DEVELOPING A FORM-PROCESS FRAMEWORK TO DESCRIBE THE FUNCTIONING OF SEMI-ARID ALLUVIAL FANS IN THE BAVIAANSKLOOF VALLEY, SOUTH AFRICA

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Abstract

The Baviaanskloof catchment is a semi - arid catchment located in the Cape Fold Mountains of South Africa. Little is known about the functioning of the complicated Baviaanskloof fluvial system and the role alluvial fans in the fluvial landscape. This thesis will contribute to field of geomorphology and, more specifically, to the field of fan morphometry by producing a standalone fan framework outlining methods to investigate the influence of external and internal control variables on alluvial fans. In this thesis, outcomes of the applied framework and case study are used to develop fan restoration guidelines for the Baviaanskloof Valley.

The framework incorporates external and internal fan control variables at a valley-wide and local fan scale. External control variables include accommodation space, base-level change, and drainage basin inputs. Internal control variables include fan style, morphometry and fan channels. In order to apply the framework, fan morphometry data was required. This data was collected by creating a spatial plan of fans and basins in the valley. Outcomes of the applied framework include; an understanding of base-level change on fans, relationships between fan basin characteristics and the fan surface and insight into fan channel processes. Results of the applied framework are investigated further using bivariate (correlation matrix) and multivariate (principle component analysis and regression analysis) analysis techniques. Significant relationships identified are: drainage basin area versus fan area, fan area and fan slope and drainage basin ruggedness and basin size.

The primary outcomes of this thesis include an alluvial fan form-process framework, key considerations to be included in alluvial fan restoration projects and fan restoration guidelines. Contributions of this thesis to broader alluvial fan morphology science includes new insights into general fan literature by compiling a form-process alluvial fan classification framework to identify external and internal fan control variables and identify fan form. Additions have been made to Clarke's (2010) evolutionary stages to describe stages 4 and 5 of fan evolution that has been adapted to describe fan evolution and differentiate between stages of mature fan evolution. This thesis has also contributed to the study of alluvial fans in South Africa, particularly in the Baviaanskloof Valley. The layout of the procedural guidelines and key considerations for an alluvial fan project provides a guide for rapid fan assessment for maximum cost and time benefits for stakeholders.

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Unless otherwise stated, this thesis presents the authors own work.

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Acronyms and Abbreviations

BICR	Baviaanskloof Integrated catchment Restoration
ECRR	European Centre for River Restoration
GIB	Gamtoos Irrigation Board
GIS	Geographic Information Systems
MASL	Metres above sea-level
NDVI	Normalised Differentiation Vegetation Index
NGO	Non-profit organisation
SPOT	Satellite Pour L'Observation de la Terre
TMG	Table Mountain Group
USA	United States of America

Chapter 1: Introduction

1.1. Introduction and overview of project research

Alluvial fans are a transitional landform that play a critical role in the buffering and coupling of the integrated fluvial system and mitigate flood events. The functioning of alluvial fans has perplexed and intrigued scientists since the early 1900s, attracting considerable attention in the early 1960s owing to the practical need for knowledge for flood mitigation practices, civil engineering, mining geology, groundwater characterization, archaeological studies and basic research in the fields of geomorphology, sedimentology, hydrology and environmental geology (Blair and McPherson, 1994: 359). Research has been conducted on semi-arid, arid and humid fans on fans in Spain, Italy, the Middle East, Iran, Pakistan, India, Argentina and Chile. Trends in fan research paradigms have spanned pre-paradigm, evolutionary, equilibrium and connectivity eras from the 1870s until present. The 'alluvial fan problem' defined by Leece (1990) alludes to the difficulty in developing a general alluvial fan model to explain the occurrence and development of alluvial fans and has been the main reason many scientists have been perplexed by fans in the fluvial landscape. Despite on-going research efforts, a general model of alluvial fan development has not yet been formulated.

Alluvial fans are a hazardous environment due to large amounts water and sediment that are transported from the fan catchment to the fan surface during or after rainfall events. This often results in the need for human intervention to protect man-made features built on the fan. Implications of human intervention on fans cannot be predicted and humans are often left with the negative consequences of fan intervention. Modifying the fan surface influences the local base-level and the role of alluvial fans in fluvial systems. A base-level change can result from human activities modifying the position of channels on the fan surface and the migration of fan channels (Charlton, 2008: 13). The construction of dams or roads on the alluvial fan deposit obstructs water flow over the fan and diverts channelled flow into a new flow path. The Wadi Feiran fan in Sinai, Egypt, studied by Hermas et al. (2010: 93-94) has undergone fan channel changes where a man-made barrier across an incised channel has resulted in channel avulsion toward the fan apex to follow a new flow path. The Baviaanskloof Valley is an example of a fluvial system where humans have modified fans in the past. The impacts of human interventions on fans in the valley are poorly understood and locals in the area believe it has contributed to a reduced water retention capacity in the valley.

The Baviaanskloof Valley is a 75km long valley located in the western part of the Eastern Cape province of South Africa and is characterised by a rugged terrain (Figure 1.1.A). This narrow (approx. 1 km wide) fault bounded valley (Figure 1.1.B) is situated within the Cape Fold mountains and has a topographic setting that allows for the occurrence of fans. The Baviaans River is incised along most of its length and is characterised by large amounts of bedload (Figure 1.1.C). Fans are most noticeable in the wide sections of the valley where they have developed at the junction between the drainage area and the floodplain (Figure 1.1.D). The increased elevation of the fan surface in relation to the floodplain provides a low flood risk alternative for buildings and agricultural activities. Berms and channels were built in 1981 to reduce flood damage and modify the flow of water over the fan surface. These have altered the functioning of alluvial fans which are believed to have decreased water retention capacity of the landscape. Restoration measures by a South African Non-governmental organisation (NGO), LivingLands, aim to restore tributary streams in the valley by focusing on closing channels and removing berms to restore fan function.

The aim of this thesis is to gain a better understanding of the functioning of alluvial fan in the Baviaanskloof Valley using geomorphological theory and a broader systems theory perspective. A framework based on published fan form-process relationships was developed to classify fans in the valley and to gain an understanding of how alluvial fans function in the integrated fluvial landscape using key concepts from systems connectivity theory, alluvial fan morphometry and empirical relationships outlined in existing alluvial fan literature. A spatial plan, form-process framework (based on fan internal and external fan control variables), empirical relationships, form-process characteristics and fieldwork components were used to develop a holistic understanding of fans in the connected fluvial landscape of the Baviaanskloof valley and to provide a springboard for characterisation of alluvial fans in future alluvial fan studies.

1.2. Fluvial system restoration

Trends in restoration science have moved towards determining geomorphic processes to enhance and promote recovery in many fluvial systems (Rinaldi et al. 2008: 377). At the fourth European Centre for

River Restoration (ECRR) Conference on River Restoration in 2008 a number of common restoration themes emerged and have been summarized here. The first was to incorporate clear spatial and temporal contexts for restoration strategies by considering the fluvial systems as a connected system with both small and large scale processes acting in the short term and in the long term. The second key theme was to extend form-based solutions to process-based approaches; this implies moving away from empirical classifications and considerations and moving towards the development of process-based

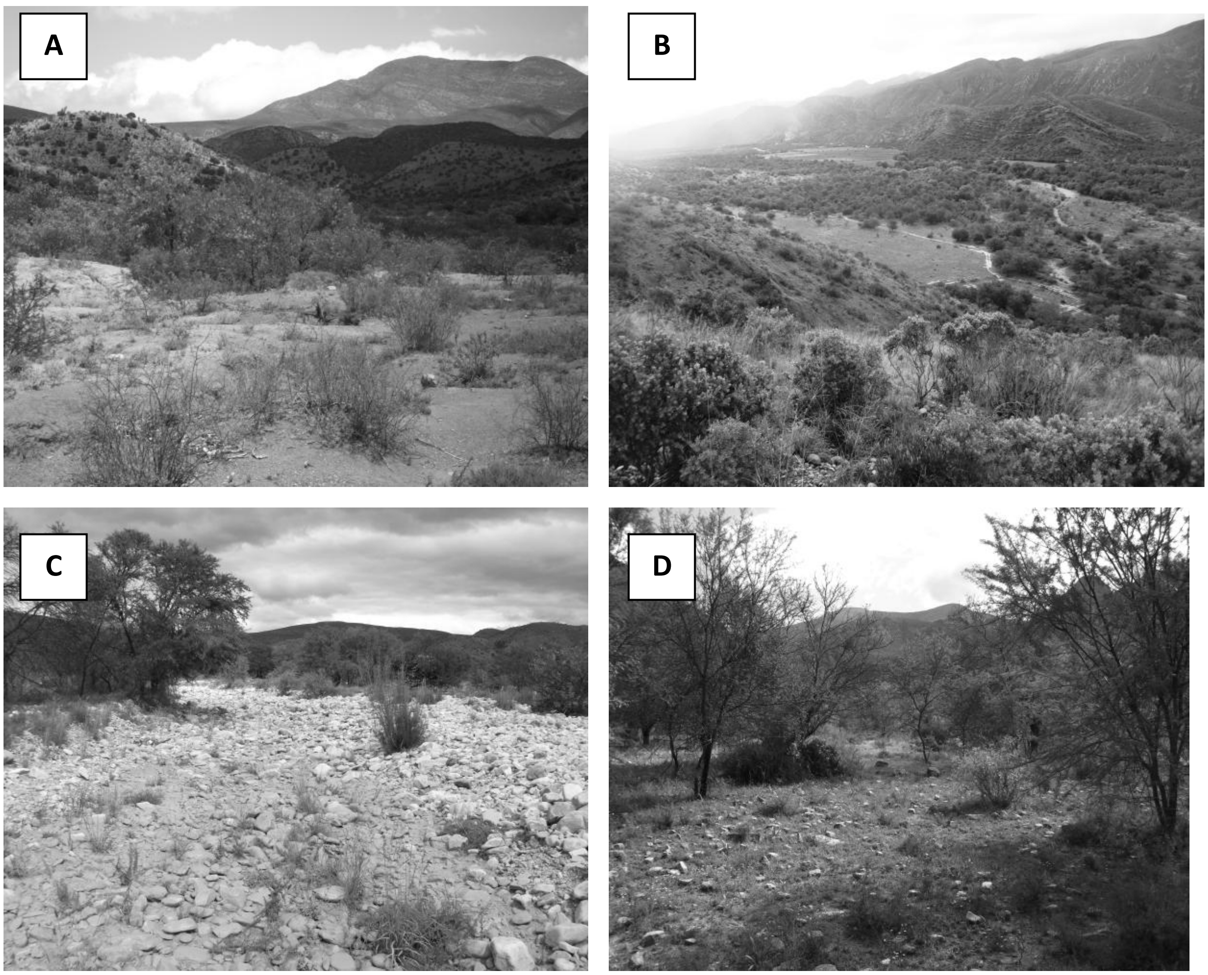

Figure 1.1: A collection of Images Baviaanskloof Valley images showing the; A) topography of the Baviaanskloof Mountains; B) Baviaanskloof Valley upstream (looking westwards); C) bedload material of the Baviaans River and increased elevation of the floodplain and; D) vegetation and sedimentation of the fan surface

models and linkages (Rinaldi et al. 2008: 378). The third key theme is, to integrate process understanding with morphological inventions. This highlights the need to promote natural channel recovery through understanding key processes rather than morphological reconstruction. Research should ideally incorporate a range of different interdisciplinary tools and approaches that include modelling, field based validation and historical analysis that provide for a more comprehensive and stronger collaboration between all stakeholders. A downfall of many fluvial restoration projects is the poor understanding of how landscape units function in the fluvial system. The key themes introduced above will be incorporated into this research project and will set about the task of using geomorphological study to inform restoration through fluvial system connectivity.

The gap between theory and practice can be bridged by understanding geomorphological processes that have shaped the landscape using an integrated approach incorporating a number of disciplinary and interdisciplinary tools to develop practical process-based restoration guidelines. Practical methods to achieve this would be to incorporate connectivity theory (process based) into a geomorphological study (form based) to link landscape components in space to gain a better understanding of how landforms function. Connectivity literature by Harvey (2001), Schumm (2003), Kondolf et al. (2006), Fryirs et al. (2007) and Jain & Tandon (2010) will be used to inform restoration guidelines.

1.3. Research Aim, research objectives, research design and project outcomes

The aim of this research project is to develop an alluvial fan framework comprised of a number of geomorphological form-process relationships that will be used to characterize the alluvial fans in the Baviaanskloof Valley. The creation of a framework based of form-process relationships does not aim to create a general fan model, but a more practical framework that can be used to investigate fans within a particular fluvial landscape. The framework is developed through a desktop study of alluvial fan control variables that influence fans in space and time. The framework will then be applied in the Baviaanskloof Valley to classify fans, identify relationship variables. This will help to gain an increased understanding of how alluvial fans function. The framework is based primarily upon alluvial fan control variables and the form-process empirical relationships identified in fan morphometry literature. Key fan morphology authors include Bull (1964), Hooke (1968), Blair & McPherson (1994), Harvey (1997, 2002, and 2005) and Mills (2000). The application of the framework in conjunction with a spatial plan and case study will create a link between the alluvial fan theory and the functioning of fans within a connected fluvial environment, namely the Baviaanskloof. Broader geomorphological themes, such as fluvial connectivity, will be incorporated into the fan framework and detailed in the case study chapter of this thesis. Project findings will contribute to alluvial fan research and, more generally, the field of geomorphology, by producing a standalone form-process alluvial fan framework that outlines the methodology required to characterize and evaluate fan functioning in space and time. This framework explores both the internal and external control variables of alluvial fans within a valley context and can then be used to classify fans in other valleys.

Farmers of the western Baviaanskloof Valley have modified alluvial fan channels to reduce flood damage during times of heavy rainfall. It is believed that modifications made to fans have affected the functioning of the Baviaanskloof fluvial system and as a result has contributed to a reduced water retention capacity of the landscape. LivingLands has engaged in a two-stage fan restoration project implemented from 2010 – 2011 to focus on water retention capacity issues in the valley. In the first stage (2010), fans were selected for restoration through consultation with the farmers in the Baviaanskloof. This thesis contributes to the second stage of restoration (2011) based on key elements of fan theory. The restoration approach has therefore been site-specific and conducted using a snapshot view of the fan surface. In both stages, experts including academics (geomorphologists and engineers) and students have visited suggested sites to recommend ways of increasing the fun functioning in the landscape. At present, fans selected for stage 1 of restoration have been engineered and fans identified in stage 2 (part of this thesis) are still in the process of being restored

1.3.1. *Research aim*

The overall aim of this thesis is to develop a theoretical framework that responds to the challenges identified at the ECCR meeting held in 2008. Although identified challenges are an underlying theme of this thesis, the challenges have not directly been incorporated into the research objectives; rather have been used to guide the methods and approach of how the research the objectives will be achieved. The focus of this thesis is to develop and test a form-process conceptual framework incorporating existing fan form-process and empirical relationships found in alluvial fan morphometry literature. The framework will be tested and used to characterize alluvial fans in the Baviaanskloof Valley to gain an understanding of how alluvial fans function in space and time. Research findings will then be used to inform the LivingLands alluvial fan restoration project.

1.3.2. *Research objectives*

1. Compile a form-process framework to characterize alluvial fans.
2. Map the spatial distribution of alluvial fans in the Baviaanskloof Valley, South Africa.
3. Use the framework to characterize alluvial fans in the Baviaanskloof Valley, South Africa.
4. Evaluate the surface characteristics of two fans in the Baviaanskloof Valley, South Africa.
5. Evaluate how the framework will inform restoration of alluvial fans in the Baviaanskloof.

1.3.3. *Research outcomes*

The framework has been developed to target a research gap in in South Africa and, more specifically, the Baviaanskloof Valley where alluvial fan restoration is currently taking place. Alluvial fan form-process relationships found in literature on fan morphometry and functioning does not currently allow for the restoration of fans based solely on geomorphological theory. It is hoped that a broader view of fan functionality in space will allow for a more informed fan restoration process with maximum benefit for both the environment and humans. This research also aims to contribute to the field of fluvial system restoration. Restoration guidelines will be given based on the findings within this thesis. The use of connectivity theory will be incorporated into this thesis to fulfil the overarching restoration themes.

1.3.4. *Research design*

The project objectives, as outline above, will be met by dividing the project into two themes and four core methodological chapters. The first theme, focused on developing the alluvial fan framework, is a theoretical component consisting of the literature review and framework chapter (Figure 1.2). The second theme is focused on applying the framework using an applied approach that will position the study area and apply the framework. In this section, the background and overview of fans and drainage basins in the Baviaanskloof Valley (Chapter 4 and 5); aims to position the study and gather spatial data required for the framework (Figure 1.2) The form-process framework to fans in the valley will be followed by a case study analysis of two fans (Chapter 7), (Figure 1.2) Outcomes of the two themes will be discussed and concluded in Chapters 8 and 9 with overarching restoration themes being addressed. An overview of the two themes is given below:

1.3.4.i. *Developing the alluvial fan framework*

The literature review chapter is structured into two sections that will provide an overview of alluvial fan theory. The first section focuses on the definition, occurrence and control variables that influence fans in space and time; the second section discusses connectivity theory, describes the role of alluvial fans in the fluvial landscape and describes their function and use to humans. In this section, this thesis will also be positioned within its broader interdisciplinary context by introducing paradigms and trends in alluvial fan research and how these have evolved over time. The alluvial fan framework (Chapter 3), compiled to assess the influence of alluvial fan control variables (external and internal) using a number of empirical and form-process relationships, will meet requirements of objective 1. The framework chapter is structured using control variables and alluvial fan theory outlined in Chapter 2 (Figure 1.2). The literature review chapter aims to answer the following:

- Where are fans found in the landscape?
- What control variables have allowed for the formation and evolution of fans in space and time?
- What is the role of fans in the landscape?
- What research has been conducted on alluvial fans in the past?
- Where is this thesis positioned within its interdisciplinary contexts?

1.3.4.ii. *Applying the framework*

The project study area (Chapter 4) provides a description of the Baviaanskloof landscape from geomorphological and anthropogenic perspectives supported by a number of photographs taken on field trip excursions. This chapter aims to provide the reader with an overview of the Baviaanskloof's rugged terrain and position the setting of alluvial fans in the valley to provide context for the applied framework section.

A map of the spatial distribution of fans in the valley is given in Chapter 5 provides the methods of valley wide data collected from aerial imagery and will serve as the primary database for the applied framework component of the research project. The mapping of fans and their drainage basins will fulfil the requirements of objective 2. In this chapter the key questions on the spatial distribution of fans are:

- What is the spatial distribution of fans?
- Are there more fans on the north facing side of the valley opposed to the south facing side?
- Are there groupings of fans along the length of the valley?

The framework will be applied to fans in the Baviaanskloof Valley (Chapter 6). Data given in the study area (Chapter 4) will be used to inform the framework analyses. The application of the framework to fans in the valley will fulfil the requirements of objective 3. Statistical analyses will be used to discover the relationship between control variables and the influence of external control variables on fan area. A detailed case study of two fans in the valley (Chapter 7) builds on the findings of the framework. Fans are selected on the basis of location and the influence of a laterally migrating main channel on the distal fan surface. A detailed survey of fan surface characteristics and sediment distribution fulfils the requirements of objective 4. Key questions addressed are:

- What are the surface characteristics of fans?
- What is the impact of a laterally migrating channel on fan function?
- How does a laterally migrating channel affect fluvial connectivity?
- Does sediment grain size vary across the fan surface?
- Does organic matter content vary across the fan surface?

The above questions will be addressed by presenting data in the form of graphs and diagrams to compare and contrast the influence of a laterally migrating main channel.

A general discussion and conclusion are presented in Chapters 8 and 9 respectively. The general discussion will bring together the findings of all four of the core chapters of the research project commenting on the success of the applied framework to describe the functioning of alluvial fans in space and time by critically analysing the applied framework (Chapter 6). The capabilities of the applied framework and case studies to conclude restoration guidelines for the valley will also be assessed along with the presentation of key restoration outcomes that can be used to guide restoration projects.

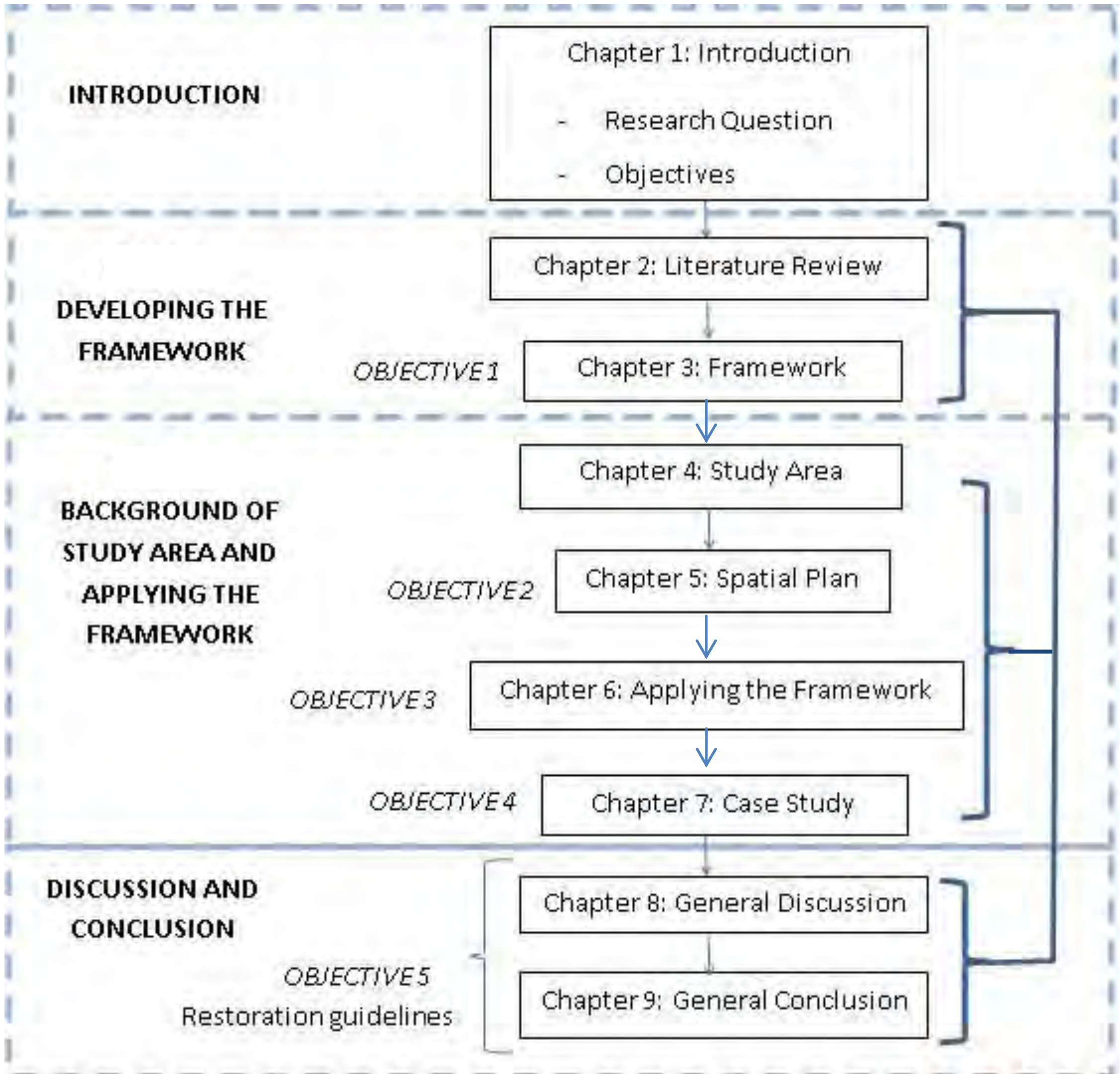

Figure 1.2: Thesis Layout

Chapter 2: Literature Review

2.1. Introduction

The aim of the literature review is to provide a summary of the present knowledge base on alluvial fans and to position this thesis within its broader disciplinary contexts. The first section of the review provides a theoretical account of fans describing the location, occurrence, external and internal alluvial fan control variables and the role of fans in the landscape. Important Information such as fan control variables and critical stream power will be explained in detail in this chapter and will be used in Chapter 3. The second section, of this chapter, presents a review of trends in alluvial fan research by identifying the current paradigms in alluvial fan research and fan models. An overview of the study of alluvial fan morphometry will then be explained.

2.2. Alluvial fan theory

2.2.1. *Defining an alluvial fan*

Alluvial fans are transitional sedimentary deposits between mountain and floodplain with a form that resembles a cone segment at the point where a confined stream emerges from a mountainous catchment (drainage basin) into a zone of reduced stream power and becomes unconfined, (Figure 2.1), (Allen, 1970; Blair & McPherson, 1994). Zones of reduced stream power most commonly occur at mountain front locations where sediment is deposited at the junction between mountains and valley plain. After this point, fan sediments spread onto an adjoining valley (Bull, 1979; Blair & McPherson, 1994). Alluvial fans occur in all global climates (desert mountain regions, arctic, alpine, humid and humid tropical) but have been traditionally studied in desert environments (Blair & McPherson 1994: 354; Harvey *el al.* 2005:1). Fan depositional processes include debris flow, sheet flow and channelized fluvial processes that occur at a variety of scales. Radii typically measure 0.5-10.0 km from the mountain front (Blair & McPherson, 1994) and vary in length from small debris cones >5 m to megafans up to 60 km in length (Harvey *el al.* 2005:1). Deposits radiate in a 180 degree arc or form laterally due to constriction by neighbouring fans to form a bajada (Blair & McPherson, 1994: 354). Their transitional position enhances sedimentological and hydrological connectivity between mountain and floodplain landforms by coupling and buffering arid region fluvial systems within broader systems connectivity (Harvey, 1997: 231 - 253).

Alluvial fans play a critical role in groundwater recharge and their location on the floodplain provides an opportune site for water diversions used for irrigation (Harvey, 1997: 253).

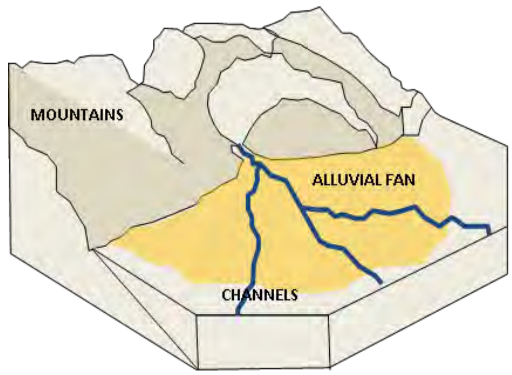

Figure 2.1: Alluvial fan form in the landscape (redrawn from The Bernardo Sun, n.d.).

2.2.2. *Fan Morphometry*

The study of fan morphometry is the measurement of external form of alluvial fan and the use of external form to identify form-process associated relationships. As described by Harvey (1997: 245), depositional processes determine the morphometry of alluvial fans and are thus a function of sediment supply. Identified morphological features constituting alluvial fans are the drainage basin, feeder channel, apex, incised channel, intersection point, distributary channels, active depositional lobe and headwater erosion gullies as shown in Figure 2.2 (Blair & McPherson, 1994; Calvanche, et al., 1997).

The surface morphology of fans is controlled by sediment and water supplied to the fan and reflects source-zone characteristics (Harvey, 1997: 245). Three basic elements of fan morphometry are channels, abandoned areas in former fan surfaces and depositional surfaces found downslope of channels (Figure 2.2), (Cooke & Warren, 1973: 175). During high intensity rainfall events, the drainage basin infiltration capacity of fans can be exceeded. At this time water is transported to the alluvial fan surface and the loci of deposition can be altered, fanhead entrenchment can be deepened and fan dissection can occur. The relationship between stream channels and the fan surface is said to be reflective of the erosional/depositional behaviour of fan systems and can determine whether fans are active or fossil (Harvey, 1997). The intersection point marks the point on the fan surface where positive accumulation (deposition) switches to negative accumulation (erosion) occurs which affects fan accumulation and preservation dynamics (Weissmann et al. 2005: 173). Active fans receive sediment from the drainage basin area which is then deposited at distal locations on the alluvial fan. . Channel switching however results in the shift of the locus of deposition on the alluvial fan (Harvey, 1997: 232), while deposition occurs down the main channel that may switch and run down steeper flanks. An entrenched or fossil channel system does not deposit sediment on the fan surface (Harvey, 1997: 234).

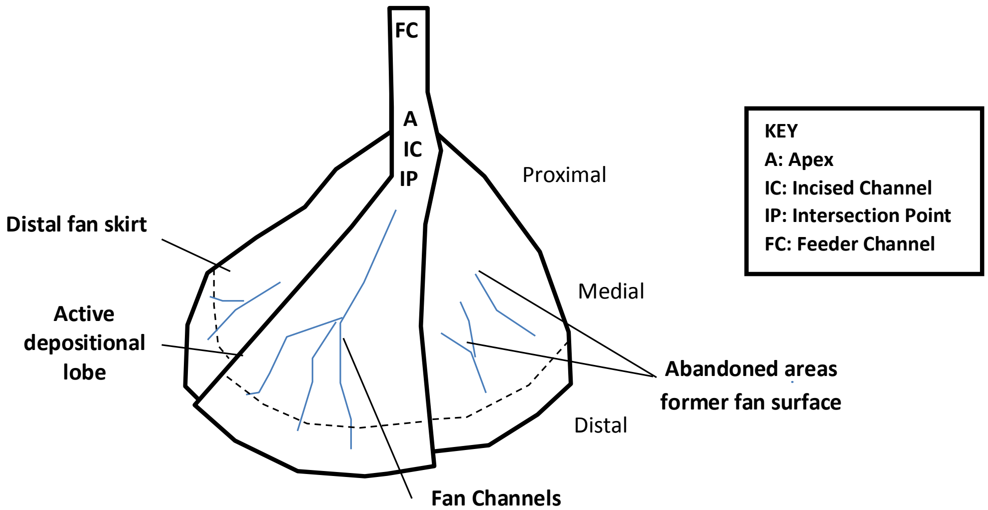

Figure 2.2: Schematic diagram modified from Blair & McPherson (1994: 357) of the main morphological elements of an alluvial fan.

2.2.3. *Occurrence*

Key factors controlling the occurrence of alluvial fans in the landscape are topographic setting, sufficient sediment supply and sufficient rainfall to induce the transport of sediment from the drainage basin to the fan (Table 2.1). This is reliant on the relationship between unit stream power and critical stream power determines points of incision and sediment deposition. When the unit stream power exceeds critical stream power incision at the mountain front location occurs, and when the unit stream power falls below critical stream power deposition occurs (Figure 2.3). This typically occurs at the intersection point.

2.2.4. *Alluvial fan control variables*

At least five key controlling factors form a system of interacting feedback relationships that influence the major sedimentary processes and deposits on fans (Blair and McPherson, 1994: 379). Controlling factors can be grouped into primary and secondary processes that bring about fan formation and the re-working of fan surfaces over time. Primary alluvial fan processes describe processes that are responsible for the transport of sediment from drainage basin to alluvial fan via debris or fluvial flow in rock falls, gravity slides, debris flows and sheet floods (Blair & McPherson, 1994: 362). Secondary processes involve the remobilization and modification of sediment on the alluvial fan surface by means of overland flow, wind erosion, bioturbation, sediment weathering and case hardening (Blair & McPherson, 1994: 362).

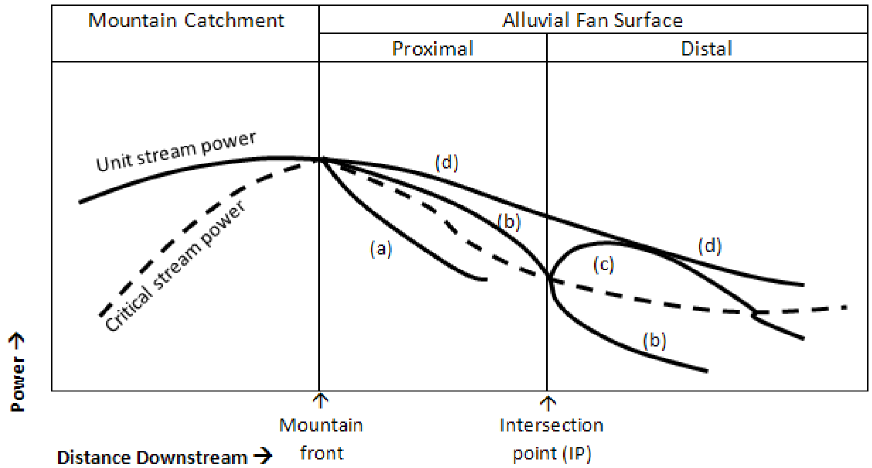

Figure 2.3: Critical stream power relationships on alluvial fans (adapted from Harvey, 1999:235). (a) aggrading fan, (b) proximally trenched fans, (c) mid-fan entrenched fans, (d) through trenched fans.

Table 2.1: Factors and conditions required for fan formation and occurrence in the fluvial landscape

Nr.	Factor	Conditions required for fan formation/occurrence
1	Topographic setting	Channel becomes unconfined by emerging from an upland area onto flat lowlands and there is a decreased stream power (Blair & McPherson, 1994: 360; Harvey, 1997: 234).
2	Sufficient source sediment	High rate of sediment is supplied by source area, determined largely by geology, relief and slope (Blair & McPherson, 1994: 360; Harvey, 1997: 234).
3	Infrequent and intense precipitation creating a high water discharge	Allows sediment to be transported onto the fan (Blair & McPherson, 1994: 360; Harvey, 1997: 234).

The following sets of controlling factors given by Harvey (1997: 235) contribute to the appearance and development of alluvial fans is given below:

A. General controls
    1. Tectonic factors
B. Environmental controls
    1. Factors that govern the rate of water and sediment supply
        - Source area geology
        - Bedrock lithology
        - Climatic factors

    2. Factors controlling sediment transport within the fan environment
        - Transport power

Due to the complex nature of integrated fan systems, fan control feedback relationships are difficult to analyse and quantify. These relationships are detailed in geomorphological and alluvial fan studies pre-1994 (Blair & McPherson, 1994: 379) and continue to be the primary thrust of alluvial fan research today. A number of alluvial fan morphometric analyses have been formulated to demonstrate the impact of each variable within the alluvial fan system to overcome the difficulties of studying alluvial fan relationships (Blair & McPherson, 1994: 379).

2.2.5. *Fan morphometry*

Alluvial fan morphometry has been studied extensively since the early 1960s and of number well-researched relationships such as drainage basin area to alluvial fan area and alluvial slope ratios have emerged. Key authors such as Bull (1964), Denny (1965), Hawley and Wilson (1965), Melton (1965), Hooke (1968), Beaumont (1972), French (1987), Harvey (1987, 2002, 2005) and Leece (1988, 1991) have described classic alluvial fan form process variables and how area and slope relationships demonstrate the influence of these variables on alluvial fans. Authors such as Bull (1964), Melton (1965) and Harvey (1987, 2002, and 2005) comment on the influence of the drainage basin as a control variable and the influence of lithology, geology and geometry of drainage basins on alluvial fan form. More recent morphometry research conducted by Suwa & Ouda (1983), Whipple & Dunne (1992) and Volker et al., (2007) utilize GIS technology to explore alluvial fan morphology and processes. Volker et al. (2007)

investigated formative surface processes using techniques given in classic GIS morphometry literature to identify formative surface processes generated by alluvial fan flows that determine the sedimentological character and morphology. Staley et al. (2006) investigate the more complex relationship between curvature and fractional downfall distance, as well as gradient. More recent use of Light Detection and Ranging (LiDAR) techniques have been used to produce high resolution topography data to analyse mainly un-vegetated dessert fans in the Mascardo Torrent, Italian Alps (Cavalli and Marcni, 2008) and in the Mojave Desert, California. Both the studies use LiDAR to examine fan morphology and roughness. LiDAR has been used a successful tool to identify human activities on fans and used in fan hazard assessments (Cavalli and Marcni, 2008).

Controls on fan processes as described in the literature review of this thesis include the factors that strongly influence the major sedimentary processes and deposits of alluvial fans and describe the interacting feedback systems of alluvial fans (Blair and McPherson, 1994: 379). Fan morphometry literature typically evaluates a number of alluvial fan control variables, using fan morphometry to demonstrate the impact of each of these variables on fans. They typically use topographic maps, aerial photographs and derived equations but are seldom paired up with a field analysis of landforms. Morphometric relationships used, in these studies, are noted to be complementary, but do not always consider alluvial fans as a landform that exists in space and time within a confined fluvial valley system due to limitations and the inability to simultaneously study the control variables influencing fans at any time.

The alluvial fan framework compiled in this thesis will be based on the alluvial fan control variables as done for a number of studies undertaken on alluvial fans, as discussed above, to best consider the main control variables that affect the functioning of fans. The alluvial fan framework will integrate internal and external control variables and evaluate fan internal and external control variables as significant controls on fan form.

2.2.6. *Alluvial fan evolution*

In a simple model, fan formation is constructed primarily by fluvial processes acting continuously to create a topographical soil texture gradient from the apex of the fan to the toe (Parker, 1995: 19). In a study conducted by Clarke et al. (2010) an experiment was designed to investigate the role of autogenic process-form interactions as controls on alluvial fan evolution. The experiment was set up in a 3x3 m fixed bed experimental table. In order to examine the spatial and temporal patterns of fan building, water and sediment was supplied to the fan apex and removed from the distal fan boundary to simulate valley variables. Variables examined include fan topography, channel migration and channel avulsion. Findings are consistent with fan theory that predicts a decline in the aggradation rate through time and identifies an autogenic transition from sheet flow to channelized flow (Table 2.2). The authors concluded that the experiments exhibited many fundamental features of natural fan systems and their evolution, processes and flow configurations observed in experiments is consistent with other studies conducted by Schumm et al. (1987), Zarn and Davies (1994), Bryant et al. (1995), Whipple et al. (1998) and Cazanacli et al. (2002). The intrinsic link between fan evolution and channel formation and migration provides a good form-process measure of fan evolution. Although the data collected and examined by Clarke et al. (2010) is based on laboratory scenarios, the consistency of findings with other fan evolutionary studies deems this study acceptable for use in characterizing fan stream channels. A summary of the results is given in Table 2.2.

2.2.7. *The role of alluvial fans in the landscape*

The primary property that has influence over the fluvial system is the internal connectivity or a linkage between the fluvial system components (Figure 2.4). This property in geomorphology has been defined by Harvey (2001) as 'coupling'. Coupling refers to the free transmission of energy and materials between components, 'not coupled' refers to no linkages between components and 'dis-coupled' refers to a system that has been previously coupled and is now not coupled (Harvey, 2001:226). Fans play an integral part in the connectivity of fluvial systems as they buffer and couple water and sediment in dry region fluvial systems (Harvey, 1997:234) to promote groundwater recharge and attenuate floods. Fans are therefore considered part of the connected fluvial system by contributing water and sediment from the tributary to the floodplain and main channel when the system is coupled and buffering sediment when the system is dis-connected (Harvey, 1997:234). Connectivity theory can be used to explain the role of fans in the valley by considering fans as an integral landform in the connected fluvial system functioning at a number of geomorphological scales. It is necessary to identify the spatial and temporal dimensions at which coupling occurs as this allows for the study of the spatial and temporal connectivity within the landscape. Jain & Tandon (2010:3) use four dimensions to describe fluvial system coupling. Three of these dimensions are spatial dimensions that include lateral, longitudinal and vertical coupling and the fourth dimension is time, which describes the temporal scale (Jain & Tandon: 2010:3). The degree of systems coupling relies heavily on the scale at which system components are functioning and the dimensions at which components interact. The local sediment buffering and coupling relationships will explain fan connectivity in the fluvial system.

Table 2.2: Autogenic stages of alluvial fan evolution (modified from Clarke et al., 2010:280).

Stage	Alluvial Fan	Channels
1	Linear increase in fan volume onto the area the fan surface occupies.	A. Sheet flow dominated flow over fan surface. No clear channels. Sheet flow deposits sediment. Rapid fan growth. B. As the fan volume increases, flow alternates between unstable braided channels and sheet flow. Sediment deposition occurs through the formation and abandonment of channels across the fan surface and during sheet flow.
2	Part of the fan extends to the drainage basin and there is a decline in the aggradation rate and rate of fan volume increase due to the increase of sediment fraction being transported.	Formation of one or two migrating main channels across the fan surface with fan avulsion and abandonment. Sediment reworking occurs with avulsion and lateral migration of channels and channel abandonment.
3	Fan volume stabilizes and net aggradation is zero. The volume of sediment supplied is equal to the volume of sediment transported out of the fan system	A single channel develops and distributes sediment on the fan surface and channel becomes trenched at the fan apex. The single channel can avulse and migrate to the mid and lower fan surfaces. Channel migration declined as experiment progressed.

2.2.7.i. *Sediment buffering and coupling*

Coupling mechanisms of fans are outlined in Figure 2.4. Local scale relationships act between two adjacent zones of the fluvial system and involve the downstream movement of sediment and feed sediment onto the alluvial fan surface (Harvey, 2002:176). Local relationships include: within hill slope, hill slope to channel, within channel, tributary junctions and reach to reach relationships (Figure 2.5). It is noted that all local spatial scale relationships act at both short and long time and spatial scales (Figure

2.5), (Harvey, 2002: 181). Alluvial fans are optimized by the zonal style of large scale coupling relationships which describes coupling between two discrete and major zones of the fluvial system occurring on larger spatial and temporal scales (Figure 2.5). Fan coupling between two major zones of the fluvial system, initiating both upstream and downstream systems coupling, can be climate-led or base-level-led (Harvey, 2002: 186). This concept can be explained by positioning fans in Schumm's (2005:5) transfer zone model (Figure 2.6). Large scale coupling or dis-coupling occurs depending on whether sediment is transported downstream or when sediment is deposited on the fan surface. During times of coupling fans become entrenched and this allows for sediment transport further down the fan. During times of dis-coupling, alluvial fans buffer sediment when sediment is trapped on their surface (Harvey, 2002: 186).

Aggrading (entrenched or proximally aggrading), distally aggrading fans and fans with fanhead trenches act as buffers within the fluvial system and break the continuity of sediment movement from the source area and sedimentary basin or main channel system on short timescales (Harvey, 1997:235). Dissected fans have continuity of coarse sediment movement and increased connectivity from the source area to arterial drainage, with increased sensitivity to the main channel with aggradation and dissection occurring due to source area environmental change (Harvey, 1997:235). These local fan coupling relationships occur at a short spatial and temporal scale. Zonal coupling between landforms in the valley occurs at a larger spatial and temporal scale.

2.2.7.ii. *Fans as aquicludes*

Alluvial fans have been described as being primarily aquicludes by Strahler (1969) as they are comprised largely of sand, mud and gravel layers. Alluvial fans allow for ground water recharge to occur by creating a local aquiclude. Water infiltrates at the fan head and is conducted to lower regions of the fan through sand and gravel layers forming aquifers trapped beneath mudflow layers (Figure 2.7), (Strahler, 1969: 443). Mudflow layers can act as aquicludes as water is trapped beneath this layer under hydraulic pressure created by water at a higher elevation toward the fan head. When a well is drilled into the valley floor the ground water rises at the wellhead due to artesian flow (Strahler, 1969: 443). In areas of heavy extraction of ground water reserves for irrigation, such as the south-western United States of America (USA) and Spain, the water table has become lowered. In the southeast USA efforts to increase ground water recharge are conducted using water spreading structures and infiltration basins on the fan surface (Strahler, 1969: 444).

Figure 2.4: Alluvial fans act as a buffer between mountain and valley plain. Image is of a north facing alluvial fan in the Baviaanskloof valley found at 33^{0}34'33.30''S, 24^{0}06'41.58''E.

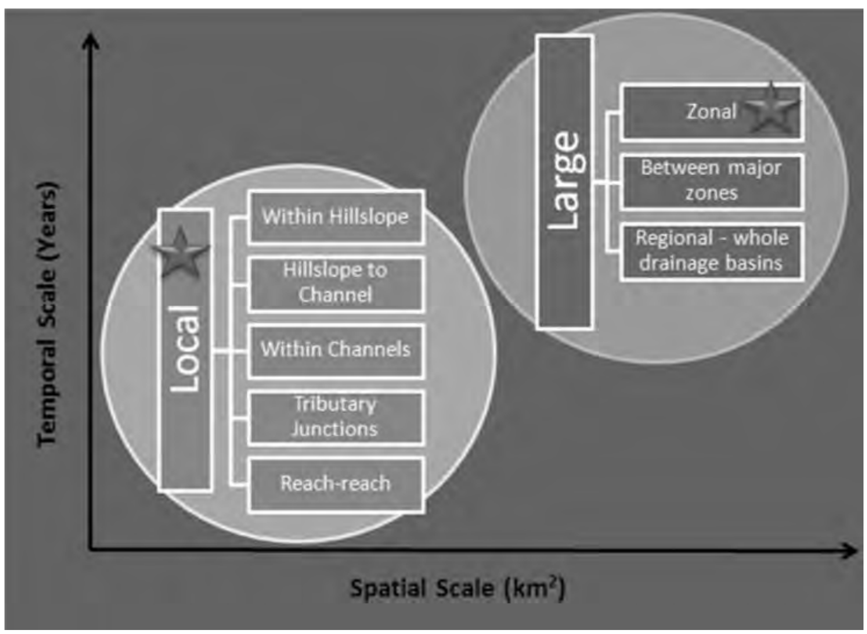

Figure 2.5: Local and large spatial scale coupling of fluvial systems plotted on a temporal and spatial scale axes. Local coupling describes processes that provide sediment to the fan and zonal coupling describes large scale coupling that occurs between two major zones of the fluvial system (adapted from Harvey, 2002).

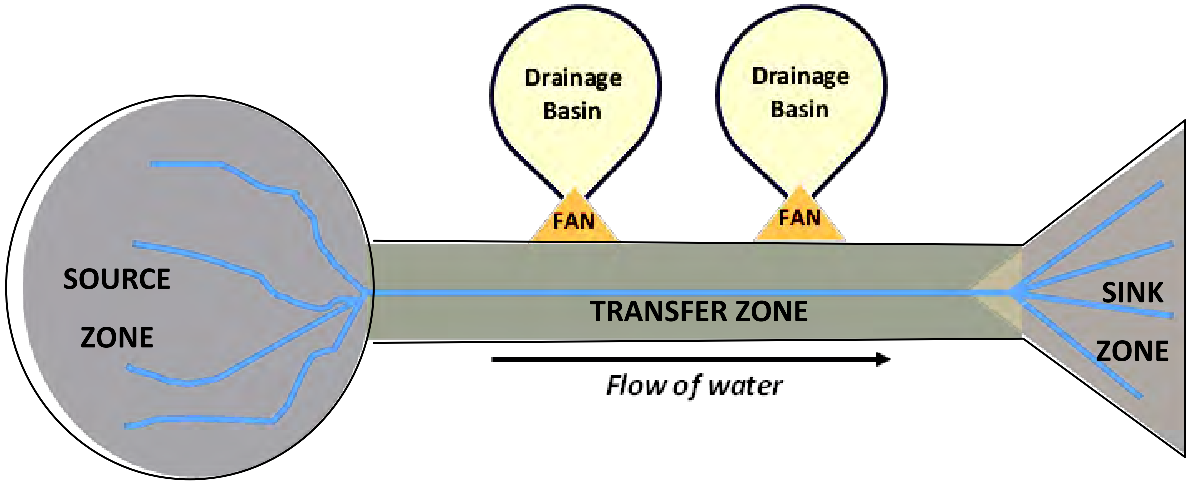

Figure 2.6: Positioning of alluvial fans in Schumm's fluvial zonation model (adapted and modified from Schumm, 2005: 5).

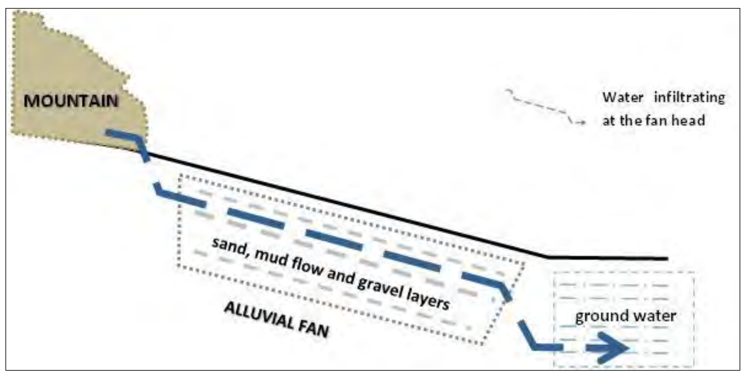

Figure 2.7: Ground water recharge through the creation of local aquicludes (adapted from Strahler, 1969: 443).

2.3. Alluvial fan research trends

Science seeks to discover new knowledge through a two-stage process involving the creation and justification of ideas and theory (Rhoads & Thorn, 1993: 287). Theory plays a critical role in the explanation of knowledge as it embodies universal propositions and law-like statements that provide a grounding to justify scientific ideas (Rhoads & Thorn, 1993: 292).

Since the early 1960s, natural scientists have developed theoretical models to describe the paradigms found in alluvial fan research (Milana & Ruzycki, 1999). Paradigms observed in alluvial fan research are shown to closely mirror those in broader science (Leece, 1990). This section provides an overview of alluvial fan paradigms and research trends since the early 1900s.

2.3.1. *The Alluvial Fan Problem*

The 'alluvial fan problem' investigated by Leece, (1990), Harvey et al., (2005) and Clarke et al*.,* (2008) alludes to the difficulty in developing a general model to explain the occurrence and development of alluvial fans in the landscape. Despite the effort put into researching the development of alluvial fans, a general model of alluvial fan development has not yet been formulated.

The alluvial fan problem attracted interest in the 1960s and many different approaches have been used in an attempt to solve it. The use of Kuhn's paradigm concept (described in Kuhn, 1970) is used by Leece (1990) to classify literature into groups of universally recognized scientific achievements that provide problems and solutions to a community of research practitioners (Leece, 1990:3). Examples of paradigms in alluvial fan research are the pre-paradigm, evolutionary paradigm, equilibrium paradigm and equilibrium paradigm considering climatic and tectonic factors (Leece, 1990:3). These paradigms are used to classify papers with recognized scientific achievements demonstrating different scientific approaches used to create a general model of alluvial fan development and solve the alluvial fan problem (Leece, 1990: 3).

The 'alluvial fan problem' persists because of a number of varied, undistinguished characteristics at each alluvial fan study site that may include drainage basin area, sedimentology, climate and history of the study site (Clarke et al*.,* 2008: 182). Although studies have been conducted to determine external (e.g. climate and tectonics) and internal factors (process-driven feedbacks) that shape and drive processes on alluvial fans, little has been uncovered to be fundamental to the development of all of the researched alluvial fans (Clarke et al*.,* 2008: 182). Limited quantitative similarities have shown fan characteristics are similar between all fans but there has been no evidence to reveal similarities in factors have shaped and driven fan formation and evolutionary processes (Clarke et al. 2008: 182)..

2.3.2. *Trends in Alluvial Fan Research*

Four extant alluvial fan paradigms in Kuhn's paradigm concept framework are used to explain progress towards resolving the alluvial fan problem (Table 2.3). Pre-paradigm fan research sought to describe and classify alluvial fans, with interest placed on geological descriptions, fan classification criteria and enquiry into depositional processes (Leece, 1990: 7). Research thrusts had no general accepted view or body of knowledge, lacked commonality of research methodology and literature, and were comprised of many disjointed research efforts (Leece, 1990: 8).

The first true paradigm identified in alluvial fan research was the evolution hypothesis. Research thrusts ignored the influence of process and variation in space and time and researched qualitative assessments of fan evolutionary stage (Leece, 1990: 9). It was believed that as fans evolved they filled the depositional basin with sediment until all remnants of the mountain range was buried in alluvium (Leece, 1990: 8). Further investigation of alluvial fan evolutionary stage introduced a concept of steady-state equilibrium, founded by Beaty (1970), describing the morphology and processes found on fans (Leece, 1990:8). To explore fan equilibrium theories a new approach was required. New theories forced a shift in the approach to ways alluvial fans were studied. Instead of examining fans from qualitative assessment perspective, the focus shifted to the existence of fans in both space and time that are subject to change. It was concluded that processes on alluvial fans would fluctuate about a changing mean condition (Leece, 1990: 10). The current alluvial fan paradigm is characterised by the connectivity concept. In this paradigm, the role of fans in the landscape involves the study of the flow of energy (water and sediment) between components in the fluvial system. Key authors include Brunsden and Thornes, (1979) and Harvey, (2010).

Most alluvial fan publications are conducted on desert fans. Alluvial fans have been studied since the 1870s with much of the data published on desert fans in the United States of America (Figure 2.8). Blair and McPherson (1994: 358) note an increase in the number of alluvial fan publications in the 1960s in response to a growing need to identify water resources and geological hazards to accommodate expanding populations. An exponential growth of papers on desert fans occurred during the 1970s and 1980s, both from the USA and other parts of the world (Figure 2.8). The number of other fans studies in Spain, Italy, the Middle East, Africa, Iran, Pakistan, India, Argentina and Chile rose to 20% of the total papers produced (Blair and McPherson, 1994: 359). Blair and McPherson (1994: 359) attributed this rapid growth to the practical need for knowledge for mitigation, civil engineering, mining geology, groundwater characterization, archaeological studies and basic research in the fields of geomorphology, sedimentology, hydrology and environmental geology. More recent fan research has been undertaken in Asia and the Middle East. Post 1994 alluvial fan research tends to predominate in USA with a few fan studies in Europe, the East and the Middle East. One of the key authors contributing to both alluvial fan morphometry study and connectivity post 1994 is Harvey. There are few papers published on South African alluvial fans. Boelhouwers et al. (2001) describes work conducted on debris fans in Du Toits Kloof in the Western cape of South Africa.

Table 2.3: Paradigm concept framework and alluvial fan models (updated and modified from the original table in Leece, 1990).

Paradigm/Period	Research View	References
Pre-paradigm	Description and classification, no general accepted body of knowledge	Blissenbach, 1954 Eckis, 1928 Tolman, 1909 Trowbridge, 1911 Knopf, 1918 Lawson, 1913
Evolution Concept	Qualitative assessments of stage; evolution models	Eckis, 1928 Clarke, 2010
Phase 1: Equilibrium Concept	Process and morphology encouraged quantitative studies and the creation of equilibrium models. Study of fan morphometry.	Bull, 1964 Melton, 1965 Denny, 1967 Hooke, 1968 Hooke & Rohrer, 1977
Phase 2: Equilibrium Concept: Climatic and Tectonic Factors	Independent variables that affect the processes occurring on alluvial fans. Study of fan morphometry.	Blair & McPherson, 1994 Harvey 1997, 2002, and 2005 Mills, 2000 Pope et al., 2005
Connectivity Concept	Study of fan variables that affect processes occurring on fans in space and time and the flow of energy (water and sediment) between components of the fluvial system.	Brunsden and Thornes, 1979 Harvey, 2010

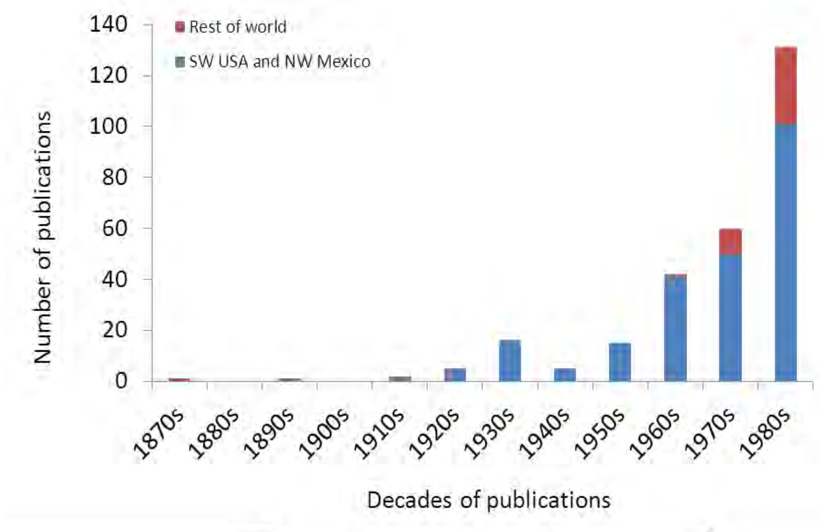

Figure 2.8: Number of desert studies conducted on alluvial fans up until the 1980s (Adapted from Blair and McPherson, 1994:358).

Chapter 3: Creation of an alluvial fan framework

3.1. Introduction

The creation of a robust alluvial fan form-process framework requires a critical appraisal of alluvial fan literature that not only includes fan empirical relationships, but a broad and more holistic approach than has been used previously. Alluvial fans develop as a result of gross morphological, sedimentological, local and regional scale water supply and local sedimentation processes within the fluvial system. It is necessary to explore all of these factors when compiling a framework to describe alluvial fans as landforms functioning in both space and time. The aim of this chapter is to compile an alluvial fan form-process framework to characterize alluvial fans and fulfils the requirements of objective 2 in Chapter 1.

External valley-wide parameters and empirical relationships described in Kochel (1990) and Taylor (1999) detail how valley parameters have shaped the formation of fans in space and time. Internal fan control variables are highlighted in papers published by Hooke (1968), Blair & McPherson (1994), Calvache et al., (1997) and Harvey (1997, 2005, 2005) Both Internal and external control variables discussed in fan literature by Blair & McPherson (1994), Harvey (1997, 2002, and 2005) and Mills (2000) have been identified and used to structure the fan framework; this includes gross morphological and tectonic factors, factors that control water and sediment to the fan surface and sedimentation to the fan and factors that control sediment transport through the alluvial fan.

A schematic diagram will be presented to the complete form-process framework representing the key themes and relationships identified in the alluvial fan framework. The diagram indicates the interaction of fan control variables and their influence of fans in the fluvial system. This diagram was created by identifying fundamental relationships and links between fan control variables.

3.2. Methods

3.2.1. *Developing the form-process framework*

A critical appraisal of alluvial fan morphometry literature in Chapter 2 provided the background knowledge on alluvial fans and identified existing descriptive criteria used to describe alluvial fan form-process empirical relationships. All literature found on the morphometry of alluvial fans was evaluated for its suitability to describe form-process relationships. External and internal control variables identified in Chapter 2 were used to structure the fan framework. Valley-wide external control variables, explained in Blair & McPherson (1994: 362), are said to influence the development and response of internal fan processes over time. These include: accommodation space, tectonics, sea-level change, lateral migration of the river channel and human activity. Factors contributing to water and sediment inputs onto the fan surface include: drainage basin variables, climatic variables and bedrock lithology. Internal fan processes are influenced by the external processes and are described before internal control variables. These include: fan style, fan morphometry and fan channels. Key headings incorporated into the framework under fan external and internal control variable include accommodation space, base level, water and sediment inputs and fan variables.

An overview of the layout and structure used in the framework is given below in section 3.2.2. It is noted that external control variables are given before internal variables and the relationships have been arranged according to the scale at which processes operate in the fluvial system. Accommodation space and base-level change are control variables operating at a large scale in the fluvial system affecting all fans in a valley context. Water and sediment inputs act on a smaller drainage basin-fan scale where climatic variables, vegetation cover and bedrock lithology, although valley-wide variables, will be considered at a drainage basin-fan scale. Internal fan control variables affecting fans at a local scale will be discussed last as these processes result as a function of processes operating at a larger scale in the integrated fluvial system. The control variables will be discussed and the methods used by authors explained. It should be noted that the methods used to calculate and measure these variables in the Baviaanskloof Valley will not be presented in this chapter and will be discussed in Chapter 6. A schematic diagram will complete form-process framework presenting the key themes and relationships identified in the alluvial fan framework and how these relationship relate to each other in the connected fluvial system.

3.2.2. *Structure of form-process framework to be developed in this thesis*

A. External factors

1. Accommodation space

2. Base level changes

    i. Valley-wide variables

- *Active tectonics*
- *Sea-level change*

ii. Local (fan specific)

- *Valley channel migration*
- *Human intervention*

3. Drainage basin inputs (water and sediment)

i. Valley-wide variables

- *Climatic variables- rainfall in relation to flood generation*
- *Vegetation cover*
- *Bedrock lithology*

ii. Fan drainage basin variables

- *Area*
- *Shape*
- *Relief/gradients*

B. Internal variables

4. Fan variables

i. Fan style

ii. Fan morphometry (form related)

- *Fan area*
- *Fan slope*

iii. Fan channels (process related)

- *Fan channels*
- *Channel switching*
- *Fan trenching*

3.3. Form-process framework

3.3.A. External factors

3.3.3. *Accommodation space*

For sediment accumulation to occur there must be sufficient accommodation space for materials to be deposited and preserved at points where channel flow expands (Viseras et al. 2003: 182).

Accommodation space defines the volume of space that can be filled by sediments where alluvial fan process regimes are governed by stream power and sediment load (Weissmann et al. 2005: 172). Accommodation space is calculated by measuring the width of the valley floor, measuring the area available for the alluvial fan to form from the location where the tributary stream meets the valley floor to the opposite side of the valley. This calculation was conducted on the flat valley floor without the fan surface being incorporated into the measurement. Wider valleys provide a greater amount of accommodation space for fan development and sediment storage and influence the occurrence and formation of fans in the valley (Taylor, 1999: 119). In wider valleys, a stronger morphometric relationship between fan area and drainage basin area exists (Taylor, 1999: 119). In narrow valleys tributary fans constrict the main river flow producing greater shear stress and negative feedback response and the development of lateral fan erosion (Taylor, 1999: 119). Taylor (1999: 221) notes that factors that contribute to continued fan aggradation in spite of a low accommodation space include high drainage density, high tributary junction frequency, steep low order channels, high valley width expansion rates, wide high-order channels and steep, colluvial hillslopes prone to debris flows.

Accommodation space can be assessed by measuring valley width and plotting the critical valley-width threshold. A log-log plot of alluvial fan area (km^2) versus valley width (km) has been used to determine the fan threshold envelope for a given valley (Figure 6.15), (Kochel, 1990; Taylor, 1999). This envelope defines the threshold at which valley width becomes too narrow and constricted to allow for fan preservation and indicates the minimum valley width required for a fan of a given area to develop (Taylor, 1999: 219). The equation given by Taylor (1999:219) to determine fan preservation space is calculated using equation 3.1. A threshold plot based on a study by Taylor (1999) is given in Figure 6.15. It is observed that a threshold envelope for fans at three sites in the central Appalachians are given by the equation A_f = $1.8W_v1.57$ and describes the minimum width at which a fan of a certain area can develop in the central Appalachians (Taylor, 1999: 194-223).

Eq. 3.1 $$A_f=1.8W_v^{1.57}$$

A_f: alluvial fan area (km^2)

W_v: valley width (km)

3.3.4. *Base level changes*

3.3.4.i. *Valley-wide variables*

Base-level is defined as the level at which a channel cannot erode any further (Chapter 2). Base-level influences the energy within the fluvial system and can be affected by tectonics, climate and locally induced base-level changes on the fan surface due to a laterally migrating main channel and/or human influence (Blair and McPherson, 2004; Harvey 1997, 2002, 2005, 2010; Mills, 2000). The critical stream power relationship (defined in Chapter 2) is influenced by base level change and governs the point of sediment aggradation and determines whether fans are either stable or unstable. Critical links between base-level and fan channel changes should be considered when viewing the fan channel section of this

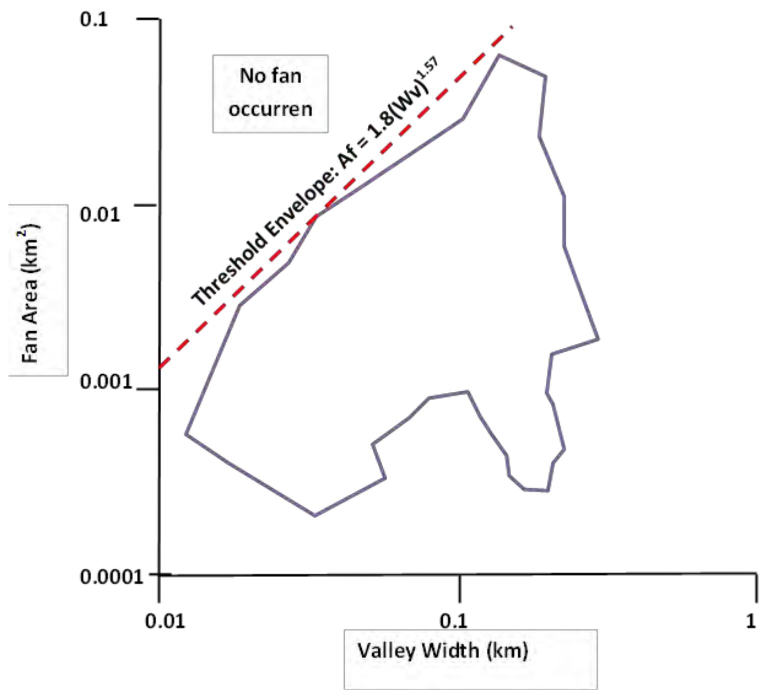

Figure 3.1: Simplified log-log plot of the valley width (km) versus fan area (km2) for the Fernow, North Fork and Little River (redrawn from Taylor, 1999:218). The polygon represents the boundary line of all points plotted below the threshold envelope for fans in the Fernow, North Fork and Little River, for a detailed graph please see Taylor (1999:218) .

chapter. An overview of base-level changes is given in Figure 3.2. For fans with stable base-levels (shown by the stable base-level, Type 1A, Figure 3.2), fan dynamics are controlled by tectonic setting and climatic factors which influence fan dynamics and morphology (Harvey, 2002: 68). For fans with unstable base levels (Type 2A and B, Figure 3.2) the fan dynamics, fan evolution and fan sedimentary processes are altered. Fans without the effect of base-level change develop until an intersection point is created and incision typically occurs at the fan apex (Type 1B, Figure 3.2), (Harvey, 2010: 165). The rise and fall in base-levels modifies the amount of energy that is transported between fluvial system components. For example, a drop in sea-level increases the energy within the fluvial system and fans aggrade (Figure 3.2). When there is a sea-level rise, there is a decrease of energy in the fluvial system reducing the transport of sediment through the fan and sediment is deposited in the lower reaches of the channel system. When sea levels rise increasing the energy in the fluvial systems fans may become trenched (or dissected) along their length (Figure 3.2), (Charlton, 2008: 13). Unstable base-level changes (Types 2A and B) due to a rise in base-level results in distal incision and headcut development and mid-fan incision and fan dissection resulting from a base-level fall (Figure 3.2).

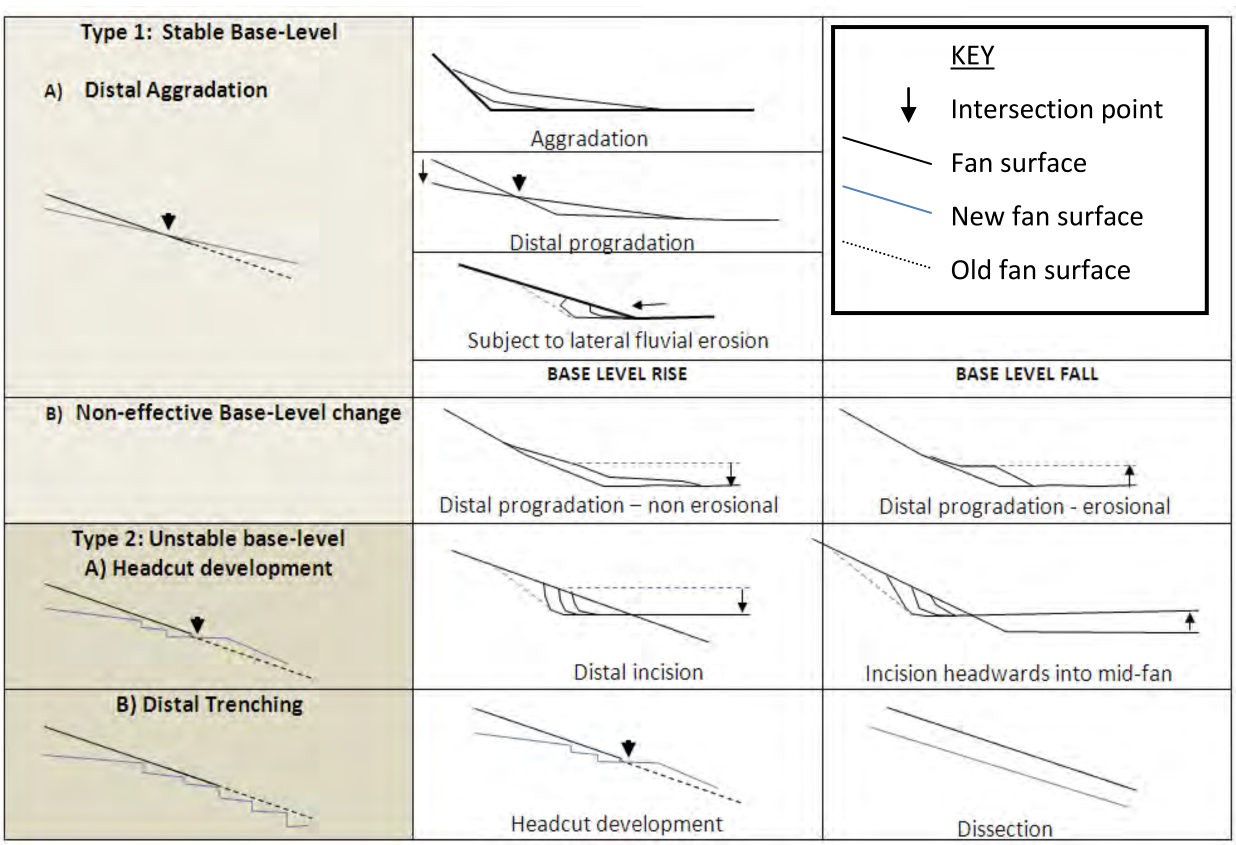

Figure 3.2: Base-level rise and fall for stable and unstable base-levels shown for type 1: stable base-levels and for type 2: unstable base-levels. For each type, the rise and fall in base level affects the intersection (condensed from Harvey, 1997 and 2010).

The effects of base-level can be determined by examining the four factors that bring about base-level change and excluding those factors that do not apply to each of the cases respectively. A change in base-level brought about by a change in sea-level is likely if there has been a recorded drop in sea-level large enough to affect an intermontane valley. A base-level change due to active tectonics is feasible if the valley is subject to active tectonics. This can be ascertained using literature and analyses as listed in the tectonics sub-section. A change in base-level due to a laterally migrating main river channel will show evidence of fan toe-trimming and fan channel incision for fans identified in the valley will be addressed below. Base-level change due to a migrating fan channel as a result of human activity can only be feasible if there has been human activity on fans. The effects of human activity will be analysed in depth within the human activity section of this chapter.

Active tectonics

Tectonic factors influence the context and setting of fans and uplift events affect gradient and base-level characteristics (Harvey, 2002: 68). Tectonic forces lead to large-scale uplift events along faults, vertically displace fan surfaces and distort the deformation of the deeply embedded depositional sequences inducing subsidence, warping, fracturing and faulting (Pope et al., 2005: 113). Active tectonism influences fan development both directly and indirectly: directly influencing fan gradients, base-level and stimulating fan sediment deformation, indirectly influencing erosion as a result of the increase or decrease of the source area elevation (Harvey, 1997: 236). The direct effects of tectonism results in the gradual and continuous long-term rise and fall in the base-level and may result in fan incision (Pope et al. 2005: 113). Blair & McPherson (1994) suggest that without active tectonism, alluvial fans may only be minor and short-term features of the environment. Tectonic activity creates and maintains relief and influences long-term transfer rates of water and sediment to the fan system.

The tectonics control variable was included because of its impact on the vertical displacement and base-level of valley systems. If tectonic uplift has occurred, the earth's crust has been vertically displaced and water inputs are likely to be found at a higher or lower elevation than previously found. The change in the amount of available energy leads to an increase or decrease in sediment production rates and affects alluvial fan channel patterns. Tectonics also has a large effect on fan morphology and sedimentary sequences through its influence on accommodation space (Silva et al. 1992; Viseras et al. 2003; Harvey, 2005). In tectonically active environments, the rise and fall of the base-level modifies patterns of sedimentation and triggers incision on the distal fan surface, see Figure 3.2 (Harvey, 2010:164). Fan styles described by Harvey (2010) show that fans with no effect of base-level change produce a fan profile that is aggrading and/or incising. Aggradation typically occurs on the distal fan surface and incision on the proximal fan surface (Harvey, 2010:165).

The effect of tectonics within a valley context can be researched by consulting geomorphological and geological literature as done for alluvial fan studies conducted by Nemec (1988), Rachocki and Church (1990), Harvey (1997, 2002, 2005), Mills (2000). In these papers an overview of active fan tectonics past and present was investigated to determine whether tectonics have played a role in the formation of the valley over time. Denny (1965) and Hooke (1968) show that alluvial fans on the western piedmont (Death Valley, USA) are larger than fans originating from the Black Mountains to the east due to differential subsidence of the valley floor (Given, 1999: 48). This is paralleled by findings by Ritter et al. (2000) where fans on the dip-slope piedmont of Buena Vista Valley (Nevada, USA) are larger for a given drainage basin area than fans traversing a range-bounding fault on the eastern piedmont of Winnemucca (Nevada, USA).

Sea-level induced base-level change

Fans that toe-out along a marine or lake shoreline are mostly susceptible to a sea-level induced base-level change. A base-level change due to a rise in sea-level can result in the distal reaches of the fan becoming inundated with water to form a fan delta, (Figure 3.2), (Harvey, 2010: 164). Fans that toe out along the marine coastlines are subject to wave action and a rise in lake or sea level may have their distal fan sediments eroded, which shortens and steepens that fan profile resulting in distal fan incision (Harvey, 2010: 164).

3.3.4.ii. *Local (fan specific)*

Valley channel migration

The lateral migration of the main river channel (main stream) under a stable base level may have the same effect as a change in base-level due to the shortening of the fan profile (Harvey, 2010: 164). This results in distal incision induced by toe-cutting (Harvey, 2010: 164). Basal trimming by a laterally migrating river channel is observed to trim the fan toe as shown in Figure 3.2. The effects of the laterally migrating main channel on local induced base-level change can be assessed by determining evidence of fan toe trimming. Although no clear methods are given in Harvey (2010), the effects of toe trimming due to a lateral migrating river can best be evaluated by comparing the form of a toe trimmed alluvial fan versus a fan that has formed without the effects of obvious toe-trimming. Toe trimmed fans often have a straight edged fan boundary as shown in Figure 3.3.

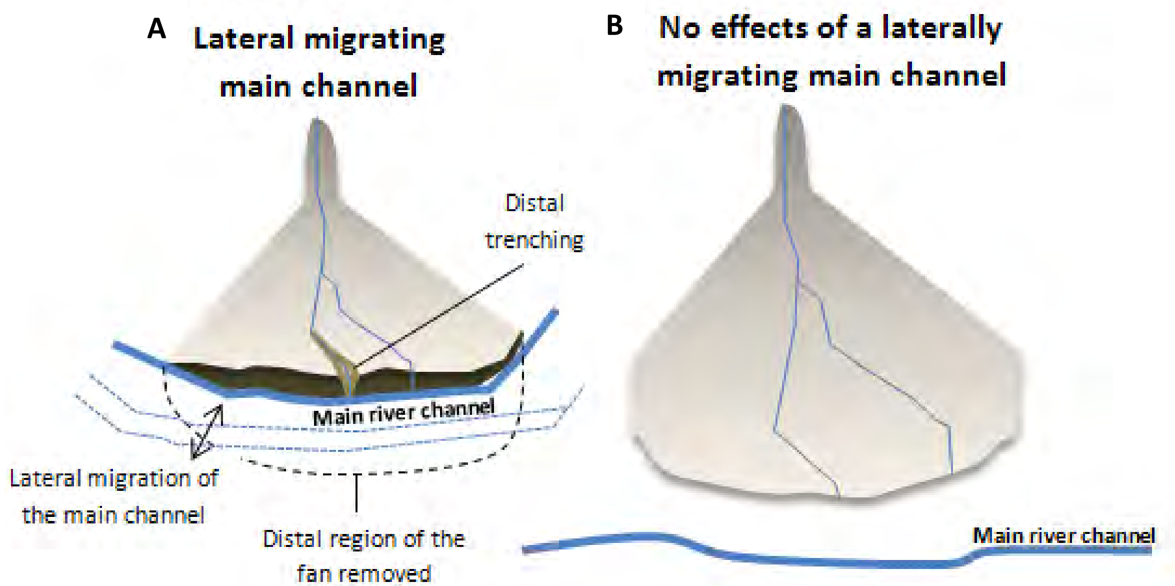

Figure 3.3: Schematic diagrams depicting A) A laterally migrating main river channel and toe trimming and B) no effects of a laterally migrating fan channel.

Human intervention as a contributor to local base-level change on fans

Human activity has a significant impact on fluvial systems and can bring about a base level change due to shortening of the fan profile as well as incision at the apex or distal region of the fan surface. Activities in the drainage basin such as de-forestation, agriculture and mining affect the flow of water and sediment through the fluvial system and modify the position of channels on the fan surface and the migration of fan channels increasing the chance of a base-level change that results in incision (Charlton, 2008: 13). The construction of dams and/or roads on the alluvial fan deposit obstructs water flow over the fan and diverts channelled flow into a new flow path. An example of this is given by Hermas et al. (2010: 93-94) who studied the Wadi Feiran fan in Sinai, Egypt, where a man-made barrier across an incised channel affected the functioning of the alluvial fan system, and the incised channel to avulse toward the fan apex to follow a new flow path. The new flow path had resulted in channel switching that had turned an active lobe into an inactive one. The evolution of the fan surface followed a progression that allowed for channel switching to occur, followed by channel braiding and lastly a process of channel widening.

3.3.5. *Drainage basin inputs (water and sediment)*

3.3.5.i. *Valley-wide variables*

Climate variables- rainfall in relation to flood generation

Heavy rainfall events modify the fan surface through a shift in the locus of the deposition due to a greater tractive force in active fans channels than on the fan surface (Cooke and Warren, 1973: 185). This results in deepened fanhead trenches at the fan apex and increased desert varnish on abandoned surfaces above the fan apex (Leece, 1990: 11). Floods have been observed to widen the stream channel, cause channel scour and sediment bar re-organization along the portions of narrow floodplains and on the margins of larger fans (Kochel, 1990: 123). Rainfall has been effectively studied by considering the intensity and frequency of rainfall events and the creation of overland flow due to the infiltration capacity of the drainage basin (Bair and McPherson, 1994: 386). Kochel (1990) and Taylor (1999) used the intensity-duration rainfall relationship to determine the effects of rainfall on fans in the north, south and central Appalachians. This technique has its advantages as sediment transport events can be monitored to determine the infiltration capacity and determine the intensity-duration for overland flow runoff events. Vegetation and temperature have not been studied in detail.

Vegetation cover

Sparse vegetation cover and high intensity rainfall events generate high runoff rates which create potential erosional events on fans (Harvey, 1997: 237). A dense vegetation cover produces a steeper alluvial fan slope due to the increased shear strength of the sediment mantle caused by rooting (Bair and McPherson, 1994: 386; Mills, 2000: 289). A case study example of this is the dense forest maintained in the Appalachians due to high amounts of precipitation and moderate temperature (Mills, 2000: 289). Methods used to determine vegetation density include plant counting, normalised difference vegetation index (NDVI) and parallel photography and terrestrial laser scanning methods outlined by (Warmink, 2007).

Bedrock lithology and source geology

The source area geology determines the rate of sediment supply and controls the dominant clast size through its inverse relationship between rock resistance and erosion rate (Harvey, 1997: 236). Source geology therefore determines the amount of sediment transported to the fan surface as well as the depositional processes that occur on the fan surface. Headcut development is also notably linked to geology. Active headcuts are more typically found in marls, sandy loams and loams than headcuts that developed in conglomerates and gravels (Bull and Kirkby, 2002: 21). The type of bedrock in drainage basins from which sediment is derived impacts alluvial fan primary processes such as the runoff regime as well as the calibre (ratio of coarse to fine sediments) and the amount of sediment supplied or discharged from the drainage basin area via fluvial or debris flow (Bair and McPherson, 1994: 379; Bull and Kirkby, 2002: 174).

It is thought that drainage basins underlain with less resistant rock types are reported to produce fans larger in area (Bull, 1962; Given, 2000; Mills, 2000) and steeper in slope (Bull, 1962). Bull (1962), working in western Fresno Country, California, studied the effect of bedrock lithology on the area and slope of alluvial fans of the San Joaquin Valley. He found that drainage basins comprised of erodible lithologies, for example mudstone and shale, produced steeper fans. In a separate study, Given (2000: 47) found that basins underlain with more resistant lithologies such as sandstone were almost half the size of those produced by erodible rock types such as shale.

Bedrock consisting of cemented, dense, tightly cemented sedimentary rocks such as quartzite undergoes brittle-fracture in proximity to mountain front faults (Bair and McPherson, 1994: 380). Angular pebbles, cobbles and boulders are produced, but little clay and sand due to the effects of cementation of matrix grains (Bair and McPherson, 1994: 380). Dense carbonate rocks produce gravel-sized angular blocks whereas stratified soft sedimentary rocks like shale cause intervening brittle rocks to fracture and weather to produce tabular gravel-sized clasts with a prominent clay size fraction (Bair and McPherson, 1994: 380). Fine-grained drainage basin bedrock lithologies such as metamorphic rocks, shale, mudstone and volcanic rocks will weather to yield sediment of varying sizes from boulders to clay with a number of finer grains excluding sand fractions (Bair and McPherson, 1994: 380).

Mills (2000) has also reported that the lithology of the drainage basins consisting mainly of intensely fractured rock results in a number of intensely fractured zones producing a large amount of sorted material transported to the alluvial fan. As an exception to this, he noted that the White Mountains in California underlain with more resistant rock-types produced larger fans (Mills, 2000: 293). Mills (2002) explained that fans produced from a drainage basin with a more resistant rock type may have a greater amount of sediment transported to the fan apex due to steep narrow valley sides or drainage basins (Mills, 2000: 294). It is also thought that the valleys underlain with more erodible rock types can provide a greater amount of storage space in the gentler valley side slopes than more resistant rock types (Mills, 2000: 294). This will result in less sediment being transported to the fan surface as sediment can be stored in the feeder catchment in a temporary sediment sink. The lithology and geology of a given area is determined using geological map series and by reviewing literature on the geomorphology and geology of the given area. The review of geology literature to determine the bedrock lithology and geology has been conducted for many alluvial fan studies. Drewers (1969) in Bair and McPherson (1994: 382) defined the bedrock and structural geology of 14 fans from Copper Canyons, south-east Death Valley, USA. The alluvial fans and drainage basins were defined within the valley and overlaid onto a bedrock and geology map. This method gives a good visual representation overview of drainage basin geometry and the spatial distribution of geologies within the valley. A further refinement would be to record the percent of each lithology that underlies each drainage basin as was done by Hooke (1968) in Deep Springs Valley and Little Cowhorn Valley, in the United States of America.

3.3.5.ii. *Fan drainage basin variables*

Area

The drainage basin is the collecting ground and storage ground for precipitation and the system route for water and sediment onto the fan surface (Selby, 1985: 293). It is expected that the larger the drainage basin area, the greater the collecting area of runoff for sediment generation (Selby, 1985: 293).

Shape

The shape and evolution of the drainage basin shape can have a major impact on the sedimentary processes of the fan system (Blair and McPherson, 1994: 380). Basin shape affects fan slope, feeder channel, relief, indicates storage capacity and flashflood generation (Blair and McPherson, 1994:380). The Gravelius Index (Gi) is an indicator of drainage basin geometry given by the basin perimeter divided by the perimeter of a circle with identical area (given by equation 3.2). Low values of Gi indicate basins are more circular, a high Gi indicates basins are more elongated (Calvache et al., 1997). Calvache et al. (1997: 78) observed that fans produce Gi values from 1.26 – 1.88 and the differences in drainage basin geometry correlated to the different sectors in the valley.

Eq. 3.2 $$Gi = \frac{\text{Basin perimeter}}{\text{Perimeter of a circle with identical area}}$$

Relief/gradients

Drainage basin relief determines the magnitude of sediment-gravity events and indirectly affects the amount of rainfall received by a drainage basin (Blair and McPherson, 1994: 386). Melton's Ruggedness number, outlined in a paper by Melton (1965), is a positive index defined by the ratio between the vertical relief above the fan apex and the square root of the drainage basin area used as a surrogate measure of the gradient down which material moves. The equation given to calculate basin ruggedness is given by equation 3.3. Melton's ruggedness number can vary from zero to 3.0 (Given, 2004: 54). A low ruggedness number is calculated for drainage basins with a high rugged relief indicating a large gradient and available relief that can feed sediment onto an alluvial fan surface; a high ruggedness number of 2 or 3 indicate low basin ruggedness. Alluvial fans supplied with sediment from drainage basins with a high ruggedness number tend to be larger than those fans supplied by a drainage basin with a low ruggedness number. The slope of the alluvial fan has been shown to correlate to the slope of the drainage basin (Given, 2000: 54).

Eq. 3.3 $$M = H / \sqrt{Ad}$$

H: Height above fan apex

Ad: Area of drainage basin

3.3.B. Internal variables

3.3.6. *Fan variables*

3.3.6.i. *Fan style*

Alluvial fan style is partly a result of fan setting and is reflective of both the topographic (tectonic evolution) and geological context of the fan and its source area (Al-Farraj & Harvey, 2005: 85). The incorporation of this parameter into the framework demonstrates the impact of topography, geological content and fan source area on fan form and explains the geometry and form of the fan surface on the valley floor. Three fan geometries, namely telescopic, stacked and truncated, describe the form of fans in the valley (Figure 3.4). Telescopic fans are comprised by a number of new and old depositional lobes where new lobes form on top of older lobes in an unplanned fashion. Stacked fan geometries are characterised by new and old fan lobes typically being stacked on top of each other. Truncated fans are fans that have been dissected. Each style, with its confinement, reflects the relationship between drainage basin area and alluvial fan area. Mountain-front fans are generally telescopic and unconfined; tributary-junction fans are confined with some having stacked or telescopic styles (Figure 3.4 and Table

3.4). Figure 3.4 and Table 3.4 can be used to classify fans in a valley context based on confinement and fan geometry.

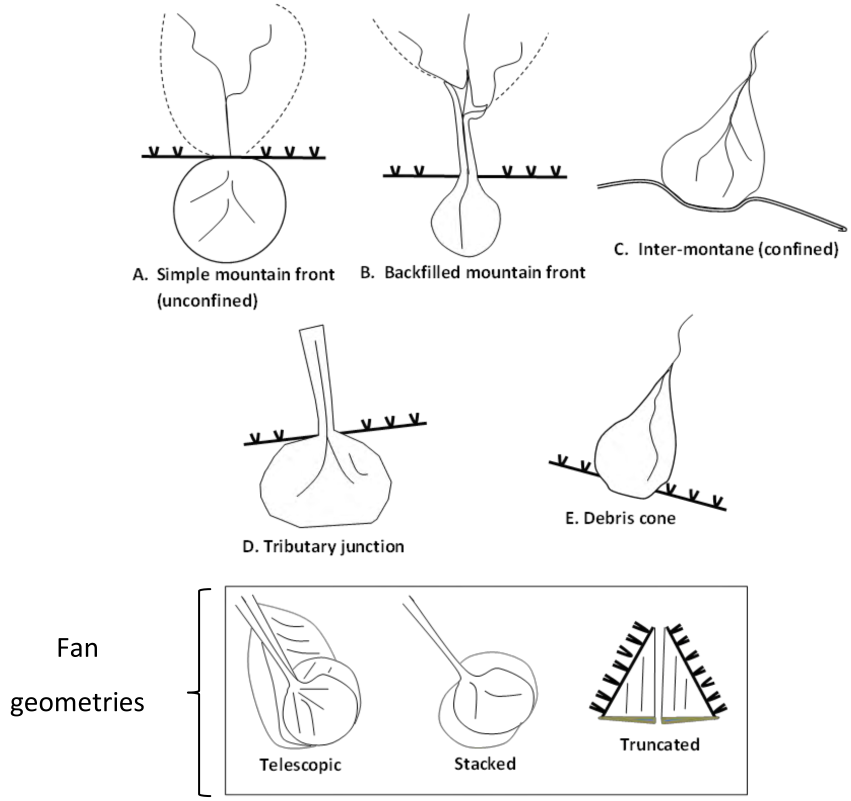

Figure 3.4: Alluvial fan style is reflective of fan geometry and fan form on the valley floor. Fan geometries include telescopic, stacked or truncated. Fan form on the valley floor is simple mountain-front, backfilled, intermontane, tributary junction or debris cones (adapted from Al-Farraj & Harvey, 2005: 88).

3.3.6.ii. *Fan morphometry*

Fan area

In order to represent the ratio of drainage basin area to alluvial fan area, which describes the transport capacity of alluvial fans, a log-log plot has been used by authors such as Bull (1964), Denny (1965), Hawley and Wilson (1965), Melton (1965), Hooke (1968), Beaumont (1972), Harvey (1987) and Leece (1988, 1991). Theory suggests that alluvial fan size is relative to drainage basin size as larger drainage basin can generate more sediment and therefore form larger fans (Harvey, 1997, Milana et al., 1999). The depositional processes that form and maintain the fan surface are controlled by sediment supply and are reflective of source-area characteristics (Harvey, 1997: 245). Figure 3.5 illustrates the correlation between drainage basin area and alluvial fan area for fans in studies. The relationship between alluvial fan area to drainage basin area is given by the equation 3.4.

Table 3.1: Fan type and geometry: telescopic, stacked or trenched fan morphometry (form related)

Type	Description
Mountain-Front	Unconfined. Toe out at stable base-levels and are mostly telescopic in style (Bowman, 1978). Proximal fan surface is dissected by fan-head trenches from which the younger sediments distally aggrade.
Tributary Junction	Confined by valley walls. Influenced by local base-levels. Telescopic and stacked. Some are trenched throughout and may be influenced by local relationships to the main channel. Many of these fans have been truncated by toe trimming (Leeder and Mack, 2001) by lateral incision or lateral migration of the main channel.
Valley-side debris cones	Simple forms. Mostly stacked styles and trenching (Al-Farraj & Harvey, 2005).

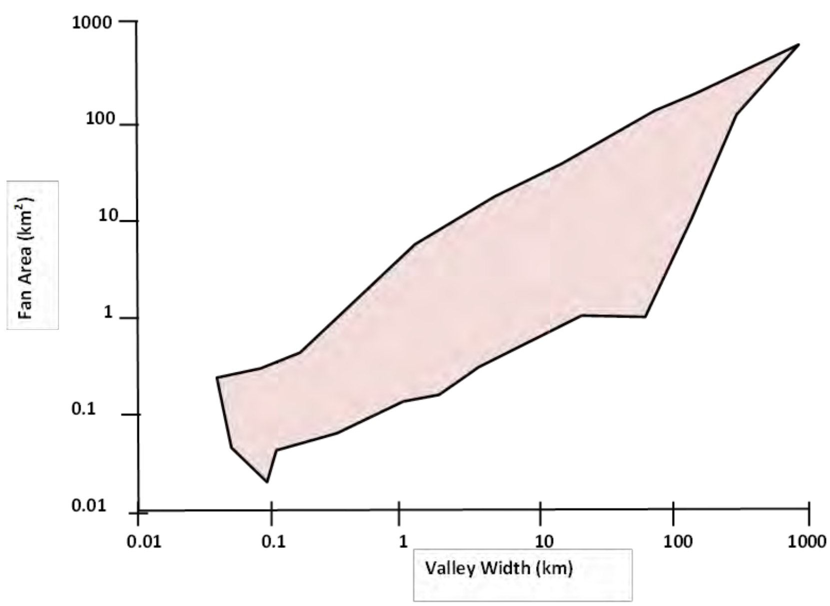

Figure 3.5: Simplified 'Classic' correlation relationship between drainage basin area and alluvial fan area (re-drawn from Blair and McPherson, 1994: 392). The polygon represents the boundary line of the points plotted for Bull (1964), Denny (1965), Hawley and Wilson (1965), Melton (1965), Hooke (1968), Beaumont (1972), Harvey (1987) and Leece (1988, 1991). For a detailed graph please see Blair and McPherson, 1994: 392.

Eq. 3.4 $F=pA^q$

F: Fan Area (km^2)

A: Drainage Area (km^2)

q: Similarity of alluvial fan; values typically between c. 0.7 – c. 1.1

p: Reflect different catchment geologies; values typically between c. 0.1 – c. 2.1

Values of *p* generally yield values of 0.1 – 2.2 and exponent *q* values between 0.7 and 1.1 with log–log correlations that are generally high (Mills, 2000: 292). Research conducted on parameters of drainage basin and alluvial fan areas, however, do not always comply with the ‘classic’ drainage basin area versus alluvial fan area plot, as reported by Milana & Ruzycki (1999) and Silva et al., (1992). If a fan is smaller than the volume of supplied debris it will increase in thickness and area more rapidly than adjacent fans assuming that fan area is proportional to the amount of sediment supplied to it (Cooke & Warren, 1972:175). Harvey, (1997), Hooke and Rohrer (1977) and Leece (1991) agree that it is difficult to describe alluvial fan relationships based solely on area ratios when geology and sediment supply may differ between fans. Milana & Ruzycki (1999) showed that while the area relationships of drainage basin and alluvial fan may not produce a proportional relationship, they do produce lines of similar gradient as indicated by the eight parallel lines in Figure 3.6.

Fan slope

Assessing alluvial fan slope is a primary determinant of sediment transport efficiency on an alluvial fan (Milana & Ruzycki, 1999: 553). Slope relationships between fans and drainage basins have been quantified over a thirty year period by authors such as Bull (1964), Denny (1965), Hawley and Wilson (1965), Melton (1965), Hooke (1968), Beaumont (1972), French (1987), Harvey (1987), Leece (1988, 1991) and Blair and McPherson (1994: 393).

Alluvial fan slope is typically measured using topographic maps or a GIS-based analysis. An overview of methods used is presented in Table 3.2. The slope of alluvial fans plotted on fan slope versus drainage basin area log-log plot is a classic means of assessing fans used by authors such as Bull (1964), Denny (1965), Hawley and Wilson (1965), Melton (1965), Hooke (1968), Beaumont (1972), Harvey (1987) and Leece (1988, 1991). The straight line equation given by equation 3.5 is the inverse relationship between alluvial fan slope and drainage basin expressed by Bull (1967), (Figure 3.7).

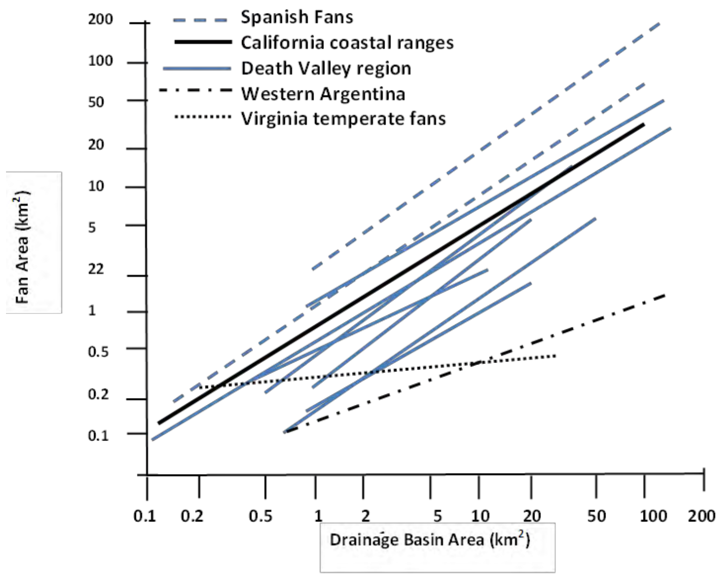

Figure 3.6: **Alluvial fan area versus drainage basin area relationships for researched fans (redrawn from Milana & Ruzycki, 1999: 559).**

Table 3.2: **Methods used to calculate fan slope**

Author	Data source	Method
Calvache et al. (1997: 77)	1:10 000 topographic map series with 10 m contour intervals	Manual calculation
Taylor (1998:208)	1:9,600 basemaps and 30 m Digital elevation Models (DEM)	GIS
Given (2000:57)	1:24 000 raster graphics and 30 m DEM	GIS
Saito and Ogushi (2005:149)	1:25 000 and 1:50 000 topographic maps with contours 5-10 m	Manual calculation
Giles (2010:321)	1:24 000 and 1:50 000 topographic maps with 40 – 100 ft contour intervals	Manual calculation

Eq. 3.5 $G=aA^b$

G: Slope of the channel in the fanhead trench

A: Drainage basin area

a: values range between c. 0.03 – c. 0.17

b: values range between c. -0.15 – c. -0.35

Research conducted by Hooke (1969) and Bull (1962) indicated that fans in the Death Valley are steeper than those found along the California Coast region. Fans studied in Murcia, Spain, by Silva et al. (1992) are shown to lie between the gradients of the Death Valley and California coast fans. Fans with a lower average slopes are observed to have larger drainage basins than those with smaller drainage basins. Small discharges from the source area will deposit sediment at the proximal region of the slope and will contribute to the slope of the fan. Large discharges may cause fanhead trenching and deposition at the fan toe which contributes to a decreased fan slope (Cooke & Warren, 1973: 180). Variation in alluvial fan gradients are said to be a function of depositional mechanisms occurring on the fans (Harvey, 1997). Differences in alluvial fan gradients are also shown to be a result of climate (Harvey, 1997; Milana & Ruzycki, 1999). A higher runoff relates to greater transport efficiency for sediment on the alluvial fan and therefore creates a flatter gradient (Milana & Ruzycki, 1999: 559).

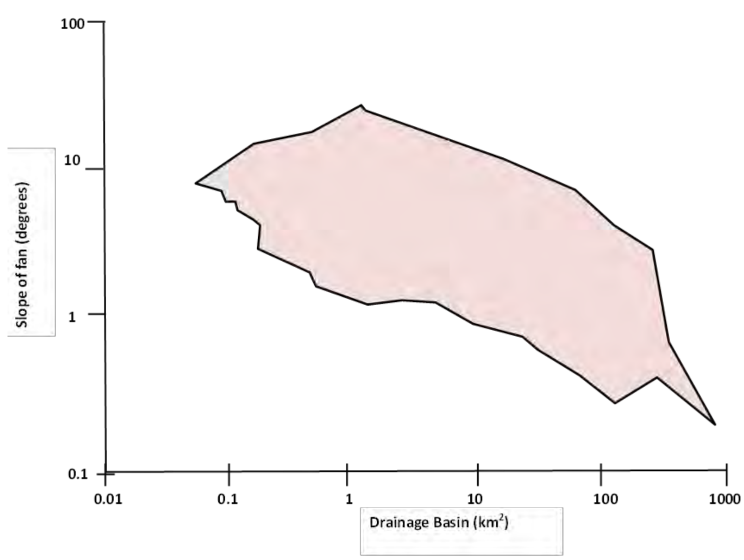

Figure 3.7: Simplified graph of alluvial fan slope versus drainage basin area (redrawn from Blair and McPherson, 1994: 393). The polygon represents the boundary line of the points plotted for Bull (1964), Denny (1965), Hawley and Wilson (1965), Melton (1965), Hooke

(1968), Beaumont (1972), Harvey (1987) and Leece (1988, 1991). For a detailed graph please see Blair and McPherson, 1994: 393.

3.3.6.iii. *Fan channels (process related)*

The erosional and depositional behaviour on an alluvial fan can be explained by the relationship between the stream channels and the fan surface (Harvey, 1997: 231). A main channel enters the apex of the fan that allows water and sediment to enter the fan surface. The critical stream power across the fan surface plays a vital role in the deposition of sediment and the formation of the fan surface. Once the stream power of water and sediment has decreased to a critical value for a channel, sediment deposition occurs and a fan is said to be aggrading (Chapter 2). At the point of intersection the channel may become a multi-thread distributary system (Harvey, 1997: 231). Fan channels are also shown to be a key indicator of fan evolution. In a study by Clarke et al. (2010) (outlined in Chapter 2), fan evolution was modelled in an experiment bed. The development and evolution of the fan surface was intrinsically linked to formation and development of channels. The table produced by Clarke (2010) can be used to determine fan stage based on evidence of fan channels on the fan surface (Table 2.2). Fan longitudinal and transverse profiles have been used to assess fan channels, channel switching and channel trenching. The construction of fan profiles requires a detailed study of fan surface characteristics using surveying techniques; the methods are given below. The use of fan profiles to discover channel form-process characteristics can therefore only be conducted on specific fans selected for study.

Channel switching is a response to various internal and external forces and is identified as being a fundamental process of fan development and evolution over time. The process of channel switching is shown in Figure 3.8 and describes the process by which the main channel of the fan changes its route across the fan surface. External forces influencing channel switching are tectonic and climatic changes while internal processes include human activities (Hermas et al., 2010: 89). Switching may occur as a result of a single flood or a result of successive floods and the filling and overflow of channels when boulders and mudflow block the channels (Cooke & Warren, 1973: 177). Over long periods channel switching allows for sediment to be distributed widely over the fan surface (Cooke & Warren, 1973: 177).

Trenching resulting from extrinsic factors and age-related causes tend to produce a deep and permanent trench at the fan apex or proximal regions of the fan surface. The channel slope in this case is less than that of the fan surface (Harvey, 1997: 239). Intrinsic causes are often short-term and create intermittent and shallow trenches (Harvey, 1997: 239). In some cases it is noted that environmental change may induce incision on the mid-fan surface at the intersection point (Harvey, 1997: 239).

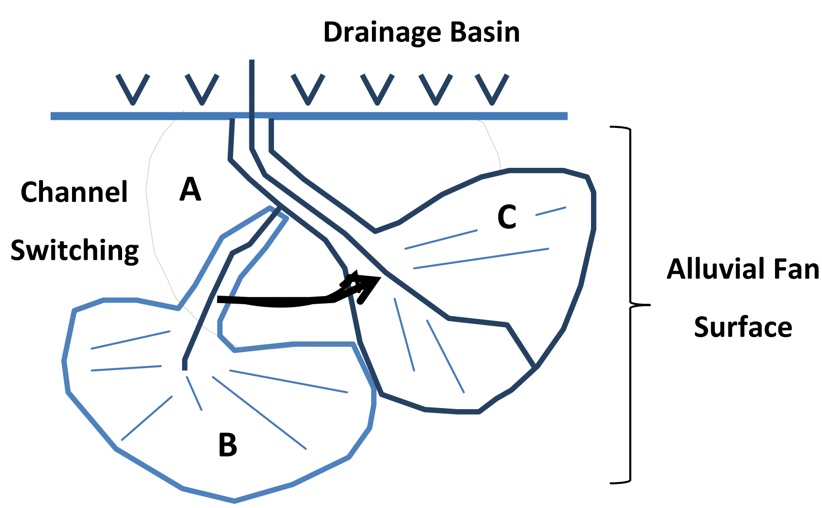

Figure 3.8: Process of channel switching (adapted from Harvey 1997: 232)

Fan profiles

Authors such as Bull (1962, 1964), Blair and McPherson (1994) and Calvache et al*.* (1997) use alluvial fan transverse transects to assess the fan surface and to identify stream channels, channel switching and fan trenching. Although more informative than average slope, this method, as for longitudinal profiles, requires appropriate surveying methods to survey the main channel and the fan surface. Fans studied Blair and McPherson (1994: 358) and Calvache (1997: 77) were surveyed on their upper and lower surface.

Transverse fan profiles show a concave upwards profile that is more pronounced in proximal regions of the fan surface, becoming more irregular in the distal zones (Figure 3.9), (Calvache et al*.* 1997: 77). It is observed in Figure 3.9 that more asymmetrical shaped fans in the SE sector of their study (fans 14, 16 and 22) contrast with more symmetrical fans in the NW sector (fans 7 and 15) (Figure 3.9) (Calvache et al*.* 1997: 77). Irregularities in fan profiles are indicative of irregularities in fan form-process relationships as found for the Lower Deadman Canyon fan Figure 3.9. It is noted that the cavity in the transverse profile accounts for the imbalanced distribution of fan deposits due to erosion from a migrating river (Blair and McPherson, 1994: 358). The shapes of transverse profiles indicate lobes of deposition and when surveyed on a more detailed scale can indicate the presence of the main alluvial fan channel and old channels. The channel switching that occurs on the fan surface can be accounted for by the change in position of the main channel over time that can be observed using fan transverse profiles.

Longitudinal and transverse profiles of the alluvial surface and fan channels are plotted on a scatter plot. This was done using survey data collected along the main alluvial channel and the longitudinal surface of the alluvial fan. The vertical y-axis is plotted as height (relief) in metres and the horizontal distance as distance from fan apex in kilometres as was done for studies by Blair and McPherson (1994: 359) and Calvache et al. (1997: 77). The theoretical diagram used to describe base-level modes is shown in Figure 3.2 and can be used to classify fan base-levels and local fan depositional processes.

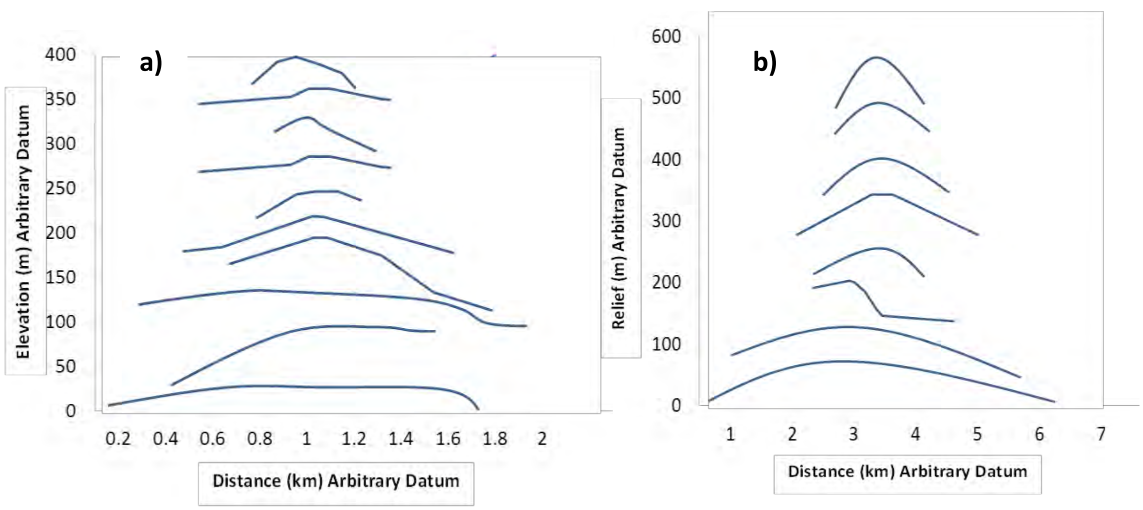

Figure 3.9: Transverse profiles of fans (a) Death Valley Canyon and Nevada (Blair and McPherson (1994: 358) (b) Fans of the south east (SE) and north-west (NW) Sierra-Nevada (Calvache et al. 1997: 77).

The profile of an aggrading fan is shown to have an exponential curve with no sharp breaks at the junction point between mountain and plain (Calvache et al., 1997: 180). Fans that have high rates of sedimentation produce steep slopes (Bull, 1969). Small discharges allow deposition to occur higher up the slope whereas large discharges result in trenching at the fan head and deposition toward the fan toe (Calvache et al., 1997: 179). Most fans toe-out at stable base-levels (therefore base-level is not a common cause of change in fans). For fans subject to toe-trimming by an axial river system, base-level may be a mechanism for triggering incision into distal fan surfaces (Harvey, 2004). The profile of an unsegmented fan is shown by a smooth exponential curve and there is no break between mountain slope and valley plain. A profile of segmented fans show segments as having a rectilinear profile and segments that slope less steeply away from the mountains (Cooke & Warren, 1973: 185). Newly laid sediments are found adjacent to the mountain slope.

3.4. Summary Diagram

A summary diagram of all the internal and external fan control variables describes the links between variables and their influence on fan morphometry (Figure 3.10). The diagram provides an overview of the connected nature of a fluvial system and describes controls, processes and responses of fans in a fluvial context (Figure 3.10). The links given between components of the summary diagram indicate that although alluvial fan connectivity is not directly evaluated in the framework, it contributes to the study of fluvial systems connectivity by assessing control variables that impact fans in space. Links between the applied framework and fan channels will be discussed in Chapter 5 and 7 and used to illustrate how the framework can be used as a tool to assess fan system connectivity.

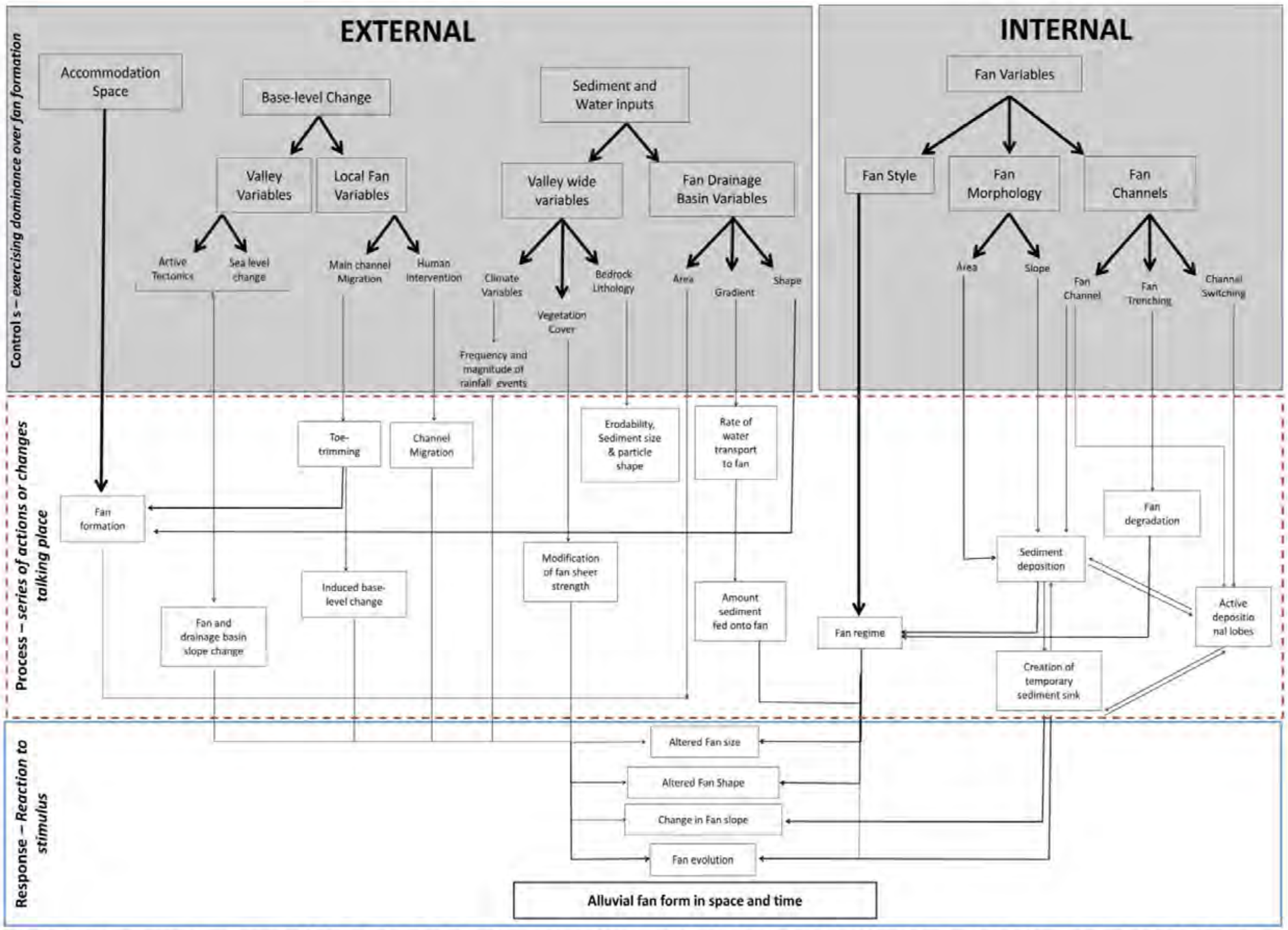

Figure 3.10: Summary diagram of fan internal and external control variables. Dark think arrows represent control variables that direc processes and thinner black lines depict control variables that contribute partly to fan processes.

Chapter 4: Study Area

4.1. Introduction

This chapter provides an overview of the biophysical environment and anthropogenic influences that influence the formation of alluvial fans in the Baviaanskloof Valley. Key objectives of this chapter are to provide a clear geographic overview of the Baviaanskloof Valley explaining the location of the valley, valley topography, geomorphology, geology and river morphology. Anthropogenic influences explained are the water budget of the Baviaanskloof Valley and the current land use including the conservation boundaries. Both the biophysical and anthropogenic themes discussed have links to the formation of and existence of fans in the valley and these will be explained and detailed within each of the sections below. The core applied framework chapter (Chapter 6) of this thesis will build on the biophysical information outlined in this study area chapter. This study area information will therefore provide a solid grounding within each of the key themes identified, allowing for a detailed analysis and critical review to follow in the framework chapter.

Key literature and knowledge used for the study of the geomorphological and geological description of the study area is drawn from Rust & Illenberger (1989), Ilgner et al. (2003), Booth et al. (2004), Tankard et al. (2009) Ellery and Rowntree (2011) and communication with a local geomorphology expert of the area, Dr. Werner Illenberger of *Illenberger and Associates*, New Zealand. A section on climate and rainfall based primarily on a paper written by Jansen (2008) in the valley will patch together existing knowledge of temperature, seasonal and inter-annual rainfall, using a number of local rainfall stations.

Anthropogenic influences discussed on water resources, floods and fan restoration in the valley will discussed in detail using information extracted from de Paoli (2008) and Jansen (2008). These papers are written by international Masters students sourced from LivingLands and PRESENCE learning network.

4.2. Project study area

The Baviaanskloof Valley is located within the western region of the Eastern Cape in the parallel east-west running Baviaanskloof and Kouga Mountain ranges of the Cape Fold Mountains. The 75km long valley is located between the co-ordinates 23^{o}35’E, 24^{o}25’E to 33^{o}30’S to 33^{o}45’S. The Baviaans River runs along the Baviaanskloof Valley bordered by the Baviaanskloof mountain range to the north and the Kouga Mountains to the south (Figure 4.1). Water in the Baviaans River and Kouga River converges and joins at the Kouga Dam.

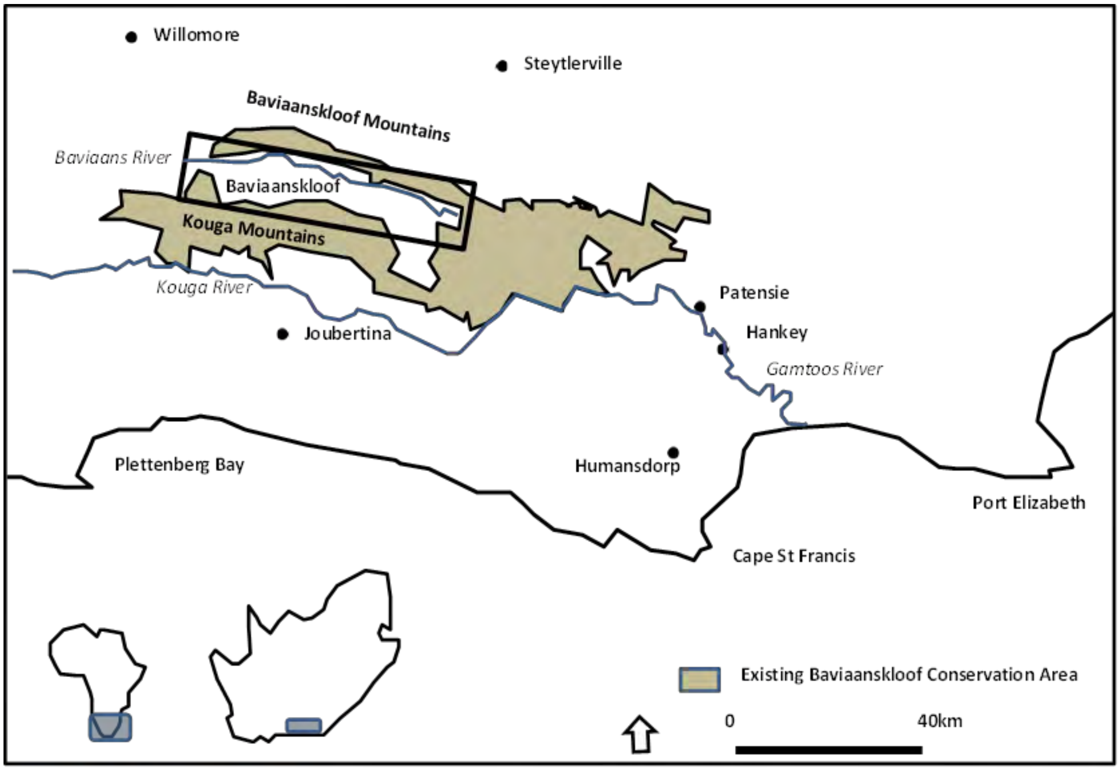

Figure 4.1: Location of the Baviaanskloof Valley within the western region of the Eastern Cape and delineation of conserved land under the Baviaanskloof Mega Reserve, map has been modified to indicate the study area. Note that the study area is outlined by a box (redrawn from Boshoff et al., 2000).

This thesis is focused on the alluvial fans in the western part of the Baviaanskloof Valley. This section runs from Nuwekloof ($33^0$31’25.68” S, $23^0$39’8.61” E) to the Eastern Cape Parks Board Boundary (ECPB) ($33^0$36’39.46” S, $24^0$13’50.61” E). The Baviaanskloof Mega Reserve, shown by the irregular polygon in (Figure 4.1) is being managed by the Eastern Cape Parks Board (ECPB). Commercial farms occupy the western Baviaanskloof Valley floor and lower slopes. Privately owned land, not included in the Baviaanskloof Mega Reserve is owned and managed by sixteen Afrikaans landowners and community shareholders of land (De Paoli, 2008).

4.3. Overview of the biophysical environment of Baviaanskloof Valley

4.3.1. *Overview*

The Baviaanskloof Valley is characterized by steep mountain sides and a flat valley floor that has both broad and narrow sections (Figure 4.2). The river channel is braided in wide sections of the valley and the channels re-join to form a single channel in narrow areas (Ellery and Rowntree, 2011: 43). Alluvial fans are observed to develop in the wider sections of the valley and form on both the north and south facing sides of the valley. Rock formations comprising the Baviaanskloof mountain range to the north differ from those that comprise the Kouga mountain range to the south and were formed during different geological time periods (Ellery and Rowntree, 2011: 30). Shales from the Bokkeveld group are found along sections of the Kouga mountain side are more easily eroded than the quartzites of the Witteberg group that comprise the Baviaanskloof Mountains; this results in the north facing Kouga Mountains having a gentler slope than the north facing Baviaanskloof Mountains (Ellery and Rowntree, 2011: 43).

Figure 4.2: Overview of the Baviaanskloof Valley and Baviaanskloof Mountain side from the north facing, Kouga mountain side of the valley. This figure shows a wide section of the valley. The floodplain is partly characterized by a cultivated land and small riparian trees (May 2011).

4.3.2. *Evolution of the Baviaanskloof Landscape*

The Baviaanskloof landscape has a remarkable biophysical environment that has evolved as a result of a number of geological and geomorphological processes operating over the last 500 Million years (Ellery and Rowntree, 2011:30). The Baviaanskloof Valley is characterized by a steep and rugged terrain that is the product of deep folding and faulting formed as a result of repeated subsidence and upliftment events. This has created a flat river floodplain (>300 – 460 masl), elevated plateaus (300 – 700 masl) and mountains peaks (1626 - 1758 masl) (Ilgner et al. 2003: 6-8).

The geological evolution of the Baviaanskloof Valley has been described from McCarthy and Rubidge (2005). The early Baviaanskloof valley originated within the interior of the Gondwana landmass at its breakup 140 million years ago. Before the breakup of Gondwanaland, the stretching and thinning of the crust created a rift depression basin which was flooded to form a marine basin, the Cape Agulhas Sea. The deposition of sediments within this basin would later form the variety of sediments found in the Baviaanskloof landscape. The first of the sediments deposited in the basin was coarse sandy materials which later formed the Table Mountain sediments. This was followed by the deposition of finer sediments as the marine depression widened and deepened. These finer sediments later became the Bokkeveld group comprised of mudstones and shales. As the depression became shallower over time, coarser sediments were deposited. Coarser sediments later became the Witteberg Group comprised of sandstones and quartzites. After the stretching and thinning of the crust subsided the sediments accumulated in the basin were hardened to form sedimentary rocks. The sediments on the floor of the marine depression began to thicken and buckle due to lateral compression from the south due to the oceanic crust being forced under the Falkland Plateau, this compression created the early Cape Fold Belt.

McCarthy and Rubidge (2005) describe how at the time of the breakup of Gondwana about 140 Million years ago, the movements of the continents resulted in the tearing and faulting along the South Cape Coast that generated a number of earthquakes which resulted in a depression in the south and large east-west running fault lines. One of these fault lines was the precursor to the formation Baviaanskloof Valley. Fault lines are clearly visible, one terminating south of the Baviaans - Kouga fracture at Joachims Kraal and at Beaco's Nek (Ilgner et al. 2003: 4) (Table 4.1). A number of secondary fault lines created weak points which eroded away the rocks of the Baviaanskloof to create kloofs. An overview of fault lines in given in Figure 4.3 and shows the distribution of fault lines and the position of the Baviaanskloof

Valley. Water flowing from the north drained into depressions on the south depositing rounded materials, coarse gravels and sands. Coarse sediments formed the Enon Formation (a conglomerate) and finer sediments (McCarthy and Rubidge, 2005: 192). The development of secondary fault lines and slot canyons (kloofs) in the valley give rise to a modern landscape conducive to fan formation.

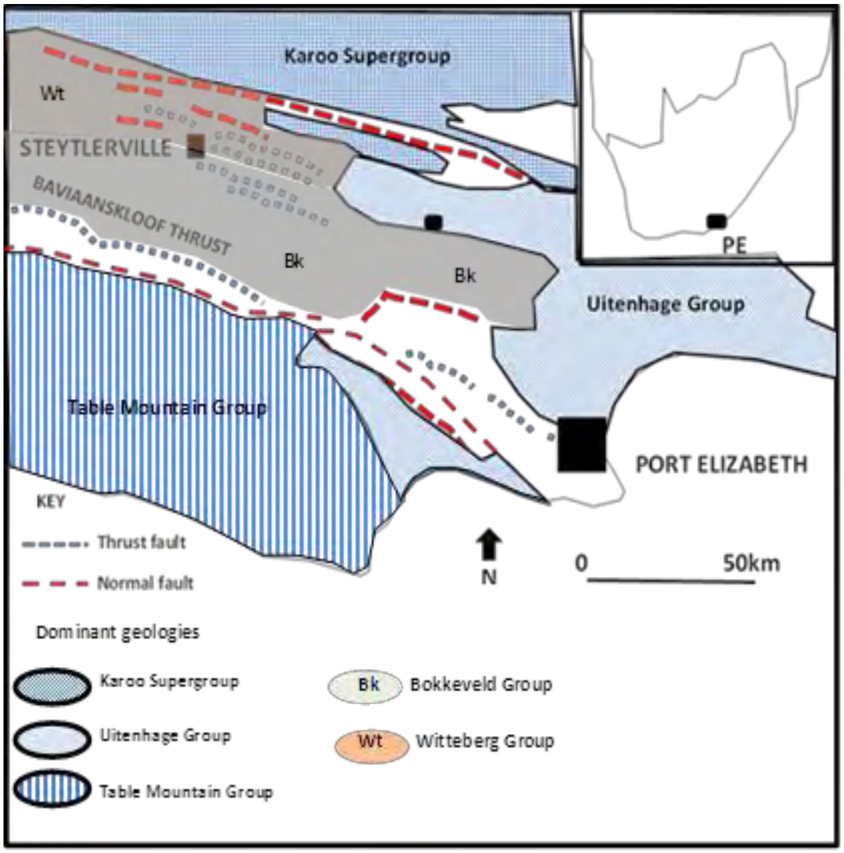

Figure 4.3: Map of the Baviaanskloof Valley and its surrounds indicating faults and stratigraphic units (Booth et al. 2004: 212)

4.3.3. *Uplift Events*

Three major uplift events created three erosion surfaces found in the Baviaanskloof Valley, they are still visible today. The first recorded uplift event was during the time of breakup of Gondwana; a long stable period thereafter created the African Erosion Surface. The second uplift event, occurring 20 million years ago, vertically displaced the land surface 200 m upwards to create the Post Africa I erosion surface at 700 – 760 masl. Displacement rejuvenated the river systems in the area (Rust & Illenberger, 1989: 42). Peaks of the Kouga and Baviaanskloof mountain ranges reached new heights located between 1200 – 1500 masl which forms part of the early sub-cycle of the African Land Surface (ALS) (Rust & Illenberger, 1989: 42). The third major upliftment event occurred 5 million years ago and once again vertically displaced the land surface 200 m upwards to create the Post Africa II erosion surface (Figure 4.4). Crustal uplift events, fault-controlled subsidence and periods of regional subsidence allowed for the formation and evolution of drainage basins in the Baviaanskloof Valley and the deeply folded and faulted Baviaanskloof landscape (Figure 4.5), (Tankard et al., 2009: 1379).

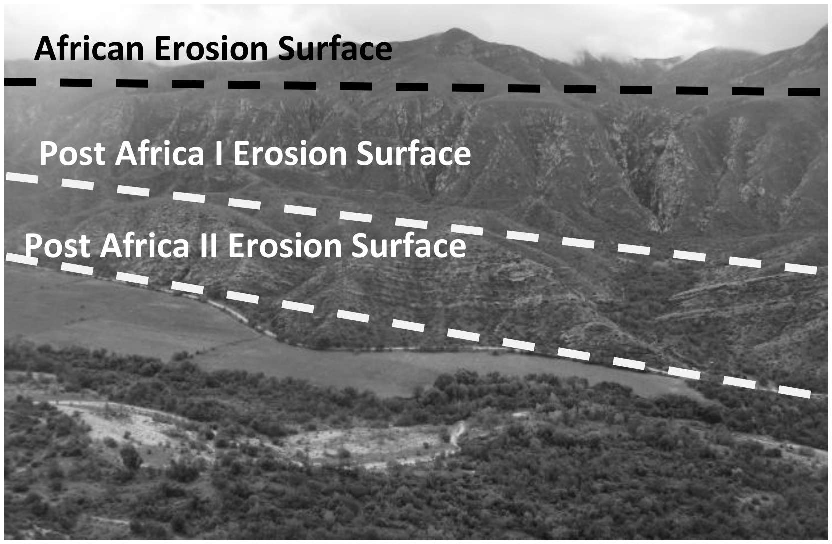

Figure 4.4: Overview of the three African Erosion Land Surfaces on the south facing side of the valley

Figure 4.5: Deeply folded and faulted Baviaanskloof landscape. Picture taken at the eastern end of the valley near the ECPB at Zandvlakte.

4.3.4. *River piracy*

According to Rust & Illenberger (1989: 42-43) river piracy caused the Groot and the Kouga rivers to join the Baviaans River (Table 4.1). River piracy was a result of the lithology and geologic fabric of the landscape and took place in weak zones of the southern Cape Mountains controlled by the major cross-jointing in the Table Mountain quartzite (Rust & Illenberger, 1989: 42-43). Deflections of pirated streams typically form at 90^0 junctions in a rectangular trellis pattern and formed three separate and parallel drainage systems (Rust & Illenberger, 1989: 42-43). The Groot and Kouga represent regional scale river capture and are unlikely to have a direct effect on fan formation. More local piracy occurs in drainage basins of fans along the valley confined to the jointed Table Mountain quartzite, especially in a north-south orientation. Tributaries in catchment areas that transport water to the main channel exploit weak joints along their path and contribute to stream piracy. The main channel tends to remain within the structural valley, but tributaries catchment areas are unconstrained and may leave the valley (Rust & Illenberger, 1989: 42-43).

4.3.5. *Sea-level change*

Three sea-level changes were recorded in a timeline by Ilgner et al. (2003: 5). Sea-level changes date back to 50 000, 20 000 and 18 000 years before present in which the sea level dropped, dropped further and rose respectively (Table 4.1); Ilgner et al. 2003: 5). Although sea level changes occurred in the history of the Baviaanskloof Valley and have contributed to the form of the land surface found in the Baviaanskloof Valley, at present there are no further reports of a sea level change post 18 000 up to the present date.

4.3.6. *Geological formations of the Baviaanskloof Valley*

The lithology of the Baviaanskloof Valley was explored by extracting information from local geomorphological and geological literature based on studies written by de Villiers (1941), Rust & Illenberger (1989) and Booth et al. (2004). Personal contact was also made with a local geomorphology expert of the area, Dr. Werner Illenberger of Illenberger and Associates for information on the geology of the Baviaanskloof. This section supplements the section on the evolution of the valley as it provides a detailed account of the geological formations of the valley linked with the geological and geomorphological processes listed above.

Folded geological formations in the landscape run along a major fault that runs east-west across the valley (Jansen, 2008: 27). Mountains located on the north and south facing slopes of the Rock formations found on the Baviaanskloof Valley floor consist mainly of fault-fractured quartzite of the Table Mountain Group, Bokkeveld shale and Enon conglomerates (Rust & Illenberger, 1989: 42). The

Bokkeveld and Table Mountain Groups form part of the Cape Supergroup and date back to the Ordovician/Carboniferous periods (Booth et al., 2004: 212). The Table Mountain Quartzite is resistant to

Table 4.1: Timeline of major geological and geomorphological events (Ilgner et al. 2003:5, McCarthy and Rubidge, 2005: 187-196)

Date before present	Event	Result
200 million yrs	Stretching and thinning of the earth's crust	Shallow marine basin formed
190 million yrs	Tensional faults in Cape fold belt mountains.	Baviaanskloof mountains move 2 - 3 kms relative to Kouga – fault. Enon gravels deposited
160 million yrs	Marine basin deepened and widened	Sediments deposited which later formed geological formations
140 million yrs	Breakup on Gondwanaland	Created the continents we know today
120 million yrs	Movement of the continents	Series of earthquakes along the south Cape Coast
	River piracy takes place	Groot River joins Baviaans. Kouga joins Baviaans
65 million yrs.	Creation of the African Land Surface up to 65 million years	Mature land surface
20 million yrs	Tectonic upheavals elevating 200 m.	Post Africa Erosion Surface I created
	Rivers rejuvenated	Rivers are rejuvenated
5 million yrs	Tectonic upheavals elevating 200 m	Post Africa Erosion Surface II created; further rejuvenation of rivers
50 000	Sea levels drop 200 m. Shoreline retreats 70 km from present level.	Occupation of southern Cape caves cease gradually over 30000 yr period
20 000	Sea levels dropped 140 m	Erosion taking place - river scouring
18 000	Sea levels rose	-

erosion, but where quartzite is faulted, planes of weakness exist and quartzite can be more easily eroded (Rust & Illenberger, 1989: 42). The Quartzitic sandstones of the Table Mountain Group that dominate the landscape include the presence of the Peninsula, Goudini and Skurweg Sandstones, Cedarberg Shales and Sardinia Bay and Baviaanskloof formations (Ilgner et al., 2003: 2). The Bokkeveld shales are restricted to the Baviaanskloof-Kouga fault line. Enon conglomerates outcrop in the area between the Kouga River and the Baviaanskloof River from Nuwekloof (Nieuwekloof) to the west of Kruisrivier (Jansen, 2008: 27). These formations are easily erodible; they occupy the low ground areas and upstanding features on the valley floor (Rust & Illenberger, 1989: 42). Rounded and angular pebbles and alluvial sands and gravels in a sandy matrix occur in low lying Table Mountain formations and overlying Bokkeveld shales (Jansen, 2008: 27).

Table 4.2: Geological formations found in the Baviaanskloof area and their location in the landscape (Ilgner et al., 2003: 2, Tankard et al., 2009: 1973).

Lithology	Formation	Group	Date of formation	Location
Quartzite	Witpoort	Witteberg	+/- 280 - 345Ma Phanerozoic, Palaeozoic, Carboniferous - Devonian	African Erosion Surface
Upper and lower sandstone and upper shale band	Cape	Table Mountain	395 - 500Ma Phanerozoic, Palaeozoic, Silurian - Ordovician	African Erosion Surface
Granite intrusions into the pre-Cape	Cape	Table Mountain	395 - 500Ma Phanerozoic, Palaeozoic, Silurian - Ordovician	Intrusions (local)
Shales, sandstones	Bokkeveld, Katberg, Karoo	Beaufort	195-280Ma Phanerozoic, Palaeozoic-Mesozoic, Triassic-Permian	Prevalent, forming shallow caves in cliffs
Conglomerates	Enon	Uitenhage	Younger than 165 Ma Phanerozoic, Mesozoic and between Cretaceous and Jurassic	The Cretaceous beds separate the Table Mountain Group along the east to west fault.
Alluvium	Schelm Hoek	Algoa	Unknown	Valley floor
High-level terrace gravels	-	Algoa	Unknown	High terraces
High-level gravels, calcareous sandstone	Alexandria	Algoa	195-280Ma Phanerozoic, Palaeozoic-Mesozoic, Triassic-Permian	High altitude areas
Grits, Phyllites slates	Sardinia Bay, Igoda	-	-	East end of Baviaanskloof at low altitudes. Mixed with phyllitic shales and pebble conglomerates.
Phyllites and slates	Igoda	-	-	East end of Baviaanskloof at low altitudes. Mixed with phyllitic shales and pebble conglomerates.

4.3.7. *Climate (past and present)*

No detailed studies have been conducted on past climates of the Bavaanskloof Valley area. Literature has been collected on changes in the South African climate since the Pleistocene, when fans are estimated to have formed. Over the last 20 million years South Africa has undergone 20 climatic cycles (approximately 100 000 years each) that mirrored the expansion and contraction of ice sheets at higher latitudes (Eeley et al., 1999: 597). The climate of fan formation and development is therefore likely to be very different from the current Baviaanskloof climate. Scott et al., (1995) describe past climates between the Pleistocene – Holocene transition as being 5^{0}C warmer than our current climate.

Both the temperature and rainfall of the Baviaanskloof Valley is highly variable between the summer and winter months. Rainfall also has a high inter-annual variability. Average summer temperatures recorded in January-February vary between 16^{o}C and 32^{o}C respectively (Figure 4.6). Dry hot winds produced during the summer months along the flat plateaus increase summer temperatures up to 44^{o}C (Ilgner et al., 2011: 6). Average winter temperatures fall between 5^{o}C and 20^{o}C during June – July with the prevalence of snow on the mountain peaks (Jansen, 2008: 23).

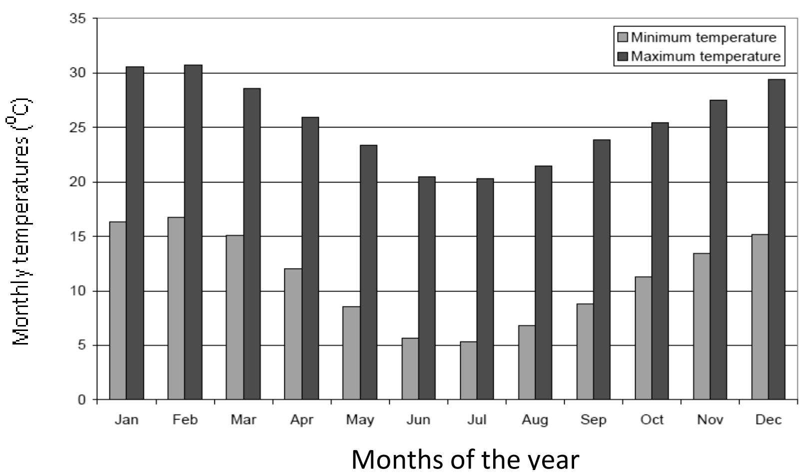

Figure 4.6: Monthly temperatures in the Baviaanskloof Valley from January (Jan) to December (Dec), (Jansen. 1998: 24).

4.3.8. *Rainfall*

Rainfall variability in the Baviaanskloof Valley was analysed using annual rainfall data for three meteorological stations along the valley. Rainfall graphs and records were sourced from Jansen (1998) on the *Water for food and ecosystems in the Baviaanskloof Mega Reserve* and farmers were also consulted on climatic variability in the valley. Data presented in Jansens's paper describe both the spatial and temporal variability of rainfall in the valley, providing sufficient information to describe the direct and indirect effects of rainfall in the valley. Jansen (1998) used rainfall data collected at eight meteorological stations along the Baviaanskloof Valley floor (and in adjacent areas) and comments on the seasonal variability in rainfall throughout the length of the valley (Figure 4.7). The names and locations of the meteorological stations are given in Table 4.3.

Annual Rainfall is low and can be both convective and orographic with frequent thunder storms during summer months (Jansen, 2008: 24). The average rainfall per annum is 300 mm with a large temporal variation in rainfall; annual totals may vary from 100 m to >700 mm (Jansen, 2008: 24). Rainfall at three weather stations positioned along the valley shows spatial variability of rainfall throughout the valley. Station 8 receives between 350 – 400mm per annum, stations 1, 2 and 7 are shown to receive 300 - 350 mm rainfall per annum and 3, 4, 5 and 6 receives less than 300 mm per annum (Figure 4.7).

Although the potential evapotranspiration has not been measured in the Baviaanskloof Valley, a realistic account of evapo-transpiration in valley is extrapolated using data collected at downstream sample sites at Twee Rivieren and Langkloof, near the Kouga dam (Jansen, 2008: 25). Data suggest potential evapotranspiration is 1125 mm per annum and exceeds rainfall for all years (Jansen, 2008: 14). Annual rainfall is characterized by years with large amounts of rainfall (1974, 1980 and 1998) and years with low amounts of rainfall (1971, 1981, 1986, 1992 and 2007) (Figure 4.8) (Jansen, 1998: 24). Rainfall varies from less than 100 -700 mm per year and is episodic in nature (Figure 4.8) (Jansen, 1998: 24).

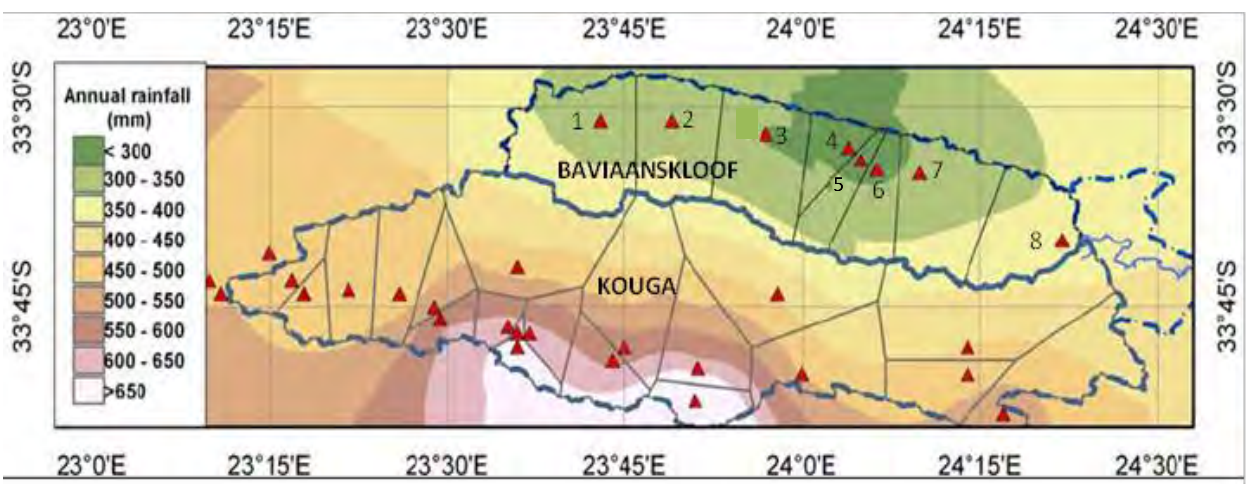

Figure 4.7: Annual rainfall distribution in the Baviaanskloof Valley determined using meteorological stations shown by red triangles. This map has been modified from Jansen (1998: 24). The valleys have been named and the meteorological station numbered. A table of meteorological stations shown in Table 4.3.

Table 4.3: Names of meteorological stations in the Baviaanskloof Valley (Jansen, 1998: 42). Use in collaboration with Figure 4.7.

Meteorological stations	
1	Voorkloof
2	Rust en Vrede
3	Kruis Rivier
4	Nuwekloof
5	Studtis
6	Studtis (police station)
7	Baviaanskloof
8	Zandvlakte

4.3.9. *Alluvial fans in the Baviaanskloof Valley*

Alluvial fans often form in semi-arid environments such as the Baviaanskloof Valley because they fulfil all three of the environmental conditions required for fan formation (topographic setting, relative erodible geology and intense erratic rainfall events). The topographic setting of the valley is characteristic by high elevation mountain ranges with tributaries that feed onto a flat valley lowland area. This provides enough of a decrease in stream power from mountains to valley plain to allow for sediment deposition. The relatively erodible geology that comprises the north and south facing side of the valley allows for sufficient source sediment to be fed onto the fan surface during rainfall events and the erratic intense rainfall resulting in flashy mountain streams producing high sediment yields and overland flow on hill slopes and increased connectivity between the mountain source area and the main river channel provides enough stream power to allow for sediment deposition on the fan surface where a critical stream power threshold has been met (Calvanche et al., 1997; Harvey, 1997). An analysis of the spatial distribution of geological formations in the Baviaanskloof Valley will be explained in the applied framework section.

Fans are most noticeable in the wide sections of the valley where they have developed at the junction between the drainage basin and the floodplain. Due to the increased elevation of fans in relation to the surrounding floodplain they are often used for cultivation and farming activities as they provide a low flood risk alternative for both buildings and agricultural activities. Farmers in the past were given incentives to divert water away from agricultural land on the fans and in doing so

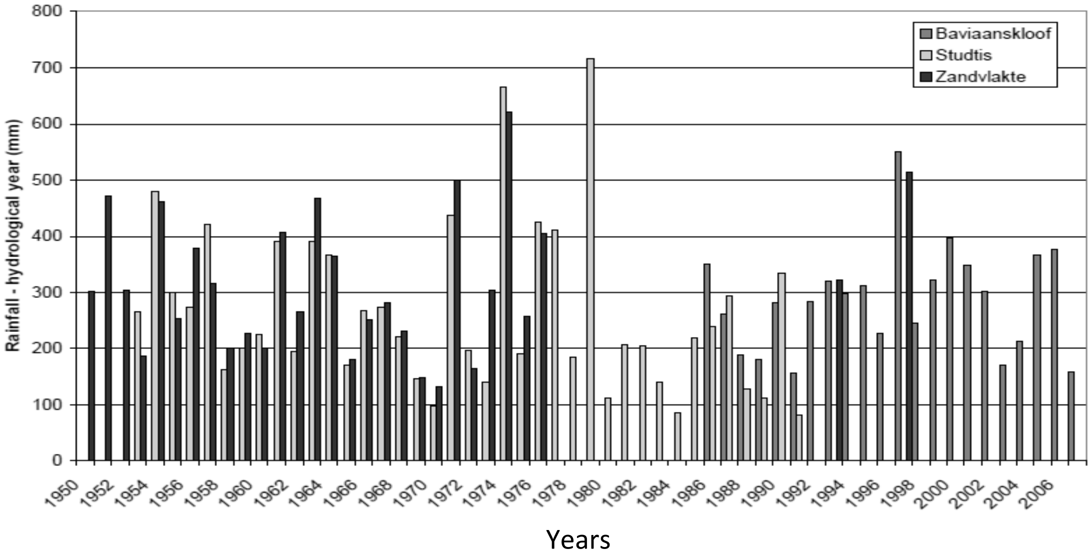

Figure 4.8: Average rainfall per year in the Baviaanskloof Valley (Jansen, 1998: 24).

modified the water flow and functioning of the fans in the valley, inducing undesirable outcomes. Many of the fans in the Baviaanskloof Valley are observed to be affected by the laterally migrating main river as many of the fans the distal region of the fan removed with obvious signs of toe trimming. The origin of fans likely postdates 5 million years ago and when the land surface was vertically displaced 200 m upwards to create the Post Africa II erosion surface.

Figure 4.9: Alluvial fan on the south facing side of the valley (fan indicated by white arrow)

4.3.10. *Vegetation*

The Baviaanskloof Valley supports a mosaic of plant life with a number of endemic species to the area (van Jaarsveld, 2011: 50). Plant life includes thicket, fynbos, succulent Karoo, Karoo shrubs and tree species. Most plants in the valley typically have survival life strategies adapted to the harsh and dry climate. Some of these adaptions include geophytic storage units, leathery leaves, facultative photosynthesis, tap root systems and leaf hairs. The distribution of plants is directly linked to water availability, soil types and conditions in the valley with the creation of niche conditions for vegetation growth. Vegetation is observed to vary between low lying flat areas, mountain, riverine environments and slot canyons (kloofs), (Table 4.4). Vegetation of fans is described below.

Vegetation on fans

Information on the vegetation of the Baviaanskloof Valley is extracted from a book chapter written by van Jaarsveld, (2011). As fans are a transitional environment between mountain and valley plain they host an assortment of vegetation types found at different locations in the valley. Information outlined by van Jaarsveld (2011) for different locations of the valley is used to patch together an overview of vegetation found on fans in the valley. Fans are characterised by vegetation found in the slot canyons (kloofs), low lying areas and riverine environments and provide the substrate for a number of endemic plant species. Key species found on fans from the sub—tropical thicket, Karoo shrubs and succulent Karoo are *Olea europaea subsp. Africana, Pappea capensis, Schotia afra var. afra, Cussonia spicata, Sideroxylon inerme, Grewia robusta, Agathosma mucronulata, A. spinosa and Diosma prama, Erica caffra, pectinifolia, E. sparsa, Euryops euryopoides, E. virgineus, Leucadendron eucalyptifolium, L. salignum, Leucospermum cuneiforme, Aloe ferox, Aloe Speciosa, aloe striata, Cotyledon campanulata, vygies, Crassula ovate, Portulacaria afra* (Table 4.4). A typical fan from the apical to the distal fan surface is characterized by woody tree species at the apex – mid fan (Figure 4.10) followed by a mix of sub—tropical thicket, Karoo shrubs and succulent Karoo on the low lying alluvial fan surface with the occurrence of grasses and Karoo shrubs on the distal fan surface.

4.4. Water in the Baviaanskloof

4.4.1. *Baviaans River*

The Baviaans River appears to go through cycles, shifting between a perennial river (along its length) to an ephemeral river in open sections with increased permeability in narrow sections. The channel bed is mostly dry except when short lived floods recharge the ground water table. Short lived floods are generated from surface runoff from the catchment areas rather than groundwater flow. Flood waters rrecharge the alluvial aquifer groundwater resource in the valley. This is significant as it is during sustained flow that farmers believe it is possible to restore perennial flow for longer periods. The river is

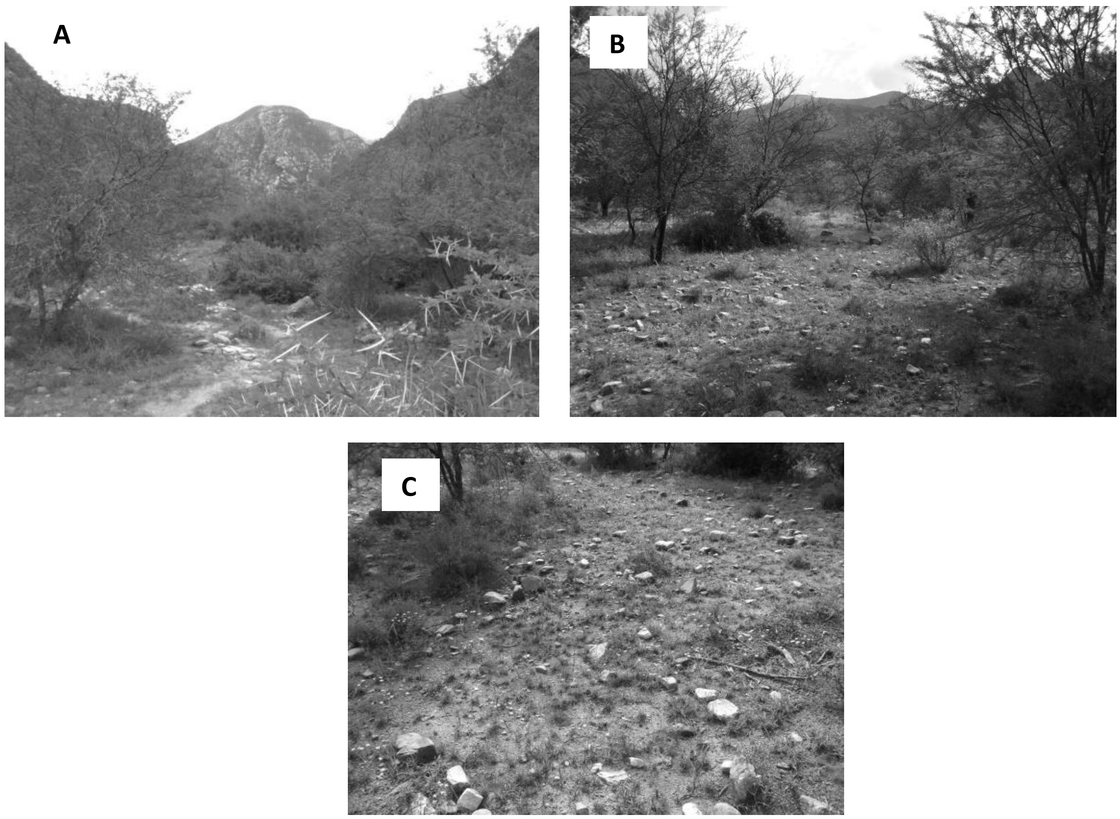

Figure 4.10: Vegetation found on the on the; A) fan apex; B) apex- mid fan surface and C) lower fans surface

4.4.2. *Role of fans in the landscape: contributions to the groundwater table and water budget of the valley*

The Baviaanskloof catchment, Kouga catchment and Groot catchment drain from their catchments and join at the Kouga Dam (Figure 4.14). The Baviaanskloof catchment is a small, but significant contributor to downstream water users. Alluvial fans play a role in the overall water budget of the Baviaanskloof valley system and the water budget devised by Jansen (2008: 14) can be used to position alluvial fans within the broader water budget of the valley (Figure 4.15). As discussed in Chapter 2, alluvial fans are a incised at sections along its length (Figure 4.11 - Figure 4.13). According to farmers channel incision occurred during floods in the 1970s and 1980s

Table 4.4: Plant type, location and species found in the valley (table created from information in van Jaarsveld, 2011: 50 - 57).

Plant type	Location	Soils	Species
Fynbos	Baviaanskloof and Kouga mountains	Mineral poor soil	*Protea nitida, P. lorifolia, P. mundii, P. neriifolia, P. punctata, P. repens, Cussonia paniculata var. paniculata, Dodonaea viscosa var. angusta*
Sub-tropical thicket, Karoo shrubs and succulent Karoo	Footslopes	Sands and gravel	Sub-tropical thicket: *Olea europaea subsp. Africana, Pappea capensis, Schotia afra var. afra, Cussonia spicata, Sideroxylon inerme, Grewia robusta, Gymnosporia polyacantha, Putterlickia pyracantha, Carissa bispinosa, C. haematocarpa, Azima tetracantha, Euphorbia atrispina, Euphorbia grandidens, Dioscorea elephantipes, Pachypodium succulentum, Sansevieria aethiopicum, Salvia namaensis, Sarcostemma viminalis, Capparis sepiaria, Bulbine frutescens, Bulbine latifolia, Rhoicissus digitata* Karoo shrubs: *Agathosma mucronulata, A. spinosa and Diosma prama, Erica caffra, pectinifolia, E. sparsa, Euryops euryopoides, E. virgineus, Leucadendron eucalyptifolium, L. salignum, Leucospermum cuneiforme, Passerina obtusifolia, Phylica axillaris, Polygala myrtifolia, Pteronia incana, Stoebe plumose, Freylinia lanceolata, Cliffortia graminifolia, Buddleja Salviifolia, Myrsine Africana, Pelargonium scabrum, Gazania krebsiana* Succulent Karoo: *Aloe ferox, Aloe Speciosa, aloe striata, Cotyledon campanulata, vygies, Crassula ovate, Portulacaria afra*
Afrotemperate Forests	Slot Canyons	Nutrient rich soils	*Nuxia Floribunda, Gonioma kamassi, Podocarpus falcatus, Celtis Africana, Halleria lucida, Ficus* *Sur, Ilex mitis Todea Barbara, Kiggelaria Africana, Cussonia Spicata, Maytenus undata, Smelophyllum capensis, Maytenus Acuminate, Maytenus oleoides, Pterocelastrus tricuspidatus, Pelargonium zonale, Diospyros scabrida*
	Along river and next to main road	Alluvial soils	Acacia Karoo, Salix mucronata subsp. Capensis, Searsia longispina, Plumbago auriculata, Ficus sur, Cyperus textilis, Gomphostigma virgatum, Typha latifolia, Zantedeschia aethiopicum, Phragmitis australis, Malephora lutea, Drosanthemum hispidum

Figure 4.11: Braided and single channel nature of the Baviaans River in a wide section of the valley

Figure 4.12: Water and vegetation found along a narrow section of the valley in contrast to the dry wider sections.

Figure 4.13: Sections of the river are incised. This photograph of an incised river bank is taken along the section of the river at Joachimskraal.

land feature that allows water to infiltrate and seep into the subsoil layers. As part of the land surface component, water inputs from fans contribute water to ground water of the valley, used for irrigation, domestic water use and downstream water users through the creation of a local aquiclude. Jansen (2008) suggests that of the 300-400 Mm^3/yr of rain that falls in the Baviaanskloof valley, an estimated 300-325 Mm^3/yr is used by nature and rain fed agriculture, 2 Mm^3/yr is used for irrigated agriculture and streamflow contributes 35-40 Mm^3/yr of water to downstream water users (Figure 4.15). Alluvial fans could play a critical role in enabling rainwater infiltration and seepage to contribute water to baseflow and the river used by the environment and water users.

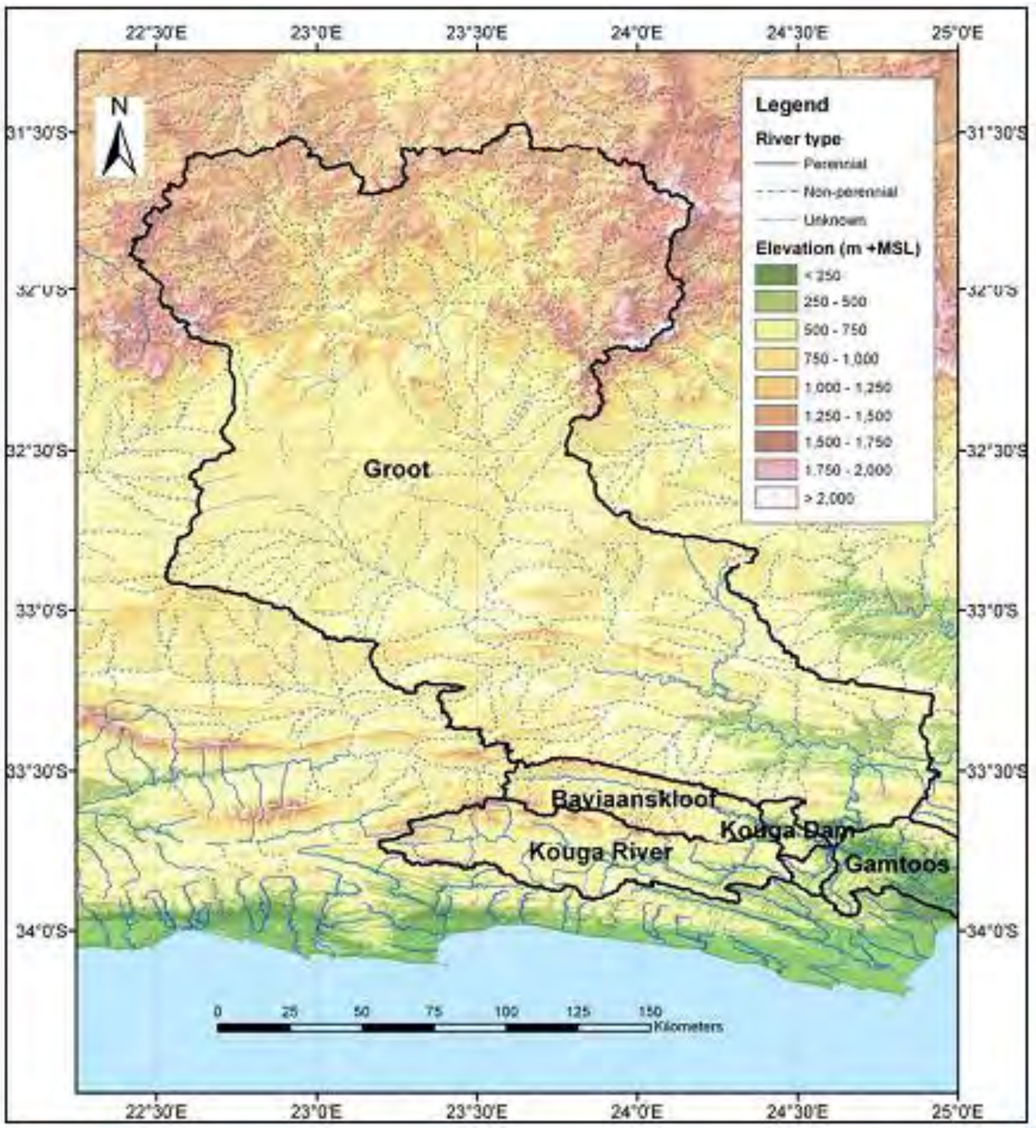

Figure 4.14: The Kouga and Baviaanskloof catchments drain into the Kouga Dam. The Groot joins the Gamtoos below the dam (Jansen, 1998: 30).

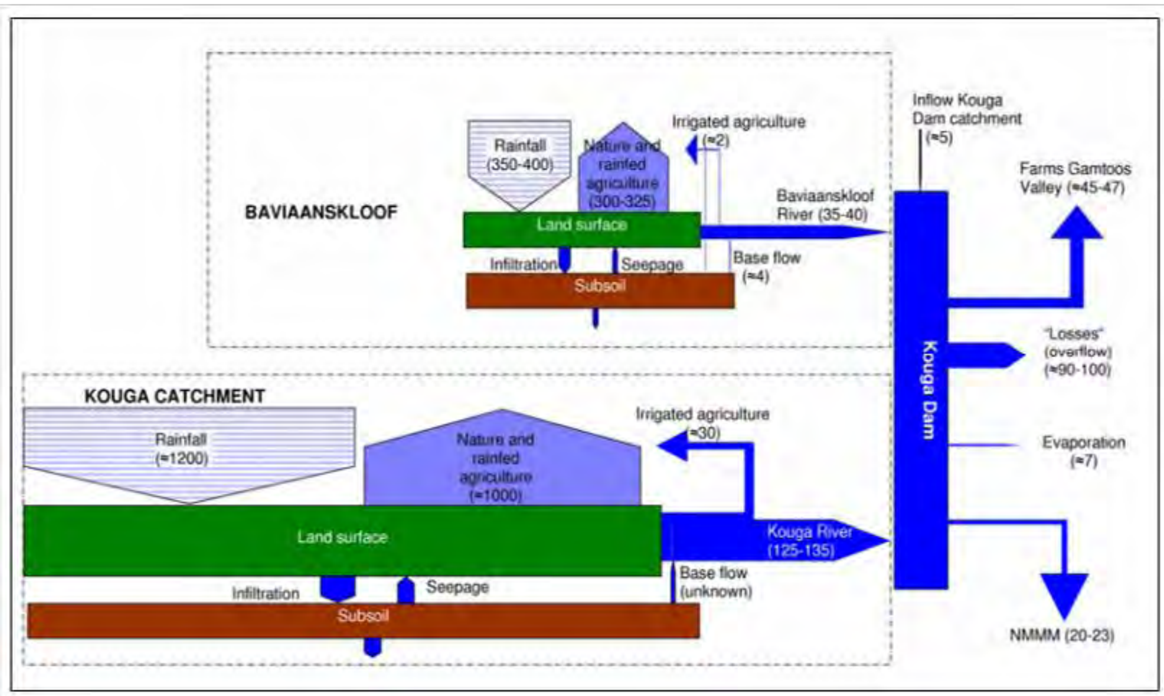

Figure 4.15: Proposed water budget of the Baviaans River (Jansen, 2008:14). Values given in Mm^3/yr.

4.4.3. *Ground water in the Baviaanskloof Valley*

The Baviaanskloof has two groundwater systems, namely the primary conglomerate alluvial aquifer and the secondary Table Mountain Group (TMG) Fractured Aquifer (Jansen, 2008: 28). The primary alluvial aquifer is comprised of reworked Enon conglomerates derived originally from TMG sandstones. This aquifer delivers water to the valley floor which is used for irrigation and domestic use (Jansen, 2008: 28). Ground water from the alluvial aquifer is the primary source of water for irrigation in the Baviaanskloof Valley and is pumped from pits, boreholes and wells that have been drilled or dug into the valley floor to intercept the ground water table (Figure 4.16). Groundwater found in the Table Mountain Group (TMG) Fractured Aquifer is confined to joints and fractures and is an isolated system providing only a limited amount of water for extraction (Jansen, 2008: 28). The TMG aquifer is recharged by rainfall events (Jansen, 2008: 28). Ground water in the secondary TMG fractured aquifer is found in the Mountainous slot canyon (kloof) regions in springs feeding the baseflow of tributaries. Some of this water is channelled through furrows and pipelines from the source to irrigation dams and used by farmers for household supply and recharges the alluvial aquifer (De Paoli, 2008). Farmers use water mostly from the alluvial aquifer to irrigate land using irrigation systems such as flood irrigation, sprinklers and pivots (De Paoli, 2008).

Figure 4.16: A man-made well used to pump ground water at Zandvlakte

4.4.4. *Flood events*

Accounts of flood events by farmers in the Baviaanskloof Valley suggest that an extreme flood event occurs approximately one in every ten years with smaller flood event occurring every year. Although the amount of water constituting a flood event is not defined, farmers' accounts can be assumed to record times of large rainfall events that induce a considerable change in the amount of water within the fluvial system. Farmers suggest large isolated rainfall events in years 1916, 1972, 1981, 1984, 1988, 1996 and 2004 have caused the river to breach its banks. Extreme flood events and smaller yearly floods are shown to generate enough sediment in the catchment area to deposit sediment onto fans (Figure 4.17). Due to the isolated rainfall events in the valley that are both spatially and temporally variable, storms can be highly localized so that only one basin-fan complex responds at a time.

Figure 4.17: Water flowing from a tributary on the north facing side of the valley over the road after a rainfall event in May 2010. Rain gauges recorded 15 mm for this event (Glenday, 2011).

4.4.5. *Water security in the Valley*

According to a farmer, Mr Piet Kruger, of the Baviaanskloof Valley, the water table has dropped as a result of the increased number of structures implemented in the Baviaanskloof fluvial system. He recalls a change in water recharge rates since 1981. Since 1984 the Baviaans River stopped flowing and water flow in furrows ran dry. The occurrence of two destructive flood events in the 1970s and 1980s prompted landowners to mitigate flood damage to low lying agricultural land below fans by constructing blocking structures such as berms on the fans and excavating channels to divert water (DETEA, 2010: 3). Flood protection measures have also been implemented on the floodplain. The objective of flood mitigation structures was to divert water from tributary streams crossing fans directly into the main river channel, bypassing both the alluvial fan surface and agricultural activity on the floodplain (DETEA, 2010:3).

De Paoli (2008), who looked at farmers' perceptions of water resources in the valley, reports that the channelling of water in tributary streams takes place mainly on the alluvial fan surface where the natural flow of water from the fan tributary would have otherwise spread over the fan surface and allowed for groundwater recharge to occur. Incision of the river channel and incising channels on the alluvial fans have increased the connectivity of the system and resulted in a reduced retention capacity of the valley as water passes through the system at a more rapid rate during rainfall events (de Paoli, 2008). The reduction of water retention capacity and lowered groundwater table has affected the livelihoods of farmers' in the valley whose main source of income is made from their agricultural produce (de Paoli, 2008). Farmers now look for other forms of income such as livestock and tourism to supplement their income.

4.5. Land use

Land use activities in the Baviaanskloof Valley have changed over time. Mr Piet Kruger, explained how the land use in the Baviaanskloof Valley has changed over time as a result of increased labour costs and water security issues in the valley. In 1926, the land use of the valley was mainly vegetable seed production and the Baviaanskloof produced 60% of South Africa's pumpkin seeds. In the 1970s, farming of ostriches and angora goats began and by the 1980s farmers began to farm other smaller stock on the land. At present, Mr Kruger believes the main form of land use in the valley is of small livestock.

4.6. Baviaanskloof Integrated Catchment Restoration (BICR) Implementation Project

4.6.1. *Overview*

The Baviaanskloof Integrated Catchment Restoration (BICR) Project strategy targets the needs of the farmers in the area by involving all stakeholders, namely researchers (universities such as NMMU, Rhodes and Stellenbosch), NGOs, landowners and local communities, to initiate restoration through their interaction and interest in restoring ecosystem goods and services (Figure 4.18). The interaction of stakeholders aims to creates a platform for the sharing of local and indigenous knowledge, technical and scientific knowledge and implementation advice to focus the needs of farmers in the valley

Proposed restoration measures in the Baviaanskloof are focused on the restoration of natural water flow in the landscape to increase its water retention capacity and to allow for increased ground water recharge. Restoration in the valley is positioned within the broader Baviaanskloof Integrated Catchment Restoration (BICR) Implementation Project (De Paoli, 2008). An informal account of the effect of fans on the groundwater table is given in Box 4.1. Although this has not been scientifically monitored, local accounts of water fluctuations are important indicators of change

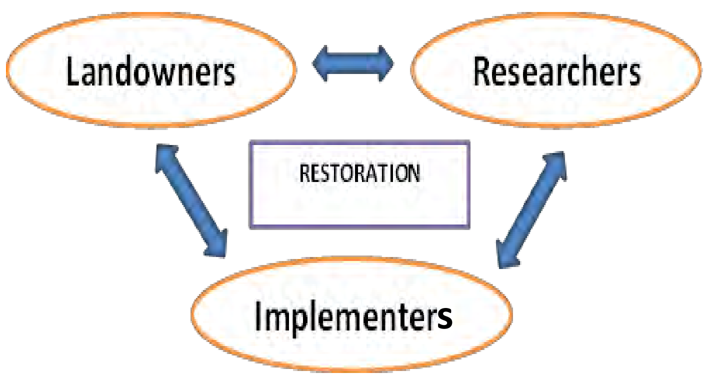

Figure 4.18: Restoration can be achieved through the interaction of stakeholders (landowners, researchers and implementers) in the Baviaanskloof under the Baviaanskloof Integrated Catchment Restoration (BICR) Implementation Project (redrawn from de Paoli, 2008).

Three restoration measures exist within the BICR and are aimed at improving service provision in the area. The first measure is to rehabilitate tributary streams on the alluvial fan surface, followed by the rehabilitation of natural vegetation on the hillslopes and finally to rehabilitate the main channel of the river. An overview of the improved services associated with restoration efforts is shown in Table 4.5.

BOX 4.1: Local account of fan restoration in the valley

In 1991, one of the first efforts to restore an alluvial fan took place when a spring downstream of a channelized fan dried up. Pressure from a downstream farmer resulted in intervention to restore the channelized alluvial fan. After a recharging flood the spring was flowing again after 3 days. Although not scientifically investigated, this local account from a farmer in the area illustrates that fan have the capabilities to buffer water within the Baviaanskloof Valley fluvial system.

Paraphrased from De Paoli, 2008

4.6.2. *Positioning of project research within the Baviaanskloof Integrated Catchment Restoration (BICR) Implementation Project*

This thesis is positioned within the stakeholder interaction of the Baviaanskloof Integrated Catchment Restoration (BICR) Implementation Project and aims to provide information on the functioning of alluvial fans in the Baviaanskloof Valley to inform fan restoration. This measure focuses on alluvial fans that have been modified in the past by channels and berms. Proposed restoration measures are to close channels on fans built after 1981 that divert water off the fan surface and directly into the main river channel. Channels will be removed to allow for water to flow in the old channels and over the fan surface to improve a host of ecosystem services as described in Table 4.5. One concern of the BICR is the lack of knowledge of the integrated functioning of the landscape. The dynamic and highly complex functioning of the Baviaanskloof Valley ecosystem poses a large obstacle in understanding the dynamic functioning of this system.

At present, LivingLands has engaged in a two-stage fan restoration project that is currently being implemented (2010 – 2011). In the first stage (2010), fans selected for restoration were identified by farmers in the area. In the second stage of restoration (2011), fans were selected using key fan theory elements outlined in this thesis. By the end of 2011 fans selected for stage 1 of restoration have been engineered and fans identified in stage 2 (part of this thesis) are still in the process of being restored. In both stages, experts including academics (geomorphologists and engineers) and students have visited suggested sites to recommend ways of increasing the water retention capacity in the landscape.

Table 4.5: Restoration measures and improved service provision (De Paoli, 2008).

Service to be improved	Restoration of tributaries and floodplain	Restoration of degraded slopes	Restoration of the main channel
Provisioning services			
Freshwater supply	X		X
Crop and food production	X		
Livestock production		X	
Regulating services			
Buffer runoff	X	X	
Soil water infiltration	X	X	X
Groundwater recharge	X	X	X
Maintenance of baseflow	X	X	X
Drought mitigation	X		X
Flood mitigation	X	X	X
Peak flow reduction	X	X	X
Erosion prevention	X	X	X
Sediment control	X	X	
Cultural and amenity services			
Landscape aesthetic	X	X	X

4.6.3. *Stakeholder participation in restoration BICR*

Members of the local Baviaanskloof community demonstrate their interest in the environment and love of the natural beauty of the valley by their actions to manage ecosystem goods and services in the valley. Local stakeholders show a good awareness of environmental issues in the valley and view themselves responsible for improving the ecosystem goods and services the valley provides. Local stakeholders in collaboration with non-governmental organizations and researchers (university partnerships with Nelson Mandela Metropolitan, Rhodes and Stellenbosch universities) participate independently of the Department of Water Affairs (DWA) to manage ecosystem goods and services such as water resources that lie outside conservation boundaries using an environment management approach.

Chapter 5: The Spatial Plan

5.1. Introduction

This chapter is designed to meet objective 1 which is to map the spatial distribution of alluvial fans and fan drainage basins in the Baviaanskloof Valley, South Africa. Methods used to develop the spatial plan and to measure spatial fan morphometry data have been outlined below. The final map of fans and the drainage basin and spatial attribute data will be used in Chapter 6. The creation of an alluvial fan spatial plan also informed the alluvial fan restoration project conducted by LivingLands (outlined in Chapter 4) and was used as a primary reference for alluvial fan restoration in the Baviaanskloof Valley.

5.2. Methods

The creation of a spatial plan in the Baviaanskloof Valley used satellite and low altitude aerial imagery at a variety of scales and resolutions. A summary of source metadata is given in Table 5.1.

Table 5.1: Aerial and satellite imagery metadata

Source	Date	Scale/ resolution	Method of data collection	Sourced from
South African topographic Map Series (3324CB, 3323DB, 3324CA, 3332DA, 3323BC, 3324DB, 3334DC, 3324DA, 3324DD and 3323BD)	2002	1:50 000	Low altitude	Surveys and Mapping, South Africa
Aerial photographs (job nr: 1027)	2006	1:50 000	low altitude	Surveys and Mapping, South Africa
SPOT imagery	2008	90m	satellite	Fundisa
Ortho-rectified images	2009	0.5m	satellite	Surveys and Mapping, South Africa
GoogleEarth	2010/2011	Image specific	satellite	GoogleEarth

5.2.1. *Draft spatial plan*

The spatial plan was created for the western Baviaanskloof Valley from Nuwekloof to the Eastern Cape Parks Border (ECPB) as described in Chapter 4. A draft plan was created in GoogleEarth 5 using polygons to define fans and drainage basins. The alluvial fan surface was delineated using a contextual definition provided by a number of well-known and reputable authors in the field of fan morphometry. Obvious sedimentological indicators such as the presence of rill lines, evidence of sheetwash, main channels, secondary channels and a raised fan surface designate the fan and define the fan margins. The fan surface delineated is the fan surface that exists at present. Drainage basins were defined using drainage networks, watersheds and feeder tributaries transporting and channelling water onto the fan surface. Data used to define the fan surface included GoogleEarth imagery, aerial photographs (1:50 000) viewed under a stereoscope and 1:50 000 topographic maps series of the area. The draft spatial plan of fans and basins identified in the valley was used to ground truth the presence or absence of fans in the valley and to determine fan margins for the final map.

5.2.2. *The final spatial plan*

The final spatial plan was based on the ground truthed pilot plan. Digitized features were organized into two shapefiles. One shapefile was created for both the north and south facing alluvial fan polygons and associated attribute information and the other for the drainage basin polygons and associated attribute information. An overview of created shapefile layers and attribute information is given in Table 5.2. Fans and drainage basins were labelled according to their location in the valley starting on the south-facing side of the valley at Nuwekloof down to the border of the Eastern Cape Parks Border and back along the north-facing side of the valley towards Nuwekloof. Alluvial fans and their drainage basins were labelled with corresponding numbers so that empirical and statistical analyses could be carried out as described in Chapter 3 and 6 and ensured attribute data recorded for both the fans and basins correlated. The methods used to calculate or measure the attribute information is given in Table 5.3 and Table 5.4. It should be noted that environmental variables such as precipitation, soil and vegetation type were not included in the attribute data as accurate data is not yet available for the valley. This data could not be measured within the confines of this thesis given time and resource constraints. SPOT 2008 imagery and aerial photographs were mainly used for spatial morphometry measurements. The digitization of polygon features and measures and/or analyses were recorded with the spatial reference system spheroid WGS1984, Transverse Mercator Lo: 25 unless otherwise stated. Fifty-eight fans and drainage basin were detailed in the survey.

Table 5.2: Overview of shapefiles created and associated attribute information (see Table 5.2 for definitions)

Nr. Shapefiles	Title of Shapefile	List of Attribute Information
1	Alluvial fan polygons	X – coordinate, Y – coordinate, Perimeter (km), Area (km2), Alluvial fan area to drainage basin area (AFA:DBA), Fan Type, Slope (%), Channels, Incision, Toe-trimmed, Cultivated, Buildings, property
2	Drainage basin polygons	X – coordinate, Y – coordinate, Perimeter (km), Area (km2)

Table 5.3: Data recoded in the alluvial fan attribute table and methods used to calculate/measure spatial morphometric data.

Parameter	Methods
Co-ordinates (x ; y)	Centroid co-ordinates of the polygon centroid obtained from ArcMap 10.
Perimeter	The perimeter of each fan polygon was calculated using the field calculator in ArcMap10. These figures were checked using perimeters calculated on a 1:50 000 topographic map of the area. The units of the final calculation were in kilometres.
Area	The perimeter of each fan polygon was calculated using the field calculator in ArcMap10. Areas of larger fans were checked using a 1:50 000 topographic map of the area. The units of the final calculation were in square kilometres.
AFA:DBA	The fan area to drainage basin ratio was calculated by dividing the fan area by the basin area. This ratio describes how large the drainage basin is compared to the alluvial fan area.
Fan Type	The fan type was classified using criteria outlined by Al-Farraj & Harvey (2005:88) in Chapter 2. Codes used for fan type include; a=simple mountain front, b=backfilled, c=intermontane and d=tributary junction.
Slope	A digital elevation model (DEM) of the valley was calculated using 20 m contours of the Baviaanskloof Valley. The slope factor was calculated for the DEM image and the alluvial fan shapefile used to calculate the average rate of change in the fan polygon using zonal statistics tool in ArcMap 10. The units of the final calculation were in percent slope.
Channels	The number of obvious channels identified on fans using ortho-rectified images (0.5 m resolution). The number of channels observed on the fan surface was recorded.
Incision	Signs of fan incision on aerial imagery was recorded and investigated in the field. Codes used for fan incision include: 0=no incision, 1=incision on upper fan surface, 2=incision on the proximal fan surface, 3=incision on the distal fan surface. Recorded from ortho-rectified

	images (0.5m resolution).
Braiding	Evidence of braiding of fan channels noted: 0=no braiding, 1= braiding. Recorded using ortho-rectified images (0.5 m resolution).
Channel migration	Evidence of fan channel migration was recorded using ortho-rectified images (0.5m resolution). Codes used for fan channel migration include: 0=absence of channel switching, 1= evidence of fan channel migration.
Toe-trimmed	Fans that have had the distal regions (lower fan surface) removed by the Baviaans River have been recorded as being toe-trimmed using the definition outlined in the literature review section (Chapter 2 and 3). This may be recent or a historic event. Fans were classified by interpreting the effect of a laterally migrating main channel shown in Figure 3.3 (Chapter 3). Data was collected using SPOT 2008 imagery (90 m resolution) and supported by fieldtrip notes. Codes used for fan incision include: 0=no evidence of toe trimming and 1=evidence of toe trimming.
Cultivated	This term was used to describe fans that are cultivated and show recent evidence of crop cultivation. Cultivation scars were included if they were observed to be recent scars. This data has been collected using SPOT 2008 imagery (90 m resolution) and often supported by fieldtrip notes. Codes used for fan cultivation include: 0=no evidence of cultivation and 1=evidence of cultivation.
Buildings	The presence or absence of buildings e.g. farm houses, outhouses, churches or sheds was noted using SPOT 2008 imagery (90m resolution) supported by fieldtrip notes. Codes used to describe buildings on the fan surface are: 0=no buildings and 1=the occurrence of buildings.
Property	The property on which fans reside was determined using cadastral shapefile data sourced from the PRESENCE network. The shapefile attribute data included farm names, farm boundaries and farm owner contact details. The cadastral shapefile was overlain onto the alluvial fan layer and the property on which fan reside. The property name was then added to the alluvial fan shapefile by adding a new column to manually input data into the spread sheet.

Table 5.4: Data recoded in the drainage basin attribute table

Parameter	Methods
Co-ordinates	Centroid co-ordinates obtained from ArcMap 10 of the polygon created were recorded for each feature.
Perimeter	The perimeter of each drainage basin polygon was calculated using the field calculator in ArcMap10. These figures were checked using areas calculated on a 1:50 000

	topographic map of the area. The units of the final calculation were in kilometres.
Area	The perimeter of each fan polygon was calculated using the field calculator in ArcMap10. These figures were checked using areas calculated on a 1:50 000 topographic map of the area. The units of the final calculation are in square kilometres (km^2).

5.2.3. *Testing the accuracy of alluvial fan slope*

Limitations on data available to calculate the slope of alluvial fans made it difficult to calculate an accurate slope of fans in the valley. Limitations on collecting alluvial fan slope data have been listed below:

1. The resolution of South Africa's topographic map series is 1:50 000. This is scale is too coarse to manually calculate the slope of fans. It was also difficult to determine fan boundaries on the 1: 50 000 map series as the scale was too small to point out local small scale features on the flood plain.
2. Slopes were collected in the field using an abney level and clinometer. Data on the average slope of the alluvial fan was limited by the distance from the slope reading device. A slope reading over a maximum distance on 50m could not be recorded due to vegetation cover and distance being a limiting factor and thus not consistent for all fans in the valley. Abney level and clinometer readings did not correlate.
3. GoogleEarth imagery is patchy and consists of a mosaic of old and new images which only allows for the height and slope values of fans to be collected for fans that have been recorded on a good image. Poor quality images do not have any spatially referenced properties.

Of the spatial data available at the time of slope analysis, GoogleEarth and DEM data were the most accurate as the resolution of imagery was fit to assess fan characteristics. At the time of analysis, data in Table 5.1 was available bar the ortho-rectified imagery which became available in the last few months of this thesis and was used to determine fan channels. A test was conducted to determine the accuracy of GoogleEarth and DEM derived fan slopes. In the accuracy test, transverse transects across the width of the valley was used. This data was collected by Lindie Adao-Smith and was used in this accuracy test as control reference from which to compare the accuracies of both the slope values calculated in GoogleEarth and from the DEM.

Transect data

The easting, southings and heights were used to construct transverse profiles across the width of the valley. Alluvial fan slope data was calculated by delineating the segment of the long profile that fell along the fan surface and the gradient of this segment was calculated and recorded. Eleven segments were identified on overlapped fan transect and fan area boundaries as transects were not always surveyed for the whole fan surface. The slope of the segment of overlap was recorded.

DEM data

The coordinates of the start and end points of the transverse transect were added as 'xy data' in ArcMap 10. The alluvial fan shapefile created in the spatial plan was added to determine overlapped segments between the transect and the fan area as transects did not run directly down the middle of fans. The overlapped segments were re-digitized and labelled appropriately. Eleven segments were re-digitized. A slope model was created from the DEM and added in the table of contents and the re-digitized segments overlain onto the slope model. The neighbourhood algorithm was used to calculate slope for every cell in an elevation grid to produce a rate of change per raster pixel. The top, bottom and mid-points rate of change was recorded and the average slopes for line segments calculated.

GoogleEarth data

The re-digitized line segment shapefiles were converted into a .kml file to open on GoogleEarth. Line segments were opened in GoogleEarth and traced using a path. The elevation profile of each path was examined to determine the average slope of the fan. All slope data collected from transects, slope model and GoogleEarth were entered into a table and compared. Results are given in Table 5.5.

The compared line segment slopes suggest that neither GoogleEarth slope profiles nor DEM slope values are significantly more accurate (Table 5.5). GoogleEarth slope values more closely correlate for three of the transect slope values calculated. Four of the DEM slope values most closely correlated to transect slopes. Two of the GoogleEarth slopes could not be calculated due to the poor quality of the image which did not provide any elevation data for fans in the valley. Two zero values obtained for the DEM slope is due to the fact that the digitized segment was shorter than the length of one pixel which measured rate of change. The calculated value was therefore zero due to the fact that to the rate of change across the length of the line segment is zero.

Table 5.5: Table of calculated slope data (grey shaded blocks indicate calculated slope values that produce similar results between two methods used and dark shaded block indicate calculation errors, errors explained in text)

OBJECT-ID	Description	Google Earth (mean %)	Google Earth *(if two values were given)*	DEM (mean %)	Transect (mean %)
1	Site6.1 Uitslag SF	4.80		2.95	3.57
2	Site6.2 Uitslag SF	1.80		2.11	2.98
3	Site6.3 Uitslag SF	4.20		0.99	3.65
4	Site6.1 Uitslag NF	5.40	1.70	**0.00**	1.72
5	Site6.2 Uitslag NF	3.60		**0.00**	1.49
6	Site5.2 Verloren Rivier SF	**Cannot Calc**		11.74	0.2
7	Site5.2 Verloren Rivier NF	0.20		2.47	0.2
8	Site5.3 Verloren Rivier NF	1.00	3.10	2.63	2.68
9	Site10.1 Rust en Vrede SF	5.90		4.53	3.46
10	Site10.2 Rust en Vrede NF	3.60	1.10	2.78	0.74
11	Site3.3 Verlaaten Rivier BWA NF	**Cannot Calc**		4.16	2.99

The DEM slopes were used as slope values in this research project as it provides the most uniform method of calculating fan slope. Although not significant, the slope values obtained were more accurate than those calculated for the GoogleEarth image. Unlike the fan transects provided by Smith-Adao, all fans in the valley are larger than one pixel and therefore a rate of change could be calculated for all fans in the valley. The GoogleEarth slope could not be calculated for all fans due to the poor quality of mosaicked images and the inability to calculate elevation for all images that comprise the Baviaanskloof Valley. The DEM slope values were the most accurate and uniform method of collecting slope values and was therefore used for this project. It is noted that a detailed survey of the fan itself is the most accurate way of determining fan slope and should be employed if an accurate fan slope is required. The surveying of 58 alluvial fans in the valley was not feasible for this study due to time and the costs involved.

5.2.4. *Work limitations and difficulties*

1. No alluvial fan identification studies had been conducted in the Baviaanskloof Valley prior to project research on fans in the valley. The identification of fans was based primarily on an applied definition of an alluvial fan to determine fan boundaries.

2. Not enough time and resources to visit all 58 alluvial fans and therefore the channel incision and evidence of channel switching was re-done using more recent rectified orthophotos.

3. The accuracy and reliability of the alluvial fan and drainage basin shapefiles relied heavily on the use of aerial images of a good resolution with the aid of topographic maps. The sourcing of good quality aerial images for the digitization of fan and drainage basin boundary was difficult. Google Earth imagery at the start of the project was a patched image of poor quality aerial images for the valley which could not be used. The analysis of SPOT imagery from 2006 also did not provide clear and identifiable features on the drainage basin and fan surfaces. SPOT imagery for 2008 provided the best coverage of valley features and was used for the analysis. The South African topographic map series is produced at a standard scale of 1:50 000 opposed to many other countries which produce topographic maps at a scale of 1:25 000. At this resolution fan elevation and characteristics are too small to be represented on the map. The coverage of the South Africa series of contoured orthophotos (scale (1: 10 000) does not extend to the Baviaanskloof Valley. Due to the poor quality of the images, fan incision could only be determined accurately for fans visited in the valley so only the most obvious signs of channel incision shown on aerial images were used.

4. Project research was started at the beginning of 2010. Since then the Google Earth imagery of the area has been updated in early 2011. The quality of images are better than before, but the mosaic of mixed old and new imagery gives for a patchy coverage of aerial photos in the valley which is still not a reliable resource when one in dealing with the digitizing of valley-wide features. Ortho-rectified aerial images at 0.5 m resolution have recently become available. The images are of high quality and good resolution. Although these images could not be used to inform the digitization of shapefiles, alluvial fan features were double-checked be cross-referencing between SPOT 2008 imagery and ortho-rectified images in the latter stages of the research project.

5. The inability to source a shapefile of 5m contour lines for the Baviaanskloof Valley did not enable the accurate calculation of fan slope in the valley. A DEM was produced using 20m contour lines. This is not the best scale to conduct a fan slope analysis given the size of fans in the Baviaanskloof Valley.

5.2.5. *Spatial distribution of fans*

The Baviaanskloof Valley is a long, narrow valley that has a south-east – north-west orientation. A total of 58 alluvial fans and fan drainage basins are located unevenly along the south-facing Baviaanskloof mountain range (33 fans) and the north-facing Kouga Mountain range (25 fans) (Figure 5.1). The attribute table information measured and calculated for alluvial fans and drainage basins are given in Appendix Tables A.1 – Table A.3. The occurrence and location of fans correlate with valley confinement. Where the valley becomes confined no fans are observed. Fan area data ranges from 0.018km^2 - 1.44km^2 with a mean fan area of 0.185km^2 (Appendix Table A.1). Four distinct groups of fans were identified, all located in areas where there is a larger valley width (Figure 5.2). The numbers of fans within each of the groups vary along the length of the valley from 2 to 28 fans per group (Table 5.6). Key characteristics of fan groups are shown in Table 5.6. Fan size will be commented on in the applied framework section. Table 5.6 provides a general overview of size and location of fans in the valley.

Table 5.6: Identified alluvial fan groups in the Baviaanskloof Valley

Group 1	Drainage basins and fans form over a larger spatial area than in other groups. Drainage basins and fans are larger.
Group 2	Drainage basins and fans form in a smaller spatial area than group 1. Many included fans found on both sides of the valley, but mainly on the north-facing side.
Group 3	Drainage basins and fans located only on the north-facing, Baviaanskloof mountain range.
Group 4	South facing fans are included. Large drainage basins found on the north-facing, Kouga mountain range.

Large drainage basins (basins 35, 36, 40, 45, 52, 54, 57, 58) are observed along the north-facing side along with a number of smaller fans (basins 14-44, 46, 47, 51), (Figure 5.3 – Figure 5.7). The drainage basins on the south-facing side of the valley are more regular in shape and area. Drainage basins on the south facing side of the valley appear to be confined along a mountain margin which regulates their shape and size, as shown by basins in group 4. The angle at which water and sediment is washed from the drainage basin and onto the valley floor has resulted in a number of alluvial fans forming at an angle to the main river channel noted by fans 1, 3, 5, 24, 33, 37, 40 and 58 (Figure 5.3 – Figure 5.7).

The occurrence of buildings is significantly higher on fans that form on the south facing side of the valley (24%), (Table 5.7). Although this was not investigated, the increased number of buildings on the south-facing side of the valley may be attributed to the fact that the main road running through the Baviaanskloof Valley runs primarily along the South facing side of the valley. The percent of fans that are cultivated or toe trimmed does not vary significantly between fans that form on the north or south (Table 5.7). Due to the very narrow form of the Baviaanskloof Valley, it is likely that many of the fans have been trimmed throughout time as the river has switched it course down the length of the valley. Fans on the south facing side of the valley are more greatly influenced by toe-trimming (Table 5.7).

Table 5.7: Total and percent values of buildings, cultivated land and toe-trimmed fans in the valley

Characteristic	Number of fans	Number north facing fans	North facing fans as a percent total fans (n = 58)	South facing fans	South facing fans as a percent total fans (n = 58)
Cultivated	32	17	29	15	26
Buildings	19	5	9	14	24
Toe trimmed	23	9	16	14	24

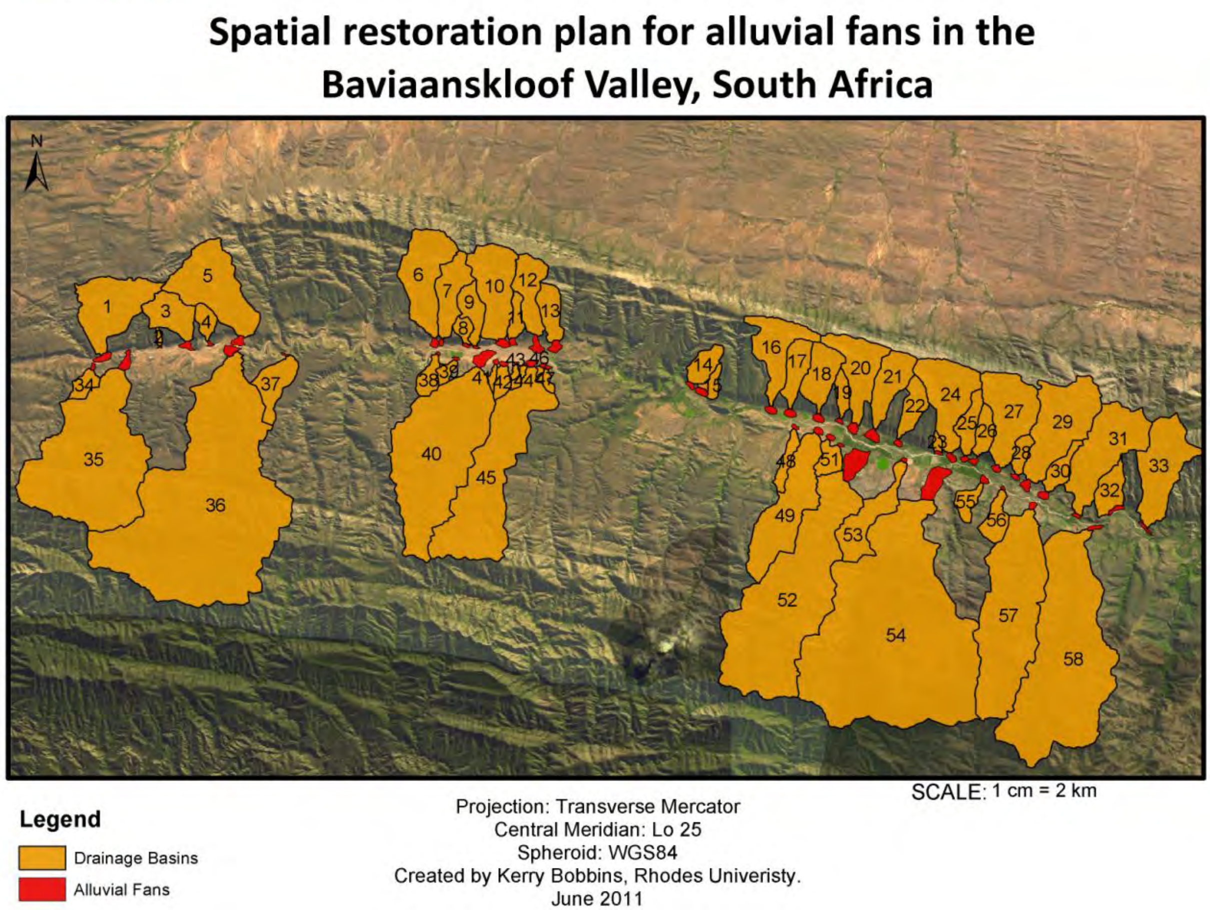

Figure 5.1: Spatial plan of maps and drainage basins in the Baviaanskloof Valley

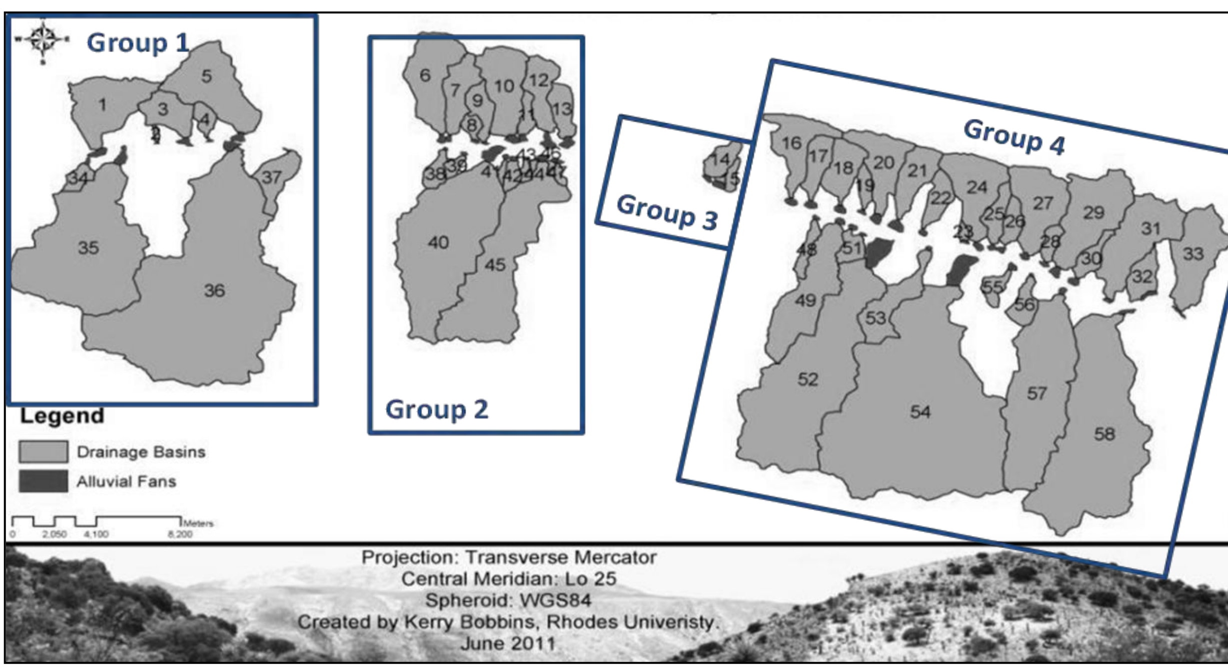

Figure 5.2: Identification of four fan groups in the valley

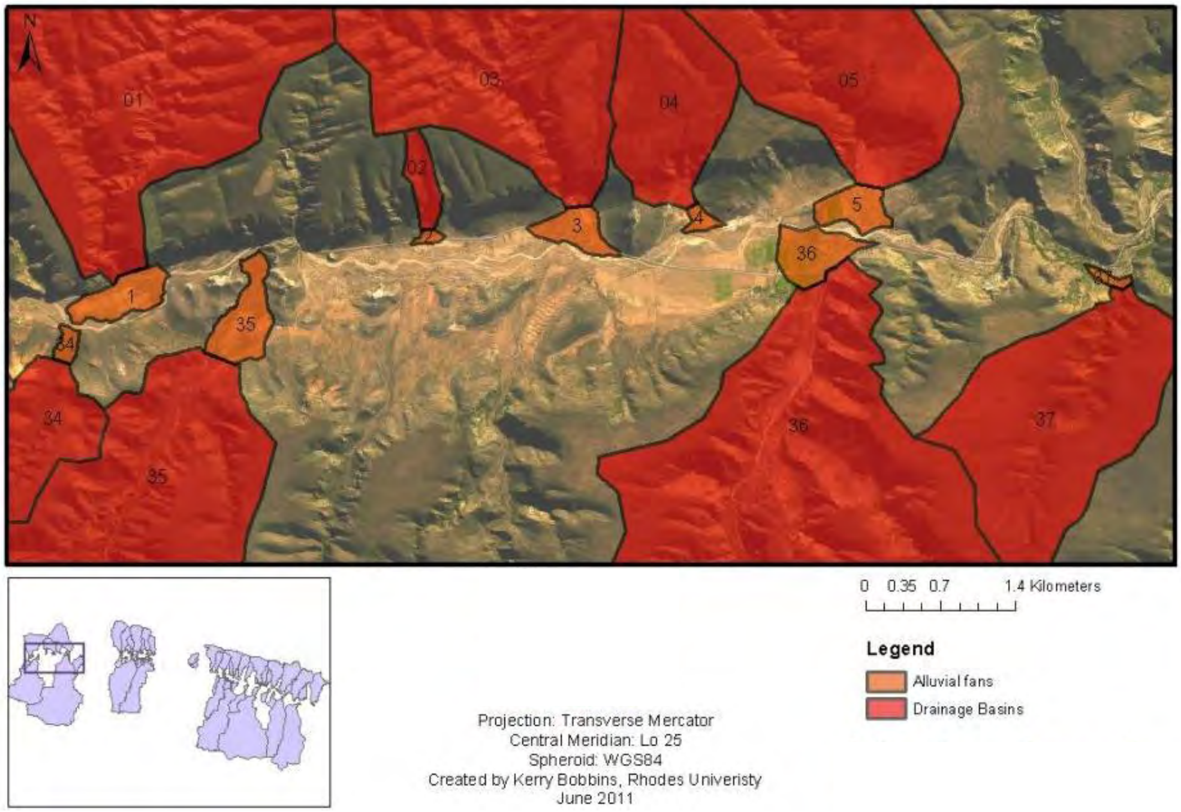

Figure 5.3: Alluvial fans in group 1

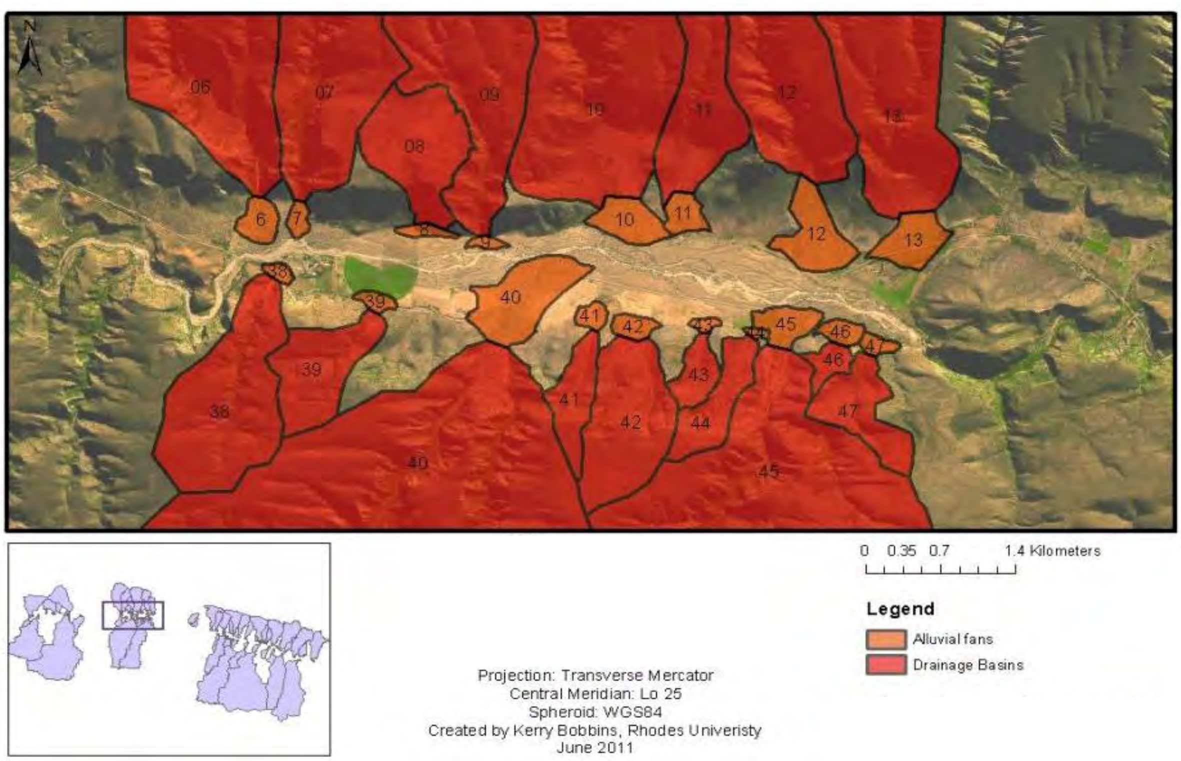

Figure 5.4: Alluvial fans in group 2

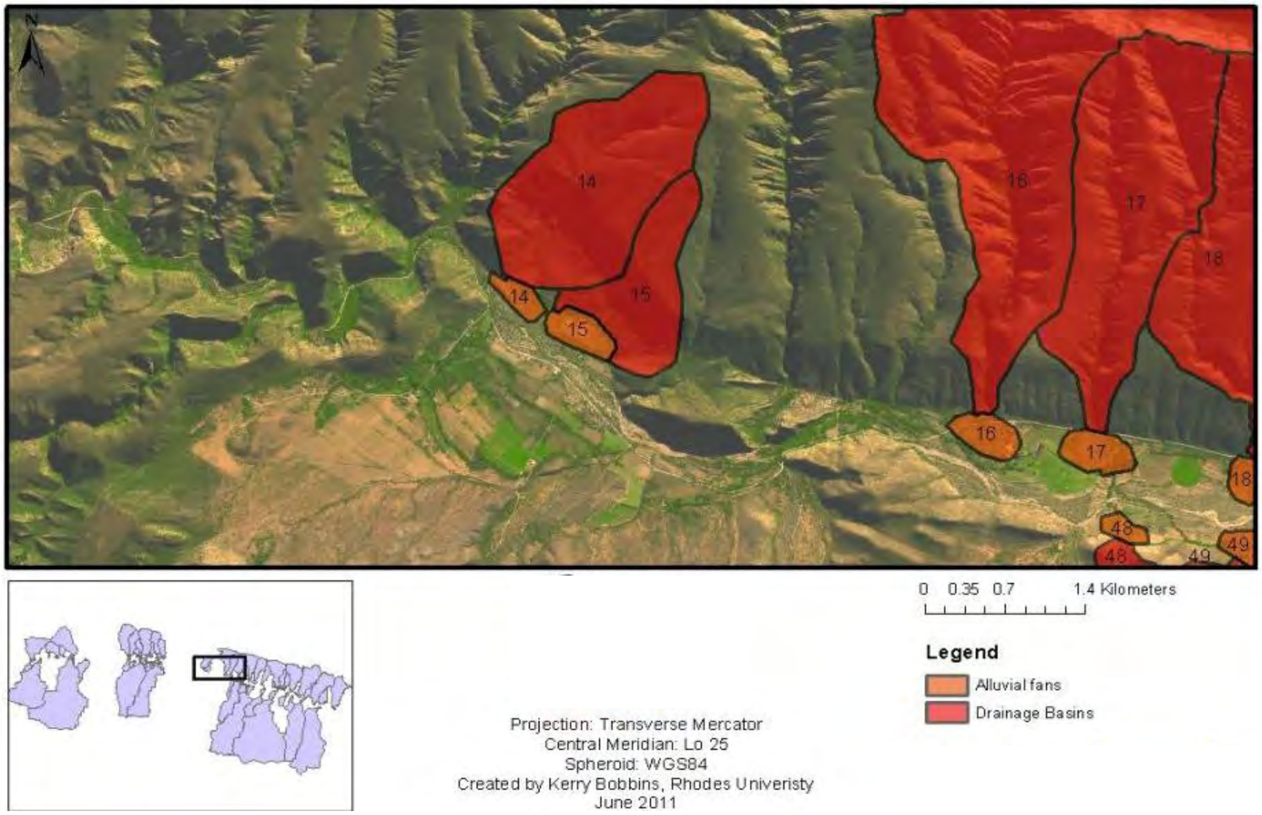

Figure 5.5: Alluvial fans in group 4 (a)

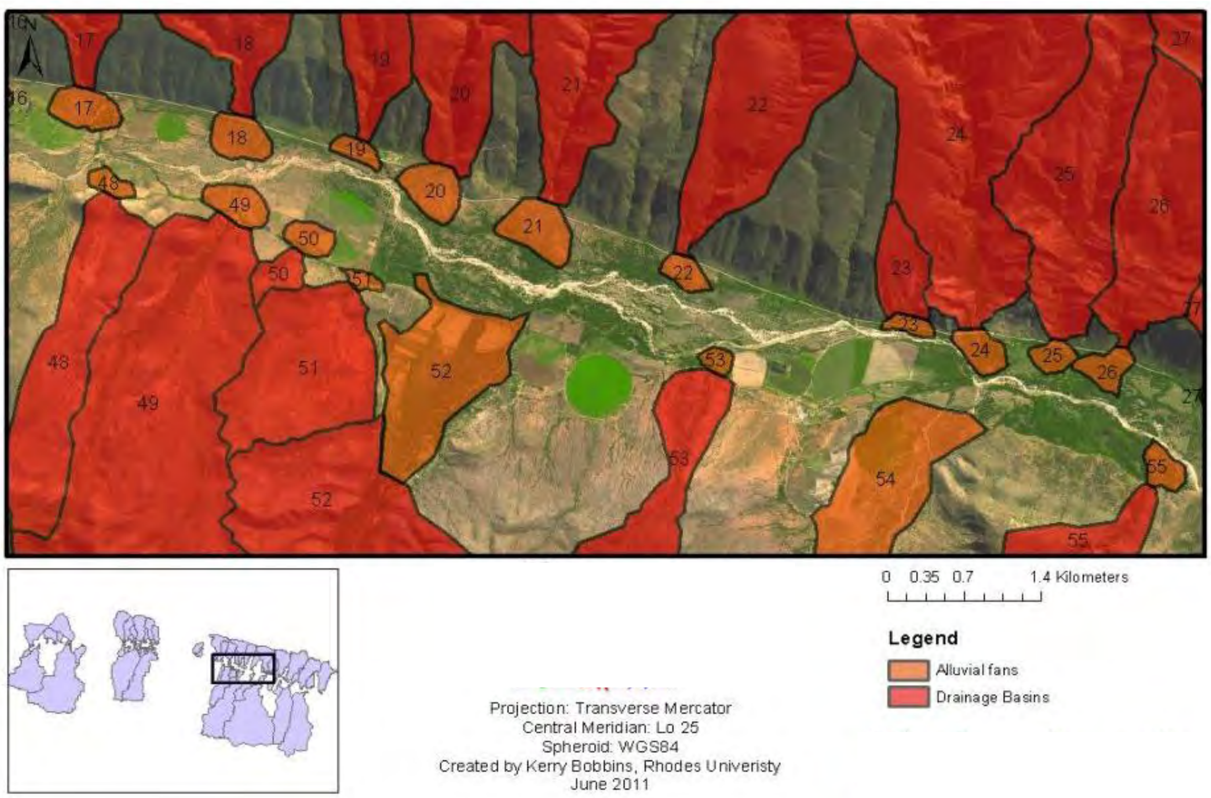

Figure 5.6: Alluvial fans in group 4 (b)

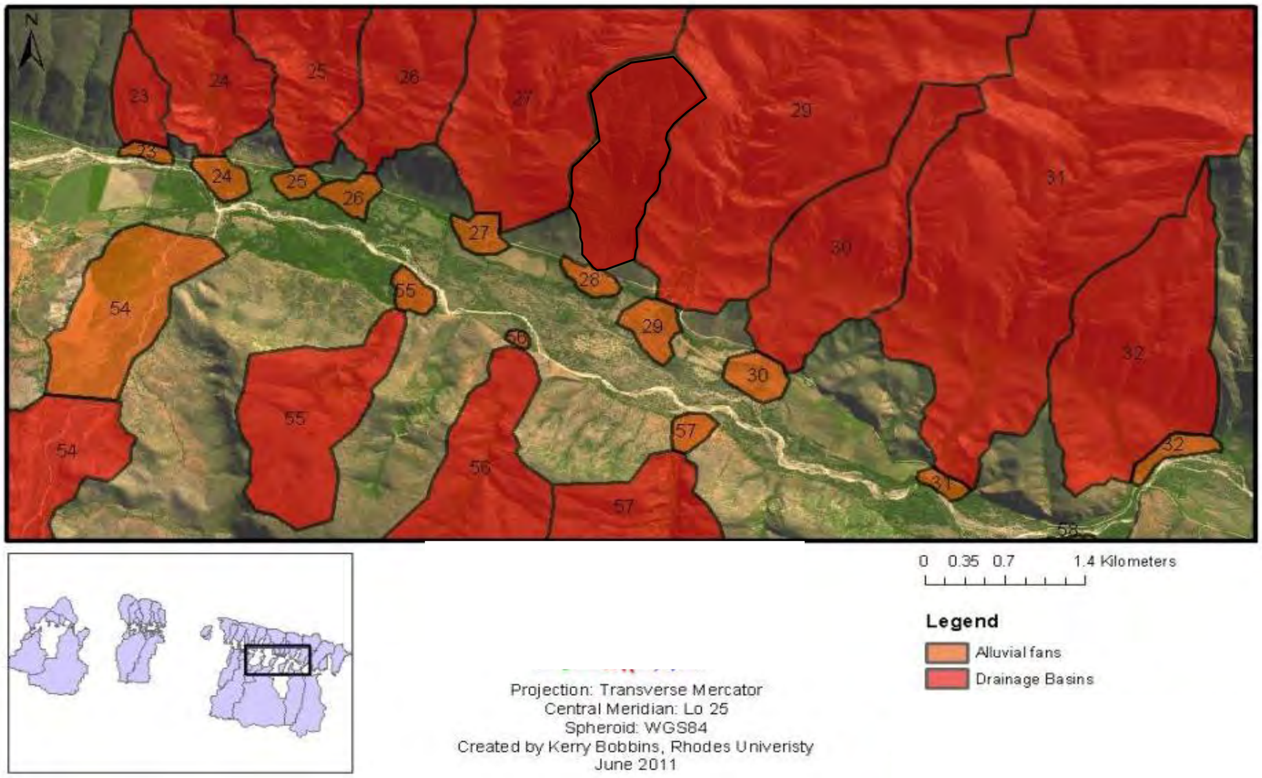

Figure 5.7: Alluvial fans in group 4 (c)

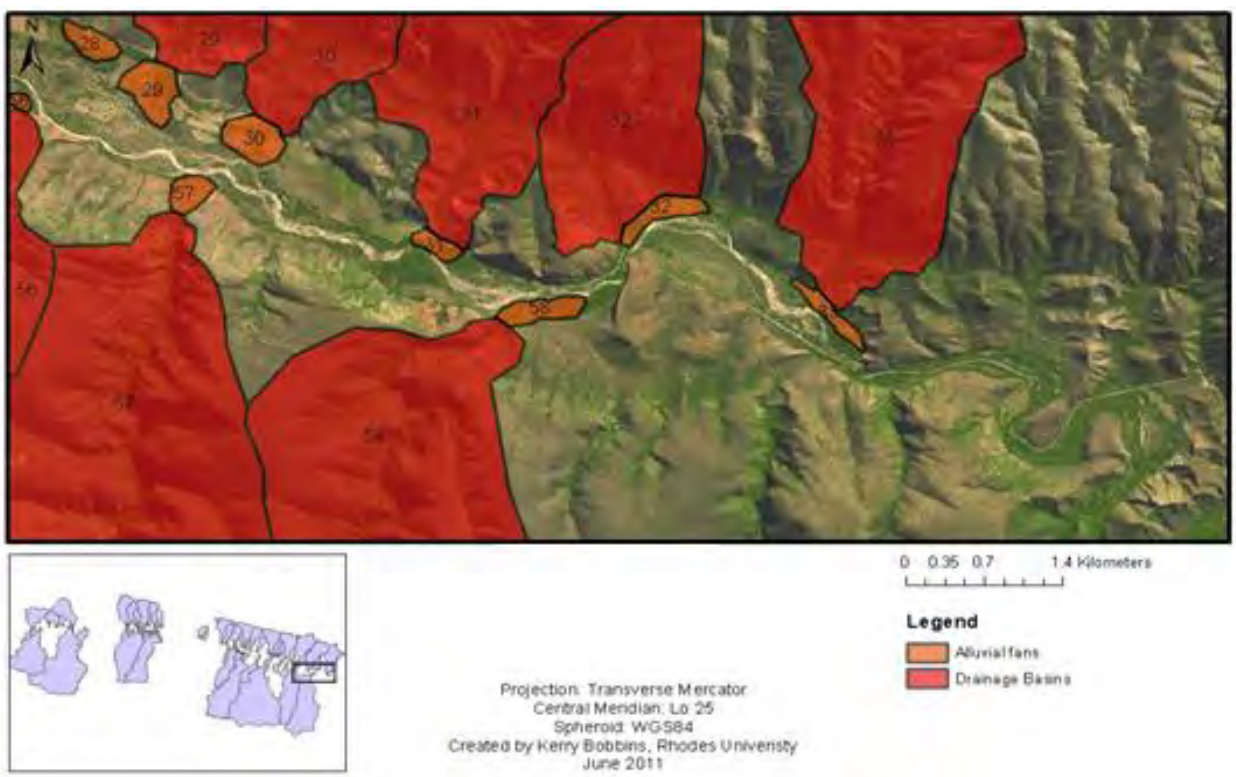

Figure 5.8: Alluvial fans in group 4 (d)

Chapter 6: Application of the framework

6.1. Introduction

This chapter applies the alluvial fan form-process framework (created in Chapter 3) to fans in the Baviaanskloof Valley using the step by step protocol of existing alluvial fan form-process and empirical relationships outlined in Chapter 3. The use of the form-process framework to characterize alluvial fans in the Baviaanskloof Valley, South Africa, fulfils the requirements of objective 3: to use the conceptual framework to characterize alluvial fans in the Baviaanskloof Valley, South Africa. The outcomes of this chapter will be to identify the external and internal control variables that most affect fans in the Baviaanskloof Valley using two approaches. Firstly, the control variables will be identified and explained by applying the framework presented in Chapter 3. Control variables will then be further analysed by investigating the relationships between fan external control variables and fan function using multivariate statistical methods. Control variables will be analysed separately for fans on the north and south facing sides of the valley and for fan groups identified in Chapter 5. The methods used to investigate fans in the Baviaanskloof Valley are considered to be the most reliable and accurate in consideration of both time and resource constraints. It is noted that Methods used to investigate relationships may diverge from those defined in the framework chapter due to data limitations and project constraints in the Baviaanskloof Valley. The framework is presented using the structure and layout used in chapter 3. It should be noted that fans groups 3 and 4 identified in Chapter 5 will be combined given the low number of fans in group 3 (n=2).

6.2. Application of the form-process framework to fans in the valley

6.2.A. External factors

6.2.1. *Accommodation space*

The Baviaanskloof Valley is characterized by a flat valley floor with the occurrence of wide and narrow sections (Chapter 2). The calculation of accommodation space is based primarily on valley width defined as the broad, flat surface at the bottom of the valley. It is expected that the accommodation space along the length of the western Baviaanskloof will fluctuate between wide and narrow sections. Valley width was measured in ArcMap 10 (Transverse Mercator, Lo: 25, WGS1984) for all fans (values recorded in kilometres). It was noted that fans either occur on one side of the valley only or on both sides. This means that the valley width calculated could be the distance for one or two fans. The accommodation space in cases where there were two opposite fans was therefore halved. This section provides an overview of fan accommodation space in the valley. A more detailed analysis of accommodation space will be further analysed in the Valley channel migration section of this chapter (section 6.2.2.ii).

6.2.2. *Base level changes*

6.2.2.i. *Valley-wide variables*

Active tectonics

Tectonic activity in the Baviaanskloof Valley was assessed using key geomorphology and geological texts by Booth et al. (2004) and personal contact with a local geomorphology expert in the Baviaanskloof area, Dr Werner Illenberger of Illenberger and Associates, New Zealand.

Three major uplift events occurred in the formation of the Baviaanskloof Valley with the last event dating to 5 million years ago (Chapter 2). There is still slight movement along faults in the valley over a time frame of millions of years (Illenberger, 2011). Although movement along faults in the Baviaanskloof Valley have shaped fans in the past due to an increase or decrease in base-level change, there is not enough movement between faults at present to initiate large-scale base-level change. Base-level change as a result of tectonic activity has little influence on present-day fans in the Baviaanskloof Valley.

Sea-level change

Sea-level induced change is the Baviaanskloof Valley is not feasible as fans do not connect to a shoreline or lake. Three sea-level changes are recorded in a timeline given by Ilgner et al*.* (2003:5) (Chapter 2). Sea-level changes date back to 50 000, 20 000 and 18 000 years before present in which the sea level dropped, dropped further and rose respectively (Table 4.1; Ilgner et al*.* 2003:5). Although these sea level changes contributed to the evolution of the Baviaanskloof topography, and would have rejuvenated the river systems, no sea-level induced a base-level response has occurred over the last 18 000 years and cannot be deemed a factor affecting current fan processes. Sea level changes and river rejuvenation could have occurred between 50 000 and 20 000 years ago.

6.2.2.ii. *Local (fan specific)*

Valley channel migration

Fan toe-trimming is evidence of a laterally migrating main river channel. In order to determine the effect of fan trimming, the fan surface was characterised as the fan surface that can be distinguished at present using aerial imagery and ground truthing methods. Toe trimmed fans are fans that have had the distal regions (lower fan surface) of the fan removed by the Baviaans River. Toe-trimmed fans were identified using the diagram of 'basal trimming by laterally migrating channel in Figure 3.3 (Chapter 2) and classified in the spatial plan (Chapter 5). This was done using SPOT 2008 imagery (Chapter 5). The results obtained in Chapter 5 will be analysed in this section providing an overview of fan toe-trimming in the valley. A more detailed study on two fans in the valley will be conducted in Chapter 7 where two longitudinal profiles will provide evidence of a laterally migrating main channel.

A laterally migrating channel in the Baviaanskloof Valley affects south facing fans (42%; n = 33) more than the north facing fans (36%; n = 25), (Table 6.1). Fans in group 1 have the greatest percent of toe-trimmed fans (89%) followed by group 3 and 4 (35%) and group 2 (22%), (Table 6.2). Of the total number of toe trimmed fans (n = 30) 37% occur in group 4, 13% in group 2 and 27% in group 1 fans. The greater the influence of a laterally migrating main channel on fans (under tectonically stable conditions), the greater the probability of an induced base-level change due to a shortening of the alluvial fan profile and an increased probability of channel incision on the distal fan surface which is noted on south facing fans.

Table 6.1: Number of toe trimmed fans on the north and south facing sides of the Baviaanskloof Valley

Valley side	No. Fans	No. of toe-trimmed fans	Percent fans toe-trimmed per valley side (%)	Percent of total toe trimmed fans (%)
North facing	25	9	36 (n=25)	**39**
South facing	33	14	42 (n=33)	**61**
Total	**58**	**23**		

Table 6.2: Number of toe trimmed fans per fan group

Fan Group	No. Fans	No. toe-trimmed fans	Percent toe trimmed fans per group (%)	Percent of total toe trimmed fans (%)
Group 1	9	8	89 (n=9)	27
Group 2	18	4	22 (n=8)	13
Group 3 and 4	31	11	35 (n=31)	37
Total	**58**	**23**		

Not only does channel migration cause fan toe-trimming in sections of the valley where fans occur on one (or both) sides of the valley but the fans also impacts the channel by creating a barrier to the main channel flow. An example of this is shown by fans 18 and 49 and 54 and 24 in group 4 of the spatial plan. Sediment deposition on the floodplain can encourages main channel switching as it creates a barrier to the main channel flow. Although not studied in detail, the influence of fan-river relationships introduces another variable to fluvial system dynamics. Two fans that face each other, on opposing sides of the valley, can create an interesting interplay between fans and the main river channel.

Human intervention

Visual evidence of human activity determined by SPOT 2008 imagery was used to identify where such activities have taken place (buildings or cultivation) and any large-scale changes that have resulted from human intervention (Chapter 5). As detailed in Chapter 5, it is noted that buildings tend to predominate on the south facing side of the valley, while fans are cultivated on both sides. Local knowledge was also used to determine why the human intervention has been initiated and dates of interventions. An overview of human intervention on selected fans flagged for further restoration in stage 1 of the Living Lands fan restoration programme is given in Table 6.3. The consequences of human intervention are also noted. The occurrence of two destructive flood in the 1970s and 1980s prompted Baviaanskloof landowners to mitigate flood damage to low lying agricultural land by constructing blocking structures (berms) on fans and excavating channels to divert water (DETEA, 2010:3) and explains the human intervention on fans in Figure 6.3 and flood protection measures have been implemented on both the floodplain and on alluvial fans. The objective of these flood mitigation structures is to divert water from tributary streams from fans directly into the main river channel, bypassing the alluvial fan surface and floodplain agricultural activities and usually takes the form of berms and channels (DETEA, 2010:3).

6.2.3. *Drainage basin inputs (water and sediment)*

6.2.3.i. *Valley-wide variables*

Climatic variables- rainfall in relation to flood generation

To estimate the rainfall that falls over fan catchments, the annual rainfall of the Baviaanskloof Valley (Figure 4.7, Chapter 4) was used together with fan catchments identified in Chapter 5. The position of weather stations in the valley were used to compare annual rainfall for fan groups (identified in Figure 4.7). Stations at Nuwekloof, Studtis, Studtis (Police station), Baviaanskloof, and Zandvlakte (stations 4, 5, 6, 7, 8) in the western Baviaanskloof indicate spatial variability of rainfall in the valley (Figure 4.7).

Groups 1, 2, 3 and parts of group 4 fall in areas receiving less than 300 mm per annum, whereas some fans in group 4 receives higher rainfall between 300 - 350 mm per annum. As weather stations are located on farms in the valley bottom they probably receive less water than in the mountain areas. The isolated nature of many rainfall events may result in only some fans becoming active during a rainfall event as not all basins will collect runoff.

Table 6.3: Overview on human intervention on selected alluvial fans (summarised from DETEA, 2010)

	Coloquial fan name	Fan number on spatial plan (Figure 5.1)	Human intervention	Consequene of human intervetion
Stage 1: Three pilot restoraton projects (2010)	a) 1st west of Gannalandkloof	26	1. Incised man-made channel in AF of 1st Kloof west of Gannalandkloof	Fan is bypassed by an incised channel located south of the road, which was originally used to lead water to the old irrigated lands in the area, which are no longer in use. This incised channel has artificial berms on either side which further concentrates all storm water flow, causing erosion and incision. The alluvial fan receives very little river flow and is thus no longer functional.
	b) Gannalandkloof	27	1. Gannalandkloof AF upstream of the road, showing man-made berm and incised channel.	South of the road an incised channel cuts through the Gannalandkloof alluvial fan and there are artificial berms on the east side of the channel. This results in the concentration and acceleration of water flow, causing further erosion and channel incision, which prevents the spreading and infiltration of water and deposition of sediment within the alluvial fan. The incised channel also results in the lowering the water table, leading to further degradation of the alluvial fan.
	c) Erasmusboskloof	31	1. downstream just below road crossing, showing incised channel man made berms on both sides. 2. Earth berm on floodplain parallel to main channel of Baviaans river at Erasmusboskloof confluence.	The construction of artificial berms (keerwalle) on the floodplain to prevent flooding on the right bank of the Baviaanskloofrivier has resulted in the narrowing of the river bed into a single channel from the natural braided channel that existed previously in this location. The concentration and acceleration of flow has led to erosion, degradation and incision of the main river bed, which in turn has exacerbated the erosion of the incised channel in the Erasmusboskloof alluvial fan.

Vegetation cover

A study of vegetation cover and species density was not conducted in this research. The following account is taken form van Jaarsveld (2011) except where otherwise attributed. As discussed in Chapter 4, the Baviaanskloof is characterized by vegetation types that include afrotemporate forests, fynbos, sub-tropical thicket, Karoo shrubs and succulents. Seasonal temperature variations together with evapotranspiration rates recorded at 1125 mm per annum indicate that vegetation survives on a water deficit (Jansen, 1998:25, Chapter 4). With episodic and inter-annual variations in rainfall one would expect intermittent vegetation growth on the fan surface. This is not true as field observations showed fans are vegetated with grasses, small shrubs and trees along with a number of small succulent species.

Fans host an assortment of vegetation types due to their transitional location in the valley and the many soil type and moisture niches that they provide and are typically vegetated for the duration of the year, with only seasonal grasses and shrubs dying back in the winter. Vegetation found on the fan surface can be expected to result in increased shear strength of the slope, increasing with denser vegetation cover with a more established root system.

Field observations confirmed that fans support vegetation types growing in slot canyons (kloofs), low lying footslope areas and riverine areas. Kloofs in the fan basin area supports woody tree species such as the *Nuxia Floribunda, Gonioma kamassi, Podocarpus falcatus, Celtis Africana, Halleria lucida and Ficus* which grow in a moist and lush niche area which contrasts with vegetation found on the mid fan surface which is predominately sub-tropical thicket species, Karoo shrubs and succulents that are well adapted to arid environments. The distal fan is observed to be characterized by Karoo shrubs, succulents and grasses.

Livestock grazing and stocking rates have fluctuated in the valley over time and this may have affected the species richness and vegetation density. Although stocking numbers were not reviewed for project research, farmers in the valley describe a greater grazing pressure on the land in the 1960s. Grazing pressure would have had a marked impact on the occurrence and density of species in the valley.

Long-term climate change is also a consideration. Scott et al. (1995: 937) detail a temperature shift in the late Pleistocene - Holocene of 5^{0}C from 15 000 – 1000 BP with a transition phase from 11 000 – 10 000 BP from cold to warm. If fans originated sometime after 20 000 BP they would have undergone a shift in vegetation type from tree-less grassland shrubs and grasses to woodlands and sub-tropical grasslands through a series of short – term oscillations as described by Scott et al. (1995: 937).

Basin geology

The geology of the Baviaanskloof Valley was classified into easily erodible rock formations found on the valley floor and more resistant quartzite found on the north and south facing mountains (Chapter 4). Sediment washed onto fan surfaces originates from quartzitic basins where water is channelled and directed through joint-directed channels. To determine the geology of the fan catchments, a map of fan catchment geology was produced in ArcMap 10 by overlaying the fan basin shapefile over the geology shapefile (Figure 6.1). A summary of fan catchment geology for valley sides and fan groups is given in

(Table 6.4). It was noted that all fan groups are comprised of quartzitic sandstone with enon conglomerates found on the south facing side and shale on the north facing side of the valley (Table 6.4). These findings were further investigated by conducting union analysis of drainage basin area and geology area (Table 6.5). Quartzitic sandstone is shown to be the primary geology of both north (174.82 km^2) and south facing fan basins (102.78 km^2). North facing basins are composed of a greater percentage of enon conglomerates (70%) and quartzitic sandstone (shale) (81%) and shale (81%) in comparison to the south facing side which is mainly comprised of quartzitic sandstones (Table 6.5).

6.2.3.ii. *Fan drainage basin variables*

Area

An analysis of fan basin area (calculated in Chapter 2) showed that there is a large overlap between the size of fans on the north and south facing sides of the valley, but some north facing basins are larger. The area of north facing basins varies between 0.14 – 70.93 km^2 and of south facing basins between 0.19 – 12.12 km^2 (Figure 6.2). Fan basins larger than 5 km^2 are found in groups 2 and 4. Groups 1, 3 and 4 constitute both the smallest basins and largest basins in the valley while fan group 2 has smaller basins ranging from >5 – 30 km^2 (Figure 6.3). Fans in group 1 and 3 and 4 have basins with greater potential for runoff and sediment generation that results in a greater amount of water and sediment being fed onto the fan.

Table 6.4: Drainage basin geology per fan group

Group number	North facing	South facing
Group 1	Alluvial valley deposits (on the valley floor) Quartzitic sandstone Quartzitic sandstone (feldspathic) Shale Terrace gravel	Alluvial valley deposits (on the valley floor) Enon Conglomerate Quartzitic sandstone Terrace gravel
Group 2	Feldspathic sandstone Quartzitic sandstone Quartzitic sandstone (feldspathic) Terrace gravel	Alluvial valley deposits (on the valley floor) Quartzitic sandstone Enon Conglomerate Quartzitic sandstone (feldspathic)
Group 3	No fans	Enon Conglomerate Quartzitic sandstone Quartzitic sandstone (feldspathic)
Group 4	Black Shale Enon Conglomerate Feldspathic sandstone Quartzitic sandstone Terrace gravel Shale	Quartzitic sandstone (feldspathic) Shale Terrace gravel

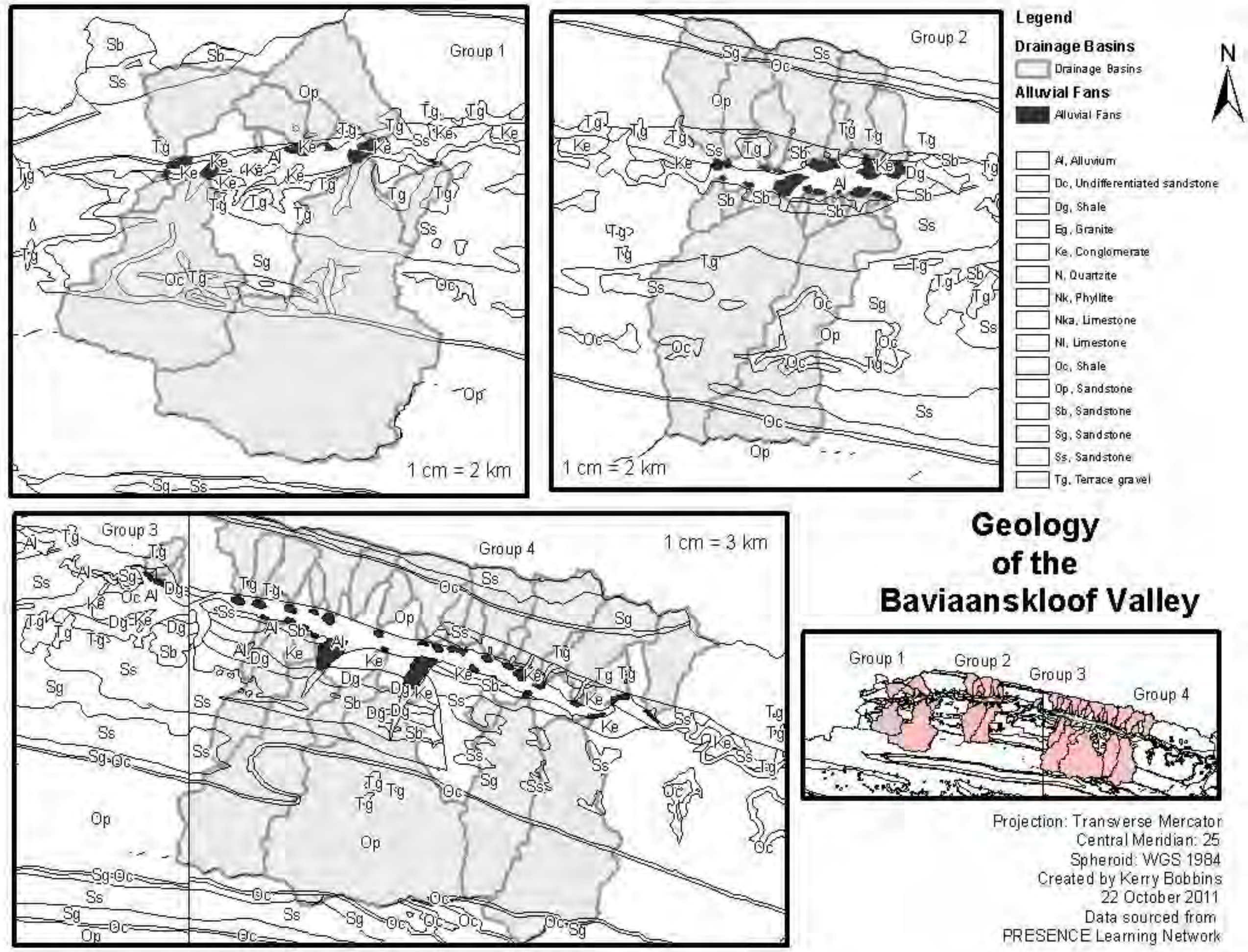

Figure 6.1: Geology of alluvial fan basins (map key used to explain Table 6.5)

Table 6.5: Geology of alluvial fan basins

Rock Type	General	Code	Total area on north and south facing sides	Total area on north facing side	Total area on south facing side	Percent of total area on north facing (%)	Percent of total area on south facing (%)
Alluvium	Alluvium	Al	5.81	4.03	1.77	69.47	30.53
Terrace gravel	Terrace gravel	Tg	5.88	3.83	2.05	65.16	34.84
Enon Conglomerate	Conglomerate	Ke	7.67	5.32	2.35	69.39	30.61
Feldspathic sandstone	Sandstone	Sb	16.29	16.29	0.00	100.00	0.00
Quartzitic sandstone	Sandstone	Op	277.60	174.82	102.78	62.98	37.02
Quartzitic sandstone (feldspatic)	Sandstone	Ss	66.88	45.93	20.94	68.68	31.32
Quartzitic sandstone (shale)	Sandstone	Sg	119.06	96.75	22.31	81.26	18.74
Shale	Shale	Oc	26.39	21.24	5.14	80.51	19.49

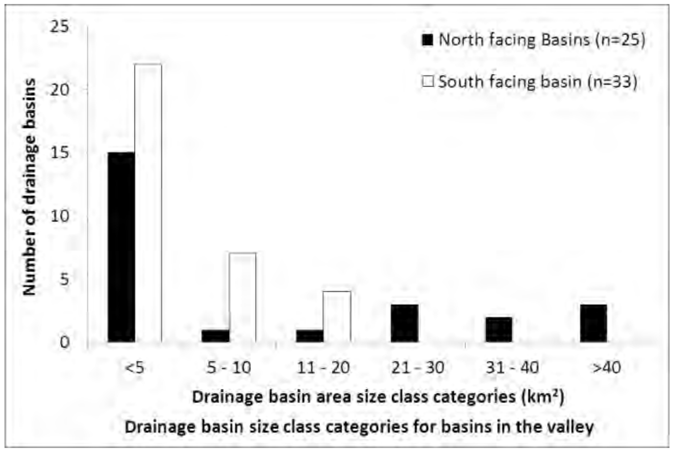

Figure 6.2: **Drainage basin size class categories for north and south facing basins in the valley**

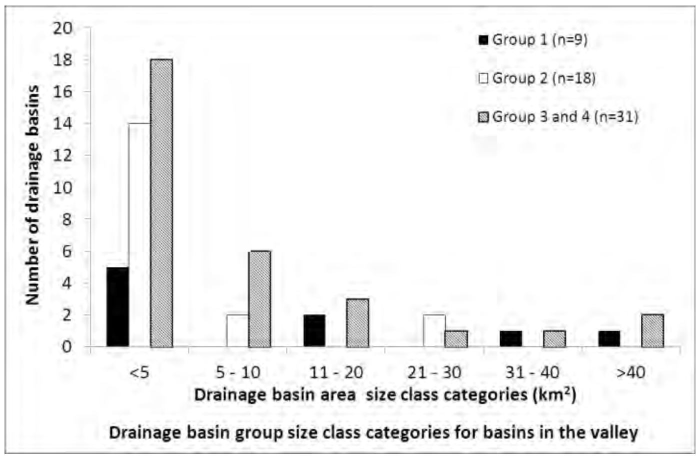

Figure 6.3: **Drainage basin group size class categories for basins in the valley**

Basin geometry/ shape

The Gravelius index (Gi) of fan basins in the Baviaanskloof Valley was calculated using methods outlined in Chapter 2 and the values are given in Table A.5. Basins on both sides of the Baviaanskloof Valley fall into all three categories: circular (Gi values <1.20-1.9), irregular (Gi values 1.40-1.59) and elongated (Gi values 1.60->1.70), (Figure 6.4). North facing basins are more notably spread over the three shape class values than south facing basins, with south facing basins are more circular to irregular in shape (basins fall between 1.30-1.59 Gi index size class categories), (Figure 6.4). Fan group 3 and 4 have been grouped for convenience as fan group 3 is only comprised of 2 fan. Fan basins in groups 1, 3 and 4 overlap for Gi values between 1.32 – 1.83 with fans in group 3 and 4 tending to have more elongated basins (Figure 6.5).

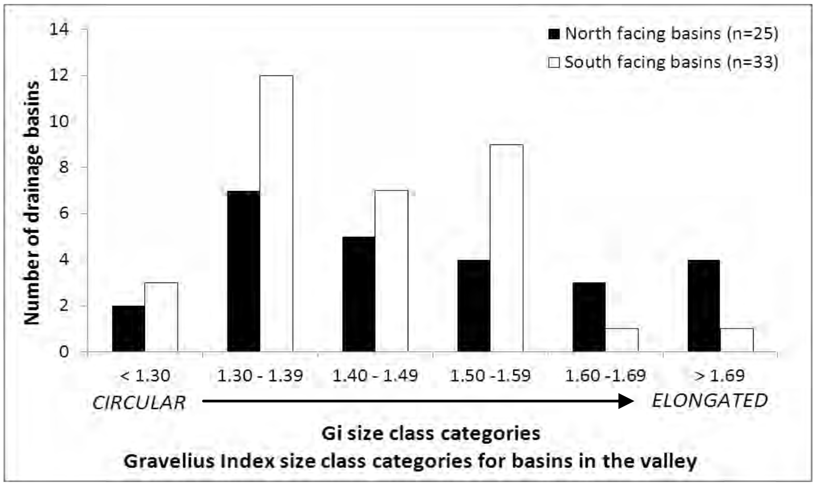

Figure 6.4: Gravelius index categories for drainage basins in the valley

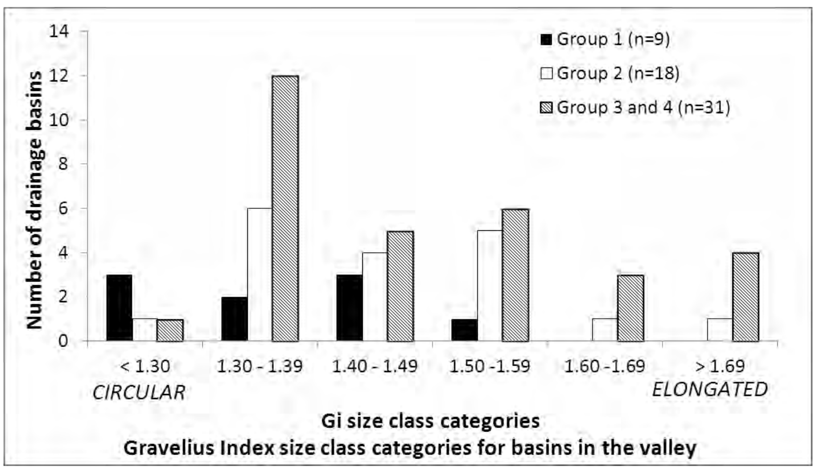

Figure 6.5: Gravelius index categories for fan groups in the valley

Relief/gradients

Melton's Ruggedness values were calculated using methods outlined in Chapter 3 and the values are given in Appendix Table A.4. Ruggedness values recorded for valley sides and fan groups are shown to be <0.19 and produce a downward trend from <0.19 - > 0.59 (Figure 6.6). Fan basins on both sides of the valley are shown to have low ruggedness with south facing basins tending to be more rugged (Figure 6.6). As explained by Given (1999: 54), very rugged basins can have a ruggedness value as low as zero and less rugged basins can produce Melton's ruggedness values as high as 2 or 3. Basins in group 3 and 4 have fan basins with lower ruggedness values compared to groups 1 and 2 indicating that these basins are more rugged (Figure 6.7). South facing fan basins and fans in group 2 therefore have a larger gradient and available relief to feed sediment onto the alluvial fan surface.

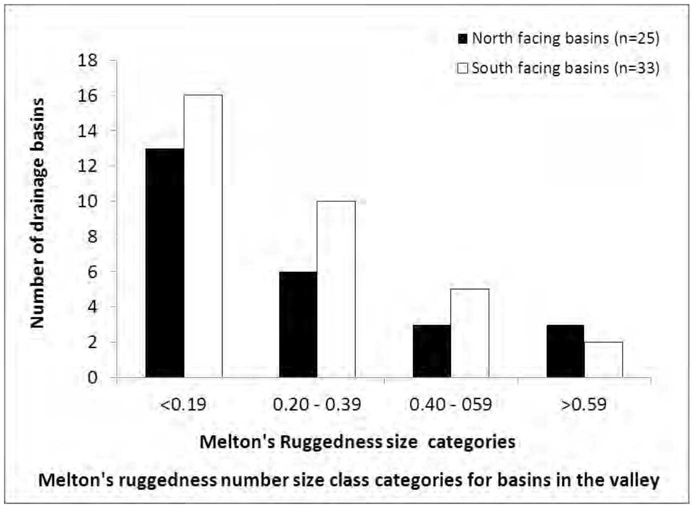

Figure 6.6: Melton's Ruggedness number size classes for north and south facing fan basins in the valley

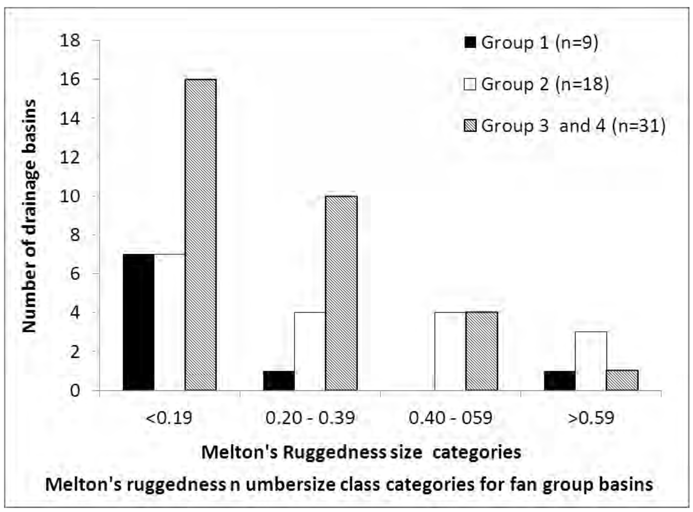

Figure 6.7: Melton's Ruggedness number size classes for fan group basins

6.2.B. Internal variables

6.2.4. *Fan variables*

6.2.4.i. *Fan style*

Fan style is defined by fan type and geometry. The fifty-eight fans in the Baviaanskloof Valley were classified using the classification of fan types illustrated in Figure 6.8 and fan style (Fan type and geometry) data is recorded in Chapter 4, Appendix Table A.1. The frequency of fan types in the valley were: 28 tributary junction, 19 simple mountain front, 9 simple backfilled and 2 intermontane. Fan types on the north facing side are mainly tributary junction fans, whereas south facing fans are comprised of simple mountain front and tributary junction types (Figure 6.8). Fans types in group 2 and 4 are shown to be most similar (Figure 6.9). Fan types conform to those identified by Leeder and Mack (2001) and Al-Farraj and Harvey (2010). Following these findings, tributary junction fan types are confined by valley walls and are strongly influenced by local fan relationships and toe trimming and are usually fluvial dominant and composed of fluvial sheet gravels or channel gravels which can be expected for the Baviaanskloof Valley.

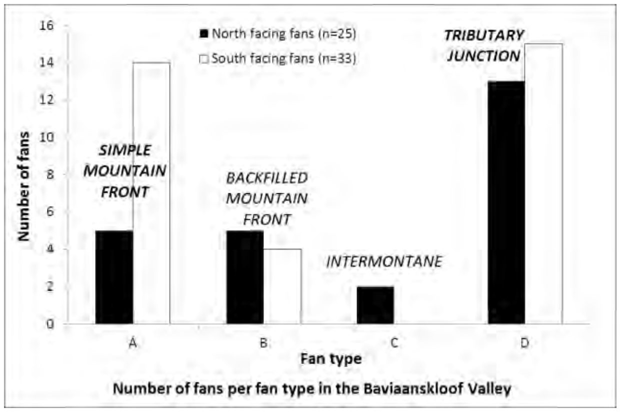

Figure 6.8: Number of fans per type in the Baviaanskloof Valley

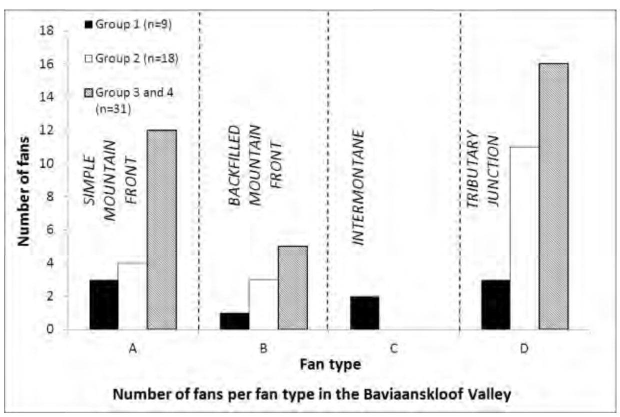

Figure 6.9: Number of fans types per group in the Baviaanskloof Valley

6.2.4.ii. *Fan morphometry (form related)*

Fan area

Fan area was calculated using methods outlined in Chapter 6 and the values are provided in Appendix Table A.1. South facing fan areas are notably smaller (<0.1 - 0.49 km^2) than north facing fan areas (<0.1 -

0.69 km^2), (Figure 6.10). Fan areas calculated for fan groups 2 and 4 are shown to have fans with areas for all size class cohorts (<0.1 to >0.69) and are the only groups to have larger fans (Figure 6.11). Fan group 1 and 3 are shown to have smaller fans (<0.1 – 0.49 km^2) than fan groups 2 and 4 (Figure 6.11). This indicates that fans areas are smaller at the top end of the Baviaanskloof Valley and the surface area of fans becomes larger along the length of the valley (from west to east).

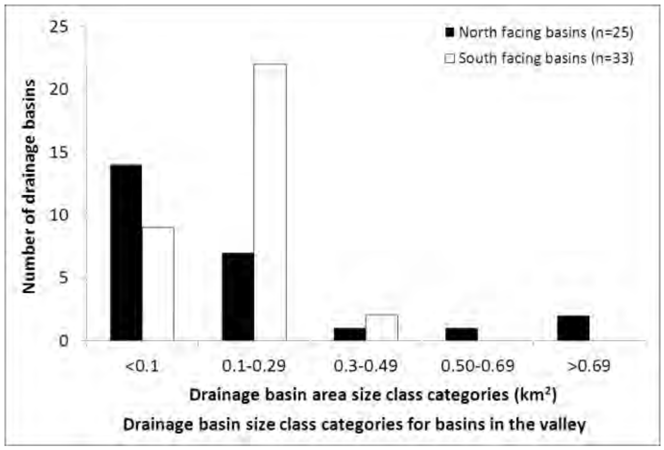

Figure 6.10: Alluvial fan size class categories for north and south facing basins in the valley

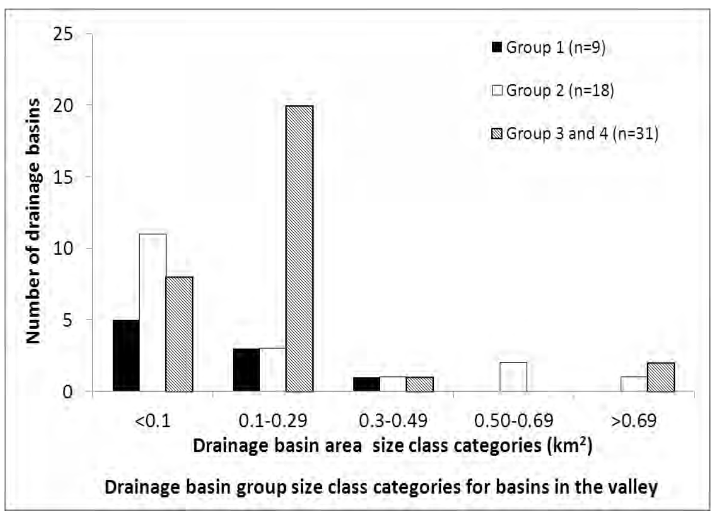

Figure 6.11: Alluvial fan group area size class categories for the valley

Description of alluvial fan control variables

Correlation matrices were produced in STATISTICA 9 to identify significant/insignificant relationships between internal and external fan control variables using the standard bivariate correlation matrix function. Significant relationships between dependent and independent variables were identified in the correlation matrix table. These were identified as either >0.6 or <-0.6 at p = 0.05 (Table 6.6). Six matrices were produced to compare and contrast significant relationships between all fans, north and south facing fans and for fan groups 1, 2, 3 and 4. Groups 3 and 4 have been combined because of the small number of fans in group 3. A list of symbols used to describe control variables used in the correlation matrix is given in Table 6.6. Both the dependent (fan area and fan slope) and independent control variables (drainage basin area, basin ruggedness and basin geometry) were incorporated into the matrix and significant values identified (>0.6 or <-0.6 at p = 0.05). Although the use of a correlation matrix infers a relationship between pairs of fan variables, it is unable to model the complexity of real fan systems. A multivariate analysis was used to assess the fan response to a number of control variables that affect fans in space. A multivariate Principle Component Analysis (PCA) and regression analysis were chosen to fulfil these tasks by providing evidence for significant relationships between fan dependent and independent variables. Multivariate analyses will be presented after fan area and independent control variable relationships are presented using a series of graphs.

Correlation matrix

The correlation between fan area and drainage basin area is the most prevalent relationship between all matrices with this relationship representing significant correlation relationships for all fans, north facing fans and for all fan groups (Table 6.7). Matrices also show that the shape of fan basins (Gi index) has little effect on fan area, but the ruggedness index has a greater effect. It is noted that all basin geometry and ruggedness correlations are negative. The significant relationship between drainage basin area to alluvial fan area was investigated by plotting a log-log graph of fan area to drainage basin area and provides evidence for the relationship. A t-test was used to determine differences between north and south facing alluvial fan area to drainage basin area ratios (AFA:DBA).

Alluvial fan area versus drainage basin area relationships

Using the same nomenclature in Chapter 2, $F = pA^q$, the fan area trend lines plotted for fans on the north and south facing slopes of the Baviaanskloof Valley are given by the equations: north facing fans $F = 0.0543A^{0.47}$, $R^2 = 0.60$ and south facing fans $F = 0.0843A^{0.38}$, $R^2 = 0.34$ (Table 6.8; Figure 6.12). Although the south facing fans have a low correlation coefficient, the range of drainage basin area is relatively small and they plot within the data spread of the north facing fans. The same applies for the fan groups (Figure 6.13). Fans in all groups produce a good R^2 value, except for south facing fans (Table 6.8). The low correlation coefficients obtained suggest that there may be another limiting factor on fan formation in the valley, due to the valley having a series of confined and unconfined sections and limited amount of accommodation space in some areas.

Table 6.6: List of control variable symbols

Independent variables	Symbol
Accommodation space	AS
Drainage basin area	DBA
Melton's Ruggedness Number	M
Gravelius Index	GI
Dependent variables	Symbol
Fan area	AFA
Fan slope	AFS

Table 6.7: Correlation matrix calculated for fan control variables (bold face shaded cells indicate significant correlation values (>0.6 or <-0.6 at p = 0.05)

All fans (n=58)

	AFA	*AFS*	*AS*	*DBA*	*GI*	*M*
AFA	1.00					
AFS	-0.44	1.00				
AS	0.31	-0.29	1.00			
DBA	**0.68**	-0.39	-0.02	1.00		
GI	0.11	-0.17	-0.04	0.20	1.00	
M	-0.32	0.27	0.16	-0.42	-0.07	1.00

North facing fans (n=25)

	AFA	*AFS*	*AS*	*DBA*	*GI*	*M*
AFA	1.00					
AFS	-0.48	1.00				
AS	0.41	-0.52	1.00			
DBA	**0.71**	-0.48	0.05	1.00		
GI	0.10	-0.25	0.11	0.14	1.00	
M	-0.43	0.13	0.31	**-0.63**	-0.22	1.00

South facing fans (n=33)

	AFA	*AFS*	*AS*	*DBA*	*GI*	*M*
AFA	1.00					
AFS	**-0.61**	1.00				
AS	0.26	-0.09	1.00			
DBA	0.35	-0.34	-0.32	1.00		
GI	0.05	-0.02	-0.20	0.13	1.00	
M	-0.45	0.34	0.09	-0.59	0.08	1.00

Group 1 (n=9)

	AFA	*AFS*	*AS*	*DBA*	*GI*	*M*
AFA	1.00					
AFS	**-0.67**	1.00				
AS	0.45	**-0.78**	1.00			
DBA	**0.68**	-0.39	0.28	1.00		
GI	0.24	0.15	-0.24	0.51	1.00	
M	-0.52	0.19	0.03	-0.32	0.30	1.00

Group 2 (n=18)

	AFA	*AFS*	*AS*	*DBA*	*GI*	*M*
AFA	1.00					
AFS	-0.52	1.00				
AS	-0.16	-0.10	1.00			
DBA	**0.71**	-0.46	-0.42	1.00		
GI	0.00	-0.38	-0.19	0.37	1.00	
M	-0.58	0.42	0.45	**-0.67**	-0.06	1.00

Group 3 and 4 (n=31)

	AFA	*AFS*	*AS*	*DBA*	*GI*	*M*
AFA	1.00					
AFS	-0.49	1.00				
AS	0.40	-0.28	1.00			
DBA	**0.78**	-0.42	0.01	1.00		
GI	0.12	-0.18	-0.05	0.15	1.00	
M	-0.36	0.32	0.29	-0.58	-0.35	1.00

South facing drainage basins produce relatively small alluvial fans, shown by the low p value obtained. North facing fans have a higher p value which suggests that topographically these fans may have a greater amount of accommodation space available for fan development. Fan groups 1, 2 and 4 produce p values ranging from 0.049 – 0.076 and q values 0.3945 – 0.5272, (Table 6.8). Small fan areas could be due to toe trimming, but not all toe trimmed fans are shown to have lower fan area to drainage basin area ratios (Figure 6.12). This may be due to the complete toe trimming taking place and the extent of trimming relative to the fan area. Relatively speaking, large fans will be less impacted by toe trimming than will small fans

Table 6.8: Equation variables of the log-log plot of fan area to drainage basin area relationships

Group	Equation	R^2 Value (log-log)	Standard Error
All Fans	$F=0.0679A^{0.44}$	0.50	2.19
South Facing Fans	$F=0.0843A^{0.38}$	0.34	3.33
North Facing Fans	$F=0.0543A^{0.47}$	0.60	0.61
Group 1	$F=0.049A^{0.52}$	0.77	5.81
Group 2	$F=0.0644A^{0.46}$	0.54	1.51
Group 3 and 4	$F=0.076A^{0.39}$	0.35	2.22

T-test: fan area to drainage basin ratios

The significance of fan area to drainage basin relationship is examined for both the north and south facing sides of the valley using a t-test. To conduct this analysis, the alluvial fan to drainage basin ratio (AFA: DBA) calculated in Chapter 5 was used and a null hypothesis formulated.

An independent groups (unequal) t-test was conducted on the ratio data. To investigate which of the independent unequal t-tests to run on the ratio data, a z-test was conducted to decide whether the variances were equal (Table 6.9). Results showed the z-test indicates that the variances for the two groups are not equal (Table 6.9). This is shown by P (F ≤ f) one-tail value which is less than 0.05 ($f = 0.53$; $p = 0.05$). The null hypothesis (H_o) is therefore rejected and the alternative hypothesis is accepted (H_a) which assumes unequal variances (Table 6.10). A two sample unequal variance t- test was selected to determine the significance between fan ratios and was carried out in Excel 2010 (Table 6.10). Null

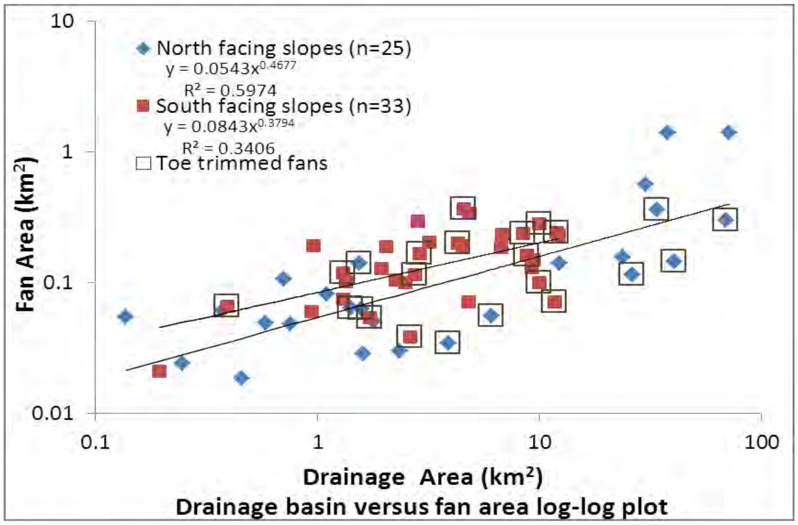

Figure 6.12: Drainage basin versus fan area log-log plot

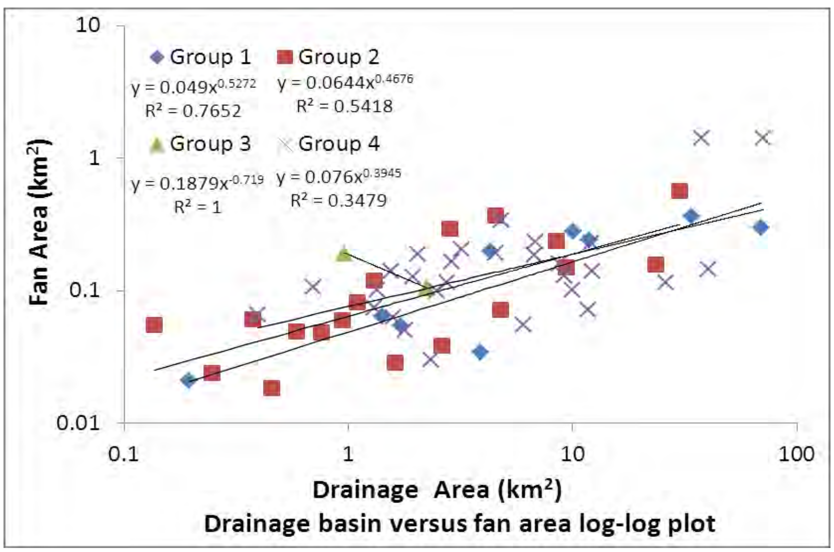

Figure 6.13: Drainage basin versus fan area group log-log plot

hypothesis and t-test settings used for the analysis are outlined in Table 6.11. The null hypothesis stated that there is no difference between the fan to drainage basin ratio for fans on the north and south facing side of the valley. The results of the t-test suggest the mean score for variable 1 (south facing fans) is 0.055, (standard deviation = 0.04, population size = 33) was significantly smaller than for variable 2 (north facing fans) which has a mean value of 0.058, (standard deviation = 0.84, population size = 25); using the two-tailed t-test for unequal variances where t (32) = - 0.17 ($p \leq 0.87$) at a 95% confidence level (Table 6.11). The null hypothesis is therefore rejected due to p > α (2.04 > 0.05) and $t < t_{critical}$ (1.17 < 2.04) and it is concluded that there is a significant difference between the means of the fan area to drainage basin area ratio for valley sides. The higher mean calculated for north facing ratios indicate that north facing basin produce larger fans/unit area.

Table 6.9: F-Test for two-sample variances

	South facing	*North facing*
Mean	0.055259776	0.058489353
Variance	0.001963355	0.007437915
Observations	32	24
df	31	23
F	0.263965736	
P(F<=f) one-tail	0.000337271	
F Critical one-tail	0.530525823	

Table 6.10: Settings used for the two sample unequal variance t-test

Parameter	Setting
H_o ($\mu_1 = \mu_2$)	There is no difference in the means of alluvial fan area versus drainage basin ratio for the south and north facing sides of the valley
Variable 1	South facing ratio
Variable 2	North facing ratio
Confidence level	0.05

Table 6.11: Two-sample T-Test assuming unequal variances

	South facing	*North facing*
Mean	0.055259776	0.058489353
Variance	0.001963355	0.007437915
Observations	32	24
Hypothesized Mear	0	
df	32	
t Stat	-0.167610796	
P(T<=t) one-tail	0.433972134	
t Critical one-tail	1.693888748	
P(T<=t) two-tail	0.867944267	
t Critical two-tail	2.036933343	

Comparing fan area with other arid fan studies

The fan area values calculated for fans in the valley are compared to relationships calculated for semi-arid and arid fans by Beaumont (1972), Bull (1964), Denny (1965), Harvey (1984), Hawley and Wilson (1965), Hooke (1968), Hooke and Rohrer (1977), Leece (1988) and Melton (1965). Locations of fan studies are given in Table 6.11.

Table 6.12: An overview of fan study area for fan literature

Fan study	Study Area
Beaumont (1972)	Elburz Mountains, Iran.
Bull (1964)	Western Fresno Country, USA.
Denny (1965)	Death Valley and Nevada, USA.
Harvey (1984)	Spain
Hawley and Wilson (1965)	Nevada, USA.
Hooke (1968)	Death valley, Springs Valley and Cowhorn Valley, USA.
Hooke and Rohrer (1977)	USA
Leece (1988)	Arizona, USA.
Melton (1965)	Southern Arizona, USA.

Compared to other studies on arid fans, fans in the Baviaanskloof valley are shown to have smaller fan areas for drainage basin areas as values plot below the boundaries of other fan studies (Figure 6.14). This could be a result of either the catchment geology contributing to low rates of sediment production and sediment supply to the fan, or sediment storage in the basin area. Another explanation could be that fans reaching stage 3 of maturity do not receive enough sediment to increase the volume of the fan surface resulting in fans not increasing in size, but rather in volume, when sediment is deposited on the fan surface.

Investigating other significant relationships

Accommodation space

The valley width envelope for fans in the valley is given by the equation $y = 0.911x^{1.88}$ (Figure 3.1). Fans in the Baviaanskloof Valley tend to be found at valley width values between 0.4 – 1.5 km and produce fans with areas in the range of 0.01 - 0.36 km^2 (Figure 3.1). One outlier is noted at a valley width of 0.55 km for a group 2 north facing fan (Figure 6.16). Fans that are shown to fall above the critical threshold line indicate (only one fan on the south facing side falls below the line) that accommodation space is not the only limiting factor on fan size and there are other factors that inhibit the size of fans in the valley.

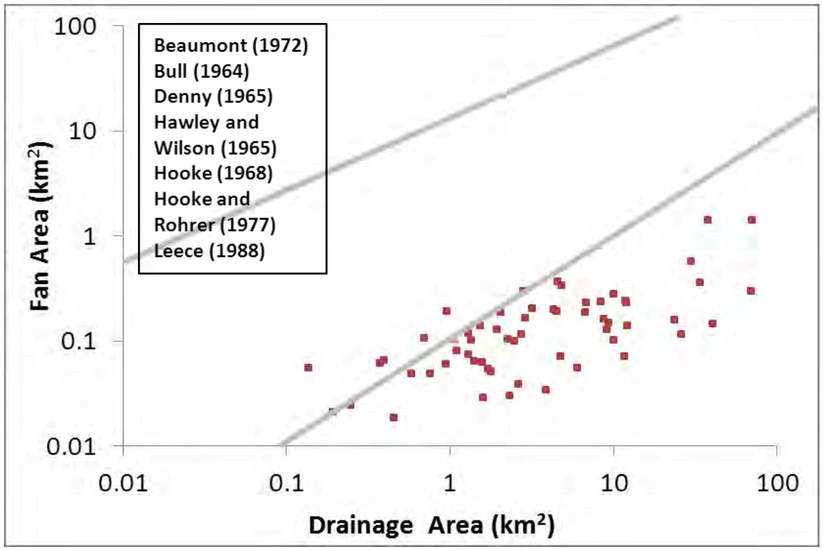

Figure 6.14: Drainage basin area versus alluvial fan area for fans in the Baviaanskloof Valley South Africa plotted alongside boundaries of data from published sources (grey lines and shaded area).

Basin ruggedness

The correlation matrix indicated a significant relationship between drainage basin area and Melton's Ruggedness number from north facing fans and fans in group 2 (Table 6.7). North facing basin ruggedness values are lower for fans with smaller fan areas indicating that smaller fans on the north facing side are produced from more rugged basins. South facing drainage basins produce larger fans with a lower Melton's Ruggedness Number (Figure 6.17). Group 2 and 4 are shown to have a larger ruggedness numbers for alluvial fans with larger areas (Figure 6.18). Group 1 basins tend to be larger in area, but are observed to have lower ruggedness values which suggesting that basins in groups 2 and 4 are more rugged than basins in group 1 (Figure 6.18).

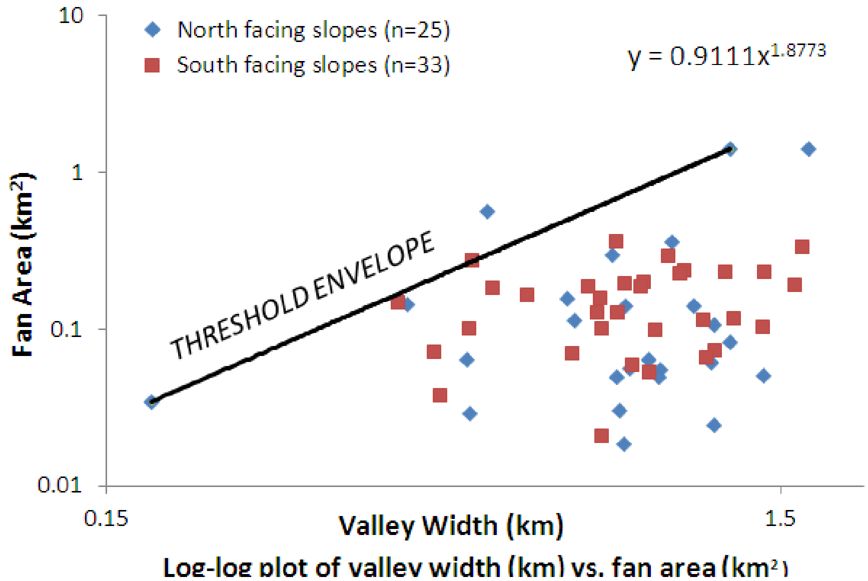

Figure 6.15: Log-log plot of valley width versus fan area

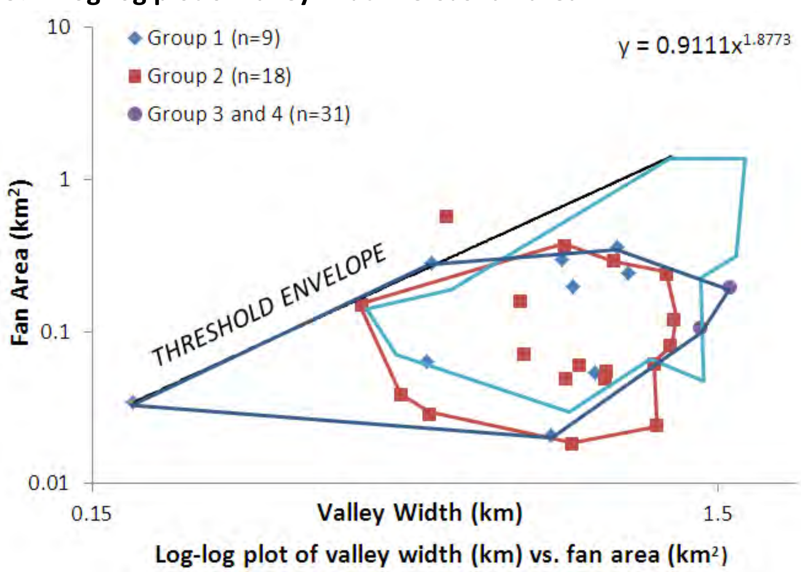

Figure 6.16: Log-log plot of valley width versus fan area for fan groups in the Baviaanskloof Valley

The more rugged south facing basins are a result of the poorly erodible basin geologies (dominated by quartzitic sandstone) and the less rugged north facing basins (dominated by quartzitic sandstone, enon conglomerates and shale) are a result of the more easily erodible geologies. In Chapter 3 it was explained that drainage basins consisting mainly of intensely fractured rock result in fractured zones producing a large amount of sorted material to the alluvial fan (Mills, 2000: 294). Drainage basins with a more resistant rock type may have a greater amount of sediment transported to the fan apex due to steep narrow valley sides or drainage basins (Mills, 2000: 294). Basins underlain with more erodible rock types provide a greater amount of storage space in the gentler valley side slopes than more resistant rock types (Mills, 2000: 294). This will result in less sediment being transported to the fan surface as it can be stored in the catchment as a temporary sediment sink. Fans on the north facing side of the valley are larger than fans on the south facing side (Figure 6.14) and can be said to produce and transport a large amount of material from the basin to fan surface as described by Mills (2000). Smaller fans on the south facing side of the valley (Figure 6.10), originate from a more rugged basin areas due to their poorly erodible basin geologies dominated by quartzitic sandstone.

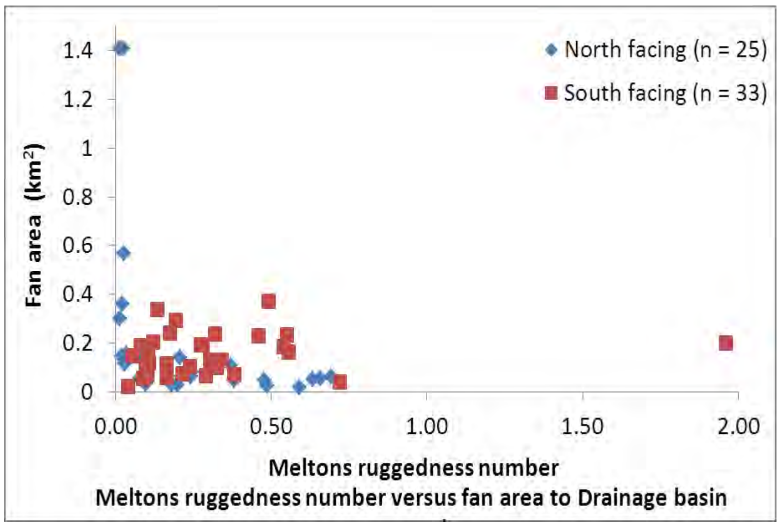

Figure 6.17: Melton's Ruggedness number versus fan area for fans in the valley

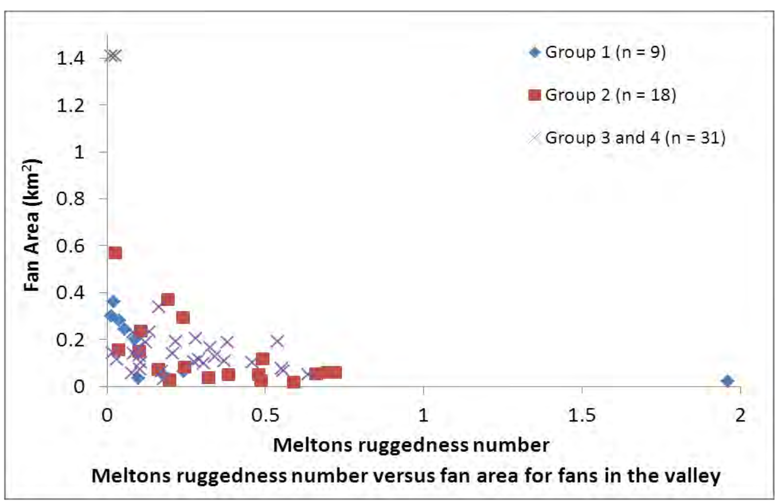

Figure 6.18: Melton's Ruggedness number versus fan area for fans in the valley

Multivariate analysis of control variables

The bivariate analysis of drainage basin area was the variable that best explained fan area and fan slope, however there is still a considerable amount of unexplained variation. A multivariate Principle Component Analysis (PCA) and regression analysis were chosen to fulfil these tasks to provide significant evidence of relationships, to gain a better understanding of control variable variation and to determine the influence of fan dependent variables. Variables considered independent variables were accommodation space, drainage basin area, Melton's Ruggedness number and Gravelius Index values (Table 6.7). The following multivariate tasks were completed:

1. To provide evidence of significant statistical relationships among the variables (multivariate: Principle Component Analysis (PCA))
2. To analyse the relationship and influence of control variables on fan area (multivariate: regression analysis)

Principle component analysis (PCA)

A multivariate PCA was used to identify the major direction of variation within a sample (Task 1) (Jolliffe, 2002). The PCA analysis was carried out in STATISTICA 9. The external control values were used as variables for the PCA values were represented as eigenvalues (eigen values explain the contribution of each factor to representing the variability of the dataset (Jolliffe, 2002)). Factors that have a latent root (eigenvalue) of one or higher were used and values less than one excluded (Jolliffe, 2002). Factors were collated and graphed on a scatterplot. Data was then scrutinised for clusters that show significant statistical relationships. The scatterplot of data clusters is shown below (Figure 6.19). The point number denotes the fan numbers identified in in Chapter 5. The PCA scatter plot indicates that there are no clear clusters of factors that influence fans in the valley as there are no clear groupings of fan points in Figure 6.19.

Regression values

The multiple R^2 and adjusted R^2 values were calculated for external fan control variables affecting alluvial fan area. Regression values were calculated for fans on both sides of the valley and between fan groups (Table 6.13 and Table 6.14). This was conducted using STATISTICA 9 software on external variables to calculate multiple R^2 and adjusted R^2 values to decide which control variables most affect alluvial fan area (independent variable). Symbols used for control variables are given in Table 6.6. The adjusted R^2 value is used to determine which of the external control variable improve the regression model and produce an improved relationship relative to the relationship above it in the table. The adjusted R^2 value will only change if the new term improves the model more than it would be expected by chance. Drainage basin area increased the adjusted R^2 value for all fans, north facing fans and group 1, 2 and 3 fans. This indicated that drainage basin area influences fan area more significantly than other external fan control variables (Table 6.13 and Table 6.14).

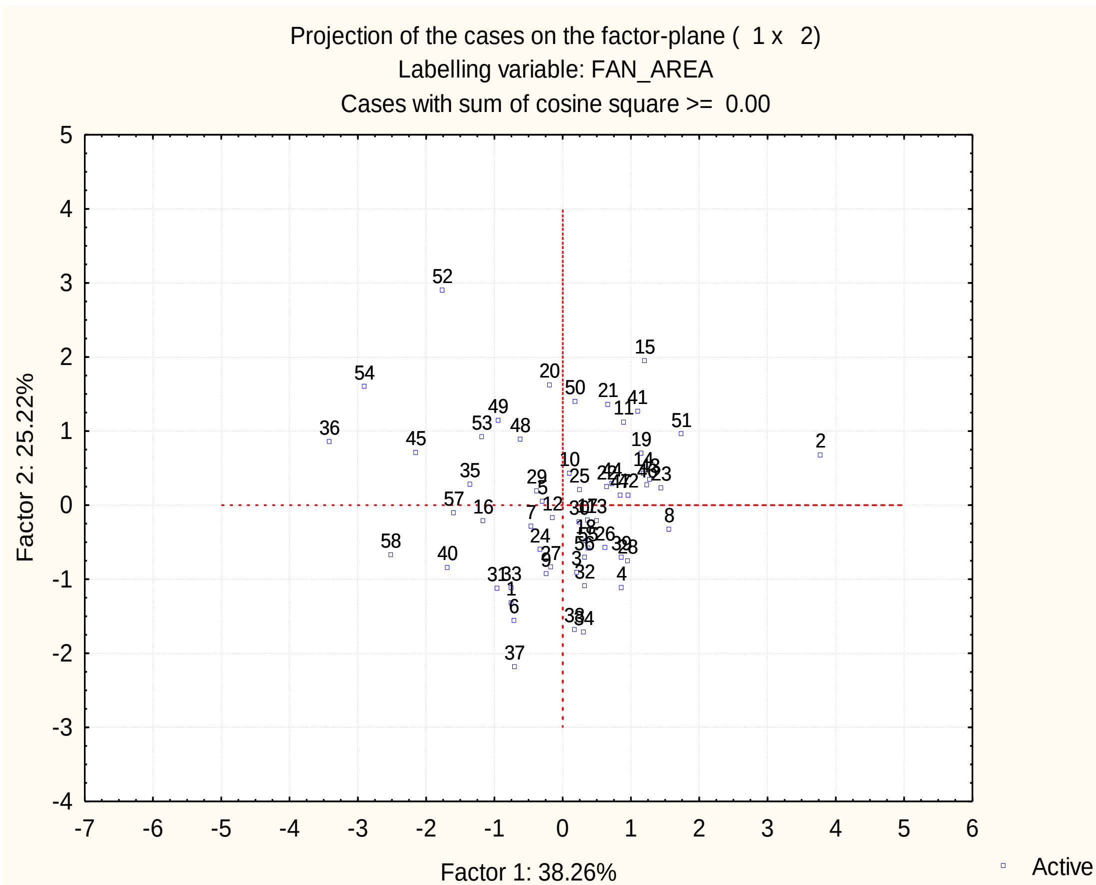

Figure 6.19: PCA scatterplot produced for fans in the valley

Summary of controls on alluvial fan area

As discussed earlier, alluvial fan areas on the north facing side of the valley are notably larger (<0.1 - >0.69 km^2) than south facing fan areas (<0.1 – 0.49 km^2). Significant control variables on alluvial fan area are indicated in a bivariate correlation matrix which points out significant relationships between alluvial fan area versus drainage basin area, alluvial fan area versus alluvial fan slope and drainage basin ruggedness versus basin area (Table 6.9). These relationships were then investigated further by conducting a t-test to discover the differences between the fan area to basin area ratio between north and south facing slopes and comparing findings to other published data. T-tests showed that north

Table 6.13: Regression values for all fans, north facing fans and south facing fans in the valley (fan area in the independent control variable)

		All Fans			North facing fans			South Facing Fans		
		Multiple R^2	Adjusted R^2	P Value	Multiple R^2	Adjusted R^2	P Value	Multiple R^2	Adjusted R^2	P Value
AS	X_1	0.10	0.08	0.63	0.17	0.13	0.33	0.07	0.37	0.06
DBA	X_2	0.57	0.56	0.24	0.64	0.61	0.02	0.27	0.22	0.97
GI	X_3	0.57	0.55	0.58	0.64	0.59	0.58	0.27	0.20	0.66
M	X_4	0.58	0.55	0.62	0.67	0.61	0.90	0.35	0.25	0.67

Table 6.14: Regression values for fan groups in the valley (fan area in the independent control variable)

		Group 1			Group 2			Group 3 and 4		
		Multiple R^2	Adjusted R^2	P Value	Multiple R^2	Adjusted R^2	P Value	Multiple R^2	Adjusted R^2	P Value
AS	X_1	0.20	0.09	0.86	0.03	-0.03	0.10	0.16	0.13	0.32
DBA	X_2	0.54	0.38	0.79	0.53	0.47	0.90	0.77	0.75	0.00
GI	X_3	0.54	0.26	0.96	0.61	0.52	0.16	0.77	0.74	0.21
M	X_4	0.81	0.61	0.18	0.62	0.50	0.20	0.77	0.73	0.30

facing basins produce larger fans per unit area (Table 6.12) but fans in the Baviaanskloof Valley produced smaller fans per unit drainage area when compared to semi-arid to arid fan studies in Iran, Spain and USA (Figure 6.19). Other significant variables investigated include accommodation space and basin ruggedness. Accommodation space does not severely influence fans in the valley, therefore the difference in fan size between the north and south facing sides of the valley may be linked to basin ruggedness as smaller fans on the south facing side of the valley originate from more rugged basins. The

PCA analysis provides no evidence that there is a particular set of factors influencing groups of fans in the valley (Figure 6.19). A regression analysis provided evidence that the relationship between drainage basin area and fan area is the most significant relationship between control variables (Table 6.13 and table 6.14).

Fan slope

Alluvial fan slope was calculated using methods outline in Chapter 5. The use of a DEM was shown to be the most accurate of methods of estimating fan slope (Chapter 4). Fan slopes incorporated the effects of toe trimming (Chapter 4). Alluvial fan slope is a function of the rate of sediment supply to the fans and the transport capacity of water flow across the fan surface. Factors that affect fan slope are basin slope and geology which affects sediment storage in the basin, basin size, geometry, ruggedness, sediment size and vegetation cover. The majority of fans on both sides of the valley and fans in fan groups have slopes between 2.00 - 3.99 % (Figure 6.20). It is noted that south facing fans have a greater slope than north facing fans (Figure 6.20) and fans in group 3 and 4 tend to have higher slope values than fans in group 1 and 2 (Figure 6.21).

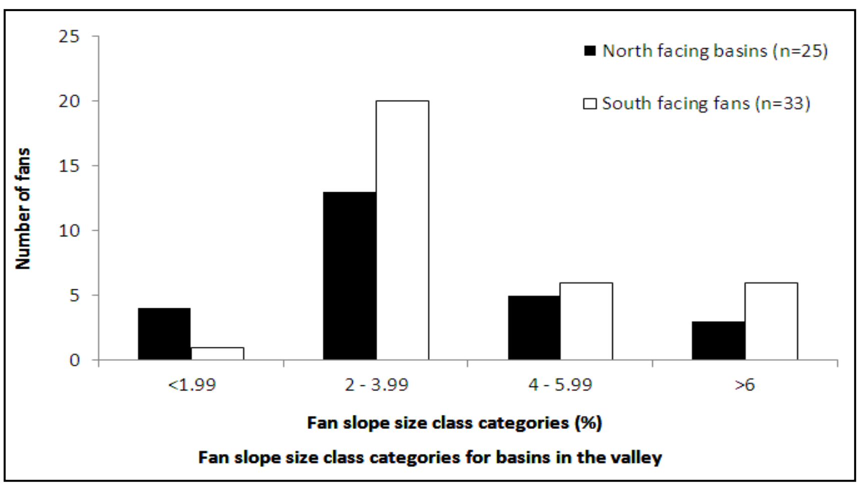

Figure 6.20: Fan slope size class categories for fans on the north and south facing side of the valley

Alluvial fan slope versus drainage basin area relationships

Using the nomenclature in Chapter 2, $G = aA^b$, the fan slope-drainage basin trend lines plotted for fans on the north and south facing slopes are given by the equations: north facing fans $G = 4.9013A^{-0.17,}$ R^2 = 0.26 and south facing fans: $G = 4.04A^{-0.122}$, R^2 = 0.20 (Table 6.15). Fans on the south facing side of the

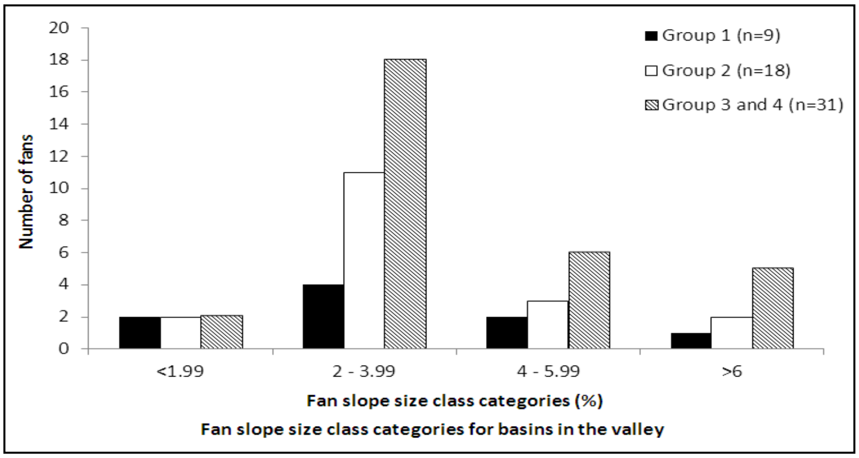

Figure 6.21: Fan slope size class categories for fans in fan groups

valley tend to steeper than those found on the south facing side (Figure 6.22). This could be due to a steep drainage basin slope and ruggedness value and consequent increased sediment transport to the fan apex (Figure 6.17). North facing fans have reduced fan slopes fed by larger drainage basins. The impact of sediment storage in the drainage basin areas may account for differences in slope values and area of fans in the valley. Fan groups 1 - 4 produce *a* values ranging from 0.4.11 – 0.4.85 and *b* values -0.12 – (-0.63), (Table 6.15). R^2 values range from 0.22 - 0.31 indicating a poor relationship. Parallel trends lines indicate that there is little difference between groups and that the relationship between fan slope and drainage basin for fans groups 1, 2 and 4 do not vary considerably.

Table 6.15: Equation variables of fan area to fan slope relationships

Group	Equation	R^2 Value	Standard Error
All fans	$G=4.445A^{-0.136}$	0.22	2.18
North Facing Fans	$G=4.9013A^{-0.17}$	0.26	3.20
South Facing Fans	$G=4.04A^{-0.12}$	0.20	0.50
Group 1	$G=4.5044A^{-0.163}$	0.31	5.582
Group 2	$G=4.1101A^{-0.134}$	0.22	1.41
Group 3 and 4	$G=4.8486A^{-0.155}$	0.23	2.10

Comparing fan area with other arid fan studies

The fan slope values calculated for fans in the valley are compared to relationships calculated for semi-arid and arid fans by Beaumont (1972), Bull (1964), Denny (1965), Harvey (1984), Hawley and Wilson (1965), Hooke (1968), Hooke and Rohrer (1977), Leece (1988) and Melton (1965) outlined in Table 6.12. Fan slope to basin area plotted for Baviaanskloof fans fall largely within the boundaries of other fan studies indicating that the fan slope to area of the basin is similar to other arid fan settings (Figure 6.24). A few fans with smaller basin areas plot below the fan boundary which indicated that fans with smaller basin in the Baviaanskloof Valley do not follow similar arid fan trends (Figure 6.24).

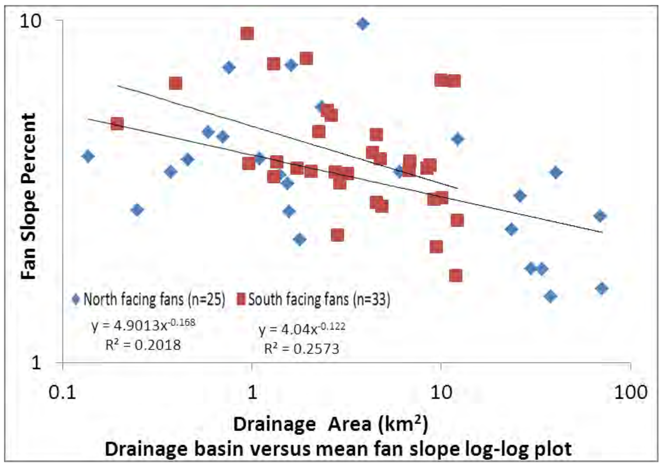

Figure 6.22: Fan slope versus alluvial fan drainage basin area plotted for all fan

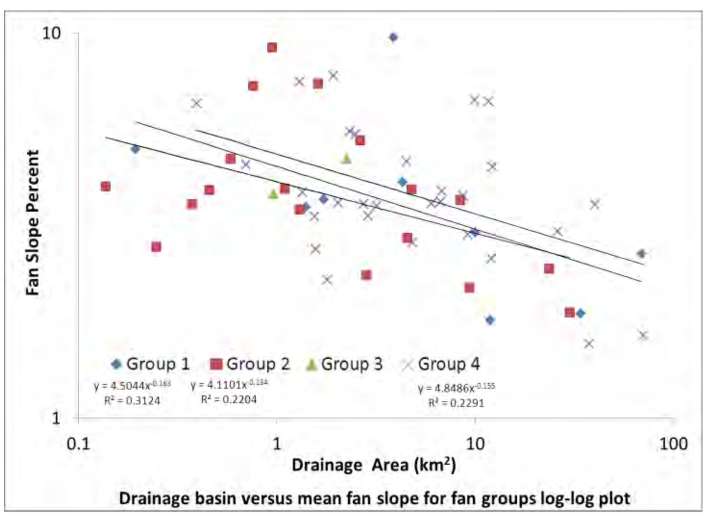

Figure 6.23: Drainage basin area versus mean fan slope calculated for fan groups

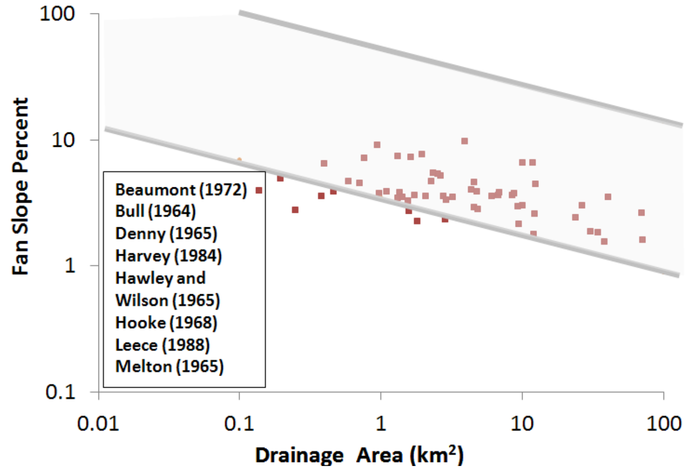

Figure 6.24: Drainage basin area versus alluvial fan slope (%) for fans in the Baviaanskloof Valley South Africa plotted alongside boundaries of data from published sources (grey lines and shaded area).

Past fan climates based on fan slope

Milana and Ruzyucki (1999: 560) identify tentative graphical separations of arid, semi-arid and humid climates for fan slope and use this graph to classify fans from a number of climatic regions that include Spain (semi-arid/temperate – arid), California coastal fans (semi-arid - temperate), Death Valley (arid) and western Argentina (arid), (Milana and Ruzyucki, 1999:560). Fans in the Baviaanskloof Valley plot in between the semi-arid - temperate to arid separation, which is in line with other fans in the Death Valley and western Argentina (located between 0.005 – 0.2 degrees), (Milana and Ruzyucki, 1999: 560). Figure 6.25 suggests that fans in the Baviaanskloof Valley have formed in a past climate that is similar to present climates, but tending towards more arid conditions.

Fan channels (process related)

As explained in Chapter 5, a detailed survey is required to provide an accurate account of fan channels, channel migration and fan trenching. In this chapter, an analysis of fan channel information collected in the spatial plan will summarize fan channel trends throughout the valley. A detailed fan survey study and fan profiles will be conducted in Chapter 7.

The modified fan evolution table of Clarke (2010) (Table 2.2) used to determine the stages of fan evolution in the valley based on fan channel information. Fan stage 1 is characterised by fans with no fan channels and accumulating volume. Fans in stage 2 have one or two fan channels with evidence of channel migration. Fans in stage 3 are incised at the fan apex. Stages 4 and 5 were an addition to Clarke's table to include fans that are incised at the fan apex and distal fan surface (stage 4) and where fans were identified as fossil features with trenched channel along its length and no sediment deposition on the fan surface (stage 5). Data used to compile the table was sourced from the spatial plan (Appendix Table A.1 and Table A.2).

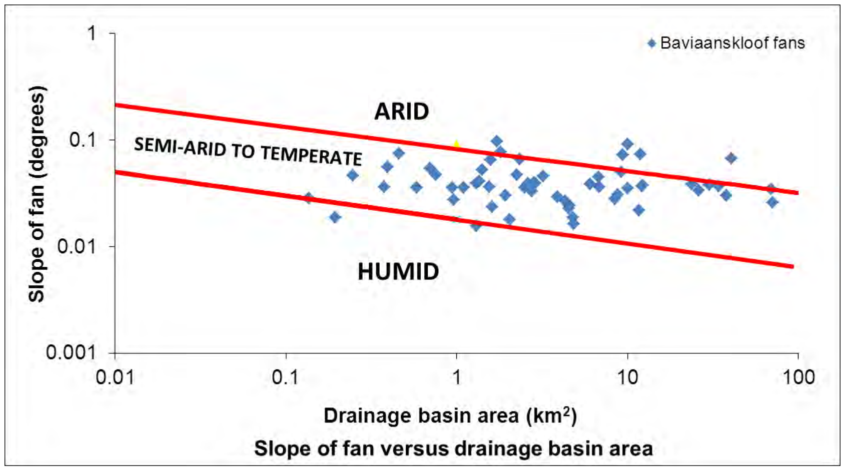

Figure 6.25: Regression lines for the relation between drainage-basin area and slope of alluvial fans for sets of fans in different geographical areas showing tentative climate separations for arid, semi-arid – temperate and humid (adapted from Milana and Ruzyucki, 1999: 560).

Fans in the Baviaanskloof Valley tend to have fan channels subject to incision in the proximal, medial and distal fan surfaces (stage 1, 2 and 3). Most fans in the valley are shown to be at stage 3 of fan evolution and are considered mature features in the landscape (Table 6.16). These stages do not appear to be confined to one section in the valley; however, fans in group 3 and 4 have the maximum number of fans in stage 3 and 5.

A chi-squared test was used to investigate the significance of toe trimming on fan incision (Table 6.17). Methods used to determine toe-trimming are outlined in Chapter 5 and data used for fan toe trimming are given in Appendix Table A.2 (part b). The test analysed the effects of toe trimming (toe trimmed, not toe trimmed) for fans that are incised and not incised (stages 3, 4 and 5) (Table 6.167 The null hypothesis (H_o) was that there is no difference between the number of toe trimmed fans for fans with incised channels and non-incised fans. The calculated x^2 value was 85.02. The critical value at 3 degrees freedom (df) is x^2 = 7.82 (significance level of 0.05). The null hypothesis was rejected at 0.05 significance level as x^2 critical > x^2 calculated and it is concluded that there is a real difference in the number of fans that have become incised due to toe trimming.

Table 6.16: Stages of fan evolution for groups of fans

Fan stage	Group 1	Group 2	Group 3 and 4
1	1	5	2
2	0	2	5
3	6	6	16
4	0	2	3
5	2	2	5

Table 6.17: Data used for chi squared test that includes fans stage (linked to incision) and toe trimming

	Toe trimmed	Not toe trimmed
Stage 1 and 2: no fan incision	1	14
Stage 3 incision (apex)	11	17
Stage 4 incision (apex and distal)	2	3
Stage 5 incision (dissected fan)	9	1

6.3. Summary of key findings

Fans are influenced by a number of external and internal control variables outlined in the form-process framework, Chapter 3, where possible, control variables were analysed between valley sides and between fan groups identified in Chapter 5. It is noted that significant relationships are found to exist between valley sides but very rarely between fan groups. This summary will provide key findings of this chapter starting with external control variables that influence fans and then focusing on fan internal control variables.

External control variables

The influence of accommodation space on fans was determined by assessing the space available for fan formation on the valley floor. It was noted that in valley sections where two fans form on opposing sides of the valley the accommodation space is halved. The influence of accommodation space on fan area was further examined using bivariate and multivariate data analyses techniques from which it was concluded that accommodation space does affect fan formation in the valley, but it not the primary variable influencing fans in the valley.

Tectonics and sea-level change have been responsible for base-level changes on the fan surface in the past. This analysis identified the lateral migration of the main river channel is the primary factor contributing to base-level induced change on the fans surface due to the effects of toe trimming. These are then linked to a greater probability of distal fan incision shown by the chi-squared test.

Fans in the Baviaanskloof Valley have been subject to man-made water diversions on the fan surface since the 1970s and 1980s and are largely cultivated and occupied (mainly on the south facing side of the valley). Rainfall in the Baviaanskloof Valley is erratic and spatially variable which owes to the formation of fans in the valley.

The spatial variation of rainfall over fan basins results in not all fans being active at once. Fans provide soil moisture niche areas for vegetation growth that allows for grasses, shrubs and trees to grow in dense populations which contribute to a greater shear slope strength. The south facing side of the valley is more rugged and is comprised of more resistant geologies which have the potential to have a less amount of sediment storage in the basin area compared to north facing basins which are shown to have a larger area, more elongated in shape and are less rugged than south facing fans.
Internal control variables

Internal control variables
Fans in the Baviaanskloof Valley are typically characterised by tributary junction fans that are shown to be more affected by the relationship between alluvial fan area and drainage basin area (Figure 6.12 and 6.13). Based on fan channel characteristics, it is noted that most fans in the valley have evolved to stages 3 – 5 of evolution (Table 6.16) and fans can be considered relatively mature features of the landscape. A chi-squared test reveals that there is a significant difference in the results of fans that are incised (Table 6.17) and toe trimmed (stages 4-5) and fans that are not incised and not toe trimmed (Figure 6.12 and 6.13).

Chapter 7: Case Study

7.1. Introduction

This chapter aims to provide an overview of the surface characteristics of two alluvial fans in the Baviaanskloof Valley to fulfil the requirements of objective 4 (Chapter 1). Criteria used for alluvial fan selection were based on toe trimming and headcut development and will be discussed in detail in the methods section. Toe trimming and headcut development, based on field observations, have been noted to be a potential indicator unstable fan systems. Fans were surveyed using a differential GPS survey system and sediment samples were collected to determine changes in the local fan slope, main channel, secondary channels and depositional zones. Methods of analysis included the creation of transverse and longitudinal fan profiles and the measurement of clast and particle size.

7.2. Methods

7.2.1. *Fan Selection*

The application of the form-process relationship in Chapter 3 indicates that a number of fans in Baviaanskloof Valley are toe trimmed due to a laterally migrating main river channel. The effects of this can be evaluated by comparing the surface and sediment characteristics of a naturally forming fan and a fan that has been toe trimmed. Two fans were selected (one natural and one toe trimmed) based on fan location within the valley (fan group), side of the valley and distance between fans. Fans selected were fans 6 and 11 as identified in the spatial plan (Chapter 5). These fans were part of the same fan group (group 2), 4kms from each other (from polygon centroid – centroid) and located on the south facing side of the valley. It can be assumed then that these fans therefore form as a result of a similar fan setting and influences. Fan 6 is identified as forming unhindered on the valley floor and shows little evidence of influence by a laterally migrating river channel. Fan 11 is a classic example of a toe trimmed fan showing evidence of the influence of a laterally migrating main channel. A summary of fan 6 and fan 11 spatial morphometry data calculated in Chapter 5 is given below in Table 7.1.

Table 7.1: Summary of fan 6 and fan 11 spatial morphometry data

1. Drainage basin morphometry						
Object-ID	X-Coord	Y-coord	Area (km2)	Perimeter (km)	GI Index	Melton's Ruggedness
6	23.837329	-33.534544	9.38	15.45	1.4	0.1
11	23.884344	-33.532501	1.30	6.16	1.5	0.5

2. Fan spatial morphometry						
Object-ID	X-Coord	Y-coord	Area (km2)	Perimeter (km)	AFA:DBA	Mean fan slope (%)
6	24.096140	-33.573952	0.15	1.59	0.016	2.2
11	24.036962	-33.558544	0.12	1.47	0.091	3.5

Other fan characteristics					
Object-ID	Fan Type	Toe Trimmed	Cultivated	Buildings	Property
6	simple mountian front	0	0	0	Verloren Rivier
11	backfilled mountain front	1	0	0	Uitslag

3. Fan channels				
Object-ID	Number of Channels	Incison	Braided	Evidence of channel migration
6	2	upper and middle fan surface	yes	yes
11	2	upper and lower fan surface	no	yes

3. Fan basin geology			
	Code	Rock Type	Percent in fan drainage basin area
Fan 6	Oc	Shale	0.18
	Op	Quartzitic sandstone	5.37
	Ss	Quartzitic sandstone (feldspatic)	2.59
	Sg	Quartzitic sandstone (shale)	1.16
	Tg	Terrace gravel	0.04
	Code	General	Percent in fan drainage basin area
Fan 11	Ke	Enon Conglomerate	0.02
	Op	Quartzitic sandstone	1.10
	Ss	Quartzitic sandstone (feldspatic)	0.01
	Sg	Quartzitic sandstone (shale)	4.59E-03
	Al	Alluvium	0.15
	Tg	Terrace gravel	0.01
	Op	Quartzitic sandstone	2.69E-04
	Sg	Quartzitic sandstone (shale)	1.06E-06
	Tg	Terrace gravel	6.62E-05

7.2.2. *Alluvial fan surveys*

A differential GPS survey system was used to survey transects across the fan surface and along fan channels (Figure 7.1). This method was the easiest means of surveying alluvial fans given the density of vegetation and limited site lines across the fan. Two Promark (Promark II and Promark III) units were used as part of the differential GPS survey system. The Promark II unit operated as a base station and the Promark unit III was used as a roving GPS unit. The DGPS real-time accuracy of the Promark II unit is between 3-5 metres and the Promark III is <1m. Three transverse transects located on the upper (proximal), middle (medial) and lower (distal) fan surface were surveyed, together with one longitudinal survey of the fan surface and main channel survey (Figure 7.1). The base station was programmed to record co-ordinates at five second intervals and co-ordinates on the roving GPS unit were manually recorded at points of interest. The co-ordinates of obvious changes along each transect such as the main channel, secondary channels, channel bends, local depositional zones, ridges, fan edges or at the beginning of channel headcuts were noted.

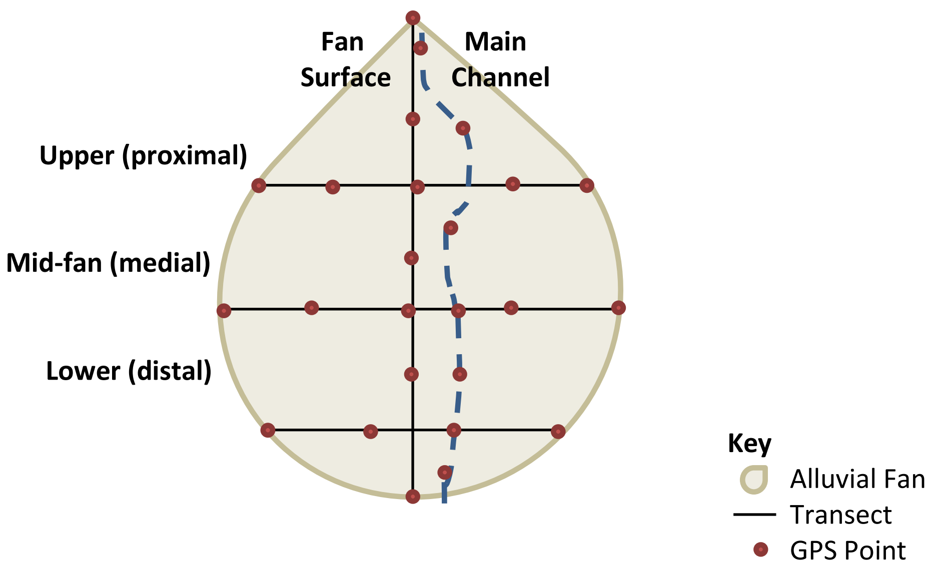

Figure 7.1: Schematic diagram of alluvial fan transect surveys

7.2.3. *Map of survey points*

Survey data was downloaded from the Promark II and III units using GNSS Solutions software. The nature of the differential system setup allowed for GNSS solutions to plot GPS points and calculate distances between survey points using the base station setup as a reference position. The raw data was then saved as a Microsoft Excel Workbook (.xls). The data was then added as 'XY data' using ArcMap 10 software using spheroid WGS 1984 and checked for accuracy by overlaying points onto SPOT imagery (as used in Chapter 5) to ensure the main channels, edges of fans and other obvious alluvial fan surface characteristics correlated with features found on the aerial (SPOT) imagery. The used points were renamed for convenience.

7.2.4. *Map of fan transects*

Transverse and longitudinal profiles were created using the same method. The transect points were opened in GNSS solutions to ensure data accuracy. The distance between points was determined by measuring the distance in meters between collected GPS co-ordinates (distance between the two centroids of consecutive points per transect and recording point heights from downloaded data). The heights of GPS points along the transect survey were recorded (in metres) from the GNSS spread sheet downloaded from the Promark III unit. Data was then captured in a MS Excel spread sheet and plotted using straight line graphs to highlight the cumulative distance along the transect on the x-axis and height values for each of the surveyed transects and the y-axis.

7.2.5. *Sediment samples*

Sediment was analysed to determine the surface material of the fan. Sediment analysis can be used as a measure to indicate the transport power of water from the catchment area, indicate the geology of the catchment and allows for the sediment size to be determined as this can reflect water infiltration rates on the fan surface. Sediment samples were collected along the proximal (upper), medial (middle) and distal (lower) fan surfaces (Figure 7.2). An average of three or four sediment samples were collected across each of the fan surfaces. Samples sites were initially selected to represent each side and centre of the fan, but at each location they were randomly selected by tossing a marker over one shoulder and taking a sample where the marker landed. For each sample site, a 1m^2 quadrat was used to analyse alluvial fan surface material (particle grain size) and sediment matrix (Figure 7.2). At each site a large clast (pebble and greater) and a matrix sediment sample were collected (Figure 7.3). Samples were collected using a trowel and stored in an airtight labelled sample bag until laboratory analysis. Measurement taken in the field included GPS co-ordinates of all sample and the measurement of pebble, cobble and boulder axes using a 5m tape measure and set of callipers (Figure 7.3). The longest (a-axis), intermediate (b-axis) and shortest (c-axis) were measured and recorded in millimetres.

7.2.6. *Work limitations and difficulties*

Analysis of field data was limited to the data collected in the field during the week long data collection fieldtrip and is therefore considered a snapshot view of fans in the landscape. Local seasonal variation in survey data or sediment samples was not considered. Although local scale processes and trends can be identified, this cannot be extrapolated for all fans in the valley. Difficulty in converting the data from two different GPS models used in the roving survey and formatting made map creation and editing time consuming. Data format issues took time to resolve.

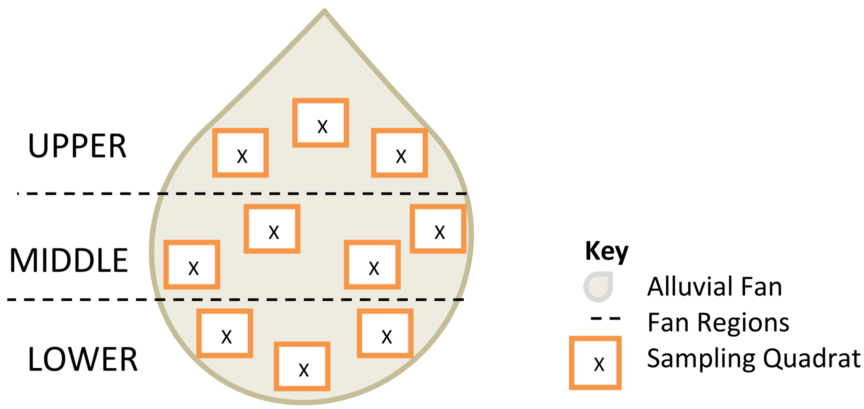

Figure 7.2: Distribution of randomly selected sediment sampling quadrats on the fan surface

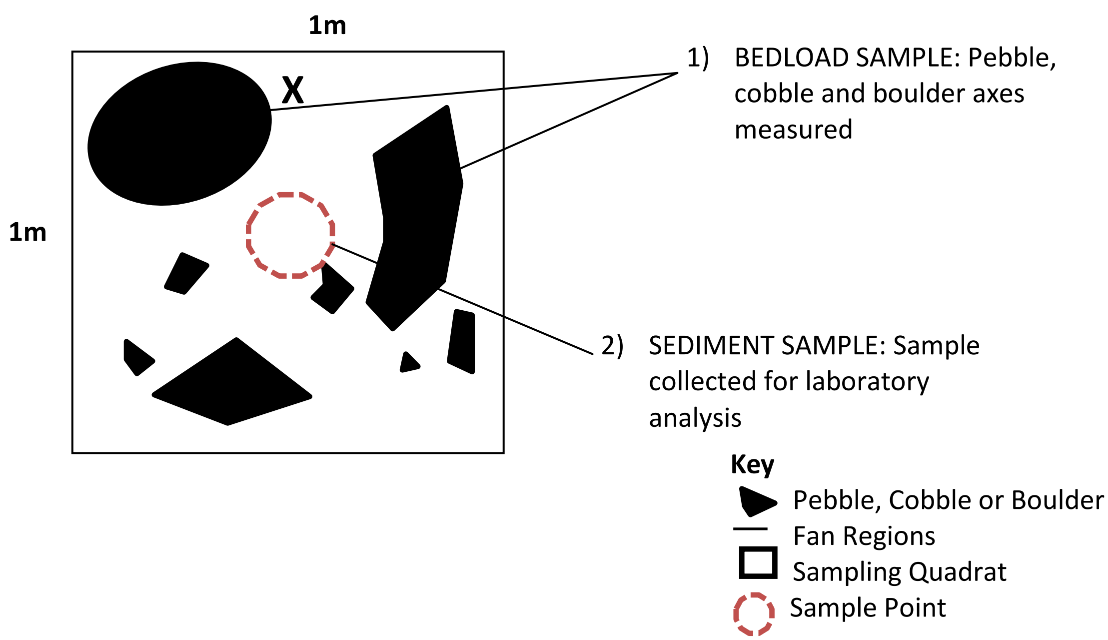

Figure 7.3: Data collected from the sediment sampling quadrat (1mX1m)

7.3. Sediment sample analysis

7.3.1. *Sediment Preparation in the laboratory*

Open Sediment sample bags were placed in a soil drying oven set at 45^0 Celsius until all moisture had been removed from collected samples. Once dried, soil bags were closed and stored until sediment analysis took place. Dried samples were used to determine organic matter content and grain size.

7.3.2. *Organic Matter Content*

The organic matter content of soil samples was determined using the loss on ignition method described by Briggs (1977). Approximately 5-6g of sediment was removed from each sediment sample bag and was fired in a muffle furnace set at 450^{0}C for 24 hours.

7.3.3. *Particle size Analysis*

Particle size classes were defined according to the Wentworth Scale and analysed according to three methods (Table 7.2), from large to small size class fractions. The dimensions of boulders, cobbles and pebbles were measured in the field using a measuring tape and a set of callipers. The sieve method was used to determine grain size distributions (gravel to fine sand); the finest fraction was then re-analysed using a sedigraph (coarse silt – clay), (Table 7.2).

7.3.4. *Coarse particle sizes (sol matrix)*

Coarse grain sizes from 4 – 0.063mm were analysed using the sieve analysis technique as given by *The Non-Affiliated Soil Analysis Work Committee* (1990). The sieve analysis procedure was followed using a mechanical shaker to sort size class fractions (Table 7.3). Size class fractions used to differentiate between particle sizes is given in Table 7.3. The approximate weight of samples was 1.00 -1.50 kg and sieving time was 20 minutes.

7.3.5. *Fine particle size analysis*

Samples with >5% or <0.063mm class fractions were re-analysed for silt and clay using the Micrometrics SediGraph III. Samples with less than 5% of <0.063 mm fractions were not sampled as the proportion of fines did not constitute enough of the sediment sample. Sample preparation required by the SediGraph III involved the removal of organic matter and suspension of the prepared sample in a 0.04% sodium hexametaphosphate solution.

Table 7.2: Particle size class and methods used for particle size analysis

Class	Diameter (mm)	Method of analysis
Boulders	>200	Manual measurement of clast dimensions
Cobbles	64-200	Manual measurement of clast dimensions
Pebbles	4-64	Manual measurement of clast dimensions
Gravels	4 - 2	Sieve
Very coarse sand	2 - 1	Sieve
Coarse sand	1 – 0.5	Sieve
Medium sand	0.5 - 0.25	Sieve
Fine sand	0.25 – 0.125	Sieve
Very fine sand	0.125 - 0.063	Sieve
Coarse silt	0.063 - 0.31	SediGraph III
Medium Silt	0.031 - 0.016	SediGraph III
Fine Silt	0.016 - 0.008	SediGraph III
Very Fine silt	0.008 - 0.002	SediGraph III
Clay	0.002 - 0.001	SediGraph III

Table 7.3: Sieve number and opening size of sieves used in analyses

Sieve nr.	Size of openings (mm)
1	Greater than 4
2	2
3	1
4	0.500
5	0.250
6	0.125
7	0.063
PAN	Less the 0.063mm

The preparation procedure can be sourced in *The Non-Affiliated Soil Analysis Work Committee* (1990:35). Organic matter was removed using the standard hydrogen peroxide removal procedure. The dry sample was then weighed, labelled and stored in an airtight sample bag until the time of SediGraph III analysis. A 0.04% sodium hexametaphosphate solution was mixed (4g $(NaPO_3)_6L^{-1}$) and used to suspend the dry sample. Three grams of the prepared dry sample was weighed in a beaker and mixed with 40ml of the 0.04% sodium hexametaphosphate solution and disaggregated with a spatula. Samples were then transferred into an ultrasonic bath for 5 minutes prior to readings being taken. This ensured sediment was in suspension at the time of analysis. To ensure all particles were transported into the chamber 10ml of the 0.04% sodium hexametaphosphate solution was used to wash out the beaker (the total amount of dry sediment in the sample chamber was 3g and the total amount of 0.04% sodium hexametaphosphate solution added to the chamber was 50ml). The time elapsed to process each sample in the SediGraph III was twenty minutes (an overview of the setup parameters are given in Appendix Z). During the rinse cycle the chamber was also manually cleaned with paper towel to ensure there was no cross contamination between samples.

7.4. Presenting grain size data

7.4.1. *Maximum clast diameter*

The maximum clast diameter of samples was determined using methods by Mills (2000:288). The boulder, cobble and pebble axes measurements recorded in the field were used to determine the largest diameter of material from the alluvial fan apex to the fan toe. This method was selected, rather than using the b-axis, as it provides a means of assessing embedded material where only two boulder axes could be measured. The maximum clast diameter is an indicator of the stream power required to deposit material from the source area. The maximum clast diameter was plotted along the fan longitudinal profile to position clast diameter along the profile distance and profile height.

7.4.2. *Coarse grain size data*

The percentage of coarse grain size data retained for gravel (2mm-4mm), sand (0.6063mm- 2mm) and combined clay and silt size class fractions (0.063-0.001) were plotted on a Sneed and Folk triangular diagram (triplot) to provides a visual representation of the data (Figure 7.4). A Sneed and Folk triangular triplot spread sheet designed by Graham and Midgley (2000) was used to input percentage retained values for gravel, sand, silt and clay. Two separate coarse grain size triplots were created for fans 6 and fan 11.

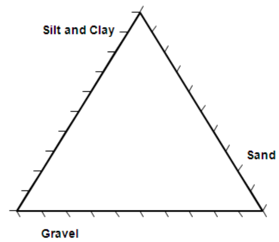

Figure 7.4: Sneed and Fold diagram (triplot) for gravel, sand and silt and clay grain size class fractions (Graham and Midgley, 2000).

7.4.3. *Fine grain size data*

A standard cumulative percent finer graph was plotted for fine grain size data against particle diameter as shown in Briggs (1977). The re-analysed silt and clay size class fractions were plotted as a line graph to show the distribution of silt and clay particles for each of the samples. Clay size class fractions are defined as clay (0.002-0.063mm) and silt (0.001 - 0.002mm).

7.5. Results and discussion

7.5.1. *Fan form*

The results and discussion will be merged in this section as it is intended to be a general summing up of results and key findings of this chapter. Further discussion is provided in chapter 8, which presents a holistic overview of project findings. The identification of key fan morphological components for fans 6 and 11 show the locations of the feeder channel (FC), the fan apex (A) and intersection points (IP), (Figure 7.5). It is noted that fan 6 is incised on the proximal and medial fan surface and fan 11 on the upper and distal fan surface with the occurrence of two headcuts (Figure 7.5). Fan 6 has one intersection point whereas fan 11 has multiple intersection points. Two alluvial fan maps were compiled using alluvial fan survey points and sediment sample sites to indicate the locations of the upper, middle and lower fan surface as well as the fan channels. Fan 6 has no obvious signs of headcut development and has been allowed to form unhindered on the valley floor with little visual evidence of limited accommodation space on the valley floor (Figure 7.5). There is also evidence of previous toe trimming as a result of a laterally migrating main river channel (Figure 7.6), but the fan does not appear to be affected by a laterally migrating main channel at present as the current fan surface is not hindered by the river. This is noted by the curved natural line that forms the boundary of the fan surface which reflects no obvious signs of hindrance.

The main fan channel on fan 11 is located on the side of the fan where the channel becomes incised at the distal face surface after a headcut (Figure 7.7). This headcut appears to be active given the depth of the headcut (3 m) and ground instability around the headcut region. Another headcut is observed on the distal fan surface with no clear channel feeding into it (Figure 7.7). The boundary of this fan shows obvious signs of a laterally migrating main river channel (that has since moved away) with a slightly dis-jointed distal region (Figure 7.7). The combined evidence of headcut development and evidence of toe trimming suggests an induced base-level change has occurred on fan 11.

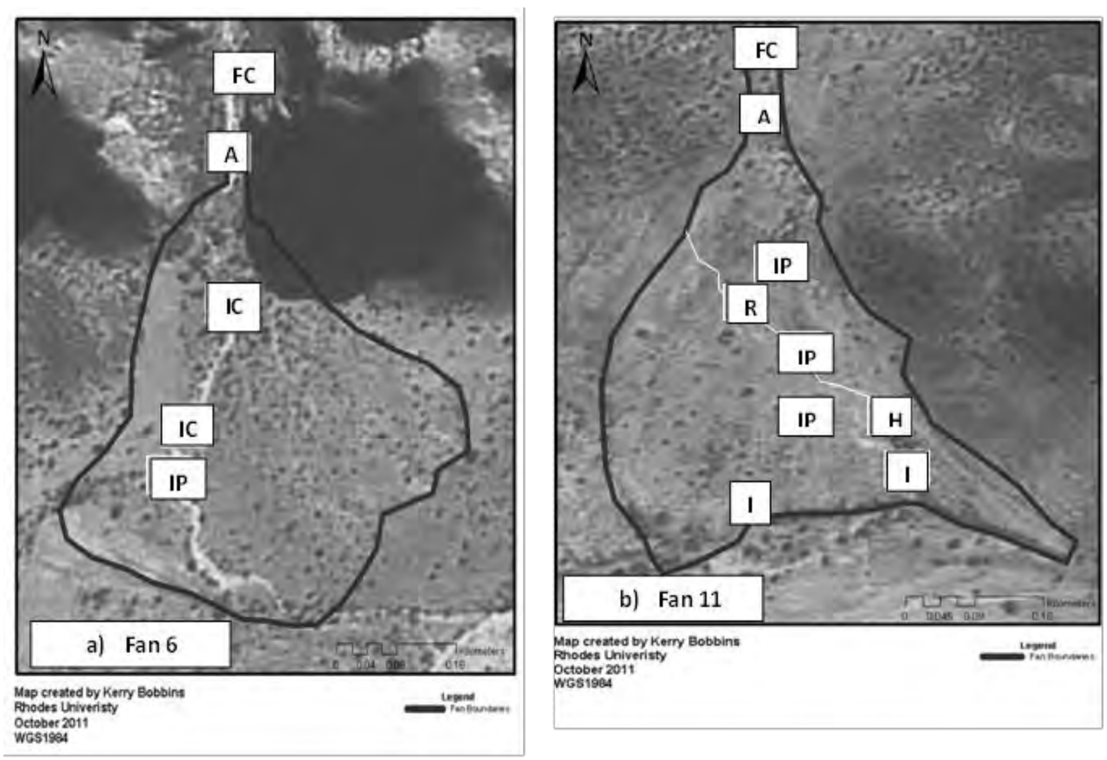

Figure 7.5: Identification of key fan morphological components for a) fan 6 and b) fan 11. Morphological units identified from Blair and McPherson (1994:357) A: Apex, IC: Incised Channel, IP: Intersection Point, FC: Feeder Channel, R: Road, H: Headcut and I: Incision.

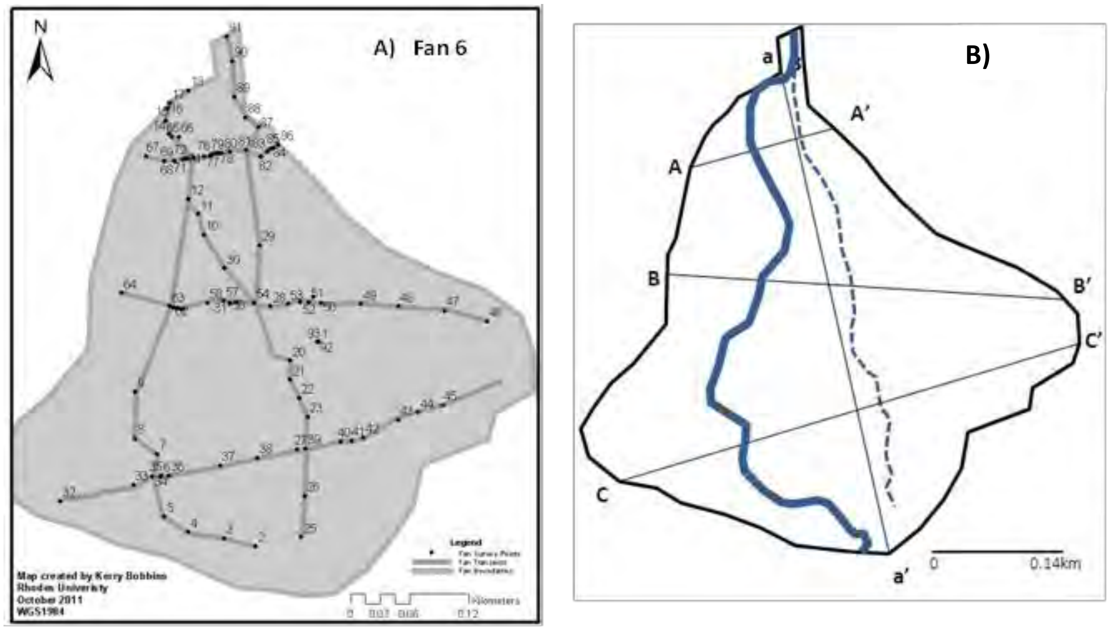

Figure 7.6: Map of fan 6 showing a) the fan surface area and survey points collected b) diagram of fan transects and channels. Transects are shown by the line AA', BB' and CC' and are drawn for the upper, middle and lower fan surface respectively. Thick dark blue lines indicate the main fan channel and the dashed line, the secondary fan channel.

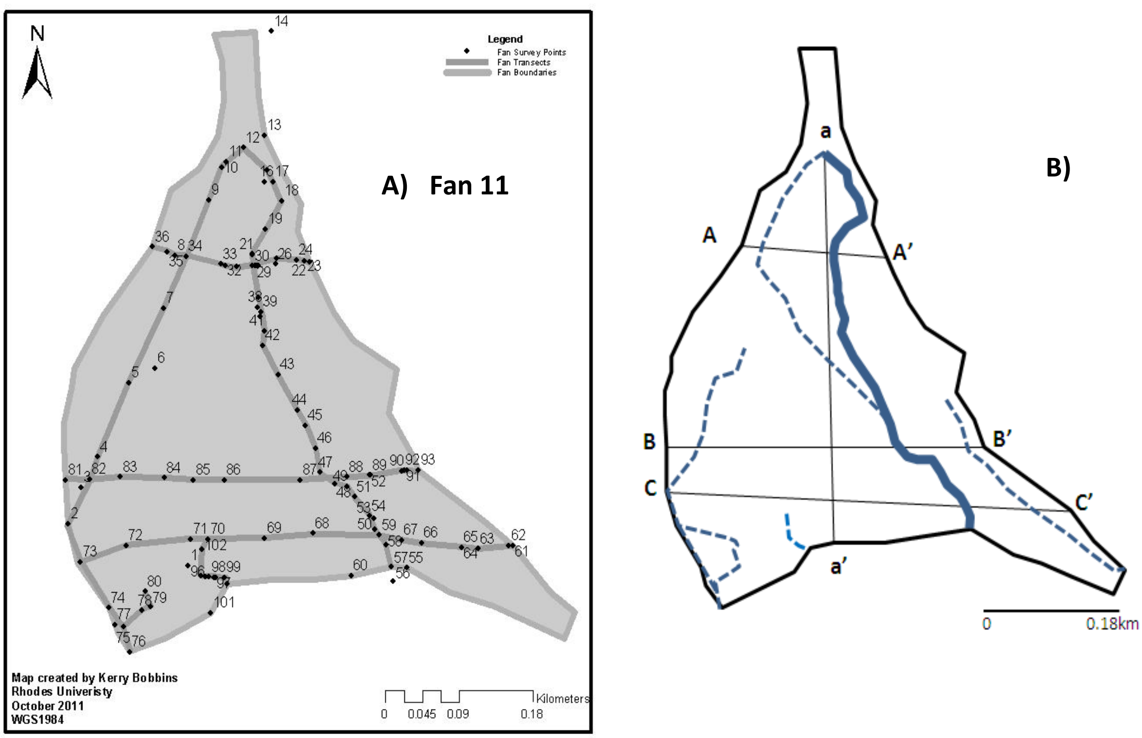

Figure 7.7: Map of fan 11 showing A) the fan surface area and survey points collected B) diagram of fan transects and channels. Transects are shown by the line AA', BB' and CC' and are drawn for the upper, middle and lower fan surface respectively. Thick dark lines indicate the main fan channel and the dashed lines, the secondary fan channels.

7.5.2. *Channels*

It is noted that the main channel of fan 6 runs down the west side of the fan with an older secondary channel that runs directly down the middle of the fan surface (Figure 7.6). The active depositional lobe of fan 6 is located on the west side of the fan where the main channel deposits sediment on the fan surface. The older fan surface is located on the east side of the fan where the older channel is located (Figure 7.6).

Fan 11 is characterised by a well-defined main channel with a number of secondary channels that flow on either side of the main channel on the fan surface (Figure 7.7). A number of the secondary channels are active and not only remnant from a previously active depositional lobe. The depositional processes are therefore not isolated to one major depositional lobe on fan 11, but rather across the whole fan surface. From field observations of sheetwash over the fan surface it was assumed that water flows across most of the fan surface during rainfall events. A gravel road positioned across the fan surface was observed to channel sheetwash and transport water to a large headcut on the fan surface, marked by "R" (Figure 7.7).

7.5.2.i. *Fan profiles*

Transverse profiles

Alluvial fan transverse profiles indicate the location of channels on the fan surface (localised depressions) and illustrate the effects of lateral erosion on the fan surface. Both fans produce a convex transverse slope throughout the length of the transverse profiles (Figure 7.8 and Figure 7.9). The convexity of the fan surface becomes more subdued in the middle and at lower regions of the fan surface due to the reduction of fan deposition from the fan apex. It is observed that areas of deposition are found in proximity to fan channels where the locus of maximum deposition is found. This is an indicator of the effective functioning of the fan surface. This is clearly observed for fan 6 and less so for fan 11 (Figure 7.8 and Figure 7.9). As explained above, transportation of water and sediment in fan 6 is confined to the main channel whereas fan 11 shows signs of surface water flow which has resulted in obvious areas of deposition for fan 6 and less so for fan 11 with the most obvious evidence of deposition being found along the main channel (Figure 7.8 and Figure 7.9).

Fan 6 is characterised by a main channel and a secondary channel that transports water and sediment from the fan apex to the distal fan, increasing the connectivity of water and sediment between the source area and the fan surface. Fan 11 is characterised by a number of smaller fan channels and sheet wash that transports water and sediment from the proximal to distal regions of the fan surface in channels and across the fan surface. Not all sheet flow is channelled and this explains the low number of localised depositional areas on the fan surface (Figure 7.9). Local deposits of sediment are largely a result of sheet wash rather that due to deposition through the main channel. The incised channel on the distal fan surface, together with the large headcut, have caused an increased connectivity between the fan source area and the floodplain. Water and sediment is not deposited on the distal fan surface, as indicated by the thickness of fan sediments in the distal region of the fan surface which is much less than the thickness of sediments at the proximal region of the fan.

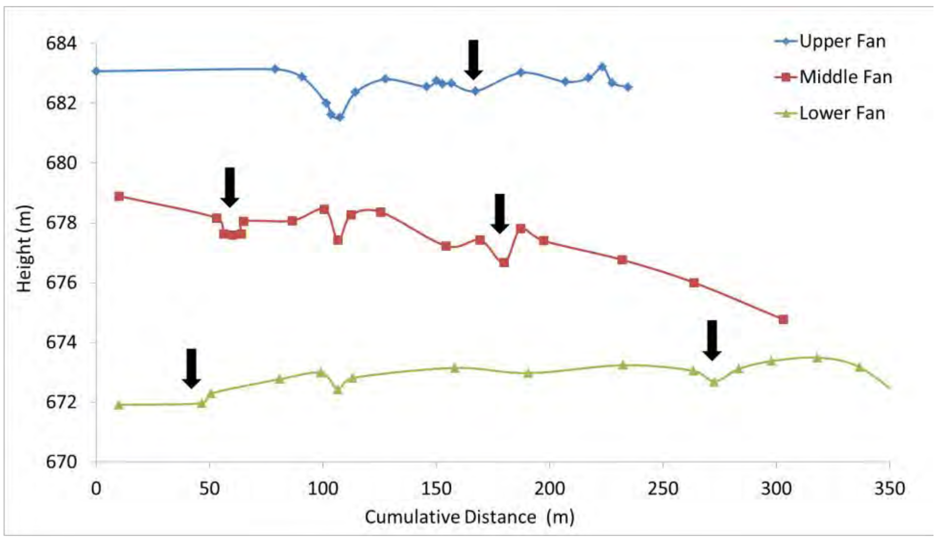

Figure 7.8: Transverse profile of fan 6. Black arrows indicate channels.

Longitudinal profiles

Sediment deposition on the proximal region of the fan surface occurs at a more rapid rate than at the distal region due to the stream power relationships as discussed in Chapter 3. The uneven distribution of fan sediments along the longitudinal fan profile produces the steep concave slope, as shown for both fans (Figure 7.10 and Figure 7.11). Using the fan channel relationships outlined by Harvey (1997: 250), the channel relationships for fan profiles were determined by analysing the fan surface and fan main channel profiles and the relationship between these two lines. The intersection point was also used to determine where fan aggradation takes place.

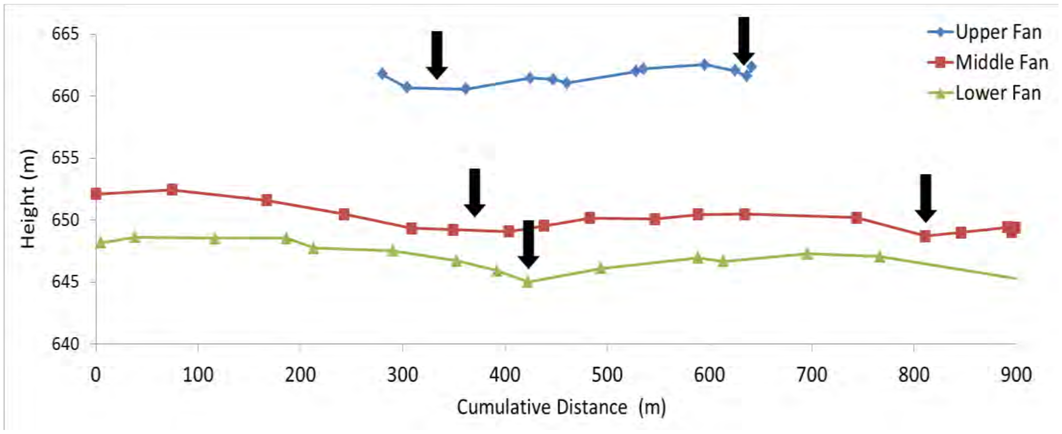

Figure 7.9: Transverse profile of fan 11. Black arrows indicate channels.

Two main styles of fans exist, namely a distally aggrading fan and fanhead trenching and intersection point headcut development (Harvey, 1990: 263). Fan 6 is classified as a distally aggrading fan with a stepped (indicated by the black star) profile indicating toe trimming in the past (Figure 7.10). The fan channel profile relationship is characterised by the intersection point and the elevation of the fan channel above the fan surface after the intersection point. Fan 11 is classified as being distally trenched with evidence of headcut development as a result of toe trimming, with evidence of aggradation on the proximal – medial fan surface (Figure 7.11). It is important to note that the fan is not trenched throughout its length it is only observed after the point of intersection on the fan surface. The fan also shows evidence of aggradation due to the many intersection points (Figure 7.11).

The intersection point is associated with increased stream power and a threshold exists between intersection point trenching and tendencies for fans to aggrade (Harvey, 1990: 263). Thresholds are controlled by the volume of sediment throughput and cross-sectional geometry of the channel and the discrepancy between the fan and slopes (Harvey, 1990: 263). Distally aggrading fans typically produce stacked sequences of sediments whereas fans prone to distal trenching produce a complex, inset stratigraphy both on the proximal and distal regions of the fan (Harvey, 1990: 263). This indicates that distally aggrading fans, such as fan 6, deposit sediments in layers across the fans surface. Distally trenching fans such as fan 11, however, do not deposit sediment on the distal fan surface and sediment is lost to the floodplain. The distinction between fan styles has implications for the connectivity of sediment and water through the fluvial system. It is further noted in Harvey (1990: 265) that trenching is base-level induced rather than fan induced. Trenching is said to be a product of local tectonics or toe trimming rather that fan morphometry (Harvey, 1990: 265). Fans produce a fan channel profile relationship characterised by an intersection point indicating fans are a product of local base-level change as a result of fan morphometry rather than a product of local tectonics due to a shortening of the fan profile as a result of toe-trimming and distal trenching explained in Chapter 2.

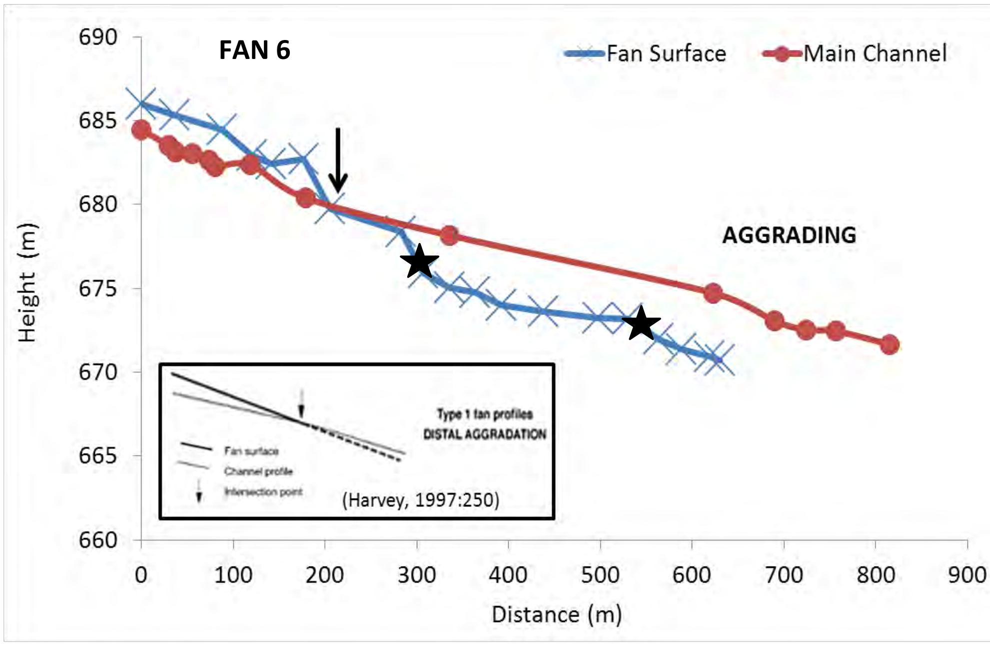

Figure 7.10: Longitudinal profile of fan 6, black arrow indicates intersection point.

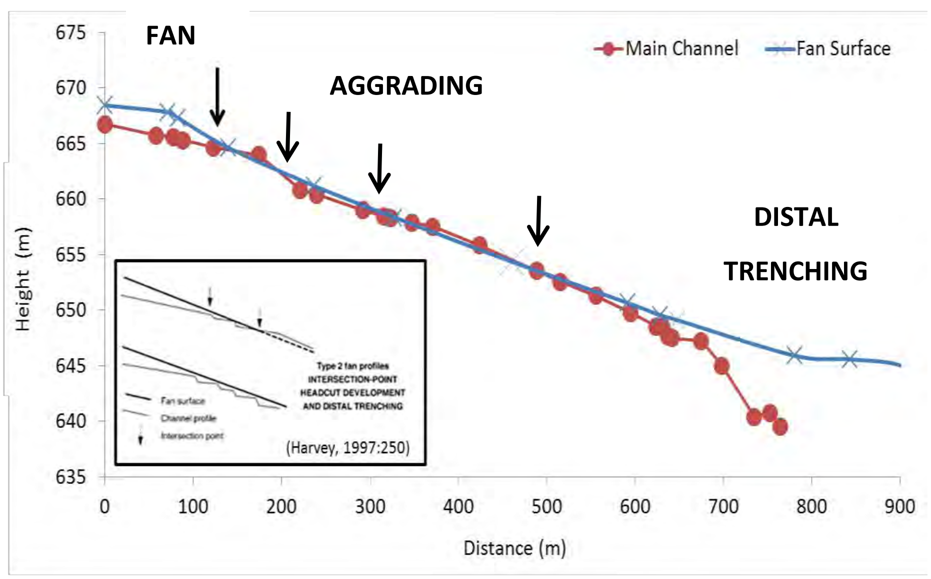

Figure 7.11: Longitudinal profile of fan 11. Black arrow indicates the intersection point.

7.5.3. *Sediment size analysis*

7.5.3.i. *Distribution of sediment sample points*

A map of sediment samples collected on the fan surface is given in Figure 7.12. Maps of the locations of sediment sample points was created in ARCMAP 10 using SPOT imagery for fans 6 and 11 as a basemap and overlaying the sediment sample point co-ordinates measured in the field. The co-ordinates were then relabelled with the sample name (Figure 7.12).

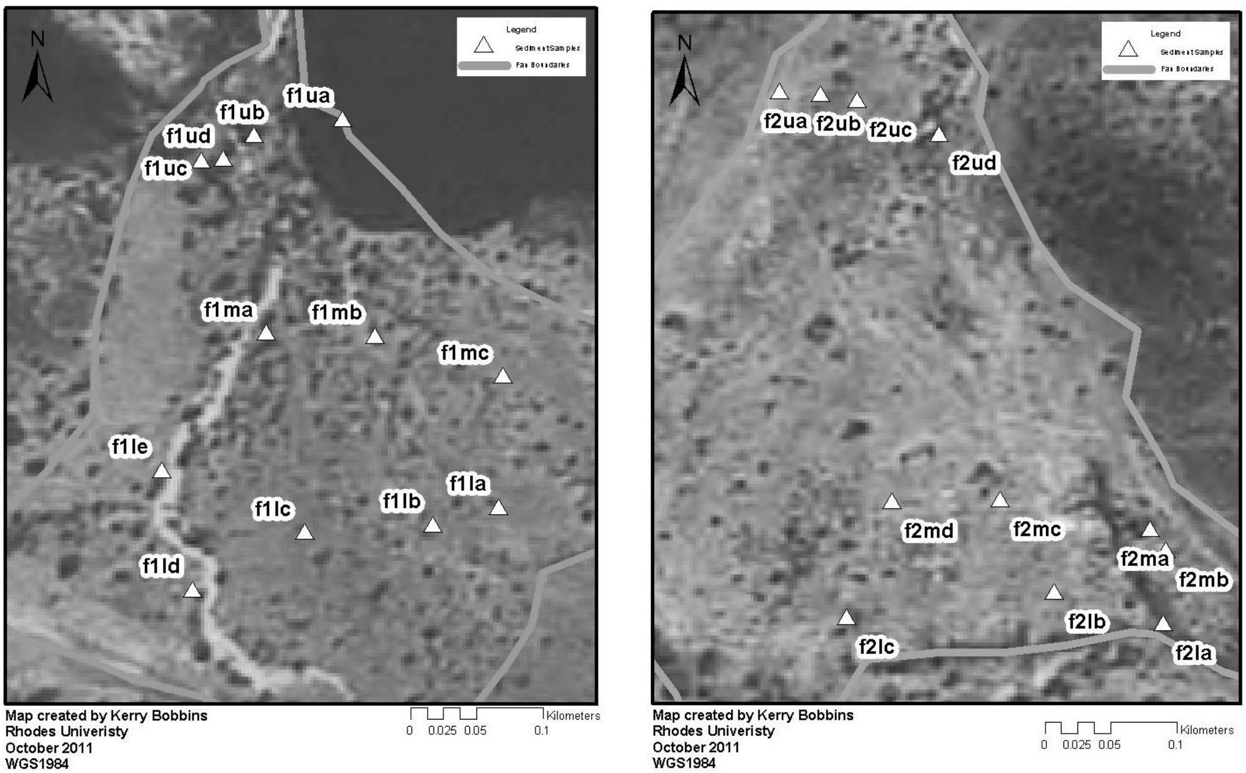

Figure 7.12: Distribution of sediment sample points on a) fan 6 and b) fan 11.

7.5.3.ii. *Maximum boulder and cast diameter*

Sediment sample points collected for fan 6 show that the maximum diameter of the largest clast per quadrant (measured for boulders, cobbles and pebbles) on fan 6 was larger than for fan 11 and are located mainly on the proximal–medial fan surface (Figure 7.13 and Figure 7.14). The maximum diameter of the largest clast per quadrant (measured for boulders, cobbles and pebbles) on fan 11 show the maximum diameter of boulders, cobbles and pebbles is located on the distal fan surface. This data suggests the critical stream power threshold on fan 6 is higher up on the fan surface as larger boulders are deposited on the proximal to medial fan surface (Figure 7.13). The critical stream power relationship based on maximum diameter suggests that the critical stream power threshold for fan 11 is lower down on the fan surface (Figure 7.14).

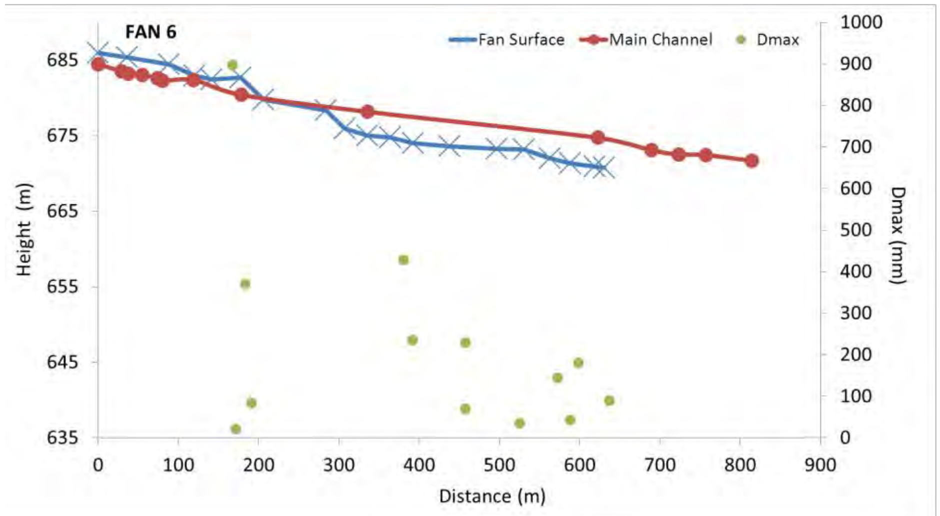

Figure 7.13: Maximum diameter of boulders, cobble sand pebbles for fan 6.

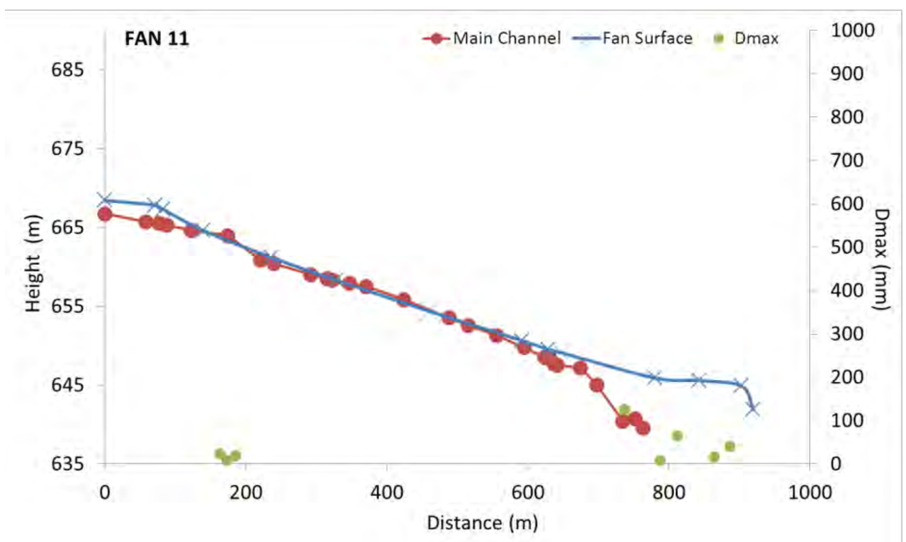

Figure 7.14: Maximum diameter of boulders, cobble sand pebbles for fan 11.

7.5.3.iii. *Coarse grain sizes (matrix)*

The Sneed and Fold triangular diagrams for coarse grain sizes (gravel, sand, silt and clay) (Table 7.4, Figure 7.15) show that samples collected from both fans were comprised mainly of sand grade material with a trend to coarser gravel size classes (Figure 7.15). The positions of samples are given in Figure 7.12.

Table 7.4: Percent gravel, sand and silt and clay per sediment sample (highlighted values indicate samples that have silt and clay fractions greater that 5%)

FAN 1				FAN 2			
PT	GRAVEL	SAND	SILT & CLAY	PT	GRAVEL	SAND	SILT & CLAY
f1la	5.6	86.5	7.9	f2la	23.6	73.6	2.8
f1lb	16.6	74.8	8.6	f2lb	2.3	89.6	8.1
f1lc	6.5	86.5	7.0	f2lc	3.8	90.8	5.4
f1ld	26.5	72.9	0.6	f2ma	12.3	82.1	5.6
f1le	46.9	51.4	1.8	f2mb	21.4	73.8	4.8
f1ma	5.1	88.0	6.9	f2mc	1.5	95.1	3.4
f1mb	6.9	89.5	3.7	f2md	9.1	82.1	8.8
f1mc	5.1	88.4	6.4	f2ua	5.5	91.0	3.5
f1ua	4.7	89.4	6.0	f2ub	3.7	93.2	3.1
f1ub	8.5	85.9	5.7	f2uc	8.2	87.4	4.4
f1uc	1.4	95.2	3.4	f2ud	41.5	57.1	1.4
f1ud	73.2	24.8	1.9				

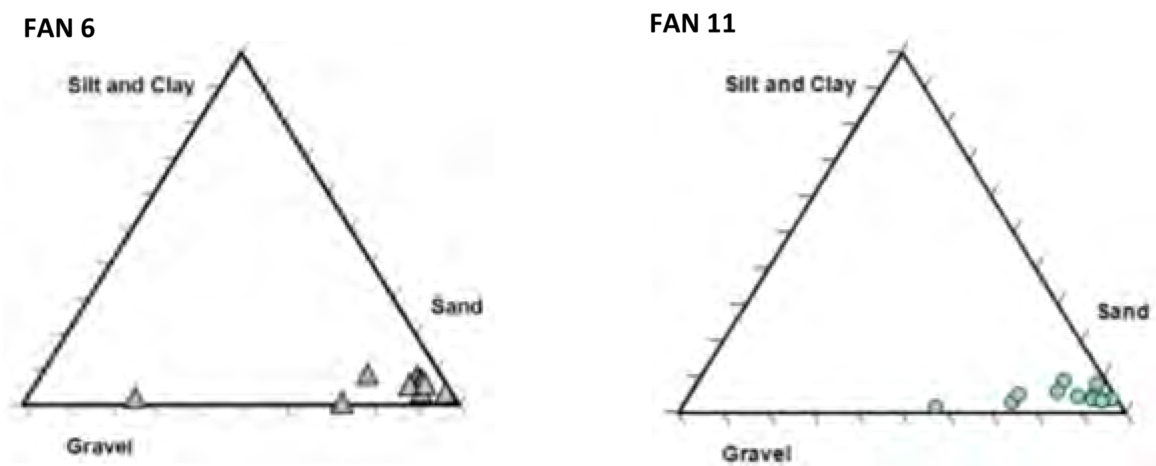

Figure 7.15: Sneed and Fold triangular diagrams produced for coarse grain sizes (gravel, sand, silt and clay) for Fan 6 and 11.

7.5.3.iv. *Fine size class fractions*

Silt and clay samples that comprise more than 5% of the total sample (highlighted in Table 6.6) were re-analysed using a sedigraph (Sedigraph II). Results were plotted as cumulative percent finer graphs versus particle diameter graphs. A mixed mode of sample analysis accounts for the increased amount of sand classified by the sedigraph. Fractions finer than 0.063 mm (classified using the sieve method) were used for the sedigraph. The results indicate the presence of some sand particles (> 0.063 mm) in the samples which are due to the diameter of sand particle having a diameter less than that of the classified diameter per sand particle (thus being classified as silt or clay by the sieve method), but exhibiting a greater mass which allows it to be classified as a sand particle by the sedigraph.

The cumulative percent finer versus particle diameter (mm) graphs for fan 6 and 11 produce a similar trend, with both samples being comprised mainly of sand (Figure 7.16 and Figure 7.17). The fine sediment fraction from fan 6 is dominated by silt and sand size class fractions, with less than 20% of the fine fraction being constituted by clay (Figure 7.16). Sediment samples from all locations on fan 6 have a similar percentage of silt and clay components. The fine sediment size class fraction from fan 11 are also shown to have just over 20% clay size class fractions and appear to have a greater percent of silt (Figure 7.17).

7.5.3.i. *Organic Matter*

The organic matter content is low for both fans with values ranging from 0 - 4.93% (Table 7.5) There is no clear relationship between organic matter content and location on the fan surface (Figure 7.18). Fan organic matter content varies between fan 6 and fan 11 and does not seem to produce a relationship down the longitudinal or cross-sectional lengths of the fan surface (Figure 7.18).

Alluvial fans, as hillslope landfoms, have the tendency to follow classic hill slope studies. Hillslope studies describe how the quantity and quality of organic matter as well as soil texture, pH and other sediment properties change downhill slope environments (Norton et al*.,* 2003:232). Studies document changes in sediment and soil properties in association with position on a hill slope that are defined by sediment movement, sorting and morphology. Studies typically report increasing organic matter content with increasing distance from mountain front areas that coincides with an increase fine sediment size class fractions down the fan (Norton et al*.,* 2003:232). In a study conducted by Norton et al*.,* (2003: 232) it was observed that the topography of the Colorado Plateau landscape favoured the growth of vegetation in some areas which impacted the location and amount of organic matter produced within a hill slope context. It has been shown that both particle size distribution and vegetation cover plays a critical role in the occurrence of organic matter content in hill slope environments (Norton et al*.,* 2003: 232)

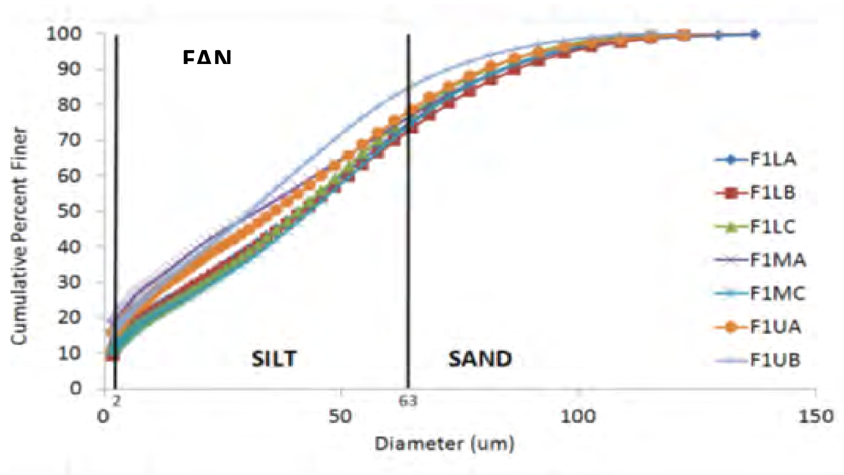

Figure 7.16: Cumulative percent finer graphs produced for Fan 6.

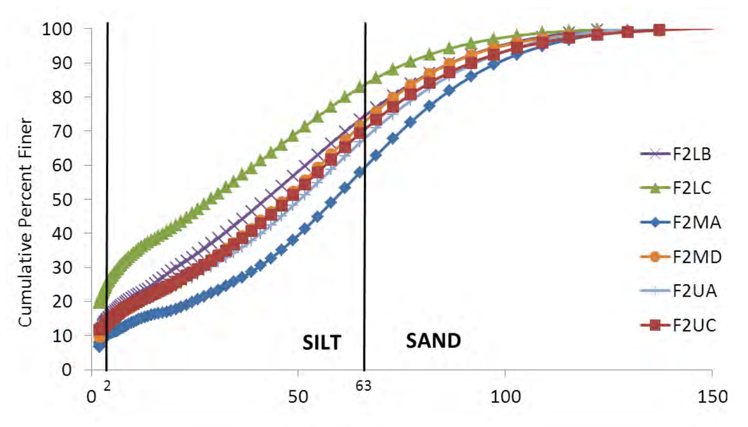

Figure 7.17: Cumulative percent finer graphs produced for Fan 11.

Fan 6 shows a decrease in organic matter content down the fan surface, this is likely to be a result of vegetation cover changes down the fan surface and may reflect groundwater recharge (Figure 7.18). This same trend is not observed for fan 11 (Figure 7.18). This could be related to the greater amount of surface wash on the fan surface which indicates less water recharge at the proximal end of the fan.

Table 7.5: Percent organic matter calculated for fans

FAN 1		FAN 2	
PT	OM (%)	PT	OM (%)
f1la	0	f2la	1.19
f1lb	1.97	f2lb	0.56
f1lc	1.54	f2lc	2.35
f1ld	0.61	f2ma	0.81
f1le	1.77	f2mb	1.72
f1ma	3.28	f2mc	1.57
f1mb	2.4	f2md	0.85
f1mc	2.43	f2ua	1.54
f1ua	4.74	f2ub	2.06
f1ub	3.35	f2uc	1.65
f1uc	4.93	f2ud	0.58
f1ud	6.8		

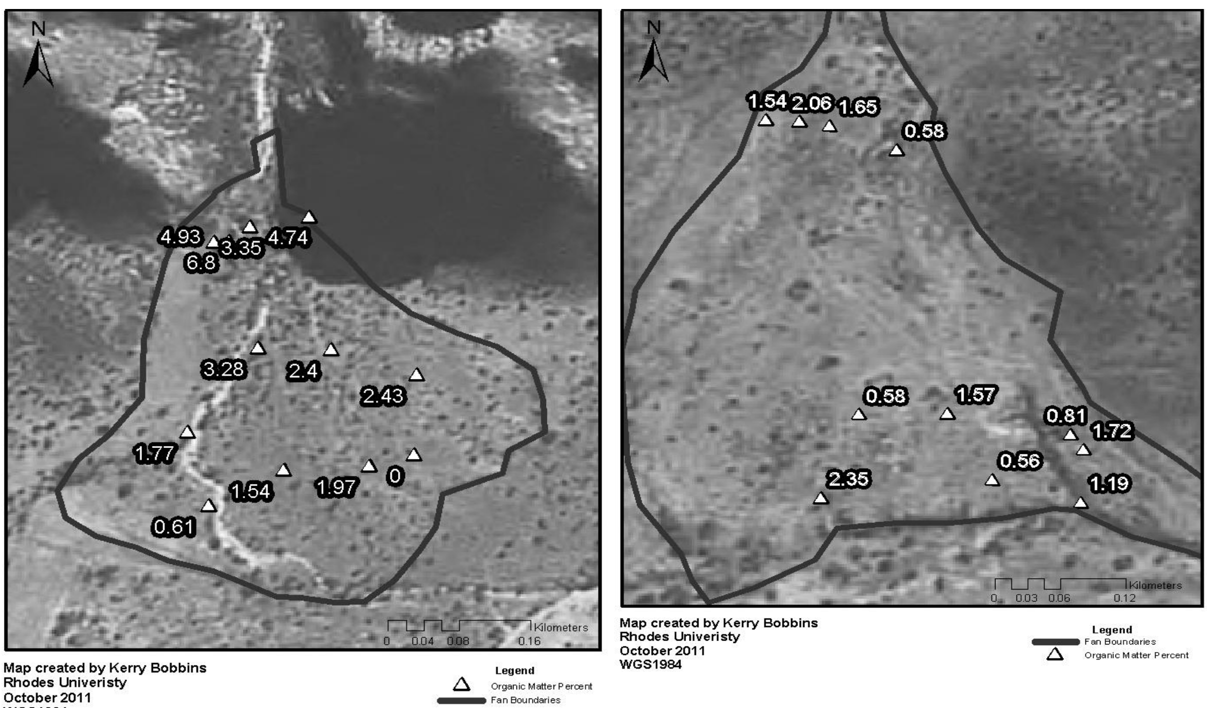

Figure 7.18: Map of fans 6 and 11 showing sediment sample points and percent organic matter

7.6. Summary of case study findings

7.6.1. *Alluvial fan form*

The map produced for fan 6 shows no obvious of signs headcut development and provides evidence for the unhindered formation of the fan surface on the valley floor (Figure 7.5). This is clearly observed by the curved line that forms the distal boundary of fan 6 (Figure 7.6). Fan 6 is characterised by a well-defined main channel and old secondary channels on the fan surface. The main channel feeds an active depositional lobe on the fan surface that is alongside the main channel; these are visible in the transverse sections of the fan surface (Figure 7.8). The high elevation of the upper fan surface in relation to the middle and lower fan surfaces indicate an active fan surface (Figure 7.8). Fan 6 has a distally aggrading fan style with the occurrence of 6 intersection point along the longitudinal length of the fan (Figure 7.10). Deposition takes place below the fan surface where sediments form stacked sequences.

Fan 11 has two headcuts on the distal fan surface (Figure 7.5 and Figure 7.6). Fan 11 has a well-defined main channel with a number of active secondary channels. Channels provide evidence of little deposition alongside the channels, with no primary depositional lobe being identified (Figure 7.9). The low elevation of the transects conducted on upper, middle and lower fan surface do not indicate a steep slope from the fan apex to the distal region of the fan surface indicating that little sediment deposited onto the fan surface over time, however, multiple intersection points located along the length of the fan indicates a number of areas of deposition on the fan surface. As these points do not give evidence of areas constituting a large depositional lobe it may represent areas of temporary sediment storage on the fan surface (Figure 7.6 and Figure 7.9). Fan 11 has a distal trenching fan style with headcut development that is not fully trenched along its length (Figure 7.11). This indicates that a complex set of stratigraphy occurs on both the proximal and distal fan surfaces. The combination of distal trenching and headcut development on fan 11 with the occurrence of an intersection point provides evidence that a local base-level change has occurred that is not a result of tectonics but rather a result of fan morphometry change, such as the laterally migrating main river that results in toe trimming. Toe trimming is therefore a factor that brings about a local fan induced base-level change, as discussed in Chapter 3.

7.6.2. *Links between fan basin parameters and fan sediment characteristics*

Fan basin characteristics investigated in Chapter 6 and fan data investigated in this chapter were used to comment on links between fan basin parameters and fan sediment characteristics. This has been summarised in Table 7.1. The weak relationship between grain size and distance from fan apex to distal surface suggests that sorted material may leave the catchment area after weathering. Fan samples for fan 6 and 11 are characterised by a greater percentage of sand and small percentages of silt and clay (Figure 7.15). This may be explained by fan basin characteristics. Fan 6 has a larger fan basin area (9.38 km^2) compared to fan 11 (1.30 km^2) and has a more rugged basin than fan 11 (Table 7.1). Basin shapes were similar. Both fan basins are dominated by quartzitic sandstone with fan 6 being comprised of more terrace gravels and fan 11 a greater feldspathic sandstone component. Fan 6 is also noted to be more vegetated with an organic matter gradient that decreases down the fan surface. Fan 6 is more likely to receive more sediment from the drainage basin area due to its larger and steeper drainage basin area. This also applies to water and fan 6 is expected to recharge the groundwater more effectively than fan 11 given the evidence of vegetation and basin dynamics. Fan 11 has a smaller, yet less steep, basin composed mainly of quartzitic sandstone (feldspathic) (Table 7.1). Fan 11 may be more susceptible to debris flows which explain larger clasts found at the fan toe. Smaller basin size may explain the less developed fan channels and prominence of sheetflow.

Chapter 8: General Discussion

8.1. Introduction

The aim of this chapter is to provide an overview of key findings of this thesis. This chapter will be structured to focus the contributions of this thesis to broader geomorphological themes such as the alluvial fan problem, contextualise key findings on the spatial distributions of fans and fan morphology in the Baviaanskloof Valley and outline contributions to the fields of fan restoration and alluvial fan restoration in the Baviaanskloof Valley.

8.2. The alluvial fan problem

The 'alluvial fan problem' investigated by Leece, (1990), Clarke et al*.,* (2008) and Harvey et al., (2005) is outlined in Chapter 2 and alludes to the difficulty in developing a general model to explain the occurrence and development of alluvial fans in the landscape. Despite research efforts made to study the development of alluvial fans in the fluvial landscape, a general model of alluvial fan development has not yet been formulated. Outcomes of this thesis do not solve the alluvial fan problem through the creation of a general model to describe fans, but rather presents a framework that can be applied to fans within a fluvial context to determine the occurrence of fans and the stages of fan evolution. Fans are identified as intricate landforms as they are found in all of the global climates and their transitional position on the fluvial landscape means that they are influenced by a number of external and internal control variables which makes the formulation of a general alluvial fan model problematic. This thesis respects fans intricacies in the fluvial landscapes and attempts to define and quantify external and internal control variables in site specific locations to understand how fans function in a particular fluvial landscape rather than formulate a more general fan model.

8.3. Overview of the spatial distribution of fans and fan morphometry

As discussed throughout this thesis, the Baviaanskloof Valley is a 75km long rugged valley that has formed and evolved over millions of years and is comprised of three African Erosion Surfaces that can be clearly seen in the landscape today. The Baviaanskloof and Kouga Mountain ranges were formed during two different geological periods and are an assortment of hardened, folded and fractured rock 300 - 400 million years old, mixed with the more recent Enon conglomerates (noted to be younger than 165 million years old), (Ellery and Rowntree, 2010: 30). The valley form is characterized by a number of narrow and wide sections, with fans predominating in the wide valley sections of the western Baviaanskloof Valley. A greater number of fans are found on the south facing side of the valley (33 fans) than the north (25 fans), Chapter 5.

Alluvial fans form at a variety of sizes and slopes along the length of the valley (Figure 6.10 and Figure 6.20). Four fan types (geometries) and four alluvial fan groups are located along the length of the valley (Figure 6.20). They are influenced by a number of external control variables such as fan setting, valley accommodation space, drainage basin area and geology and amount of rainfall collected by the fan basin. These external fan control variables affect the dynamic functioning of fans at different scales. External valley-wide parameters affect the functioning of all fans and influence fan form – process responses. External fan control variables include accommodation space, tectonics, sea-level, drainage basin inputs such as climate, vegetation and basin geology. The internal control variables are linked to fan style and include fan morphometry controls and fan channel dynamics. Control variables will be discussed from a valley-wide scale to a local fan basin – fan scale.

8.4. Application of the framework

8.4.1. *Accommodation space*

As presented earlier, accommodation space is the space available on the floodplain given the valley width and is related to fan area (Taylor, 1999:221). The critical width calculated for fans in the valley was given by the equation $y=2.416x^{2.43}$ (Chapter 6). The minimum width for a fan of a particular area to develop is between 0.16 – 1.69 km wide, although the majority of fans in the valley form between 0.01 – 0.36 km^2. Accommodation space is shown not to be the primary control variable of fans in the Baviaanskloof Valley (bivariate and multivariate data analysis), but it may induce a base-level changes on smaller fans in narrow sections of the valley where there is a laterally migrating channel. In narrow valleys such as the Baviaanskloof Valley, the main channel has less valley width to laterally migrate which influences the functioning of alluvial fans by removing the distal end of the fan and inducing this base-level change. This increases the lateral connectivity of the fluvial system which then has knock-on effects on fan-channel functioning (Taylor, 1999: 221; Harvey 2010: 164). Where there is a wide valley, there is enough space to accommodate a laterally migrating channel. This allows for the main river channel and fan to function without influencing each other in the fluvial system.

8.4.2. *Base-level change*

External control variables such as tectonics, sea-level and climate change directly influence fan channels, they modify the threshold of critical stream power and impact the base-levels of fans (Harvey, 2005: 126). While tectonics and sea-level change may have influenced the formation of fans in the valley in the past and they are not considered to influence fan systems at present. Climatic variability can also affect base-level change through their direct influence on the locus of deposition and influence on both fan channel location and channel entrenchment (Cooke and Warren, 1973: 180); this is found to be the case in the Baviaanskloof Valley where during erratic and flash flood events, increase sediment and water transport to the fan (which is influenced by drainage basin size and shape). This modifies the locus of deposition and may induce a base-level change. Apart from climatic variables, locally induced base-level change is brought about by both toe trimming (a result of a laterally migrating channel) and human activity. These cause the fan profile to shorten, which induces a change in base-level response. As fan toe trimming is observed on 23 fans in the Baviaanskloof valley, it is hypothesised that local base-level induced change on fans in the valley is probable. Harvey (2005:126) notes that smaller fans with a steeper gradient are more greatly affected by a laterally migrating main channel as the fan slope is significant enough to induce a base-level change. The low slope of larger fans may not be sufficient for channel migration to trigger a base-level induced change and distal fan incision (Harvey, 2005:126). If only a small portion of the fan surface is removed, way below the intersection point, the fan may continue to both deposit sediment on the fan surface and transport sediment to the main channel (Harvey, 2010: 164). A shortening of the fan profile leads to incision and headcut development and in turn the channel will eventually dissect (Harvey, 2010: 164).

For larger fans with an intersection point located higher up the fan surface the effects of toe-trimming are small due to sediment accumulation below the fan intersection point. Small fans have a smaller amount of sediment on the distal fan surface due to the size of the fan and the location of the intersection point; they therefore have a greater probability of being influenced by a laterally migrating fan channel. The influence of a laterally migrating channel on both small and large fans could account for the variability in the areas of toe trimmed fans shown in Figure 6.12, indicating that fans in the Baviaanskloof Valley respond differently to a laterally migrating main river channel.

The history of human intervention on fans in the Baviaanskloof Valley in the 1970s and 1980s has been discussed in Chapter 6. Man-made channel diversions that disrupt fan processes have resulted in conditions that promote channel incision and fan dissection. This provides evidence for human induced base-level change on fans Climate, toe trimming and human activity all exacerbate local induced base-level change of alluvial fans within the western Baviaanskloof valley.

8.4.3. *Drainage basin inputs (water and sediment)*

Valley wide water and sediment inputs influenced by climate, vegetation and basin geology will be discussed below followed by local drainage basin controls that include basin area, shape and relief.

Episodic rainfall events, typically in the summer months, result in episodic water and sediment transport to the fan surface. It is shown that rainfall in the valley is spatially variable receiving >350 - <450 mm per annum (Chapter 4) and not all fans will be active during a particular rainfall event. Some fans in the valley are therefore more active due to the greater amount on rainfall over particular fan basin. Active fans receive more water and sediment from basin areas and water and sediment inputs will increase during this time.

Dense vegetation cover on the fans in the Baviaanskloof Valley, especially at the fan apex, suggests that fans have not received any recent appreciable depositional activity and have a greater shear strength (Blair and McPherson, 1994: 286). A study conducted on forested, humid fans in the Appalachians (Kochel, 1990: 123) uncovers fan inactivity since the late Holocene as fans have developed soils and densely forested vegetation. Fans in the Baviaanskloof Valley may have formed in the Pleistocene, during which time the temperature fluctuated by 5^{0}C (Scott et al. 1995: 937). Fans could have formed during a colder, drier period during the last glacial period, but have stabilised during the Holocene as temperatures became warmer and a denser vegetation cover developed. Vegetation cover on the fans has undergone a shift from tree-less grasses and shrubs to woodlands and subtropical grasses from the late Pleistocene until present, as described by Scott et al. (1995: 937). Fans are positioned mainly within the tentative semi-arid to temperate climate separation in Figure 6.25 along with other arid fans from the Death Valley and western Argentina (Milana and Ruzyucki, 1999: 350).

The geology of fan basins on the north facing side of the valley are characterised mainly by fractured quartzitic sandstones (Table 6.4). The south facing basins are comprised of quartzitic sandstone, enon conglomerates and shales. Basins on the north facing side of the valley are therefore relatively more resistant than basins on the south facing side on the valley. Source geology that is prone to erosion increases the potential sediment input and the calibre of sediment fed onto a fan (Blair and McPherson, 1994). Basins with more erodible geology produce steeper fans, but have also been shown to have a larger storage capacity in the drainage basin area (Mills, 2000:294). The results of the t-test to determine the difference between the fan area to basin area prove that north facing fans have a larger fan area to basin area ratio (Table 6.11). North facing basins are underlain by quartzitic sandstones and shale and have larger fan areas compared to south facing basins underlain by quartzitic sandstone, enon conglomerates and shale (Table 6.5). Fractured rock, such as quartzite, results in a higher drainage density and provides increased amount of sediment to the fan (Calvache et al. 1997). In this case data suggests that fans in the Baviaanskloof Valley follow this trend, which may not be the case.

Modes of sediment deposition in the Baviaanskloof compare with a study conducted by Basu and Sarkar (1990:324). They distinguish the following modes of deposition: flash flood, stream, stream flood and debris flow. During times of flash floods, which are typical in the episodic and erratic rainfall region of the Baviaanskloof Valley (Chapter 4), large amounts of water emerge from the mountains and deposit large material at the fan apex (Chapter 2). After a rainfall event, the slot canyons (kloofs) flow with water for some time. Floods deposit finer silts and sands on the fan surface (medial and distal regions) when fan channels breach their banks during a high intensity rainfall event (Basu and Sarkar, 1990:324). This may explain the fine sediment found on fan 6 and 11 as there is no sediment gradient down the fan (Table 7.5). The occurrence of coarse sediment on the distal fan surface of fan 11 suggests that sediment is deposited via debris flows rather than fluvial flows.

Internal water and sediment control variables such as basin area determine the amount of sediment fed onto the fan surface as larger basins tend to produce more sediment that can be transported to the fan surface. Basin shape and relief also influence the water and sediment inputs onto the fan surface. Basins that are more rugged and circular transport water and sediment to fans more rapidly than basins that are less rugged and more elongated in shape. Fans on the north facing side of the valley are shown to be less rugged and have a larger fan area per unit drainage basin area (Figure 6.2 and Figure 6.6). Fans on the south facing side of the valley are more rugged and produce smaller alluvial fans (Figure 6.2 and Figure 6.6). The geology of basins, described above, indicates that the south facing basins are more resistant and this may explain the increased ruggedness values for these fans (Table 6.5). The more easily erodible geologies on the north facing side of the valley may explain the lower ruggedness values calculated for north facing basins. Fans on the south facing side are therefore more susceptible to flashflood events given their circular basins and low ruggedness values and do not allow for much sediment storage in the drainage basin given resistant basin geology. Conversely, fans on the north facing side of the valley have a higher ruggedness value, a more elongated shape and less resistant basin geology. The less rugged and elongated shape of the drainage basin implies that basins are less susceptible to flashflood events. Basins are more elongated in shape and the less rugged topography allows for an increased amount of sediment storage in the drainage basin (Mills, 2000:294).

8.4.4. *Fan variables*

As discussed earlier, fans in the Baviaanskloof Valley constitute 4 fan styles: 28 tributary junction, 19 simple mountain front, 9 simple backfilled and 2 intermontane, (Figure 6.8) (Al-Farraj and Harvey, 2005: 88). Tributary junction fans are confined by valley walls and are influenced by local base-level change due to the lateral migration of the main channel (Al-Farraj and Harvey, 2005: 88). This is observed in previous investigations of fan base-level change where fans in the Baviaanskloof Valley are identified base-level induced due to the influence of a laterally migrating main channel that brings about toe trimming (Chapter 6). Fan areas are shown to be greater on the north facing side of the valley than on the south facing side, but fan slopes are steeper on south facing fans than on north facing fans (Figure 6.20). The relationships between fan area and drainage basin area indicates that north facing fans produce a greater alluvial fan area per unit drainage basin area than for fans and basins on the south facing side of the valley (t-test), (Table 6.11). In the graph of alluvial fan area to drainage basin area (Figure 6.12) it is shown that not all fans with smaller fan areas are toe trimmed. This follows findings in the base-level section above which indicates that fans with smaller fan areas are susceptible to changes in location of a laterally migrating main channel. Compared to other fans studies in Iran, Spain and USA, fan area to drainage basin areas for fans in the Baviaanskloof Valley are lower. This is due to sediment storage characteristics on the north facing side of the valley and fan evolutionary stage which will be discussed in the fan channel section below.

Comparisons between fan slope (%) and drainage basin area plot largely within the boundary of other fan groups apart from fans with smaller fan areas. A comparison between fan slope versus basin area in the Baviaanskloof valley and other fan studies indicate that these relationships are similar to other semi-arid fans investigated in other fan studies (Figure 6.24 and Figure 6.25).

Fan channels

Fans evolutionary stage was investigated using Clarke's (2010) adapted model to classify fan channel process and to determine the relationship between fan incision and toe trimming which leads to a local base-level induced change (Table 2.2). It was found that the majority of fans in the valley fall within fan stages 3 - 5 which suggests they are incised at the fan apex, fan toe or along the medial section and are relatively mature features of the landscape. A significant relationship exists between fans in stages 4 and 5 (distal incision) and fan toe trimming, which suggests toe trimming exacerbates fan distal incision (supported by the chi square analysis). Baviaanskloof fans in stages 3, 4 and 5 will have entrenched channels and water and sediment is transported out of the fan rather than within the fan system, as shown by Clarke et al. (2010). This also applies to the additional stages 4 and 5. This leads to further channel entrenchment and has a large impact on connectivity within the fluvial system.

8.4.5. *Field work component*

The field work component conducted on two fans in the valley was based on the assessment of fan surface characteristics and sediment dynamics of fans. These have been used to compare characteristics between fans that have been toe trimmed and fans that are not toe trimmed. The fan surface of 11 is noted to be steeper than the fan surface of fan 6 which may be influenced by grain size found on the fan surface (Figure 7.16 and Figure 7.17). In a paper on grain size studied by Kochel (1990) and Basu and Sarkar (1990) in the Appalachians and the Darjeeling Himalayas a grain size gradient is shown to correlate with distance from basin area with coarse sediments at the fans apex and by sediments at the fan toe. Fan 6 in the Baviaanskloof Valley showed no obvious differences in coarse and fine grain sizes of matrix sediment down the fan surface and was identified mainly as gravel–sand size classes with cobbles, pebble and boulders and may explain the steep fan slope. Fan 11 did however produce a grain size gradient down the fan surface and may explain the gentler fan slope profile. Fan organic matter content tends to decrease down the fan surface on fan 6. Calvache et al. (1999: 81) found that sediment characteristics of fans originating from basins with fractured source geologies produce sorted material upon leaving the fan basin and are responsible for the poor grain size gradient down the fan surface. The two fans selected for the case study were both located on the south facing side of the valley where the source geology is fractured quartzite. The low rate of grain size gradient down the fan radial profile may thus be a result of the source geology for fan 6.

8.4.5.i. *Connectivity*

The role of fans in the valley is intrinsically linked to the connectivity within the fluvial system and is based on fan - channel responses. The buffering and coupling role played by fans is a result of the local depositional zone on the fan where fan sediments act as a buffer to the fluvial system (Harvey, 2010: 166). Aggrading (untrenched or proximally), distally aggrading and fan head trenches fans act as buffers in the fluvial system and break the continuity of sediment movement from the source area and sedimentary basin or main channel system (Harvey, 1997:235). Dissected fans have continuity of coarse sediment movement and increased connectivity from the source area to the floodplain and increased sensitivity to the main channel, with aggradation and dissection occurring due to source area environmental change (Harvey, 1997: 235).

The transverse profiles of fans 6 and 11 follow trends identified in the Dunn fans studied by Mukerji (1990: 137). Both fan transverse profiles produce a convex curve that is accentuated in the proximal zone and become subdued in the middle and distal areas Mukerji (1990: 137). Fan 6 is shown to deposit sediment on either side of the main and secondary channels. This is shown by the raised banks and raised shape of the fan surface on either side of fan channels (Figure 7.8). This is a visual representation of increased connectivity between fan channels and the fan surface. The transverse profile of fan 11 does not have obvious signs of sediment deposition on either side of the fan channels (Figure 7.8). Transverse profiles follow trends identified by Mukerji (1990: 137) as fans 6 and 11 are steeper and more concave in the upper surface than the lower surface.

Longitudinal profiles of fans indicate fan sediment dynamics and the fan regime (Figure 7.10 and Figure 7.11). Fan 6 is a distally aggrading fan with sediment being deposited on the distal regions of the fan surface. The intersection point on the fan surface is an indicator that sediment is being deposited on the surface from 400 metres (Chapter 7) to the distal fan boundary. As there is no clear evidence of channel incision and headcut development on the distal fan surface it can be deduced that the aggrading fan surface acts as a buffer in the fluvial system. During times of large rainfall events the critical stream power threshold is influenced by a higher flood power and the sediment buffers are mobilized, increasing connectivity through the fluvial system by coupling sediment from the fan to the floodplain. Fan 11 has two headcuts on the distal fan surface and has been severely impacted by the laterally migrating Baviaans River. The many intersection points produced between the fan surface and the fan main channel indicate a number of local depositional zones on the fan surface. At these points sediment is stored in a temporary sink which buffers and breaks the continuity of sediment transport through the fan surface.

Headcut development on the distal fan surface indicates an increased continuity between the mid-fan surface and the floodplain as the critical stream power threshold for sediment deposition has not been reached and sediment transport is coupled with the floodplain. Headcut development given the right combination of flood power and/or a change in sediment transport to the fan may stimulate the migration of the headcut further up the main channel towards the intersection point. When the intersection point is reached the fan will no longer deposit sediment on the fan surface and the fan surface will not aggrade. The dissection of the main channel from the fan surface results in an increased continuity of water and sediment through the fan surface and onto the floodplain and increased connectivity through the fluvial system.

Fan 6 has a greater systems coupling between fan channels and the alluvial fan surface as sediment is deposited on the distal fan surface below the intersection point. This fan has increased periodic connectivity between the fan and the floodplain during rainfall events that are large enough to transport water and sediment to mobilized temporary sediment sinks on the fan surface (Harvey, 2010: 164). Fan 11 has a greater systems coupling with the floodplain as the fan channel is entrenched and has the development of two headcuts. More local coupling occurs as a result of sheetwash on the fan surface which deposits a number of smaller temporary sedimentary deposits. At a large scale, temporary sediment sinks on the fan surface are dis-coupled from the floodplain area.

8.4.5.ii. *Scale*

On a local scale, individual fans experience a change in alluvial fan regime due to increased flood power or due to an increase/decrease of sediment supplied to the fan which alters the buffering and coupling role of fans in the valley. Distally aggrading fans allow for the temporary storage of sediment and water infiltration on the fan surface and contributes to the stable base-level functioning of an alluvial fan within the valley context (Harvey, 2010: 164). Distally aggrading fans allow for the temporary storage of sediment and water infiltration on the fan surface and contribute to the stable base-level functioning of an alluvial fan within the valley

On a valley-wide scale, environmental changes impact flood power and the amount of sediment transported to the fan surface. Headcut development and dissection of the fan surface (fan 11) results in increased connectivity between the hill slope processes and the floodplain and result in an increased connectivity within the fluvial system.

8.5. Restoration guidelines

Key themes for an effective restoration study outlined in Chapter 1 have been used as overarching themes of this thesis. The first theme was to incorporate spatial contexts for restoration strategies by considering the fluvial systems as a connected system with small and large scale processes acting both in the short and long term. This theme is incorporated into this thesis by defining the role of alluvial fans in the Baviaanskloof landscape and studying these landforms as being intrinsically linked in the broader fluvial system. This approach allowed for scale related processes to be identified. The remaining process related themes were to extend form-based solutions to process-based approaches, to promote natural channel recovery through a greater attention to key processes rather than restoration via morphological reconstruction and to incorporate a range of different disciplinary tools and approaches including modelling, field based validation and historical analysis (Rinaldi et al. 2008: 379). This stimulates the movement away from empirical classifications and considerations and towards the development of process-based models and linkages based on geomorphic processes (Rinaldi et al. 2008: 378).

Other restoration themes include the merging of interdisciplinary groups in the restoration process which provide a more comprehensive and stronger collaboration. The larger restoration programme run by LivingLands in the Baviaanskloof Valley (within which the alluvial fan restoration project is situated) is informed by a number of interdisciplinary working groups including farmers, stakeholders, academics and environmental authorities. The final restoration theme is integrating process understanding with morphological inventions. This theme will be met by providing restoration guidelines for fans in the valley based on geomorphological form-process relationships. Two types of guidelines will be given a) general procedural guidelines for fan restoration projects and; b) guidelines specific to the Baviaanskloof Valley. Procedural guidelines provide a stepwise process that can be followed in a valley context to gain a geomorphological and geological perspective of the area and to assess fan form-process relationships through the study of external and internal alluvial fan control variables (Figure 8.1 and Figure 8.2). It can be used to define fans and fan basins in a valley context, determine both external and internal alluvial fan control variables, and identify alluvial fan channel processes to inform fan evolutionary stage and connectivity within the broader fluvial system. This guide therefore provides a tool for alluvial fan restoration which identifies alluvial fan control variables quantified fan relationships to be used to inform fan restoration. Guidelines specific to the Baviaanskoof Valley include a list of restoration recommendations for fans in the Baviaanskloof Valley that can be used for fan restoration projects. Procedural guidelines for fan restoration is a guide indicating key considerations of fan restoration projects and an overview of processes used to assess fans in the fluvial landscape is given in Figure 8.1 and Figure 8.2

8.5.1. *Procedural guidelines for alluvial fan restoration projects*

The first procedural guide is comprised of key considerations that should be included in an alluvial fan restoration projects. Considerations are given below in Table 8.1 and correspond to procedure outlined in Figure 8.1. The second set of procedural guidelines outline the steps required to investigate the influence of internal and external control variables on fan function which can be used to assess alluvial fan restoration projects (Figure 8.2)

Table 8.1: Key considerations of alluvial fan restoration projects

Consideration	Method of analysis
1. Identify fans that are being actively incised.	Field observations
2. Investigate where the channel is incised (upper, middle or lower fan surface, or is it a combination of these) and whether it is a cause for concern (evaluate reason for restoration)	Assess transverse and longitudinal profiles of the fan surface and fan channels.
3. Investigate the cause of fan incision using fan framework.	Investigate the influence of: a) EXTERNAL CONTROL VARIABLES: accommodation space, base-level (valley-wide and local), laterally migrating main channel (toe trimming) and human activity b) INTERNAL CONTROL VARIABLES: fan evolutionary stage
4. Assess whether channel incision can be reversed (based on the cause of incision and how likely the	Consider whether channel incision can be reversed given the location on the fan surface and causes of fan incision

fan would become incised again)	
5. Develop local scale restoration guidelines to remediate the cause of fan incision	Develop restoration guidelines based on causes and location of fan channel inscision

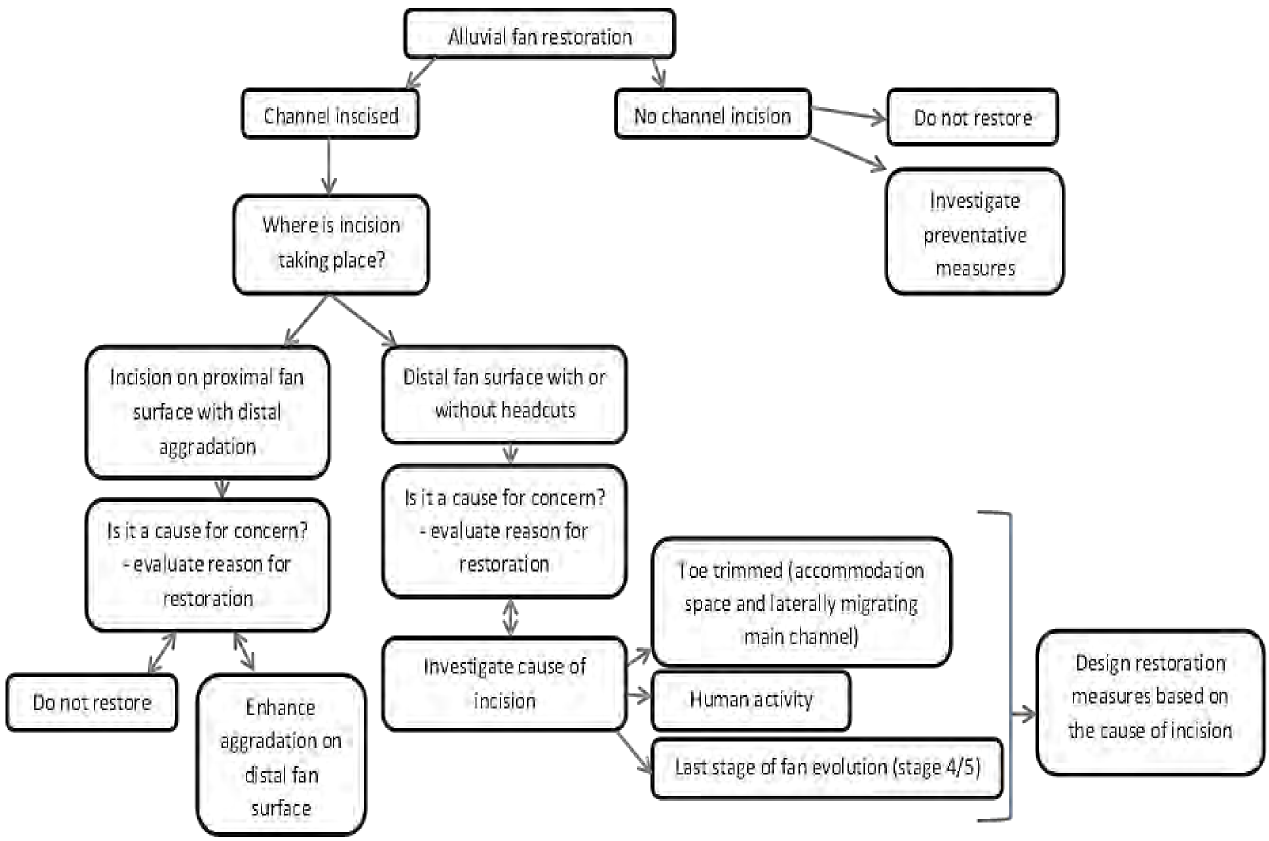

Figure 8.1: Key considerations that should be included in an alluvial fan restoration project

Procedural guide to investigating external and internal alluvial fans control variables to inform fan restoration

1. Collect all available imagery (at appropriate scale to view fans)

A) Topographic map series

B) Aerial imagery (aerial photographs, SPOT imagery, orthophotos)

2. Map the spatial distribution of fans and drainage basins in the valley - this can be done using ArcMap 10 or Quantum GIS (freeware)

3. Assess the influence of external fan control variables:

A) Accommodation space - calculate critical valley width for a given fan area

B) Base-level change: valley wide and internal variables

- **Valley-wide**: recent active tectonics (yes/no) and recent sea-level change (yes/no)
- **Internal**: valley channel migration - evidence of toe -trimming (yes/no) and evidence of human intervention (yes/no)

4. Assess valley-wide and local factors that influence basin water and sediment inputs:

- Valley wide Variables:

A) Climate – determine rainfall over fan basin

B) Vegetation cover – determine vegetation type and density

C) Basin geology – determine basin geology and relative catchment geology erodability

\- **Local variables:**

A) Basin area – define catchment area

B) Basin shape – define basin as being more circular or elongated

C) Basin relief – assess basin ruggedness

5. Determine fan morphometry:

A) Fan style – determine the fan type and geometry; simple mountain front, tributary junction, backfilled and intermontane

B) Fan area – calculated as the total planimetric area of the fan surface

C) Fan slope – determine using topographic map series, infield readings or DEM

D) Fan channels – determine the number of channels, channel incision, channel braiding, evidence of channel migration. Chi square test can be used to determine the relationship between fan incision and toe trimming

6. Determine which external variables most affect alluvial fan area using a Statistics software package or MS Excel:

A) Correlation matrix – determine significant relationships >0.6 and < -0.6.

B) Principle component analysis (PCA) – determine groups of control variables that influence clusters of fans.

C) Regression analysis – determine which control variables influence fans the most significantly

7. Formulate guidelines based on significant control variables identified in step 6.

Figure 8.2: Procedural guidelines for fan restoration

8.5.2. *Restoration guidelines for fans in the Baviaanskloof Valley*

The following applied restoration guidelines are suggested for fan restoration in the Baviaanskloof Valley:

1. Tectonics and sea-level change has little impact on the base-level changes in the valley at present and local base-level induced changes in the valley are brought about by fan-channel modifications and a laterally migrating channel.
2. The primary determinant of fan area is drainage basin area. Fans on the north facing side of the valley produce larger fans per unit area than south facing fans. It is observed that if the fan area is altered significantly, fans will have and an impaired buffering and coupling function in the landscape.
3. Fan groups show little variation in basin and fan characteristics along the valley indicating that down valley fan setting does not strongly influence groups of fans in different local fan setting.
4. Surveys of individual fans are critical in identifying fan form-process characters to gain an understanding of how fans function. The use of longitudinal and transverse profiles can facilitate this.
5. Given the diversity of the Baviaanskloof Valley form, geology and rainfall, alluvial fan restoration should be done on a site specific basis as there are few trends that can be concluded for groups of fans or between valley sides. A poor recognition of fan processes and connectivity may result in the implementation of the incorrect fluvial modifications that will bring about an undesirable outcome.
6. Human activity has a significant impact on alluvial fans and can bring about a base level change due to shortening of the fan profile as well as incision at the apex or distal region of the fan surface. Human activity has influenced the fan evolutionary process by either preventing channel switching or encouraging it. An example of this is shown in fan 11 of the case study where a road has diverted water across the fan surface and created a new path of water flow. Restoration should therefore reduce the features that confine fan channels or prevent man-made structures from influencing fan channels.
7. One external factor that indirectly affects the alluvial fan system in the valley, noted in field observations, is grazing pressure (see spatial plan attribute table). A reduced grazing pressure would lead to a better vegetation cover, increased shear strength of fans and reduction in the potential for gully erosion. Increased vegetation however allows for the formation of steeper fans that are therefore more likely to incise, especially if vegetation is subsequently disturbed.

8. Once a fan channel has begun to develop headcuts on the distal fan surface, it becomes difficult to reverse its effects as a critical threshold has been exceeded. Fans that are dissected have exceeded the critical threshold and reached the final stage of fan evolution. In this case morphological interventions should be implemented to stimulate main channel switching and to create a new main channel on the fan surface which revives fan fluvial environment.

Chapter 9: General Conclusion

9.1. Overview of thesis outcomes

The aim of this thesis was to develop an understanding of alluvial fan functioning in the Baviaanskloof Valley using a geomorphological perspective. A framework based on published fan form-process relationships was developed to classify fans in the valley and to gain an understanding of how alluvial fans function using alluvial fan morphometry. A spatial plan, form-process framework (based on fan internal and external fan control variables), empirical relationships, form-process characteristics and fieldwork were used to develop a holistic understanding of fans in the connected fluvial landscape of the Baviaanskloof valley.

This thesis contributes to alluvial fan literature, more specifically, fan morphometry literature through the creation and application of a form-process alluvial fan conceptual framework. Key outcomes of the thesis includes a form – process alluvial fan framework, procedural guidelines to determine fan control variables and restoration guidelines that are specific to the Baviaanskloof valley.

The spatial plan (Chapter 4) provided an overview of the spatial distribution of fans and their drainage basins and formed the primary database of information for the framework and case study chapters. The case study component presented a detailed analysis of two fans in the valley; a laterally migrating channel affected one fan, but not the other. The four core chapters (Chapters 3, 5, 6 and 7) were used to investigate the local and large scale variation of fans in the valley, determine the effects of a lateral migrating main river channel and influence of human activity. The links made between geomorphic form and process through a number of overarching restoration themes allowed for the development of alluvial fan restoration guidelines.

9.2. Contributions to fan morphology studies and fan restoration

Thesis outcomes have made contributions to the general field of alluvial fan morphometry, alluvial fan restoration (both general and local) and created an alluvial fan knowledge base of fans in the Baviaanskloof Valley.

This thesis has also contributed to the study of alluvial fans in South Africa, particularly in the Baviaanskloof Valley. This study has provided a means of explaining fan form, fan drainage basin characteristics of fans and control variables to determine variations in fan characteristics along the valley or within valley group. This thesis can provide grounding for further fan studies in the Baviaanskloof Valley and can be used as a springboard for comparative fan studies in South Africa.

Contributions to general fan research have been made through the development of a standalone alluvial fan form – process framework that can be used classify fan form and identifies alluvial fan external and internal control variables. This framework can be tested in other fluvial settings to gain an understanding of integral links between fan-basin characteristics, fan form and quantify fan control variables. Additions have been made to Clarke's (2010) evolutionary stages model to describe fans in stages 4 and 5 of fan evolution. The 5 stages of fan evolution can be used to describe young and mature fans in the landscape by considering the location of fan incision and distal trenching which was not clear in Clarke's (2010) explanations.

The procedural guidelines can be used in general alluvial fan restoration studies by providing a stepwise method to determine key fan characteristics and to identify and quantify fan control variables. The more tailored guidelines for the Baviaanskloof Valley can be employed by Baviaanskloof Valley stakeholders. The layout of the procedural guidelines and key considerations for an alluvial fan project provides a guide for fan assessment which has the potential to cut down resource costs and time given the context. Alluvial fans in other research areas can be steered using findings from this thesis, particularly, the restoration guidelines which may provide a potential low-cost and low-time benefits for NGOs such as LivingLands.

9.3. Future studies

As described above, this thesis developed a theoretical framework that defines alluvial fan internal and external control variables to identify fan control variables in a valley setting used to inform fan restoration projects. The application of the framework in the Baviaanskloof Valley has characterised fan type, style and identified internal and external fan control variables. Data analysis techniques have investigated which of the external variables mostly affect fan parameters in the valley. This thesis however, did not quantify the functioning of fans in space and time due to data and resource constraints and did not provide a detailed timeframe analysis of channel processes. To gain an informed perspective of the functioning of fans in space and time as part of an integrated fluvial system, the following future studies are recommended.

A timeframe analysis of fan toe and river relationships would inform the impact of the main river on fans in the valley and indicate how often the main river affects fans in the valley and how this has changed and will continue to change over time. Furthermore, a detailed study of fan channel characteristics in space and time will provide a more informative account of fan channel changes such as channel incision, braiding, channel migration and trenching. This can be used to investigate the response of a fan system that has been modified by humans or used to monitor fan channel and surface adaptation after restoration engineering has taken place. Relative dating techniques can be used to date fan sediments to determine the age of fans in the Baviaanskloof Valley and can be used to date channel incision. The aquifer created by fans in the valley can also be investigated to determine spatial and temporal changes in the ground water table as a result of fans. This data can be used together with rainfall data to investigate how much water is required to induce active sediment and water transport to the fan and how often fans are active in the valley.

Detailed vegetation transects across the fan surface can be used to investigate other means of identifying unstable and degraded (unstable incision) fans in the valley and could be used as a surrogate measure to identify fan restoration opportunities. A suggestion for this study would be to identify key species between disturbed and undisturbed fan sites and to scientifically assess the distribution of shrubs, grasses and woody tree species between degraded and intact fans.

The future study suggestions identified above build on findings presented in this thesis which aim to classify and characterise fan morphology and identify fan external and internal control variables that can be used to inform fan restoration projects. It is hoped that this study will be used as a springboard from which a series of other fan studies can emerge.

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Appendix A

Table A.1: Table of alluvial fan attribute information (part a)

Object-ID	X-Coord	Y-coord	Area (km2)	Perimeter (km)	AFA:DBA	Fan Type	Mean fan slope (%)
1	24.199975	-33.605616	0.28	2.48	0.028	a	3.0
2	24.166125	-33.595324	0.02	0.75	0.108	a	5.0
3	24.149951	-33.587307	0.20	2.19	0.046	a	4.1
4	24.139841	-33.583375	0.05	1.24	0.031	d	3.7
5	24.112494	-33.584421	0.24	2.19	0.020	d	1.8
6	24.096140	-33.573952	0.15	1.59	0.016	a	2.2
7	24.069067	-33.575366	0.07	1.08	0.015	a	3.9
8	24.061634	-33.566940	0.06	1.07	0.064	a	9.2
9	24.056252	-33.563364	0.04	0.99	0.015	a	5.3
10	23.899690	-33.529129	0.24	2.06	0.028	b	3.7
11	24.036962	-33.558544	0.12	1.47	0.091	b	3.5
12	23.893741	-33.528082	0.37	3.00	0.081	d	2.9
13	23.902630	-33.530117	0.29	2.26	0.104	d	2.4
14	24.049651	-33.560462	0.10	1.43	0.047	d	4.7
15	23.885466	-33.528100	0.19	1.81	0.200	d	3.8
16	23.890707	-33.528918	0.19	1.68	0.028	a	3.6
17	23.878268	-33.528289	0.20	1.73	0.063	a	3.6
18	23.874193	-33.527320	0.19	1.69	0.042	a	4.6
19	23.867138	-33.525614	0.07	1.22	0.057	a	7.5
20	23.852376	-33.525660	0.23	1.92	0.034	d	3.9
21	23.842693	-33.523260	0.34	2.37	0.070	a	2.9
22	23.759127	-33.522850	0.12	1.33	0.042	a	3.6
23	23.729553	-33.520701	0.07	1.20	0.167	d	6.6
24	23.672390	-33.525368	0.16	1.59	0.018	d	3.8
25	23.654481	-33.527433	0.10	1.24	0.040	d	5.5
26	23.718357	-33.517620	0.13	1.68	0.066	d	7.7
27	23.690974	-33.518839	0.13	1.45	0.014	d	3.0
28	23.660135	-33.523322	0.10	1.40	0.075	d	3.9
29	23.705726	-33.518466	0.23	2.01	0.019	b	2.6
30	23.733874	-33.516633	0.19	1.75	0.092	d	3.6
31	23.840742	-33.518523	0.07	1.17	0.006	d	6.6
32	23.844476	-33.518264	0.17	2.15	0.057	a	3.4
33	23.858181	-33.519715	0.10	2.05	0.010	b	6.7
34	23.863389	-33.520676	0.06	1.06	0.045	c	3.5
35	23.878043	-33.518857	0.36	2.88	0.011	c	1.9
36	23.883414	-33.518369	0.30	2.41	0.004	b	2.7
37	23.896418	-33.520119	0.03	1.00	0.009	d	9.7
38	23.906607	-33.520740	0.03	0.66	0.018	b	7.4
39	23.980157	-33.539015	0.05	0.93	0.064	d	7.3
40	23.986088	-33.542041	0.57	3.33	0.019	d	1.9
41	24.023976	-33.550664	0.06	0.92	0.164	d	3.6
42	24.034302	-33.552235	0.08	1.13	0.074	d	3.9
43	24.049693	-33.554573	0.02	0.67	0.098	d	2.8
44	24.061110	-33.555935	0.02	0.60	0.040	d	3.9
45	24.068569	-33.559314	0.16	1.67	0.007	d	2.4
46	24.079143	-33.562789	0.05	0.90	0.402	d	4.0
47	24.093083	-33.566292	0.05	0.91	0.084	d	4.7
48	24.115022	-33.570980	0.06	1.05	0.040	a	2.8
49	24.122149	-33.573231	0.14	1.45	0.011	d	4.5
50	24.129132	-33.573737	0.11	1.25	0.152	a	4.5
51	24.134186	-33.574804	0.05	0.95	0.028	d	2.3
52	24.146406	-33.578293	1.41	5.11	0.037	b	1.6
53	24.156762	-33.582145	0.06	0.92	0.009	a	3.6
54	24.162621	-33.585936	1.41	5.39	0.020	b	1.6
55	24.172156	-33.590696	0.14	1.48	0.091	a	3.3
56	24.189941	-33.600130	0.03	0.67	0.013	a	5.6
57	24.211758	-33.597359	0.11	1.30	0.004	b	3.1
58	24.227425	-33.605993	0.14	1.96	0.004	d	3.6

Table A.2: Table of alluvial fan attribute information (part b)

Object-ID	Channels	Incison*	Braided	Channel migration	Toe Trimmed	Cultivated	Buildings	Property
1	1	1	1	1	1	3	1	RIET RIVIER
2	0	0	0	0	0	1	0	RIET RIVIER
3	1	1	1	1	1	2	0	RIET RIVIER
4	1	1,2,3	0	1	1	5	0	RIET RIVIER
5	1	1,2,3	0	0	1	3	0	RIET RIVIER
6	2	1,2	1	1	0	4	0	VERLOREN RIVIER
7	2	1,2	1	1	0	4	0	VERLOREN RIVIER
8	1	1	1	1	0	3	0	VERLOREN RIVIER
9	1	1,2,3	1	1	1	4	0	VERLOREN RIVIER
10	1	1,2,3	1	1	1	5	0	UITSLAG
11	2	1,3	0	1	1	4	0	UITSLAG
12	2	1,3	1	1	1	3	1	UITSLAG
13	2	1,2,3	1	1	0	3	0	UNKNOWN
14	1	1	1	0	0	3	0	DE KLIP FONTEIN
15	1	0	0	0	0	2	0	DE KLIP FONTEIN
16	1	1	0	1	0	3	1	DE KLIP FONTEIN
17	1	1	1	1	0	3	0	KLEIN POORT
18	1	1	1	1	0	3	0	KLEIN POORT
19	1	0	0	0	0	2	0	KLEIN POORT
20	2	1,3	1	1	0	4	0	RUST EN VREEDE
21	2	1,2	1	1	0	3	1	RUST EN VREEDE
22	1	1,2	0	0	1	3	0	RUST EN VREEDE
23	1	1,2,3	0	0	1	5	0	JOACHIMS KRAAL
24	2	1,2	1	1	1	3	0	JOACHIMS KRAAL
25	1	1	0	1	0	3	0	JOACHIMS KRAAL
26	1	1	1	0	0	3	0	JOACHIMS KRAAL
27	1	1,3	0	1	0	4	0	ZANDVLAKTE
28	1	1	1	1	0	3	0	ZANDVLAKTE
29	1	1	0	0	0	3	1	ZANDVLAKTE
30	1	0	0	0	0	2	0	ZANDVLAKTE
31	1	1,2,3	0	0	1	5	0	ZANDVLAKTE
32	3	1	1	1	1	3	0	UNKNOWN
33	1	1	0	1	1	3	0	UNKNOWN
34	2	1	1	1	1	3	0	RIET RIVIER
35	3	1	1	1	1	3	0	RIET RIVIER
36	2	1	1	1	1	3	0	RIET RIVIER
37	1	1	1	0	1	3	0	VERLAATEN RIVIER
38	1	0	0	0	0	2	0	VERLOREN RIVIER
39	0	0	0	0	0	1	1	VERLOREN RIVIER
40	1	1,2	1	1	0	3	1	VERLOREN RIVIER
41	0	0	0	0	0	1	1	UITSLAG
42	0	0	0	0	0	1	1	UITSLAG
43	1	1	0	0	0	3	1	UITSLAG
44	0	0	0	0	0	1	0	UITSLAG
45	1	1	0	0	0	1	1	UITSLAG
46	1	1	1	1	0	3	1	UNKNOWN
47	1	0	0	0	0	2	0	UNKNOWN
48	1	0	0	0	1	2	1	KLIP FONTEIN
49	1	0	0	0	0	2	1	KLIP FONTEIN
50	0	0	0	0	0	1	1	KLIP FONTEIN
51	0	0	0	0	0	1	0	KLIP FONTEIN
52	1	1,3	1	1	0	4	1	RUST EN VREEDE
53	1	1,2,3	1	1	1	5	1	JOACHIMS KRAAL
54	1	1	1	1	0	3	1	JOACHIMS KRAAL
55	1	1	1	1	1	3	0	UNKNOWN
56	1	1	1	1	0	3	0	ZANDVLAKTE
57	1	1,2,3	0	0	1	3	1	ZANDVLAKTE
58	1	1,2,3	1	1	1	3	1	ZANDVLAKTE

*Codes recorded for incised fans are 1: incision at the fan apex, 2: medial channel incision and, 3: distal channel incision (Chapter 5).

Fans visited in the field (Chapter 5).

Table A.3: Table of drainage basin attribute information

Object-ID	X-Coord	Y-coord	Area (km2)	Perimeter (km)
1	23.714523	-33.591385	10.03	15.82
2	23.649693	-33.535627	0.19	2.33
3	23.652426	-33.570760	4.31	9.28
4	23.753537	-33.536529	1.72	5.24
5	23.842010	-33.569183	11.90	16.76
6	23.837329	-33.534544	9.38	15.45
7	23.846705	-33.531756	4.78	12.14
8	23.870912	-33.580436	0.94	4.57
9	23.872341	-33.534689	2.62	9.01
10	23.877268	-33.536774	8.42	14.04
11	23.884344	-33.532501	1.30	6.16
12	23.886541	-33.534928	4.55	11.35
13	23.901367	-33.536418	2.84	8.05
14	23.897962	-33.531629	2.25	6.49
15	24.182276	-33.665681	0.96	5.34
16	24.153261	-33.645584	6.73	16.00
17	24.032059	-33.574252	3.20	8.96
18	24.145952	-33.601909	4.53	10.05
19	24.088985	-33.654160	1.30	5.83
20	24.032118	-33.637626	6.80	14.87
21	24.076170	-33.601186	4.83	10.61
22	24.031715	-33.596194	2.75	8.08
23	24.055202	-33.573573	0.39	2.95
24	23.721080	-33.491761	8.74	14.62
25	23.715361	-33.507756	2.49	8.45
26	23.697300	-33.503975	1.94	6.66
27	23.665086	-33.499951	9.19	14.21
28	23.690681	-33.514197	1.35	5.40
29	23.904161	-33.504438	12.12	17.57
30	23.893191	-33.494970	2.05	7.74
31	23.885412	-33.507056	11.72	18.28
32	23.873763	-33.492934	2.90	8.29
33	23.861419	-33.503564	10.00	16.47
34	23.856698	-33.512049	1.41	5.43
35	23.850289	-33.494969	34.02	28.41
36	23.836197	-33.487297	69.21	45.41
37	23.987799	-33.529824	3.88	10.07
38	24.206042	-33.570089	1.61	5.89
39	24.237152	-33.577785	0.76	4.03
40	24.208546	-33.588558	29.98	27.92
41	24.181555	-33.578708	0.37	3.49
42	24.181841	-33.557658	1.10	4.69
43	24.160310	-33.571377	0.25	2.37
44	24.153691	-33.552452	0.46	3.77
45	24.140083	-33.561176	23.63	31.51
46	24.120452	-33.544306	0.14	1.91
47	24.114367	-33.566140	0.59	3.93
48	24.132161	-33.557572	1.58	7.92
49	24.101279	-33.549440	12.29	20.97
50	24.089169	-33.538620	0.70	5.07
51	24.071582	-33.531881	1.80	6.28
52	24.062772	-33.543090	37.82	36.76
53	24.051411	-33.534459	6.05	16.00
54	24.037954	-33.531716	70.93	42.43
55	24.027243	-33.522146	1.55	5.97
56	23.992114	-33.538299	2.34	7.20
57	24.130522	-33.593535	26.14	27.86
58	24.042554	-33.580491	40.37	35.03

Table A.4: Micrometrics SediGraph III setup parameters used for sample analysis

	Parameter	Setting used
1.	Baseline	a pure sample of 0.04% sodium hexametaphosphate was used to calibrate the SediGraph III
2.	Chamber parameters	chamber will remain empty
3.	Chamber speed	6
4.	Grain size analysis options	150.00 um – 2.00um
5.	Density of sample	1.400g/cm^3 (selected for coarse sandst6 sediments)
6.	Analysis time	standard
7.	Rinse	three times
8.	Rinse: cell pump speed	set at 5

Table A.5: Melton's Ruggedness and Gravelius Index values calculated for fans in the valley

Fan nr.	GI Index	Melton's Ruggedness	Fan nr.	GI Index	Melton's Ruggedness
1	1.4	<0.1	34	1.5	0.2
2	1.5	2.0	35	1.3	<0.1
3	1.3	0.1	36	1.4	<0.1
4	1.1	0.2	37	1.5	0.1
5	1.4	0.1	38	1.4	0.2
6	1.4	0.1	39	1.3	0.4
7	1.6	0.2	40	1.3	<0.1
8	1.3	0.7	41	1.4	0.7
9	1.6	0.3	42	1.6	0.2
10	1.4	0.1	43	1.3	0.5
11	1.5	0.5	44	1.3	0.6
12	1.5	0.2	45	1.6	<0.1
13	1.3	0.2	46	1.8	0.7
14	1.2	0.3	47	1.5	0.5
15	1.5	0.5	48	1.5	0.2
16	1.7	0.1	49	1.8	0.1
17	1.4	0.3	50	1.7	0.4
18	1.3	0.2	51	1.7	0.6
19	1.4	0.6	52	1.3	<0.1
20	1.6	0.1	53	1.7	0.1
21	1.4	0.2	54	1.8	<0.1
22	1.4	0.3	55	1.4	0.2
23	1.3	0.6	56	1.4	0.2
24	1.4	0.1	57	1.3	<0.1
25	1.5	0.3	58	1.5	<0.1
26	1.4	0.3			
27	1.3	0.1			
28	1.3	0.5			
29	1.4	0.1			
30	1.5	0.4			
31	1.5	0.1			
32	1.4	0.3			
33	1.5	0.1			