slope, channel width and sinuosity

The Baviaanskloof River thalweg over the entire study reach averages 0.0066 m/m (Figure 6.7). This average channel slope falls within the moderately steep, upper-foothills zone of the geomorphological zonation system described by Rowntree et al. (2000). Both the left and right floodplain surfaces, approximating the pre-degradation channel slope, have an average longitudinal slope of 0.0067 m/m which can be considered to be the same as the average longitudinal slope of the present trunk channel thalweg.

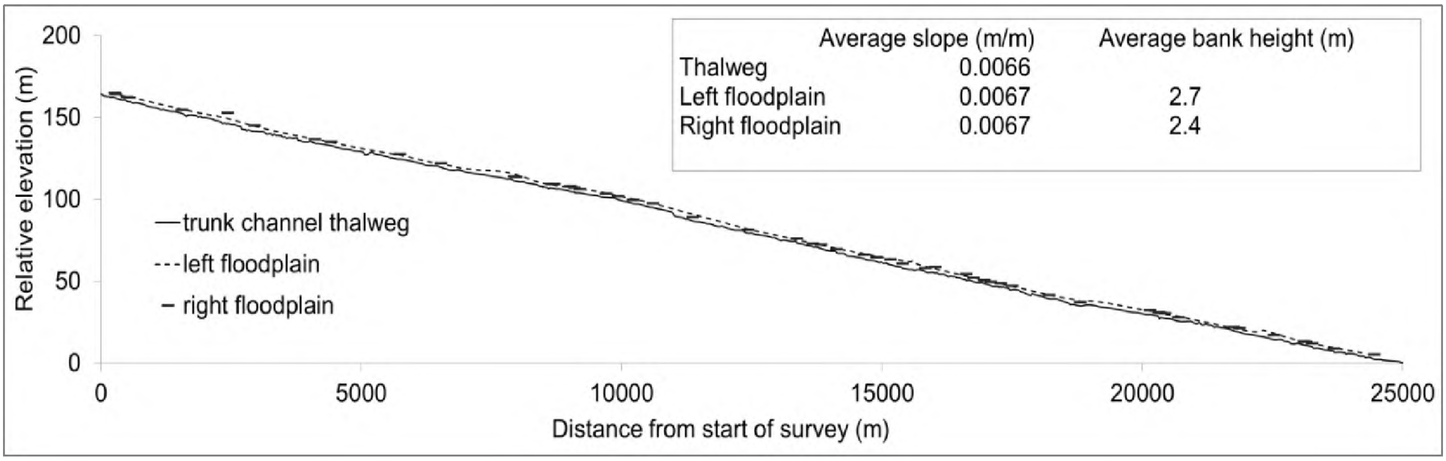


Figure 6.7: Longitudinal profile of the Baviaanskloof River thalweg and the floodplain surface ('Left floodplain' and 'Right floodplain'), indicating average slope along the study reach.

The longitudinal profile of the trunk channel thalweg and surrounding floodplain surface indicate a downstream pattern of slope changes characterised by alternation between relatively gentle and steep sloping channel reaches (Figure 6.8). The trunk channel thalweg and left and right floodplain surface all indicate contrasting patterns of change in longitudinal slope. In most cases a break in trunk channel thalweg slope occurs where one or more tributaries, of varying catchment size, connect to the trunk channel ((K2 and B3), B9, B8 & K8; Figure 6.8). However there are several tributaries, also of variable catchment size, that do not appear to be associated with a downstream break in thalweg slope (K1, K3 and K12). Tributaries that are associated with a break in thalweg slope either initiate a downstream decrease in slope ((K2 & B3), K6, K8 and K10; Figure 6.8), or a downstream increase in slope (K5, B9, (G7 and K7), K10; Figure 6.8), independent of tributary catchment size.The circled areas in Figure 6.8 represent areas of higher relief than is expected if the floodplain has a uniform longitudinal slope, and illustrate the influence of tributary fans on local floodplain topography, where they initiate a local downstream steepening of slope along the floodplain.

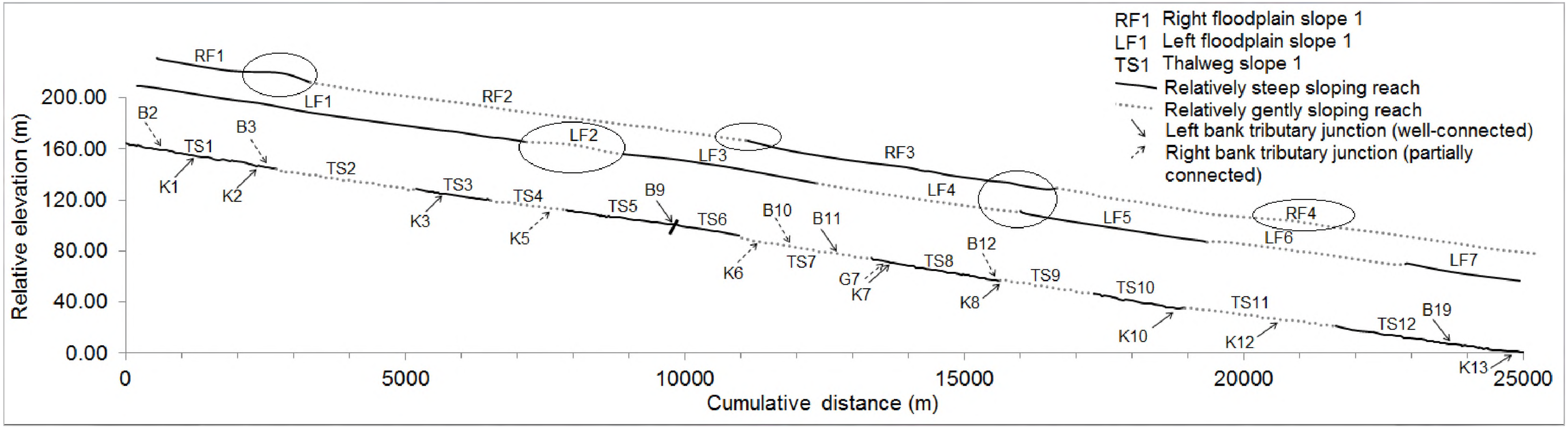


Figure 6.8: The longitudinal profile of the Baviaanskloof River thalweg, indicating slope break reaches (TS1-TS12), and left and right floodplain surface slope break reaches (RF1-RF4; LF1-LF7). The latter profiles are plotted above the thalweg without reference to elevation. The arrows indicate the location of well- and partially-connected tributary streams along the trunk channel profile, with left-bank tributaries indicated by the prefix B and right-bank tributaries by K. The prefix G refers to a gully entering the trunk stream. The oval symbols on the left and right floodplain indicate zones elevated above the floodplain if it is plotted as having a linear slope.

Figure 6.9 shows local-scale variations in trunk channel and floodplain slope. The reach indicated in the figure has incised up to 6 m, in the zones where it is imposed upon two alluvial fans entering the valley from opposite sides (K8 and B12; Figure 6.9). Both alluvial fans are dissected by their respective tributaries such that they are well-connected to the trunk channel. It is clear that both tributary fans initiate an upstream reduction of floodplain slope and a downstream steepening of floodplain slope in areas where they impinge upon the trunk channel. The tributary junction streams also initiate a downstream steepening of channel thalweg slope where they join the trunk channel. The channel bed slope is 0.0053 m/m (JS2, Figure 6.9), upstream of and in the vicinity of where the two streams join the trunk channel. However, thalweg slope increases to 0.0067 m/m shortly downstream of the tributary junctions (Slope reach JS3; Figure 6.9).

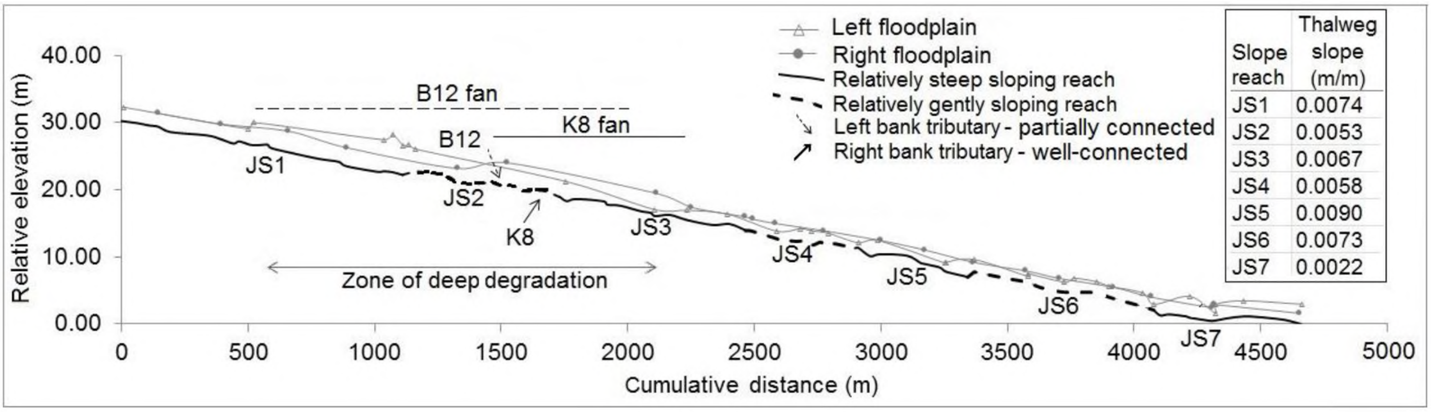


Figure 6.9: The longitudinal profile of the Baviaanskloof River thalweg and left and right floodplain surfaces at the local scale along a selected reach where pronounced river degradation has occurred.

Figure 6.10 compares local scale variations in trunk channel sinuosity over 400 m reaches upstream and downstream of connecting tributary streams. In 9 out of the 12 cases there is a slight decrease in channel sinuosity along the 400 m reach downstream of a connecting tributary stream, regardless of the relative catchment size of the connecting tributary stream (B11, B9, K7, K3, B19, K12, K6, K1, K8; Figure 6.10). The influence of tributary junction streams on trunk channel width is not clear. Several trends in variation in trunk channel width upstream and downstream of tributary junctions are indicated in Figure 6.11a-d. In some cases there is a decrease in channel width toward a tributary junction ('Upstream', Figure 6.11a and d), followed by a downstream increase or decrease in channel width away from a tributary junction ('Downstream', Figure 6.11a and d). In other cases there is an increase in channel width toward a tributary junction ('Upstream', Figure 6.11b and d), followed by a downstream decrease or increase in channel width away from a tributary junction ('Downstream', Figure 6.11b and c). There are a few cases where there is no apparent trend in channel width either toward or away from a tributary junction (e.g. B11, Figure 6.11a; K3, B2, Figure 6.11c). In most cases, the trends indicated above occur regardless of tributary catchment size.

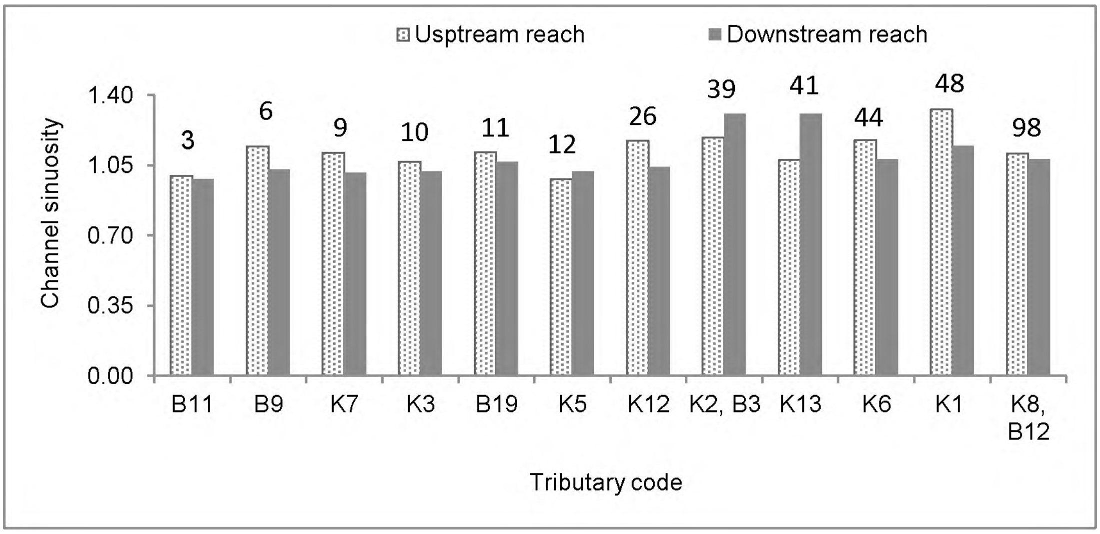
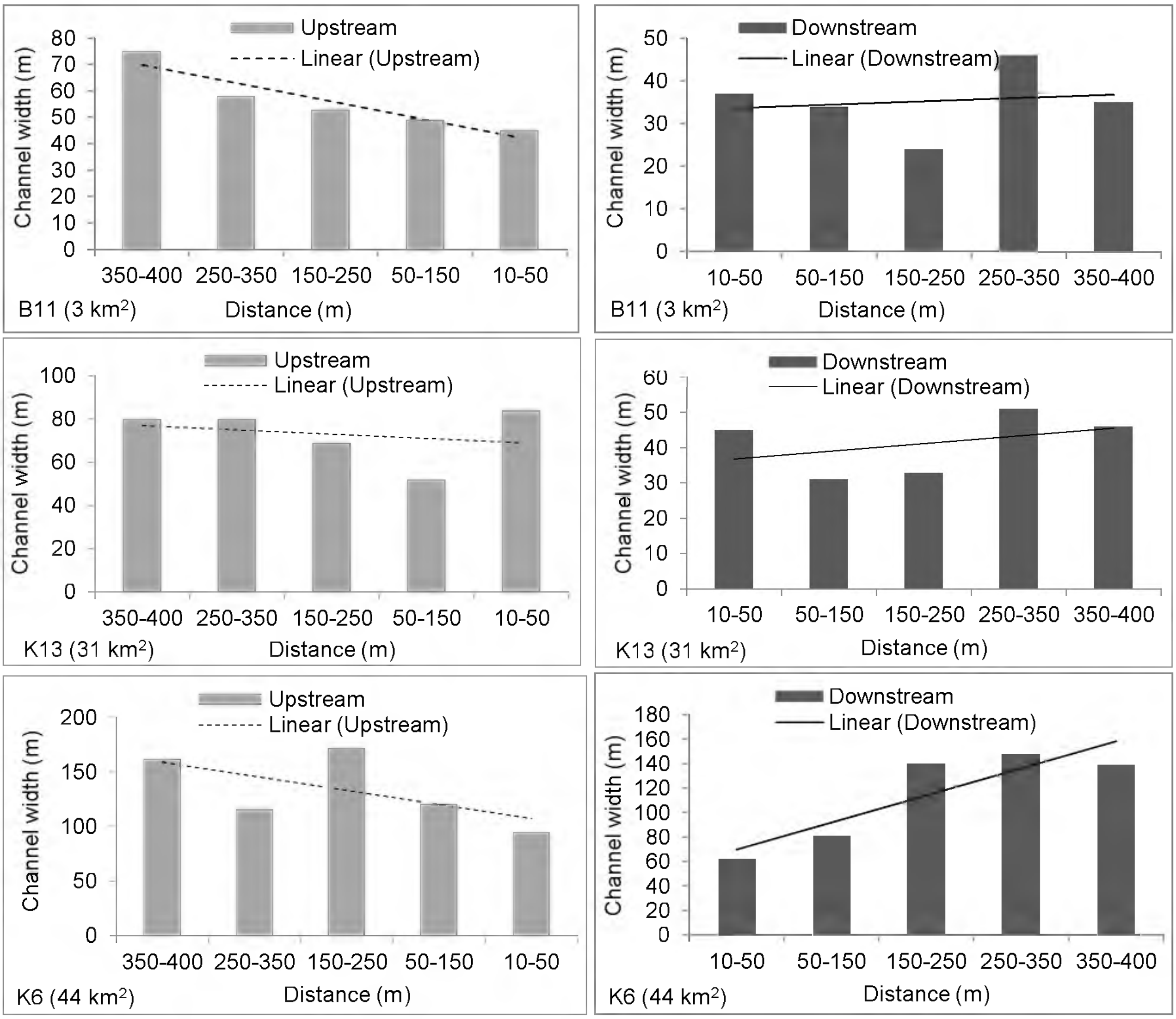
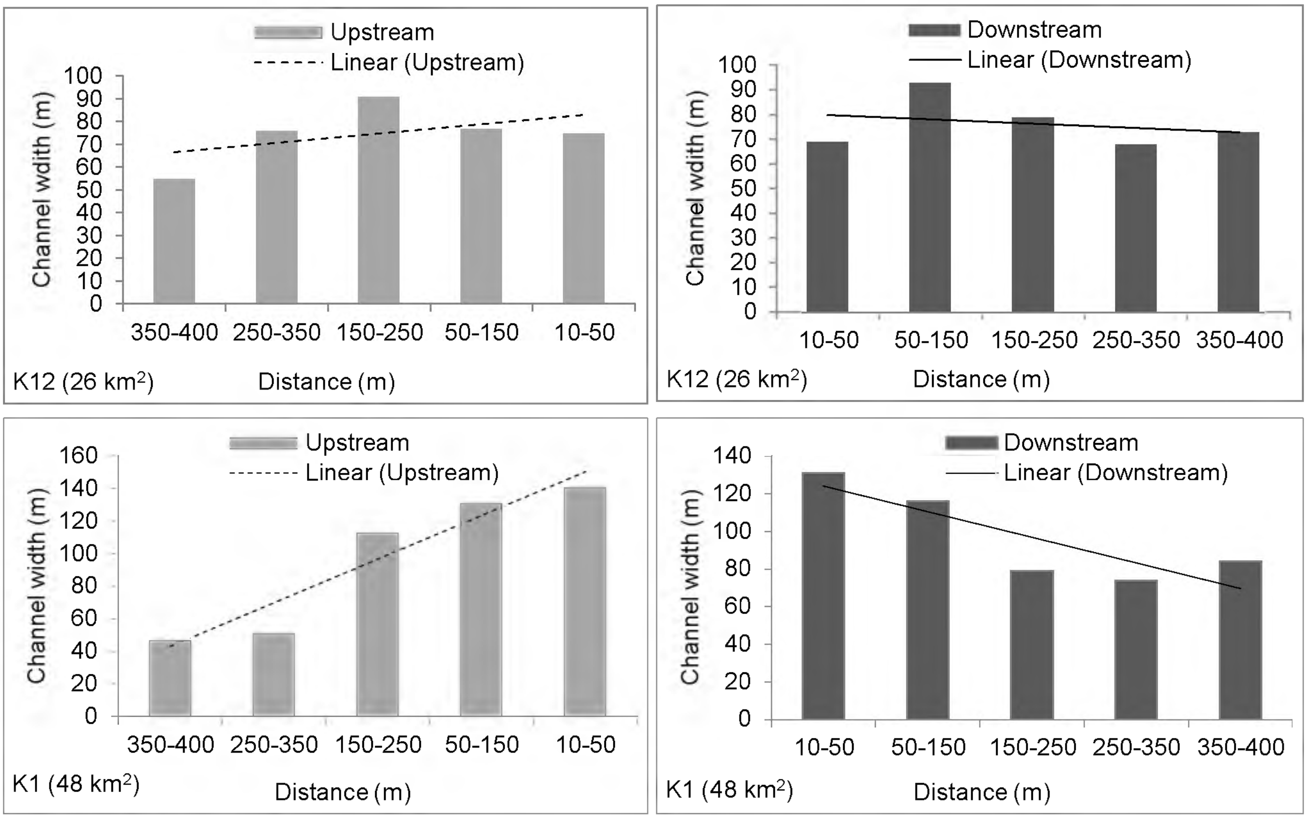


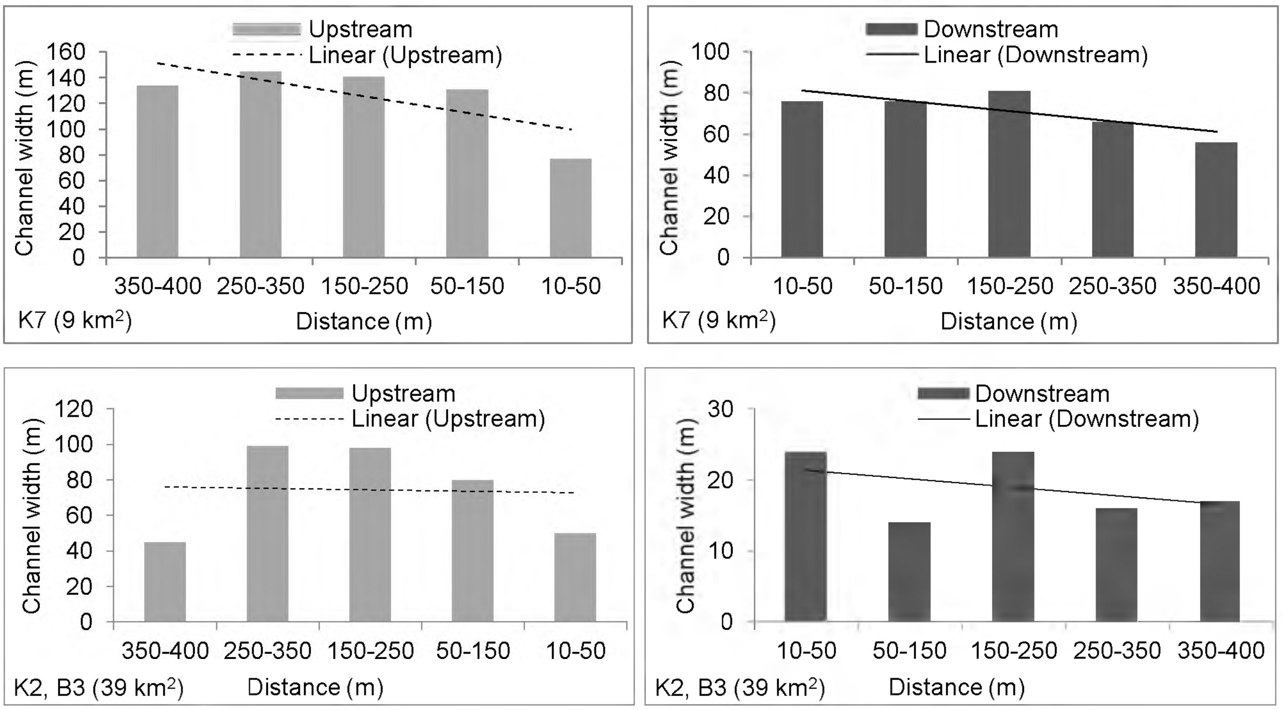
Figure 6.10: Trunk channel sinuosity calculated for channel reaches 400 m upstream and downstream of tributary stream junctions. The tributaries are arranged in order of increasing catchment size (indicated above the bars in km^2), such that B11 has the smallest catchment area and K8 and B12 collectively have the largest catchment area.


Upstream
Linear (Upstream)
Channel width (m)
350-400 250-350 150-250 50-150 10-50
B11 (3 km2)
Distance (m)
Downstream
Linear (Downstream)
Channel width (m)
10-50 50-150 150-250 250-350 350-400
B11 (3 km2)
Distance (m)
Upstream
Linear (Upstream)
Channel width (m)
350-400 250-350 150-250 50-150 10-50
K13 (31 km2)
Distance (m)
Downstream
Linear (Downstream)
Channel width (m)
10-50 50-150 150-250 250-350 350-400
K13 (31 km2)
Distance (m)
Upstream
Linear (Upstream)
Channel width (m)
350-400 250-350 150-250 50-150 10-50
K6 (44 km2)
Distance (m)
Downstream
Linear (Downstream)
Channel width (m)
10-50 50-150 150-250 250-350 350-400
K6 (44 km2)
Distance (m)

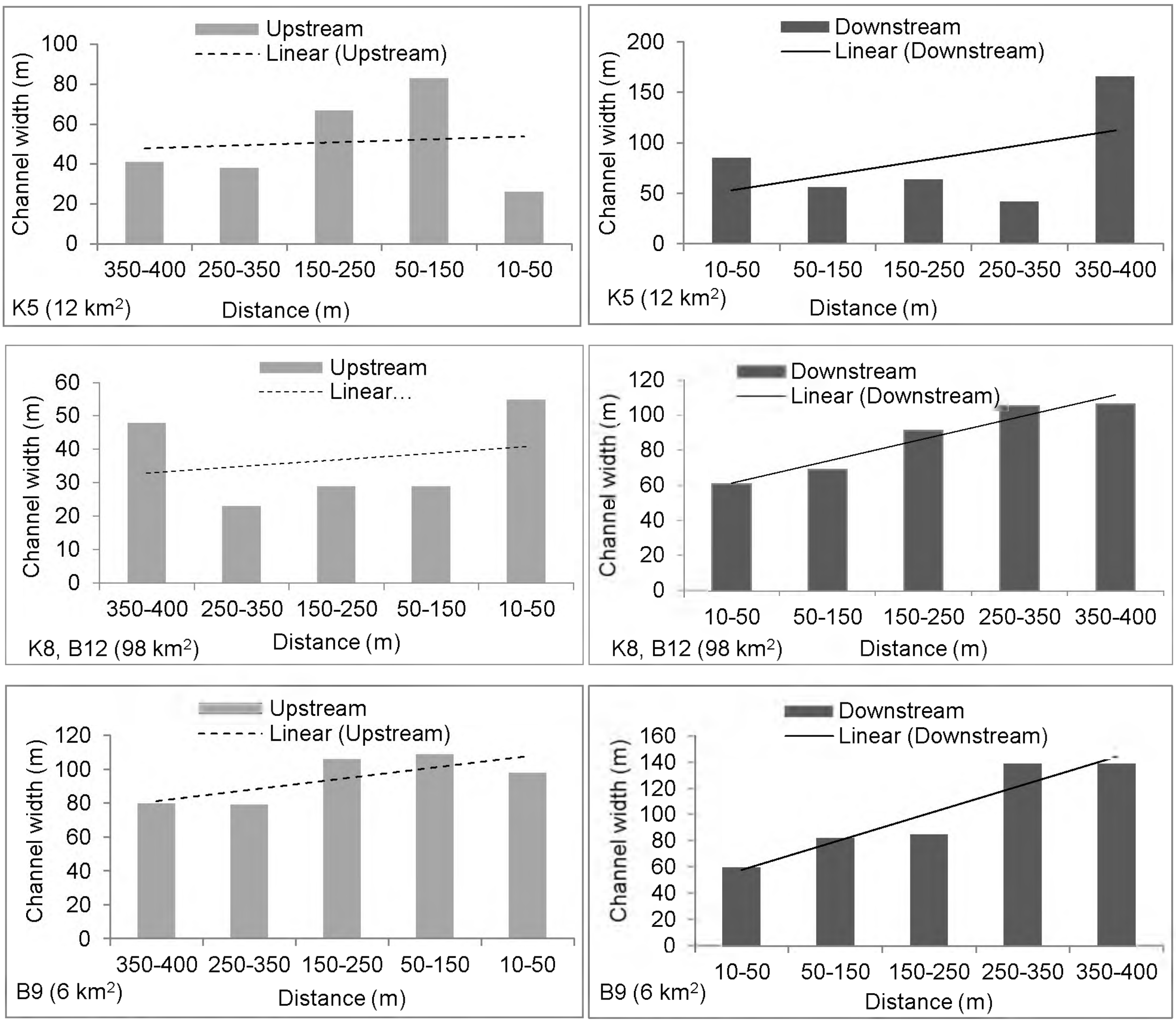
(a)


Upstream
Linear (Upstream)
Channel width (m)
350-400 250-350 150-250 50-150 10-50
K12 (26 km2)
Distance (m)
Downstream
Linear (Downstream)
Channel wdith (m)
10-50 50-150 150-250 250-350 350-400
K12 (26 km2)
Distance (m)
Upstream
Linear (Upstream)
Channel width (m)
350-400 250-350 150-250 50-150 10-50
K1 (48 km2)
Distance (m)
Downstream
Linear (Downstream)
Channel width (m)
10-50 50-150 150-250 250-350 350-400
K1 (48 km2)
Distance (m)

(b)


Upstream
Linear (Upstream)
Channel width (m)
350-400 250-350 150-250 50-150 10-50
K7 (9 km2)
Distance (m)
Downstream
Linear (Downstream)
Channel width (m)
10-50 50-150 150-250 250-350 350-400
K7 (9 km2)
Distance (m)
Upstream
Linear (Upstream)
Channel width (m)
350-400 250-350 150-250 50-150 10-50
K2, B3 (39 km2)
Distance (m)
Downstream
Linear (Downstream)
Channel width (m)
10-50 50-150 150-250 250-350 350-400
K2, B3 (39 km2)
Distance (m)

(c)



(d)

Figure 6.11: Trends in variation of trunk channel width, 400 m upstream ('Upstream') and downstream ('Downstream') of connecting tributary streams of different catchment size. The figures are grouped according to similarity in trends (a)-(d).

The variation in trunk channel width upstream of and downstream of a tributary junction at the scale of a 400 m reach, may be explained in some cases by other controlling variables, such as changes in valley width and relative channel and floodplain confinement, the effect of impingement of alluvial fans on the trunk from opposite sides of the valley and possibly by variation in artificial stream channelization. In the case of tributary K2 and B3 (Figure 6.11c), the valley narrows considerably downstream of where the tributary joins the trunk stream, which may explain the decrease in channel width downstream of the tributary junction. For tributary K6 (Figure 6.11a), the channel divides into two major anabranching channels directly downstream of where K6 joins the trunk channel, resulting in an increase in active channel width, also explaining the increase in channel width downstream of the tributary junction. In the case of K8 and B12 it is evident that the trunk channel is confined where the alluvial fans of the two tributaries impinge upon the trunk stream, but the channel loses confinement shortly downstream resulting in channel widening. Thus the trunk channel is relatively narrow in the vicinity of the impinging fans, but increases in width from 150 to 400 m downstream of the tributary junction

6.4 Discussion

6.4.1 Controls on the pattern and degree of tributary-trunk connectivity

Valley morphology and tributary catchment size and slope

The average longitudinal slope of the Baviaanskloof River thalweg along the study reach falls within the moderately sloping 'Upper Foothills' class of the geomorphological (longitudinal) zonation system developed for South African rivers by Rowntree and Wadeson (2000). This class of river means that runoff and erosion is relatively high due to the steep nature of the catchment. In the Baviaanskloof, the floodplain and river channel are much lower sloping than the surrounding tributary catchments. The effects of valley floor faulting may be one explanation for the relatively low slope of the valley floor. The steep nature of the catchment surrounding the study reach means that water and sediment are delivered with high energy to the valley floor, following which deposition occurs on alluvial fans and the river bed, as transport capacity and competence decrease. Valley morphology has thus been a key feature determining the presence of buffers and barriers to water and sediment transport for the study reach. These features would have been important in increasing the resilience of the trunk stream to storm events occurring in the surrounding mountain catchment, prior to widespread channel incision.

The significant difference in the slope, size and connectivity of tributary streams on the north versus south side of the river valley is largely owing to the morphology of the river valley, which is indirectly controlled by the variable resistance to erosion of different lithological units that outcrop along the valley. The northern Baviaanskloof Mountains are considerably shorter and steeper than the southern Kouga Mountains due to relatively resistant quartzitic sandstone that characterizes the northern side of the river valley. As a result, northern tributaries are significantly steeper and their catchments smaller than the southern tributaries. The southern tributaries flow through longer and lower sloping mountains which have formed on more easily weathered lithologies than the quartzitic sandstone on the northern side of the valley. As a result, the southern tributaries are larger on average in catchment area, resulting in larger tributary fans than on the northern side of the river valley. The southern fans thus extend further across the valley floor, such that the trunk channel is more frequently influenced by these fans as they impinge on or become impinged upon by the trunk channel as it shifts from north to south across the floodplain.

The different morphological characteristics of the northern versus southern tributary streams and fans, has resulted in different fan slopes (Bobbins 2011). Bobbins (2011) conducted a study of alluvial fan morphology in the Baviaanskloof for fans along the upper and middle reaches of the catchment, including the study reach. Bobbins (2011) concluded that the northern fans are generally steeper and smaller than fans on the southern side of the valley, similar to the findings presented in this research for the study reach. There is thus a clear relationship between tributary catchment size, tributary stream slope and tributary fan size and slope. The catchment size of tributary streams determines whether a tributary is able to connect to the trunk stream following truncation by the trunk stream, and associated base-level lowering of the tributary (Harvey 2012). The larger size of the southern tributary catchments and fans has been a key factor in determining the higher degree of connectivity of these tributaries to the trunk channel, since these tributaries will have a higher discharge during storm events than the northern tributaries.

The results of this chapter have also indicated that the position of the trunk channel on the floodplain is an important control on the pattern and degree of tributary-trunk connectivity and impingement of the trunk channel on tributary fans. This is supported by the findings of Bobbins (2011) who suggested that the lateral migration of the trunk stream across the floodplain explains why nearly all alluvial fans are toe-trimmed along the study reach. Episodic fan toe-trimming has thus been an important factor influencing the timing and degree to which a tributary becomes connected to the trunk channel. The process of tributary-trunk connected may be considered in three phases:

1) Tributary streams enter the valley floor and flood-out depositing coarse debris in a cone shape across the floodplain. Over time, tributary fans intermittently prograde

across the floodplain during large flood events toward the active channel zone, within which the trunk stream laterally migrates.

2) Lateral migration of the trunk channel during flood events results in impingement of the trunk stream upon one or more tributary stream fans. The trunk stream, influenced by the localized topography created by prograding fans, begins to erode through fan sediments during successive flood events.
3) During channel widening in the 1970s, the river would have further truncated the fans, lowering the local base-level of fan streams. The southern fans with larger tributary streams would have been powerful enough to connect to the river channel, as they attempted to establish an appropriate gradient in response to the establishment of a new base-level, largely defined by the newly truncated fan toe.

The above process explains why most of the southern tributaries are connected to the Baviaanskloof River at present and have been toe-trimmed.

Human influences

The results of Chapter 5 indicated that many of the larger tributaries on the southern side of the valley have been artificially channelized toward the trunk stream such that they are well-connected. This bias is due to the preferential selection of the southern alluvial fans for cultivation since these fans are large and gently sloping, and generally comprise finer-grained sediments than the more steeply sloping northern fans. In an attempt to protect cultivated lands farmers have built berms on either side of many of the southern tributary streams, thus channelizing flood flows

toward the trunk stream and enhancing fan entrenchment. These human influences have enhanced the role of the southern fans as sources of coarse sediment and water to the trunk stream during flood events.

Rainfall patterns and flooding magnitude and frequency

The flow regime of the Baviaanskloof along the upper-middle reaches of the floodplain closely follows that of an intermittent stream, as indicated in Chapter 5. At present the river along the upper-middle reaches flows for part of the year following large rainfall events, although the river may flow for a year or more during wet periods when groundwater levels are high (P Kruger, pers. comm., 2013; Glenday 2015). The braided pattern of the

Baviaanskloof River reflects the flashy nature of river flows (Bridge 2003; Bertoldi et al. 2010). During the peak of flood flows, coarse sediment connectivity is increased and channel morphological change is relatively common, as would be expected for a 'flashy' bed load system (Bertoldi et al. 2010). During the waning phase of floods coarse sediment is stored in varying landforms such as alluvial fans and flood-outs on the floodplain, and in bars, riffle sequences and sedimentation zones along the channel. These varying sediment stores form buffers and barriers to coarse sediment transfer over several years to decades between the occurrence of moderate and large floods that previously induced coarse sediment transport and morphological change (Fryirs et al. 2007a).

The spatial and temporal variability of rainfall in the Baviaanskloof produces variable spatial and temporal patterns of flow and coarse sediment connectivity. Several authors describe coarse sediment connectivity in high-energy systems such as the Baviaanskloof, as pulses or waves of bed load movement during efficient, near-bankfull to flood events (Hooke 2003; Fryirs et al. 2007a; Fryirs et al. 2007b; Fryirs and Gore 2013). The high degree of hillslope-channel and tributary-trunk connectivity means that floods are highly effective in switching on sediment delivery to the channel network and inducing channel morphological change along the trunk stream, as observed and reported by landowners during the course of this study. This effectiveness has been considerably enhanced by human channelizing features that serve to increase the power of storm flows, together with connectivity enhancers such as entrenched alluvial fans and a deepened trunk channel, which has further enhanced storm flow power and coarse sediment connectivity.

Chapter 3 indicated that rainfall varies along a west-east and south-north gradient for the upper-middle reaches of the Baviaanskloof catchment. The study reach is thus subject to spatially variable water and sediment connectivity. For example, the south-north rainfall gradient means that tributaries on the southern side of the river valley are more important sources of discharge and coarse sediment delivery to the trunk channel during storm events, than northern tributaries, since mountains to the south receive higher average rainfall than the northern mountains. The greater contribution of water and sediment from the southern mountains would be enhanced by the larger catchment area and higher degree of connectivity of the southern tributaries compared to the northern tributaries.

Given the degraded nature of hillslope vegetation along the study reach, it is unlikely that woody vegetation will respond to annual or decadal-scale variation in rainfall (Draaijer 2010), as might be expected under near-pristine to pristine conditions. Thus, during relatively wet climatic phases lasting for several years, hillslope-channel connectivity would be expected to be relatively high compared to dry periods when runoff and erosion are expected to decrease. During these wet periods hillslope runoff and sediment yields would easily transfer to the trunk channel through gully networks and connecting tributary streams, resulting in heightened stream instability. Contributions of runoff and sediment delivery during these wet periods is assumed to be highest for the hillslopes on the southern side of the river valley, since these are the most degraded in terms of vegetation cover removal.

6.4.2 Localised impacts of tributary connectivity on trunk channel process, form and sensitivity

The spatial pattern of tributary-trunk and associated coarse sediment connectivity along the study reach described above means that the southern tributaries are a more important control on trunk channel process, form and sensitivity to either erosion or aggradation. These southern tributaries effectively supply more water and coarse sediment to the trunk stream, and most of the tributary fans of these streams are currently impinged upon by the trunk channel. In general, the study reach is characterised by a high degree of water and sediment connectivity, which has resulted in widespread channel degradation in recent years. However, the tributary streams that connect to the trunk channel also exert reach to sub-reach scale control on channel process, form and sensitivity, by influencing channel slope, sinuosity and patterns of channel width upstream of and downstream of a tributary junction.

The reach to sub-reach scale impacts of connecting tributary streams was variable along the study reach. Some tributary streams that connect to the trunk stream promote a downstream steepening of bed slope and widening of the trunk channel, whilst others promote a downstream decrease in channel bed slope, indicating the importance of tributary stream junctions in determining the sensitivity of the trunk channel to morphological change. This form of control was particularly noticeable at the sub-reach scale where pronounced channel incision has occurred downstream of two laterally impinging tributary streams and fans. The changes in planform downstream of tributary stream junctions indicates that the trunk stream attempts to accommodate either increased discharge or sediment delivered from connecting tributaries, or a local base-level created by laterally impinging alluvial fans, by adjusting sinuosity, channel width and depth (slope).

The above findings are similar to that of other upland catchments, in which tributary-trunk connectivity has been an important control on recent trunk channel morphodynamics. Farraj and Harvey (2010) found that in the Bowderdale Beck, an upland catchment in NW England, local widening and braiding of the channel occurred downstream of major sediment supply points attributed to connecting tributary streams. Similarly, Harvey (2007b) described the response of two upland catchment channels in NW England to a 100-year flood event that resulted in large inputs of coarse sediment to trunk channels from upstream and tributaries. The trunk channel responded by widening and switching from a single to a braided channel form. Bravard (2010) demonstrated that braiding in the River Rhone occurs downstream of tributaries supplying coarse sediment to the trunk channel, and that connecting tributaries are an important control on the river longitudinal slope, by influencing bed load flux.

The response of the Baviaanskloof River to tributary stream junctions is variable in magnitude for different channel reaches. In most cases, trunk channel sinuosity decreases albeit only slightly, downstream of a tributary junction. This indicates the adjustment of the trunk to excessive inputs of coarse sediment from tributaries, resulting in widening and associated channel straightening downstream of tributary sediment supply points (Brierley and Fryirs 1999; Farraj and Harvey 2010). At the sub-reach scale, trunk channel width may either increase or decrease upstream of and toward a tributary junction or downstream of and away from a tributary junction, and in some cases there is no apparent influence of a tributary junction on trunk channel width. It is expected that trunk channel width would decrease toward the junction of a tributary fan and stream, as the trunk stream deposits sediment in response to the local base-level formed by the tributary fan (Joubert and Ellery 2013). It is also expected that trunk channel width would initially increase and then decrease downstream of and away from a tributary junction, as the channel expands in the immediate vicinity of the tributary to accommodate increased discharge and coarse sediment (Farraj and Harvey 2010). However, the aforementioned trends were only indicated for approximately half of the tributary junctions along the study reach, whilst the others indicated contrasting trends in channel width upstream and downstream of connecting tributaries. The variable influence of tributary junctions on trunk channel sinuosity, slope, and width, makes it difficult to predict the influence of different sized tributary stream junctions on trunk channel process, form and change. However, it is clear that tributary streams, particularly the larger ones, influence trunk channel process and form, the nature of which is dependent upon the interplay with local geomorphological and artificial variables.

Tributary junction fans influence the behaviour of the Baviaanskloof River by influencing channel confinement where they enter from either side of the valley, and local floodplain and channel slope, where they impinge upon the trunk stream. The trunk channel has toe-trimmed most of the tributaries along the study reach (Bobbins 2011), indicating that tributary fan junctions are important localized controls on trunk channel sensitivity to erosion where they impinge on the trunk. The fans initiate a localized (over several hundred meters) downstream steepening of floodplain slope, to which the trunk channel has adjusted by deep incision. Tributary fans have thus been important in initiating local slope thresholds of erosion, where the trunk channel became impinged on one or more fans.

The frequency of tributary stream junctions, along with variations in valley confinement and floodplain slope, influence river style and associated geomorphological behaviour at larger scales (over several thousand meters). Three major river styles were defined for the trunk stream along the study reach, adapting the approach of Brierley and Fryirs (2000, 2005). The most unstable of these styles occurs along the middle of the study reach, where valley width is widest and where the frequency of connecting tributary streams is highest. The transfer and floodplain accumulation styles identified at the head and lower-reaches of the study reach are less sensitive to geomorphological change where they are characterised by a more confined floodplain and lower frequency of connecting tributary streams. These findings have implications for understanding river sensitivity and for prioritizing river-floodplain interventions for the study reach.

The complex nature of trunk channel adjustment to connecting tributary streams in the Baviaanskloof is not uncommon for ephemeral or intermittent flowing gravel-bed streams (Hooke 2015), and may be explained by a complex set of interacting factors including:

- The available stream power and related capacity and competence of the receiving trunk channel reach to transport the sediment being supplied. This relates to the size of a tributary and associated magnitude of water and sediment inputs relative to discharge and channel slope of the receiving trunk channel reach. For example, if a receiving trunk channel reach has a low capacity/competence relative to tributary sediment inputs, then localised deposition will occur, leading to down-valley slope steepening.
- The relative amounts of water and sediment supplied by one or more tributaries and upstream river reaches. For example, if water inputs to a particular reach are high relative to coarse sediment load, then local channel widening or deepening may occur together with transport of sediment through the receiving reach, resulting in slope reduction downstream. Sediment deposition will occur further downstream where stream competence decreases (e.g. along a relatively wide, gently sloping channel reach).
- The resistance of bed and bank materials to erosion is an important factor determining the propensity for channel adjustment (Hawley et al. 2012) at tributary confluences. Along the study reach, the superimposition of the trunk upon palaeo-channel gravels has limited the degree of trunk channel degradation (vertical and lateral erosion). In contrast, reaches with less resistant bank and bed sediments, comprising silts and sands, have been able to adjust relatively rapidly through deep (up to 6 m deep) degradation of the floodplain.
- Local variations in valley width and relative floodplain width and the confining influence of tributary fans that impinge on the trunk channel from opposite sides of the river valley.
- Possibly, varying intensity of human channel engineering along the study reach which influences trunk channel behaviour and associated width, slope and sinuosity.

In summary, the results of this chapter have indicated that tributary stream junctions have three main impacts on trunk channel process, form and sensitivity:

1) A connecting tributary may induce a downstream steepening of channel bed slope, where the transport capacity and competence of the receiving channel reach is insufficient to transport the coarse sediment being supplied by the connecting

tributary. This scenario increases the sensitivity of the trunk channel to erosion over time as deposition increases slope slope along the channel bed in a downstream direction.

2) Channel widening occurs over a short distance downstream of a junction as the trunk stream attempts to accommodate increased discharge and coarse sediment load from a connecting tributary stream. Over time, downstream coarse sediment deposition may result in channel bed steepening and increased capacity to transport coarse sediment downstream.
3) Channel bed deepening and bed slope lowering occurs if the transport capacity of the receiving trunk channel reach is higher than is necessary to transport the coarse sediment being supplied by the connecting tributary stream.

All of the above scenarios were observed along the trunk channel to varying degrees, indicating that the Baviaanskloof River has been sensitive to the impacts of connecting tributary streams and associated coarse sediment connectivity in recent years.

6.4.3 Slope thresholds of river sensitivity

In the Baviaanskloof, coarse sediment connectivity driven largely by episodic high-magnitude flood events and the engineering of stream channels by humans, have been important in initiating threshold breaches and a switch to channel braiding and degradation in recent years (Godfrey et al. 2008). Channel widening, bed lowering and braiding in the Baviaanskloof thus represent the response of the trunk stream to increased inputs of water and coarse sediment from connecting tributary streams (Ashmore 2013). River channels adjust morphology (cross-section dimensions, gradient, and planform) in order to obtain just enough energy to transport the caliber and amount of sediment being supplied to the channel. This state of approximate balance between variables of discharge, sediment load and channel geometry has been termed 'quasi-equilibrium' (Langbein and Leopold 1964; Van De Wiel and Coulthard 2010). The distinct pattern of longitudinal slope of the Baviaanskloof River and floodplain and changes in channel planform, reflects the attempt of the river to approximate an overall quasi-equilibrium state such that coarse sediment is continually pulsed through the channel network, albeit in a 'stop-start' fashion during episodic flood events. Harvey (2007b) noted that for the two upland catchments, coarse sediment was transported downstream in a wave-like form as a result of localized erosional and sedimentation zones. In the Baviaanskloof it appears that coarse sediment moves in a similar wave-like fashion to that described by Harvey (2007b), and is locally eroded and deposited in features of varying size including channel bars and riffles (tens of meters in length) to sedimentation zones several kilometers long. The result is a downstream pattern of gentle and steep sloping channel reaches and alternating narrow or wide channels. This quasi-equilibrium state manifests as a relatively uniform overall longitudinal profile with a particular gradient (0.0067 m/m) which has been maintained for both the pre-degradation and post-degradation state. However, local-scale slope thresholds were identified during this study, which have been important in defining local-scale response of the trunk to connecting tributary streams. The maximum slope of the trunk channel thalweg identified at the sub-reach scale and local scale was approximately 0.0075 m/m. It is thus suggested that a thalweg slope of 0.0075 m/m is the threshold for channel erosion over reaches several kilometers to several hundreds of meters long. Alternatively, the minimum thalweg slope observed at the sub-reach to local scale of 0.0052 m/m, indicates that this is the minimum slope towards which a degrading channel reach will proceed before switching to channel bed aggradation (Van De Wiel and Coulthard 2010).

The present-day enhanced levels of sediment and water connectivity means that the river and surrounding catchment may be relatively sensitive to natural and anthropogenic disturbances that enhance flow magnitude and coarse sediment delivery to the channel network. Disturbance responses initiated along the trunk channel may propagate easily through surrounding tributary streams and gully catchments that connect to the trunk stream (Fryirs et al. 2007b).

6.5 Conclusion

In the Baviaanskloof, coarse sediment connectivity is a critical determinant of the sensitivity of the river-floodplain to morphological change at the reach, sub-reach and local scales. The river has adjusted to increased discharge and coarse sediment inputs from tributary streams and gullies at multiple nested spatial scales. These scales include the entire study reach comprising a stretch of 25 km of river channel, to the channel sub-reach scale, comprising several thousands of meters of channel length, to the channel local scale, comprising several hundreds of meters of channel length.

The spatial and temporal variability of coarse sediment connectivity results in variable river channel morphology, river style, and geomorphological sensitivity in space and time. From a spatial perspective, the southern tributaries show a higher degree of connectivity with the trunk channel, controlled by tributary catchment size, higher incidence of rainfall events, and numerous hillslope gully networks, on the southern side of the river valley. These factors have resulted in increased runoff and sediment supply to the southern tributaries. Furthermore, human engineering of the southern tributaries and fans has increased the degree of tributary-trunk stream connectivity. Downstream variations in the frequency of connecting tributary streams has influenced downstream patterns of river style and associated sensitivity to geomorphological change. Within a temporal context, connectivity is determined by the episodic nature of rainfall events such that coarse sediment pulses through the system during flood events of differing magnitude and frequency, where sediment is stored on the trunk channel bed over periods of several months to years in between high-magnitude events. The trunk channel self-regulates internal coarse sediment transport capacity through local morphological adjustments that result in an overall quasi-equilibrium channel and floodplain slope of 0.0066 m/m.

Drawing from the results of Chapters 4, 5 and 6 of this thesis, it is suggested that the sensitivity and nature of channel morphological adjustment of the Baviaanskloof River along the study reach is controlled largely by:

1) The relative magnitude of water and coarse sediment inputs to the trunk channel from one or more connecting tributary streams, which determines whether the receiving channel reach has excess or insufficient capacity to transport coarse sediment to downstream reaches. A sediment deficit relative to available discharge will result in morphological adjustment in the form of widening and slope lowering, and a sediment excess relative to available discharge results in sediment deposition on the channel bed and associated downstream steepening of channel bed slope.
2) The physical structure of the receiving channel reach is related to bed slope, channel width and depth, and the degree of armouring of the channel bed and banks to erosion, all of which influence coarse sediment transport capacity and competence, and the resilience of the channel boundary to erosive forces that result in channel morphological change.

3) The degree of human stream flow channelization which increases sediment transport capacity relative to sediment supply making the channel more sensitive to morphological adjustment.

CHAPTER 7: A PROCESS-BASED EVALUATION OF RIVER REHABILITATION IN THE BAVIAANSKLOOF AND RECOMMENDATIONS FOR IMPROVED PRACTICE

7.1 The context for process-based river rehabilitation

In their book entitled “River Futures: An Integrative Scientific Approach to River Repair”, Brierley and Fryirs (2008) identify a recent shift in approach to river management from largely command and control of river form and condition, to working with ecosystem processes that promote natural river recovery and increased resilience to disturbances. This shift in thinking within the discipline has resulted from the experience that ‘command and control’, or form-based measures, often fail to achieve a set rehabilitation goal and sometimes enhance the problem at hand (Wohl et al. 2005). The process-based approach to river rehabilitation is now considered fundamental for sustainable and effective recovery of ecological condition in degraded streams (Brierley and Fryirs 2005; Wohl et al. 2005; Beechie et al. 2010; Mika et al. 2010). Along with this shift in thinking, has been increasing recognition of the role of geomorphological processes as an underlying determinant of the ecological functioning of rivers, by determining for example habitat diversity and fluxes of sediment and nutrients that influence biotic communities (Gilvear 1999; Brierley and Fryirs 2000; Florsheim et al. 2008). There is thus an emerging school of river science focused at concepts and tools for planning and implementing geomorphological process-based rehabilitation, targeting processes occurring across a range of spatial and temporal scales of a catchment (Brierley and Fryirs 2000; Newson 2002; Brierley and Fryirs 2008; Fryirs and Brierley 2009; Rosgen 2011; Fryirs et al. 2012; Fryirs and Gore 2013). Within this school of thought, several authors have stressed the importance of understanding the geomorphological history of a targeted river, the geomorphological mechanisms by which channel adjustment occurs, and the potential future geomorphological trajectory of the targeted river (Fryirs and Brierley 2009; Fryirs et al. 2012; Campana et al. 2014).

In mountainous catchments such as the Baviaanskloof, high-energy and variable stream flows promote episodic coarse sediment fluxes and channel instability at annual to inter-annual time scales (Hooke 2003; Fryirs et al. 2007a; Wohl 2010). Hence, the use of structural interventions such as weirs and bank revetments to halt erosion and reinstate a particular channel-floodplain condition is discouraged as such interventions are costly due to the need for continual maintenance work (Wohl et al. 2005; Galia et al. 2016). Moreover, many rehabilitation projects in human disturbed catchments attempt to regain a pre-disturbance condition, without considering how the controls on channel behaviour (e.g. runoff and sediment regime) may have changed over time, thus altering the behavioural regime of the contemporary river (Brierley and Fryirs 2005; Hughes et al. 2005). The unpredictability of these types of systems makes it difficult to set restoration goals where a river channel may shift towards one of several potential stable states (Kondolf et al. 2001; Hughes et al. 2005).

Some common structural interventions employed in high-energy fluvial environments for rehabilitation purposes include the creation of secondary channels that disperse flows across a floodplain, removing bank protections and re-injecting gravel to raise the channel bed and promote channel-floodplain reconnection ('1', Table 7.1). Bed and bank stabilization is often promoted by reconstructing a sinuous, meandering channel, planting log stands, or installing concrete groins on eroding channel banks ('2', Table 7.1). A common approach to channel bed stabilization in high- to medium-energy gravel-bed streams is the construction of artificial pool-step or pool-riffle features. These features naturally form in gravel-bed streams as a result of self-organization as a stream attempts to stabilize the channel bed ('2', Table 7.1; Plate 7.1). The aforementioned bed features exist naturally in streams characterised by a flashy flow regime, coarse bedload, and channel reach slopes of 3-7% for step-pool features (Maxwell and Papanicolaou 2001; Chin et al. 2009; Yu et al. 2010), and <3% for pool-riffle features (Montgomery and Buffington 1997; A Riley, pers. comm., February 2016). The aforementioned bed features may promote relative channel stability along degrading channel reaches by controlling flow energy, but only when they are artificially constructed to be adjustable and mobile (Chin et al. 2009; Yu et al. 2010). Many of the above interventions may induce channel recovery over localized reaches and over relatively short time periods, but, they often lack recognition of upstream, downstream and hillslope processes that may promote or undermine recovery at the channel reach-scale.

Table 7.1: Examples of common types of rehabilitation interventions employed in degraded, high-energy catchments, as identified in the literature.

Approach	Target area/process	Description of intervention
Form-based	1. Channel-floodplain connectivity	▪ Creation of multiple or secondary channels or re-connection of side-arms or oxbows that promote floodplain re-wetting (Bravard et al. 1999; Lüderitz et al. 2011); ▪ Channel widening and raising stream bed by re-injecting gravel (Campana et al. 2014); ▪ Levee setbacks or removal combined with creation of an intermediate terrace to encourage floodplain re-wetting in incised channels (Haltiner and Beeman 2003; Lüderitz et al. 2011; Guida et al. 2014).
	2. Channel bed and bank stability	▪ Reconstruction of a sinuous, meandering channel (Kondolf et al. 2001); ▪ Removal of bank protections and channel widening (Rohde et al. 2006); groins to stabilize banks (cement or boulders) or planting log stands on eroding banks (Mikuś et al. in press); introducing log jams to decrease flow velocity (Bennett et al. 2015); ▪ Building artificial step-pool, riffle-pool or log step features (Lenzi 2002; Chin et al. 2009; Yu et al. 2010); ▪ Cement or gabion weirs or drop structures (Haltiner and Beeman 2003).
Process-based	3. River reach processes	▪ Dynamic process conservation areas and riparian buffers: allow floodplain connectivity, and natural channel processes- widening and avulsions (Florsheim et al. 2008); ▪ Flow deflectors made of reed stands/woody debris/groins that promote flow variation and channel sinuosity (Bravard et al. 1999; Radspinner et al. 2010).
	4. Catchment-level processes	▪ Efforts to decrease soil erosion and run-off on degraded hillslopes through: re-forestation, stone and soil bunds, terraces and (Asfaha et al. 2016).

Process-based or ‘soft’ approaches to rehabilitation are often effective in achieving river recovery since they consider the fluvial system as a nested hierarchy of geomorphological process zones that should be considered when attempting to reinstate or enhance geomorphological and hydrological processes across different zones (Brierley and Fryirs 2008). This approach requires longer periods of investigation of the key geomorphologic processes and structure at different hierarchies determining channel dynamics and sensitivity at the reach scale. The process-based approach may also require a broader suite of rehabilitation interventions in attempting to aid the system toward a resilient state. Process-based approaches that include instating dynamic process zones and wide riparian buffers, that give a river opportunity for natural adjustment, and targeting hillslope runoff and erosion processes ('3', '4'; Table 7.1), are less commonly found for high-energy mountain streams. Such approaches may or may not be cheaper than structural interventions, depending on the scale at which rehabilitation is required, but the process-based approach is more effective and sustainable in achieving ecological recovery and resilience.

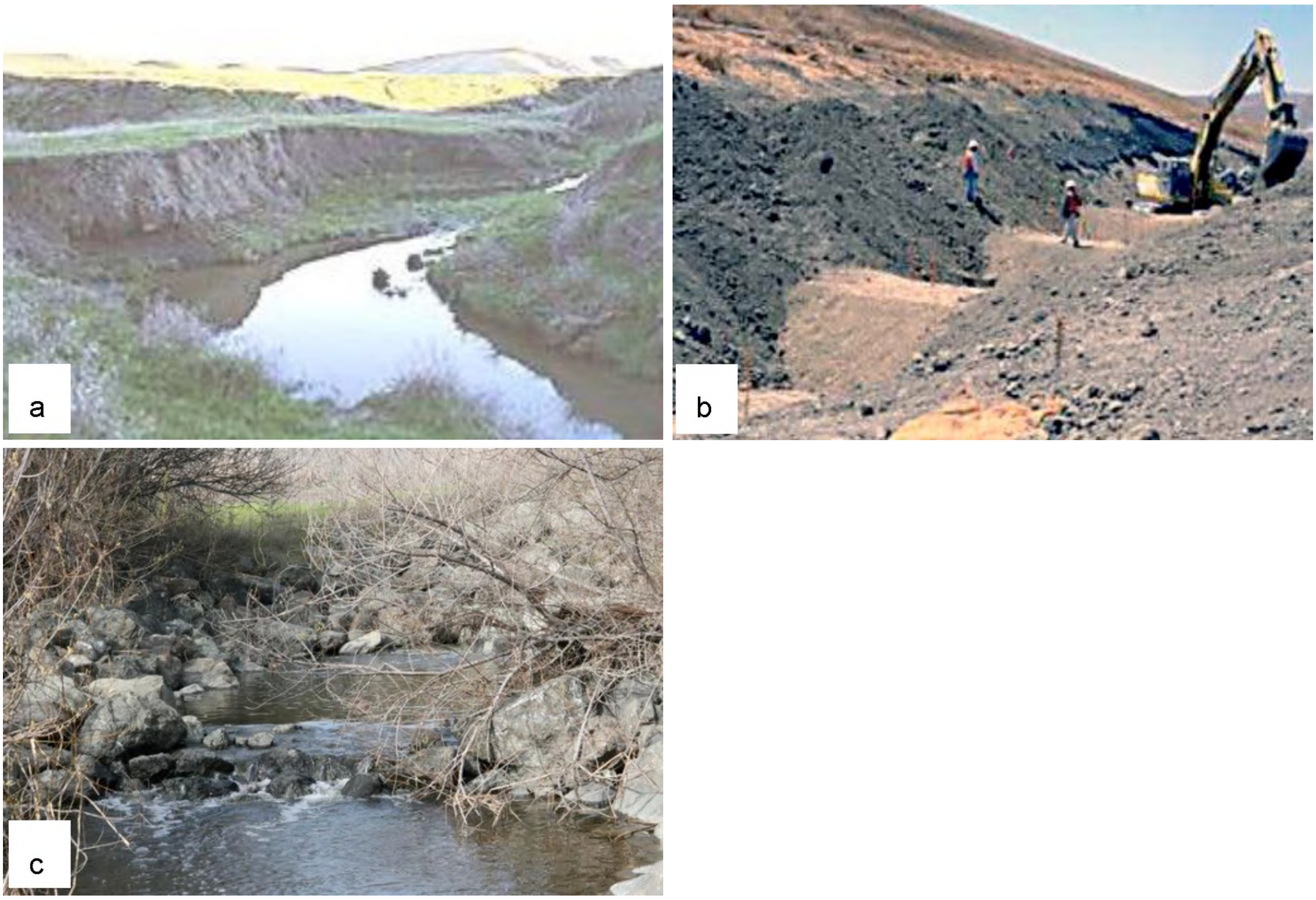


Plate 7.1: Rehabilitation of an incised channel reach (a), along East Alamo Creek in California. The re-shaped channel and floodplain and creation of artificial step-pool features are indicated (b), and the rehabilitated, relatively stable channel (c); (Photos by Jeff Haltiner).

Chapter 2 introduced two useful conceptual tools for guiding process-based river rehabilitation: 1) the river styles framework (RSF) of Brierley and Fryirs (2000, 2005), and 2) the concept of water and sediment connectivity (Brierley et al. 2006; Kondolf et al. 2006; Fryirs et al. 2007a; Fryirs et al. 2007b; Fryirs and Gore 2013). The concepts have been applied within a few river catchments in Australia, the UK and the USA, but have not been applied across a range of different types of rivers with regards to river-floodplain rehabilitation.

In 2009 the Baviaanskloof River-floodplain along the study reach was targeted for floodplain wetland rehabilitation by the statutory agency, Working for Wetlands (WfWet), following which gabion weir interventions were implemented between 2012 and 2016. The aim of this chapter is to evaluate the WfWet approach to river-floodplain rehabilitation drawing on knowledge that has been generated during the present study and the principles of process-based rehabilitation exemplified by the river styles and connectivity frameworks.

To fulfil the above aim, the objectives are to:

1) Develop a conceptual model illustrating the interaction of adaptive geomorphological cycles across different scales of the study reach, highlighting the role of connectivity and human and climatic drivers of threshold breaches and phase changes in these adaptive cycles. From the conceptual model and results of this study, future geomorphological behaviour of the river-floodplain will be predicted based on an understanding of historical and present-day river styles, for the trunk and distal reaches of tributaries, and the connectivity of water and sediment.
2) Evaluate the WfWet approach to river-floodplain rehabilitation planning and implementation within the process-based rehabilitation framework (hereafter referred to as PRF) using information generated under objective 1.
3) Develop a conceptual model of PRF for the Baviaanskloof along the study reach, drawing on principles of the RSF and geomorphological connectivity, and make recommendations for strategic rehabilitation areas that could be targeted in the future for increasing the geomorphological resilience of the study reach.

7.2 Approaches to river and wetland rehabilitation and conservation in South Africa

As indicated in Chapter 1, South Africa has two main programmes focused at river and wetland rehabilitation and conservation management, the RHP and the WfWet Programme. Each of these programmes has historically focused on biotic and hydrological aspects of rehabilitation with very limited attention to geomorphological processes that are important for driving ecosystem functioning and dynamics. Several research initiatives adopted in recent years have resulted in increasing knowledge and tools for geomorphological assessment and management of rivers and wetlands in South Africa.

The RHP assesses several components of the river environment including: invertebrate and fish diversity, riparian vegetation structure, habitat integrity, water quality, hydrology and geomorphology. From a geomorphological perspective, the RHP incorporates several geomorphological tools which assist with defining the ecological condition of a river and monitoring changes in condition over time, and for defining instream flow requirements (IFRs) for maintaining ecosystem health, as legislated under the National Water Act of 1998. The nature and purpose of each of the geomorphological tools that guide monitoring under the RHP is outlined below.

Geomorphological assessment tools under the River Health Programme

1) ***Geomorphological framework for determining instream flow requirements; (Rowntree and Wadeson 1998; Wadeson and Rowntree 2005):***

Rowntree and Wadeson (1998) developed a tool to assist the determination of the magnitude-frequency of low flows, including introduction of short-lived flow increases or floods that move sediments, which are important for maintaining geomorphological form and diversity of a river, and hence habitat conditions for healthy ecosystem functioning. Four metrics are assessed within the geomorphological framework:

1) Catchment conditions (land-use, vegetation cover etc.) that determine the potential for morphological change of a river in the near future;
2) The geomorphological characteristics of the river network such that representative reaches can be selected for defining for defining IFRs;
3) The frequency and magnitude of flow discharges that maintain channel form and morphological diversity using hydraulic models for each IFR site;
4) Potential impacts on instream flow regime and channel morphology of water-use interventions such as inter-basin transfers and dams.

The tool was further refined by Wadeson and Rowntree (2005) for determining IFRs for the Ecological Reserve, legislated under the NWA of 1998.

2) ***Geomorphological classification of South African rivers (Rowntree and Wadeson 1999; Rowntree et al. 2000):***

Under the above classification system, two generic models are presented to aid geomorphological zonation and classification of rivers in South Africa. The first model classifies whole river systems within a nested hierarchical framework according to topographic position along the longitudinal profile of an entire river basin (i.e. source zone or lowland zone). The second model hierarchically divides a single catchment to indicate interlinked process zones at different spatial scales: catchment – zone – segment - reach - morphological unit - hydraulic biotopes. The first model provides a generic classification system that can be used to group similar river catchments for comparison during monitoring and rehabilitation works under the RHP. The second model recognizes process linkages within a catchment that influence channel reach scale geomorphological processes and behaviour. The model was developed to guide holistic catchment management and for determination of IFRs under the RHP.

3) ***An index of stream geomorphological condition (Rowntree and Ziervogel 1999; Rowntree and Wadeson 2000)***

This index of stream geomorphological condition provides a measure of the degree to which a channel reach has been altered from the natural condition and monitors changes in geomorphological condition over time due to natural processes or human disturbances. The index includes several metrics: a channel classification metric (e.g. bedrock channel vs. alluvial channels) based on the Rowntree et al. (2000) hierarchical classification of rivers; a channel stability index that defines the potential for morphological change at a particular channel site due to natural processes or human impacts; and an index of channel condition (based on bed and bank conditions and diversity of hydraulic habitats) which is monitored at regular intervals. The index of geomorphological condition was further improved to contribute to assessment and monitoring of changes in the ecological state of rivers monitored under the RHP (Kleynhans and Louw 2007).

4) ***Geomorphological reference condition/driver assessment index* (du Preez and Rowntree 2006; Rowntree et al. 2013):**

The Geomorphological Driver Assessment Index (GAI) is a modified version of Rowntree and Wadeson's (2005) geomorphological condition index described above. It was developed for the RHP for comparing present ecological state with regards to geomorphologic condition (processes and forms), to a derived reference condition representing minimal human impact and the natural array of processes and biota that should be expected for a particular river type (du Preez and Rowntree 2006). The GAI takes a systems approach to assessing river history (channel form and flooding), and human impacts on various metrics. These metrics include examining drivers of river geomorphological condition and connectivity (catchment, upstream-downstream, hillslope-channel and channel-floodplain), sediment balance (degree of hillslope and/or channel erosion or sedimentation) and channel stability (conditioned by resistance of bed and bank materials, vegetation). Channel morphology is also assessed as a separate indicator of present ecological state in terms of altered channel geometry and instream and riparian vegetation. Each of the above metrics is rated in terms of deviation from a pre-defined reference condition. The reference condition for each of these attributes is derived from the Rowntree et al. (2000) zonal classification of rivers, which outlines the natural channel processes and geometry which should be expected for different types of channels.

The above GAI tool provides a useful approach to river ecological assessment and monitoring since catchment-scale drivers of geomorphological condition and dynamics, which are framed within the concept of connectivity, are included in defining the present ecological state and deviation from the natural condition. This knowledge may then guide the types of interventions required within different catchment hierarchical zones for effective river-wetland rehabilitation and conservation management. However, the tool has not been widely applied as yet from the perspective of process-based river or wetland rehabilitation in South Africa. In addition, the use of a reference condition to determine the degree to which a given river has been impacted by humans is problematic, since the reference condition is difficult to define and identify accurately without in-depth historic knowledge of the range of behaviours of a river prior to human disturbance (K Rowntree, pers. comm., August 2016).

Wetlands assessment and rehabilitation tools under the Working for Wetlands (WfWet) Programme

The Wetland Management Series (WMS) developed in 2009 is the most comprehensive guiding framework for wetland rehabilitation and conservation management in South Africa, and has resulted in substantial advancement toward a process-based approach. There are 10 tools under the WMS which form an integrative framework for process-based rehabilitation planning, implementation, and monitoring and evaluation of South Africa's palustrine wetlands. Each of the tools tackles a different component of rehabilitation and conservation management. For example, *WET-Legal* guides environmental practitioners as to when a wetland impact assessment and rehabilitation is required under legislation that protects South African water resources (Armstrong 2009); *WET-Prioritise* guides the prioritization of wetland systems for conservation management efforts at the national, regional and local scales (Rountree et al. 2009); *WET-Health* and *WET-EcoServices* were developed to guide rapid (days) assessment of ecosystem services delivery (Kotze et al. 2009b) and present-day or future health related to impacts of human activities (Macfarlane et al. 2009). The tools are most commonly used during wetland rehabilitation planning in South Africa, usually by an experienced scientist (>5 years experience). Geomorphological process and form is incorporated into site assessments in minor ways, including defining different hydro-geomorphic units in the wetland. A hydro-geomorphic unit is defined by landscape setting, the absence or presence of a river channel, the nature of channel-floodplain processes and the dominant source of water and sediment inputs to the wetland (see Figure 7.1 for examples). The Wet-Health assessment includes analysis of the impacts and threats of human land-use activities to three primary ecosystem components: hydrological, geomorphological and vegetation processes and conditions. The health assessment is qualitative, using a scoring system to document the level of impact of different land-uses on the three ecosystem components. These assessments include estimating the extent and intensity of impacts of dams in the catchment or floodplain drains on wetland hydrology (hydrological module), estimating the impacts of stream channelization or channel infilling on geomorphological and hydrological processes, and documenting the extent of degradation due to the presence of an incising river channel (geomorphological module), and estimating the extent and impacts of alien plant invasion or riparian vegetation removal in the wetland (vegetation component).

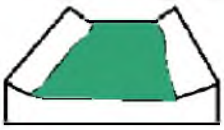
Hydrogeomorphic types	Description	Source of water maintaining the wetland[1]	
		Surface	Sub-surface
Floodplain 	Valley-bottom areas with a well defined stream channel, gently sloped and characterized by floodplain features such as oxbow depressions and natural levees and the alluvial (by water) transport and deposition of sediment, usually leading to a net accumulation of sediment. Water inputs from main channel (when channel banks overspill) and from adjacent slopes.	***	*
Valley-bottom, channelled 	Valley-bottom areas with a well defined stream channel but lacking characteristic floodplain features. May be gently sloped and characterized by the net accumulation of alluvial deposits or may have steeper slopes and be characterized by the net loss of sediment. Water inputs from main channel (when channel banks overspill) and from adjacent slopes.	***	*/ ***
Valley-bottom, unchannelled 	Valley-bottom areas with no clearly defined stream channel, usually gently sloped and characterized by alluvial sediment deposition, generally leading to a net accumulation of sediment. Water inputs mainly from channel entering the wetland and also from adjacent slopes.	***	*/ ***

Figure 7.1: Examples of three commonly found hydro-geomorphic wetland types in South Africa, defined according to dominant source of water and geomorphic processes and form (adapted from Kotze et al. 2009b: 17).

WET-EcoServices evaluates the degree to which a suite of ecosystem goods and services are delivered by a particular hydro-geomorphic wetland unit (Kotze et al. 2009b). The evaluation is rapid, involving desktop and field based assessments of hydro-geomorphic wetland type and related hydrological characteristics. These factors determine the relative importance of the delivery of cultural/social, regulating, supporting and provisioning services provided by the wetland (Kotze et al. 2009b).

WET-Origins guides the assessment of the geological and geomorphological processes that have led to the formation of a wetland and forms the basis of understanding the geomorphological processes driving both contemporary and long-term wetland dynamics. The tool also guides an understanding of the hydro-geomorphic aspects of ecosystem functioning necessary for process-based rehabilitation and catchment management (Ellery et al. 2009).

The remaining tools provide an overview of the principles for guiding effective and sustainable wetland rehabilitation and post-rehabilitation monitoring including:

- Planning of wetland rehabilitation from national level to local (wetland) level (Kotze et al. 2009c).
- Description of different types of rehabilitation interventions for different types of wetlands, with different drivers of degradation (Russell et al. 2010).
- Monitoring and evaluation of rehabilitation outcomes/impacts (Cowden and Kotze 2009)
- Reviewing the impacts of national level natural resource management and ecosystem rehabilitation programmes in South Africa that impact on wetland systems (Kotze et al. 2009a).

All of the above tools developed under the RHP and WfWet programmes indicate substantial advancement toward a process-based approach to rehabilitation and conservation management of South Africa's rivers and wetlands, including geomorphological aspects. However, there are several constraints that limit in-depth or comprehensive application of the tools. Firstly, the monitoring data and use of the various assessment tools within the two programmes are kept separate, when in fact they should be integrated since rivers and wetland are commonly linked in South Africa. Both riverine and wetland assessment tools under the two programmes should be employed when assessing a targeted riverine wetland. For instance, geomorphological condition assessment tools under the RHP may be beneficial to the planning process of rehabilitation for riverine wetlands under the WfWet programme. Similarly, some of the principles of *Wet-RehabPlan* could be adapted to guide a process-based approach to rehabilitation and management of degraded rivers monitored under the RHP. The in-depth monitoring procedures under the RHP should be applied to wetlands targeted by the WfWet programme since ecological monitoring under the latter programme is not as rigorous.

Secondly, there are usually time and political constraints that hinder in-depth application of the various tools that have been developed under each of the programmes. For example, to apply the principles of the 10 tools of the WMS is very time consuming and costly. Comprehensive stakeholder engagement at the catchment level may take several months. This time is usually not available for individual projects since wetland practitioners are often under strict budgetary and time constraints. These constraints include national government budget spending requirements and the need to achieve annual performance indicators which may include the number of wetlands rehabilitated or the number of gabion weirs built. These performance indicators are linked to the overall mandate of the WfWet programme of job creation and poverty alleviation set out by national government (Kotze et al. 2009a; DEA 2016). These political processes are difficult to alter and a hindrance to the advancement of process-based rehabilitation and monitoring and evaluation practice in South Africa. Hence, many of the WMS tools have been formulated for rapid assessment of wetland condition and processes, resulting in superficial knowledge of the underlying processes driving change and determining the functioning of the system.

7.3 Adopting a process-based rehabilitation framework in the Baviaanskloof

7.3.1 Understanding adaptive geomorphological cycles and future river behaviour

Drawing from principles of process-based rehabilitation and the concept of geomorphological connectivity, several key questions are posed to guide development of a conceptual model of process-based river rehabilitation for the Baviaanskloof, as follows:

1) *Has the Baviaanskloof River and associated floodplain entered a new geomorphological state characterised by a new set of process-form interactions and behavioural regime?*

It is suggested that the channel has entered a new state and behavioural regime due to several factors. Severe to moderate degradation of more than 50% of hillslope vegetation along the study reach was reported by Vlok (2010). Vegetation degradation has had a direct impact on hillslope runoff and soil erosion processes, increasing storm discharges (van Luijk et al. 2013) and sediment delivery to the trunk channel. Glenday (2015) modeled the effects of increased hillslope vegetation cover on the hydrology of the Baviaanskloof catchment. The modeling results indicated decreased storm flow peaks and reduced annual discharge from the catchment associated with increased water retention due to increased vegetation cover. The subtropical thicket vegetation that occurs in the Baviaanskloof catchment is an ancient vegetation type (Cowling et al. 2005) which is unlikely to recover through rapid succession of species (Powell 2009). Thicket rehabilitation in South Africa has been dominated thus far by planting the hardy species *P. Afra*, which is often able to survive harsh conditions. However, most of the rehabilitation projects, including those in the Baviaanskloof have shown no more than 60% survivorship of *P. Afra* (Powell 2009). This relatively low survivorship together with a time lag of between 30-50 years following planting for *P. Afra* to begin to mature (Powell 2009), means that it is unlikely that hillslope re-vegetation will result in significant changes in catchment hydrology in the near future. Although it may be possible to reverse artificial increases in tributary-trunk connectivity for major tributaries of the study reach, it is almost impossible to reverse altered hillslope runoff and soil erosion linked to vegetation degradation, in the near future. There is thus little chance for full river-floodplain recovery to the former condition, even with human intervention such that the present-day behavioural regime characterized by channel braiding and relative channel instability may persist for several decades to come.

2) *What has been the role of cross-scale interactions of geomorphological adaptive cycles in determining recent changes in the behavioral regime of the river?*

Altered connectivity has been the means by which various geomorphological adjustment processes and related adaptive phases of Panarchy became connected across spatial scales of the study reach, from sub-catchment hillslopes and tributary streams to the river reach and sub-reach scale. Figure 7.2 is a conceptual illustration of the nature of adaptive geomorphological cycles and their interactions across different spatial and temporal scales for the study reach.

At the hillslope scale vegetation degradation initiated a phase of increased hillslope runoff and erosion, resulting in the onset of gully formation from the 1960s onwards ('1', Figure 7.2). Hillslope vegetation degradation and associated enhanced runoff would have resulted in breaching of discharge thresholds and tributary channel widening ('2', Figure 7.2). At the same time tributaries would have become better connected to the trunk stream such that increased storm discharges would have been experienced along the trunk channel, initiating a threshold breach along the trunk stream. This would have initially resulted in channel widening ('3', Figure 7.2), followed by a phase of channel deepening ('4', Figure 7.2) as the river attempted to lower its bed in response to increased stream energy. The recent crossing of stream power and geomorphological thresholds of change means that the river-floodplain has entered a creative destruction phase (**Ω**) of an adaptive geomorphological cycle characterised by breakdown (destruction) of geomorphological structure, but opportunity for a new geomorphological state and behavioural regime (creative) during the reorganization phase (**α**). The creative destruction phase in this case occurred as critical thresholds of erosion were surpassed such that an overall shift in river process and style and associated channel-floodplain condition occurred along the study reach. Destruction occurred in the form of widespread channel erosion and associated channel widening and deepening, decreased floodplain inundation and loss of floodplain wetland along the trunk channel, and alluvial fan entrenchment along tributary streams. The creative part of this phase has manifested as a switch to a braided channel form, with higher energy storm flows, higher channel instability and lower retention of water within the alluvial aquifer. Hence a new geomorphological state and behavioural regime now exists. The degradation would have been most obvious within a several hundred meter zone downstream of connecting tributary streams, but may have been initiated elsewhere along the trunk where local slope thresholds were breached. Localized head cuts that form along the trunk channel bed, such as at the toe of a channel bar or an over-steepened riffle, were observed to be the means by which degradation is transferred upstream along the trunk and tributaries, given that no localized bed and bank armouring is present along upstream reaches. Local-scale degradation would have propagated to upstream channel reaches through headward erosion during flood events (Simon 1994), thereby connecting local-scale channel processes.

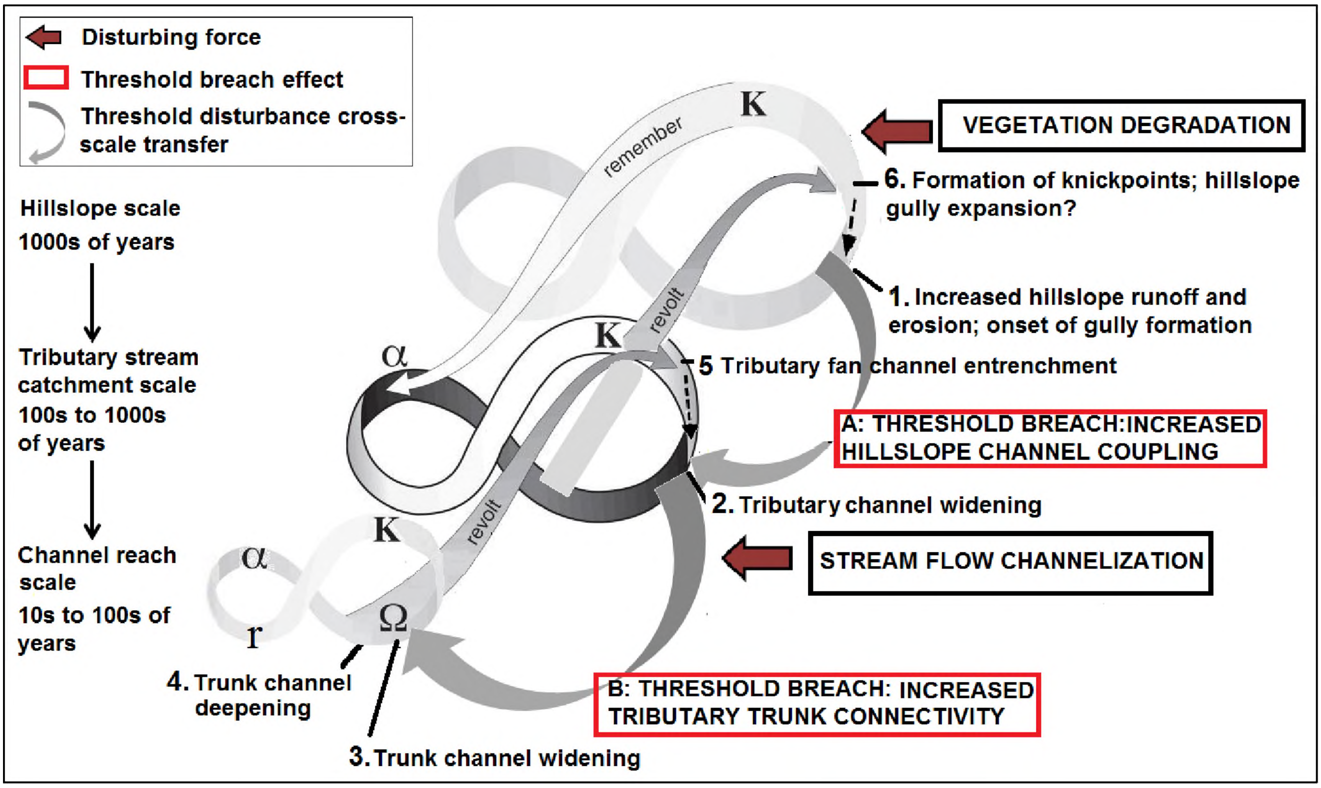


Figure 7.2: A conceptual representation of cross-scale interactions of adaptive cycles (Panarchy) at the hillslope, tributary stream and fan, and trunk channel reach scale, for the Baviaanskloof. Disturbing forces influencing degree of water and sediment connectivity within and between the different scales are indicated (adapted from Holling 2001).

Degradation processes occurring along the trunk were easily transferred to tributary fans that were impinged on the trunk channel as a result of trunk stream bed-level lowering and a drop in tributary local base-level (Fryirs and Brierley 1999; Cohen and Brierley 2000; Anders et al. 2005; Harvey 2012). Lowering of local base-level for tributary fan streams would have resulted in rejuvenation and channel incision along tributary streams ('5', Figure 7.2), explaining why distal fan entrenchment is common along the study reach for connecting tributary streams (Bobbins 2011). Thus the direction of cross-scale interaction of geomorphological processes was reversed such that processes at the trunk channel reach scale were transferred to the surrounding sub-catchment scale ('revolt') creating a positive feedback characterised by enhanced stream power due to channel degradation and associated channelization of stream flows.

As a result of this positive feedback between channel degradation, channelization of stream flows, and enhanced stream power, many of the large tributaries on the southern side of the valley and some of the smaller tributaries on the northern side of the valley became well-connected to the trunk. This increased tributary-trunk connectivity further enhanced connectivity of the hillslope erosional adaptive phase with trunk stream processes, creating a positive feedback situation of enhanced discharge and sediment flux to tributaries and the trunk stream. Tributary stream erosion may then have been transferred to the hillslope scale through incision along gully networks already connected to tributary streams and the formation of knickpoints in channel banks, resulting in the formation of new gullies ('6', Figure 7.2).

Thus creative destruction was experienced across multiple scales resulting in reorganization of the geomorphological form of the study reach and a shift to a new channel behavioural regime. The apparent stabilization of the trunk channel in recent years suggests that the river is entering the reorganization phase of an adaptive cycle characterised by slower rates of change such that the channel may begin to accumulate sediment as gravel, sand and silt is episodically supplied from connecting tributaries (Simon and Rinaldi 2000; Fryirs and Brierley 2001; Harvey 2007a), indicating a shift toward a new growth phase in the adaptive cycle. Such a phase is characterised by a new geomorphological behavioural regime and state. This stabilization is partially attributed to a decrease in water and coarse sediment connectivity following decreased agricultural activities and some recovery of natural levels of tributary-trunk connectivity and vegetation cover from the 1990s onwards. This decreased connectivity has led to the contraction of the trunk channel and several major tributaries. The new geomorphological trajectory of the Baviaanskloof River along the study reach has implications for the impacts and effectiveness of channel-floodplain rehabilitation interventions that have already been employed by WfWet.

3) *What is the potential future geomorphological behavioural regime of the river-floodplain along the study reach?*

It is impossible to pin-down the future geomorphological style toward which any river is progressing given that river systems are characterised by complex interactions and unpredictable change, and environmental drivers of change are also only partially understood and unpredictable. It is however possible to predict the behavioural range of a river-floodplain into the future based on knowledge of river geomorphological history, controls on sensitivity and change (Fryirs et al. 2009). The uncertainty of future climate change for the study region and the interplay of climate with vegetation, soils and local topography make it difficult to predict future hydrological trends for the study reach. Long-term rainfall analyses in this study indicated that the study area has recently entered a relatively wet climate phase within the 10-12 year cycle that may last for several years to come. The future climate may thus be characterised by above average annual rainfall and more frequent, short duration rain events and small to moderate floods. The persistence of a relatively wet climate over the next several years will enhance coarse sediment connectivity and the potential for partial recovery of the trunk channel (Brierley and Fryirs 2000; Fryirs et al. 2009).

Aggradational processes may become dominant in the near future since substantial channel adjustment has already occurred (Simon 1992; Simon and Rinaldi 2006). Channel monitoring surveys indicated that aggrading channels may experience bed elevation increases of up to 34 cm over several months in which small floods and below bankfull flow events occur. These levels of aggradation mean that various floodplain reaches may become more frequently inundated during storm flows in years to come, increasing the potential for the formation of floodplain wetland depressions. The potential for natural river-floodplain recovery is thus a highly possible scenario for the study reach. Reconnection of the trunk stream to the floodplain will increase the potential for channel avulsions such that the river may switch to a mixed braided to anabranching river style characterised by channel contraction. The channel will still remain laterally unstable but may enter a period of relative stability compared to levels of instability that have occurred over the last few decades. This scenario will encourage the formation of floodplain wetlands, promoting greater water retention and potentially enhancing base-flows. The buffering role of the floodplain will thus be reinstated, reducing the effects of floods for valley reaches downstream of the study reach. The re-creation of these connected floodplain depressions and wetland areas, however, is dependent upon the availability of floodplain that is devoid of human cultivation and infrastructure such that natural geomorphological adjustment and overbank flooding may occur. At present, floodplain areas devoid of human development is restricted to isolated areas along the upper- and lower-end of the study reach, where floodplain cultivation has been abandoned. The reinstatement of floodplain wetland areas at the aforementioned locations would be contingent on approval by local landowners.

4) *What are the present and future social desires and socio-economic trajectories for the catchment and how does this relate to the future geomorphological trajectory of the river-floodplain along the study reach?*

Several documents were used to inform present and future socio-economic and rehabilitation desires for the study reach. These included a study on future rehabilitation and land-use visions of landowners in the Baviaanskloof by Stokhof de Jong (2013) and information provided on future socio-economic trajectories for the study reach by the NGO, LivingLands, through their work over several years engaging with stakeholders in the catchment with regards to integrated catchment management.

In recent years there has been a shift in land-use from predominantly agricultural activities that have high impact on river-floodplain processes, toward conservation (stewardship) and nature-based tourism activities. The future vision for the upper- to middle-reaches of the catchment within which the study reach is located is a 'Living with nature' scenario, which will include mountain areas under conservation and related nature-based tourism activities, rehabilitation of vegetation and river-floodplain areas, and zones in which high-value crops are grown (Stokhof de Jong 2013; Four Returns 2016). The trajectory towards this scenario has been clear in recent years and has been facilitated by the work of LivingLands through ongoing engagement with local stakeholders, creation of a shared vision and funding that has been raised for various rehabilitation activities. This new socio-ecological trajectory has promoted a decrease in stocking numbers and on some farms a removal of goats from the landscape. The recent investment of large businesses into catchment rehabilitation initiatives in the Baviaanskloof, including hillslope vegetation and stream rehabilitation, has further enhanced the potential for improved river-floodplain health in degraded parts of the catchment. Although areas of the floodplain and alluvial fans will remain under cultivation in years to come, there is now more floodplain space for the natural dynamism of the river and tributaries to occur.

7.3.2 Evaluation of the WfWet rehabilitation planning process

The floodplain wetland rehabilitation planning process of the WfWet team involved desktop and field-based assessments of ecosystem services and the impacts and threats to ecosystem health for a selected degraded floodplain are along the middle of the study reach. The assessment tools, *WET-EcoServices* and *WET-Health* were applied. Two channel sites were initially targeted in 2009 for rehabilitation using a gabion weir structure built across the channel zone. The two sites were proposed for the middle of the study reach where the channel has eroded up to 2 m into the surrounding floodplain that once hosted seasonal-permanent wetlands. The aim was to build gabion weir structures across the width of the active channel, to trap coarse sediment for a short distance upstream of the weir structure, raise the level of the river bed, and thereby initiate more frequent inundation of the floodplain during small and moderate flood events.

Based on information gained during the present research, the WfWet rehabilitation planning process and choice of intervention for the Baviaanskloof was evaluated. The results of the wetland assessment are presented below along with a critique on 1) classification of the hydro-geomorphic type (HGM type); 2) identified threats, rehabilitation goals and type of intervention; 3) management recommendations; 4) monitoring and evaluation of rehabilitation impacts.

1. **Classification of HGM type**

The targeted rehabilitation site was classified as a floodplain wetland HGM unit, characterized by a well-defined channel and a floodplain marked with oxbows, meander scars and natural levees. This HGM type is dominated by the accumulation of sediment and surface water inputs to the floodplain (see Figure 7.1). Although most of the study reach could be classified as an active floodplain, it could be argued that the degraded and intact wetland units in the area selected for rehabilitation by WfWet resemble more closely the characteristics of channeled and unchanneled valley bottom HGM types respectively. Aerial photography from 1960 indicates that the degraded wetland area indicated in Figure 7.3 was characterised by narrow anabranching channels that dispersed flows across the floodplain ending in a flood-out (white circled area, Figure 7.3a). The latter conditions characterize an unchanneled valley-bottom HGM wetland type where sub-surface flows are relatively important in sustaining permanent to semi-permanent wetland (see Figure 7.1). The presence of reed stands and denser tree canopy cover along the reach circled in Figure 7.3a, prior to channel-floodplain degradation, would have contributed to the dispersed flow environment. Figure 7.3b indicates the same floodplain area circled in white in Figure 7.3a, illustrating how the river has switched to a single-channel flowing through an infrequently inundated floodplain. Water inputs to the floodplain occur via fractures in the bedrock, non-entrenched tributary fans and the upstream alluvial aquifer, with limited overbank inputs from the trunk stream at present-day (Glenday 2015). Transmission losses from the channel bed are important inputs of sub-surface water input to the floodplain (Glenday 2015). All of the latter conditions more closely fit a channeled valley-bottom HGM type rather than a floodplain HGM type. The reach may have briefly existed as a floodplain HGM type prior to the present-day condition, as there is evidence of an old channel cutoff (circled in yellow, Figure 7.3b). At present the floodplain is only inundated once every few years and sediment erosion is the dominant process along the reach. The new channeled valley-bottom HGM type that exists along the proposed rehabilitation reach is characterized by higher energy stream flows than the previous unchanneled valley-bottom HGM type. The downstream intact wetland site still resembles unchanneled valley-bottom HGM characteristics such that permanent wetland still exists in this region.

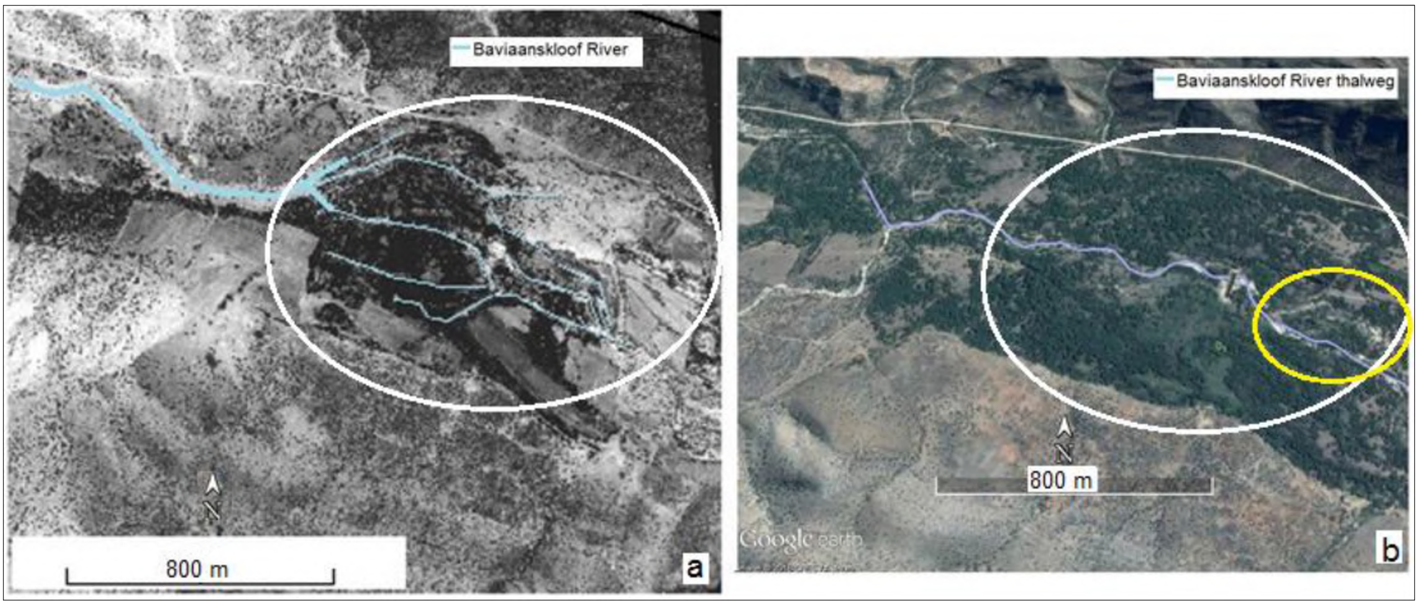


Figure 7.3: Aerial photo view of the proposed rehabilitation reach (circled in white) for 1960 (a) and 2016 (b). The yellow circle indicates a historical channel cut-off.

Different HGM types have different driving processes and flow and sediment regimes, which have implications for the types of ecosystem services the different wetlands offer, their potential sensitivity to disturbances of a particular magnitude, and the type and location of rehabilitation interventions that are suitable for reinstating driving processes and healthy functioning. For example, maintaining upstream-downstream water and sediment connectivity is important in a channeled valley-bottom setting; maintenance of dispersed low-flow conditions in an unchanneled valley-bottom HGM type is essential; and for a floodplain HGM type, a sinuous channel that is able to adjust both vertically and laterally to flood events should be encouraged. In South Africa most rehabilitation projects tackle similar drivers of degradation in different HGM wetland types in a generic way, discounting that these different systems may have different responses to similar types of interventions. The failure to classify the HGM type accurately in the case of the Baviaanskloof would have influenced the results obtained for assessment of present-day ecosystem services and health and the assessment of the potential impact of the proposed rehabilitation intervention on the delivery of ecosystem services.

2. Identified threats, rehabilitation goals and type of intervention

The identified threats to wetland health and functioning for the proposed rehabilitation reach included:

- Head cut erosion and channel degradation;
- Enhanced erosional capacity of flood flows due to channelizing berms upstream of the target reach;
- Small dams in the surrounding catchment and surrounding land-use practices.

Some of the above supposed threats to the targeted reach are minor. For example, dams in the catchment are very small and are only present along gully networks or high-order streams feeding into lower-order tributaries on the southern side of the valley. Many of the gully networks along which the dams have been built do not connect to the trunk stream. It is therefore unlikely that the dams are a major barrier to flow and sediment inputs to the trunk stream, and may rather act as local-scale sediment buffers along tributaries supplied with sediment from surrounding denuded hillslopes and gullies. Land-use activities at present in the surrounding catchment include minor grazing of livestock on hillslopes. An area where floodplain agriculture has been largely abandoned is indicating slow recovery of woody vegetation.

In contrast to the above identified threats, the present study has indicated that loss of vegetation cover on hillslopes, channelization of stream flows and associated enhancement of water and sediment connectivity, have been the most important drivers of recent channel-floodplain degradation, particularly during high-magnitude flood events. Although groundwater abstraction may have impacted base flows, deepening of the trunk stream appears to have been a more important threat to groundwater levels in the surrounding floodplain aquifer and hence to the functioning and existence of the floodplain wetlands that existed.

Based on the threats identified during the WfWet assessment, several rehabilitation goals were set for the targeted reach including:

- Re-hydration of the floodplain sediments;
- Increased frequency of overbank flooding;
- Stabilization of the trunk stream and an adjacent furrow which shows signs of degradation;
- Rehabilitation of floodplain vegetation.

The wetland assessors assumed that the presence of several peat layers in erosion banks along the targeted reach indicate that a permanently inundated floodplain wetland existed in the recent past (a few decades ago), and that this condition could be easily re-instated. The type of intervention planned in accordance with the above goals was a gabion weir 140 m wide (the same width as the active channel), with a height calculated to induce overbank flooding during a moderate or large flood event. This kind of intervention and the proposed rehabilitation goals are problematic for the following reasons:

1) The OSL dating of sedimentary units conducted during the present study indicated that the peat layers, which were interpreted to represent recent permanent wetland conditions, were deposited thousands of years ago. The most recent floodplain deposits of the last few decades indicate that the more recent floodplain wetland was drier, due to the absence of gleying and the presence of iron mottling, indicating seasonally to temporarily inundated wetlands (Kotze et al. 2009b).
2) The trunk and tributaries have entered a new geomorphological state and associated behavioural regime. Thus, attempts to return the present system to a previous state characterised by a completely different set of flow and sediment dynamics and sub-surface-surface water interactions, would be extremely difficult and costly. The achievement of desired outcomes requires catchment-scale interventions. The proposed gabion weir structures may have localised impacts on water and sediment dynamics (some aggradation and flow spreading), but are unlikely to be successful in achieving the goal set out. Furthermore, under the present state, coarse sediment connectivity is an important system attribute allowing for channel adjustment (lateral and vertical) and recovery. Features that hinder coarse sediment movement along the trunk stream hinder these processes. The structures may also be abandoned since the trunk stream frequently shifts across the floodplain (Rowntree and Joubert 2013).
3) The deep nature (>2 m deep in some places) of the trunk stream upstream of the proposed rehabilitation site means that multiple structural interventions would be required to induce the frequency of flooding required to re-instate floodplain wetland across the proposed area. The deep nature of the main channel along this reach is partly a consequence of the response of the main river to two impinging

alluvial fans, through which the river has attempted to erode toward a desired stable channel gradient. Restoring river-floodplain connectivity by raising the level of the river bed thus counteracts the natural evolution of the channel, in response to impinging alluvial fans. It would have been more beneficial to focus conservation and/or rehabilitation activities at relatively intact floodplain wetland depressions that occur at a few places downstream of the rehabilitation site. Here, strategic interventions could be employed to limit threats to these wetland depressions, and possibly aid expansion of the existing wetland area such that flood attenuation and base-flow services that are already being delivered are enhanced.

The proposal of the two gabion interventions was contested by a small group of geomorphological and hydrological researchers employed in the catchment at the time, including the author of this thesis. The latter team felt that this type of intervention was unsuited to the geomorphological and hydrological dynamics of the river-floodplain and the scale of drivers initiating channel degradation. As a result, the research group and the WfWet project manager at the time discussed the impacts of the two proposed interventions. The group agreed on possible adjustments to the location and number of rehabilitation interventions for the proposed reach that would be more suited to the present state and geomorphological dynamics of the river-floodplain. However, there was little chance to approach the rehabilitation in a completely different way, as building gabion weir structures in degrading wetlands is part of the mandate of the WfWet programme. This mandate included at the time, targets for the number of hard structures built across eroding river channels and wetlands, employing presently unemployed people for several months to build the hard structures, and spending a particular budget allocated to an identified rehabilitation site within an allocated period of time. The best alternative for the Baviaanskloof therefore, was to move the planned weir structures to channel sites that would possibly result in more effective hydrological and geomorphological outcomes along the proposed rehabilitation reach. The discussed alternatives are described in an unpublished report by Rowntree and Joubert (2013), who formed part of the geomorphological assessment team, from Rhodes University. As indicated in Figure 7.4 below, three weir sites were proposed by Rowntree and Joubert (2013), to be located at relatively gently sloping channel sites, with shallow erosion banks, such that re-wetting of the surrounding floodplain would be most likely. The sites were located upstream of the intact wetland area that exists along the reach (Figure 7.5), to enhance the area of wetland should re-wetting of the floodplain occur. However, Rowntree and Joubert (2013) indicated in their report that the laterally dynamic nature of the river at present means that the proposed type and scale of intervention in not suitable, as the channel could avulse around the weir structures. Avulsion would leave the structure abandoned and ineffective in achieving the stated rehabilitation goals.

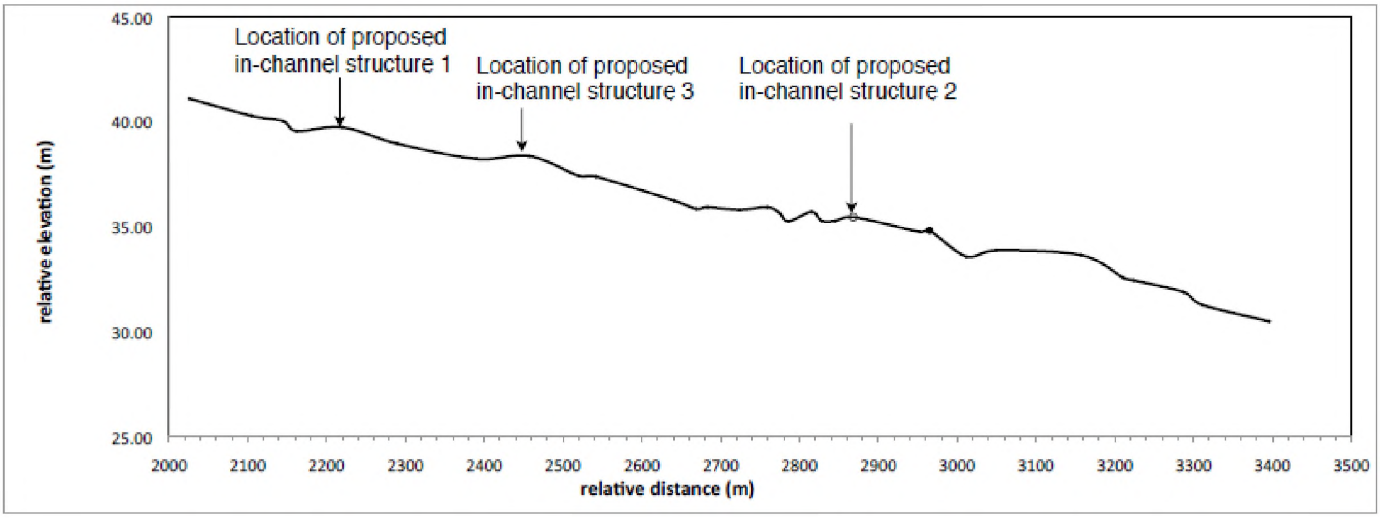


Figure 7.4: A longitudinal profile of the Baviaanskloof River thalweg for the proposed river-floodplain rehabilitation reach indicating the location of three proposed gabion weir structures (adapted from Rowntree and Joubert 2013: 3).

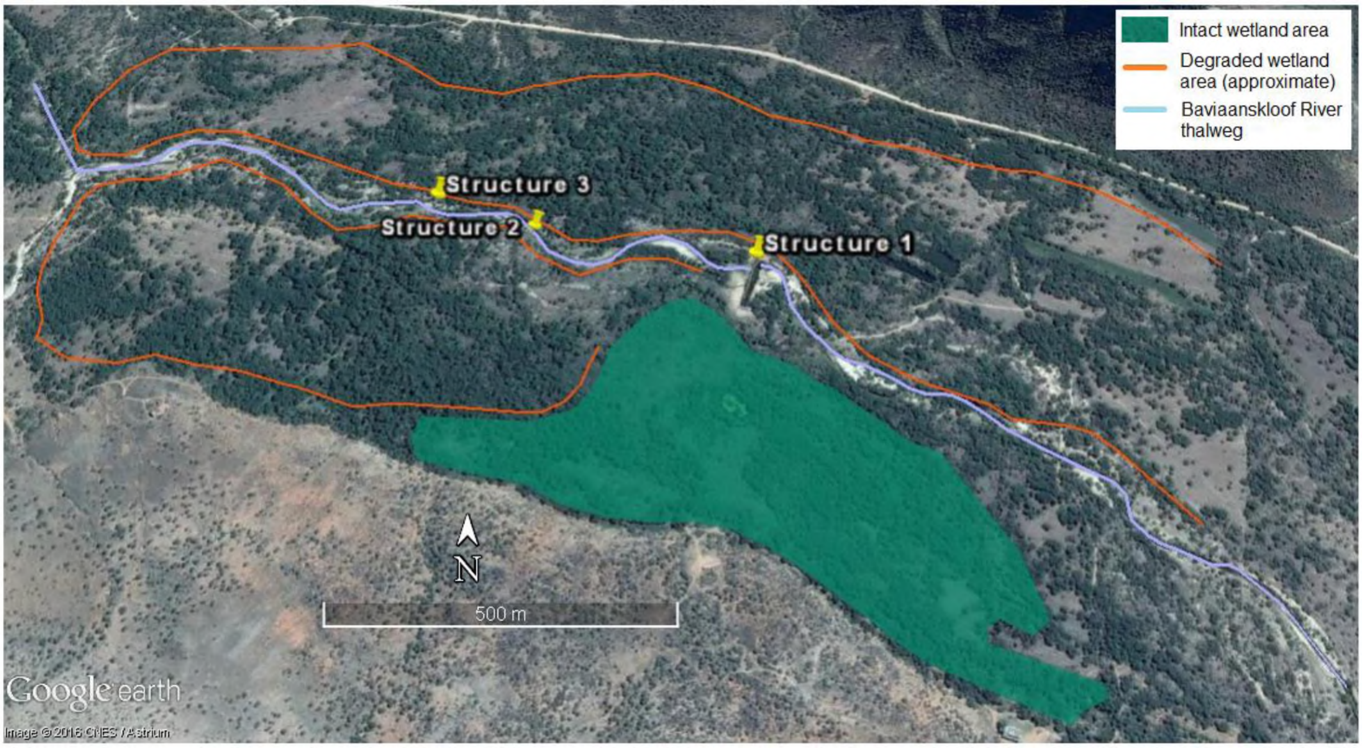


Figure 7.5: An aerial view of the location of the proposed gabion weir structures in relation to degraded and intact floodplain wetland for the proposed rehabilitation reach. Structure 1 which was built between 2014 and 2016 is visible in the google earth image, dated 2016.

3. Management recommendations

The recommended management activities in the rehabilitation plan were:

- A buffer of 20-30 m on either side of the channel;
- Biodiversity assessments pre- and post-rehabilitation;
- Removal of alien vegetation from the wetland;
- Control access to wetland by using existing dirt roads;
- No harvesting of threatened or protected plants or animals.

The above recommendations are all site specific and do not consider off-site drivers or impacts on recent wetland loss. In addition the number of people living in the river valley who harvest local fauna and flora for cultural purposes is low and there is no evidence that harvesting levels are impacting on local biodiversity. The alien plant found along the targeted reach is a species with low levels of infestation. The tree in fact helps to stabilize the floodplain and channel banks in localized areas and if removed would need to be replaced by other mature indigenous tree species to maintain some form of stability. A buffer of 20-30 m is insufficient to accommodate the extent to which the trunk channel may avulse during a moderate or large flood event. The buffer should be increased to at least 100 m either side of the present-day channel.

1. **Monitoring and Evaluation procedures**
   - Use of fixed-point photography to assess channel and floodplain condition pre- and post-rehabilitation;
   - WET-Health and WET-EcoServices assessment pre- and post-rehabilitation to assess changes in health and ecosystem services delivery of the wetland (assuming it can be re-instated).

The above procedures are insufficient for monitoring the impacts and success of the rehabilitation interventions. Geomorphological and hydrological surveys prior to and following the rehabilitation intervention should be conducted to indicate changes to channel-floodplain process and form and associated impacts on ecological integrity of the floodplain.

Based on the evaluation above it is clear that a form-based approach to rehabilitation planning and implementation was initially adopted by WfWet for the Baviaanskloof. This kind of approach is unsuitable for most stream degradation scenarios (Wohl et al. 2005), and particularly unsuitable for a high-energy mountain stream transporting large amounts of coarse bed load. There has however been a concerted effort on the part of the WfWet team during the four year rehabilitation process, to trial soft interventions on the southern hillslopes of the study reach where vegetation denudation and gully erosion is most severe. These interventions have included, creating hollows in the ground which trap hillslope runoff during storm events, as well as re-shaping the head-region of gullies following which several silt-traps are erected across the re-shaped gully area. These rehabilitation efforts have occurred on a small scale within the wider catchment, and indicate a shift in thinking toward tackling the problem causing degradation, rather than focusing on the degrading channel reach.

In the Baviaanskloof, widespread catchment-scale initiatives are required to address the problem of increased hillslope runoff and erosion, and to diffuse flow along tributaries which have been channelized and are well-connected to the trunk stream. This catchment-scale approach has been adopted by the NGO, LivingLands, in their integrated catchment rehabilitation programme over the last several years. The programme has involved reinstatement of diffusive flows at a few selected entrenched alluvial fans along the study reach and removal of a few earthen berms alongside the main river channel. LivingLands has also partnered with government to rehabilitate thicket vegetation cover on several farms. However, the timing and location of these different interventions has been haphazard and limited to small areas due to funding and capacity constraints. LivingLands has recently secured a large amount of funding from a large corporate in South Africa for land and river rehabilitation of more than 1 000 ha. The author presents a suggested process-based and catchment-scale rehabilitation framework below, feeding into what has already been planned by LivingLands, and drawing from the lessons learned from various interventions implemented by WfWet. Thus, the recommendations are meant to compliment and possibly improve the process-based river-floodplain and hillslope rehabilitation approaches that are already being considered within the Baviaanskloof.

7.3.3 A conceptual model of process-based rehabilitation for the Baviaanskloof

Based on knowledge generated in the present study and the above evaluation of WfWet rehabilitation, a conceptual model of process-based rehabilitation and associated land management was formulated for the study reach. The model attempts to align with the plans of LivingLands Integrated Catchment Rehabilitation. Although catchment-scale land management and rehabilitation should be the ultimate goal of any river rehabilitation project, working at broad spatial scales is not always financially viable, and requires lots of time, and buy-in from local landowners and land managers. According to Piégay et al. (2006) catchment-scale rehabilitation should be strategic and target catchment areas that are sensitive to future geomorphological change, since this approach is more effective than random system-wide rehabilitation. In the case of the Baviaanskloof, it is not ecologically, financially or socially feasible to attempt rehabilitation of all degraded areas within the catchment over the next few years. Catchment-wide rehabilitation would comprise an area of more than 10 000 ha, incorporating the valley reach upstream of the study reach, as well as the study reach itself. This scale of rehabilitation may become a possibility through ongoing engagement with WfWet and large corporates with vested interest in catchment rehabilitation and sustainable development. The conceptual model has thus been formulated for the study reach since there is in-depth knowledge of river history and contemporary fluvial process and form, drivers of change, the spatial arrangement of sensitive river reaches, and the socio-economic trajectory of the study reach.

Since the factors influencing recent shifts in river behavior and future trajectories operate at varying spatial and temporal scales, a hierarchical strategic approach to river-floodplain rehabilitation is suggested for the Baviaanskloof. A conceptual model of this hierarchical framework is indicated in Figures 7.6 and 7.7. The model draws on the principles of process-based river rehabilitation, and from the hierarchical approaches to classifying and managing river catchments presented by Rowntree and Wadeson (1999) and Brierley and Fryirs (2000, 2005). Four process zones occurring at different spatial hierarchies of the study reach are defined (Zones 1-4, Figure 7.6 and 7.7). Zone 1 comprises the mountain peaks and upper-mountain slopes where high-energy runoff is generated and where hillslope-channel connectivity is high; Zone 2 comprises an extensive region of rolling, relatively gently sloping foothills that exist on the southern side of the valley where moderate to severe degradation of thicket vegetation has occurred, along with extensive hillslope gullying. These factors have impacted considerably on hillslope processes (van Luijk et al. 2013), hillslope-channel connectivity, and concomitant sensitivity of the trunk and connecting tributary streams; Zone 3 comprises tributary fans and associated streams on either side of the valley floor that form either buffers or enhancers of water and sediment supply to the trunk stream (Fryirs et al. 2007a), thereby influencing trunk channel geomorphological process and form. Zone 3 is directly impacted by hillslope processes occurring in Zone 2; Zone 4 comprises the trunk stream characterised by downstream variations in river style and associated behaviour (Brierley and Fryirs 2000, Brierley and Fryirs 2005), influenced by processes occurring in Zones 1-3, particularly tributary-trunk connectivity relations characterizing Zone 3. Within each process zone, strategic rehabilitation and land-use management activities are proposed (boxes A-C, Figure 7.7). The high-energy nature of stream flows in the catchment area surrounding the trunk stream means that rehabilitation measures need to target hillslope runoff and erosion processes, as well as tributary fan dynamics, in order to have any impact on stream power and associated morphodynamics and relative trunk stream stability. The hierarchical approach to rehabilitation planning for the Baviaanskloof is hence considered useful.

The proposed rehabilitation interventions involve 'soft' measures that influence inputs of water (energy) and sediment from surrounding hillslopes and tributaries to the trunk channel, to aid self-recovery of the trunk stream (Pasternack 2013). This passive approach however, is considered within the confines of what is socially feasible since agricultural practices are still a necessary function of the landscape, requiring floodplain area for cultivation and grazing practices, and to some extent, control of flooding impacts.

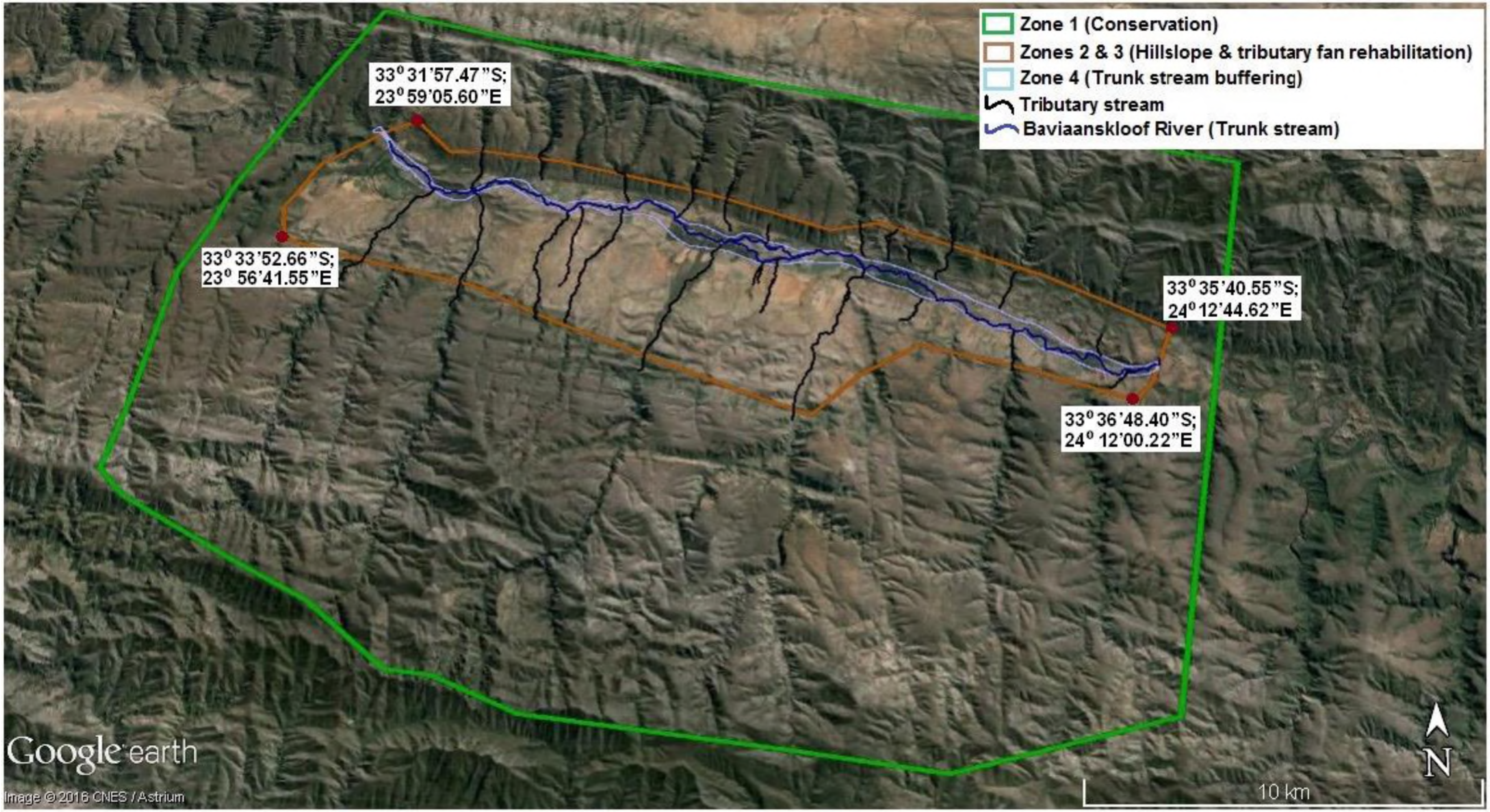


Figure 7.6: An aerial image of the study reach indicating the four process zones defined within the rehabilitation framework indicated in Figure 7.7.

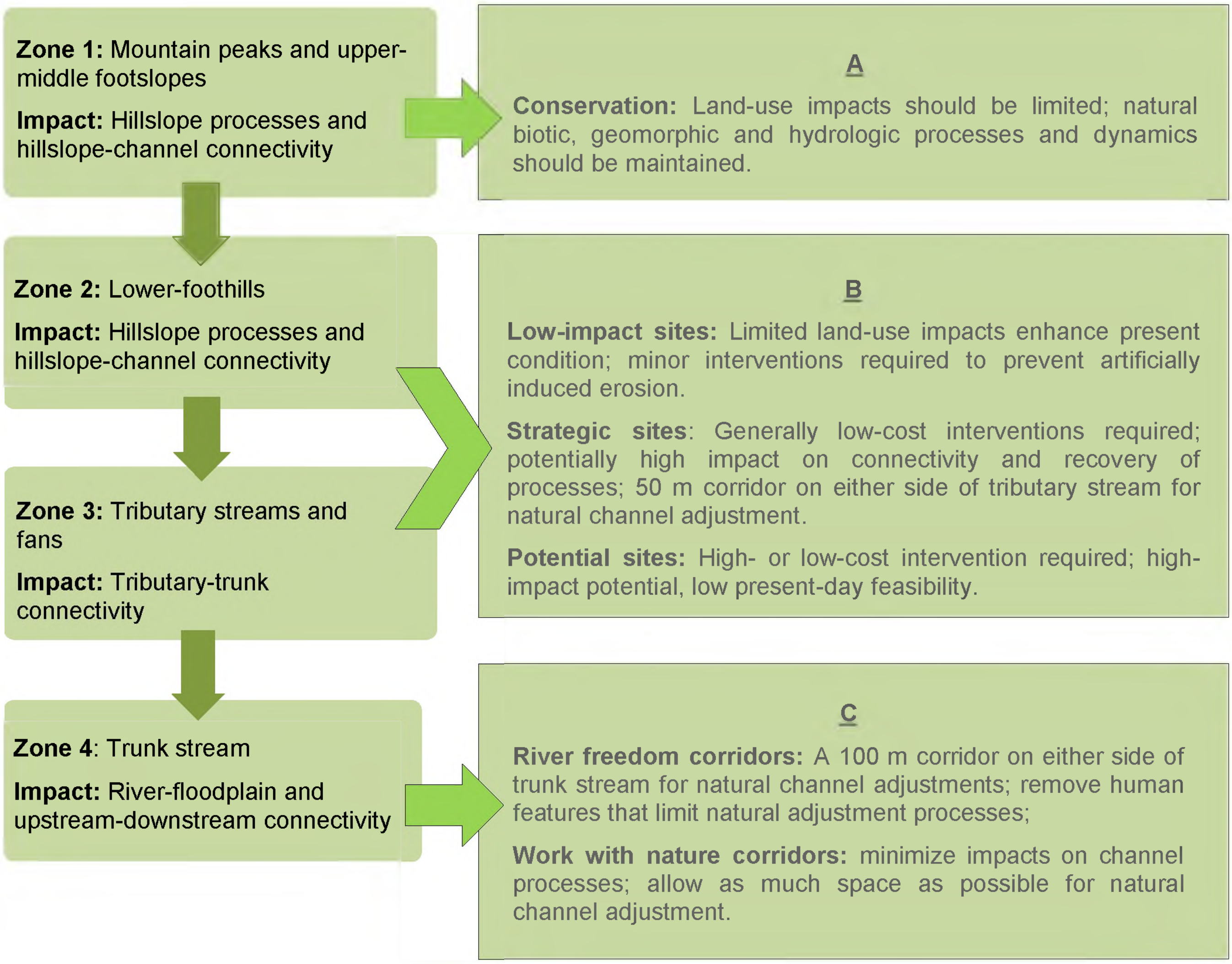


Figure 7.7: A conceptual model to guide process-based rehabilitation for the middle-reaches of the Baviaanskloof floodplain, indicating four process zones at different spatial hierarchies of the study reach (Zones 1-4), and strategic rehabilitation and land management approaches for each zone (Boxes A-C).

Zone 1 has been selected for conservation and a largely 'hands-off' approach since this area is relatively intact and should be preserved in the current state; Zones 2 and 3 have been accorded a range of rehabilitation and land management approaches including 'low impact sites', where land-use impacts should be restricted and where little rehabilitation intervention is required (Box B, Figure 7.7); 'rehabilitation sites', where low-cost interventions could be employed in areas where impact on local water and sediment processes is potentially high; and 'potential sites', as areas that should receive rehabilitation, but where present-day land-use practices limit the feasibility of rehabilitation. Zone 4, comprises the trunk stream, with two main rehabilitation approaches: 'river freedom corridors', where a corridor alongside the channel should be maintained for natural channel adjustment (O'Hanley 2011; Biron et al. 2014) and, 'work with nature corridors', where land-use impacts on stream processes and local scale sediment connectivity should be minimized as far as possible (Box C, Figure 7.7).

7.3.4 Specific recommendations for strategic rehabilitation in the Baviaanskloof

Specific rehabilitation sites are proposed by the author for zones 2-4 (foothills, tributary fans and trunk channel) of the study reach. It is hoped that the recommendations will contribute into the LivingLands integrated catchment rehabilitation plan, in conjuction with work that will be implemented by WfWet in the catchment in the future. Figure 7.8 and Table 7.2 in Appendix 7A indicate the location and type of interventions and management approaches proposed for the study reach. Many of the proposed sites have already been proposed for rehabilitation by LivingLands, thus the recommendations made here, serve as a means by which LivingLands can compare and possibly adjust the integrated rehabilitation plan for the Baviaanskloof. The recommendations are made according to several categories of strategic rehabilitation, with detail and GPS coordinates of the sites indicated in Table 7.2. The various categories or rehabilitation and management approach include:

1) Strategic hillslope rehabilitation;
2) Low impact alluvial fan strategy;
3) Strategic alluvial fan rehabilitation;
4) Potential alluvial fan rehabilitation;
5) Trunk channel rehabilitation.

These categories are detailed below, for each hierarchical zone of the study reach.

Rehabilitation approach for upper hillslopes (Zone 1)

This zone requires relatively little intervention since land-use impacts have been relatively low and current management of the zone falls under the government agency, Eastern Cape Parks and Tourism. This agency adopts a largely hands-off approach to management such that fires occur at natural time intervals of on average, once or twice every 10 years for most of the vegetation types that exist along the study reach (Reeves and Eloff 2012), and browsing pressure is limited to small populations of indigenous antelope species. This zone has also recently been declared as a formal conservancy area through the partnership of local landowners, LivingLands and the Eastern Cape Parks and Tourism Agency. The zone will thus be preserved in a largely natural state into the future.

Rehabilitation of middle-lower hillslopes (Zone 2)

Zone 2 comprises the rolling foothills on the southern side of the valley (Figure 7.6), and contains around 6 000 ha of degraded hillslope thicket vegetation and gullied area. Ultimately this entire area should receive rehabilitation, particularly through erosion control measures and revegetation. Comprehensive hydrological modeling of the catchment by Glenday (2015) indicated that re-vegetation of thicket on hillslopes could decrease flood peaks to the main channel (i.e. decrease flow power), but could result in decreased annual average water yields from the catchment due to decreased storm peaks and base-flows (Glenday 2015). The results of Glenday's (2015) modeling exercise also indicated that re-instatement of diffusive flows at presently entrenched alluvial fans would increase river base-flow compared to a scenario where the river continues to deepen. Mander et al. (2010) used the ACRU hydrological model and available vegetation cover and water balance information (precipitation, evapotranspiration) for the Baviaanskloof to estimate the impacts of various vegetation restoration scenarios for the catchment on water (including baseflows) and sediment yield. The study suggested that revegetation of denuded areas may substantially decrease stream flow, but result in more consistent flows, an increase in annual base flows, and improve water quality by decreasing sediment yield from the catchment area. Sommeijer (2010) modelled the effects of re-vegetation of hillslope thicket on runoff using the curve-number, which indicates the degree to which rainfall is converted into direct runoff utilizing an understanding of local soil type and properties, vegetation land cover and slope. Although the model is relatively simplistic and may only provide an estimation of runoff generation under different conditions, the results of the study indicated that re-vegetation on hillslopes may considerably decreases runoff. These findings concur with findings from the van Luijk et al. (2013) study, which demonstrated greater water infiltration and reduced runoff and soil erosion in a plot with higher thicket canopy cover than an adjacent degraded plot with relatively low canopy cover. Re-vegetation of hillslopes on the southern side of the valley where degradation is highest may thus reduce storm discharges and sediment delivery from hillslopes to the channel network, with implications for increasing the resilience of stream channels to storm events.

The substantial decrease in stocking densities along the study reach from the early 1990s onwards together with efforts to re-forest degraded hillslopes by various Government and non-government rehabilitation programmes may promote gradual recovery of vegetation cover on hillslopes. However, the dense subtropical thicket that once existed was old-growth (Powell 2009). The potential for recovery of the vegetation to a semi-pristine condition following a major disturbance such as overgrazing is reported to be almost impossible to very slow (Powell 2009; van Luijk et al. 2013). The loss of topsoil due to high runoff and erosion on degraded hillslopes has left little chance for seeding of pioneer trees and shrubs. It may be that a few grass species are gradually able to propagate areas where some topsoil remains, forming a savannah-like vegetation cover. The vegetation community on the hillslopes of the study reach has entered a new state defined by low canopy cover, with relatively high runoff and soil erosion. Without intensive rehabilitation interventions that improve soil conditions for seeding of thicket species, hillslope vegetation may remain in a severely degraded state for several decades to come. Hillslope runoff and erosion may thus remain relatively high over the next few decades for the study reach.

To recover hillslope vegetation cover across the 6 000 ha of degraded land will be extremely costly and may not be within the budget of government rehabilitation programmes within the next few years. Thus 'Strategic hillslope rehabilitation sites' have been identified for this zone (Figure 7.8). These sites are where hillslope degradation is moderate to severe but where relatively low-cost, 'soft' interventions could be employed to limit further degradation and aid recovery of damaged hillslope processes. These interventions could include creating small circular depression to trap water and sediment on hillslopes

(‘Ponding’, Table 7.2), stone or earthen bunds (Plate 7.2 and 7.3), and packing ponded areas with thorn tree branches. The ponding interventions have already been trialed by WfWet in the Baviaanskloof and have proven to be successful in trapping water and sediment and increasing the survivorship of planted *P. Afra* stems.

The above ‘soft’ interventions do not require sophisticated machinery and could be executed largely by a local labour force, aligning with the job creation mandate of WfWet and other government rehabilitation programmes. Re-vegetation of these targeted areas should make use of initial erosion control measures to further improve water infiltration and slow erosion (van Luijk et al. 2013). The species *Portulacaria afra* (‘spekboom’) has been widely used for thicket rehabilitation in the Baviaanskloof and in other degraded thicket areas across South Africa. However, the species is highly palatable and would require control of natural and domestic livestock browsers and grazers for the rehabilitation to be successful (Powell 2009). Although local farmers are gradually beginning to remove livestock from the land there are still areas that are grazed- particularly the lower-foothills where the above-mentioned strategic rehabilitation sites are located. The grazing would hamper efforts for rehabilitation using spekboom. The planting is also costly and not always successful (Powell 2009). The feasibility of planting non-palatable species should be investigated as well as the possibility of keeping livestock such as goats and sheep in camps with pastures on the valley floor.

Plate 7.2: Stone bunds used to reduce runoff and erosion on hillslopes in agricultural landscapes. The arrow indicates direction of hillslope runoff (Farming First 2012).

Plate 7.3: Earthen terraces used to reduce runoff and erosion in the upper-Mississippi catchment in the 1930s (Wikipedia 2016).

Rehabilitation of tributary fans (Zone 3)

'Low impact alluvial fan' sites (Figure 7.8) have been identified as those tributary fans that are least degraded, such as those with relatively intact vegetation, no erosional gullies and limited fan entrenchment. These fans perform an important buffering role against the effects of high-energy storm flows generated in the surrounding catchment, and in general form important areas of recharge of the alluvial aquifer (Glenday 2015). The fans should be protected from land-use activities that are potentially harmful to vegetative cover and natural erosional and depositional processes (Table 7.2). The enhancement of the buffering role of these fans would improve the resilience of the study reach to storm generated runoff and enhance groundwater recharge. Minor interventions may be required to aid flow dispersion across the fan surface or prevent degradation associated with roads or cultivated fields, where these occur.

'Strategic rehabilitation alluvial fan' sites (Figure 7.8) are identified as those fans that have been degraded due to loss of vegetation cover, erosional gullies and/or a channelized tributary stream which has entrenched the fan surface. These factors have limited the buffering role these fans have historically offered to the trunk stream as well as the potential for groundwater recharge. Interventions that encourage water flow dispersion across the proximal- to middle-fan surface in areas devoid of land-use should be encouraged on these rehabilitation fans (Table 7.2). The latter may require the inclusion of features such as earthen bunds that aid flow energy dissipation to prevent renewed erosion of the fan surface. In addition, the newly flooded areas should be re-vegetated with small shrubs and grasses commonly found on fans, in order to further enhance flow dispersion and water infiltration. Where possible, features such as earthen levees that channelize stream flow should be removed. These interventions would improve water infiltration into the fan surface during storm events thereby potentially increasing localized base-flow duration and reinstating the buffering role provided by the fans. However, some degree of connectivity between the entrenched tributaries and the trunk should be maintained since coarse sediment connectivity is essential for self-recovery processes in mountain streams (Wohl 2006).

'Potential alluvial fan rehabilitation' sites (Figure 7.8) are those fans that should receive rehabilitation but where rehabilitation is limited by present-day land-use activities or infrastructure. In similarity to the 'rehabilitation sites' described above, these potential sites require flow dispersion and vegetation rehabilitation efforts (Table 7.2).

Trunk stream rehabilitation (Zone 4)

Zone 4 comprises the trunk channel and forms the final level in the hierarchy of the rehabilitation framework for the study reach. Although 3 major river styles were mapped for the study reach, most of the trunk stream constitutes the cut-and-fill river style. Each zone requires varying rehabilitation intervention based on differences in dominant channel-floodplain processes, stream behaviour (river style), and connectivity with the surrounding catchment that determines river sensitivity and potential for self-recovery (Brierley and Fryirs 2000; Brierley and Fryirs 2005; Fryirs and Brierley 2009).

The cut-and fill style connected to upstream and lateral inputs of coarse sediment from the surrounding catchment, should be managed such that channel bed aggradation is encouraged as a future trajectory, especially along reaches that have widened and lost transport capacity. Human made features that disrupt sediment movement along the channel and between tributaries and the trunk stream may be detrimental to this natural recovery process. The suggestion is therefore to create river freedom corridors where floodplain cultivation is absent or has been abandoned. In these areas the river should be left to continue along an adjustment trajectory to recent changes in coarse sediment connectivity from the surrounding catchment until relative stability is reached. This kind of approach is suggested to enhance the resilience of a river to perturbations such as moderate and large flood events (Biron et al. 2014). Aggradation of the channel bed will be a final evolutionary character along this trajectory and will encourage channel avulsions and more frequent reconnection of the channel with the floodplain. Thus, earthen berms that occur in these corridors and that restrict lateral connectivity should be removed. Once the channel bed aggrades naturally the floodplain will be more frequently flooded such that services such as flooding attenuation and groundwater recharge would be enhanced.

The employment of 'work with nature corridors' (Figure 7.8) may require extensive dialogue with local land users, such that viable options for reducing the impacts of land-use on channel processes are discussed. For example, the shift to higher-value cash crops (lavender and nut trees) that is occurring at present in the valley may mean that less land is required for cultivation on the floodplain than has been necessary for lower-value crops such as maize and vegetable seeds. Hence, floodplain cultivation could be set-back several tens of meters from the present channel along with removal of earthen berms, such that the channel has more space for adjustment.

7.3.5 Recommendations for monitoring and evaluation

It is essential that the conceptual model of river rehabilitation and catchment management presented in Figure 7.7 and detailed in Figure 7.8 and Table 7.2, is accompanied by a strategic monitoring programme. This programme should assess changes in geomorphological process and form, stream and floodplain hydrology, and ecological condition of rehabilitated areas (Downs and Kondolf 2002; Kristensen et al. 2014; Morandi et al. 2014). Several channel erosion monitoring sites were set-up during the present study that could be used to monitor changes in channel morphology and geomorphological process (i.e. degradation vs. aggradation), stream hydrology and ecological condition. Furthermore, Glenday (2015) set up stream flow and groundwater monitoring sites along the study reach during her PhD research. These sites are being monitored on an ongoing basis and could inform hydrological impacts of different rehabilitation and land management interventions employed in the future, as well as the impacts of the gabion weirs implemented by WfWet.

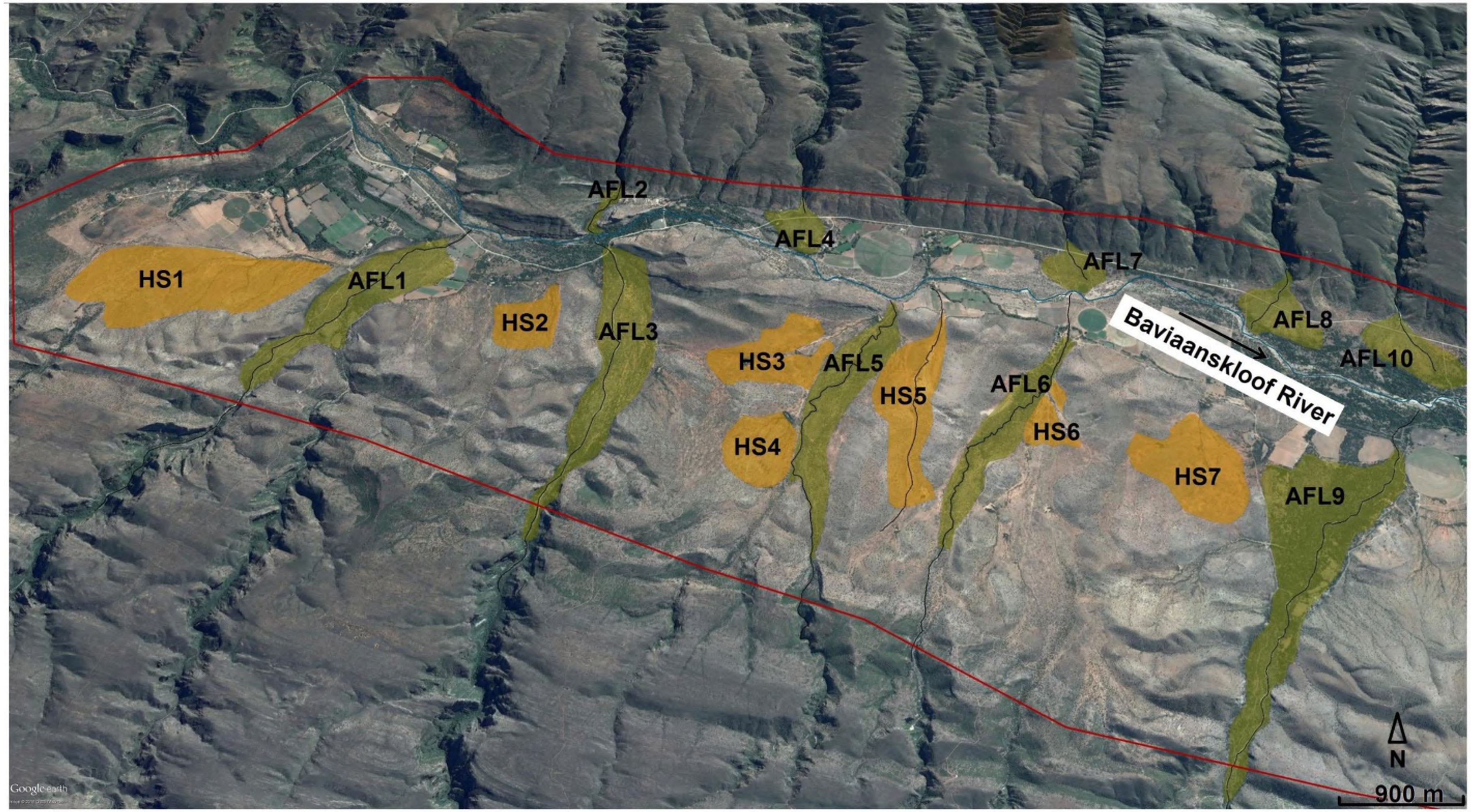
7.4 Summary

This chapter has demonstrated the importance of a thorough understanding of geomorphological process and dynamics that is context-specific for rehabilitation practice in a high-energy upland catchment in South Africa. The concept of geomorphological connectivity and appreciation of adaptive cycles of geomorphological change across different scales have provided useful guiding frameworks for identifying strategic rehabilitation sites in areas that will aid recovery of hydro-geomorphological processes, thereby increasing the geomorphological and social resilience of the system to flood events in the future. Evaluation of the approach of the statutory agency, WfWet, to river-floodplain rehabilitation in the Baviaanskoof suggests that the programme adopts a largely 'form-based' approach, applying interventions that may often work against the natural recovery processes, disregarding the history and potential future dynamics of the targeted river and wetland. In the case of the Baviaanskloof, placing a gabion weir across the river channel to halt degradation does not consider that the channel may have entered a new behavioural regime and that maintaining coarse sediment connectivity, conditioned by wider catchment vegetation and hydro-geomorphic processes, is a key attribute of this new condition. The superficial nature of monitoring of the impacts of the WfWet rehabilitation in the Baviaanskloof does not allow for accurate evaluation of the hydrological, geomorphological and ecological impacts of rehabilitation, so that lessons can be learned and applied to rehabilitation practice in other high-energy mountain streams in South Africa. There are several important factors not commonly considered in river-wetland rehabilitation practice in South Africa including:

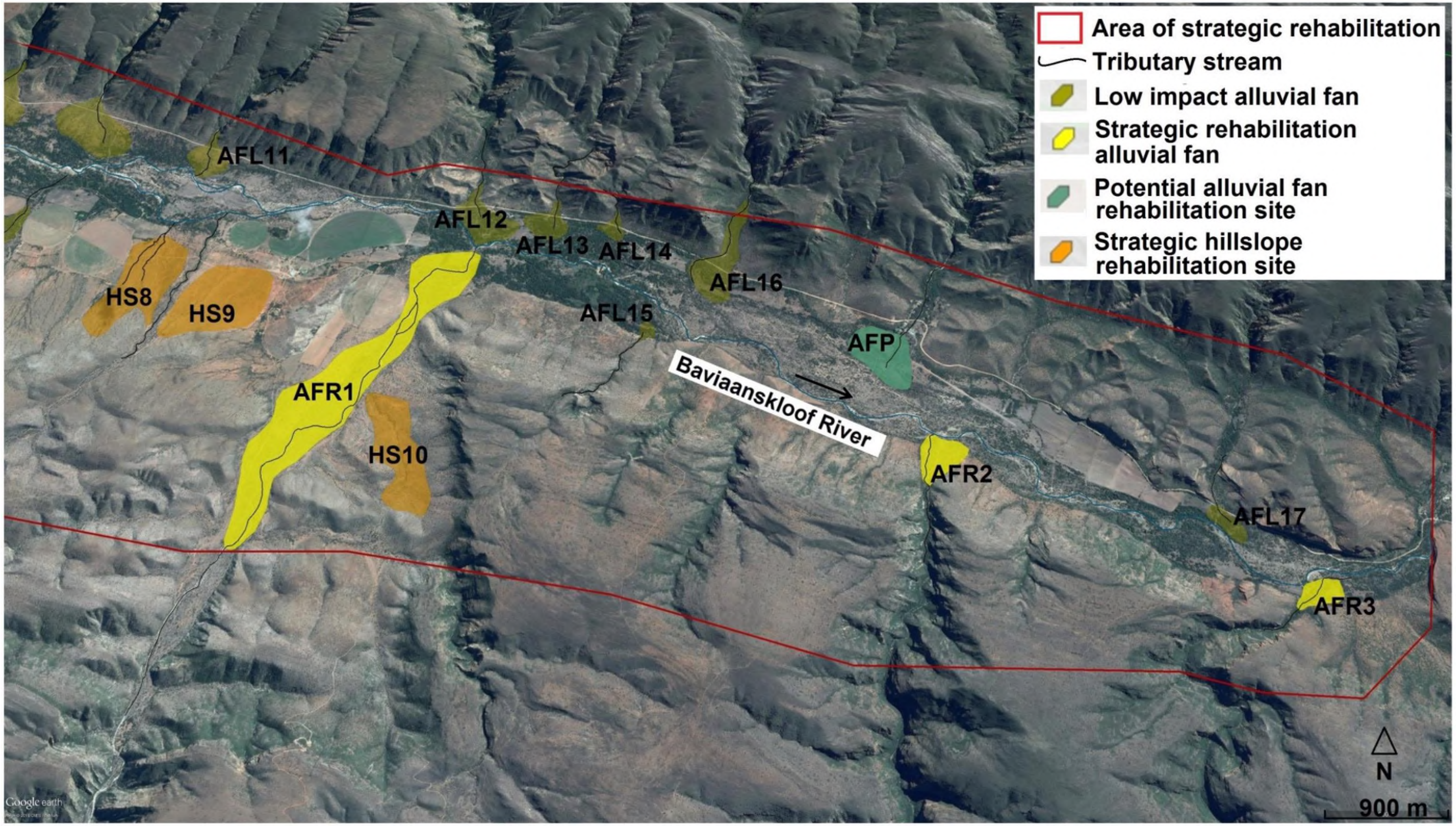
1) Historical analyses of channel-floodplain condition, processes and behaviour;
2) Consideration of controls of channel-floodplain reach behaviour that are operating at the catchment scale;
3) Ecological and social values and needs specific to the rehabilitation site;
4) Future geomorphological, ecological and land-use trajectories that determine the sustainability and success of individual rehabilitation interventions.

A hierarchical conceptual model of process-based rehabilitation for the study reach has been suggested as a more appropriate means of aiding the self-recovery and improved geomorphological resilience of the study reach. The model considers strategic rehabilitation within different geomorphological process zones of the study reach, from headwater areas, to rolling hillslopes, to tributary fans and the trunk stream. The consideration of sediment connectivity and potentially sensitive areas to future degradation, the impacts of rehabilitation on natural river recovery, and local social needs and desires, were the major factors considered in identification of strategic rehabilitation sites. It is hoped that the findings of this chapter can encourage more thorough geomorphological and social investigation prior to and during rehabilitation planning and implementation, such that more sensitive and effective rehabilitation strategies can be employed in South Africa. The findings have also highlighted the essential role of NGOs and large corporations in driving and funding integrated catchment management and rehabilitation processes that are often beyond the financial and time capacity of government agencies or landowners.

APPENDIX 7A: DETAILS OF RECOMMENDATIONS FOR STRATEGIC REHABILITATION, INCLUDING AN AERIAL VIEW OF THE LOCATION OF STRATEGIC REHABILITATION SITES (FIGURE 7.8), AND A DESCRIPTION OF THE REHABILITATION APPROACH FOR EACH SITE (TABLE 7.2)



(a)



(b)

Figure 7.8: Maps indicating the distribution of strategic hillslope and tributary stream alluvial fan rehabilitation sites indicated in Table 7.2 below, for the upper-half (a) and lower-half (b) of the study reach.

Table 7.2: Strategic hillslope rehabilitation sites identified within zone 2 and 3 of the process-based rehabilitation framework for the study reach, indicating geographic coordinates and recommendations of types of rehabilitation intervention and land management. Each of the coded hillslope sites is indicated in Figure 7.9a and b.

Type of intervention and/or management	Site code	Latitude (South)	Longitude (East)	Description
Strategic hillslope rehabilitation	HS1	33 33' 22.98"	23 57' 51.08"	Create small (~1.5 m x 1.5 m wide and ~20-30 cm deep) depressions at 20-40 m intervals on hillslope. Pack the surface of the depression with *Vachellia karoo* or other woody tree branches that are locally available, and plant *Portulacaria afra* (spekboom) in ponds. Also seed non-palatable pioneer grass species in and around each depression.
	HS2	33 33' 38.26"	23 59' 49.65"	Same as above
	HS3	33 33' 51.19"	24 01' 09.92"	Same as above
	HS4	33 34' 18.18"	24 01' 09.62"	Same as above
	HS5	33 34' 10.28"	24 01' 58.26"	Same as above
	HS6	33 34' 10.15"	24 02' 41.96"	Same as above
	HS7	33 34' 24.82"	24 03' 28.63"	Same as above
	HS8	33 34' 48.14"	24 05' 21.28"	Same as above
	HS9	33 34' 52.68"	24 05' 49.45"	Same as above
	HS10	33 35' 40.10"	24 07' 01.78"	Same as above

Type of intervention and/or management	Site code	Latitude (South)	Longitude (East)	Description
Alluvial fan low impact and conservation sites	AFL1	33 33' 23.23"	23 58' 55.68"	Entire alluvial fan area conserved, only allow low-impact activities: no clearing of natural vegetation for cultivation, and no- to low-impact browsing and grazing. Avoid building dams on tributary streams and channelizing stream flows. Remove channelizing earthen berms where possible and stabilize any head cuts that have formed on the alluvial fan surface.
	AFL2	33 33' 01.65"	24 00' 09.57"	same as above
	AFL3	33 33' 45.97"	24 00' 25.67"	same as above
	AFL4	33 33' 03.55"	24 01' 25.19"	same as above
	AFL5	33 33' 58.02"	24 01' 35.03"	same as above
	AFL6	33 34' 04.94"	24 02' 35.25"	same as above
	AFL7	33 33' 17.78"	24 02' 59.06"	same as above
	AFL8	33 33' 33.09"	24 04' 03.81"	same as above
	AFL9	33 34' 37.47"	24 04' 04.00"	same as above
	AFL10	33 33' 45.39"	24 04' 47.97"	same as above
	AFL11	33 34' 00.30"	24 05' 35.78"	same as above
	AFL12	33 34' 24.55"	24 07' 20.79"	same as above
	AFL13	33 34' 25.70"	24 07' 44.35"	same as above
	AFL14	33 34' 36.41"	24 08' 07.98"	same as above
	AFL15	33 35' 02.97"	24 08' 21.00"	same as above
	AFL16	33 34' 42.94"	24 08' 43.47"	same as above
	AFL17	33 36' 02.43"	24 11' 26.46"	same as above

Type of intervention/ management	Site code	Latitude (South)	Longitude (East)	Description of nature of intervention and/or land management
Alluvial fan strategic-rehabilitation site	AFR1	33 35' 11.58"	24 06' 49.08"	Remove channelizing earthen berms and divert some of the stream flow out of the main stem channel. Revegetate the alluvial fan surface with natural grass, forbes and woody species found on alluvial fans where possible.
	AFR2	33 35' 43.33"	24 09' 56.54"	same as above
	AFR3	33 36' 21.65"	24 11' 50.77"	same as above
Alluvial fan potential-rehabilitation site	AFP	33 35' 11.64"	24 09' 44.07"	Alluvial fan should receive similar rehabilitation to above strategic rehabilitation sites however present land-use activities inhibit this.
Trunk channel rehabilitation		Entire channel reach; focus on cut-and-fill style first, then the floodplain accretion style, finally the upper transfer style		Where possible, remove channelizing earthen berms from alongside trunk channel to prevent further channel erosion. Over time, aggradation of the channel bed may result in floodplain re-wetting.

CHAPTER 8: IMPLICATIONS OF THE APPROACH AND FINDINGS OF THIS RESEARCH

8.1 Summary of the findings of this research

The aim of this thesis was to identify drivers of recent river sensitivity in the Baviaanskloof catchment within the framework of geomorphological connectivity and geomorphological adaptive cycles, and evaluate river-floodplain rehabilitation strategies that have been employed.

Fryirs (2013) describes the hierarchical nature of sediment cascades, referring to the movement of sediment from relatively broad scales of an entire catchment to sub-catchment, river reach and sub-reach scale. The nature and degree of connectivity within the sediment cascade influences the way in which different parts of a river system respond to disturbances that alter water and sediment fluxes. Coarse sediment connectivity across spatial scales in the Baviaanskloof, defines the geomorphological structure and sensitivity of the river and surrounding tributary streams to disturbances. In this regard, connectivity influences the degree to which a geomorphological response at the hillslope scale is transmitted to tributary and trunk channel reach scales. Connectivity in this study has therefore been described in both structural and functional terms, the two of which are inherently linked to determine the degree to which a river system or parts thereof, respond to perturbations (Heckman and Schwanghart 2013). Structural and functional connectivity in the context of the study are defined below:

Structural connectivity in the context of the Baviaanskloof refers to the coarse sediment cascade which is characterised by pulsed 'waves' of coarse sediment movement from hillslopes to the channel network and along the channel network, with temporary (over several years) storage in varying landforms. The degree of structural connectivity determines the degree to which geomorphological processes occurring within different landforms situated at different spatial and temporal hierarchies interact with one another. This process connectivity may be described as functional in nature, determining the degree to which landforms and their processes are coupled across space and time (Heckman and Schwanghart 2013; Bracken et al. 2015). In the Baviaanskloof, erosional processes that have been induced at the hillslope scale for the next several hundred years, are coupled to erosional and depositional processes occurring over several decades at the tributary-fan and trunk stream scale. Hence there has been a cross-scale interaction of geomorphological adaptive cycles. A high degree of structural connectivity was the mechanism by which threshold breaches at the hillslope geomorphological adaptive cycle scale were transferred to geomorphological adaptive cycles at the tributary-fan and trunk channel scales. In turn, geomorphological response at the trunk stream scale was transferred up the hierarchy of adaptive cycles to the tributary fan and hillslope scales. This upscale transfer was indicated by fan entrenchment and expansion of hillslope gullies following years in which trunk and tributary channel responses took place.

In the Baviaanskloof structural connectivity determines the degree of functional (process) connectivity, which in turn determines the nature and rate of adjustment to environmental and human-induced disturbances across scales. In dryland mountain catchments with steep hillslopes and high-magnitude storm events, such as the Baviaanskloof, connectivity is relatively high (Harvey 2002a; Fryirs et al. 2007a) compared to lowland systems. This means that geomorphological adaptive cycles, in dryland mountain catchments such as the Baviaanskloof, should be well-coupled across different spatial scales, increasing the sensitivity of these types of systems to perturbations relative to lowland systems. However, prior to human land-use impacts in the Baviaanskloof, the river-floodplain and surrounding catchment was characterised by a relatively high structural resilience to geomorphological change, due to dense woody vegetation growth on hillslopes and the floodplain, and the buffering role of alluvial fans within a wide accretionary floodplain. This structural resilience was owing to the geomorphological history and associated morphology of the river valley, associated with tectonic uplift events and faulting of the Baviaanskloof valley floor. These events promoted the formation of a gently sloping valley floor surrounded by steep mountains, such that alluvial fans and an accretionary floodplain formed on the valley floor. Following human induced increases in coarse sediment connectivity from the 1960s, in the hillslope, tributary-trunk and upstream-downstream dimensions, the structural resilience of the study reach was reduced as incising stream channels became enhancers of water and sediment connectivity. This increased connectivity reduced the effective role of geomorphological buffers along the study reach. The rapid changes in river-floodplain geomorphological and hydrological form observed and reported for the Baviaanskloof River and tributary fans during the mid-late 20th century, mirror the abrupt and episodic changes that occur in complex adaptive systems as thresholds are breached, and the system enters a creative destruction phase of an adaptive cycle. In the Baviaanskloof, this creative destruction phase occurred through the predominance of erosional processes, inducing hillslope soil erosion and gullying, and channel morphological change. Although, sedimentological and geochronological evidence suggests that the Baviaanskloof River-floodplain and surrounding catchment is naturally a cut-and-fill landscape, the recent river cutting phase was rapidly approached and was relatively short-lived, lasting a few decades due to human engineering of the system. This kind of adaptive erosional phase may have lasted several hundred years under natural geomorphological process conditions.

The present-day condition of the river-floodplain is suggested to be analogous to the re-organization phase of the adaptive cycle whereby the trunk, tributaries and floodplain are adjusting channel morphology to new conditions of discharge and sediment amount and caliber. The new river state has been artificially induced through human design and the crossing of multiple thresholds resulting in a transformed ecosystem that is self-sustaining, but in which humans are a key role player in defining the structure and dynamics of the system (Morse et al. 2014). Humans should therefore be considered as inherent and important role players in river-floodplain process, form and sensitivity to geomorphological change into the future, for the Baviaanskloof. The view is that these transformed ecosystems should be managed according to the new set of properties and processes, strongly influenced by human intervention, instead of trying to restore natural structure and processes that existed prior to human induced change (Morse et al. 2014). In the Baviaanskloof, the role of humans in engineering form and process, however, may be episodically altered, during large and extreme floods within the catchment, as these types of events have historically be powerful enough to destroy human engineered features , such as earthen berms, furrows and cultivated areas.

The role of future climate change in either synergizing or counteracting present-day and future geomorphological processes should be considered in future management activities. There are mixed predictions of changes in annual rainfall amount, frequency and intensity of rainfall events, and droughts, associated with climate change in South Africa. Lumsden et al. (2009) attempted to predict future climate scenarios for South Africa using several global climate scenario models developed at a daily time-step and empirically downscaled to the region. The model predicted more rainfall and more intense events for the east of southern

Africa and less rainfall and a slight increase in inter-annual variability for the west and adjacent interior. These climatic changes are predicted to result in increased and decreased runoff respectively and higher flow variability. It is difficult to predict the future scenario for the Baviaanskloof as it falls on the boundary of the western and eastern parts of the country (Lumsden et al. 2009). The study by Lumsden et al. (2009) predicted an increase in the number of days with >5mm rainfall for the area in which the Baviaanskloof falls, with a mixed signal for changes in the frequency of days with >10mm and >20mm rainfall events. The results of the present study did not suggest an increasing frequency of small to moderate flood events over the last few decades, but it was noted that there was an increase in the frequency of ≥20 mm one-day rain events from the early 2000s. The La Niña (wet) climatic phase that existed during the period of this study may explain this increase in frequency of one-day rainfall events of this kind. Under reduced hillslope vegetation cover, this relatively wet local climate would have initiated an increase in hillslope runoff and sediment yield for the study reach. The enhanced tributary-trunk and upstream-downstream connectivity of the study reach, means that coarse and fine sediment connectivity is potentially high throughout the study reach. However, enhanced connectivity is dependent on the prevailing climatic regime and associated rainfall event magnitude and frequency. The recent shift in the climate of South Africa to a La Niña phase, means that conditions are dry and rainfall will most-likely remain below average over the next few years. Connectivity will thus be relatively low, as sediments are locally trapped in depositional features, slowing the rate of recovery of the trunk stream along degraded reaches.

Catchment management and river rehabilitation in the Baviaanskloof should be defined within the parameters of the transformed ecosystem, recognizing the role of humans in defining the structure and dynamics of the river-floodplain and boundary conditions of runoff, sediment fluxes, and storm discharges. Considerations of structural and functional connectivity should form the basis upon which a strategic, hierarchical rehabilitation plan is built, such that the framework guides the extent, location and type of rehabilitation activities within different process domains of each hierarchy (Okin et al. 2015).

8.2 An eclectic approach to understanding river complexity

The present study has contributed to understanding the distribution of barriers, buffers and enhancers of water and sediment connectivity, the types and arrangement of river styles, and the most important physical drivers of the recent channel dynamics of the Baviaanskloof. The use of connectivity integrated within the framework of Panarchy and adaptive geomorphological cycles, was useful for understanding the interaction of geomorphological processes, structure and threshold breaches at different scales of the study reach. This knowledge then provided the basis for informing the functional connectivity of the study reach and for devising a hierarchical process-based approach to river rehabilitation.

The present study has not been able to determine rates of geomorphological processes and change, or the degree to which geomorphological processes occurring at different scale ranges are either synergistic or counteractive. Furthermore, there were a number of assumptions made, such as the existence of a deepened and widened tributary stream that directly joins the trunk stream, is indicative of a high degree of water and sediment connectivity. In many cases connectivity was visually evidenced by sediment deposits at the junction of an eroding tributary with the trunk channel (indicating tributary-trunk connectivity). However, stream channels undergo erosion until a point of relative stability and in doing so, deposit sediment in a complex way. It may therefore be the case that a well-adjusted tributary channel may be depositing sediment along the channel bed, upstream of where it joins the trunk channel. This process would result in only partial connectivity of sediment- of mostly the finer sediment component.

Qualitative approaches to describing the nature and degree of sediment connectivity therefore require thorough assessment of channel morphology and the nature and arrangement of erosional and depositional features that indicate the degree of water and sediment connectivity, during normal to high flows. This kind of approach to investigating connectivity and complex response is most common at present in the fluvial geomorphology domain, and Heckman and Schwanghart (2013) stress the importance of developing more quantitative approaches to measuring connectivity. Quantitative approaches, such as measuring sediment budgets for different parts of a catchment, and determining the relationship between stream power and sediment entrainment of different particle sizes, may substantially improve the confidence attributed to qualitative descriptions of the nature and degree of connectivity Despite its lack of quantitatively measuring connectivity, the approach in this study has allowed an assessment of the interaction between several variables, including human land-use activities and climate regime, with geomorphological processes. The important contribution has been towards developing a new way of thinking about river process, form and change within a complex adaptive systems framework (Church 2010; Wainwright et al. 2011). The study has demonstrated that Panarchy occurs in the Baviaanskloof system, evidenced by sudden, chaotic change, yet self-organization of processes and forms, which happen between periods of relative geomorphological resilience to external perturbations. The framework of Panarchy and geomorphological adaptive cycles should thus be investigated as a conceptual tool for understanding sensitivity and change across space and time in geomorphological systems. The two concepts have not to the author's knowledge been interlinked within the discipline of fluvial geomorphology, and the concept of Panarchy has not yet been applied to investigate sensitivity and change in fluvial geomorphological systems. This study has therefore provided a starting basis to encourage further investigation of the application of the two concepts in studies of fluvial geomorphological complexity, and for studies that have an applied rehabilitation and catchment management component. The application of the two concepts however, requires a critical realist philosophical stance in approaching fluvial geomorphological investigation.

8.3 Approaching dryland, mountain stream rehabilitation in a new way

Understanding fluvial systems within a complex, adaptive systems framework has implications for how applied scientists approach investigation and management of river catchments (Okin et al. 2015). Yet, adoption of a process-based approach to river rehabilitation, understanding complexity and drivers of change and future needs and desires of local communities, conservation managers and government, is not always possible and not encouraged in modern river rehabilitation practice. It is difficult to integrate scientific knowledge and the desires of ecologists and conservationists, such that a rehabilitation project is effective and sustained into the future (Richardson and Lefroy 2016). It may be, that the only way to shift toward widespread adoption of a process-based, and integrative approach to river rehabilitation, is to encourage a shift in thinking and practice within funding agencies, and rehabilitation practitioners linked to these agencies. In this regard, the criteria defining the success of a project should not driven by quantitative results of simple metrics that are politically aligned, such as the number of rehabilitated rivers, or structures built, or people employed. It is better practice to define the success of a project by the degree to which key hydrological and geomorphological processes and structural components (including vegetation and landforms) have been reinstated, such that the system has greater physical resilience to perturbations. Measuring and evaluating the aforementioned is difficult, and requires a thorough historical investigation of river behavior and drivers of geomorphological change, present-day key geomorphological processes and their interactions across scales, and the derived resilient condition toward which a rehabilitation project aims. Indeed there will always be ecological and/or social tradeoffs made during any river rehabilitation project that should be weighed against the long-term impacts of following through with the specific trade-offs.

Based on the need for a new way of thinking and practice in rehabilitation of dryland streams, it is suggested that several critical areas should be considered:

1) It would be useful to investigate the concepts of connectivity and geomorphological adaptive cycles, as supportive frameworks for developing a hierarchical, process-based framework of rehabilitation, that is specific to the geomorphological characteristics of the target catchment. Strategic rehabilitation of key processes and their relative degree of (dis)connectivity should be targeted before intervention at a degraded channel or wetland reach scale.
2) Implementation of an extended (>10 years) geomorphological, hydrological and ecological monitoring of the upstream, local and downstream impacts of different rehabilitation interventions. There is a general absence of systematic monitoring of rehabilitation impacts in South African rivers and wetlands. Under the WfWet programme, the success of a particular rehabilitation intervention is commonly evaluated based upon visual and photo comparisons of stream channel form before and after rehabilitation. A successful outcome is deemed as a stream in which erosion has been largely halted, and where the delivery of one or more ecosystem services has been improved. More detailed monitoring is an essential component of

adaptive management such that continual learning and improvement may take place.

3) Adoption of adaptive river and wetland rehabilitation practice such that improvements are continually made to rehabilitation approach and design as rehabilitation outcomes of monitored (Downs and Kondolf 2002; Kingsford et al. 2011). This requirement is dependent on the presence of long-term monitoring of rehabilitation impacts in projects that have already been implemented.
4) Recognition of the needs and desires of people living in and (to a lesser degree) downstream of a catchment, into rehabilitation planning objectives, such that interventions attempt to balance the desires of conservation managers with local community needs and desires. So far, the stakeholder engagement process is hardly applied in river and wetland rehabilitation in South Africa. Furthermore, community based river rehabilitation and catchment management is a useful tool for creating a sense of environmental stewardship, and for effecting more sustained management into the future (Rowntree et al. 2010).
5) In South Africa there is need for greater knowledge and development of existing geomorphological and ecological assessment tools for rivers and wetlands, in relation to understanding geomorphological processes and change across scales. Geomorphological connectivity (structural and functional) may provide a useful tool for understanding the drivers and sensitivity of different rivers and wetlands, and for planning and locating rehabilitation interventions.

Although important for improved rehabilitation practice, the abovementioned issues are contingent upon buy-in and adoption by State river management agencies, and local communities. A collective shift in thinking, practice and knowledge around approaching river-wetland rehabilitation practice and catchment management is complicated, and often never fully achieved.

8.4 Considering the impacts of a critical realist approach in this study

The grounding of critical realism is based on the fact that it is invalid to make truth claims upon a limited representation of reality (data) in science (Easton 2010). The traditional positivist approach to scientific investigation expects systems (social and natural) to behave in a linear manner, abiding by general laws, and understood by simple cause-and-effect relations (Easton 2010). Complex systems do not always abide by these simple laws, since unique sets of interacting processes and structure, nested at different spatial and temporal scales, determine unique and often non-linear interactions between variables. Hence, the assumptions of the positivist approach do not suite investigation of geomorphological processes and dynamics across multiple scales within the discipline of fluvial geomorphology. For example, although it is expected, in general, that sediment transport capacity of a river should increase with increasing discharge and channel slope, the relationship may not be proportional and this theory may not always hold true. Factors such as the erosivity of sediment within the channel boundary, and the presence of biotic and geomorphological features that act as enhancers or buffers to sediment transfer, influence sediment transport capacity.

The present study has subscribed to the main principles of the critical realist ontology, as summarized by Easton (2010):

- There is a reality separate to our own understanding that cannot be fully known.
- Our understanding of reality is socially constructed; the way in which we make observations during scientific investigation, and our interpretations thereof, are influenced by the personal history and values of the investigator.
- Critical realism makes allowances for prejudices during scientific investigation, as long as these prejudices and their influence on the interpretations and evaluations we make as scientists are well understood and clearly stated. These prejudices influence our account of reality and the associated way in which we manage social-ecological systems.

The methodological approach chosen by the author in this study, the interpretation and evaluation of the findings of the research, and the rehabilitation recommendations made, were biased in several ways. The main biases included:

Methodological approach: An inductive approach was adopted, using qualitative and quantitative observations and measurements to investigate and describe patterns and trends in geomorphological behaviour, and the characteristics of the driving forces of recent changes in river behavior. This approach contrasts to deductive reasoning which involves the rigorous testing of hypotheses through statistical analysis of representative data of the particular system being investigated. The inductive approach in the present study allowed the author to approach a multi-scaled (spatial and temporal) investigation with greater ease, and realistically from a time and funding constraints perspective. In system-based studies, obtaining representative data of processes and structure across scales of space and time is very difficult and often requires that inductive reasoning is applied. However, the present study could have benefitted from more rigorous sampling and testing of hypotheses, such that greater insight into the fluvial geomorphological nature and dynamics of the Baviaanskloof system could be obtained. The inductive approach although flawed with many more assumptions than a deductive approach, provided a suitable means to address the objectives of this study.

Rehabilitation and management recommendations: The evaluation of the approach of WfWet to rehabilitation of the Baviaanskloof River-floodplain was conditioned by the personal value system of the author, and the limited experience the author had gained with other WfWet rehabilitation projects in South Africa. The author feels strongly about the use of structural engineering approaches to river-wetland rehabilitation, since it is felt that this approach limits the natural ability of a system to adjust to disturbances and approach a new ecological and geomorphological condition. This value-based bias meant that the author responded with a negative stance to the structural approach of WfWet to rehabilitation in the Baviaanskloof, and biased recommendations toward 'soft' interventions. However, the author did attempt to appreciate the ideological and financial constraints that shape the approach of WfWet to river-wetland rehabilitation in South Africa. The author has also had experience in wetland health and ecosystem services assessments for a limited number of WfWet rehabilitation projects in South Africa. Experience during these projects led the author to conclude that, in general, the assessments of health and ecosystem services were rapid, and involved insufficient depth of investigation of the driving forces of the dynamics of a particular system. This personal experience then biased the author in her evaluation of the WfWet approach to rehabilitation in the Baviaanskloof.

8.5 Conclusion

Geomorphological connectivity is an emerging conceptual framework for investigating and understanding more clearly the complexity of fluvial geomorphological systems. It is argued here, that geomorphological connectivity described in both structural and functional terms, can be linked to the concept of Panarchy, traditionally used to describe unpredictable change, self-organization, and cross-scale interactions of processes and structure in socio-ecological systems. The present study has attempted to describe the influence of coarse sediment connectivity on the nature and interaction of geomorphological adaptive cycles of a river Panarchy, for the Baviaanskloof catchment in South Africa. In dryland, mountain catchments such as the Baviaanskloof, threshold breaches and switching between phases of predominantly transport and sediment accretion, and predominantly sediment erosion and channel morphological change, is determined by the degree of coarse sediment connectivity. Recent changes in coarse sediment connectivity in the upper-middle reaches of the catchment influenced the sensitivity of the river to moderate and large flood events, and determined the switch from a phase of relative channel stability and high geomorphological resilience to a phase of channel erosion and instability. These adaptive responses at the river reach scale were transferred to larger scales initiating geomorphological responses at tributary streams and the surrounding hillslopes. Understanding coarse sediment connectivity and the interaction of geomorphological processes at different scale ranges of the Baviaanskloof enabled the development of a process-based framework to guide better rehabilitation practice.

The findings of this research define a single and restricted version of multiple possible realities that could be measured and interpreted to explain the geomorphological behaviour, dynamics and sensitivity of the Baviaanskloof River-floodplain. The author has, however, been able to provide insight into the main environmental and human variables, and geomorphological structure and processes that influence the resilience of the Baviaanskloof River-floodplain to different types of disturbances. It is suggested that an understanding of the interaction of coarse sediment connectivity and river process and form, in dryland mountain catchments such as the Baviaanskloof, should form a basis for planning process-based river rehabilitation.

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