A FLUVIAL GEOMORPHOLOGICAL STUDY OF RIVER REHABILITATION IN THE KOUGA REGION, EASTERN CAPE

by

ADRIAN PIETERSEN

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ABSTRACT

The Kouga Riparian Rehabilitation Project (KRRP) is seen as a pilot rehabilitation project in the Kouga region that is heavily invaded with *Acacia mearnsii* along the riparian zones of many mountain streams. Clearing of these black wattles and re-planting of indigenous vegetation are imperative to rehabilitation efforts. In this context, two invaded catchments were identified - the Baviaans and the Heuningnes. The aim of this research is to characterise the effects that the woody alien invasive *Acacia mearnsii* has had on the river channel morphology of the Baviaans and Heuningnes Rivers.

A desktop and initial field analysis of the relevant study area catchments was completed. This was followed by a comparison of the channel morphology of the various study channel reaches using fixed channel transects. Ecological resource quality objectives (RQOs) for river rehabilitation from a fluvial geomorphological viewpoint were then established. A long-term monitoring protocol to assess whether or not these RQOs will be achieved was recommended. Follow-up channel transects were measured post wattle clearance in the Baviaans and short-term (<2yrs) changes in channel form were described. Differences in terms of the effect of *Acacia mearnsii* on channel form were then interpreted by direct comparison and through statistical analysis.

Results indicate a number of significant differences between those channels impacted by black wattle infestation and those channels seen as unimpacted and natural. Short-term changes (<2yrs) that occurred within the study period post Baviaans wattle clearance were shown to be minimal for channel form as well as for bed material.

The lack of any clear relationship or explanation between channel form and other channel controls suggests vegetation as the primary control. Vegetation, specifically the invasive alien vegetation, is the key controlling variable acting on channel form in the two study catchments.

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

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LIST OF ACRONYMS

D50	**Bank median size particle**
DWAF	**Department of Water Affairs and Forestry**
EDM	**Electronic distance measurement instrument**
e.g.	**Example**
et al.	**Latin** ***et alia***
GIS	**Geographical information system**
i.e.	**That is**
Kpa	**Kilopascals**
KRRP	**Kouga Riparian Rehabilitation Project**
LWD	**Large woody debris**
m	**metre**
m^2	**Square metre**
$m^3 s^{-1}$	**Cubic metres per second**
PCA	**Principal component analysis**
pers. Com.	**Personal communication**
RLP	**River long profile**
RQOs	**Resource quality objectives**
SDA	**Stepwise discriminant analysis**
SOM	**Soil organic matter**
WfW	**Working for Water**
WWF	**World Wildlife Fund**

APPENDICES (on accompanying cd)

Appendix A	**Transect data and Bankfull discharge data**
Appendix B	**Bed material data**
Appendix C	**Bank and Terrace particle size data**
Appendix D	**Bank and Terrace organic data**
Appendix E	**Correlation Coefficient and other statistical analysis data**
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CHAPTER 1

INTRODUCTION

1.1 PROBLEM STATEMENT

The literature is full of examples of the negative environmental effects that alien invasive vegetation can exhibit e.g. out-competing or outgrowing surrounding indigenous vegetation, consuming considerable amounts of water, inability to cope with the natural fire regime, shading out the indigenous vegetation and so forth (Holmes *et al.*, 2000; Richardson & van Wilgen, 2004; Richardson *et al.*, 2007; Blanchard & Holmes, 2008) Thus, as Tickner *et al.* (2001) emphasise, any change in plant communities (including alien invasion) will have potential impacts on the structure and processes of that ecosystem. Tickner *et al.* (2001) further emphasise that this increased recognition of biological invasions has coincided with an expansion of research into riparian ecosystems. This is because riparian zone vegetation has an important role to play in both aquatic and terrestrial ecosystems and the vulnerability of the riparian zone to alien invasion is clearly recognised. In the case of *Acacia mearnsii* which has invaded large tracts of riparian zone within South Africa including the study area for this thesis, it has the tendency to form monospecific stands that reduces biodiversity while also inducing channel modification (Rowntree, 1991).

> *"Given that hydro-geomorphological processes clearly influence the structure of riparian plant assemblages and that these in turn affect the hydrology and fluvial geomorphology of rivers, surprisingly little attention has been paid to the interactions between invasions and these physical processes"* (Richardson *et al.*, 2007, p.132)

Thus, fluvial geomorphological processes and the effects of alien invasions within the riparian zone require further examination. The riparian zone provides natural habitat for various types of aquatic and terrestrial flora and fauna and a fluvial geomorphologist studies the riparian zone because its nature or characteristics will depend on what occurs within the river channel (Freeman & Rowntree, 2005). *Acacia mearnsii* has the tendency to disrupt the river channel and it is a recognised transformer species that can disturb and transform habitats (Rowntree, 1991).

1.2 BACKGROUND AND CONTEXT OF RESEARCH

The Kouga River catchment and riparian zones are severely infested by the woody invasive alien tree *Acacia mearnsii.* Experimental rehabilitation trials were set up following the clearing of these woody aliens from two tributary catchments by Working for Water (WfW). This Kouga Riparian Rehabilitation Project (KRRP) is being carried out by R3G (Rhodes Restoration Research Group) with the financial and professional help of the World Wildlife Fund (WWF) and WfW. It is seen as a pilot rehabilitation project and the Kouga region was selected as a priority degraded system due to its proximity to the Baviaans Mega-reserve with its high levels of endemic biodiversity and because of private land ownership (February, pers. com., 2008).

Both the clearing and the rehabilitation of the tributary catchments, the Baviaans and the Heuningnes in the Kouga region of the Eastern Cape, are being carried out by Working for Water which falls under the Department of Water Affairs and Forestry (DWAF). This long-term endeavour aims to establish itself as a pilot rehabilitation project, stimulate a riparian rehabilitation programme and contribute towards restoring ecological functionality to priority degraded systems. Thus, the Kouga River rehabilitation project hopes to develop and test cost-effective and robust methods of monitoring that could be applied to other rehabilitation projects. Interviews with key project individuals highlighted the main objective as the rehabilitation of key riparian zones in this priority catchment so as to restore ecological functionality. It is reasoned that the rehabilitation of the riparian zones through removal of invasive alien vegetation and re-vegetation of indigenous species will allow for an improvement in ecosystem functionality. This in turn will lead to an increase in water quantity and quality with an obvious additional benefit for biodiversity.

It was within this larger and longer-term Kouga River riparian rehabilitation project that this thesis was conducted. The primary focus of this thesis is the study of fluvial geomorphology. Thus, it examines the geomorphological processes and characteristics relating to the rehabilitation of the riparian zones of these tributary catchments i.e. Heuningnes and Baviaans. The Heuningnes River is a particularly degraded system with significant bank erosion and severe Black Wattle *(Acacia mearnsii)* infestation, particularly dense old growth in upstream areas (see Plate 1). While the Heuningnes River has never been cleared of alien vegetation along its riparian zone (invasion is believed to have started as long as 50 years ago), the Baviaans River was cleared in 2001 and there has been extensive re-growth in this short time period. The upper reaches of the Heuningnes River are only lightly invaded along short stretches. This provides for a reference against which the channel morphology of the invaded reaches can be assessed. A description and comparison of an uncleared river system, a recently cleared but reinvaded river system and a more 'natural' reference site is thus possible.

Clearing the Baviaans catchment of alien invasives began in earnest in September 2007. Starting at the lowest site, the Working for Water clearing teams moved upstream over the following months, clearing the riparian zone of woody alien invasives with the use of chain saws and initially also a chipping machine. The cut trees were removed and stacked on the side of the banks and the stumps coated with herbicide. A cursory follow up clearing was done in April 2008 where alien re-growth was sprayed with a folia herbicide. This was followed by a programme of indigenous vegetation re-planting along the riparian zone.

In the longer term, the post-clearing phase becomes one of monitoring. While this thesis concentrates on the fluvial geomorphology of the study catchments, it ends with a recommendation for a long-term monitoring system. This is to be done so as to measure or understand changes in channel morphology after the alien invasive clearance and rehabilitation measures.

Plate 1 *Acacia mearnsii* infestation along the riparian zone of the Heuningnes River

1.3 INVASIVE ALIEN VEGETATION

The characteristics of an invasive species are: 1) exotic to the country or region, 2) becoming more abundant and widespread, 3) has a 'pest' value attached to it, 4) has usually been introduced by humans (Tickner *et al.*, 2001). Many exotic species display these invasive characteristics. Exotic species of vegetation can overtake indigenous populations by out-growing and suppressing the local indigenous species (Freeman & Rowntree, 2005). In South Africa, exotic species often consume more water and reproduce at a faster rate than indigenous vegetation. In fact, it is estimated that as much as 16.1% of South Africa's water yield could be lost if invasive plants in mountain catchments and riparian areas are left uncontrolled (Marais & Wannenburgh, 2008). The riparian zone is particularly vulnerable to alien invasion because river channels provide a highly suitable habitat for colonizing species due to the constant supply of nutrients and water along a variety of habitats (Tickner *et al.*, 2001; Galatowitsch & Richardson, 2005). It is also this water that provides a means of transport for the alien invasive seeds.

The negative effects of alien species on riparian zones are made abundantly clear by Holmes *et al.* (2005). Aliens replace indigenous vegetation, can increase transpiration, change the natural fire regime, affect local soil erosion and thus impact catchment hydrology and sediment yield. Indigenous fynbos vegetation is both fire-prone and fire-adapted, but regular fires also help to promote the spread of invasive tees (Holmes *et al.*, 2000). The following quotation seems a fair description of the black wattle stands found along the riparian zone of the Baviaans and Heuningnes Rivers.

> *"Once alien trees have established, they grow faster and taller than indigenous species and after one or two fire-cycles form closed stands with reduced light penetration and altered nutrient cycling patterns, litterfall and fuel properties. Such stands typically replace fynbos vegetation and their impacts intensify with time elapsed since invasion"*
> (Holmes *et al.*, 2000, p. 631)

Impacts on channel form such as undercutting and slumping have been identified along the Heuningnes and Baviaans River channels. According to Rowntree (1991), these mature woody alien trees add to bank loading and induce slumping. Due to black wattle's intense invasiveness, they can quickly change a riparian vegetation community, leading to a spectacular change in erosion rates and channel form (Rowntree & du Plessis, 2003). The authors also say that while a good grass cover tends to protect banks against erosion and encourages deposition, trees tend to encourage deeper and narrower channels. This is in contrast to what is seen along the black wattle invaded sites of the Baviaans and Heuningnes rivers with their much wider channels.

Alien species can also change channel morphology by increasing flow resistance, dampening turbulence and causing sediment deposition (Holmes *et al.*, 2005). With their different root systems and by contributing large amounts of large woody debris (LWD) into the system, woody alien invasives such as black wattle can affect change in channel morphology. That alien invasive vegetation will have an effect on channel morphology is clear. In terms of the long-term Kouga River riparian restoration project, the removal of black wattle is vital for rehabilitation success along with the re-planting of more indigenous vegetation. The black wattle is seen as being a disrupting factor to channel morphology and thus needs to be cleared. Consequently, Chapter 2 examines the concepts of rehabilitation and restoration of these disturbed and altered river systems to something resembling a more 'natural' state.

1.4 REHABILITATION

Today, conservation is approached from an ecosystem perspective i.e. it is realised that the ecosystem is dynamic and stochastic and temporal and spatial heterogeneity among biotic and abiotic factors is emphasised (King *et al.*, 2003). Furthermore, the connection and relationship between biotic and abiotic factors is crucial, that is a 'healthy' biologically diverse and indigenous community will not be possible if the underlying abiotic and physical characteristics are not in place (King *et al.*, 2003). Thus, the core principle behind rehabilitation is that the underlying abiotic conditions will influence and have an effect on the kinds and diversity of biota that will occur.

Rehabilitation efforts towards a more 'pre-disturbance' type habitat assume it will bring about a desired biological response. The example given by King *et al.* (2003) is that a desired response might be the regeneration of indigenous vegetation within an area that was previously occupied by alien species. This is exactly what the KRRP aims to achieve by removing alien invasive vegetation and by re-planting more indigenous vegetation.

When speaking of stream rehabilitation, it is often understood that by restoring the stream's natural hydrology and morphology there is a high probability that ecological recovery will follow (Gordon *et al.*, 2004). This is because "stream morphology is the foundation of physical habitat availability, and therefore is a major determinant of the potential for ecological recovery" (Gordon *et al.*, 2004, p.321). Because riverine ecosystems and biota have evolved in conjunction with natural stream channel instabilities and variability, true stream rehabilitation should aim for a level of channel mobility. Thus, the expectations of a stream rehabilitation activity should be a partial return from a degraded state where stream morphology and physical habitat may have been severely affected to a more 'natural' reference condition. Alternatively, rehabilitation could bring about a different but nonetheless sustainable condition. Either way, any rehabilitation activity needs to recognise the importance of geomorphological change.

1.5 AIM, KEY RESEARCH QUESTIONS AND OBJECTIVES

1.5.1 Research aim

The aim of this research is:

To characterise the effects that the woody alien invasive *Acacia mearnsii* has had on the river channel morphology of the Baviaans and Heuningnes Rivers.

1.5.2 Key research questions

The research aim requires answering the following questions:

1) What are the characteristics of the uninvaded channel that acts as the reference for rehabilitation efforts?

2) Does the *Acacia mearnsii* invasion affect channel processes and therefore channel form?

3) What is the affect of wattle clearing on channel processes and channel form?

1.5.3 Research objectives

The following objectives have been identified:

1) Conduct a catchment analysis of the relevant study area catchments so as to determine a sampling framework.
2) Compare the channel morphology of the various channel reaches i.e. invaded Heuningnes, invaded Baviaans and the Reference.
3) Establish the ecological resource quality objectives (RQOs) for river rehabilitation from a fluvial geomorphological viewpoint.
4) Recommend a long-term monitoring protocol to assess whether or not these RQOs are being achieved.
5) Monitor any short-term (<2yrs) changes in channel form after the clearing of alien wattles in the Baviaans.
6) Interpret differences in terms of the effect of *Acacia mearnsii* on channel form.

1.6 THE STUDY AREA

The study area is situated in the Kouga region of the Eastern Cape. Roughly 100km west of Port Elizabeth and 40km inland from the coast, the Baviaans and Heuningnes sub-catchments are located in the Kouga Mountains approximately 21km from the town of Kareedouw (see Figure 1.1). Immediately north of the study area lies the large Baviaanskloof Nature Reserve, for which plans are in place to make it the much larger Baviaanskloof Mega-reserve. This is a valuable area with high biodiversity and lots of endemic species.

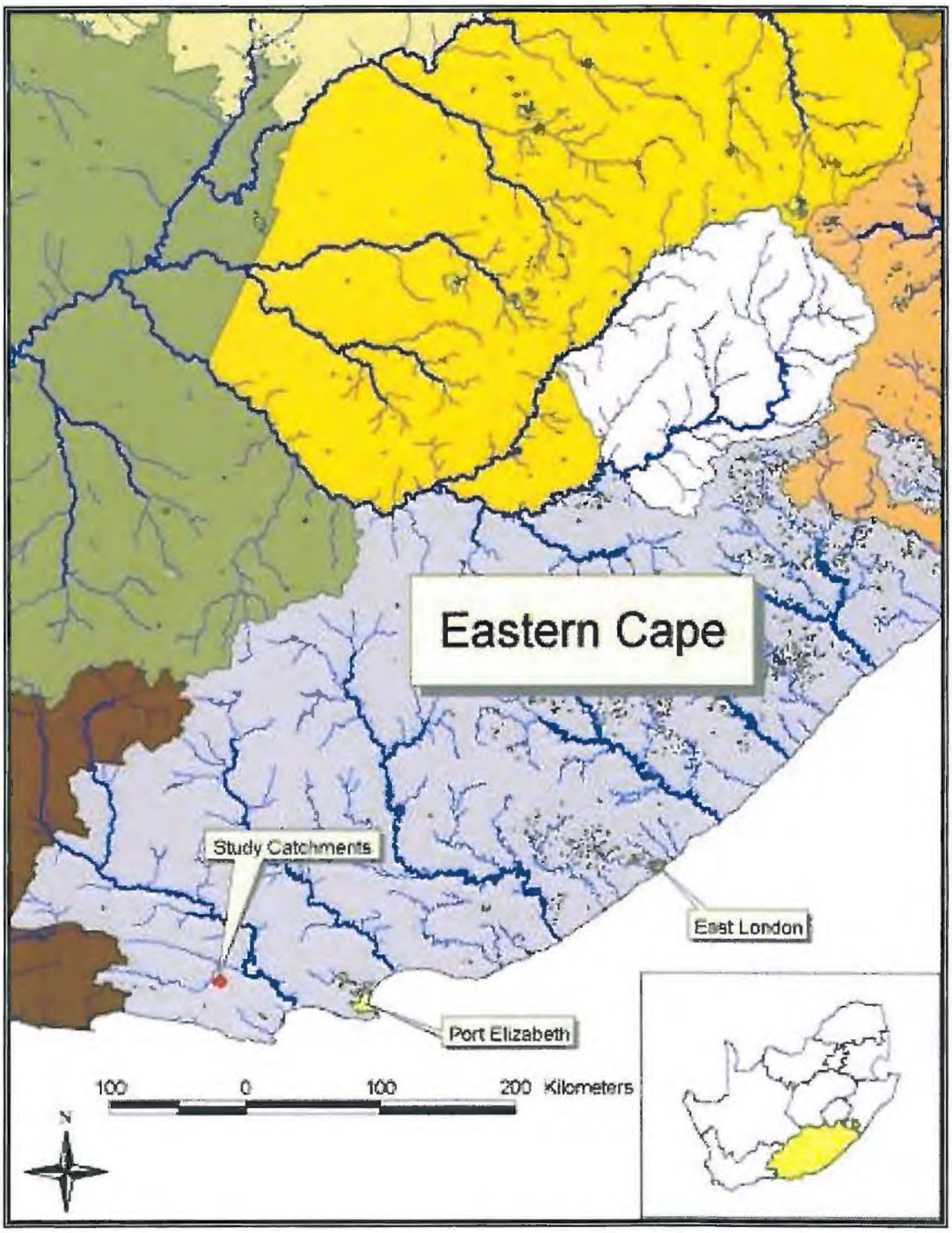

Figure 1.1 Location of study area within South Africa

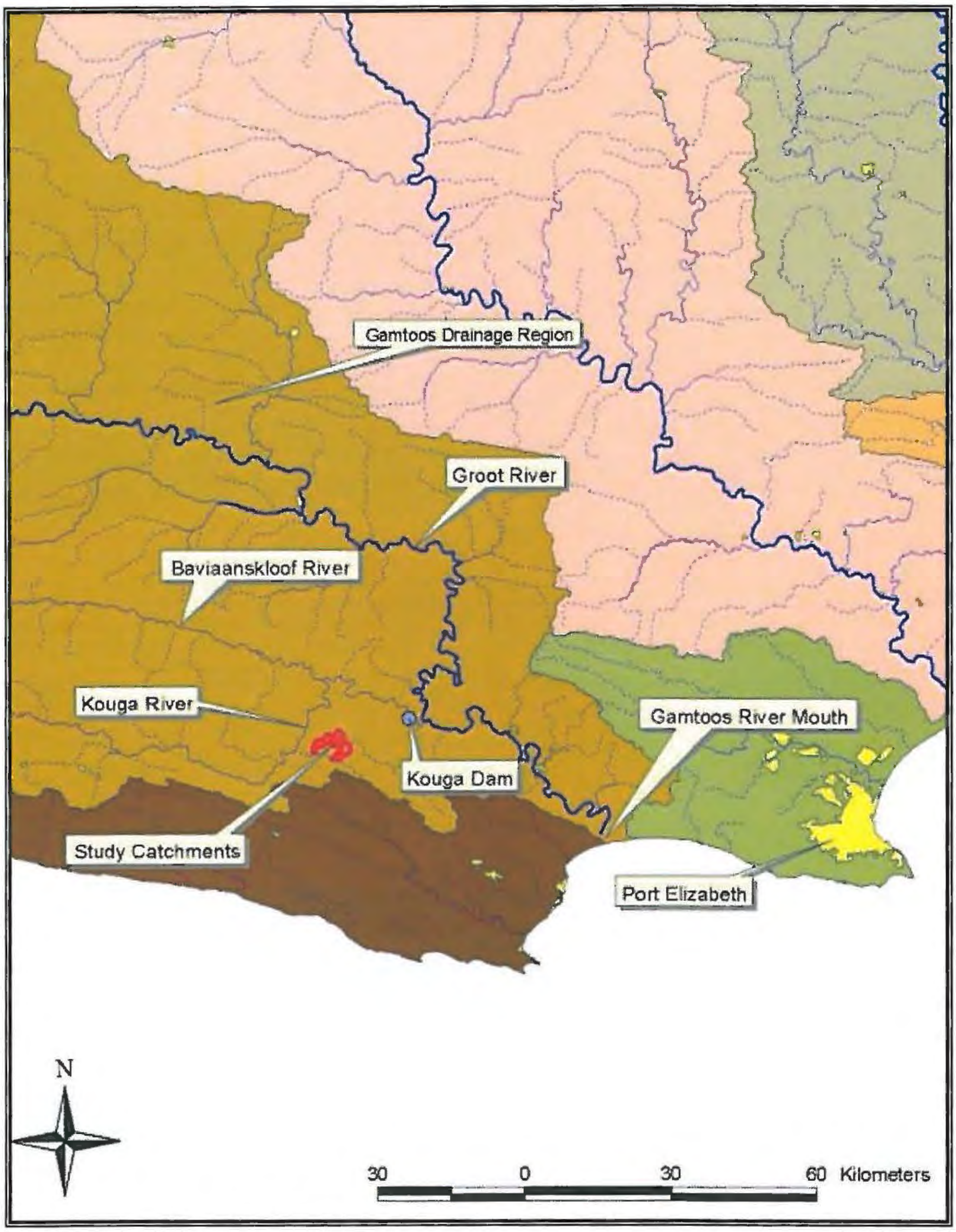

Figure 1.2 Location of study area within the Gamtoos Drainage Region

Figure 1.2 shows the study area relative to the DWAF defined Gamtoos Drainage Region. It shows the location of the Kouga dam and also where the Gamtoos river mouth empties into the Indian Ocean midway between the study area and Port Elizabeth. Figure 1.3 shows the two study sub-catchments adjacent to each other and shows the Kouga River flowing north-east towards the Kouga Dam. The nearby town of Kareedouw and Onverwacht farm, which both serve as rainfall stations, are also shown.

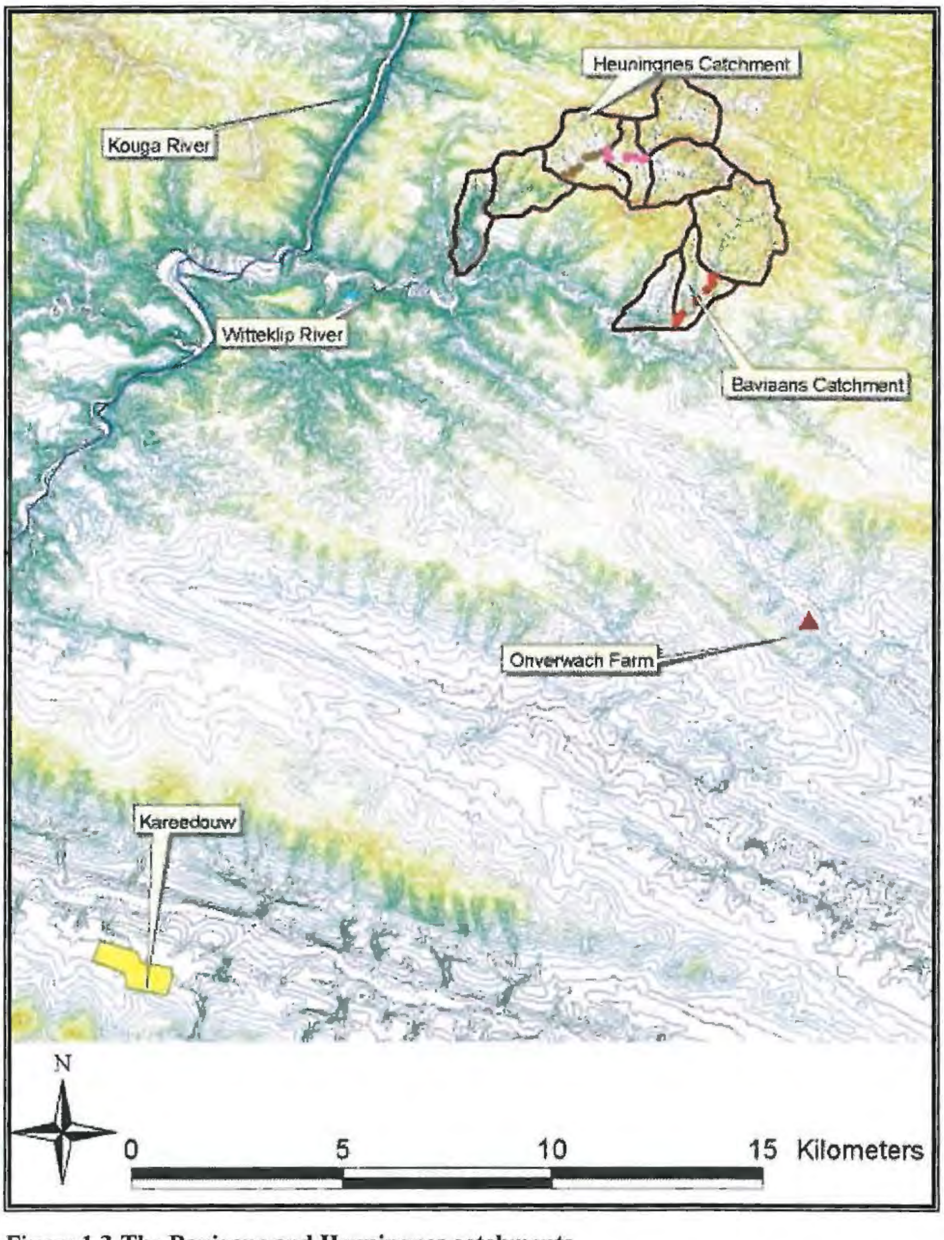

Figure 1.3 The Baviaans and Heuningnes catchments

1.7 THESIS OUTLINE

Chapter 1 has served to provide a general introduction to the thesis. Chapter 2 follows with a discussion of the approaches to rehabilitation and restoration as a re-creation of the right physical and abiotic factors that benefit indigenous species recovery. Chapter 3 provides a theoretical background to the thesis with a discussion of fluvial geomorphology. Research methodology is discussed in Chapter 4 which clarifies the experimental design framework for this thesis. Chapter 1 has provided only a general overview of the study area. Chapter 4 examines the study area in more detail. Chapter 5 provides a detailed examination of the two mountain sub-catchments so as to demonstrate differences in channel morphology between an impacted and invaded catchment and a more 'natural' reference catchment. Chapter 5 also examines any possible short-term (i.e. within the study time period) effects on channel morphology brought about due to the clearing of alien invasives. Chapter 6 provides an analysis and discussion of the results and findings. Chapter 7 then recommends a system for long-term monitoring of these study sites based on the outcomes of Chapter 6 and literature relating to monitoring. Finally, Chapter 8 serves as a conclusion to the study by also discussing limitations and making recommendations.

CHAPTER 2

APPROACHES TO RIVER REHABILITATION

2.1 THE TERMINOLOGY OF 'ECOSYSTEM REPAIR'

Prior to any discussion concerning the concepts of rehabilitation and restoration, it is essential that their terminology first be clarified. Clarity and consistency of the key terms used in any field of research is crucial for the progress of that field (Grenfell *et al.*, 2007). Precise terminology will have implications for research intentions and objectives as well as for measuring project success through monitoring and post-project evaluation.

Grenfell *et al.* (2007) propose applying the term *restoration* to parts of or entire systems that have been entirely lost through total and permanent (yet not irreparable) modification of ecosystem structure, function, biotic composition and services. In contrast, the term *rehabilitation* should apply to parts of or entire systems that have not been removed through complete and permanent alteration, but are indeed in a degraded state as a result of losing some measure of ecosystem structure, function, biotic composition and services (Grenfell *et al.*, 2007). Both these terms apply to some starting point along a continuum from totally modified ecosystem to partially modified ecosystem (also see Section 2.2).

However, this definition of rehabilitation begs the question: What is degradation? Degradation can be seen as the process of the environment becoming damaged or worsened, resulting in a lower 'quality' environment. Degradation can arise through a combination of processes brought about through human activities and habitation patterns e.g. soil erosion and degradation, long-term loss of vegetation, water pollution, deforestation, alien invasive vegetation and so forth. Degradation also has a direct impact on an ecosystem's resilience because as degradation increases so the ecosystem becomes more vulnerable to external shocks and surprises (Holling and Gunderson, 2002).

Thus, this understanding of rehabilitation, as emphasised by Grenfell *et al.* (2007), clearly applies in this study to the reaches of the Baviaans and Heuningnes Rivers that have become degraded due to invasive alien infestation. It is also clear that rehabilitation demands a lower level of intervention, effort and resources than that of restoration. Having explained the difference in terminology it must be said that the interchangeable use of these two terms is still widespread throughout the literature. This underlines the call by Grenfell *et al.* (2007) to emphasise clarity and consistency of key terms. Even though some references within this thesis use the term *restoration*, the author of this thesis follows the definition of *rehabilitation* as emphasised by Grenfell *et al.* (2007). Thus, for the purposes of this thesis, the work being conducted in the study catchments is seen as an effort to rehabilitate the ecosystem rather than to restore. It has not been completely removed through permanent alteration and thus is further along the continuum requiring specific localised interventions that will help move it along the continuum to a more 'natural' and sustainable state or end-point.

2.2 PURPOSE AND OBJECTIVES OF REHABILITATION

Today, rehabilitation of rivers is becoming an area in which an increasing number of water management bodies in many countries are intensifying their time, money and efforts (King *et al.*, 2003; Giller, 2005). River rehabilitation is seen as a new era in the approach to the river management which originates from an increased environmental awareness and accountability thereof. It is clear from the literature that any rehabilitation project or effort needs to have established aims and objectives.

Brookes & Sear (1996) emphasise three important questions from a geomorphological viewpoint. Firstly, is full restoration of the natural condition necessary or will an intermediate rehabilitation suffice? Essentially, any rehabilitation effort lies on a continuum with full restoration of natural processes and ecological functioning at one end and small-scale enhancements or addressing specific localised problems at the other end (Brookes & Sear, 1996; Gillilan *et al.*, 2005). Wherever the rehabilitation project lies on this continuum there must be consideration of the overall larger catchment area and its transfer of water and sediment and land use effects. Secondly, is the rehabilitation to be carried out for ecological or aesthetic reasons? Many river rehabilitation efforts have been carried out in the past due to aesthetic reasons, but from a purely scientific and ecological perspective the primary objectives of any rehabilitation effort should be for the ecological improvement (Brookes & Sear, 1996). Finally, is intervention necessary or is there the potential for natural recovery? The larger the intervention the more the costs and the potential for failure increase. However, sometimes direct intervention is immediately necessary and unavoidable. It is evident that the KRRP is an intermediate rehabilitation intervention being carried out for ecological reasons. With any rehabilitation effort, knowing the answers to these questions will help the managers or implementers to understand the primary objectives of the rehabilitation project. Once you know your objectives you can evaluate whether it will be successful in the wider context of environmental, technical and land use constraints.

2.2.1 Stream rehabilitation

The literature indicates that within the river channel, stream rehabilitation interventions should be aimed at improving the diversity of hydraulic, substratum and other environmental conditions. Furthermore, rehabilitation of the physical and abiotic characteristics within the river channel should bring about a change in the assortment of velocities, depths and substrata (King *et al.*, 2003). However, it is important to remember that the rehabilitation work being conducted on the KRRP is not primarily aimed at rehabilitating the channel habitat. Rather, it is focussed on the rehabilitation of indigenous vegetation within the river channel and the riparian zone. However, the underlying channel morphology will obviously directly affect any efforts to rehabilitate indigenous vegetation and conversely the removal of alien invasives and return of indigenous vegetation should directly benefit efforts to rehabilitate channel morphology.

With regards to the invaded Heuningnes and Baviaans catchments, the clear answer to impacts such as undercutting and slumping is the removal/clearing of the black wattle along the riparian zones. This is because controlling riparian alien vegetation is often the primary activity in stream rehabilitation. In fact, according to a study by Blanchard & Holmes (2008), fell and remove was seen as the best treatment for invasive alien clearance as it allowed for the best indigenous vegetation recovery. However, due to the remoteness of the study site, fell and stack is the treatment being used in this project.

Richardson *et al.* (2007) highlight four important issues relating to the restoration of riparian zones after alien invasion. Firstly, full catchment restoration is usually impossible and the authors stress that it is more feasible to restore certain segments of the riparian corridor. Any restoration/rehabilitation effort is confined within the catchment through its condition and through the processes taking place at the catchment scale. Any impacts on catchment condition or catchment processes will ultimately affect restoration efforts at the river channel scale. Secondly, clear physical and biotic goals should be defined based on sufficient baseline data such as a reference system. However, this is essentially a limitation given that complete, clear and pristine reference systems are rare (Richardson *et al.*, 2007). Thirdly, because old dense thickets of alien invasives can destabilise the river channel and alter fluvial-geomorphological processes, an important aspect following the clearing of the alien invasives may be a return to a more natural erosion-sedimentation cycle that will benefit indigenous vegetation recovery. A commitment to clearing is indeed long-term and will also require follow-up control. Finally, whatever the reasons for rehabilitation, it must be planned with full appreciation of the various biogeographical processes that are taking place on differing spatial and temporal scales. Furthermore, various aspects of ecosystem functioning must be acknowledged and realistic endpoints set (Richardson *et al.*, 2007).

Stream rehabilitation can be carried out either 'passively' or 'actively' (Gordon *et al.*, 2004). Passive rehabilitation implies the removal of the factors that will prevent recovery of the stream, which is left to heal or adjust undisturbed. Active rehabilitation is where detailed repair measures are applied. Passive rehabilitation is nearly always the less expensive and less risky option but it takes a much longer time to see any results. The removal of non-native species and revegetation with indigenous species (which is exactly what is being done in the KRRP) is seen as an 'active' and 'positive' rehabilitation activity usually done for the benefit of both humans and non-humans (Gordon *et al.*, 2004). According to Wissmar & Beschta (1998), the primary aim of active rehabilitation is to create the conditions within which natural hydrologic, geomorphic and biotic processes can occur.

Galatowitsch & Richardson (2005) discuss some interesting points in relation to riparian zone rehabilitation of headwater streams in the Western Cape that are relevant to the Kouga study. Here too, alien trees were cleared from the riparian zone and revegetation of indigenous vegetation carried out. However, the sheer amount of alien propagules supplies in a densely invaded section of river will affect recolonization rates and patterns after clearing. Furthermore, the overall lower rates of indigenous vegetation regeneration and the fact that unstable substrates and conditions created by the clearing can favour alien vegetation re-invasion are two more factors that seem to work against any successful indigenous recovery (Galatowitsch & Richardson, 2005). Thus, the authors emphasise how previously densely invaded sections of river will most likely exhibit prolonged transitions from dense alien invasions to revegetation of indigenous species, requiring many follow-up clearings. The authors also emphasise the use of specially selected indigenous species that can be used to catalyze natural recovery by closing off the canopy to alien re-invasion.

2.3 THE USE OF A REFERENCE

If one is to know exactly what needs to be 're-introduced' through rehabilitation efforts, a reference condition of the natural undisturbed state of the river is required. A reference condition is used as a template for rehabilitation activities and to aid rehabilitation objectives (King *et al.*, 2003). A reference is also necessary so as to establish the degree to which a given river system has changed or been altered. Thus, the reference is essentially used as a control against which a modified stream or streams can be compared (du Preez & Rowntree, 2006). There is no established methodology that can be used to determine the geomorphological reference condition for a river or stream. This is due to the inherently dynamic nature of rivers whereby no two are the same. According to du

Preez & Rowntree (2006), when determining the geomorphological reference condition for a river it is important to differentiate natural processes of change from change brought about through human activity.

"Discerning reference conditions for river reaches is confounded by the complexity of river systems and the elusiveness of clear cause and effect relationships between many variables at a range of spatial and temporal scales" (du Preez & Rowntree, 2006, p. 17)

The above quotation emphasises the complex nature of river systems which in turn explains the difficulty with reference conditions in that it is difficult to know what the condition of the river system was like prior to disturbance or anthropogenic influence (Grenfell *et al.*, 2007). In fact, as Richardson *et al.* (2007) point out, even if one can match up reference sites, their inherent dynamic nature finds them on a continuous trajectory of post disturbance recovery which causes difficulties for comparisons between systems. However, King *et al.* (2003) emphasise that, providing the reference reaches are in a fairly natural state, they can provide applicable channel morphology and guide rehabilitation methods that are compliant with and appropriate to the catchment. Also, the reference allows for the assessment of how far the impacted river reach being studied has moved towards an 'ideal' or 'natural' state after rehabilitation efforts (Kondolf & Downs, 1996; Wissmar & Beschta, 1998). In essence, the reference provides a mechanism for 'ground truthing' local processes and functions that are associated with healthy intact river systems (Wissmar & Beschta, 1998).

According to Kondolf & Downs (1996), the reference site should be relatively natural with a high conservation value and close to the impacted rehabilitation site. Thus, for the purpose of this thesis it is understood that the reference condition be defined as "the channel morphology that would be characteristic of a river reach under natural conditions and that would provide habitat to support the natural fauna and flora" (du Preez & Rowntree, 2006, p. 21).

2.4 CONSTRAINTS, RESTRICTIONS AND DESIGN ISSUES

Often, rehabilitation efforts are hampered either due to fundamental design flaws or by constraints and restrictions that surface while carrying out the rehabilitation work. Erskine (2001) describes how rehabilitation works to address bank erosion on the Williams River, New South Wales, Australia were designed to protect the site and not take into account larger catchment wide processes that could be driving the channel instability. Brookes & Sear (1996) mention that many projects focus on the reach in question while ignoring the influence of catchment wide processes. They emphasise the importance of looking upstream for the source of sediments and water and also understanding any land use changes that could have an effect on runoff and sediment production.

An obvious constraint is the inherent lack of scientific understanding of river processes by management organisations and the academic community (Brookes & Sear, 1996). This is where the authors emphasise the value of a qualitative assessment of river channel processes so as to understand and provide guidance on the most appropriate morphology and possible river dynamics of the rehabilitated channel. They also mention that in many instances rehabilitation projects based on geomorphological principles have been more successful even though a sound theoretical base is not in place. By building up the knowledge base, gaining experience and sharing this in accessible literature it is possible to guide future river rehabilitation works. Here, post-project evaluation becomes invaluable. Erskine (2001) mentions how rehabilitation techniques were repeated on the Williams River despite their previous lack of success. Post-project evaluation would help the agency conducting the rehabilitation work to understand the mistakes made and help to address rehabilitation issues and constraints. However, due to the inherent complexity of river systems when trying to understand the processes taking place, it is important to recognise that there will be a level of uncertainty with any geomorphological prediction (Kondolf & Downs, 1996). Uncertainty will only be reduced with the analysis of as much relevant information as possible.

2.5 DEFINING "SUCCESS"

How does one define a successful restoration or rehabilitation? According to Dollar (2004), there has been a pragmatic realisation that complete restoration of a fluvial system is often neither possible nor desirable. He rather asks what is an acceptable rate of change towards a more natural system and how sustainable is that change? Stewardson *et al.* (2004) point out that if biological goals are used as a measure for a rehabilitation project, the outcome needs to be measured using appropriate biological parameters. After a disturbance has taken place, Du Preez & Rowntree (2006) speak of geomorphological recovery and biological recovery, although the two are interrelated and affect one another. Biological recovery often occurs at a faster rate than geomorphological recovery. However, the initial biological recovery may require improved geomorphological conditions to start with and alternatively biological recovery can benefit geomorphological recovery (du Preez & Rowntree, 2006). Thus, rehabilitation efforts can be measured using natural variables. In the case of a stream's morphology, stream power, sediment supply, frequency of floods and riparian vegetation will all affect the rate of recovery and can thus serve as measurable parameters.

Richardson & Wilgen (2004) stress that research in riparian systems should define achievable goals for repair, provide criteria that can be measured and also develop protocols for future monitoring purposes. This would benefit the degree to which a rehabilitation effort can be seen as successful or not. However, Giller (2005) mentions that despite the great interest in river restoration there still exists a lack of practical criteria for judging ecological success of a given restoration or rehabilitation effort. Problems can arise due to this lack of measurable criteria whereby a rehabilitation effort is cited as a success when in fact it is not an *ecological* success. The following quotation emphasises the need to learn from these past mistakes and poorly designed restoration projects.

"We must learn from these mistakes and ensure that future projects include well-planned, adequately replicated studies with carefully chosen reference reaches and appropriate measurements of relevant dependant variables for assessment of ecological success" (Giller, 2005, p.205).

Palmer *et al.* (2005) also caution that projects labelled as a restoration success should not automatically assume to be an ecological success. They continue to say that the most effective restoration project usually lies at the intersection of a stakeholder success, a learning success and an ecological success. However, restoration success or failure is ultimately about ecological improvement and will thus always be seen or measured from an ecological viewpoint and here the authors mention five important criteria for an ecologically successful rehabilitation project (Palmer *et al.*, 2005).

Firstly, a guiding image must be expressed or proposed that describes the condition the river could or should exhibit at a given site. According to Gillilan *et al.* (2005), establishing this dynamic ecological end state is the most critical aspect of a restoration project. Secondly, to be judged successful, ecological conditions must be seen to be measurably enhanced and improved towards the guiding image. Here, the importance of a reference and baseline data becomes vital. Even though baseline data merely gives an idea of conditions at one point in time, they are still valuable and necessary information (Gillilan *et al.*, 2005). Thirdly, resilience is increased, allowing for the river to become a self-sustainable system with the capacity to recover from 'shocks' or disturbances. Fourthly, the project exhibits no lasting harm to the environment. Finally, a pre- and post-project ecological assessment should be carried out to evaluate its achievements in relation to the initial project objectives. Here, both positives and negatives of the rehabilitation project need to be clarified and the information made readily available. Jansson *et al.* (2005) echo the call for this valuable final criterion. The importance of post-monitoring and the sharing of successes and failures cannot be underestimated. Jansson *et al.* (2005) also mention that the complexity of a post-monitoring programme rarely matches the magnitude or cost of the restoration project itself. Thus, these five criteria for ecological success become important for any future restoration or rehabilitation project. With the support of the funding and implementing agencies, there exists an incentive to assess and report the outcomes of the project.

2.6 INTERVIEWS WITH KEY PROJECT INDIVIDUALS

To gain an understanding of the theoretical approach of the KRRP, key project individuals were interviewed. These included the land owner and manager, the project coordinator (as a restoration ecologist) and the WWF project sponsor supervisor. They were questioned on rehabilitation and what the primary purpose and objectives should be with regards to a rehabilitation project. There was unanimous agreement that the primary purpose should be the return of ecosystem functioning, that is the improvement of ecosystem services such as water quantity and quality is seen as the primary aim with improvements to biodiversity an added benefit. The development of protocols and methodologies which will benefit a best management practice for the future rehabilitation of other riparian zones was also a key objective of the KRRP. A successful rehabilitation project was one with positive measurable improvements to the river ecosystem whereby it is becoming more 'natural' and sustainable. However, defining and measuring this success requires long-term monitoring and evaluation systems to be put in place. Success was also seen as a project that has a straight forward research process with few implementing, managerial, methodological or procedural issues.

Interviewees were also questioned on major problems encountered with rehabilitation or restoration projects. Previous experience with rehabilitation projects showed that there were always problems or issues with implementation. Often there exists a misunderstanding from minor stakeholders that are unsure of what is being carried out. Thus, trying to conduct scientific experiments within a social system becomes problematic. Furthermore, problems due to a lack of funding as well as a lack of genuine expertise or knowledge tend to surface.

2.7 CONCLUSION

Disturbances to a riparian system that are initiated through human actions (such as black wattle invasions) are often long-term and can restrain any natural recovery processes (du Preez & Rowntree, 2006). Thus, rehabilitation interventions are necessary. River rehabilitation efforts should re-introduce a variety of physical habitats so as to improve and benefit ecological functioning within the river ecosystem (King *et al.*, 2003). The natural processes of recovery after a rehabilitation intervention can also be measured through indicators such as the re-appearance of pools and riffles, changes in bank slope and flood terrace development, adjustment and stabilisation of channel cross-sections, and the establishment of aquatic and riparian vegetation (King *et al.*, 2003). These are measures of a successful rehabilitation intervention from a fluvial geomorphological viewpoint and are the indicators that require monitoring in the long-term so as to measure the degree of rehabilitation success.

CHAPTER 3

FLUVIAL GEOMORPHOLOGY

3.1 A FLUVIAL GEOMORPHOLOGICAL APPROACH

3.1.1 Fluvial Geomorphology

Fluvial geomorphology is the study of those relief features that have been shaped by the hydraulic action of running water. Rivers and streams, landscape components central to the study of fluvial geomorphology, are important ecosystems that are made up of a multitude of interconnected components that have concomitant effects (Freeman & Rowntree, 2005). Fluvial geomorphologists want to know how these components within the river respond to changes or alterations in the short and long-term and furthermore to try and understand what has caused this change in the river system. Rivers are essentially 'open systems' experiencing a constant inflow and outflow of energy and matter (Gordon *et al.*, 2004). Furthermore, rivers are dynamic systems and change is constant, that is stream levels can shift, sediment loads fluctuate, meanders migrate, banks collapse, floods scour and deposit sediment. Thus, the fluvial geomorphologist tries to identify, understand and predict change and its effects on the river system, always bearing in mind that the effects of change at one point along the river system are reflected elsewhere in the system (Gordon *et al.*, 2004; Freeman & Rowntree, 2005).

A river acts as an agent for the erosion and transportation of sediment and water. These processes of erosion and transportation result in a wide range of network and channel forms (Knighton, 1998). It is the character of these forms relative to the underlying processes at work within the river that are of importance to the fluvial geomorphologist. It is also acknowledged that the unique character and behaviour at a given location (i.e. site) along a river channel is the result of a group of upstream controls (e.g. catchment dynamics, land use, geology, climate, etc.). Local variables also come into play within the reach as will be discussed in more detail later. Figure 3.1 shows some important variables and their relationships at work within a fluvial system. Climate is of great importance as it relates directly to key processes. Geology also has a large influence but is less easily quantified (Knighton, 1998). The most significant driving mechanisms in fluvial geomorphology are those exerted by the hydraulic forces of flow since these characterise the stream system and as a result define the geomorphology of a given reach (Hardy, 2006). Figure 3.1 clearly demonstrates that underlying the primary controls of flow discharge and sediment load lies many other factors that influence the channel form at a variety of scales.

For the purposes of this research, the following definition of a fluvial geomorphological system will be used: "an organised assemblage of resources (components/variables) and procedures (processes) regulated by interaction or interdependence to accomplish a set of specific functions." (du Preez & Rowntree, 2006, p.83)

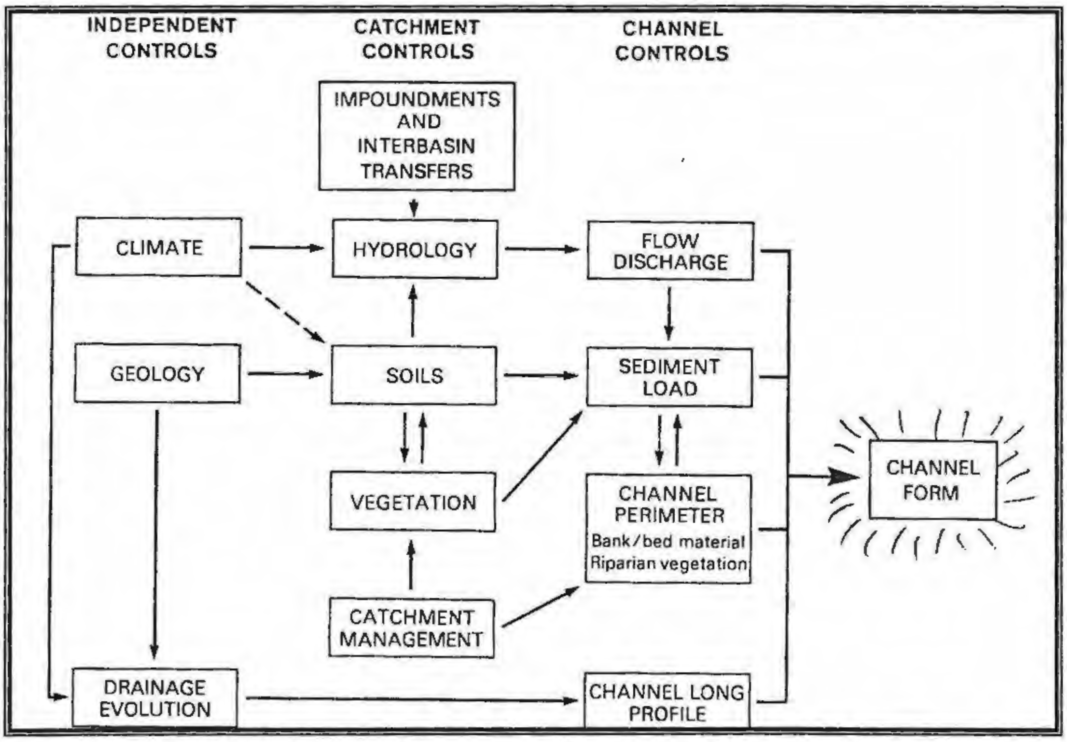

Figure 3.1 Controls and variables at work within the fluvial system (Rowntree & Wadeson, 1999, pp16)

3.1.2 Scale and complexity

The characteristics of a river channel develop over three particular time scales: geological, geomorphological and ecological (Dollar & Rowntree, 2003; Freeman & Rowntree, 2005;). Geological time explains the development of the entire catchment with its river network and valley forms. Geomorphological time (in years to centuries) is the timescale in which an 'equilibrium' state is reached in the river channel processes and channel geomorphology. At this scale, channel adjustment occurs in response to longer term changes in the flow and the sediment regime (Dollar & Rowntree, 2003). Ecological time (hours to days) considers geomorphology to be stable while only the river's flow discharge and the movement of sediment within the river channel vary. Thus, within this timescale, hydraulic habitat is a result of the variety of hydraulic patterns which are ultimately a result of channel morphology (Dollar & Rowntree, 2003). While geological timescale is obviously outside the time frame of river management, geomorphological and ecological timescales are used in conjunction because "it recognizes immediate changes to habitats and ecosystems caused by variations in flow and sediment through the channel" (Freeman & Rowntree, 2005, p.36). It is the ecological timescale that provides the framework within which many processes are observed and data is collected (Dollar & Rowntree, 2003). Another obvious scale relevant to any environmental study is that of space. Recognising the spatial scale helps us to understand, question and link location with rates of change within the river channel that occur because of various processes (Freeman & Rowntree, 2005).

Understanding that the river is a complex system goes hand in hand with understanding the issue of scale. This is because within the river there are various processes taking place over various spatial and temporal scales e.g. erosion of the catchment over geological time vs. erosion of a channel bank due to vegetation or a large flood. Dollar (2004) emphasises this complexity by stating that a river channel's form, the processes happening within the river channel and the channel's behaviour can all be understood through a scale-sensitive hierarchical approach.

Understanding a river system's complexity and the issue of spatial and temporal scales results in the realisation that predictions in fluvial geomorphology are often qualitative and imprecise (Dollar, 2004). Because each geomorphic situation is so unique, one finds that opportunities for repeatable observation, falsifying hypotheses and the application of experimental and laboratory data are all limited. Furthermore, a river reach is situated within a hierarchical system where larger catchment scale processes will constrain the smaller scale processes. Thus, Dollar (2004) argues that a "rigorous, defensible scale-based conceptual approach to prediction (and management) is preferable to a precise, yet conceptually flawed scale-less numerical approach" (Dollar, 2004, p.421).

3.1.3 Recognising a hierarchical geomorphological approach

With temporal and spatial variability operating among the many dynamic factors within a river system, it is implicit that a useful approach for classification is one that is hierarchical, whereby higher levels in the system either completely or partially determine the characteristics, features and attributes of the lower levels in the system (Rowntree & Wadeson, 1999).

"The hierarchical framework for river classification provides a scale based link between the river channel and the catchment, so as to account for catchment dynamics."
(Freeman & Rowntree, 2005, p. 42).

As the abovementioned quotation indicates, a hierarchical system helps to clarify the relationships of dependency between all the various aspects of a river system (Freeman & Rowntree, 2005). It is for this reason that the hierarchical system is important as a practical classification system that allows for the description of streams at various scales as well as the integration of work carried out by ecologists, river managers and geomorphologists, all three of which work on a number of different scales (Rowntree & Wadeson, 1999; Freeman & Rowntree, 2005).

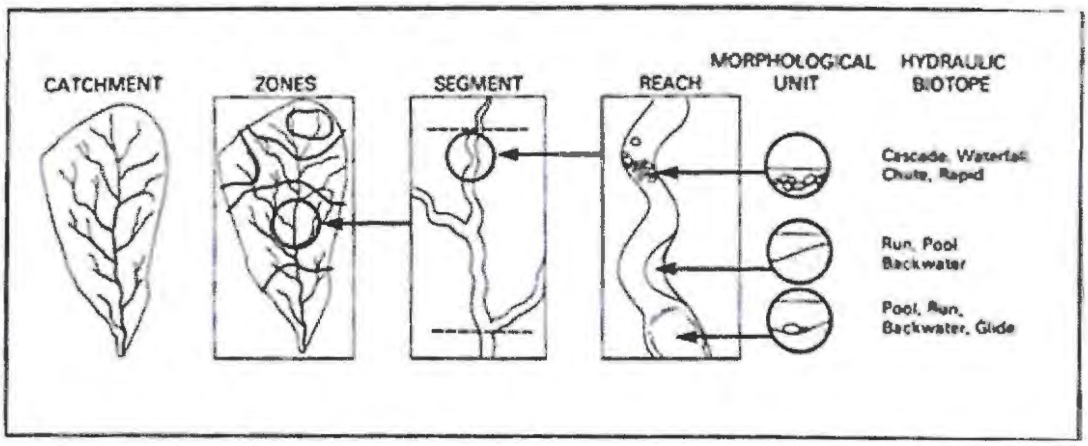

Figure 3.2 The hierarchical organisation of a South African stream system
(Rowntree & Wadeson, 1999, pp24)

By using the South African hierarchical geomorphological model of Rowntree & Wadeson (1999) and studying at reach level, it is apparent that the processes that influence that reach are all contained within the levels above (See Figure 3.2). Refer to Section 3.1.5 for a definition of a river reach. Thus, the levels above the reach influence and help to characterise the reach. Conversely, the reach will influence the characteristics of a given study site and the morphological units contained within that site. It is the morphological units that are seen as the basic structures that help to make up river channel morphology and thus it is at this level or scale where most of the fluvial geomorphological research work is conducted e.g. transects and channel eross-section analysis. Morphological units within a stream channel will form in response to the flow and sediment regimes and are identified as either being erosional or depositional features (Freeman & Rowntree, 2005). By removing invasive alien vegetation along the riparian zone of a stream, the flow and sediment regimes will be altered. Thus, by studying the Heuningnes and Baviaans Rivers, it should be possible to characterise and comment on changes at the morphological unit at given sites within the reaches of these rivers.

Although the hierarchical geomorphological model is essentially used for *classifying* different rivers, it is an important approach that is recognized and used in this research. The study of any river must recognise the spatial and temporal scales and thus the various processes at work within the catchment which will affect the river channel and its morphology. Chapter four makes use of this approach by recognising the hierarchical geomorphological model towards a sampling framework used to research the study rivers.

3.1.4 The Catchment

Having emphasised a hierarchical approach to understanding the dynamics of a river, and having mentioned that most fluvial geomorphological research is carried out at the reach and morphological unit scale, this section now examines the all encompassing catchment. The catchment can be seen as a starting point from which to understand the processes that are taking place within a river channel that ultimately result in a specific channel form. It represents a clearly defined physical unit with inputs, throughputs and outputs (Knighton, 1998). The input, in the form of spatially distributed precipitation and sediment, moves through the system via hillslopes and channel networks to a single output at the mouth of the catchment (Knighton, 1998). Catchments have their own hierarchies with 1st order streams at the top of a catchment draining into 2nd order streams which drain into 3rd order streams, etc. First order catchments being generally quite small are usually homogeneous with regards to runoff, sediment yield, geology, soils and vegetation (Freeman & Rowntree, 2005). This is relevant to the study area of this research, all of which are first order streams.

Knighton (1998) emphasises characteristics that are particularly relevant to many South African catchments, including the study area used in this thesis. With the study catchments being in a fairly dry region, rainfall input is usually low, unreliable, variable and in the form of spatially concentrated high intensity events. Throughput may be dominated by overland flow, rapid surface runoff and a decrease in downstream discharge due to transmission losses. Output is usually intermittent and extremely variable with a sharp peak in runoff and an overall flashy regime.

3.1.5 The Reach

The basis of any classification or river study is the reach, in which a stretch of river is homogenous and the controls on channel form are the same or similar, resulting in a fairly consistent channel morphology (Rowntree & Wadeson, 1999). The variables that control the reach (i.e. gradient, hydrology, geology, bed and bank material, riparian vegetation) will directly determine how the reach will respond to changes in flow and/or sediment load. The reach control variables will directly affect whether the particular reach acts as a source zone, transfer zone or sink zone with regards to sediment. The end result of all these dynamic fluvial geomorphological processes is a distinctive channel form which can then be measured, characterised and compared to other reaches. Thus, the following section continues by discussing fluvial processes and forms.

3.2 FLUVIAL PROCESSES AND FORMS

3.2.1 Channel morphology

Channel morphology is the result of three important fluvial geomorphological processes, i.e. erosion, sediment transport and deposition, that are in turn dependent on the energy provided by streamflow. The morphology or shape of a river channel depends on the interaction between the water flow and the erodible materials within the channel boundary (Knighton, 1998).

Thus, the channel morphology for a given reach is the result of the interaction of these three fluvial processes which are themselves primarily controlled by discharge and the sediment load (especially bed material load), variables that relate to the catchment scale. In turn, these primary controls are a result of the combination of the effects of climate, geology, basin physiography, vegetation and soils (Knighton, 1998). Furthermore, a change in one of the underlying variables (e.g. the introduction of alien invasive vegetation, land use change, climate change, etc.) can bring about a change in discharge and sediment load which will result in a change in channel morphology.

This shows the importance of understanding that channel morphology is a manifestation of a variety of processes occurring at all scales of the hierarchy within a river system, but that it is evident at the morphological unit. Thus, it is at the morphological unit where the measurement of channel form variables would take place.

Knighton (1998) relates the three-dimensionality shown in Figure 3.3 to four different planes of adjustment i.e. cross-sectional form, bed configuration, channel pattern (planform) and channel gradient/slope. Of the four planes, cross-sectional form is probably the most common channel data type collected through a variety of measurable variables (Knighton, 1998; Simon & Castro, 2003). Thus, the channel width, channel depth, channel cross-sectional area and channel form ratio (width-depth ratio) are four measurable variables that can be used to describe channel morphology. Although seen as four distinct planes they are not independent of each other and one plane can affect or be affected by another.

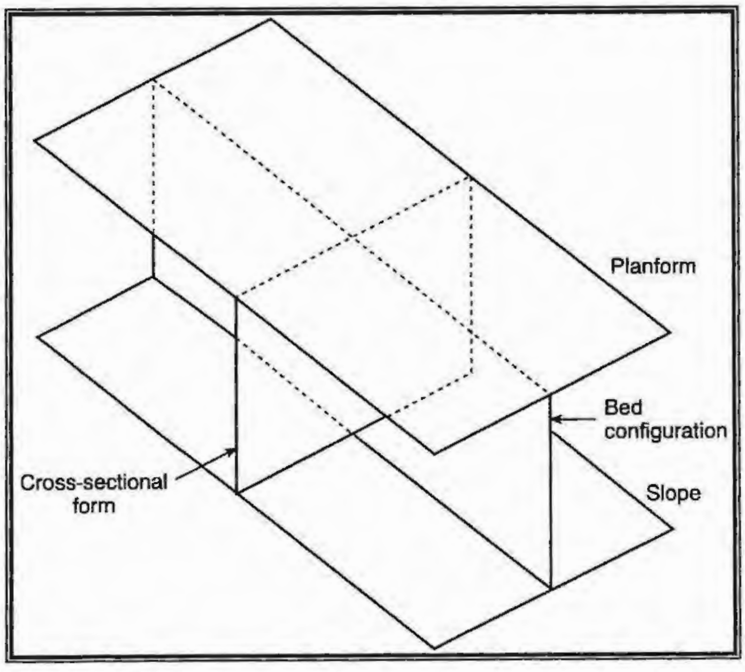

Figure 3.3 The different planes of channel form adjustment (Knighton, 1998, pp157)
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3.2.2 Erosion, transport and deposition

A river is a 'mechanism' for the transport of sediment and material, the three process that in turn determine the morphology of the channel. In order to understand how changes to the vegetation can affect channel morphology it is pertinent to first examine the processes of erosion, transportation and deposition in more detail.

Erosion

As water works down the river system it uses some of its energy to transport and rearrange materials in the bed and banks of the river (Gordon *et al.*, 2004). The physical properties of size, shape, density and the arrangement of material will affect its movement within the river channel (Knighton, 1998). River bank material is highly variable but characteristically becomes finer and more uniform downstream (Knighton, 1998). Bank erodibility is also further complicated by the effects of vegetation on the bank. Banks tend to erode either through the hydraulic action of flow or through mass failure, both of which can be exacerbated by the introduction of invasive alien vegetation. While it is the distribution of velocity, shear stress on the banks and local turbulence characteristics that will influence the erosive potential of the hydraulic action of flow, it is the geometry, structure and material property of a bank that will affect mass failure (Knighton, 1998).

Transport

The total load of material transported consists of three types: flotation load, dissolved load and sediment load (Gordon *et al.*, 2004). Flotation load is generally the organic debris such as logs, leaves and branches. The dissolved load is material that is transported in solution and is closely associated with local geology, land use and weathering processes. The sediment load consists of the washload and bed material load. Washload refers to the smaller sediments, clays, silts and fine sands, which are all readily carried in suspension by the stream and brought into the stream from upland areas and river banks. It moves along the river at the same speed as the water. Bed material load is comprised of a suspended bed material load (which is carried with the washload) and a bed load.

Bed load comprises the largest sized particles and is that load which slides roles or otherwise moves along the river bed. Bed load is an important aspect of the total material load transported along a river channel because it offers resistance to the flow of water, unlike the other load types. Thus, it directly influences channel patterns and channel morphology through the rate of energy loss to the flow caused by this resistance (Gordon *et al.*, 2004). The majority of a stream's energy is used to overcome the resistance along its bed and banks. Therefore, for erosion and transportation processes to take place, a critical energy level must be reached (Gordon *et al.*, 2004). The erosion and transportation processes are sustained as long as the critical energy level can be sustained. If not, it can no longer carry its load and the final process of deposition will occur.

Deposition

The ensuing process of deposition and the selectivity of the size of the material that is deposited results in characteristic bedforms e.g. pools, riffles, cascades and so forth (Gordon *et al.*, 2004). These bedforms consequently affect local flow resistance, velocities and turbulence which encourage further erosion or deposition. It is the interaction between these various bedforms that "is part of the self-regulating feedback that enables a stream to adjust to changing discharges and sediment loads" (Gordon *et al.*, 2004, p.190). It is for this reason that bed material size generally decreases downstream in conjunction with channel slope. This is because the larger, heavier material (which requires a higher critical energy level to transport) is deposited first as the stream loses energy (Knighton, 1998).

3.2.3 Controls on channel morphology

The following sections take a closer look at channel morphology as an outcome or product of a range of processes all taking place within a three dimensional context over varying spatial and temporal scales. Figure 3.3 shows the three dimensional context in which change in channel morphology occurs while Figure 3.4 shows various components of channel morphology and their timescales and spatial scales of adjustment. It is important to understand that an analysis of a channel's form requires understanding whether processes occurring over various spatial and temporal scales are localised or catchment wide adjustments (Simon & Castro, 2003).

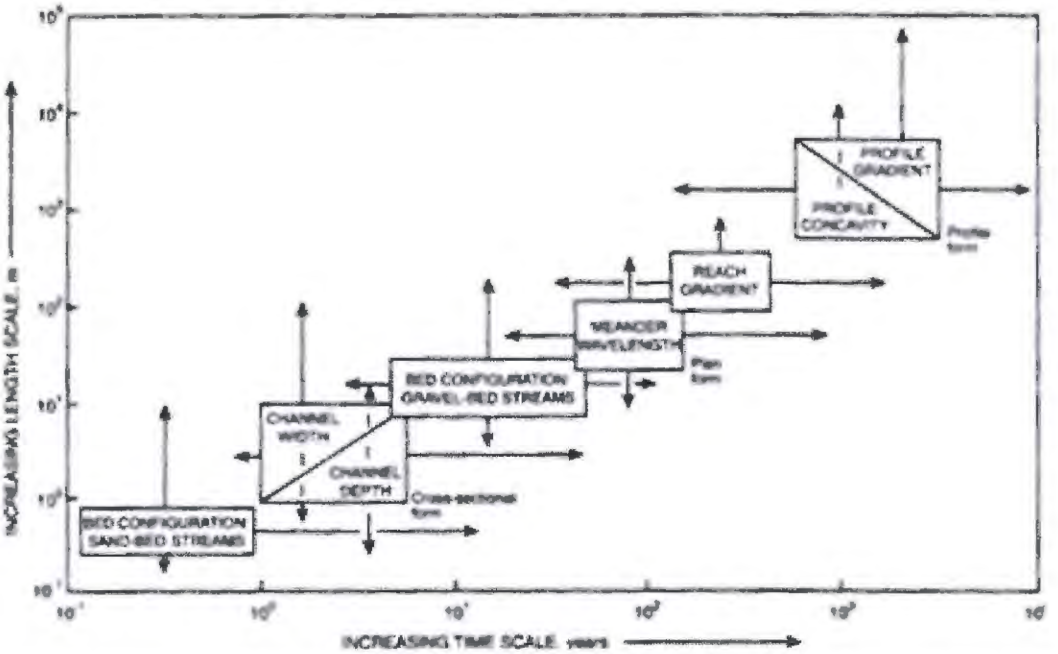

Figure 3.4 Temporal and spatial scales of adjustment of various components of channel morphology (Knighton, 1998, pp158) Reproduced by permission of Edward Arnold (Publishers) Ltd

Describing channel morphology is fundamental to the approach and study of fluvial geomorphology. According to Rowntree & du Plessis (2003), channel morphology is the ultimate determinant of the in-stream flow environment in which medium to long-term (10-100years) processes must be considered.

The four key controls on channel morphology are: *the river long profile* (RLP), *flow, sediment and bank resistance* (Rowntree & du Plessis, 2003). These four controls are interrelated and influenced by various underlying variables. However, they provide a basis from which to understand controls on changes in channel morphology.

The river long profile provides a longitudinal indication of the downstream change in gradient and thus characterises the downstream change in potential energy (Rowntree & du Plessis, 2003). It is an extremely useful piece of graphic information showing a stream's elevation change over distance. The characteristic concave shape is associated with an increase in discharge and a decrease in sediment size in the downstream direction (Gordon *et al.*, 2004). Sudden changes in gradient along the river long profile can be caused by changes in geology or occur at stream junctions. Furthermore, the river long profile can be divided into various reaches which represent a stretch of river with the same gradient.

Flow can be considered a "master variable" due to its strong association with channel geomorphology and habitat diversity (Poff *et al.*, 1997). In terms of the biotic response, flow limits the distribution and abundance of species and also controls the ecological integrity of the stream. From a fluvial geomorphological viewpoint, three flow classes are important: low flows that maintain the availability of habitat, intermediate flows that maintain substratum characteristics and high flows that maintain channel form (Dollar & Rowntree, 2003).

When studying the river channel it is important to characterize or define the active channel. It is the part of the river channel that receives water flow most often and is usually marked by fairly noticeable banks on either side of the channel (Freeman & Rowntree, 2005). In terms of discharge this is often seen as being a "bankfull". Thus, a discharge at "bankfull" is taken roughly as the elevation of the active floodplain and is thus a physical measure of the flow capacity of the channel. The flood plain as well as the shape and pattern of a river channel are all related to flow discharges that approximate the bankfull condition (Wolman & Miller, 1960). Wolman & Miller's 1960 study also showed how effective discharge, bankfull discharge and the 1.5 year flood are strongly related to each other.

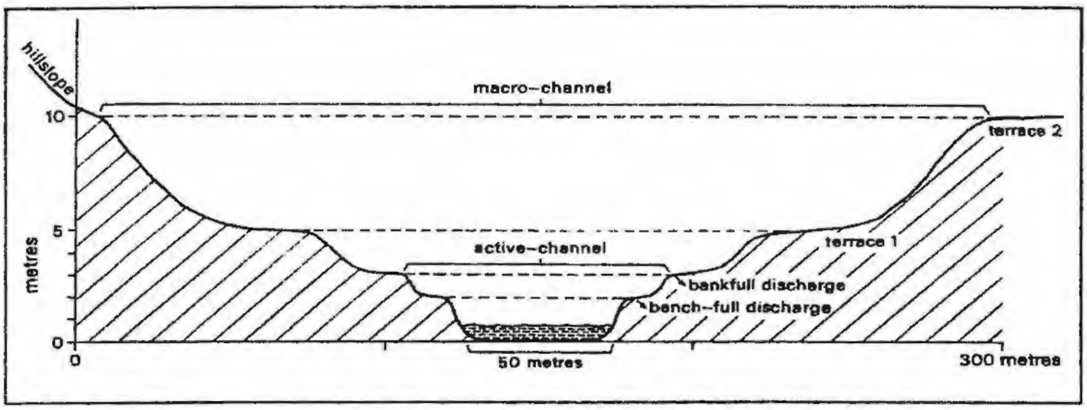

Figure 3.5 The macro-channel, active channel, benches, estimated bankfull discharge and terraces (Dollar & Rowntree, 2003, pp25)

Figure 3.5 shows the relation between bankfull discharge, the active channel and the macro-channel. Bankfull discharge is essentially a way of trying to determine and define a river channel's dominant discharge (Knighton, 1998; Dollar & Rowntree, 2003). Dominant discharge defines the discharge where there is equilibrium between the channel form and discharge. Extreme floods and high discharges play a large role in geomorphological processes and may individually transport a greater load of sediment. However, according to Knighton (1998), they occur too infrequently to have a greater cumulative effect than the dominant discharge which is equated to "bankfull" discharge. Bankfull discharge may not always be easy to define in the field, might not be of constant frequency and may not even be the most effective flow with regards to sediment transport. Nonetheless, it is a way of characterising a dominant discharge so that one site can be compared with another. Bankfull discharge is a discharge that occurs relatively frequently and is thus seen to transport most of the sediment.

A feature of South Africa with its many arid and semi-arid rivers and many bedrock influenced rivers is that large floods are often the only flows considered to be effective (Dollar & Rowntree, 2003). This also raises the issue of using "bankfull" discharge as an effective means of understanding the fluvial processes at work within a river channel.

Sediment and material which constitute the load carried along the stream have also been discussed and is again re-emphasised as a control on channel morphology. According to Rowntree & du Plessis (2003), if a stream's channel form or morphology is to be maintained, the channel gradient and dimensions must accommodate floods with sufficient stream power to 're-work' and transport the sediment being delivered from upstream. If sediment delivery exceeds the stream's capacity to transport, deposition will take place. Alternatively, if stream capacity is greater than the sediment delivered, bed and bank erosion will take place (Rowntree & du Plessis, 2003). In both cases, the stream channel morphology will naturally adjust towards a more stable configuration.

Bank resistance was discussed previously in the context of bank erodibility. While bank erosion is the process, the *resistance* of the bank to the erosive forces of flow is a control on the stability of the channel bank and thus its shape and form. The strength or resistance of the bank to erosion is influenced "by factors which affect cohesion between grains, soil drainage, and the amount of surface protection afforded, for example, by vegetation" (Rowntree & du Plessis, 2003, p.62). Cohesion is enhanced through the presence of silt and clay (Knighton, 1998; Rowntree & du Plessis, 2003). Furthermore, vegetation (through the presence of a dense mat of roots) plays a large role in the stability of channel banks and will be discussed in more detail in a later section.

In trying to understand the recovery mechanisms of a river following a disturbance, Cohen & Brierley (2000) studied channel controls along a section of the Genoa River in Victoria Australia. They found that the over-riding control on the pattern and extent of the channel adjustments was most likely induced by changes to the channel bedslope. Thus, as the channel stability threshold was exceeded (due to changes in bedslope) it induced a series of secondary channel adjustments. This study emphasised the manner in which landscapes in southeastern Australia could possibly be on the threshold of instability, only requiring a suitable trigger. This shows how a river's channel morphology is the product of these controls and a suitable trigger (e.g. alien vegetation) could result in channel instability.

It is also important to remember that a channel's form is the product of a variable flow regime. According to Poff *et al.* (1997) the flow regime of a river is variable and it is this variability that is vital for ecosystem function and biodiversity. Of similar significance is a river's "sediment regime" which "refers to the processes associated with the movement of sediment down a river channel" (Freeman & Rowntree, 2005, p.13). A flow regime and a sediment regime will be unique to each river and they work together to shape a river's morphology even though they can be defined as separate regimes. Thus, regarding river protection and rehabilitation, it is important that a natural flow regime and sediment regime be maintained and that the natural hydrologic cycle be protected against river development, alterations, damaging land use changes, alien invasives and so forth (Poff *et al.* ,1997).

3.2.4 Channel geometry and cross-sectional form

A channel's geometry is described as the three-dimensional form typically measured at an appropriate stage e.g. bankfull discharge. The examination of a channel's cross-section at a given site along a river allows for the description of the topographic variation across that channel and a description of the arrangement of morphological units within the given cross-section (Rowntree & du Plessis, 2003). These morphological units can then in turn be related to the varying levels of flow and vegetation zones along the river. This shows the importance of conducting cross-section surveys (and the analysis that this entails) in describing the channel morphology for a given river.

Two important factors re-emphasise the importance of discharge. Firstly, since discharge increases downstream with increasing drainage area, channel width and mean depth should also increase. Secondly, because channel width and depth are systematically related to bankfull discharge it suggests that discharge is the principal control of channel dimensions. So while discharge is the principal control of a channel's dimensions, sediment characteristics have a dominant indirect effect. Sediment characteristics will thus affect the mutual adjustment mechanism of a channel's width and depth i.e. a channel's width and depth will not adjust independently from one another (Knighton, 1998). A river will adjust its channel form not only in response to isolated events such as a high flood but also to more persistent changes brought about through either natural or anthropogenic factors e.g. the impact of invasive alien vegetation causing a disturbance to the river channel. Vegetation is therefore clearly a variable that can influence or affect a channel's form.

3.2.5 Channel morphology as a diagnostic 'tool'

Having already discussed the controls on channel morphology and described cross-sectional form, this section now examines the characteristics that can be studied at a given site that allows one to use channel morphology as an all encompassing diagnostic tool. If one is to determine a channel's stability, to quantify channel processes and to explain channel form, it is necessary to conduct direct measurements of channel form (Simon & Castro, 2003).

> *"Measurement and analysis of channel form provide a context for interpretation of present and future channel morphologies and are often a central theme in studies which thrive to identify and determine the magnitude and extent of channel change"* (Simon & Castro, 2003, p. 292).

Figure 3.6 shows how channel morphology can be approached theoretically as the centre of three aspects of a river channel: profile, cross-section and channel pattern. All three aspects operate on varying time scales with cross-section responding the fastest. The above quotation demonstrates how profile, channel pattern and especially cross-section can be used to measure the degree of channel change. A channel's morphology can be defined by measuring the width, depth, form ratio (width-depth ratio) and cross-sectional area of a channel based on a discharge that would be "bankfull". These measurements can then also be combined with other variables measured at a given site (e.g. riparian vegetation, bed material, bank material, etc.) to understand the main trends in channel processes and response (Simon & Castro, 2003). A more detailed explanation of which of these characteristics are to be examined within the Baviaans and Heuningnes Rivers will be described in the methodology chapter.

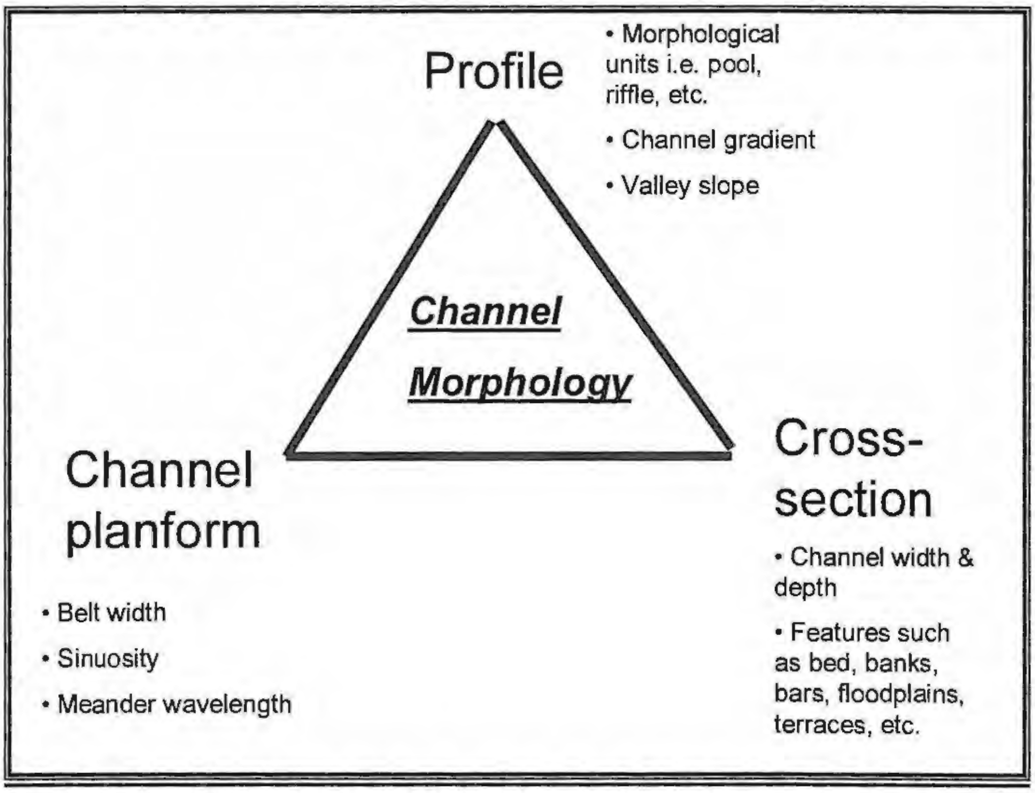

Figure 3.6 Channel morphology as the outcome of 3 components of the river channel (Simon & Castro, 2003)

3.3 VEGETATION AND THE RIVER CHANNEL

3.3.1 The Riparian zone

A significant component of the river system is the riparian zone, but there is often great difficulty associated with defining such a zone (Bren, 1993; Tickner *et al.*, 2001). In effect, the riparian zone is restricted to the vegetation along the water's course. However, it is apparent that the term has evolved to include areas adjacent to the river channel associated with non-flowing waters (Bren, 1993; Freeman & Rowntree, 2005). The ecosystems along this zone depend directly on the river for water, sediment and nutrients and vegetation in this zone usually has direct access to stream water or groundwater.

The riparian zone can therefore be seen as that area in close proximity to the stream found along the river's banks and can include the flood plain. The environment, vegetation and conditions of this zone are thus influenced by its proximity to the stream (Bren, 1993). Of great importance to the riparian zone is the stream channel itself. Bren (1993) emphasises the spatial and temporal variability of the stream channel as its most complicated and yet visually distinctive characteristic. Good riparian management can benefit biodiversity and river health by allowing for the periodic connection of the flood plain and adjacent areas to the main stream channel through a natural flow regime (Boon *et al.*, 1990).

3.3.2 The river channel

The shape and conditions of the river channel at a given site or location are not only affected by the flow of water and sediment, but they are also affected by vegetation (Freeman & Rowntree, 2005; Hardy, 2006). Rowntree & Dollar (1996) showed how riparian vegetation and bed material size acted as two controls on channel form and pattern in the Bell River in the Eastern Cape. In this area, willows (*Salix babylonica* and *Salix caprea*) were planted along the river banks in the 1950s in an attempt to stabilise channel banks. This raises questions about the origin for the spread of *Acacia mearnsii* along the riparian zones of the Heuningnes and Baviaans Rivers. Bank vegetation and the density thereof were highlighted by Rowntree & Dollar (1996) as two key factors that influence channel form. They showed that willow trees along the river banks with their dense root matting clearly had an impact by increasing bank stability. This is because the presence of vegetation on a stream bank can have effects on the geotechnical stability as well as the hydraulic conditions within and around the stream bank (Gordon *et al.*, 2004; Hardy, 2006). Rowntree & Dollar (1996) found that narrow, stable channels were associated with finer bed material and stable tree lined banks while wider, shallower and more unstable channels were associated with larger bed material and lower riparian vegetation densities. Thus, where the willows provided stability to the banks, the long-term result was a reduced channel capacity and a reduced channel form ratio (i.e. width-depth ratio).

The willow example above reemphasises the point by Hardy (2006) that an understanding of the dynamics of sediment is vital for comprehending the dynamic geomorphology taking place within the river channel. There are complexities involved in the interaction between hydraulics and sediment dynamics within fluvial systems due to several layers of feedback occurring between the two processes (Hardy, 2006). Add to this the effects of vegetation and the result is even more complexity. In-channel vegetation affects sediment dynamics because it can either provide resistance and obstruction to the flow or because it can stabilise channel bars or banks. Vegetation directly affects sediment dynamics by increasing the rates of either erosion or deposition of the sediment. This interaction between vegetation and flow is thus highly complex due to the various feedbacks between the interacting processes which occur over varying spatial and temporal scales.

3.3.3 The effects of vegetation on the river channel

Due to the greatly variable nature of vegetation, it is hard to measure the relationship between vegetation and channel form. Vegetation can vary in species composition, age, density and frequency, all of which will affect channel form differently (Rowntree & du Plessis, 2003). According to Hupp & Osterkamp (1996) riparian zone vegetation and fluvial-geomorphic processes and landforms are closely linked within the riparian zone. Riparian vegetation patterns develop and adapt to the existing environmental processes (i.e. natural flow regime, sediment erosion/deposition dynamics, soil moisture regime) associated with particular fluvial landforms. Riparian vegetation not only affects channel processes but also channel morphology, which in turn affects the availability of habitat for other riparian vegetation. According to Rowntree & du Plessis (2003), it has been shown that in general a good vegetation cover will increase a bank's stability but that the type of vegetation is important. While grasses and shrubs are effective at low flow velocities, they become less effective at high flows. Woody vegetation stems and roots can retard flow up to high velocities but can also cause serious bank scour (Thorne, 1990; Trimble, 2004). This is relevant to the study area which is heavily invaded with woody black wattle. It is important to re-emphasise the river system as an open dynamic system consisting of interacting variables whereby "a complex set of interactions between channel width, bank strength due to soil cohesion, bank strength due to rooting effects, root volume and silt/clay content occur" (Anderson *et al.*, 2004, p.1165).

A vegetated bank is both drier and better drained in comparison to an unvegetated bank so it is less likely to become saturated and therefore subject to slumping (Thorne, 1990; Rowntree & du Plessis, 2003). Furthermore, a vegetated bank's stability is also enhanced because of the binding properties of vegetation growing on or near the river banks. To be effective, the roots of the bank vegetation type must extend to the low water plane otherwise the flow will undercut the root zone during significant flow events (Thorne, 1990). This is due to the fact that reinforcement extends only down to the vegetation type's rooting depth i.e. a few centimetres for grass, tens of centimetres for shrubs and metres for trees (Thorne, 1990). This explains why a higher bank can be maintained for woody trees (Thorne, 1990; Rowntree, 1991; Anderson *et al.*, 2004).

Dollar (2004) discusses how many studies emphasise the importance of vegetation as a stabilising factor when in fact some hydrological processes may be unfavourable for the bank vegetation and thus bank stability. The author thus emphasises that when the potential stabilising or destabilising effects of riparian vegetation on bank stability is being studied it is important to consider hydrological, mechanical and ecological criteria. Understanding of all three of these criteria will help to explain the erosion type taking place within a particular channel e.g. sub-aerial, fluvial scour or mass wasting. This is also relevant to the study area. The fact that channel banks are lined with woody black wattle does not necessarily result in a stable bank. The nature and intensity of the invasion as well as its effect on stream flow can have negative consequences for the river channel and its banks and thus become a disturbance to the system.

Disturbance is seen as that described by White & Pickett (1985) in King *et al.* (2003, p. 11) in which it is "...any relatively discrete event in time that disrupts an ecosystem, community, or population structure, and changes resources, substrate availability or the physical environment". If a disturbance occurs within the system, the association and relationship between the riparian vegetation and the fluvial landforms may collapse resulting in a modified hydrogeomorphological regime and a resultant re-shaping of the bed or banks, or a straightening, widening, deepening or narrowing of the channel in other ways (Hupp & Osterkamp, 1996; Tickner *et al.*, 2001; King *et al.*, 2003). Invasive alien vegetation is thus one such example of a disturbance that has the potential to rupture this connection and alter channel form.

Esau (2005) emphasises this in her study of the Klein Berg River in Tulbagh, Western Cape. She identified vegetation type, collapsed trees, large organic debris (or large woody debris) and rooting systems as the four variables that affect the stability of channel banks in her study area. All of these variables were associated with the woody alien invasive species *Acacia mearnsii*. They prohibited indigenous vegetation growth, thus rendering the ground bare and susceptible to erosion. They were also identified as being prone to collapse with negative consequences for bank stability and soil erosion. The large organic debris contributed by the wattles disrupted the flow of water leading to bank erosion while the rooting systems of collapsed wattles were identified as shallow. Thus, the negative effects of this alien invasive on the river channel as shown in Esau (2005) have direct comparisons to the invaded catchments in the study area of this research. The following section examines *Acacia mearnsii* as a woody alien invasive that is seen to be creating a disturbance in the two study catchments.

3.3.4 *Acacia mearnsii*

As an exotic woody species, black wattle (*Acacia mearnsii*) is found along the riparian zones of many rivers in South Africa where they shade indigenous grasses, plants and fynbos that act as protective ground covers. Deliberately introduced to South Africa from Australia in the 19th century to be cultivated for a variety of purposes, it has since spread extensively throughout South Africa (Richardson *et al.*, 1992). Regeneration is triggered by fire and the high seed production in addition to dispersal by water along the riparian zone ensures rapid distribution of propagules downstream of the initial invasion (Galatowitsch & Richardson, 2005). The pervasive nature of black wattle is perceived as having a significant negative effect on streamflow and catchment water yields because it consumes vast amounts of water, spreads rapidly along riparian zones and quickly forms dense thickets with high biomass and leaf area (Dye *et al.*, 2001). It was found that annual total evaporation from black wattle occurring in riparian zones may exceed 1500mm in comparison to the 600 to 850mm for grasslands and fynbos (Dye & Jarmain, 2004). These authors further emphasise that the removal of wattles and replacement by seasonally dormant indigenous vegetation in regions of high evaporative demand where they experience minimal water stress will result in the greatest increases in stream flow.

Wattles are also often associated with river channel erosion (Rowntree, 1991; Esau, 2005; Freeman & Rowntree, 2005). The stability or lack thereof in river banks depends on the root system of the vegetation growing on it. *Acacia mearnsii* has a shallow root system and this makes them unstable along river banks and often they can easily fall over. This has repercussions for the river in question in the form of debris dams, large woody debris and a widening river channel due to increased erosion. The shallow root systems mean the wattles are unable to withstand floods and are likely to enhance scour as opposed to protecting the soil (Rowntree, 1991; Esau, 2005; Freeman & Rowntree, 2005).

The issue of alien invasive vegetation impacts on channel morphology are most clearly brought together in Rowntree (1991). Here the author emphasises how it is predominantly woody species (such as *Acacia mearnsii*) that possess the potential for bringing about a change in channel morphology. Furthermore, woody species are often found colonising the channel bed and bars, especially in ephemeral rivers in semi-arid regions. Rowntree (1991) explained how *Acacia mearnsii* on the banks of the Mooi River near Maclear had resulted in deeper and narrower channels than those where the banks supported a natural grass cover. However, as the author points out, the actual impact and direction of channel change will vary in each case depending on the "physical characteristics of the channel (bed and bank sediments, flow regime, channel slope and initial morphology), characteristics of the invasive vegetation (species, life form, age, stand density), the part of the channel which is subject to colonisation and its position in the stream network" (Rowntree, 1991, p.40). Furthermore, she points out that in terms of their effects on bank stability, an important distinction can be made between grassy and woody vegetation.

A review of the literature shows how (in an Australian context) Tamarisk and Willows are analogous to black wattle in that they are the alien invasives disrupting Australian river channels. Furthermore, Cohen & Brierley (2000) discuss how black wattles in their natural setting benefited recovery mechanisms following channel instability along the Genoa River by acting as a dominant early successional species and colonising and stabilising newly formed depositional surfaces.

3.3.5 Large woody debris (LWD)

Associated with woody vegetation such as black wattle is the characteristic of large woody debris within the river channel. According to Rutherfurd *et al.* (2000), the effects of LWD are site specific and may either increase or decrease bank erosion. Examples given show how an abundance of LWD can provide flow resistance in some cases (thus reducing erosion and protecting banks) while causing an increase in flow velocity or local bed depth in other cases (thus increasing bank scour or bank erosion through slumping). Furthermore, LWD has demonstrated effects on pool spacing, channel pattern and river evolution, thus clearly having a direct influence on channel morphology (Trimble, 2004).

Another interesting point is that due to the short life span of riverine trees, within two to three decades there is a marked increase in LWD (Trimble, 2004). This is important when considering the Baviaans and Heuningnes catchments in the study area with the aerial photographs dating to the 1960s already showing dense stands of black wattle upstream. In the case of the study area, LWD is ubiquitously originating from this alien invasive black wattle rather than from any indigenous vegetation. Consequently, with a surge in LWD comes an increase in bank and channel erosion (Trimble, 2004). Provisional field measurements in the study area indicated a large amount of LWD and the presence of many debris dams. These debris dams become temporary storage sites within the channel which become important controls on channel form by limiting the downstream movement of sediment. Similar to the effects of vegetation, the size and location of the debris dam along the channel causes it to either have an erosional or depositional effect.

Thus, according to Erskine *et al.* (2007), the importance of LWD cannot be underestimated with regards to restoration efforts. A comprehensive understanding of the interactions between the dynamic changes to channel morphology, the riparian vegetation and the LWD is required for any customised restoration effort. Furthermore, different river restoration templates will be needed for varying river morphologies and riparian plant communities. Thus, what works in one river/region/country cannot merely be applied to another. This is clearly demonstrated whereby the LWD in the northern Australian study of Erskine *et al.* (2007) is unlike the LWD at the study site of this research. The Australian LWD is generally short in comparison to the channel widths and can therefore readily move downstream whereas LWD at the study site of this research caused many debris dams and blockages along the river channel.

3.4 CONCLUDING THEORETICAL DISCUSSION OF LITERATURE

According to King *et al.* (2003, p. 239), the general consensus is "that the science of river rehabilitation is still in a pre-paradigmatic state, with a weak conceptual basis to guide the plethora of procedures being undertaken". It is for this reason that Hardy (2006) emphasises further research into methodological advance and the improvement of research methods so as to benefit insight into the various aspects of fluvial geomorphology. However, the author does mention that fluvial geomorphological research remains innovative, wide-ranging and dynamic.

As a scientific discipline, fluvial geomorphologists identify two important sets of variables that influence channel form, catchment variables and site variables (i.e. reach-scale variables) (Rowntree, 1991). At a larger scale, catchment variables (geology, climate, land use, etc.) will affect the runoff and sediment regime while on a smaller scale site variables (valley and channel slope, bed and bank sediment characteristics, riparian vegetation, etc.) will affect the stability of the channel locally. Because of the nature of a catchment as a system, catchment variables will have direct impacts on the site variables. Thus, as a science and as input to the management of complex river systems, fluvial geomorphology has much to offer (Dollar, 2004). This is because it tries to understand the river system as a nested hierarchical system occurring over varying spatial and temporal scales.

According to Webb & Erskine (2003) there is now a greater awareness of the value of riparian zone function as well as its vulnerability to alien invasives and the well known effects that such vegetation can exert on fluvial geomorphology. All of this has resulted in much effort being put into conserving many river ecosystems. According to Holmes *et al.* (2005), more research is needed into the influences of various alien species and their clearing treatments on indigenous riparian vegetation recovery. It is hoped that this study/research will benefit this cause in some small way. The following quotation further emphasises the importance of researching alien invasive species' effects on river geomorphology.

> *"If we are to carry out effective riparian zone management it is recommended that research is directed towards unravelling the dynamic relationships between vegetation and channel processes and to assessing more rigorously the degree to which alien invasives have already impacted on the geomorphology of our river channels"*
>
> (Rowntree, 1991, p. 40)

Within catchments that have been highly alien-transformed, the re-introduction of natural or indigenous riparian species will benefit recovery and also suppress re-invasion by the alien vegetation (Holmes *et al.*, 2005). This is the ultimate aim of the rehabilitation intervention to be conducted within the larger Kouga project which includes the Baviaans and Heuningnes catchments. However, as has been discussed, the correct or required underlying physical conditions are necessary if there is to be any success in re-vegetation of indigenous species.

Hardy (2006) makes an important point by saying that the spatial and temporal resolution at which the study/research focuses depends entirely on the specific processes being investigated. In this instance the alien invasive vegetation is being cleared at the reach level and the effects and outcomes of clearing should become evident at the morphological unit scale at the given study sites. It is for this reason that this literature also included a brief discussion on the hierarchical geomorphological framework as a way of understanding the dynamics of a river system and the complex approach of studying such a system.

As has also been discussed, the important relationship between channel form and the vegetation growing along the channel is explained in terms of its effect on bank stability as well as its effect on channel boundary shear stress (Rowntree, 1991). Because velocity and boundary shear stress seems to be at a maximum along the lower bank, fluvial erosion will tend to scour the base of the bank with the result being an increase in the angle and the height of the bank. Thus, as was discussed, undercutting of a river bank is affected by the presence of vegetation. Vegetation effects are usually localised and vary due to the unique vegetation characteristics. Furthermore, root systems play an important part in controlling bank erosion. Nonetheless, the role of riparian zone vegetation and its effects on bank erosion is often neglected due to the inherently variable effects of the vegetation and the difficulty in quantifying this. Woody alien invasive vegetation was also discussed. With their relatively shallow root systems, they can cause erosion after a flash flood uproots them leading to a collapsed bank (Rowntree, 1991). Thus, vegetation plays an important part in channel morphology. In-channel vegetation and bank vegetation can be seen as a major factor contributing to either channel stability or instability depending on the extent and nature of the vegetation growth (Nanson *et al.*, 2002).

In reference to the available literature, a considerable amount originates from the United Kingdom and Australia. South Africa and the United States of America also feature significantly. Australian research into river rehabilitation is especially significant and a fair amount of such literature is available. It is important to acknowledge that many of the relationships discussed in the literature (i.e. channel form adjustment to discharge/sediment) applied to transport limited channels with sufficient mobile sediment to mould into the required channel form. In supply limited channels (e.g. headwater channels), where erosion dominates, this may not be the case.

There were three key readings that contributed solidly towards a better understanding of the subject. Knighton (1998) provided a good theoretical grounding of fluvial forms and processes while Gordon *et al.* (2004) approached the subject from a more practical viewpoint by helping to understand how to approach the study of a river. From a South African perspective, Rowntree & Wadeson (1999) helps to understand the hierarchical approach necessary in the study of any river while also providing further practical information, theoretical understanding and methodology. The issues of resource quality objectives (RQOs) and monitoring are discussed in further theoretical detail in Chapters six and seven as separate objectives of this thesis.

CHAPTER 4

RESEARCH DESIGN AND METHODOLOGY

4.1 INTRODUCTION

With large parts of the Kouga River catchment and its riparian zones being severely invaded with the invasive alien *Acacia mearnsii*, the aim of the KRRP was to begin experimental restoration/rehabilitation trials. The KRRP was seen as a pilot rehabilitation project and the Kouga region was selected as a priority degraded system. These rehabilitation trials would begin after selected sub-catchments were cleared of their invasive aliens. The study sub-catchments were thus required to have a riparian zone colonised by invasive alien vegetation. Accessibility by road was also a key criterion for a long-term project such as this.

The present researcher was not part of the initial sub-catchment selection process. Thus, this research was essentially constrained by the selection of the study sub-catchments based on the requirements of the KRRP as a rehabilitation project. The purpose of this master's research within the larger KRRP was to compare the channel morphology of invaded and natural channels and to monitor the initial geomorphological impacts of alien vegetation removal.

This chapter is divided into three sections. The following section deals with the initial analysis of the study catchments so as to determine a sampling framework. It is purposely included as the first section in Chapter four as it explains and emphasises the research design so as to make sense of where the field analysis would take place. Section 4.3 examines the methods used during field analysis and Section 4.4 explains the methods used during laboratory analysis.

4.2 INITIAL ANALYSIS OF STUDY AREA CATCHMENTS

4.2.1 Choice of catchments

At the outset, a helicopter flight over the Kouga region was arranged so as to identify priority invaded sub-catchments that could be used in the study. The outcome was the identification of the Heuningnes and Baviaans Rivers. Figure 4.1 shows how the headwaters of these catchments are adjacent to one another and both flow south-westerly into the Witteklip River which flows west into the Kouga River.

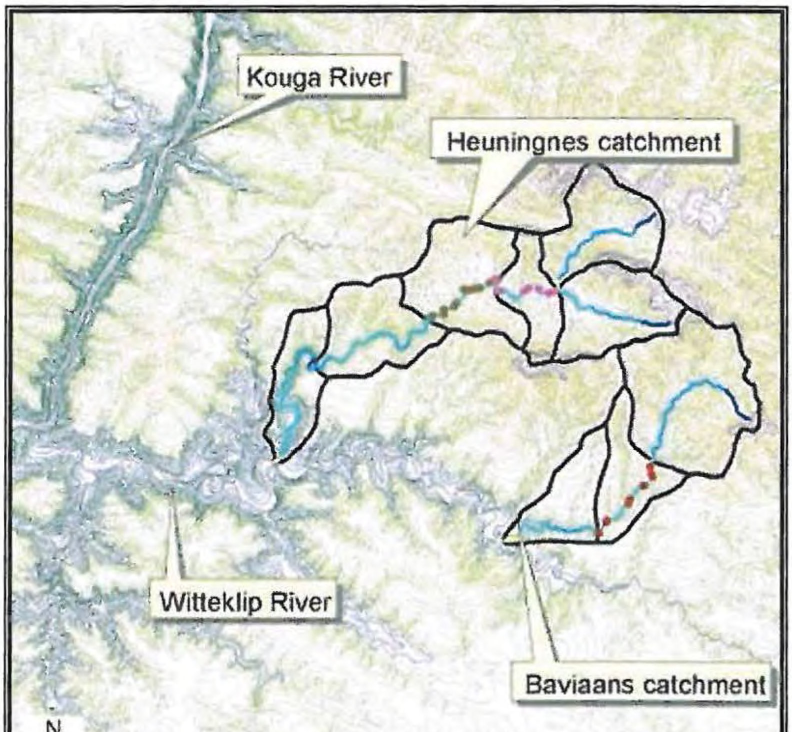

Figure 4.1 Baviaans and Heuningnes catchments showing study reaches and sites
(Brown = Heuningnes invaded sites; purple = Reference sites; red = Baviaans invaded sites)

These catchments were both identified as being invaded, but their geomorphological similarity was a key criterion used in the selection process. Just upstream of the invaded Heuningnes reach was another reach that was seen to be uninvaded and could thus be used as a reference condition. Thus, the Reference was initially chosen more because of vegetation conditions. A perfect, pristine and fully natural reference was unlikely given the need for catchments that could be accurately compared. This is emphasised because the Reference was not totally free of alien vegetation, although there was much less than the invaded study reaches. Thus, *Acacia mearnsii* could be found at the middle sites of the Reference reach. Channel gradients and drainage areas were similar for the three reaches as will be shown later. In Figure 4.1, the Reference sites (purple) are located upstream of the invaded Heuningnes sites (brown).

After the completion of an early reconnaissance trip to the study sites, resulting in preliminary data on channel measurements (see Section 5.2), the next step was to complete a desktop analysis comparing the two catchments. The catchments were analyzed with the help of a geographical information system (GIS). This benefited the investigation into catchment topography by helping to identify whether or not the study catchments were sufficiently similar for the purposes of comparing the effects of alien vegetation. The GIS and relevant data were also used to analyse, understand and display the area, gradient, geology, river long profiles and valley form of each study catchment.

4.2.2 Vegetation of the study area

The study site as a whole is found within the Fynbos biome and the major vegetation type within the study area is that of Grassy Fynbos. Grassy Fynbos replaces the much more widespread Mountain Fynbos in areas with a higher proportion of summer rainfall i.e. as one starts moving east into the Eastern Cape (Rebelo, 1996a). Grassy Fynbos is found on the sandy soils of the Cape Supergroup i.e. Table Mountain Group. The major difference between these two fynbos types is the higher proportion of grassy elements which replaces the restiod component of Mountain Fynbos. Because of the higher grassy component, Grassy Fynbos exhibits a more frequent fire regime. Although Rebelo (1996b) mentions the woody alien species of pine, hakea and wattle as a major threat to Mountain Fynbos, they are also found in the study area with its Grassy Fynbos.

4.2.3 Aerial photo analysis

A set of aerial photographs showing the Heuningnes and Baviaans catchments in 1954 and 1969 was acquired prior to the initial field measurements and to assist in site selection. These photos were used to provide an understanding of the initial conditions of infestation. From the photos it is clear that within the period of 1954-1969 a significant amount of black wattle infestation already existed throughout the region, particularly within the riparian zones of both the Heuningnes and Baviaans. It is interesting to note that in this time period there are other areas with thick infestations similar to that of the invaded Heuningnes. Today, the upper sites of the invaded Heuningnes seem to be the oldest infestation in the study area based on invasion density and because of their sizes. Thus, the wattle infestation is clearly present in the Heuningnes in 1954 and the photos show only natural vegetation growing along the Reference sites with no black wattles present.

The photos also show a minimal difference in black wattle density between 1954 and 1969 although it can clearly be seen to be spreading further downstream. It is important to reiterate that while the Heuningnes River has never been cleared of any alien vegetation along its riparian zone, the Baviaans River was cleared in 2001 and was followed by a fire that burned through the catchment the following year. There has been extensive re-growth in this short time period.

4.2.4 Geology of the study area

The geology of the study area (Figure 4.2) is made up of mainly sandstone (the Goudini and Peninsula formations) and, locally, shale (the Cedarberg formation) (Toerien & Hill, 1989). All three formations in the study catchments form part of the Table Mountain Group which is the most predominant as well as being the most evident in the region as a whole "due to the resistant nature of the quartzitic sandstone of which it is composed" (Toerien & Hill, 1989, p.1). During the Permian to Triassic periods the Cape Supergroup (of which the Table Mountain Group is a sub-group) was subjected to immense compressive stress resulting in a folded and partly thrusted Cape Fold Belt. A fault line runs underneath the Baviaans River channel in a north-easterly direction.

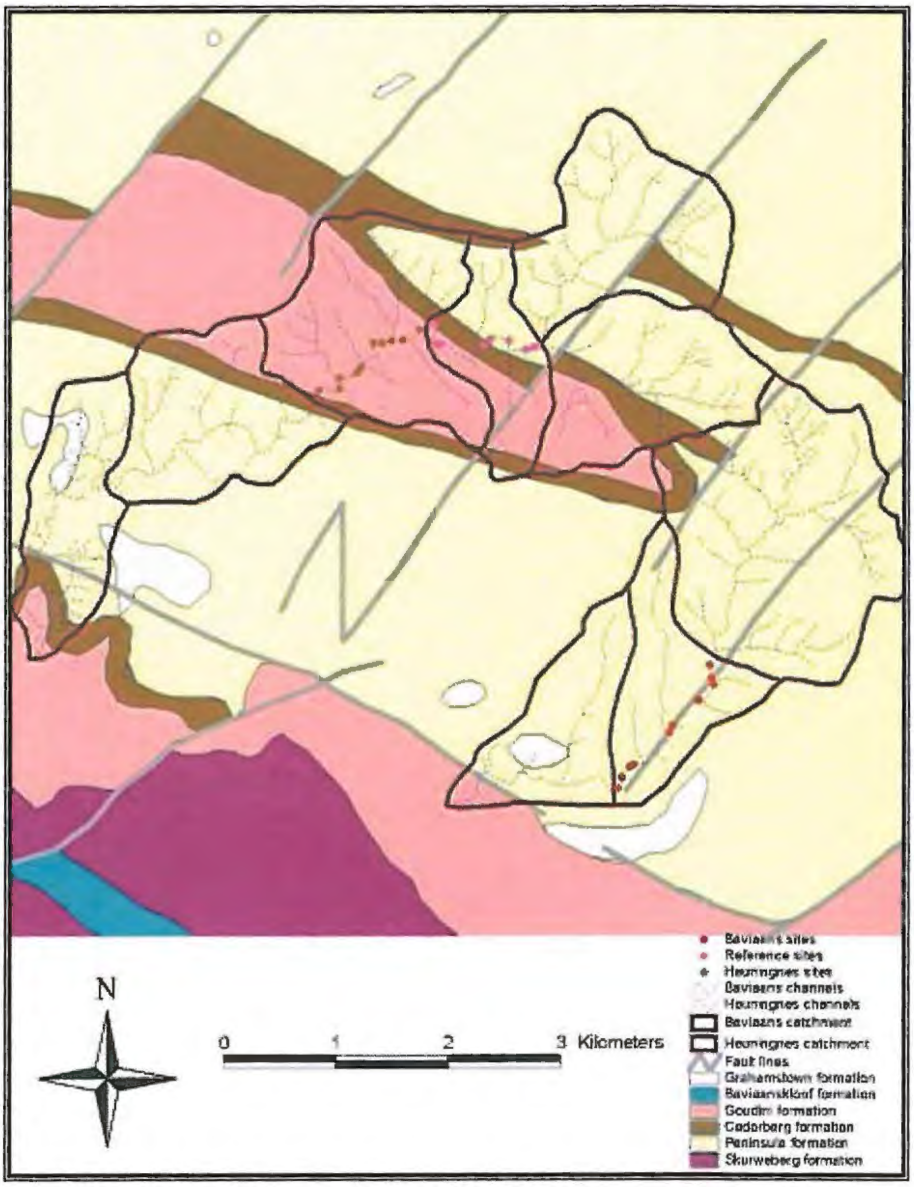

Figure 4.2 Geology of the study area (source: Chief directorate of surveys & mapping)

4.2.5 Catchment analysis

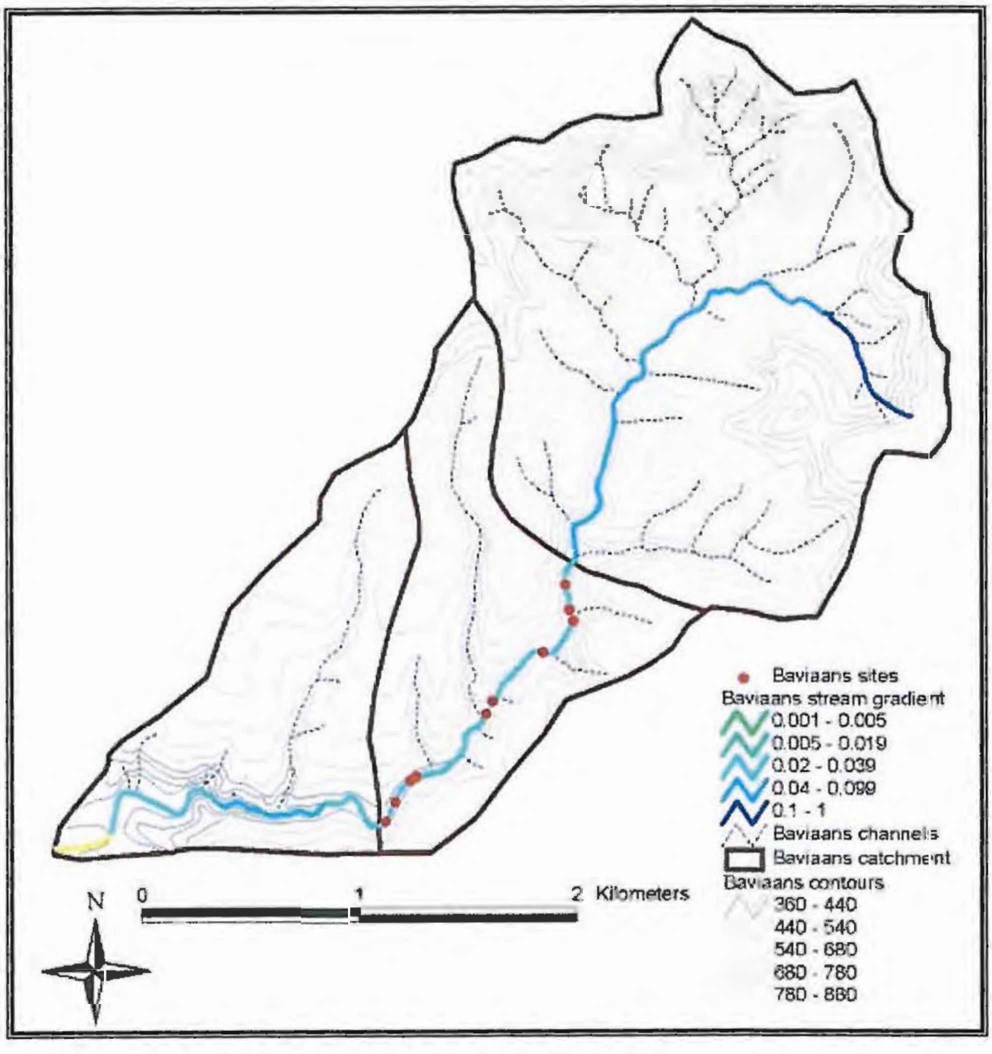

Figure 4.3 Baviaans River catchment showing transect sites

Figures 4.3 and 4.4 show the entire Baviaans and Heuningnes catchments to where they join the Witteklip River. They have been subdivided into sub-catchments for the purposes of calculating catchment variables such as area, gradient, stream length and so on. Thus, they define a reach of river. These maps indicate the locations of the thirty sites used to collect more accurate transect and channel cross-section data. Ten sites in the invaded Baviaans, ten sites in the invaded Heuningnes and ten sites above the Heuningnes invaded area which acted as the reference. The maps also show the channel gradient underlying the reaches, all of which lie on similar gradients. Larger scale maps focussing on only the study reaches can be found in Chapter 7 in reference to long-term monitoring.

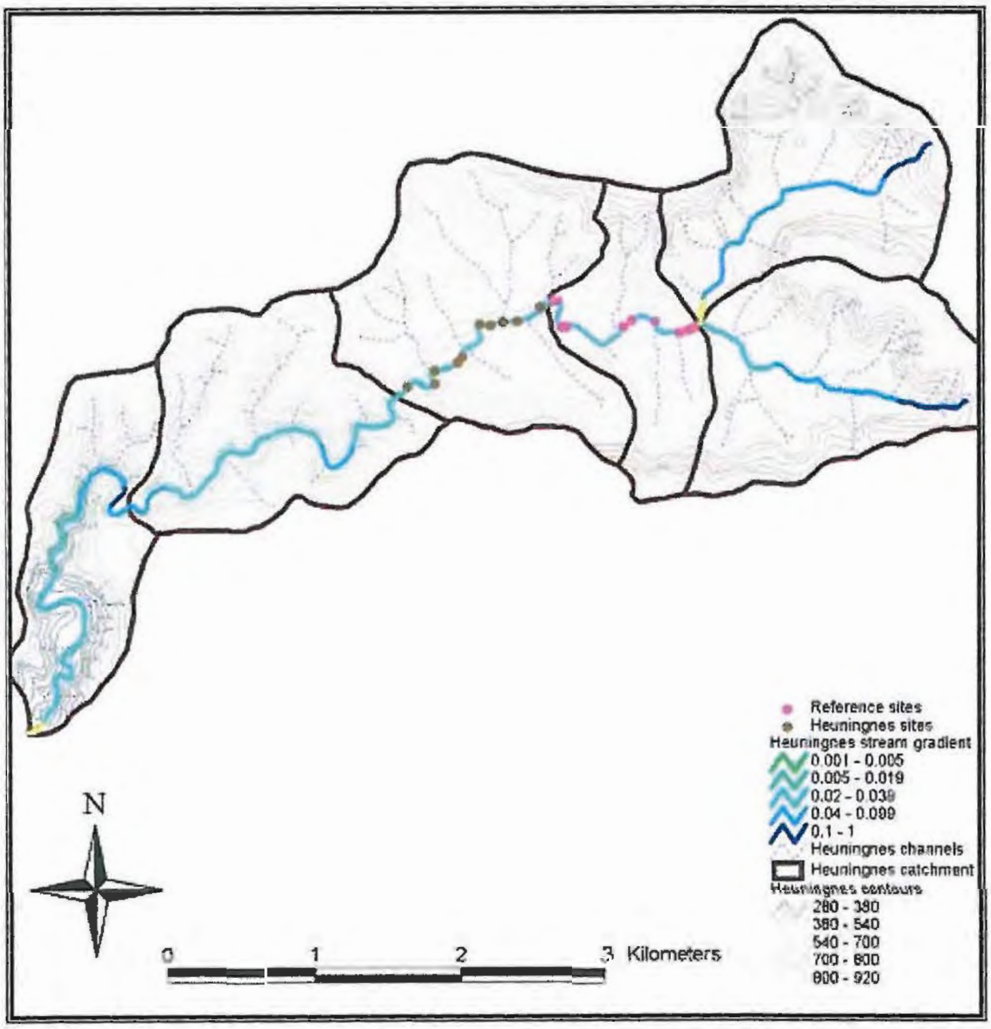

Figure 4.4 Heuningnes River catchment showing transect sites

4.2.6 River long profiles

Figure 4.5 shows the full extent of the river long profiles of the Heuningnes and Baviaans Rivers from the top of their catchments to the Witteklip River. Both rivers start close to the 800m contour line. The study sites are all located roughly midway down the profiles.

The similarity in gradient between all three study sites is clear and it puts the Reference in context as being located just above the invaded Heuningnes sites. Gradient is of geomorphological importance because it affects the potential for material to be transported and sorted down the river long profile. With the catchments in such close proximity, they should exhibit a similar climate and rainfall patterns. Along with similar underlying geology and vegetation type, the similar gradients means that one should be able to compare the one system with the other i.e. the Baviaans catchment with the Heuningnes catchment (which also contains the Reference). However, it is important to bear in mind that no two river systems are the same due to their innate dynamic nature. Finding a reference is often complicated for numerous reasons and human influence is nearly always unavoidable even within the reference. Nonetheless, as was emphasised in Chapter 2, providing the reference reaches are in a fairly natural state they can provide applicable channel morphology and guide rehabilitation methods that are compliant with and appropriate to the catchment (King *et al.*, 2003).

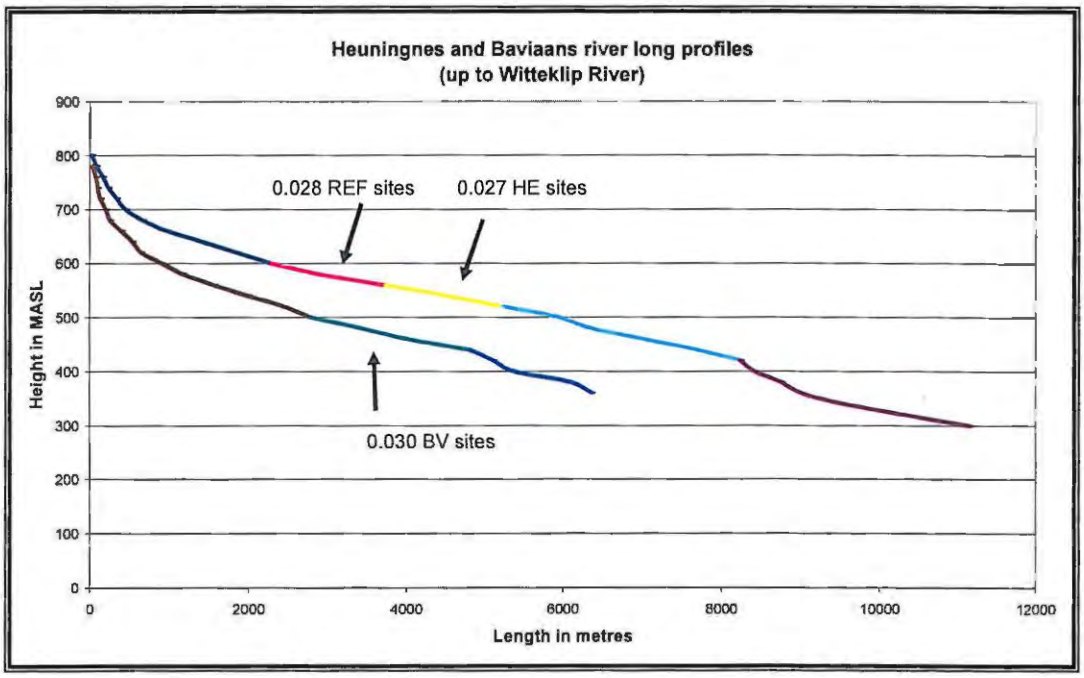

Figure 4.5 River long profiles of the Baviaans (BV), Heuningnes (HE) and Reference (REF) Rivers
(showing location and gradients of study reaches)

Table 4.1 Catchment data relating to the study area

	Upper area (km^2)	Lower area (km^2)	Gradient of study reach	Drainage density (km stream/km^2)	Max MASL	Min MASL
Baviaans invaded reach	4.26	5.86	0.030	3.66	880	440
Heuningnes invaded reach	5.98	8.70	0.027	3.48	920	500
Reference reach	4.73	5.98	0.028	3.63	920	540

Figures 4.3 and 4.4 (above) showed the location of the study reaches within the catchments of the Baviaans and Heuningnes rivers. Table 4.1 provides important catchment data that was gathered, analysed and understood through the use of a GIS and is relevant to the geomorphology of the study reaches. Upper area is the catchment size at the start of that reach (i.e. the uppermost study site) and the Lower area shows the catchment size at the end of the reach (i.e. the lowermost study site). Note that Baviaans' total catchment area (i.e. Lower area) is similar to that of the Reference. All three study reaches also exhibit very similar stream gradients and drainage densities.

4.2.7 Valley form

Figures 4.6 – 4.8 show the valley cross-sectional view through the three study reaches. These valley cross-sections are taken at the middle sites for each sub-catchment i.e. BV5, HE5 and REF5. They illustrate the slope or gradient of the valley side-walls in which the river channels exist. They also show the shape of the valley bottom. Baviaans exhibits a narrow and confined valley bottom. This is different to the widened valley bottom with floodplain development seen in the Heuningnes and Reference reaches. Knighton (1998) highlights two important aspects of hillslopes. Firstly, the larger the discharge within the catchment, the greater the significance of fluvial activity relative to hillslope activity. Secondly, wider floodplains or valley bottoms progressively buffer the channel from hillslope inputs. These two aspects have important consequences for the study catchments, since the Baviaans has a significantly narrower valley cross-section and steeper valley slopes in relation to Heuningnes and the Reference.

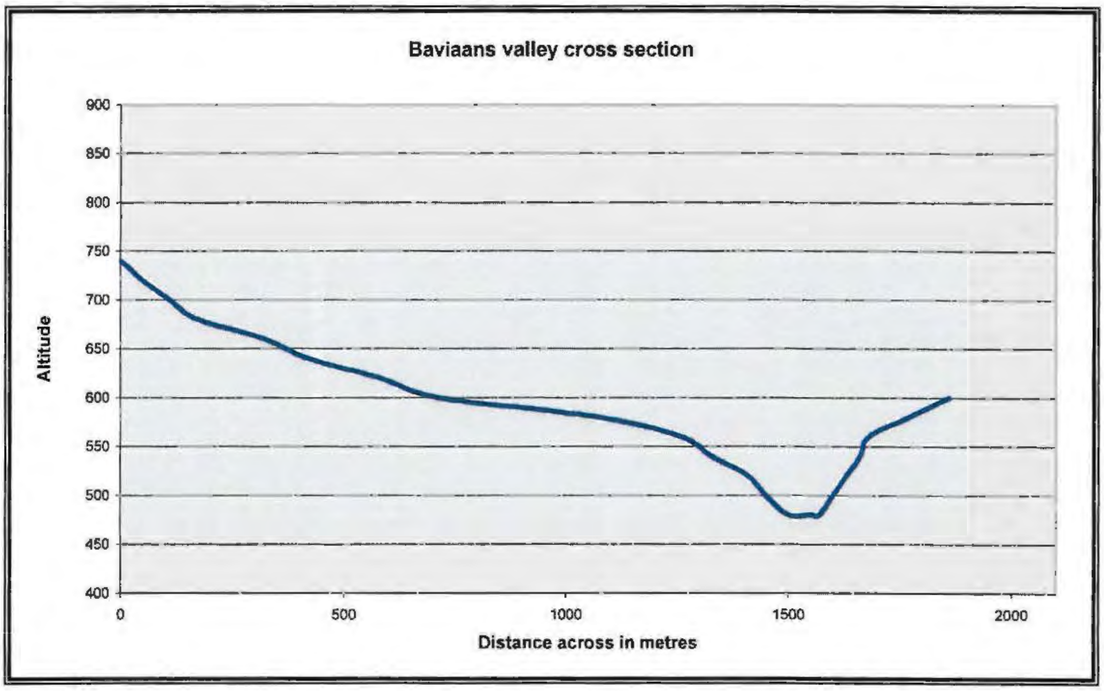

Figure 4.6 Valley cross-section of the Baviaans River facing upstream

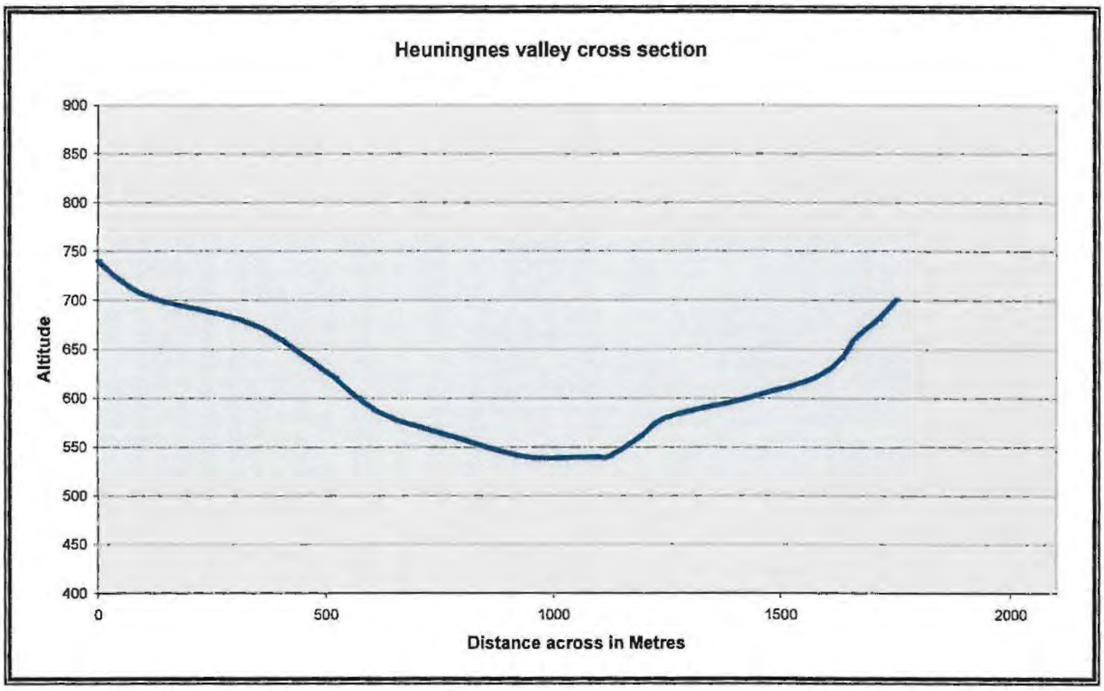

Figure 4.7 Valley cross-section of the Heuningnes River facing upstream

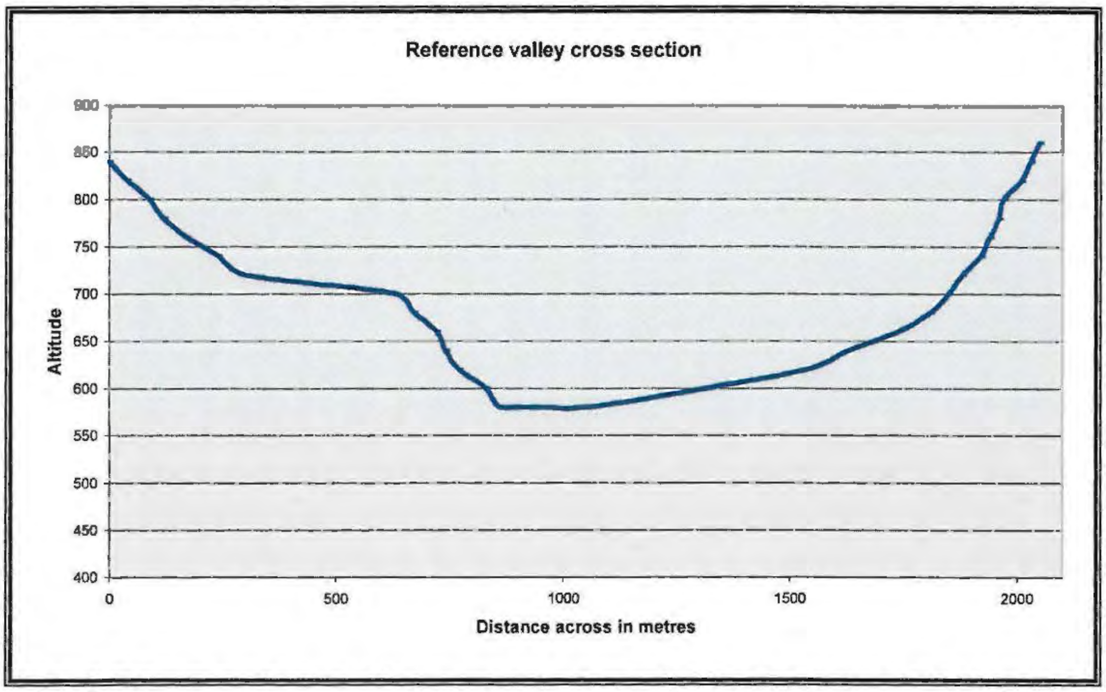

Figure 4.8 Valley cross-section of the Reference facing upstream

4.2.8 Rainfall analysis

While the purpose of the preceding subsections was to describe the similarity of study catchment variables on a spatial scale, an analysis of rainfall is essentially on a temporal scale. Rainfall is an important variable as it provides an idea of the climatic conditions with obvious associated effects on runoff, discharge and the movement of sediment.

The town of Kareedouw lies 22km to the south-west of the study catchments and provides long-term data for rainfall in the region (see Figure 1.3). Figure 4.9 shows the variability in regional total annual rainfall from 1929 to 2006 over a long-term average of 731mm. A gap exists from 1943 to 1955 and a few other years are missing due to a lack of a complete data set. It is clear that the total annual rainfall is highly variable. Note the long dry period from 1998 – 2005. This same data also illustrates the seasonality of the rainfall. Figure 4.10 shows that on average the highest amount of rain falls in spring (September – November) while the least amount falls in summer (December – February).

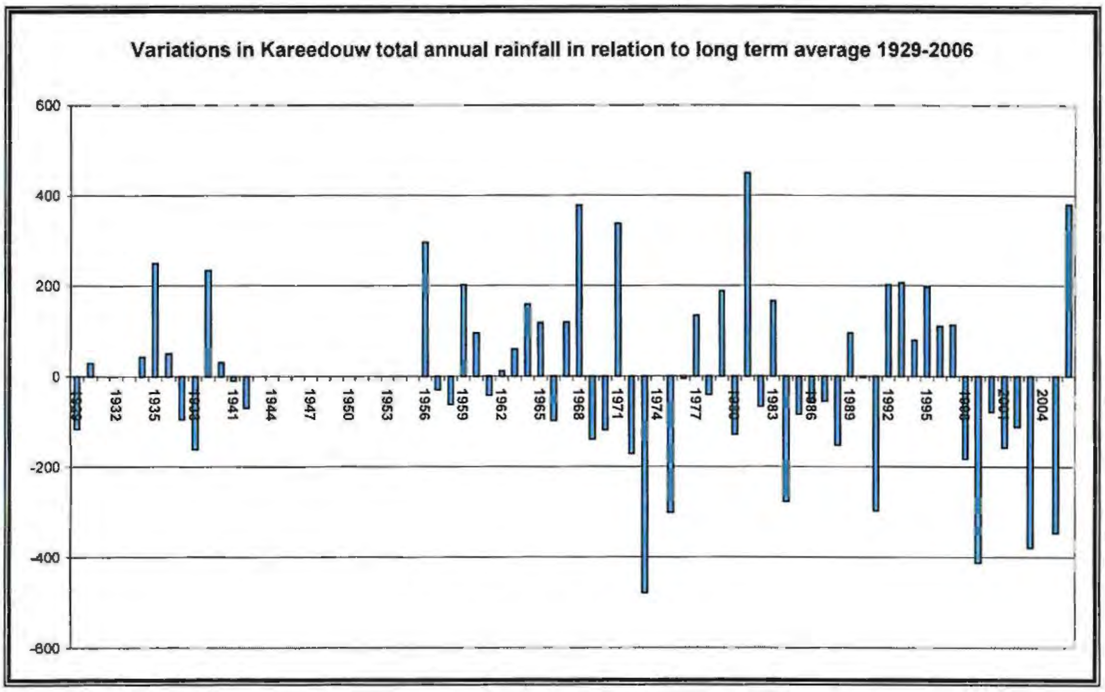

Figure 4.9 Kareedouw annual rainfall variations (with missing data 1943 – 1955)

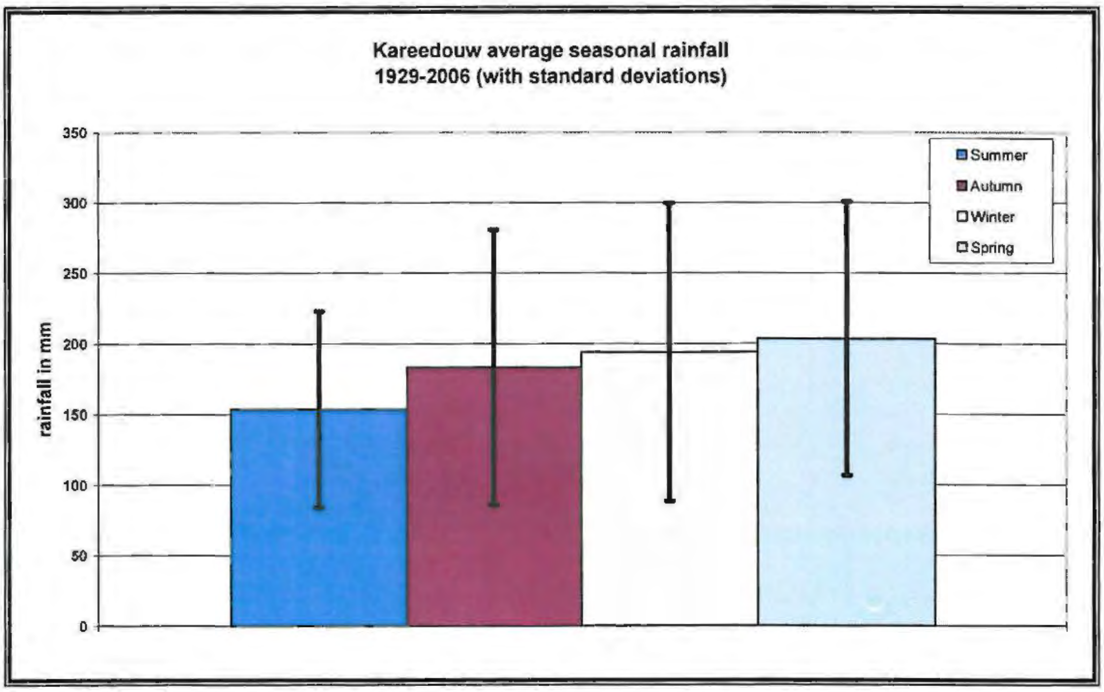

Figure 4.10 Kareedouw seasonal rainfall

The seasonality of the rainfall has obvious impacts on the indigenous riparian vegetation e.g. water availability and the competition for water with invasive woody species. Figure 4.11 shows the closest available daily evaporation data from the Kouga Dam which lies approximately 16km to the east of the study sites. It clearly shows the marked increase in evaporation rates over the hot summer months. Thus, the highest evaporation rates and least rainfall occur over these summer months. This will also have repercussions for the timing of re-vegetation and planting of indigenous flora to be carried out as part of the rehabilitation efforts of the KRRP.

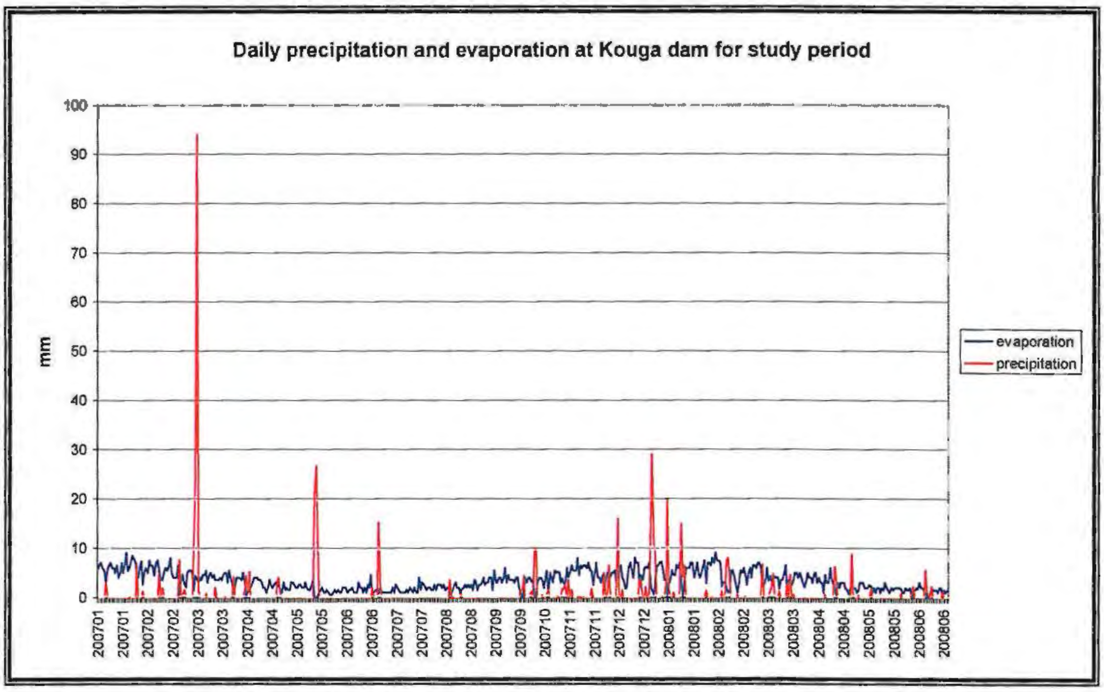

Figure 4.11 Daily precipitation and evaporation data for the study period (source: DWAF)

Closer to the study catchments is the farm of Onverwacht, located approximately 11km to the south-east of the study sites (see Figure 1.3). It provides the closest available daily rainfall data starting March 2005 through to June 2008 (Figure 4.12). Data were missing from June 2006 – August 2006. Knowing that August 2006 was an extremely high rainfall month for most of the Eastern Cape and given the Kareedouw rainfall data, this gap was likely to have been a high rainfall period.

The study period for this thesis started in January 2007 and evidence of the 82mm that fell towards the end of May 2007 was still visible with a fieldtrip in early June. Figure 4.13 shows how good rainfall in May and December 2007 resulted in a total annual rainfall slightly above the 1993 - 2006 annual average. This is in contrast to the first half of 2008 with its lack of significant rainfall. Based on conditions during the many fieldtrips, the Onverwacht farm's daily rainfall data provides a good account of the rainfall conditions taking place within the study catchments.

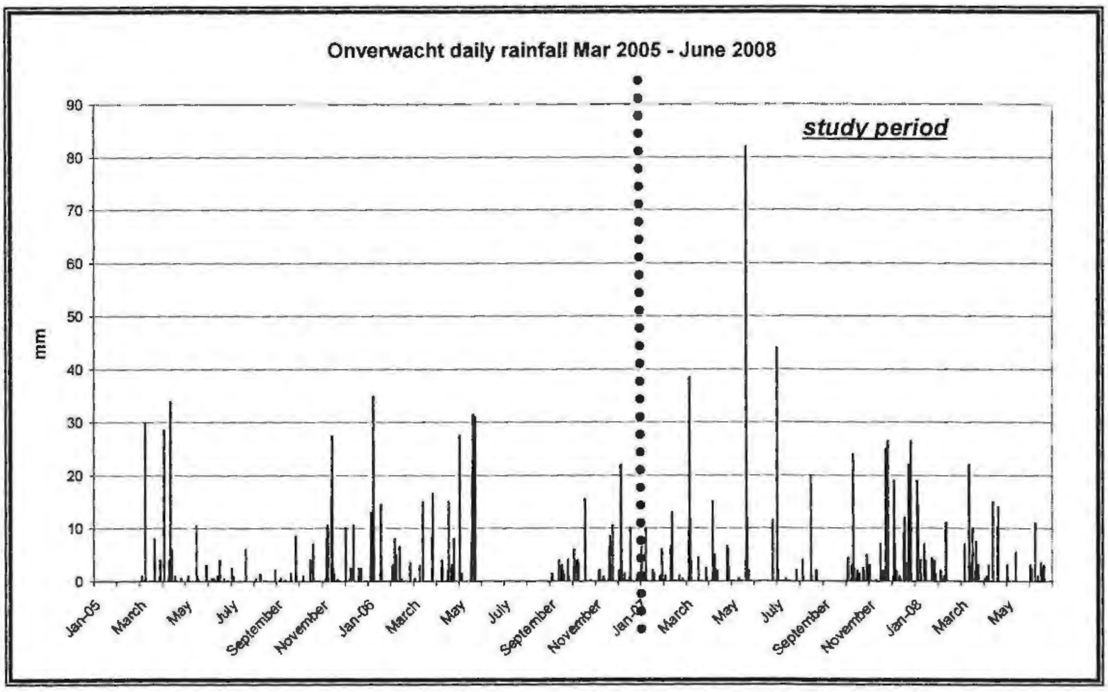

Figure 4.12 Onverwacht farm daily rainfall (source: Dept of Agriculture, Joubertina)

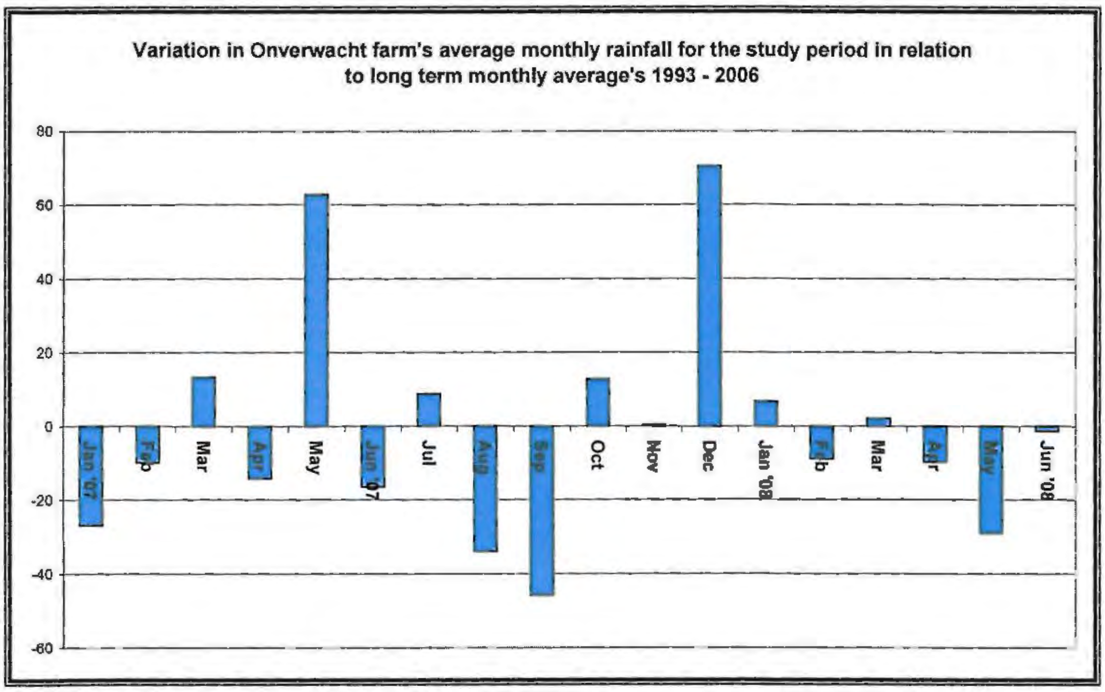

Figure 4.13 Onverwacht monthly rainfall variations for study period
(source: Dept of Agriculture, Joubertina)

4.2.9 The reference condition

This section justifies the choice and location of the reference conditions in comparison to the two alien invaded catchments. Many characteristics relating to these catchments have already been discussed and thus the aim of this section is to summarize and conclude the discussion relating to reference conditions.

Discharge and sediment load act as the primary controls on channel morphology and are themselves a product of the effects of other variables i.e. climate, geology, vegetation, gradient, etc. It is for this reason that the choice in reference condition and location are justified and explained by discussing and comparing these many characteristics so as to emphasise their similarities. Similar characteristics should result in a similar influence by these two dominant controls on channel morphology.

The two study catchments are very close in proximity and adjacent to one another. Not more than 4km apart and sharing a catchment divide, it is clear that they undoubtedly share a similar type of climate, rainfall regime, underlying geology and vegetation types. Further proof of similar climate and rainfall could be the fact that all three study reaches exhibit very similar drainage densities. Aspect, or the direction a catchment faces, has a large influence on vegetation types, rainfall, evaporation rates, etc. Studying these two study catchments one notices that both have a majority of south facing slopes. However, proportionally, more of the Baviaans catchment is south facing.

A desktop GIS (Section 4.2.5) revealed that all three study reaches (i.e. Baviaans invaded, Heuningnes invaded and the Reference) exhibit similar catchment areas. Of greatest geomorphological importance was the fact that all three study reaches exhibit very similar channel gradients and displayed similar river long profiles. Aerial photographs (Section 4.2.3) prove that the Reference reach clearly remained uninvaded by alien invasive vegetation from 1954 to 1969 while it is seen to be spreading further downstream along the riparian zones of the Baviaans and Heuningnes reaches. Given these similarities, the reach identified as a reference for the two invaded reaches seems justified

4.3 FIELD ANALYSIS

4.3.1 Channel surveys and transects

Two major groups of factors are seen to affect the channel form i.e. temporal control variables and spatial control variables. Discharge and sediment load are key channel control variables that occur at the *temporal* scale. Local *spatial* control variables that need to be taken into account include riparian vegetation, bed and bank material, channel slope, valley gradient, etc (Dollar, 1992). When conducting a fixed point cross-sectional survey or transect it is important to characterize or describe these two groups of factors so as to understand and explain the effects on local channel form instability (Dollar, 1992).

A ground-level inspection of the research catchments was conducted in February 2007. The present researcher, the thesis supervisor and the larger project coordinator walked the channels of the two catchments to gain a preliminary understanding of the situation and conditions. Potential site locations, inspection of accessibility, understanding reference type conditions and rapid measurements of channel width and depth were all conducted on this reconnaissance fieldtrip. Rapid channel measurements of width and depth were made at equidistant points along the channel. This was done with the use of a GPS receiver. Measurements were made with a wooden measuring pole and a 5m tape measure. This preliminary rapid assessment of channel measurements helped to show similarities between the invaded catchments that contrasted with the more natural areas higher up in the Heuningnes catchment. This confirmed the viability of more in-depth research.

On subsequent fieldtrips, ten sites were located within each study reach so as to characterize the channel conditions of that reach. At each site, cross-sectional profiles were carried out for five transects located along a 16m stretch of the channel. The purpose was to select a site as a homogenous length of stream in which bed/bank material, vegetation, terraces, slope, etc. were all similar so as to minimize variance (Simon & Castro, 2003; Gordon *et al.*, 2004). Although this process of selection was largely achievable, other factors had an influence. Site accessibility, mobility within a site, avoidance of local disturbance such as a road and the sensitivity of the electronic distance measurement instrument (EDM or total station) measuring through vegetation all affected the final choice of site selection.

Because this study would eventually lead to the long-term monitoring of channel change, permanent markers were put in place beyond the active channel. Within each 16m site there were five transects, each four metres apart and perpendicular to the direction of the channel. Metal pegs were hammered into the ground as permanent markers a few metres away from either side of the channel. The centre pegs also being cemented. Thus, each site produced five cross-sections representative of the channel form. The total station accurately records the height of the reflective retroprism at each reading to produce a cross-section. It was then possible to calculate the channel form variables of: channel width, channel depth, cross-sectional area and form ratio (width-depth ratio). Hydraulic radius, bank gradients and the stream gradient over each site's 16m channel length could also be calculated.

Re-surveys or follow-up surveys of all sites in all three study reaches were completed approximately a year after the initial surveys. They were done using the same methodology and allowed for a comparison of any changes to channel form within the study period post wattle clearance from the Baviaans study reach.

4.3.2 Estimating bankfull discharge

The use of bankfull as a measure can be problematic. An example is highly incised rivers that experience mean annual floods that are well below their bankfull, suggesting that adjustment/readjustment is still taking place. This is seen in the study area at the Baviaans River's upper sites where the channel is clearly heavily incised. A bankfull discharge at these upper sites would not be comparable to a bankfull discharge at sites further downstream. Thus, a reliable definition of bankfull discharge is often quite difficult and can be defined using either sedimentary, discharge or morphometric criteria (Dollar & Rowntree, 2003). However, it is usually morphometric criteria that are used to define bankfull. For the purposes of this thesis, a discharge that is "bankfull" was measured at the elevation of a clear break in slope between the channel banks and adjacent flood plain or terrace. The reason for identifying this clear break in slope was because it was taken to be roughly equivalent to the dominant discharge and represented the 'equilibrium' morphology.

Thus, channel form (i.e. width, depth, cross-sectional area and form ratio) were based on discharge at "bankfull". This was done so as to emphasise the differences in channel morphology between the Baviaans, Heuningnes and Reference channels. However, as already mentioned, at some sites a discharge at "bankfull" seemed problematic and impossible. A more likely occurrence at these sites is a discharge at the lower active channel (equivalent to a bench-full discharge).

Channel width was measured at the bank edges of a "bankfull" width. Some sites were measured at bankfull even though they were clearly incised and a bankfull discharge seemed totally unrealistic (e.g. the upper sites of the Baviaans). Clearly there are issues with defining bankfull and these have been discussed in Chapter 3 and also above. Channel depth was calculated as the average depth between these two bankfull edges.
Knowing bankfull width and depth it is possible to calculate a bankfull discharge through the use of the slope-area method and by using Cowan's method of estimating Manning's n (Gordon *et al.*, 2004):

$$\mathbf{Q = 1/n \cdot A \cdot R^{2/3} \cdot S^{1/2}} \qquad \textbf{(Eq. 3.1)}$$

Where:
- Q is discharge in $m^3 s^{-1}$
- n is "Manning's n"
- A is cross-sectional area of the flow in m^2
- R is hydraulic radius in metres
- S is slope

This slope-area method is a frequently used technique to estimate discharge indirectly, especially if there is a lack of flow measurements and data (Gordon *et al.*, 2004). Throughout the study period, no significant flow occurred in the study rivers which could be measured, hence the use of the slope-area method. Errors can occur with the accurate estimation of Manning's n and in measuring slope. Thus, estimates of discharge should only be used as approximations. To minimise error in Equation 3.1, the effect of slope on discharge calculations was standardised by using the same slope for all 10 sites in each study reach rather than using the slope over each individual 16m site which varied greatly.

4.3.3 Bed material

The material type that comprises the channel bed influences channel roughness, with concomitant effects on flow. It also affects habitat availability and quality. Surface bed material was described along the five transects within each site. Along a given transect the channel's bed width was measured and divided into ten points. At each point five bed material assessments were made i.e. two upstream, one on the transect line and two downstream. Bed material was defined and measured as the material lying on the channel bed at the point where the researcher placed a metal peg. It was then classified into a category range based on the grade scale for particle size provided by Gordon *et al.* (2004) which uses Wentworth class intervals (see Table 4.2). Thus, 50 measurements were made along each transect for five transects, giving a total of 250 measurements to describe the bed material within a given site.

4.3.4 Bank and terrace material

Material from channel banks are collected for various reasons, but most importantly to gain an understanding of the bank stability and to determine the resistance of a channel's banks to erosion by hydraulic forces (Simon & Castro, 2003; Gordon *et al.*, 2004). Samples were taken as cores extracted to a depth of 10cm from the lower banks and terraces with the use of a mallet and corer (2.5 cm diameter, 10cm length). Channel bank samples were taken at a standard height of 30 cm from the low water surface because, firstly, the stability of the lower bank was deemed most critical and secondly, this height was exceeded by all channel banks. Both left and right channel banks were sampled at equally spaced points within the site. Both left and right bank terraces were sampled higher up the bank slope and usually along the line of permanent metal pegs hammered in place for the transects. Thus, each site has two integrated channel bank samples and two integrated bank terrace samples. In some cases extra samples were taken giving a combined total of 46 samples for Baviaans, 41 samples for Heuningnes and 51 samples for the Reference. Samples were bagged and correctly labelled with relevant information for further analysis in the soils laboratory. The same grade scale for particle size was used.

Table 4.2 Grade scales for particle size

Class (Wentworth)	mm	Ø
Very large boulder	4096-2048	-12 to -11
Large boulder	2048-1024	-11 to -10
Medium boulder	1024-512	-10 to -9
Small boulder	512-256	-9 to -8
Large cobble	256-128	-8 to -7
Small cobble	128-64	-7 to -6
Very coarse gravel	64-32	-6 to -5
Coarse gravel	32-16	-5 to -4
Medium gravel	16-8	-4 to -3
Fine gravel	8-4	-3 to -2
Very fine gravel	4-2	-2 to -1
Very coarse sand	2-1	-1 to 0
Coarse sand	1-0.5	0 - 1
Medium sand	0.5-0.25	1 - 2
Fine sand	0.25-0.125	2 - 3
Very fine sand	0.125-0.0625	3 - 4
Coarse silt	0.0625-0.0312	4 – 5
Medium silt	0.0312-0.0156	5 – 6
Fine silt	0.0156-0.0078	6 – 7
Very fine silt	0.0078-0.0039	7 – 8
Coarse clay	0.0039-0.0020	8 – 9
Medium clay	0.0020-0.0010	9 – 10
Fine clay	0.0010-0.0005	10 – 11
Very fine clay	0.0005-0.00024	11 - 12

4.3.5 Bank shear strength

The shear stresses of banks were measured with a shear vane meter to estimate the strength of the banks along each site. Although there are issues related to the use of shear vanes (i.e. provides only a single value, shear strength varies with soil moisture content, etc.), it is a rapid and inexpensive way of understanding bank strength (Simon & Castro, 2003). The soil stability of the upper and lower banks was measured with the use of an Edeco Pilcon shear vane meter. The 13mm vane was used for measurements and was inserted a few centimetres into the bank. For Baviaans and the Reference, ten measurements were done at each site, that is five along the upper bank and five along the lower bank. The Heuningnes had 20 measurements at each site because a different fieldworker was used on this fieldtrip. However, it was decided to keep all the data as it was averages that were being compared. Measurements were done on both the left hand and right hand banks within the 16m stretch of channel being surveyed. Upper and lower banks were divided midway between the vertical height of the bank.

4.3.6 Vegetation

A *basic* description of vegetation was also completed for each site. Vegetation type (tree, shrub, grass); vegetation density (dense, moderate, sparse); vegetation frequency (widespread, frequent, local); vegetation diversity (low, medium, high) and location within the channel (right bank, left bank, instream) were recorded for each site. Although this may seem a rather simple and largely subjective assessment, classifying according to some known vegetation variables as used by Thorne (1990), and also used by Dollar (1992), brings about a certain degree of objectivity.

These variables were then given a score. The total score for each site was then used to calculate its rank within the study reach. A rank of 1 was assigned to the site that was seen as being the most impacted by the wattle invasion. Additional rankings were then done for each of the four channel form variables at each site using the site average. Here, the largest width, depth, cross-sectional area and form ratio were assigned a rank of 1.

4.3.7 Visual records

Finally, every site was sketched, photographed and a GPS location recorded for mapping purposes.

4.4 LABORATORY ANALYSIS

4.4.1 Sample preparation

Bank and terrace samples were dried and then ground with a pestle and mortar to break up any aggregates. The samples were then sieved through a 2mm sieve so as only to analyse particles < 2mm. According to Briggs (1977), it is only this fine earth fraction that is normally analyzed because it is considered to be both physically and chemically active. Coarser material tends to contribute less to soil processes and plant growth. At this point the loss on ignition test (i.e. total organic matter) was conducted. Before the particle size analysis was conducted, samples first had any macro-organic material removed.

4.4.2 Total organic content

The first test conducted on the samples was the loss on ignition so as to assess total organic matter. This is a semi-quantitative method of determining soil organic matter (SOM) based on the removal of the organic matter by gravimetric weight loss (Briggs, 1977; Foth *et al.*, 1980; Schumacher, 2002). Samples were first air-dried. A 5-10g sample was then placed in a crucible, weighed and placed in the muffle furnace overnight at 440°C. The next morning the furnace was reduced to ~100°C and the cooled samples placed in a desiccator until they could be handled and re-weighed. The difference in sample weight pre and post furnace results in a percentage organic content.

4.4.3 Particle size analysis

The second test to be conducted on the bank and terrace material was that of soil texture or particle size analysis. This is a quantitative method of determining the particle size distribution of a given soil (Foth *et al.*, 1980; Gee & Bauder, 1986; Gordon *et al.*, 2004). A 100-300g sample was placed at the top of a sieve-stack and placed on a shaker for 12 minutes. Five sieves were used to correspond with 1 phi intervals i.e. 1000μm, 500μm, 250μm, 125μm and 63μm. Thus, what collected in the bottom tray was everything <

63μm i.e. the silt-clay fraction. The content of each sieve was then weighed. Results were expressed as a particle size distribution showing the cumulative percentage of particles finer than a given phi class i.e. phi -1 through 12.

4.5 CONCLUSION

It is precisely because any process study of channel change over time is essentially dependant on prior investigation of that channel's dimensions and location that a lack of data becomes a major limiting factor for that study. In addition, time and budgetary constraints can also prove further limiting factors for any study.

With this in mind, there were two aims to this chapter. Firstly, to provide an understanding of the research design so that, secondly, the methodology behind this research could be explained. It has described and examined various relevant study area variables. The outcome has been a variety of data that has shown similarities and differences in one way or another between the three study reaches (i.e. Baviaans invaded, Heuningnes invaded and the Reference).

This chapter has explained the location of catchments and it has given reasons for the choice in reaches studied. Furthermore, it has clarified and justified the choice of reference conditions emphasizing the Reference as being unimpacted by woody alien invasives in comparison to the impacted and invaded reaches of the Baviaans and Heuningnes. It has also shown overall research design and the reasons for following this design route. Finally, it has also described the methods used to measure the many variables within each site.

The methodologies behind the various statistical analyses of the available data were not explained in this chapter. These are explained in Section 5.9 along with the various statistical analysis results.

CHAPTER 5

RESULTS

5.1 INTRODUCTION

This chapter examines a multitude of variables from all three study reaches. It begins by presenting the initial rapid measurements of channel form variables. This is followed by showing all the site variables for all three reaches emphasising downstream changes. It then examines the vegetation characteristics of the study reaches. This is followed by a comparison and then statistical analysis of the channel form variables for all three study reaches. An analysis of some channel control variables follows. The influence of catchment area and bankfull discharge is then examined. Further statistical analysis of the three study reaches is then conducted so as to test for any differences between the three study reaches. Finally, it investigates any changes to channel form and channel bed material that may have occurred within the study period after alien wattle clearance from the Baviaans reach.

5.2 PRELIMINARY ASSESSMENT

Figure 5.1 shows the results of the initial rapid assessment of channel measurements completed during the earlier reconnaissance fieldtrip to the study sites. It suggests a marked difference in channel form ratio (width-depth ratio) between the invaded Baviaans and Heuningnes channels and the channels higher up the Heuningnes catchment considered as 'natural' at this stage.

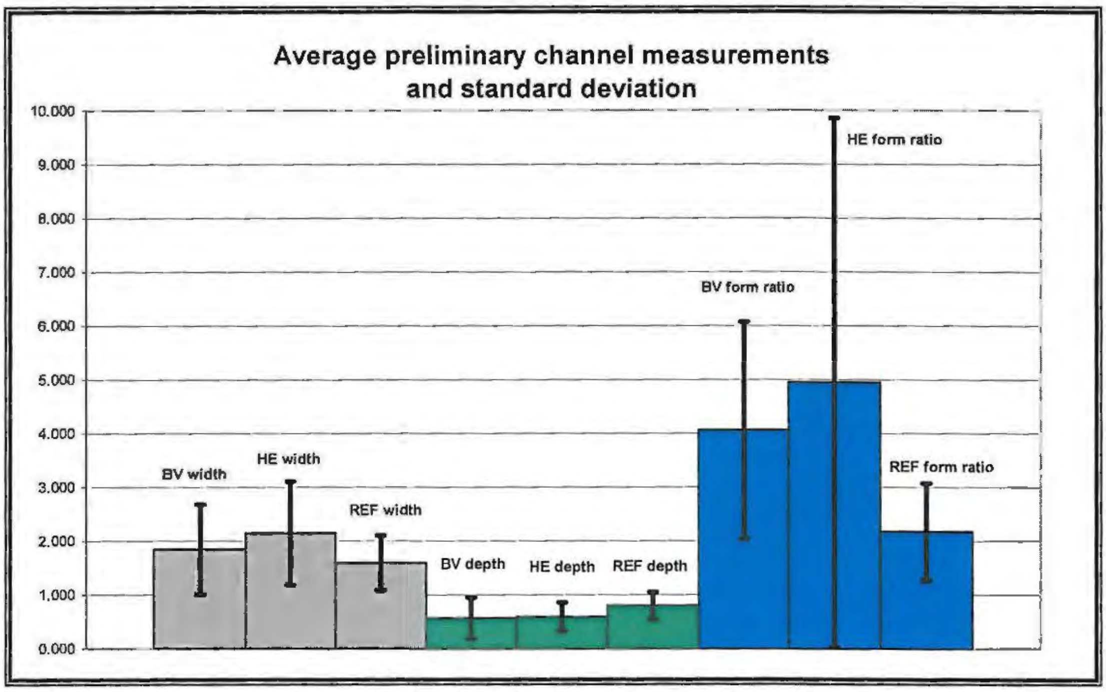

Figure 5.1 Preliminary assessments of channel measurements (width and depth in metres)

5.3 ALL SITE VARIABLES

Tables 5.5 – 5.7 show the complete range of variables that were measured at every site for all three study reaches. They are divided into three categories: Catchment controls, Reach controls and Channel form measurements. Note that site gradient is the measured gradient over the 16m stretch of river surveyed at each site while local gradient is the gradient occurring over the two closest 20m contour lines. These are different to the reach gradient which is the gradient over the entire reach containing all 10 sites.

5.4 RIPARIAN AND CHANNEL VEGETATION

5.4.1 Description of study reach vegetation characteristics

Tables 5.5 – 5.7 also provide a description of vegetation characteristics at each study site. When comparing all three study reaches there is an obvious distinction in vegetation characteristics. The Reference vegetation is very different from the two invaded reaches. The Reference reach has dense fynbos growing along its channels (Plate 2). In the

Reference, the upper banks and terraces are not barren as found under the wattle canopy in the two invaded reaches (Plates 3 & 4). There is also a greater diversity of vegetation compared to the mono-specific wattle stands of the invaded reaches. In the Reference, the dense fynbos is confined to the immediate channel. While in the invaded reaches, the wattle invasion can be found along the bank terraces and also further upslope.

The two invaded reaches exhibit dense stands of wattle along their channels. In the Baviaans, especially the sites lower downstream, a large amount of this wattle is still young (< 5yrs) (Plate 5). The Heuningnes has wattles that are clearly much older and larger. While most fynbos plants are shrubs, wattles in the study area can grow up to several metres, are more exposed to strong winds and are heavier, thus making them vulnerable to windthrow. A greater above ground weight to root depth ratio makes wattles more vulnerable to collapse and the study sites show plenty of evidence for this (Plate 6). A few measurements from some collapsed wattles showed root depths of only 50-100cm. In both invaded reaches, collapsed wattle trees are common and upon collapse they destroy the channel bank. Furthermore, collapsed wattles can also disrupt the flow in the channel and lead to severe scouring and undercutting. Bank undercuts of varying degrees are a common feature in the invaded reaches (Plate 7). These were noted as basal erosion in Tables 5.5 – 5.7. Both invaded reaches thus contain a large amount of large woody debris (LWD). This LWD results in debris dams that are common to the invaded reaches but are not found in the Reference (Plate 8). The Baviaans was cleared of alien vegetation in 2001 and was followed by a fire that burned through the catchment the following year. This clearing and the fire that followed have added to the load of old dead wood.

The presence of cattle within all three study reaches must also be acknowledged. Although the study area is now free of cattle and only contains game, all three reaches were part of a farm in which cattle roamed freely. The effects of stocking cattle (i.e. cattle paths, destruction of river banks, 'watering holes', etc) are most clear in the Heuningnes.

Plate 2 A site in the Reference reach with transect lines laid out

Plate 3 Barren undergrowth of the Baviaans canopy

Plate 4 Close-up of barren terrace soil in the Heuningnes showing the plentiful supply of wattle seeds (Photo: Saskia Fourie)

Plate 5 Young Baviaans wattles (Photo: Kate Rowntree)

Plate 6 Collapsed wattles and other LWD in the study area (Photo: Kate Rowntree)

Plate 7 Undercutting in the study area (Photo: Kate Rowntree)


Plate 8 A debris dam in the Heuningnes (Photo: Kate Rowntree)

5.4.2 Statistical analysis of channel vegetation

In trying to understand the relationship between two given variables a correlation coefficient can be calculated as a quantitative measure of this relationship strength (Gordon *et al.*, 2004). The value of r varies between -1 to +1 and in general, a value between 0.8 and 1 (thus also -0.8 to -1) indicates a strong linear relationship (Gordon *et al.*, 2004; Taylor, 1996). A value ranging 0.5 – 0.79 indicates a moderate linear relationship and a value near zero implies there is little or no linear relationship between the variables. A relationship does not imply direct cause and effect. It is rather the existence of the relationship and the implications thereof that are important.

An assessment of channel vegetation characteristics was conducted at every site (see Section 4.3.6). Tables 5.1 – 5.3 are the result of this assessment. A Spearman's Rank correlation coefficient was then used on the ranked data to make sense of any relationships between vegetation and the four channel form variables (Table 5.4). See Appendix F for all calculations.

Table 5.1 Scores and ranks for each site in the Baviaans reach

Site	BV1	BV2	BV3	BV4	BV5	BV6	BV7	BV8	BV9	BV10
Type	trees	trees	trees	trees	trees	trees	trees & shrubs	trees & shrubs	trees & grass	trees, shrubs & grass
Diversity	low	low	low	low	low	low	medium	medium	medium	medium
Dominant species	wattle	wattle	wattle	wattle	wattle	wattle	wattle	wattle	wattle	wattle
Density	dense	mod-dense	dense	dense	dense	moderate	dense	dense	dense	dense
Frequency	widespread	widespread	widespread	widespread	widespread	widespread	widespread	widespread	widespread	widespread
Total Score	5	5.5	5	5	5	6	7	7	7	8
Rank	2.5	5	2.5	2.5	2.5	6	8	8	8	10

Table 5.2 Scores and ranks for each site in the Heuningnes reach

Site	HE1	HE2	HE3	HE4	HE5	HE6	HE7	HE8	HE9	HE10
Type	trees & shrubs	trees & shrubs	trees & shrubs	trees	trees & shrubs	trees & shrubs	trees, shrubs & grass	trees	trees	trees
Diversity	low	medium	low	medium	medium	low	medium	low	low	low
Dominant species	wattle	wattle	wattle	wattle	wattle	wattle	wattle	wattle	wattle	wattle
Density	moderate	mod-dense	moderate	dense	mod-dense	dense	moderate	dense	dense	dense
Frequency	widespread	widespread	widespread	widespread	widespread	widespread	widespread	widespread	widespread	widespread
Score	7	7.5	7	6	7.5	6	9	5	5	5
Rank	6.5	8.5	6.5	4.5	8.5	4.5	10	2	2	2

Table 5.3 Scores and ranks for each site in the Reference reach

Site	REF1	REF2	REF3	REF4	REF5	REF6	REF7	REF8	REF9	REF10
Type	shrubs & grass	shrubs & grass	shrubs & grass	shrubs & grass	shrubs & grass	shrubs & grass	trees & shrubs	shrubs & grass	shrubs & grass	shrubs & grass
Diversity	high	high	high	high	high	high	high	high	high	high
Dominant species	fynbos	fynbos	fynbos	fynbos	fynbos	fynbos	fynbos	fynbos	fynbos	fynbos
Density	dense	dense	mod-dense	dense	mod-dense	dense	mod-dense	dense	mod-dense	mod-dense
Frequency	widespread	widespread	widespread	widespread	widespread	widespread	widespread	widespread	widespread	widespread
Alien veg. presence	no	no	yes	yes	no	no	yes	no	yes	yes
Score	12	12	9	10	11	12	8	12	9	9
Rank	8.5	8.5	3	5	6	8.5	1	8.5	3	3

Table 5.4 Correlation coefficients for vegetation and channel form variables

	Baviaans	Heuningnes	Reference
Width	-0.240	0.439	0.090
Depth	-0.509	0.433	0.085
Cross-sectional area	**-0.661**	**0.597**	0.170
Form Ratio	0.564	-0.297	0.030

Table 5.4 shows the correlation coefficients between channel form variables and vegetation. A value between 0.8 and 1 (thus also -0.8 to -1) indicates a strong relationship. Only two moderate relationships with cross-sectional area are apparent (highlighted in orange). These results do not reveal much with regards to vegetation and channel form variables. This is possibly due to the following reasons: Firstly, it should be emphasised that the assessment of channel vegetation characteristics and the subsequent scoring system was a subjective and basic assessment. Secondly, the vegetation characteristics of the invaded sites of both the Baviaans and the Heuningnes varied minimally. Often, the degree of impact from alien vegetation was similar. Thirdly, the Reference was clearly and obviously different to the two invaded reaches and there was an understandable lack of alien wattle trees providing an 'impact'.

Table 5.5 Site variables for invaded Baviaans reach

	CATCHMENT CONTROLS	REACH CONTROLS											CHANNEL FORM			
Site	Drainage Area (km²)	Reach gradient	Site gradient	Local gradient	Bed material	D50 (median) bank particle in mm	Ave. % silt/clay in bank material	Ave. bank gradient	Ave. % organic content in bank material	Bank shear strength (Kpa)	Vegetation Description	Bankfull discharge (m³ s⁻¹)	Ave. Width (m)	Ave. Depth (m)	Ave. cross-sectional area (m²)	Ave. Form ratio
BV10	4.256	0.030	0.030	0.032	59% cobble	0.28	15.59	82° Frequent basal erosion	6.43	41	dense wattle on banks; dense frequent shrubs/grass on banks/instream	4.034	1.73	0.88	1.52	2.06
BV9	4.434	0.030	0.015	0.032	41% cobble; 40% gravel	0.24	19.46	76° Widespread basal erosion	7.04	52	dense wattle on banks, scattered to moderate local grass on banks/instream	0.895	1.99	1.09	2.29	1.80
BV8	4.612	0.030	0.026	0.032	44% boulder	0.29	14.25	67° Widespread basal erosion	5.16	44	dense mature wattle on banks; scattered local indigenous shrubs on banks	2.080	2.27	1.23	2.83	1.84
BV7	4.789	0.030	0.004	0.032	69% gravel	0.21	21.69	32°	8.58	40	dense wattle on banks/instream; moderate grass on banks/instream sparse instream reeds	1.053	1.81	0.33	0.64	5.65
BV6	4.967	0.030	0.020	0.035	49% silt/sand	0.23	23.59	53° Frequent basal erosion	7.72	33	dense wattle on banks/instream	1.380	1.24	0.47	0.59	2.70
BV5	5.145	0.030	0.010	0.035	75% silt/sand	0.19	27.62	52° Localised basal erosion on RHB	10.09	22	dense wattle on both banks; indigenous veg. LHB; severe debris dam upstream	0.642	1.13	0.33	0.38	3.40
BV4	5.323	0.030	0.020	0.024	42% cobble; 31% gravel	0.21	22.87	50° Frequent basal erosion	8.98	50	dense wattle on banks	0.684	1.38	0.34	0.47	4.17
BV3	5.500	0.030	0.000	0.024	49% silt/sand; 35% gravel	0.20	21.93	45° Localised basal erosion on RHB	5.82	44	dense wattle on banks/instream	0.676	1.41	0.41	0.60	3.50
BV2	5.678	0.030	0.016	0.024	90% silt/sand	0.18	26.60	27°	8.94	57	moderate to dense wattle on banks	0.669	1.84	0.16	0.28	14.68
BV1	5.856	0.030	0.034	0.024	52% silt/sand; 39% gravel			20° Localised basal erosion	7.65	36	dense wattle on banks/instream	0.547	2.46	0.23	0.58	11.76

Table 5.6 Site variables for invaded Heuningnes reach

	CATCHMENT CONTROLS	REACH CONTROLS											CHANNEL FORM			
Site	Drainage Area (km^2)	Reach gradient	Site gradient	Local gradient	Bed material	D50 (median) bank particle in mm	Ave. % silt/clay in bank material	Ave. bank gradient	Ave. % organic content in bank material	Bank shear strength (Kpa)	Vegetation Description	Bankfull discharge ($m^3 s^{-1}$)	Ave. Width (m)	Ave. Depth (m)	Ave. cross-sectional area (m^2)	Ave. Fo
HE10	5.981	0.027	0.028	0.026	76% silt/sand	0.23	21.87	58° Widespread basal erosion	6.78	65	dense mature wattle on banks	0.322	2.18	0.57	1.64	3.75
HE9	6.284	0.027		0.026	42% cobble; 39% silt/sand	0.36	9.75	60° Localised basal erosion	5.83	65	dense wattle on banks; debris dam at reach centre	0.849	1.50	0.80	1.26	2.00
HE8	6.586	0.027	0.015	0.026	79% silt/sand	0.24	12.35	16° Widespread subaerial erosion	8.09	50	dense wattle on banks	0.374	2.89	0.20	0.59	15.14
HE7	6.889	0.027	0.019	0.026	84% silt/sand	0.24	18.37	49° Localised basal erosion	6.15	60	moderate wattle on banks; sparse shrubs and grasses on banks	0.348	1.07	0.31	0.39	4.27
HE6	7.191	0.027	0.048	0.026	64% silt/sand	0.27	16.71	51° Frequent basal erosion	7.10	42	dense wattle on banks/instream; sparse shrubs on banks; debris dam at reach centre	1.265	1.30	0.38	0.51	3.72
HE5	7.494	0.027	0.000	0.028	74% silt/sand	0.18	24.88	41° Widespread subaerial erosion	10.81	51	moderate to dense wattle on banks; moderate shrubs further up both slopes; grasses instream	0.781	1.74	0.18	0.36	9.11
HE4	7.796	0.027	0.020	0.028	74% silt/sand	0.32	11.47	54° Frequent basal erosion	4.90	55	dense wattle on banks/instream; dense indigenous shrubs further up both slopes; scattered grass instream; debris dam at reach centre	0.345	2.00	0.55	1.16	3.72
HE3	8.099	0.027	0.008	0.028	66% silt/sand	0.32	9.53	37° Widespread subaerial erosion	4.21	45	moderate to dense wattle on banks, sparse shrubs and grasses on banks	0.906	2.16	0.37	0.78	6.26
HE2	8.401	0.027	0.033	0.028	56% gravel	0.32	9.33	55° Widespread basal erosion	4.09	86	dense wattle on banks; indigenous shrubs scattered RHB & dense LHB	1.798	2.01	0.57	1.15	3.77
HE1	8.704	0.027	0.000	0.028	52% silt/sand	0.42	7.37	45° Frequent subaerial erosion	4.68	44	moderate wattle on banks; moderate to sparse shrubs on banks	0.371	1.97	0.34	0.68	6.06

Table 5.7 Site variables for the Reference reach

	CATCHMENT CONTROLS	REACH CONTROLS											CHANNEL FORM			
Site	Drainage Area (km²)	Reach gradient	Site gradient	Local gradient	Bed material	D50 (median) bank particle in mm	Ave. % silt/clay in bank material	Ave. bank gradient	Ave. % organic content in bank material	Bank shear strength (Kpa)	Vegetation Description	Bankfull discharge ($m^3 s^{-1}$)	Ave. Width (m)	Ave. Depth (m)	Ave. cross-sectional area (m^2)	Ave. Form ratio
REF10	4.726	0.028	0.022	0.035	54% silt/sand	0.34	10.11	55°	6.70	67	dense fynbos on banks/instream, moderate grass instream/LHB, dense wattle stand just upstream of reach	0.374	0.94	0.32	0.32	3.09
REF9	4.865	0.028	0.025	0.035	84% silt/sand	0.31	10.92	60°	7.64	70	dense fynbos on banks/instream; moderate grass on LHB	0.811	0.81	0.38	0.31	2.31
REF8	5.005	0.028	0.002	0.035	87% silt/sand	0.28	12.43	66°	8.15	33	dense fynbos on banks, moderate grass on LHB	0.827	0.70	0.31	0.22	2.62
REF7	5.144	0.028	0.027	0.035	60% silt/sand	0.28	10.68	74° Localised basal erosion on RHB	8.56	35	dense fynbos on banks/instream; localised reeds instream; large stand of blue gums and wattles just upstream of reach	0.684	1.63	0.47	0.84	3.49
REF6	5.284	0.028	0.023	0.024	38% boulder, 23% silt/sand	0.34	10.15	50° Localised subaerial erosion	5.02	68	dense fynbos on banks/instream; moderate grass on banks, scattered reeds instream	0.369	1.74	0.50	0.90	3.81
REF5	5.423	0.028	0.012	0.024	37% boulder; 25% silt/sand	0.31	11.01	56° Localised basal erosion	5.95	63	dense fynbos on banks/instream; moderate grass on banks; scattered reeds instream	3.244	1.74	0.66	1.10	3.15
REF4	5.563	0.028	0.000	0.024	65% silt/sand	0.22	21.76	49°	14.64	58	dense fynbos on banks/instream; wattles located upstream and downstream of reach	0.176	1.53	0.36	0.57	5.12
REF3	5.702	0.028	0.033	0.024	47% silt/sand	0.28	17.70	41°	8.04	88	dense fynbos on banks/instream; moderate grass on LHB	0.608	1.44	0.30	0.44	4.84
REF2	5.842	0.028	0.024	0.024	39% silt/sand, 31% gravel	0.35	14.94	51°	6.90	84	dense fynbos on banks/instream, localised grass on banks	1.274	1.13	0.42	0.46	2.92
REF1	5.981	0.028	0.022	0.024	42% silt/sand	0.34	13.76	46°	7.07	96	dense fynbos on banks/instream, moderate grass on RHB	0.445	1.19	0.24	0.30	5.09

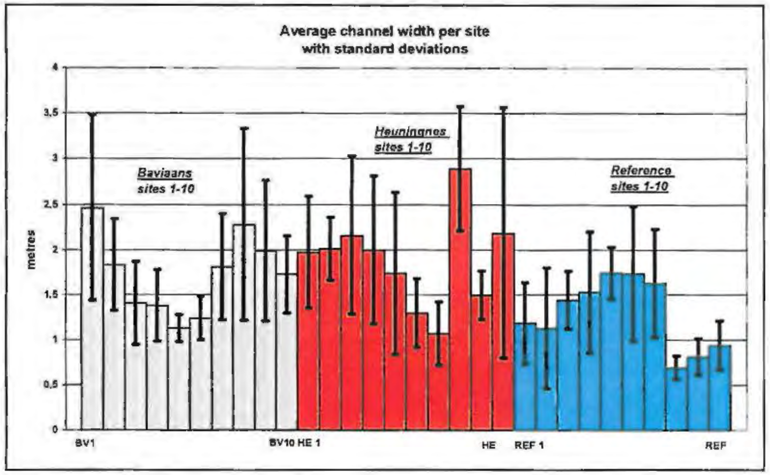

Figure 5.2 Average channel widths per site

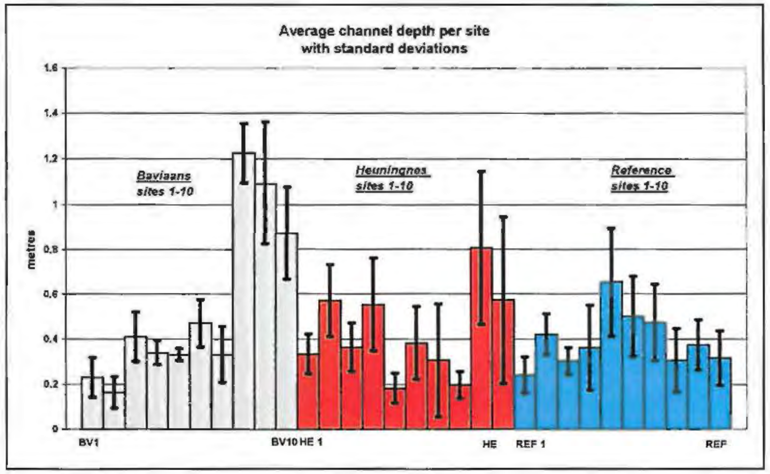

Figure 5.3 Average channel depths per site

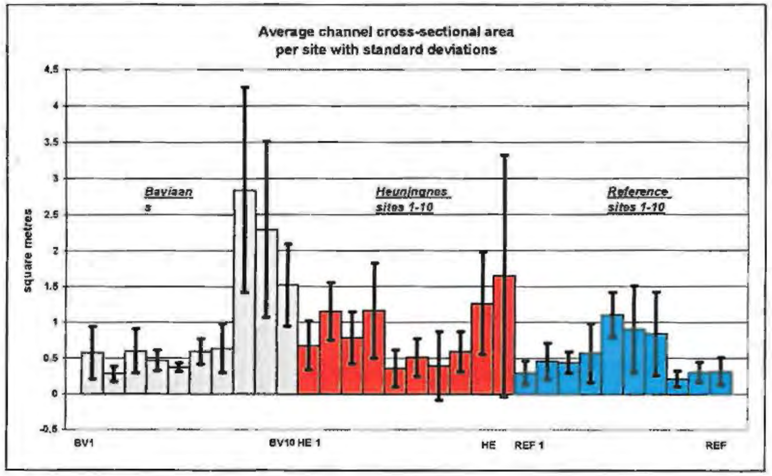

Figure 5.4 Average channel cross-sectional areas per site

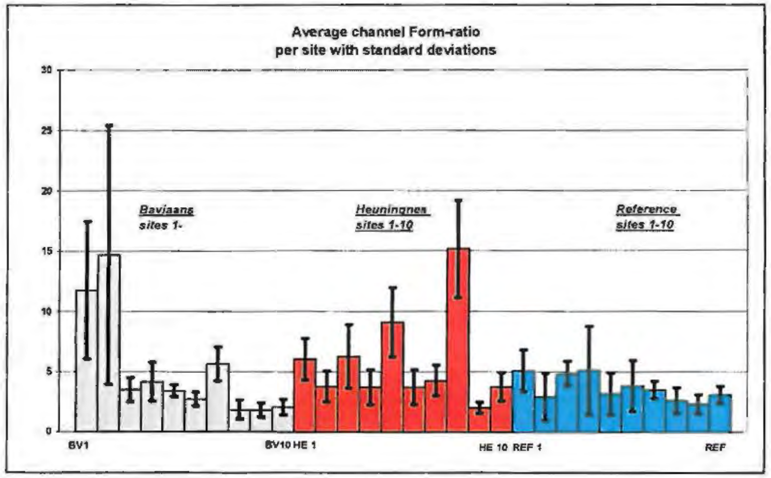

Figure 5.5 Average channel form ratios per site

5.5 CHANNEL FORM VARIABLES

This section examines those variables that describe channel form. Measured with the use of an electronic distance measurement instrument (EDM or total station) as part of the channel survey, it is possible to accurately calculate these channel form variables as well as several other variables. Figures 5.2 – 5.5 above, provide a summary of the average channel dimensions for five transects at each 16m site. Appendix A shows all transects in more detail. Note that site numbers increase in numerical order in the upstream direction i.e. sites BV10, HE10 and REF10 are the sites highest upstream while BV1, HE1 and REF1 are the sites furthest downstream. These figures show the trends occurring in a downstream direction for all three study reaches.

5.5.1 Channel width

As mentioned previously, channel width was taken as the bankfull width. Figure 5.2 clearly shows the invaded Heuningnes and Baviaans as having wider channels than the Reference. There exists much variability in channel width in all three study reaches.

5.5.2 Channel depth

Channel depth was calculated as the average depth across the channel relative to the 'bankfull' edges. Figure 5.3 shows how the Baviaans has relatively similar channel depths until the upper sites of the catchment i.e. sites 8-10. These upper three sites are severely incised with widespread basal erosion and undercutting. The Heuningnes exhibits no clear trends while the Reference has its deepest (and widest) channels at the middle sites just downstream from a stand of alien blue gum and wattle trees.

5.5.3 Channel cross-sectional area

Cross-sectional area is the product of a channels width and depth. Figure 5.4 shows the large cross-sectional area of the channel in the upper three sites of the Baviaans (BV8-

10). There are no clear trends in the Heuningnes while the Reference's wide and deep middle sites result in its largest cross-sectional areas. In comparison to the invaded reaches, it is clear that the Reference reach's channels exhibit a much smaller cross-sectional area, thus emphasising its smaller widths and depths.

5.5.4 Channel form ratio (width-depth ratio)

The form ratio usually increases in a downstream direction (Gordon *et al.*, 2004). All three study reaches are variable with no significant downstream trends (Figure 5.5). Site HE8 was located almost at the confluence of a tributary and was clearly an area of deposition. This could be the reason for the low channel depth and large channel width resulting in the exceptionally high ratio. Note also the much higher form ratios at sites BV1 and BV2 in relation its other sites. These two sites have low channel depths.

Figures 5.2 – 5.5 point to the importance of local controls rather than a downstream control related to increases in discharge. This supports the sampling assumption that discharge does not differ significantly within the three study reaches and would not therefore be expected to increase significantly downstream.

5.5.5 Bed material

Bed material is included here as a component of channel form. In terms of rehabilitation, the importance of bed material is that it provides habitat for both aquatic fauna and vegetation. Here, bed material is examined as the result of fluvial processes occurring within the channel to give an idea of the bed material within each study reach. It is necessary in the study of any stream to understand the type of bed material and bank material that exists within that stream. Figures 5.6 – 5.8 show the bed material type within each site for all three study reaches. Appendix B provides further detail on each site's bed material.

Baviaans bed material consists mostly of sand and gravel in the lower sites but bed material size clearly increases in size further upstream. There is a marked increase of cobbles and boulders in the three uppermost sites. This corresponds with the large cross-sectional area for these three sites.

Most sites in the Heuningnes consist predominantly of silt/sand and gravel (except HE2 which is situated just below a road crossing). Although some cobbles are to be found within the Heuningnes sites, even fewer boulders are present. This is in contrast to the larger percentage of cobbles and boulders in the Baviaans and Reference system. There is no clear trend in the downstream pattern of bed material in the Heuningnes system.

The Reference seems to show a slight downstream decrease in silt/sand. This system also clearly has more cobbles and boulders in its sites when compared to Heuningnes invaded (bearing in mind that the Reference as a reach is located above the Heuningnes reach). Once again the large cross-sectional areas (relative to other Reference sites) of REF5 – REF7 correspond with the greater abundance of cobbles and boulders found in these sites.

5.5.6 Comparing the three study reaches

While Figures 5.2 – 5.5 show the downstream trends of the four channel form variables being studied, Figure 5.9 emphasises the difference in channel from variables between each study reach based on all 50 cross-sections or transects (49 for Baviaans and Reference).

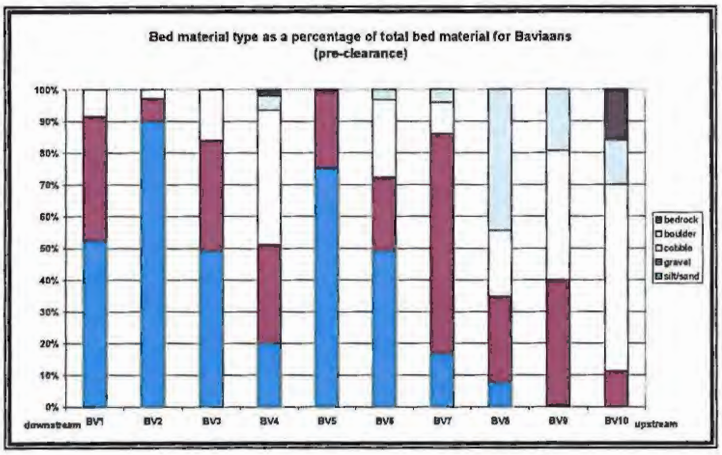

Figure 5.6 Baviaans bed material type per site

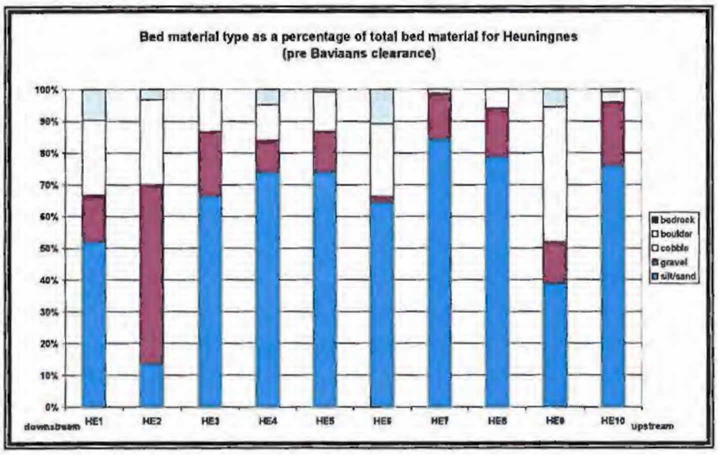

Figure 5.7 Heuningnes bed material type per site

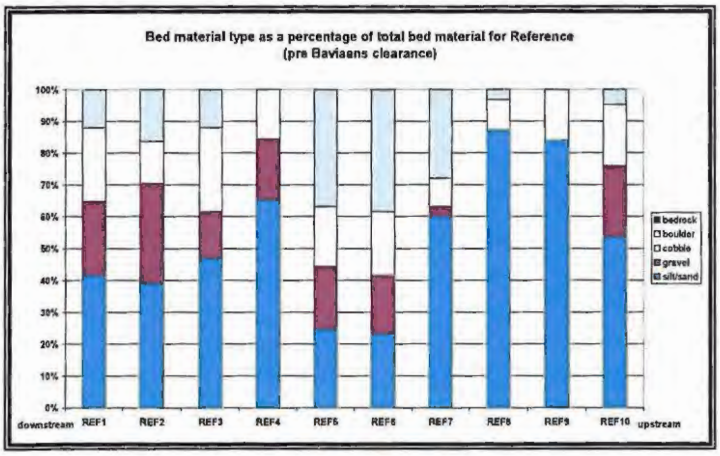

Figure 5.8 Reference bed material type per site

It is clear that the Reference as a reach has the narrowest channels in comparison to the two invaded reaches. There is more than half a metre average difference between Heuningnes and Reference. All three reaches exhibit reasonably similar channel depths although it is the two invaded reaches that have the deepest channels on average. The outcome is clearly a Reference that has a much smaller average cross-sectional area. The Baviaans channels are almost double the cross-sectional area than that of the Reference channels. These narrow Reference channels thus also result in a much lower average form ratio in comparison to the two invaded reaches. Thus, in terms of channel form, Figure 5.9 provides a clear indication of a distinct difference between the two invaded/impacted reaches and the more 'natural' and unimpacted Reference reach.

Figure 5.9, the result of repeated precise channel measurements, can also be compared to Figure 5.1, the preliminary rapid measurements. This comparison provides an indication of the accuracy of using basic rapid measurements rather than the use of a total station with its more accurate measurements. The sites where the preliminary rapid measurements were measured were not in identical locations to the study sites. Thus, any differences could possibly be due to the variation in sites sampled rather than the assessment itself being rapid. When comparing the two figures, there are fairly similar trends in widths but slight differences in depths. However, the identical trend in form ratio whereby the Reference is significantly lower than the two invaded reaches is clear.

It seems that a basic rapid assessment of channel measurements is thus not the most desirable manner with which to measure channel form and is definitely not a feasible substitute for multiple and highly accurate measurements. However, if the exact same sites were compared perhaps the results would be more decisive. Furthermore, with fairly similar trends and considering the time saved with fieldwork, a basic rapid assessment seems practicable. This should be considered in connection to any possible rapid measurements that might be conducted as part of future long-term monitoring of the channel post rehabilitation efforts.

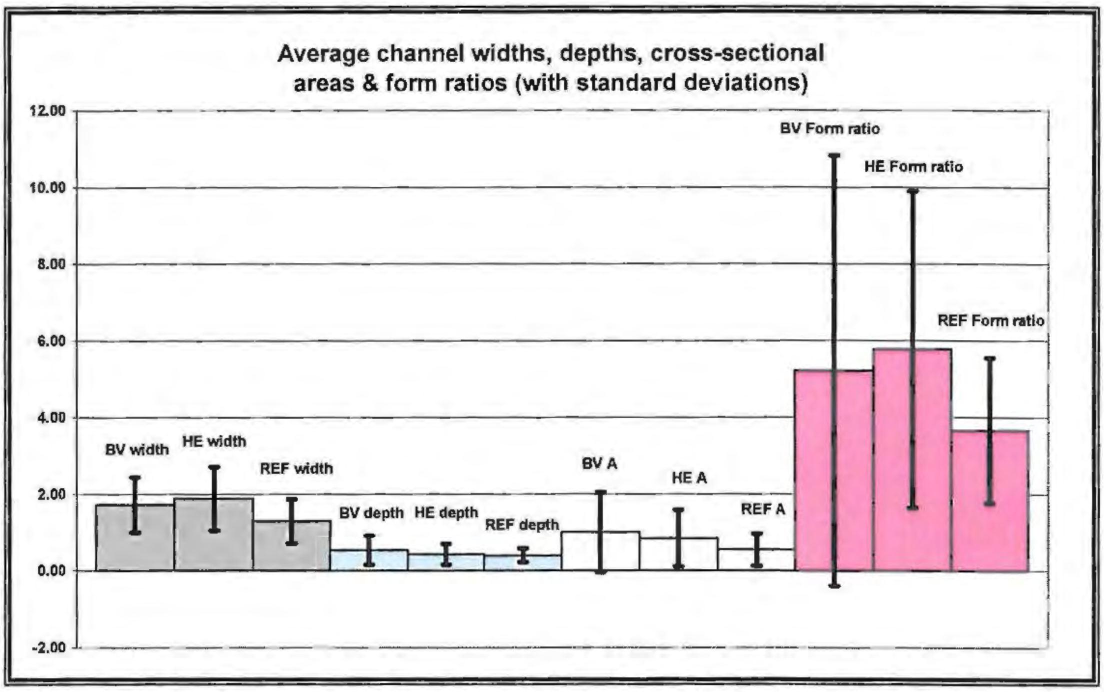

Figure 5.9 Overall average channel width, depth, cross-sectional area and form ratio for the study reaches

5.6 STATISTICAL ANALYSIS OF CHANNEL FORM VARIABLES

5.6.1 F-tests

Tables 5.8 – 5.11 show the f-values comparing variance of the four channel form variables from each study site. With f-tests, an f-value close to 1 indicates that the underlying population variances are equal i.e. their variances are similar or the same. These f-tests used the data from each transect (not only a site average) to increase the statistical population size i.e. 50 transects for Heuningnes and 49 for Baviaans and the Reference. Values >1.7 are statistically significant at 0.05 level of significance. They are highlighted in red. The f-tests were done using Microsoft Excel.

Table 5.8 F values for F-tests on channel widths

Width	Baviaans	Heuningnes	Reference
Baviaans			
Heuningnes	0.74		
Reference	1.57	2.11	

Table 5.9 F values for F-tests on channel depths

Depth	Baviaans	Heuningnes	Reference
Baviaans			
Heuningnes	2.05		
Reference	4.57	2.23	

Table 5.10 F values for F-tests on channel form ratios

Form ratio	Baviaans	Heuningnes	Reference
Baviaans			
Heuningnes	1.84		
Reference	8.80	4.77	

Table 5.11 F values for F-tests on channel cross-sectional areas

Cross-sectional area	Baviaans	Heuningnes	Reference
Baviaans			
Heuningnes	1.99		
Reference	6.07	3.05	

For all four channel form variables, Baviaans and Heuningnes exhibit more similar variances in comparison to the Reference. That is, the Reference has much higher f-values indicating that it is uniquely different in comparison to the two invaded reaches. Thus, the following hypothesis may be posed: There is no significant difference between the four channel form variables for the Baviaans and Heuningnes invaded reaches.

5.6.2 Correlation matrices

For figures 5.10 – 5.13, strong relationships are highlighted on the matrices in red and moderate relationships in orange. All highlighted correlations are statistically significant at 0.05 level of significance. Correlation matrices were conducted using Microsoft Excel. Appendix E shows all the correlation coefficient calculations in detail.

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Correlation matrix for Baviaans	Drainage Area (km²)	Reach gradient	Site gradient	Local gradient	Ave. % silt/clay in bank material	Ave. bank gradient	Ave. % organic content in bank material	Bank shear strength (Kpa)	Bankfull discharge (m³/sec)	Ave. Width (m)	Ave. Depth (m)	Ave. cross-sectional area (m²)	Ave. Form ratio	Bed % silt/sand	Bed % gravel	Bed % cobble	Bed % boulder	Bed % Bedrock	D50 (median) bank particle
2	Drainage Area (km²)	1.00																		
3	Reach gradient	0.00	1.00																	
4	Site gradient	-0.06	0.00	1.00																
5	Local gradient	-0.74	0.00	-0.03	1.00															
6	Ave. % silt/clay in bank material	0.76	0.00	-0.53	-0.18	1.00														
7	Ave. bank gradient	-0.86	0.00	0.17	0.55	-0.71	1.00													
8	Ave. % organic content in bank material	0.37	0.00	-0.21	0.01	0.82	-0.45	1.00												
9	Bank shear strength (Kpa)	0.02	0.00	0.00	-0.55	-0.22	0.03	-0.25	1.00											
10	Bankfull discharge (m³/sec)	-0.71	0.00	0.46	0.40	-0.73	0.67	-0.49	-0.04	1.00										
11	Ave. Width (m)	-0.01	0.00	0.53	-0.25	-0.68	-0.14	-0.43	0.24	0.10	1.00									
12	Ave. Depth (m)	-0.80	0.00	0.28	0.46	-0.86	0.84	-0.79	0.18	0.59	0.34	1.00								
13	Ave. cross-sectional area (m²)	-0.71	0.00	0.31	0.36	-0.85	0.71	-0.71	0.24	0.48	0.51	0.98	1.00							
14	Ave. Form ratio	0.75	0.00	0.14	-0.63	0.55	-0.82	0.39	0.27	-0.42	0.36	0.64	-0.52	1.00						
15	Bed % silt/sand	0.78	0.00	-0.22	-0.28	0.85	-0.67	0.54	-0.22	-0.55	-0.29	-0.75	-0.72	0.65	1.00					
16	Bed % gravel	-0.05	0.00	-0.40	0.06	-0.06	-0.29	0.04	-0.11	-0.36	0.19	-0.08	0.00	-0.12	-0.34	1.00				
17	Bed % cobble	-0.64	0.00	0.37	0.12	-0.63	0.75	-0.39	0.30	0.65	-0.03	0.57	0.45	-0.56	-0.77	-0.19	1.00			
18	Bed % boulder	-0.83	0.00	0.24	0.34	-0.82	0.62	-0.65	0.21	0.47	0.48	0.91	0.95	-0.47	-0.64	-0.06	0.34	1.00		
19	Bed % Bedrock	-0.56	0.00	0.42	0.14	-0.48	0.54	-0.24	0.00	0.88	-0.03	0.29	0.17	-0.26	-0.42	-0.40	0.71	0.11	1.00	
20	D50 (median) bank particle	-0.83	0.00	0.72	0.42	-0.94	0.81	-0.73	0.02	0.80	0.56	0.89	0.85	0.61	-0.77	-0.11	0.64	0.84	0.52	1.00
21																				

Figure 5.10 Correlation matrix of Baviaans variables

Correlation matrix for Heuningnes	Drainage Area (km²)	Reach gradient	Site gradient	Local gradient	Ave. % silt/clay in bank material	Ave. bank gradient	Ave. % organic content in bank material	Bank shear strength (Kpa)	Bankfull discharge (m³/sec)	Ave. Width (m)	Ave. Depth (m)	Ave. cross-sectional area (m²)	Ave. Form ratio	Bed % silt/sand	Bed % gravel	Bed % cobble	Bed % boulder	Bed % Bedrock	D50 (median) bank particle
Drainage Area (km²)	1.00																		
Reach gradient	0.00	1.00																	
Site gradient	-0.32	#DIV/0!	1.00																
Local gradient	0.87	0.00	[illegible]	1.00															
Ave. % silt/clay in bank material	-0.49	0.00	0.07	-0.23	1.00														
Ave. bank gradient	-0.06	0.00	0.49	-0.02	0.06	1.00													
Ave. % organic content in bank material	-0.45	0.00	-0.16	-0.27	[illegible]	-0.35	1.00												
Bank shear strength (Kpa)	-0.10	0.00	0.32	-0.01	-0.08	0.48	-0.27	1.00											
Bankfull discharge (m³/sec)	0.34	0.00	0.49	0.22	-0.20	0.24	-0.18	0.42	1.00										
Ave. Width (m)	0.04	0.00	-0.28	0.19	-0.26	[illegible]	0.00	-0.03	0.19	1.00									
Ave. Depth (m)	-0.22	0.00	[illegible]	-0.14	-0.34	[illegible]	[illegible]	[illegible]	0.23	-0.18	1.00								
Ave. cross-sectional area (m²)	-0.27	0.00	0.30	-0.06	-0.18	[illegible]	-0.42	[illegible]	0.02	0.25	[illegible]	1.00							
Ave. Form ratio	-0.04	0.00	-0.46	0.00	0.09	[illegible]	[illegible]	-0.37	-0.29	[illegible]	[illegible]	-0.48	1.00						
Bed % silt/sand	-0.40	0.00	-0.23	-0.36	[illegible]	-0.40	0.49	[illegible]	[illegible]	0.04	[illegible]	-0.35	0.39	1.00					
Bed % gravel	0.35	0.00	0.12	0.36	-0.28	0.14	-0.41	[illegible]	[illegible]	0.25	0.25	0.35	-0.10	[illegible]	1.00				
Bed % cobble	0.19	0.00	0.19	0.10	[illegible]	0.40	-0.29	0.21	[illegible]	-0.25	[illegible]	0.21	-0.42	[illegible]	0.16	1.00			
Bed % boulder	0.30	0.00	0.32	0.07	-0.38	0.37	-0.24	-0.27	0.27	-0.34	0.24	-0.03	-0.40	-0.38	-0.28	[illegible]	1.00		
Bed % Bedrock	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	1.00	
D50 (median) bank particle	[illegible]	0.00	-0.19	0.33	-0.98	0.26	[illegible]	0.00	0.10	0.00	0.47	0.26	-0.38	[illegible]	0.14	[illegible]	[illegible]	#DIV/0!	1.00

Figure 5.11 Correlation matrix of Heuningnes variables (The error messages are the result of no bedrock within the reach)

Correlation matrix for Reference	Drainage Area (km²)	Reach gradient	Site gradient	Local gradient	Ave. % silt/clay in bank material	Ave. bank gradient	Ave. % organic content in bank material	Bank shear strength (Kpa)	Bankfull discharge (m³/sec)	Ave. Width (m)	Ave. Depth (m)	Ave. cross-sectional area (m²)	Ave. Form ratio	Bed % silt/sand	Bed % gravel	Bed % cobble	Bed % boulder	Bed % Bedrock	D50 (median) bank particle
Drainage Area (km²)	1.00																		
Reach gradient	0.00	1.00																	
Site gradient	0.09	0.00	1.00																
Local gradient	[illegible]	0.00	0.00	1.00															
Ave. % silt/clay in bank material	[illegible]	0.00	-0.31	[illegible]	1.00														
Ave. bank gradient	[illegible]	0.00	-0.17	[illegible]	[illegible]	1.00													
Ave. % organic content in bank material	0.12	0.00	[illegible]	-0.03	[illegible]	-0.02	1.00												
Bank shear strength (Kpa)	[illegible]	0.00	[illegible]	[illegible]	0.24	[illegible]	-0.26	1.00											
Bankfull discharge (m³/sec)	0.09	0.00	-0.15	-0.20	-0.27	0.16	-0.36	-0.04	1.00										
Ave. Width (m)	0.38	0.00	0.18	[illegible]	0.14	-0.18	0.04	0.02	0.25	1.00									
Ave. Depth (m)	-0.10	0.00	-0.06	-0.18	-0.39	0.28	-0.29	-0.27	[illegible]	[illegible]	1.00								
Ave. cross-sectional area (m²)	0.08	0.00	0.01	-0.35	-0.20	0.10	-0.17	-0.21	[illegible]	[illegible]	[illegible]	1.00							
Ave. Form ratio	[illegible]	0.00	0.08	[illegible]	[illegible]	[illegible]	0.44	0.41	-0.37	0.49	-0.34	0.05	1.00						
Bed % silt/sand	[illegible]	0.00	-0.32	[illegible]	0.11	0.49	0.46	-0.49	-0.37	[illegible]	-0.19	[illegible]	-0.32	1.00					
Bed % gravel	[illegible]	0.00	0.05	[illegible]	0.27	[illegible]	-0.12	[illegible]	0.11	0.29	0.05	0.13	0.38	[illegible]	1.00				
Bed % cobble	0.39	0.00	0.40	[illegible]	0.18	[illegible]	-0.24	[illegible]	-0.05	0.23	-0.20	-0.03	[illegible]	[illegible]	0.44	1.00			
Bed % boulder	0.17	0.00	0.28	-0.36	-0.44	0.08	[illegible]	-0.04	0.49	[illegible]	[illegible]	[illegible]	-0.02	[illegible]	0.21	0.07	1.00		
Bed % Bedrock	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	1.00	
D50 (median) bank particle	0.03	0.00	[illegible]	-0.05	[illegible]	-0.15	[illegible]	0.49	0.16	-0.18	0.08	-0.05	-0.34	-0.49	0.43	0.25	0.33	#DIV/0!	1.00

Figure 5.12 Correlation matrix of Refereuce variables (The error messages are the result of no bedrock within the reach)

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T
1	Correlation matrix for all reaches	Drainage Area (km²)	Reach gradient	Site gradient	Local gradient	Ave. % silt/clay in bank material	Ave. bank gradient	Ave. % organic content in bank material	Bank shear strength (Kpa)	Bankfull discharge (m³/sec)	Ave. Width (m)	Ave. Depth (m)	Ave. cross-sectional area (m²)	Ave. Form ratio	Bed % silt/sand	Bed % gravel	Bed % cobble	Bed % boulder	Bed % Bedrock	D50 (median) bank particle
2	Drainage Area (km²)	1.00																		
3	Reach gradient	[illegible]	1.00																	
4	Site gradient	-0.06	-0.06	1.00																
5	Local gradient	-0.27	0.22	-0.07	1.00															
6	Ave. % silt/clay in bank material	-0.30	[illegible]	-0.21	-0.06	1.00														
7	Ave. bank gradient	-0.37	0.07	0.18	[illegible]	-0.21	1.00													
8	Ave. % organic content in bank material	-0.32	0.22	-0.29	0.03	[illegible]	-0.16	1.00												
9	Bank shear strength (Kpa)	0.17	-0.41	0.28	-0.47	-0.30	-0.04	-0.20	1.00											
10	Bankfull discharge (m³/sec)	-0.25	0.27	0.22	0.15	-0.12	0.44	-0.25	-0.08	1.00										
11	Ave. Width (m)	0.31	-0.03	0.04	-0.29	-0.11	-0.36	-0.21	-0.13	0.06	1.00									
12	Ave. Depth (m)	-0.30	0.22	0.21	0.23	-0.20	[illegible]	-0.38	-0.04	[illegible]	0.22	1.00								
13	Ave. cross-sectional area (m²)	-0.17	0.17	0.19	0.13	-0.15	[illegible]	-0.38	-0.06	0.41	[illegible]	0.93	1.00							
14	Ave. Form ratio	0.29	-0.07	-0.14	-0.28	0.22	-0.83	0.26	-0.00	-0.31	[illegible]	[illegible]	-0.35	1.00						
15	Bed % silt/sand	0.30	-0.41	-0.19	0.02	0.15	-0.37	0.31	-0.14	[illegible]	-0.20	[illegible]	[illegible]	0.41	1.00					
16	Bed % gravel	-0.06	0.39	-0.09	-0.08	0.19	-0.22	-0.10	0.07	0.07	0.27	0.13	0.21	-0.02	[illegible]	1.00				
17	Bed % cobble	-0.19	0.20	0.24	0.01	-0.19	[illegible]	-0.21	0.14	[illegible]	-0.05	[illegible]	0.39	-0.42	[illegible]	0.09	1.00			
18	Bed % boulder	-0.31	0.11	0.24	0.01	-0.36	0.43	-0.31	0.10	0.43	0.13	[illegible]	[illegible]	-0.36	[illegible]	-0.03	0.24	1.00		
19	Bed % Bedrock	-0.27	0.28	0.19	0.14	0.01	0.39	-0.05	-0.15	[illegible]	0.03	0.30	0.21	-0.16	-0.39	-0.11	[illegible]	0.06	1.00	
20	D50 (median) bank particle	0.31	-0.48	0.23	-0.03	-0.89	0.23	[illegible]	0.42	0.09	-0.04	0.20	0.12	-0.33	-0.22	-0.14	0.27	0.36	-0.01	1.00

Figure 5.13 Correlation matrix of all 3 study reach variables

Baviaans

Of the three reaches, Baviaans clearly exhibits the most numerous significant relationships. Bank silt/clay content, the bank median size particle and the influence of boulders in the channel bed are the three control variables which are most strongly correlated to channel form. The Baviaans' deeper and larger channels have a clear and significant association with: reduced amounts of silt/clay in the banks; larger bank median size particles; lower bank organic content; and less silt/sand and more cobbles and boulders in the channel bed. Furthermore, larger channel form ratios are associated with lower bank gradients, smaller bank median size particles and more silt/sand in the bed. This explanation seems to match the differences between the three uppermost sites and all the other sites. These upper Baviaans sites are possibly located on an alluvial fan that is deposited at the point where the channel gradient becomes less steep and the valley floor widens. This would help to explain the upper Baviaans sites with their deeper channels that incise into deeper sediments and also the coarser bed and bank material. However, this is not to imply that the geomorphic setting of these upper sites is so different from the other sites as to negate the experimental design. Baviaans correlations show that increases in cross-sectional area are largely the result of increases in depth, rather than width, and that the form ratio is also more closely related to depth than width.

An examination of the bed material variables shows the following trend: a channel bed with larger amounts of silt/sand is associated with reduced bank gradients and a smaller bank median size particle. Conversely, a channel bed with more boulders is associated with increased bank gradients, less bank organic content and a larger bank median size particle. This trend re-emphasises the difference between the Baviaans' deeply incised upper sites and the rest.

Heuningnes

Heuningnes exhibits few significant relationships. Only bank shear strength and bank organic content stand out as controls with possible effects on channel morphology. It does however have a similar association to that of Baviaans, small as it may be, whereby deeper channels are associated with less silt/sand and more cobbles in the channel bed. Note the positive relationship between cross-sectional area and depth and the negative relationship between form ratio and bank gradient. The former is an indication of the manner in which deeper channels help to increase the channel's cross-sectional area while the latter shows how the wide channels of the Heuningnes (possibly due to a lengthy wattle invasion) are related to smaller bank gradients. The 'division' errors that occur for Bed % bedrock in the Heuningnes and Reference matrices are due to no bedrock being present at the study sites in these reaches.

A closer look at bank variables reveals a strong relationship where channels with larger form ratios exhibit lower bank gradients. This makes sense in the context of Heuningnes' much wider channels with their much reduced bank gradients. Heuningnes channels also seem to contain less silt/clay and organics in those banks where the bank median size particles are larger. This could possibly exacerbate erosion of the banks that are already affected by the wattle invasion. Note the strong relationship whereby banks with high shear strengths correlate to a larger amount of gravel in the channel bed.

Reference

In the Reference, there is a clear relation whereby larger channels are associated with more boulders and less silt/sand in the channel bed. Wider channels are also associated with less silt/sand and more boulders in the channel bed. This follows conventional theory. With regards to the banks, there is a clear trend whereby banks with increased amounts of silt/clay and a lower bank gradient correlate to channels with a higher form ratio. Furthermore, there is a strong trend whereby banks with higher amounts of clay also contain more organics and thus a smaller median size particle. It is this trend that could be resulting in the Reference reaches' high bank shear strengths. There is also a strong trend whereby channels with higher bank gradients exhibit lower bank shear strengths, smaller form ratios and reduced amounts of gravel and cobble in the channel bed.

Summary of correlations

The above relationships point to a clear trend across all three reaches where larger and deeper channels are associated with more cobble/boulder and less silt/sand in the channel beds. Also, Baviaans and the Reference share six relationships that exhibit the same trends with almost similar correlation coefficients. However, this Baviaans-Reference similarity (in reference to correlation ratios only) indicates that similar processes are occurring within the channels and that the presence of woody alien vegetation in the Baviaans may be the difference, acting as the impacting or disrupting factor and thus affecting channel form. By combining all the variables from all the sites in all three reaches into one overall matrix (Figure 5.13), the exact same relationships appear as those found in the Heuningnes. Although two further trends show how deeper channels have the steepest bank gradients and channels with large form ratios are associated with gentler bank gradients. i.e. large form ratios are associated with shallow channels with low gradient banks. Deeper channels also tend to be wider, but the correlation is low.

5.7 CHANNEL CONTROL VARIABLES

This section examines variables that control channel form other than vegetation. They have a large influence on the dynamic processes taking place at a given site and thus directly affect channel morphology. By studying and understanding these variables it is possible to understand or explain the channel form variables examined in Section 5.5.

5.7.1 Bank and terrace material

Bank material composition acts as one type of control on channel form and thus influences geomorphological processes within the channel. Finer bank material (especially silt and clay) should increase bank cohesion or strength (Gordon *et al.*, 2004). Figure 5.14 compares the study reaches and indicates the Heuningnes and Reference banks as being very similar while the banks of the Baviaans have a higher percentage of finer material. The banks of the Heuningnes and Reference exhibit the largest median size particles (Figure 5.15). All three study reaches exhibit a silt/clay (< 63μ) percentage ranging 11 – 21 % with the banks of Baviaans the highest and the terraces of the Reference the lowest.

Looking at the terraces, Heuningnes and Reference again follow a fairly similar pattern different to that of Baviaans with its higher percentage of finer material (in fact the highest percentage of finer material of all on average). Again, this similarity could be explained because of the proximity of the Reference to Heuningnes within the same catchment. Terrace material provides an understanding of the composition of the top of the banks and is important from the perspective of plant growth and therefore the associated rehabilitation efforts which entail the re-planting of indigenous vegetation along these terraces. Note that in all cases the terrace sediments are finer textured than the banks. The difference between bank median size particle and terrace median size particle is greatest for the Heuningnes.

Figure 5.16 shows the downstream trend in silt/clay percentage of bank material. Baviaans clearly has a higher amount of bank silt/clay content and is fairly consistent at each site. The Heuningnes and Reference exhibit differences in bank silt/clay content between their upper and lower study sites. Note that bank soil sampling was not done at site BV1.

The results clearly indicate the similarity between the Reference and Heuningnes, thus supporting the use of the upper Heuningnes as a reference site. Comparing the two invaded reaches, Baviaans has smaller bank particles and a higher percentage of silt/clay (see Figures 5.15 and 5.16). This will have an effect on bank cohesion and bank strength, especially considering the effect of alien wattles growing along the invaded channel banks. Appendix C provides all the data relating to bank and terrace material.

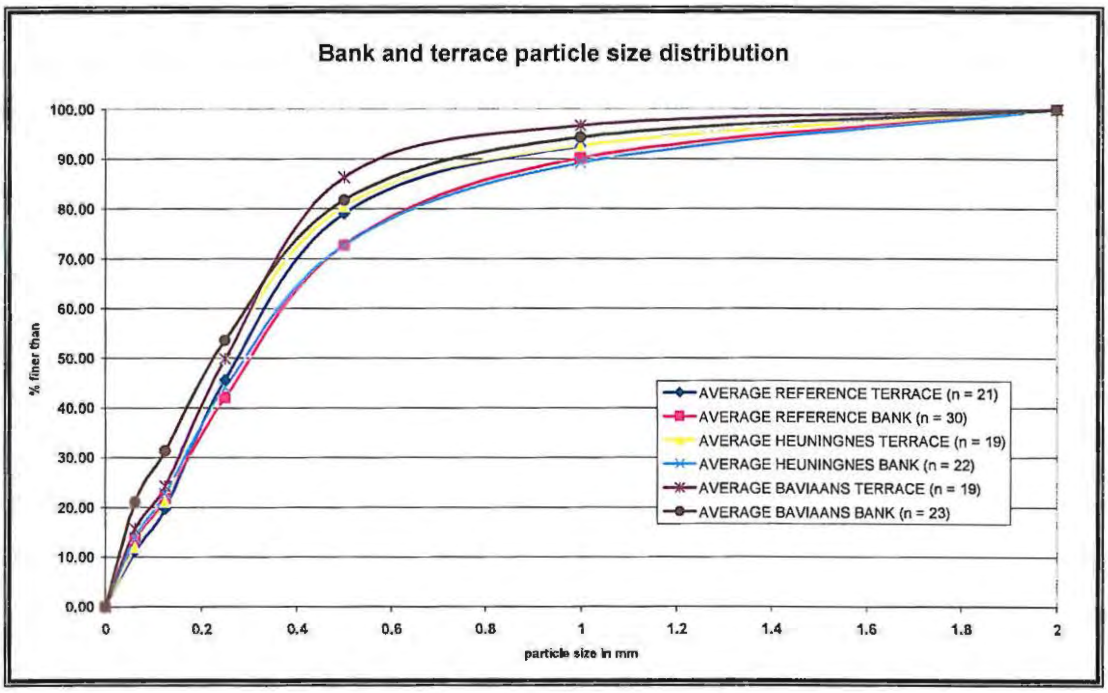

Figure 5.14 Bank and terrace particle size distribution

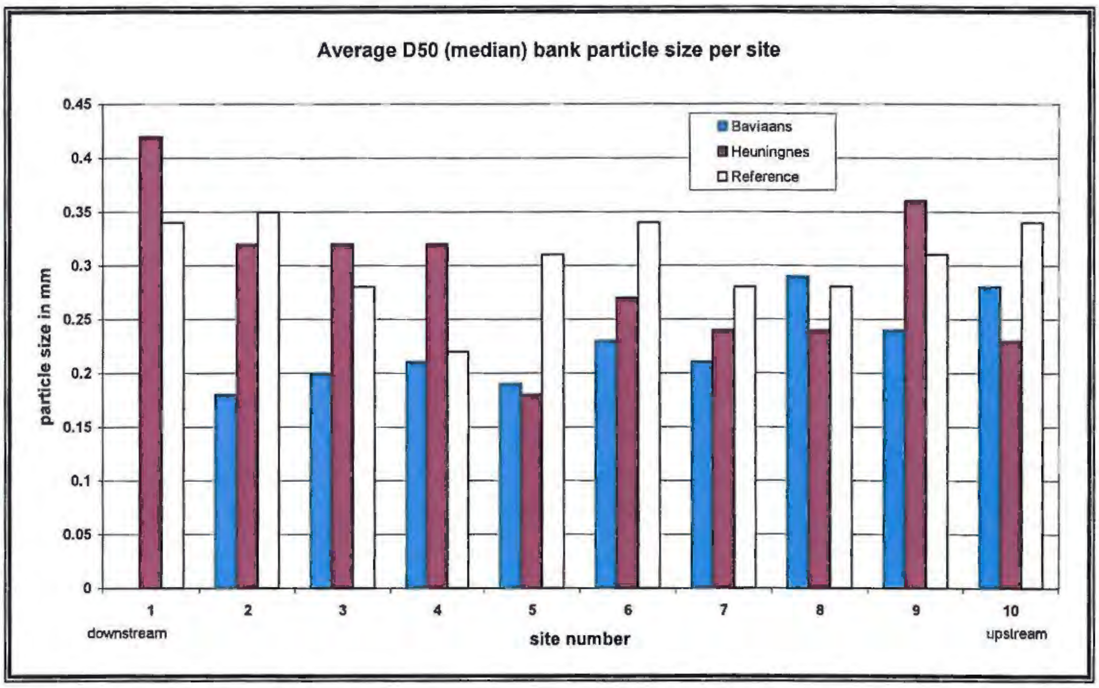

Figure 5.15 Average D50 (median) bank particle size per site

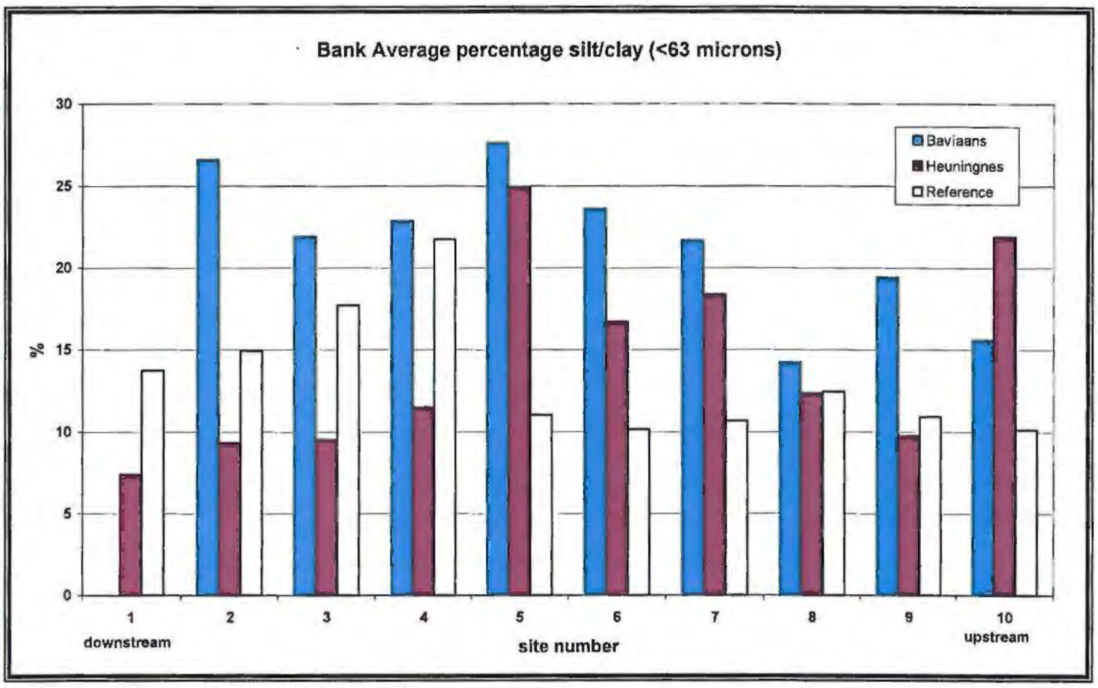

Figure 5.16 Average bank silt/clay content per site

5.7.2 Bank and terrace organic content

Soil organic matter (SOM) content in the banks and terraces acts to improve soil structure and is another factor relating to bank stability. While Tables 5.5 – 5.7 show the downstream trend in bank organic content at each site, Figure 5.17 compares the reaches with regards to organic content in the banks and terraces. Appendix D provides all the data relating to bank and terrace organic content.

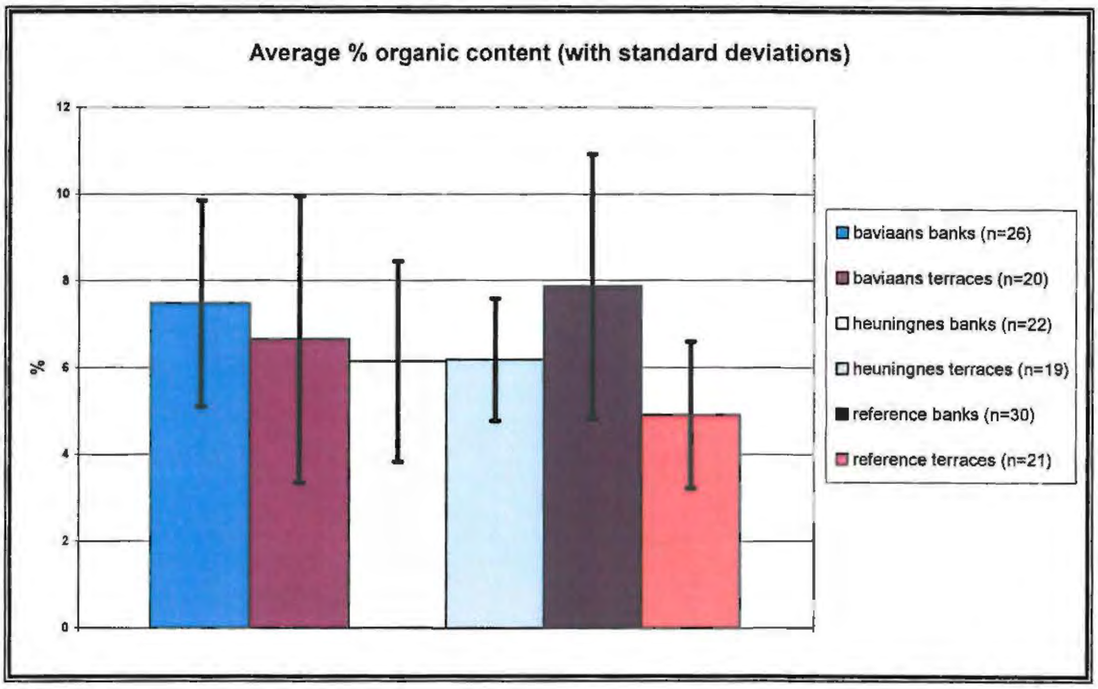

Figure 5.17 Bank and terrace organic content

Of the banks, Reference at 7.87% has the highest average organic content followed closely by Baviaans with 7.48%. Heuningnes bank organic content is significantly lower. Baviaans and Heuningnes terrace organic content are fairly similar but significantly higher than the Reference terraces. While Heuningnes banks and terraces contain virtually the same percentage of organic content, the Reference banks and terraces exhibit the greatest difference.

5.7.3 Bank shear strength

Figure 5.18 clearly indicates how the banks of the Reference have greater average shear strength in their upper and lower banks in comparison to the invaded reaches. There is however great variability in all three reaches. Baviaans is much lower than the other two reaches. This is an unexpected result, given the higher silt/clay content and organic content in its banks. Also note the Heuningnes whose upper and lower banks are the exact same on average. There is evidence from the literature that shear strength increases with the silt-clay ratio, but soil drainage may also be important.

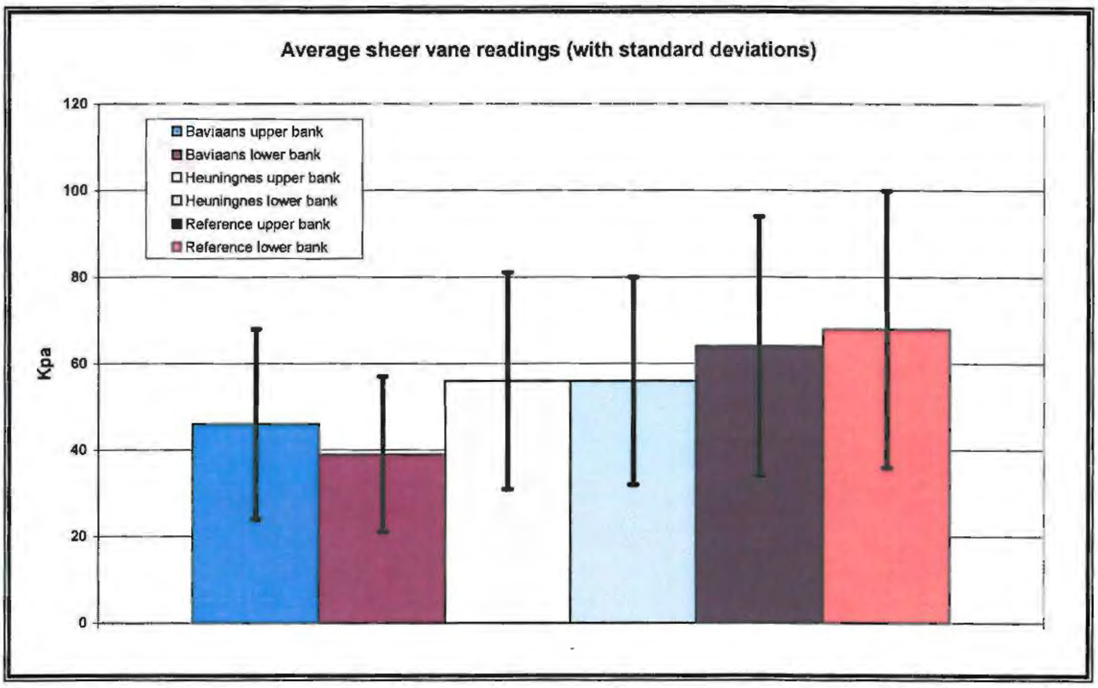

Figure 5.18 Bank shear vane readings

However, a significant point here is that the shear strength of the lower banks are not noticeably different from the upper banks in any of the three reaches, so this on its own should not lead to undercutting of the banks. The measurement of shear strength could possibly have been affected by fine roots in the soil. These fine roots may be important because it could explain the lack of a correlation with bank silt/clay content or with bank organic content. However, the lack of a significant relationship between shear strength and bank material, organic matter or bank gradient could therefore lead to the conclusion that shear strength as measured is not a controlling variable within each site.

5.8 CATCHMENT AREA AND BANKFULL DISCHARGE

5.8.1 Catchment area

Table 5.12 shows the correlation coefficients between site average channel form variables and the site catchment area (an approximate value adjusted from the known value for the uppermost site). Baviaans has the most numerous and strongest relationships. Since catchment area logically increases in a downstream direction, the relationships with depth, cross-sectional area and form ratio all correspond with what has already been discussed i.e. depth and cross-sectional area *decrease* while form ratio increases in a downstream direction. Since it is usual for depth and cross-sectional area to *increase* in a downstream direction, it suggests that catchment area as such is not affecting channel forming processes within the study reaches. Note that Baviaans and Heuningnes are similar in that their median size bank particles decrease with catchment area downstream. This is as expected.

Table 5.12 Correlation coefficients for catchment size and channel form variables (including D50)

	Baviaans	Heuningnes	Reference
Width			
Depth	-0.805		
Cross-sectional area	-0.711		
Form ratio	0.748		0.666
D50 (bank)	-0.831	-0.510	

5.8.2 Bankfull discharge

Using one of the five transects as a clearly defined and representative cross-section from each site, the bankfull discharge was then calculated using the slope-area method (Appendix A shows all the calculations for bankfull discharge). As has already been mentioned, results from the use of the slope-area method should be used with caution. Actual readings during times of high flow would be much more valuable. Figure 5.19 shows the downstream trends in all three study reaches. Heuningnes and Reference exhibit slight trends in bankfull discharge increasing downstream while Baviaans clearly decreases downstream. The extremes at BV8 and BV10 are almost certainly due to the larger cross-sectional areas of these severely incised channels. This is probably what is also happening with the extreme discharge at REF5.

By excluding these three extreme outliers, the average bankfull discharge for the study reaches is calculated as $0.82m^3 s^{-1}$ for Baviaans and $0.62m^3 s^{-1}$ for both Heuningnes and the Reference. Given the wide margin of error, channel forming discharge does not seem to increase significantly downstream and there are minimal differences between reaches. It can be therefore be concluded that discharge be excluded as a control variable that might explain differences in channel form between sites.

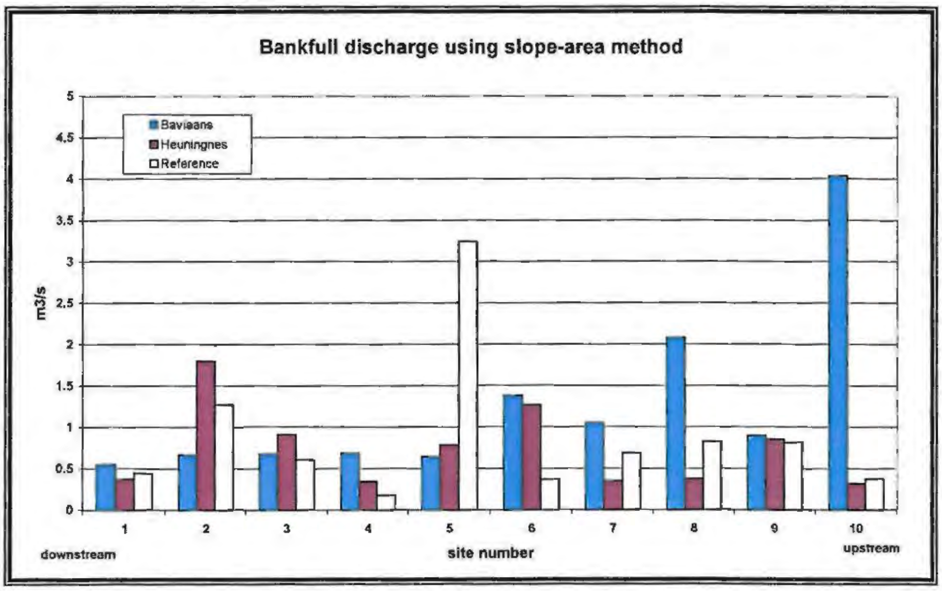

Figure 5.19 Bankfull discharge for the study sites

5.9 STATISTICAL ANALYSIS

Further statistical analyses were conducted on the large amount of available data so as to confirm apparent relationships, associations or differences between the three study reaches. First, a principal component analysis (PCA) was done in Statistica using all of the available data collected. PCAs condense the information contained within the data into indices and are used to analyse total variance (Gordon *et al.*, 2004). A discriminant analysis was then also done in Statistica to predict membership in groups based on all of the available data.

5.9.1 Principal components analysis (PCA)

PCAs reduce a large amount of variables into a smaller number of components (or factors) (Gordon *et al.*, 2004). Table 5.13 shows the six factors that resulted from this PCA. The visual outcome of a PCA is Figure 5.20 which plots two axes representing a pair of factors. Factors are scrutinised to reveal their underlying principle i.e. what they signify or relate to. In this PCA, the data from all variables for all three study reaches were used (except for vegetation description which was not numerical). The result was six possible factors with Factor 1 and Factor 2 accounting for almost half (48.5%) of the variation in the data.

With strong correlations to channel depth, channel cross-sectional area, bed material and bankfull discharge, it seems as though Factor 1 relates to channel form. With Factor 2, the variables relating to the channel banks seem to take precedence i.e. bank clay content, bank organic content and bank median size particle. Thus, it seems that Factor 2 relates to bank strength. When plotting all the study sites relative to these two factors there are no absolute clear trends or groupings.

Table 5.13 The six components or factors (strong correlations in bold)

Factor coordinates of the variables, based on correlations

	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Factor 6
Area (km^2)	0.376	**0.661**	0.311	-0.062	0.200	-0.298
Reach gradient	-0.387	**-0.802**	0.048	0.087	-0.141	-0.034
Site gradient	-0.378	0.301	-0.240	0.269	0.149	**0.470**
Local gradient	-0.207	-0.335	-0.495	**-0.571**	-0.064	-0.239
Ave. % silt/clay in bank material	0.290	**-0.805**	0.246	0.209	-0.018	0.161
Ave. % organic content in bank material	0.460	**-0.627**	-0.047	0.165	0.042	0.222
Bank shear strength (Kpa)	-0.008	0.555	0.038	**0.658**	-0.248	0.205
Bankfull discharge ($m^3 s^{-1}$)	**-0.726**	-0.114	-0.048	0.083	0.397	-0.087
Ave. Width (m)	-0.188	0.216	**0.834**	-0.292	0.268	0.065
Ave. Depth (m)	**-0.889**	-0.067	0.135	-0.272	-0.069	0.168
Ave. cross-sectional area (m^2)	**-0.770**	0.008	0.379	-0.348	-0.045	0.217
Ave. Form ratio	0.590	0.027	0.532	0.026	0.379	0.087
Bed %silt/sand	**0.863**	0.069	-0.236	-0.283	0.182	0.174
Bed % gravel	-0.282	-0.177	0.510	0.239	-0.531	-0.442
Bed % cobble	**-0.717**	-0.081	-0.078	0.406	0.266	-0.218
Bed % boulder	**-0.687**	0.204	0.010	-0.139	-0.184	0.426
Bed % Bedrock	-0.516	-0.238	-0.156	0.220	**0.687**	-0.187
D50 (median) bank particle	-0.313	**0.803**	-0.307	-0.031	-0.092	-0.190

Closer analysis reveals most of the Baviaans sites are located in the bottom left quadrant, most of the Heuningnes sites in the top right quadrant and Reference sites spread over three quadrants. It seems the Heuningnes and Reference sites are closer in terms of their location on the PCA and are thus more similar in comparison to the Baviaans. The reason for this could possibly be due to their proximity as reaches within the same catchment.

The results from this PCA alone are not definitive. It is important to re-emphasise that vegetation data were not used in this analysis although it can probably be assumed that vegetation is consistent within each group. More precise vegetation data in a numerical format that could also be used in the PCA could change the outcome of these results. However, in the context of these two factors (bearing in mind that they only account for half the variation in the data), the explanation of Factor 1 as channel form and Factor 2 as bank strength seems plausible.

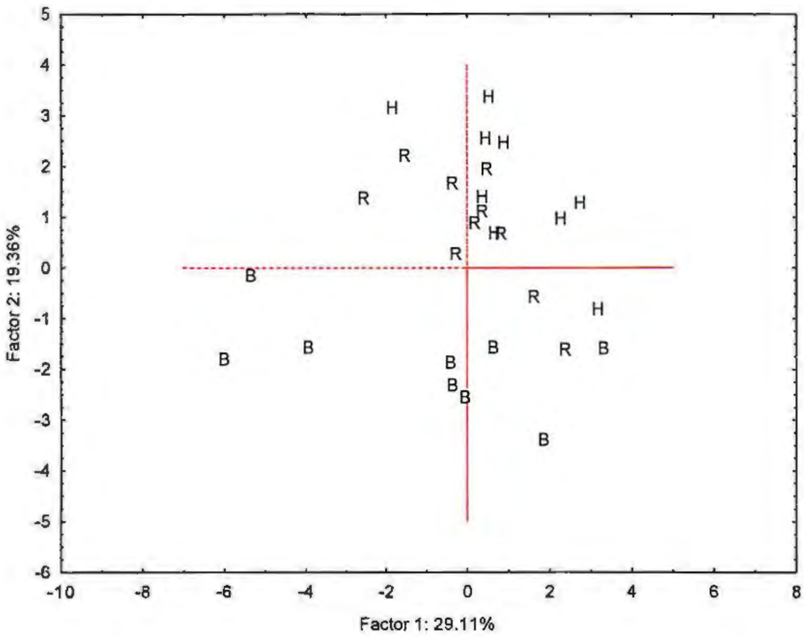

Figure 5.20 The principal components analysis plotting the two strongest factors
(B = Baviaans, H = Heuningnes, R = Reference)

5.9.2 Discriminant function analysis

Another statistical analysis performed on the data was a Stepwise Discriminant Analysis (SDA). This is used so as to establish which variables discriminate between two or more naturally occurring groups i.e. it predicts membership of a group based on a set of independent variables (Gordon *et al.*, 2004). The same variables that were used in the PCA were used for the SDA. With a SDA, some variables are discarded and not used in the model. Those variables that were used in the model are found in Table 5.14. These are called the discriminant functions. These discriminant functions produce a 'score' which helps to separate or differentiate the study sites into separate groups. Several discriminant functions may be required to separate groups reliably.

Table 5.14 The variables that entered the model

Discriminant Function Analysis Summary N of vars in model: 11; **Wilks' Lambda: .00340 approx. F (22,30)=22.033 p< 0.0001**						
	Wilks' - Lambda	**Partial - Lambda**	**F-remove - (2,15)**	**p-level**	**Toler.**	**1-Toler. - (R-Sqr.)**
Area (km²)	0.0132	0.2564	21.7468	**0.0000**	0.3994	0.6006
D50 (median) bank particle	0.0037	0.9176	0.6734	0.5247	0.1814	0.8186
Ave. % organic content in bank material	0.0126	0.2705	20.2253	**0.0001**	0.1256	0.8744
Ave. % silt/clay in bank material	0.0094	0.3603	13.3160	**0.0005**	0.0954	0.9046
Bank shear strength (Kpa)	0.0220	0.1542	41.1268	**0.0000**	0.1344	0.8656
Bed %silt/sand	0.0121	0.2805	19.2363	**0.0001**	0.1357	0.8643
Ave. cross-sectional area (m²)	0.0075	0.4547	8.9961	**0.0027**	0.0677	0.9323
Bed % boulder	0.0126	0.2704	20.2415	**0.0001**	0.1260	0.8740
Ave. Form ratio	0.0074	0.4620	8.7333	**0.0031**	0.0799	0.9201
Site gradient	0.0052	0.6583	3.8930	**0.0435**	0.4813	0.5187
Ave. Width (m)	0.0043	0.7943	1.9427	0.1777	0.1125	0.8875

SDA is so-named due to the stepwise fashion in which each variable (or predictor) is entered into the model and its contribution to prediction of a group membership is assessed (Gordon *et al.*, 2004). This stepwise procedure is led by each predictor's F-value which is an indication of the predictor's statistical significance in predicting membership to a given group. Table 5.14 shows bank shear strength (41.13) as having the highest F-value. However, it is the predictors with the highest regression coefficient (or R-sqr.) values that contribute most to prediction of group membership. Table 5.14 shows channel cross-sectional area (0.932), channel form ratio (0.920) and bank silt/clay content (0.905) with the three largest regression coefficient values.

The visual outcome of the SDA can be seen in Figure 5.21 which plots the 'scores' of the discriminant functions that contributed most to prediction of group membership. If a large and noticeable distance exists between groups along an axis, then the discriminant function is effective in separating them (Gordon *et al.*, 2004). Figure 5.21 shows all three study reaches as separate groups with the Reference as a unique cluster separate from the two invaded reaches. However, it is only with Root 1 where a large distance exists along the axis between the groups. Here, the Reference is clearly a distant and separate group in comparison to the Baviaans and Heuningnes groups. With Root 2, the groups are much closer along the axis with the Reference group in the middle of the two invaded groups. It thus seems plausible that the primary question of the discriminant function analysis can be answered i.e. group membership can be reliably predicted based on the discriminant function represented by Root 1 in Figure 5.21.

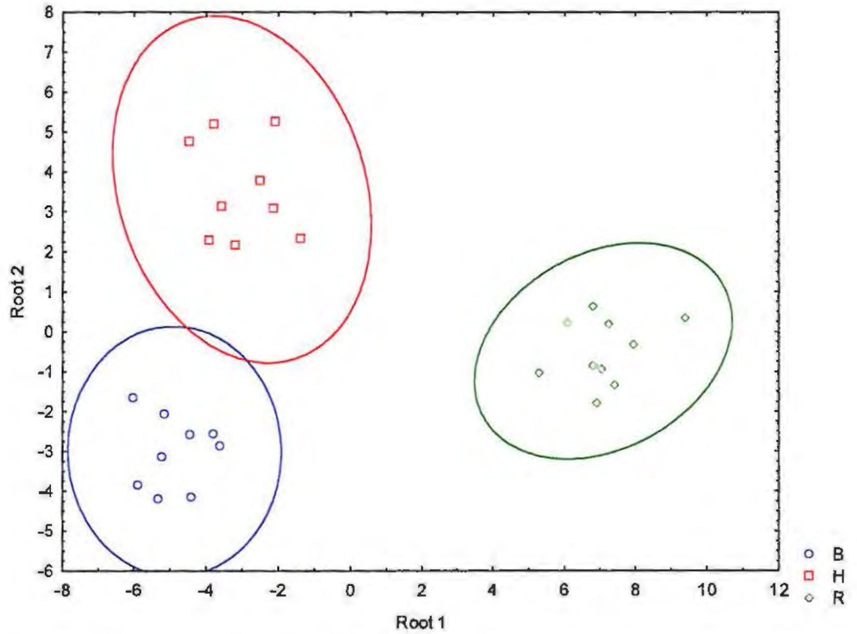

Figure 5.21 The stepwise discriminant analysis
(B = Baviaans, H = Heuningnes, R = Reference)

The statistical analysis in this section (which is based on all the measured data) serves more to emphasise the occurrence of three distinctive study reaches than to explain precise environmental processes. It has shown (as have the results in preceding sections) that the data clearly reveals three study reaches based on the many variables measured.

5.10 CHANGES TO CHANNEL FORM WITHIN THE STUDY PERIOD

This section shows the results of the short-term (<2yrs) monitoring of channel morphology i.e. a comparison of possible changes within the study period. The three study reaches were surveyed both pre- and post- black wattle clearance from the

Baviaans River (see Plate 9). The following section compares the follow-up channel surveys to the surveys conducted prior to clearance and the section thereafter compares any changes in bed material between the two surveys.

Plate 9 Lower Baviaans sites post wattle clearance

5.10.1 Follow-up channel surveys

The initial channel surveys of the three study reaches were conducted in June (Baviaans), September (Heuningnes) and November (Reference) of 2007. Follow-up surveys were carried out for all three study reaches at the same time in May 2008. The result was a period of 11 months (Baviaans), 8 months (Heuningnes) and 6 months (Reference) between the initial and follow-up surveys. Figure 4.13 shows that the rainfall at the study sites for the second half of 2007 was normal to well below average except for December which was 60mm above average. Logically, this seems the only period when a significant flow event could have taken place. However, it should be re-emphasised that this rainfall data was recorded at Onverwacht farm approximately 11km to the south-east of the study sites. Rainfall in this region can be highly sporadic and localised. The first quarter of 2008 saw normal rainfall conditions again but from April onwards it started becoming drier. There was therefore little fluvial activity during this period.

A major problem with the follow-up surveys in the Baviaans River was locating both metal pegs on either bank. After cutting alien trees, the WfW workers stacked them along the banks and often on top of the metal transect pegs, despite these having been clearly marked. This created problems at some sites during the follow-up surveys because only one bank's pegs could be located and thus a perfect follow-up transect (i.e. peg to peg) could not be carried out. Nonetheless, a similar follow-up transect was still possible (i.e. peg to opposite bank, perpendicular to the flow of the river). However, the results shown in this section are based only on those sites and transects where accurate follow-ups could be conducted, that is peg to peg. Furthermore, during WfW wattle clearance, some pegs seem to have been relocated or disrupted by clearing teams. For example, site BV1 was completely ruined by WfW workers due to their tents and accommodation being set up on top of the study site prior to the commencement of wattle clearing.

Vegetation changes in the Reference and Heuningnes reaches over this period were minimal. The Baviaans was the only reach to have major changes to vegetation. Besides the clearing of the wattle itself, there was a notable return of some grasses growing within the Baviaans channels. A significant amount of wattle re-growth also took place over this period although this was more confined to the upper terraces and valley slopes. This period also saw the start of rehabilitation efforts whereby indigenous vegetation was planted at strategic places along the riparian zone. Sites BV1 – BV4 saw cleared wattle put through a chipper as opposed to sites BV5 – BV10 which had their cleared wattles stacked on the upper river banks and terraces. This could have possible repercussions for future long-term monitoring or rehabilitation efforts. Furthermore, a long-term comparison is possible of sites that were chipped with sites that were stacked.

Figures 5.22 – 5.30 are a selection of various transects from all three study reaches. The same scale is used throughout. The *initial* transects are in blue with the post wattle clearing *follow-up* transects in pink. They illustrate that channel form has seen almost no change in all study reaches within the study period. Even the follow-up transects that did not follow the initial line exactly (therefore they were measured peg to opposite bank) indicated that the channel forms for all three study areas have changed little over this extremely short time period. There was insufficient time following the wattle clearance, without any significant storm events, for any adjustment to have occurred. Continued monitoring over a longer time scale is required. Although the follow-up transect data reveals little change in channel form, some initial bank slumping was noted for the severely incised upper Baviaans sites. See Appendix A for all data relating to follow-up transects.

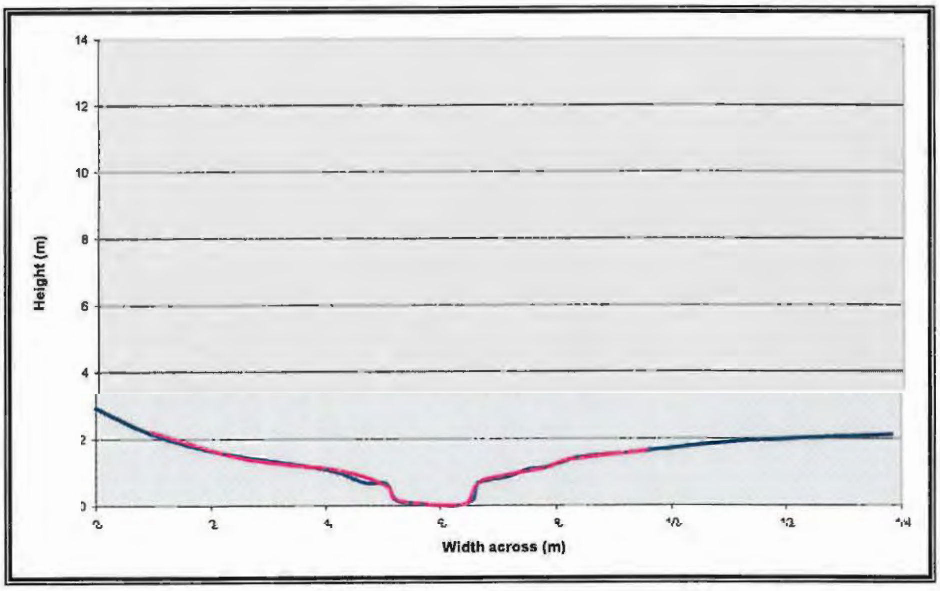

Figure 5.22 Transect BV3.1 (initial survey in blue, follow-up survey in pink)

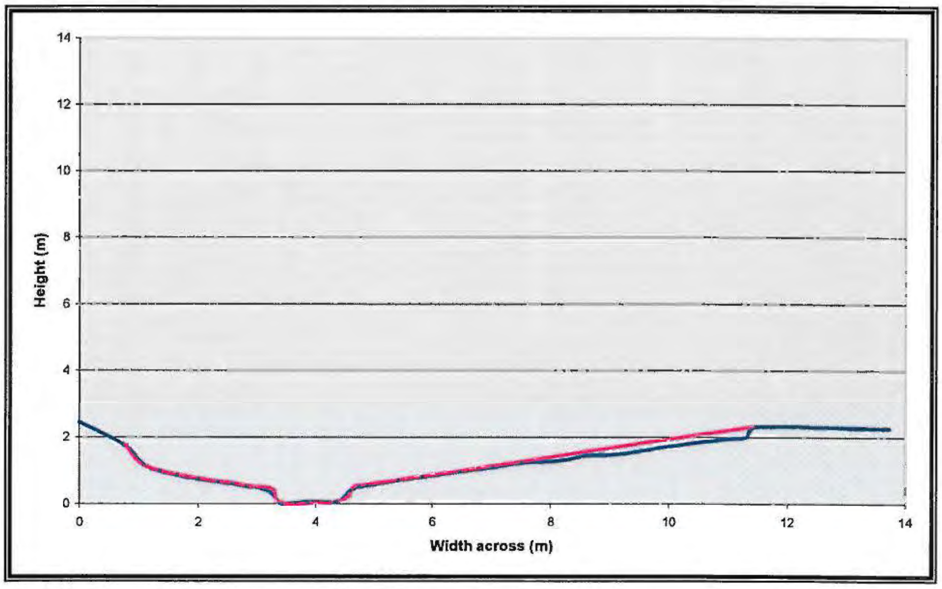

Figure 5.23 Transect BV4.2 (initial survey in blue, follow-up survey in pink)

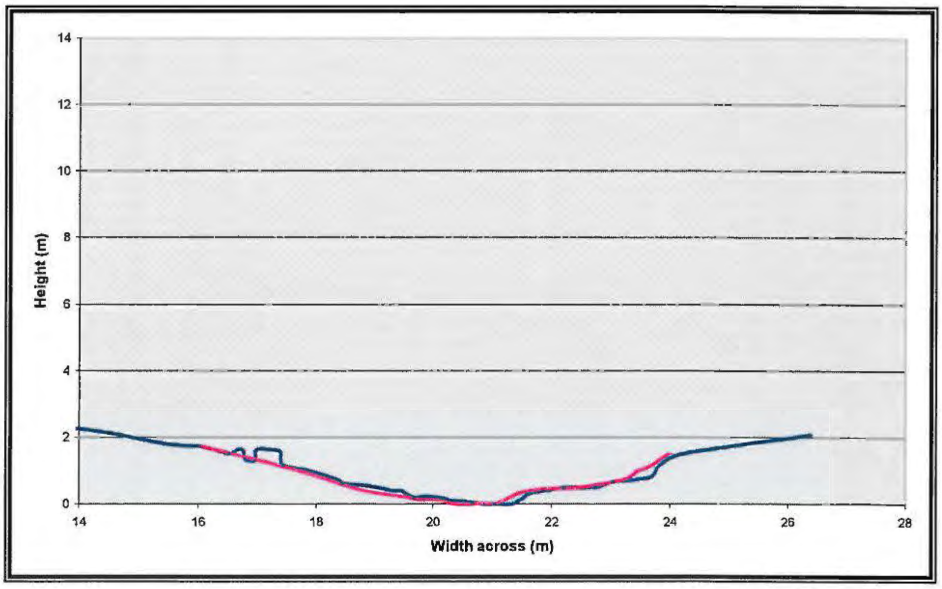

Figure 5.24 Transect BV 7.3 (initial survey in blue, follow-up survey in pink)

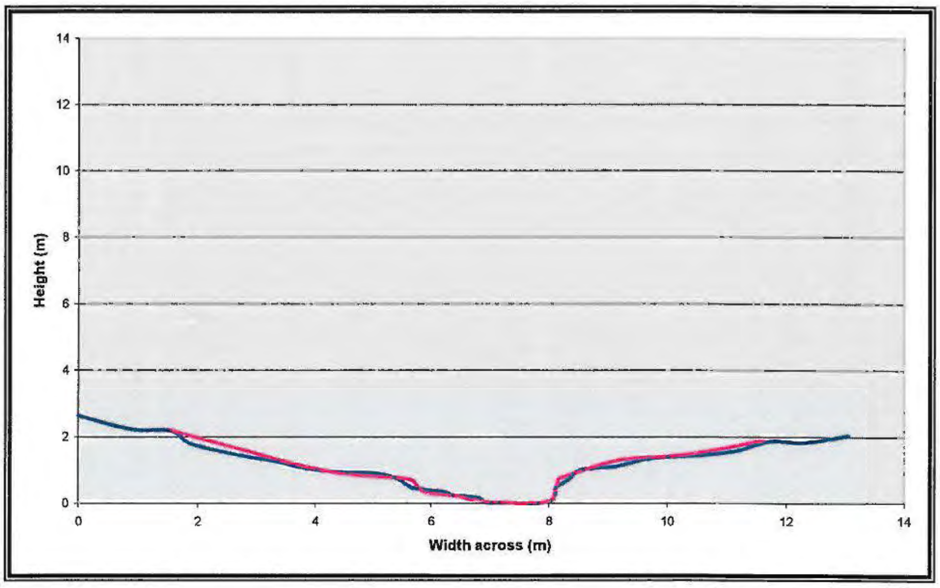

Figure 5.25 Transect HE 3.3 (initial survey in blue, follow-up survey in pink)

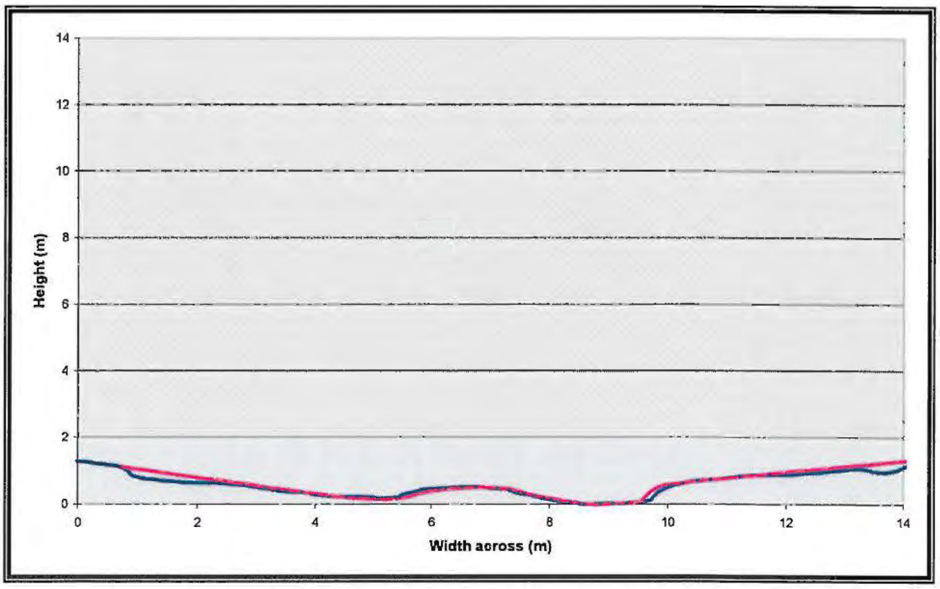

Figure 5.26 Transect HE 5.3 (initial survey in blue, follow-up survey in pink)

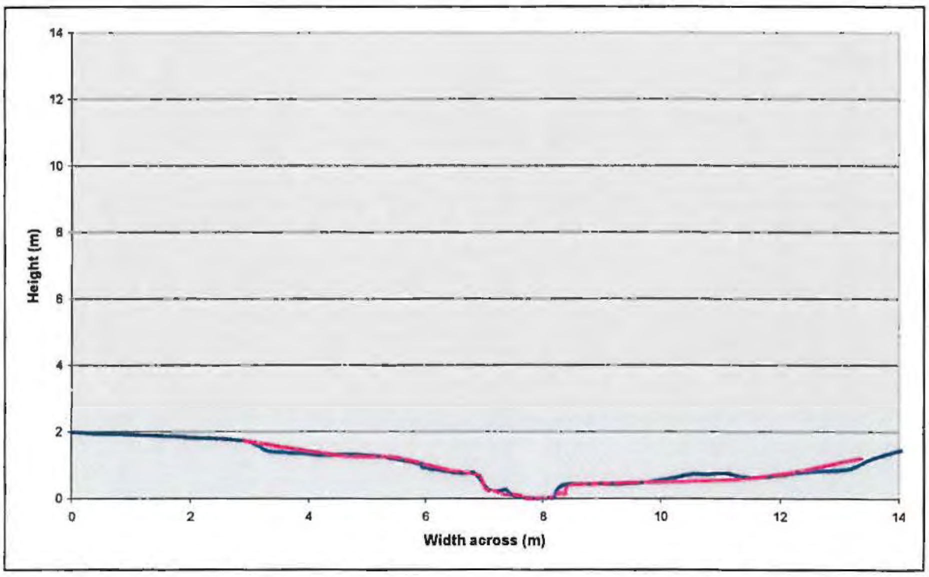

Figure 5.27 Transect HE 6.2 (initial survey in blue, follow-up survey in pink)

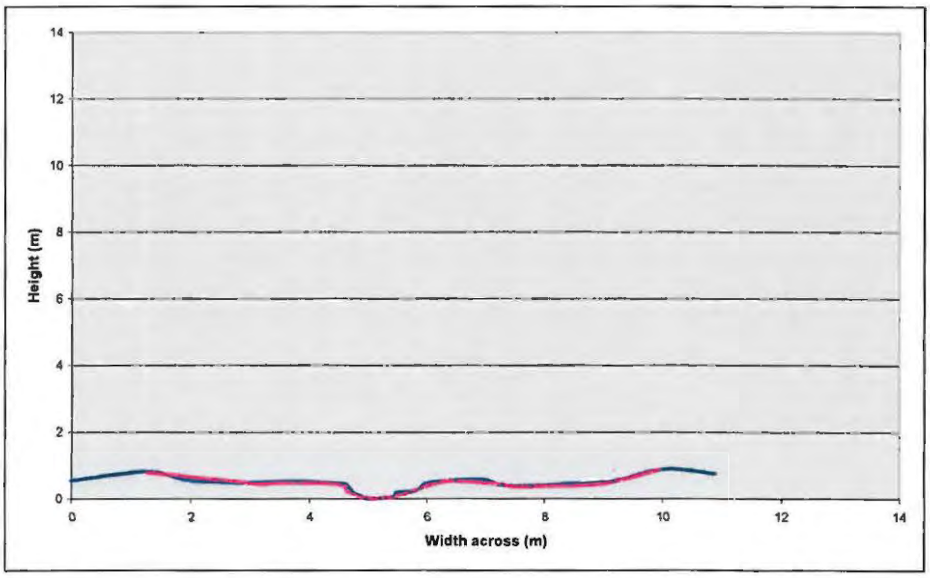

Figure 5.28 Transect REF 1.4 (initial survey in blue, follow-up survey in pink)

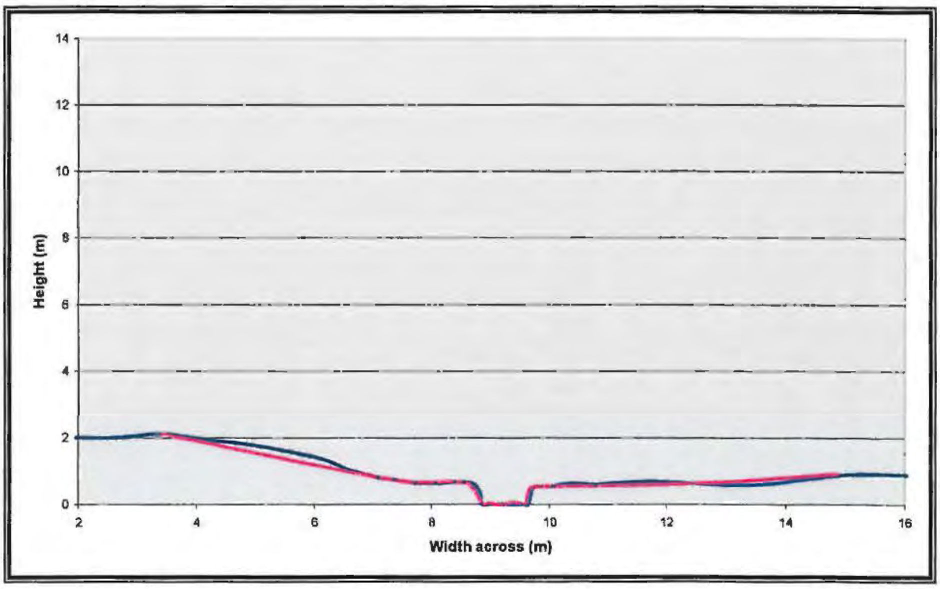

Figure 5.29 Transect REF 2.3 (initial survey in blue, follow-up survey in pink)

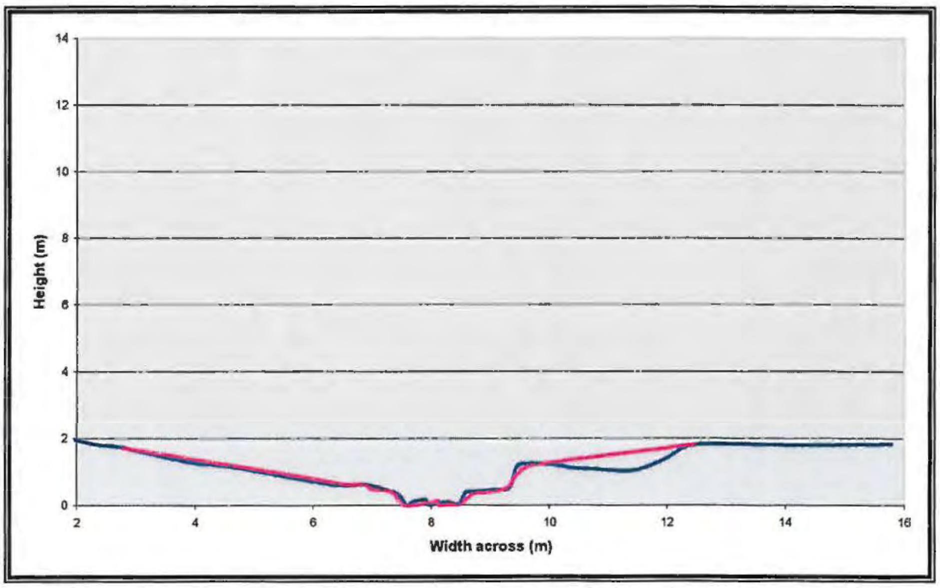

Figure 5.30 Transect REF 7.3 (initial survey in blue, follow-up survey in pink)

5.10.2 Follow-up bed material

Tables 5.15 – 5.17 show the percentage change in the composition of the follow-up bed material. Of the three reaches it is clear that the greatest changes have occurred within the Baviaans reach (the reach where the clearing and rehabilitation work took place within the study period). While the Heuningnes and Reference reaches have changed minimally and are essentially similar to pre Baviaans clearance conditions, Baviaans seems to have significantly less silt/sand bed material at a number of sites. At these sites, gravel seems to have increased with regards to a reduced amount of silt/sand. Note that the missing follow-up data at site BV1 is due to the site being completely ruined as noted above. See Appendix B for all data relating to follow-up bed material.

Table 5.15 Percentage change in follow-up bed material per site for Baviaans

	BV1	BV2	BV3	BV4	BV5	BV6	BV7	BV8	BV9	BV10
Silt/Sand		-0.6	-12.8	-8	-4.8	-14.8	0.8	-12.4	-1.6	0
Gravel		-0.2	10.8	15.2	4.8	7.2	-2.8	19.2	-6.4	-0.8
Cobble/Boulder/Bedrock		0.8	2	-7.2	0	7.6	2	-6.8	8	0.8

Table 5.16 Percentage change in follow-up bed material per site for Heuningnes

	HE1	HE2	HE3	HE4	HE5	HE6	HE7	HE8	HE9	HE10
Silt/Sand	2	0.2	2.6	1	2.2	1.6	-1.2	-1.2	1.6	1.4
Gravel	-1.6	-2	-0.2	-1	-1.4	-1.8	1.2	2	0.4	0.2
Cobble/Boulder/Bedrock	-0.4	1.8	-2.4	0	-0.8	0.2	0	-0.8	-2	-1.6

Table 5.17 Percentage change in follow-up bed material per site for Reference

	REF1	REF2	REF3	REF4	REF5	REF6	REF7	REF8	REF9	REF10
Silt/Sand	-1.6	-3.2	2	2.2	0.6	1.2	0	-1.8	-1	1.8
Gravel	0.8	0.6	0.4	-1.4	0.4	-1.2	-2	0	0	-1.2
Cobble/Boulder/Bedrock	0.8	2.6	-2.4	-0.8	-1	0	2	1.8	1	0.6

5.11 SUMMARY

This chapter has examined the channel form variables for the three study reaches. They demonstrate clear differences between invaded and uninvaded channels. It also discussed channel control variables. Relationships between these controls and channel form variables were shown. An understanding of how these variables correlate and understanding their relationships allow for a better understanding of the fluvial geomorphological processes taking place within a given channel.

One particular and clear trend found across all three reaches was the relationship between larger and deeper channels with more cobble/boulder and less silt/sand in the channel beds. However, there was an overall lack of any consistent within-reach relationships between channel form and control variables. Where these were suggested, they often made no sense. Therefore, the significant differences of channel form between the invaded and the reference sites are likely to be due to the black wattle invasion.

Various statistical analyses were then conducted to emphasise the difference between all three study reaches. In particular it has revealed the Reference as different to the other two invaded reaches. Short-term changes (<2yrs) that occurred within the study period post Baviaans wattle clearance were shown to be minimal for channel form as well as for bed material.

CHAPTER 6

ANALYSIS AND DISCUSSION

6.1 INTRODUCTION

This chapter has three main sections. The first provides a synthesis of the results so as to demonstrate the effect the woody alien invasive *Acacia mearnsii* has had on the stream channel morphology of the Baviaans and Heuningnes Rivers, thus meeting the primary aim of this research. Hence, the following section discusses the difference between channels impacted by wattles and unimpacted Reference channels of the study area. An objective set out in this research was to examine the short-term effects of removing *Acacia mearnsii* from the riparian zones of the Baviaans and Heuningnes Rivers. This is discussed in Section 6.3. A further objective was to characterise and recommend a long-term programme to monitor any changes to channel morphology after the wattle clearing rehabilitation measures. Thus, Section 6.4 aims to establish and understand the resource quality objectives (RQOs) for river rehabilitation success from a fluvial geomorphological viewpoint. These RQOs relate directly to long-term monitoring and are tied into a theoretical discussion and conclusion at the end of the chapter.

6.2 IMPACTED AND UNIMPACTED CHANNELS

6.2.1 Reference characteristics

In many ways, Heuningnes seems the most impacted as a system. This would seem logical for a system that has possibly been exposed to the wattle infestation for the longest time. The Heuningnes clearly exhibits the widest channels and the Reference the narrowest. Some of the oldest and largest wattles are found in the upper sites of the Heuningnes reach and, according to aerial photos, it is possible that this could be an original source of the wattle infestation. Furthermore, the Heuningnes has never been cleared of alien vegetation, unlike the Baviaans which was cleared in 2001 and also experienced a big fire in 2002 which burnt all debris.

All three study reaches display differences in relation to channel depth. While, the upper three sites of the Baviaans are clearly deeply incised, the sites below these are all of similar depths. This is in contrast to Heuningnes which exhibits great variability in channel depths and the Reference with its deepest channels in its middle sites. Because cross-sectional area is related to width and depth, the resulting trends are similar i.e. the invaded sites have average channel cross-sectional areas that are 84% (Baviaans) and 55% (Heuningnes) larger than the Reference. With similar total catchment sizes, similar reach gradients and a range of other similar variables (e.g. rainfall, geology), it would seem logical that the outcome should be similar cross-sectional areas for Baviaans and Reference. It is likely therefore that the impact of the black wattle infestation is causing these differences in channel form.

These upper three Baviaans sites mentioned in the previous paragraph with their higher bank gradients, smaller bank percentage of silt/clay, smaller percentage of bank organics and deeper incised channels seem to indicate more erosional processes. Lower down the reach, the reduced site gradients, higher bed percentage of silt/sand, reduced bank gradients, shallower channels and greater bank percentage of silt/clay seem to indicate depositional processes. These upper Baviaans sites are located within an alluvial fan deposit providing a deep valley fill and thus there is more available sediment to erode and within which to incise than further downstream.

The following four variables showed significant relationships on channel form across all three study reaches: bank percentage silt/clay; bank median size particle (D50); bed percentage silt/sand; bed percentage boulder. There is clearly a greater abundance of cobbles and boulders in the channel beds of the Baviaans and Reference systems while the Heuningnes is dominated by silt/sand and gravel. Thus, there seems a clear relationship between bed boulders and the channel form variables of the Baviaans and Reference. However, if one considers fluvial processes, these correlations with channel form may purely be coincidental. A high silt-clay ratio should increase shear strength and allow deeper channels to develop. This is not the case in the study channels. Large bed material should be associated with wider channels – again not evident in the invaded reaches although this occurs in the Reference reach.

Bearing in mind that the Reference and Heuningnes reaches are part of the same catchment, it is evident that they share similar bank particle size distributions. Baviaans differs in that it has a higher percentage of finer material. The amounts of silt/clay in the banks and the median (D50) size particle have a strong influence on Baviaans channel form variables. There is evidence from the literature that shear strength increases with the silt-clay ratio, but soil drainage may also be important. It thus seems possible that the Reference, with its larger bank median size particle soils and lack of wattles, drains more readily and is thus less prone to slumping. However, the fynbos' denser fine root mat is also a likely contributor to bank shear strength.

Examining the terraces, their particle size distribution follows almost the exact same trends as with the banks. There is a clear distinction between the Baviaans as a catchment and the Heuningnes and Reference as part of another catchment. Maybe the most important finding is that if the terrace particle size and organic matter does not vary much between sites and should thus not be a factor controlling the rehabilitation/replanting process.

The Heuningnes thus appears as a system with no clear trends in variables exhibiting high variability for many variables that were measured. As a system, the Reference seems the most uniform throughout for all channel form variables by displaying the least variability. This is relevant from a rehabilitation viewpoint. In comparison to the Reference, the invaded reaches which are to be rehabilitated need to return to these Reference-like conditions of minimum variability with regards to the channel form variables. It is also interesting to note that the three Reference sites with the largest cross-sectional areas correspond with: 1) the presence of dense alien wattle and blue gum stands; 2) the only basal and subaerial erosion recorded along the Reference channels; 3) the deepest channels. These sites also have an increased amount of boulders in the channel bed. It seems as though the presence of alien wattles at these three sites could possibly be the cause of these impacted-site type characteristics.

6.2.2 Effects of *Acacia mearnsii*

A downstream increase in form ratio is usually expected and this was not found in any of the study reaches. It is also likely that the Heuningnes, with its older, larger wattles and longer rates of infestation could be creating an impact on the system and contributing to the largest average form ratios and a lack of a downstream trend. Conversely, the Reference exhibits a considerably lower average form ratio. This is possibly due to the notable lack of wattles; the lack of debris dams associated with the wattles; and the lack of a clear influence in the past of cattle within the channel. The debris dams of the invaded reaches were more abundant and much larger in the Heuningnes. This would have an effect on channel form variables. It is also possible that the fire in the Baviaans in 2002 burnt much of the debris, thus reducing the effects of the debris dams.

The wattle infestation acts as a control on channel form by affecting the sediment dynamics in a manner different to that of natural vegetation. This is especially relevant during periods of high flow. The woody stems and roots along with the ubiquitous LWD retard the flow up to high velocities and can cause serious bank scour. This is evident in many places. One outcome of this research that seems similar to the literature on wattle invasions is the widening of channels due to the increased erosion associated with the wattle invasion. The research by Esau (2005) is especially comparable. Wattle collapse (along the banks) and LWD have a direct effect on channel stability and thus channel form.

There is also a distinct difference between invaded and uninvaded channels with regards to similarities between bank and terrace organic content. While the invaded channel's banks and terraces are quite similar in organic content, the Reference displays a significant difference between its banks and terraces. This could be due to the density of the black wattle stands growing along the invaded channel's riparian zones. This dense mono-specific canopy provides an abundance of organic material for the terraces and upper banks in the form of leaves, branches and seeds. This is in contrast to the Reference, where the cover of indigenous fynbos vegetation is dense along the channel but less dense and more grassy away from it. However, it is this extremely dense fynbos along the uninvaded channels that gives these banks the highest bank organic content of all study areas. The higher organic content and the dense fynbos vegetation with its fine root mat could be the key factors in strengthening the banks and improving stability. The result is the highest shear bank strengths of all the study areas with a noticeable absence of basal erosion i.e. undercutting and slumping. However, the study sites revealed statistically insignificant relationships between bank shear strength and bank organic content, bank silt/clay content and bank gradient. Nonetheless, other factors may be at work here. Another possible reason for fynbos cover being more beneficial to bank strength than a dense cover of wattles is due to its lower mass relative to root depth.

In identifying a relationship between channel vegetation characteristics and channel form variables, only cross-sectional area produced a moderate relationship. It can be argued that the assessment was somewhat subjective and perhaps a more detailed investigation into channel vegetation is required in the future. Nonetheless, within-reach relationships were inconclusive and therefore variability within a reach can be assumed to be due to complex local factors.

> *"The channel form is the result of the balance between the available sediment and the transport capacity of the flow. Channel form can be considered to be in dynamic equilibrium with the flow and sediment regimes"* (Rowntree, 2000, pp 413)

The above quotation underlines the importance of flow and sediment as controls on channel form. The results showed fairly similar bankfull discharges throughout all three study reaches. Since a stream is dynamic in nature it is constantly changing and adjusting to the many variables that influence its function. Thus, if the study channels were in dynamic equilibrium with their bankfull discharge, they would all be of a fairly similar channel form, and would exhibit downstream trends that are related to downstream increases in discharge. This is clearly not the case.

So when a channel becomes impacted such as through a wattle infestation, the channel form can be affected. With this in mind, the channels of the Reference exhibit some distinctive characteristics in comparison to the invaded channels. Reference banks have a higher organic content. The banks are covered with a high diversity of dense fynbos vegetation. Even though the Reference bank percentage silt/clay is lower than the invaded channels, the result is banks that exhibit higher shear strengths. Here it is interesting to point out that even though Baviaans has a higher bank percentage of silt/clay and almost similar bank organic content to Reference, it is clearly more impacted. The obvious direct conclusion is the difference brought on by the impact of the black wattle infestation on the stream channel. Furthermore, Reference channels reveal much less undercutting and basal erosion. There are also no debris dams along the uninvaded channels (a feature exclusive to the channels under the dense wattle canopy). The uninvaded channels also exhibit steeper bank gradients and significantly lower form ratios. The result is narrow channels that are fairly deep with steep banks covered in dense fynbos. Furthermore, there are no bare and barren patches along these Reference channels, unlike what is found under the thick monospecific wattle canopies in the Baviaans and Heuningnes reaches.

The effects of stocking cattle cannot be ignored. While all three reaches were part of a farm in which cattle roamed freely, the effects of stocking cattle are most clear in the Heuningnes. Here, cattle crossings, subaerial erosion from livestock trampling, cattle paths and watering holes are abundant. This would have a direct influence on channel form and erosion rates. The Reference in comparison (which also saw cattle roaming freely) exhibits a thick, dense and great variety of indigenous vegetation growing right up to the bank edge. This would have limited the movement of cattle to a degree but not completely. Thus, in the case of the wattle invaded reaches, the effects of stocking cattle and their tendency to move about or congregate along the river channel and under the wattle infestation (possibly for water and shade) has acted as a secondary effect of the invasion.

A correlation matrix of all three study reach variables produced two notable strong relationships across all three study reaches: channels with large cross-sectional areas were closely related to deeper channels and a bigger channel form ratio was closely related to a reduced bank gradient. These relationships possibly show the similar manner with which fluvial processes are carried out within the study reaches. This would be expected, as the study catchments are similar in many ways, as has been shown. Both catchments share many underlying variables and you would expect the same types of channels from two catchments in such close proximity with so many similarities. But it is argued here that the wattle infestation is the key factor with regards to differences in channel form between invaded and uninvaded channels. The wattle infestation clearly acts as an impact on the Baviaans and Heuningnes reaches. Even though these two reaches experience the same fluvial geomorphological processes as the Reference, the wattle invasions impact and disrupt these fluvial processes. The result is a direct effect on channel form making it different to the more 'natural' Reference channel form.

The F-tests and to a lesser extent the PCA and SDA all emphasised the Reference reach as being separate and different in comparison to the invaded reaches. F-tests on the channel form variables showed the Baviaans and Heuningnes as having similar variances in comparison to the Reference. With the PCA, the two factors plotted accounted for almost half the variation in the data and seemed a fair explanation for the location of the study sites on the PCA axes (even though no clear grouping was present). With the SDA however, clear grouping was obvious but it could only be reliably predicted based on the first discriminant function.

6.2.3 Controls on channel form

The four key controls on channel morphology are: *the river long profile* (RLP), *flow, sediment and bank resistance* (Rowntree & du Plessis, 2003). These four controls are interrelated and influenced by various underlying variables. However, they provide a basis from which to understand controls on changes in channel morphology. A further obvious control on channel form is vegetation.

Due to a similar underlying geology, similar climate and similar gradients/RLPs, one can directly compare the three study reaches. There exists no significant difference in stream gradient as a variable between the impacted and Reference reaches. It can therefore be concluded that gradient/RLP be excluded as a control variable that might explain differences in channel form between sites.

With regards to flow, given the wide margin of error, channel forming discharge does not seem to increase significantly downstream and there are minimal differences between reaches. It can therefore be concluded that discharge be excluded as a control variable that might explain differences in channel form between sites.

The banks and the terraces of the Heuningnes and Reference are both very similar. Thus, there is no significant difference between sediment as a variable for the invaded Heuningnes and the Reference. It can therefore be concluded that sediment be excluded as a control variable that might explain differences in channel form between an impacted and a 'natural' reference site.

With bank resistance, the lack of a significant relationship between shear strength and bank material, organic matter or bank gradient leads to the conclusion that shear strength (as measured to represent bank resistance) is not a controlling variable within each site.

The lack of any clear relationship or explanation between channel form and the other channel controls suggests vegetation as the primary control. Even though bank resistance is an obvious important variable for channel form, no controlling variables could be identified. Vegetation is thus seen as the key controlling variable acting on channel form in the study area. The stability and bank resistance in river banks depends on the root system of the vegetation growing on it. As mentioned previously, wattles are often associated with river channel erosion because their shallow root system makes them unstable along river banks. This has repercussions for the river in the form of debris dams, LWD and a widening river channel due to increased erosion. The shallow root systems are also likely to affect flow forces and enhance scour as opposed to protecting the soil. All of these aspects would directly affect the river channel morphology.

6.3 SHORT-TERM EFFECTS OF THE WATTLE CLEARANCE

Short-term changes (<2yrs) within the study period comparing pre and post Baviaans wattle clearance have revealed no significant change to channel cross-sections in any of the three study reaches. Furthermore, change within this period was also shown to be minimal for bed material. This is not unexpected due to the short time period that lacked any large rainfall events, any larger flows of significant geomorphological importance and any fluvial activity. The rainfall data indicated that the period post Baviaans wattle clearance has seen rainfall lacking except for a wetter than usual December 2007.

6.4 RESOURCE QUALITY OBJECTIVES (RQOs)

This section aims to establish RQOs for river rehabilitation success from a fluvial geomorphological viewpoint. These RQOs are based on the research findings and thus first required an investigation of the impacted and reference channels. Chapter 3 of the South African National Water Act describes the purpose of RQOs as establishing clear goals that relate to the quality of the relevant water resources (DWAF, 1998). RQOs are defined objectives for aspects such as flow, water quality, biota, habitat, channel morphology and so forth. It is important to define these RQOs and necessary to have them in place so that monitoring procedures can be defined. Long-term monitoring will measure whether the RQOs are being achieved.

With regards to this research, which forms the basis of longer term monitoring, it should be acknowledged that preliminary and precise fluvial geomorphological objectives of rehabilitation in conjunction with the KRRP may be somewhat difficult to comprehend. However, until a full long-term monitoring programme is in place, the following eight objectives can be taken as RQOs that are seen as being important from a fluvial geomorphological viewpoint with regards to the impacted study reaches. The RQOs are structured 1 – 8 starting with short-term objectives and each subsequent objective becomes more long-term. Objectives 1 – 3 deal with controls on the channel while objectives 4 – 7 deal with channel processes:

1) Replanted indigenous vegetation remains in place in the riparian zone and flourishes to prevent black wattle re-growth and to benefit bank shear strength.
2) Channel bed and bars are not re-colonised by black wattle.
3) Black wattle debris dams disappear and excess wattle debris is washed down the system.
4) Bank slumping and undercutting are reduced. Those sites currently exhibiting severe basal erosion perhaps require the bank to collapse completely so that a new channel form is created similar to that of the reference.
5) Channel width does not increase.
6) Form ratio (width-depth ratio) decreases for impacted channels.
7) Cobble substrate remains in place and does not become embedded thereby causing a loss of habitat for certain fauna.
8) A reduction in the variability of impacted channel form conditions i.e. a more uniform channel morphology.

These eight RQOs should be achieved through the rehabilitation efforts so as to benefit the fluvial geomorphological processes of the impacted streams. They are to be monitored in the long-term to assess the 'success' of rehabilitation of the impacted study reaches from a fluvial geomorphological viewpoint. Essentially, these RQOs represent positive measurable improvements to the river ecosystem. The achievement of these RQOs emphasises the ecosystem as shifting along the continuum to a more 'natural' and sustainable state or end-point. As previously explained from interviews with key project individuals, this is what would define a 'successful' rehabilitation project. Another benefit to long-term monitoring is that it can help redefine the RQOs if needs be.

6.5 THEORETICAL DISCUSSION

This chapter has emphasised the difference between impacted and unimpacted channel morphology within the study area. The results indicate a number of significant differences between those channels impacted by black wattle infestation and those channels seen as unimpacted and natural. It is clear that the black wattle infestation acts as an impact affecting channel form. It adds to bank loading and collapsed wattle trees, slumping and undercutting are ubiquitous in the two invaded reaches. The impacted catchments provide a working example where the type of bank vegetation is also important in relation to bank stability, not only that a good cover exists.

The Baviaan's upper sites are clearly more entrenched and enlarged beyond normal. The Baviaans demonstrates variability and instability and is a highly disturbed system. Through the abovementioned RQOs it is hoped that this variability can be 'smoothed over' or reduced in the long-term to something resembling a more uniform Reference channel. As a system the Heuningnes is also highly chaotic with various destabilizing factors and processes taking place. Here again, the RQOs apply as a means of measuring the degree to which rehabilitation is taking place from a fluvial geomorphological viewpoint.

Invasion by black wattle creates a change in environmental conditions and becomes an impact to the river. Although the rehabilitation effort is primarily the clearing of this black wattle and the re-planting of indigenous vegetation, rehabilitation from a fluvial geomorphological viewpoint is to instil the correct underlying abiotic conditions. Geomorphological recovery such as abiotic conditions more similar to the Reference, a natural hydrology and restoring the natural channel morphology should allow for ecological recovery. In turn, this ecological recovery will benefit the geomorphological recovery. The two are interconnected and the RQOs reflect this. Already, initial results from concurrent research into the study sites' aquatic biodiversity indicate a marked increase in species richness for the Baviaans sites post wattle clearance (Lowe, pers. Com., 2008). He emphasised the rapid recovery of aquatic species but stressed the lower

Baviaans sites are not as healthy as the upper sites. The two factors most likely influencing the initial recovery of species are the removal of the wattle canopy and the associated increase in sunlight.

Statistical analyses performed on all variables from all three study reaches emphasised the Reference and its channels as a distinctive reach in comparison to the impacted channels of the Baviaans and Heuningnes reaches. The four key controls on channel morphology (gradient, flow, sediment, bank resistance) were all examined, compared and discussed in relation to impacted and unimpacted channels. The lack of any clear relationship or explanation between channel form and the other channel controls emphasises vegetation as the primary control. Nevertheless, it should be acknowledged that the close geographic proximity of the three study river reaches is emphasised through the similarity of the data for many sites. To some extent, this results in a data limitation causing difficulty with the explanation and statistical analysis of some results.

Initial comparisons of all three study reaches pre and post Baviaans alien clearance revealed channel form and bed material conditions as having changed minimally. This short-term monitoring (<2yrs) was done within the study period so as to reveal any short-term changes that may have occurred in the channel post alien invasive clearing. In fluvial geomorphological terms this is a short time period and the lack of any significant change is understandable. However, a channel's form is the ultimate determinant of the in-stream flow environment in which the medium to long-term (i.e. 10 – 100 years) processes should be considered. Thus, long-term monitoring is justified and will entail monitoring of the RQOs. This will be done by monitoring key sites in the study area. Chapter 7 examines the approach to a long-term monitoring system and its protocols. Long-term monitoring not only provides a measure of rehabilitation success but is also important for the sharing of project successes and failures.

CHAPTER 7

LONG-TERM MONITORING

This chapter discusses the important topic of monitoring from a fluvial geomorphological viewpoint as it relates to the resource quality objectives (RQOs). The monitoring system recommended here should be carried out continuously post thesis research for the benefit of the Kouga Riparian Rehabilitation Project (KRRP). This is the umbrella project being carried out by R3G of Rhodes University with the help of the World Wildlife Fund and Working for Water. Following an initial theoretical background, Section 7.2 provides a recommended framework for a fluvial geomorphological long-term monitoring system.

7.1 MONITORING

Post project evaluations allow for a longer-term examination of response, with obvious direct benefits for riparian zone rehabilitation (Stewardson *et al.*, 2004). Since monitoring is generally quite costly, it is important to plan the monitoring of a rehabilitation work early on, preferably prior to detailed design. Monitoring should ideally start one year prior to the rehabilitation efforts (i.e. pre-rehabilitation data) with monitoring and sampling done simultaneously at reference and rehabilitation sites (Nielsen, 1996; Stewardson *et al.*, 2004). This has been done in this study by assessing channel form at the study sites prior to alien invasive clearance.

"Rigorous planning and a sound ecological basis means that data collected in dedicated experiments can be used to explore underlying mechanisms responsible for changes in the condition of the river, to generate hypothesis for further research, and to suggest improved management approaches" (Stewardson *et al.*, 2004, p.22)

The quotation above emphasises how monitoring should only take place if there is sound project planning; the study sites are typical of future rehabilitation sites; and there is sufficient time for pre-rehabilitation data collection (Stewardson *et al.*, 2004). According to Giller (2005), the most important aspect of a rehabilitation project is that a 'guiding image' be envisaged early on, one that has a dynamic ecological end state. This stresses the importance of monitoring because it assesses the 'success' or 'movement' towards this envisaged dynamic end state. Knowing if there have been any ecosystem improvements relies directly on comparison of pre- and post-project conditions. Thus, a project without this baseline data will benefit scientific understanding only minimally (Gillilan *et al.*, 2005). According to Stewardson *et al.* (2004), a restoration or rehabilitation effort can be regarded as successful if monitoring reveals that the restored sites are starting to mirror the undisturbed sites more than the disturbed sites. Unfortunately, often by the end of the rehabilitation effort, project funds are depleted with nothing left to continue the vital monitoring.

It is unfortunate that until now well-designed monitoring programs that assess restoration or rehabilitation successes and failures are quite rare. According to Klein *et al.* (2007) this has meant plenty of missed learning opportunities that would benefit future rehabilitation works and a loss of valuable information that would essentially benefit the scientific basis of river rehabilitation. The authors give several reasons for this lack of monitoring. They include a lack of funds; a lack of monitoring standards to evaluate success; a lack of information on the implementation of a monitoring program; seeing monitoring as labour intensive; and the difficulty in understanding the actual effects of the rehabilitation effort within a complex and dynamic ecosystem. The authors also emphasise that despite the increase in efforts to monitor and establish monitoring standards to measure a rehabilitation project's success, agreement among the river restoration/rehabilitation community on how to define success is minimal.

Through the investigation of erosion and deposition dynamics, Lawler (2005) emphasises the importance of paying greater attention to the selection of an appropriate monitoring frequency that will accurately explain or describe fluvial geomorphological processes. The long-term monitoring system being presented in this chapter recognizes the importance of an appropriate monitoring frequency. With geomorphological change occurring at various scales, setting up a correct monitoring framework becomes important.

> *"Monitoring change in the geomorphology of the river environment is therefore (and belatedly) becoming an important measure both of river management practice and system resilience to external environmental change"* (Sear & Newson, 2003, p.18)

Sear & Newson (2003) emphasise the value of re-surveying. Firstly, it allows for similar time-scale coverage in comparison to the rehabilitation sites. Secondly, it allows for the comparison of synchronous events taking place at different site types. This can help to identify regional variations in stream channel processes which could be associated with external driving variables. Thirdly, the subsequent monitoring provides direct data relating to geomorphological attributes.

> *"Research level monitoring with sufficient time and funding to collect extensive pre-restoration data and to spatially and temporally replicate treatment, control, and reference sites can increase the strength of inference."* (Klein *et al.*, 2007, p. 236)

As the above quotation emphasises, research level monitoring (i.e. the type of monitoring to take place post research of this thesis) represents an opportunity to advance the science and the practice of restoration and rehabilitation. Thus, a long-term monitoring system is an obvious and necessary next step for this research.

7.2 SETTING UP A LONG-TERM MONITORING SYSTEM

7.2.1 A framework for monitoring

The importance of monitoring cannot be underestimated. Monitoring is the means by which to define and measure positive or negative changes to the river ecosystem. From a fluvial geomorphological viewpoint, these improvements are defined by the RQOs and are thus the indicators that require monitoring in the long-term. Table 7.1 provides a framework for relating the RQOs to a long-term monitoring system. It shows how monitoring frequency will depend on the RQO in question. It is recommended that only a few key sites be selected for long-term monitoring purposes. This is done for efficiency, to save time and to reduce costs. It is recommended that initial monitoring should be at key sites in a basic form that can be done fairly easily and often. The following Section 7.2 2 identifies and justifies the key sites.

It was emphasised from within the KRRP that a requirement of any long-term monitoring is that it is fairly simple and quick. With a basic approach to measuring channel form, the channel form ratio can be assessed faster and more often (i.e. every three months and also perhaps after major rain events) and by a non-technical person. Chapter 5 in Gordon *et al.* (2004) provides detailed information on measuring channel cross-sectional profiles with a measuring tape and rule. When this basic data starts to reveal a change in channel width or depth, more technical monitoring should be conducted i.e. detailed assessments of the channel form using an electronic distance measurement instrument such as a total station (also see Ch.5 in Gordon *et al.*, 2004).

Due to the large amounts of data from monitoring measurements, a data storage system is a pre-requisite for any serious monitoring programme. Analysing the data so as to understand changes at the study sites will require a structured approach to recording and accessing these data.

To fulfil monitoring of each RQO, the individual conducting the monitoring research will have access to readily available methodologies in this thesis. In this manner it is envisaged that researching all the RQOs on an annual basis should result in regular monitoring survey results that will provide information on the changes taking place along the study channels. It will also provide an idea of whether the impacted study sites are moving towards a more 'natural' state.

Table 7.1 Relating RQOs to a long-term monitoring framework

RQO	Action	Equipment	Minimum grade of personnel	Minimum frequency	Extent
Replanted indigenous vegetation remains in place in the riparian zone	Fixed point photographic monitoring of the site	Camera and standard data sheet	Field technician	12 months	All sites
Channel bed and bars are not re-colonised by black wattle	Fixed point photographic monitoring of the site	Camera and standard data sheet	Field technician	12 months	All sites
Wattle debris dams disappear and excess debris is washed down the system	Fixed point photographic monitoring of the site	Camera and standard data sheet	Field technician	12 months	All sites
Bank slumping and undercutting are reduced	Measure channel form, visual observation	Total station, accessories and standard data sheet to note local slumping within surveyed sections and without	Graduate geomorphologist	12 months	All sites
Channel width does not increase	Measure channel form	Total station and accessories	Graduate geomorphologist	12 months	Key monitoring sites
A decrease in form ratio (basic assessment)	**Measure channel form**	**Tape measures, String/rope**	**Field technician appointed by a monitoring & evaluation unit**	**3 months**	**Key monitoring sites**
A decrease in form ratio (detailed assessment)	Measure channel form	Total station and accessories	Graduate geomorphologist	12 months	Key monitoring sites
Cobble substrate remains in place and does not become embedded	Assess bed material	Sharp metal peg	Field technician	12 months	Key monitoring sites
A reduction in the variability of impacted channel form conditions i.e. more uniform channel morphology	*Combining all the above monitoring results and data into a central data base*		Graduate geomorphologist	*An annual complete assessment of all results and data*	

The initial basic monitoring, the subsequent more detailed monitoring and the data storage system should fall under the commitments of a monitoring and evaluation unit with its academic contribution. Any issues of funding for monitoring need to be resolved by the parties involved in the KRRP. It is envisaged that monitoring will be carried out for another three years (i.e. 2009 – 2011) while the KRRP is still being conducted. Monitoring after completion of the KRRP will need to be reviewed at that juncture.

Using the same field workers for successive trips into the field will improve accuracy and save time. This is especially true for the field workers that operate the total station, which can sometimes cause problems at sites where visibility and mobility are limited.

It is recommended that any future monitoring and research have clear marking of all transect pegs to prevent disruption of accurate follow-up measurements. Due to the disruptions at many sites, not all follow-up transects could be compared and only the 'perfect' follow-up monitoring transects (i.e. peg to peg) were displayed in this thesis. This was not ideal. Highly visible transect markers and boards with information at each site are recommended. It is also important to ensure that all of the relevant managers and field workers involved in any manner with monitoring are aware of the transects and their importance.

Fixed point photography was planned for this research but for various reasons (e.g. limited time in the field, many other tasks were required, etc.) it did not transpire. Fixed point photography can be used in conjunction with the channel form measurements to emphasise changes to channel form. It will also show changes in bed material and vegetation.

Two possible recommendations for future researchers: 1) Obtain a sequence of pre and post wattle clearance aerial photos along the river channel for analysis; 2) Take accurate measurements of channel undercutting rather than merely noting them. This would allow for the long-term monitoring of these undercuts to understand the rate at which undercutting is taking place.

7.2.2 The key sites

It is unnecessary to monitor every single site every 12 months. By grouping the sites based on similar channel types, it is possible to monitor change and draw conclusions from selected key sites. Figure 7.1 plots all study sites' cross-sectional areas relative to their form ratios giving an idea of whether a site is enlarged (e.g. BV8) or it has an extreme form ratio (width-depth ratio) e.g. BV2. Note the close clustering of the Reference sites, reemphasising the minimal variability as a reach in comparison to the invaded catchments. Thus, by examining Figures 5.2 – 5.5 and by analysing the relationship between form ratio and cross-sectional area at every site (Figure 7.1), it is possible to group similar study sites based on their channel form variables.

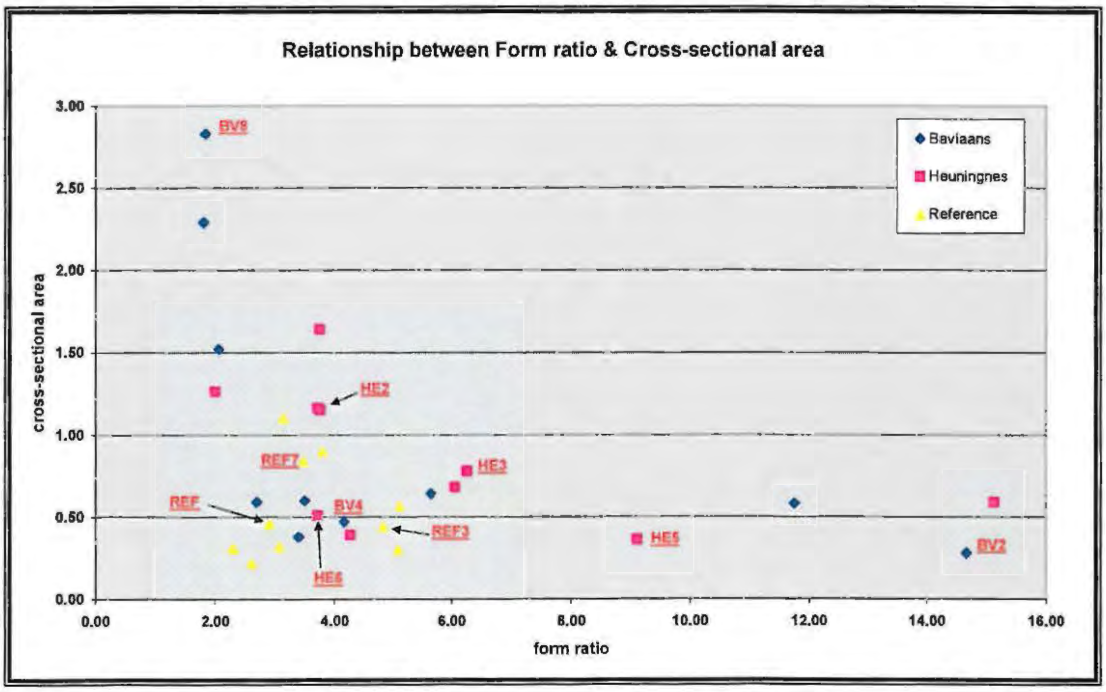

Figure 7.1 The key long-term monitoring sites (marked with red labels)

Figure 7.1 above shows those sites that are important for long-term monitoring and can be used to represent other sites within a similar grouping based on channel form. These selected key sites have been chosen based on additional criteria of accessibility, simplicity of monitoring and to allow 'perfect' follow-up monitoring transects i.e. peg to peg. Tables 7.2 – 7.4 show the current status of the study sites applicable for any future long-term monitoring. Table 7.5 shows the sites grouped based on their channel form variables with the key long-term monitoring sites highlighted in red. BV8 and BV9 in the first Baviaans group are to be monitored simultaneously due to the future construction of a gauging weir between these two sites. This should benefit the long-term monitoring of flow and possibly also raise the groundwater level. Figures 7.2 and 7.3 show the study catchments in closer detail and highlight the recommended key long-term monitoring sites. Future appointees or researchers from the monitoring and evaluation unit could possibly choose to re-construct 'disrupted' sites or choose alternative sites for long-term monitoring. An example might be to re-establish BV5 or BV6 to include a long-term site in the middle of the Baviaans reach. Tables 7.6 – 7.8 provide the geographic co-ordinates of the study sites.

Table 7.2 Status of Baviaans sites for long-term monitoring

Site	Ave. form ratio	Ave. cross-sectional area (m^2)	Accessibility	% pegs disrupted	Additional comments
BV1	11.76	0.58	Easy	100	Severe site disruption
BV2	14.68	0.28	Easy	0	
BV3	3.50	0.60	Easy	30	
BV4	4.17	0.47	Easy	0	
BV5	3.40	0.38	Easy	50	Wattle stacks; Severe debris dam
BV6	2.70	0.59	Easy	60	Wattle stacks
BV7	5.65	0.64	Easy	0	
BV8	1.84	2.83	Easy	40	Downstream of future weir site; Wattle stacks
BV9	1.80	2.29	Easy	30	Upstream of future weir site; Wattle stacks
BV10	2.06	1.52	Easy	50	Wattle stacks

Table 7.3 Status of Heuningnes sites for long-term monitoring

Site	Ave. form ratio	Ave. cross-sectional area (m^2)	Accessibility	% pegs disrupted	Additional comments
HE1	6.06	0.68	Easy	0	
HE2	3.77	1.15	Easy	0	
HE3	6.26	0.78	Easy	0	
HE4	3.72	1.16	Limited	0	
HE5	9.11	0.36	Limited	0	
HE6	3.72	0.51	Limited	0	
HE7	4.27	0.39	Limited	0	
HE8	15.14	0.59	Easy	0	
HE9	2.00	1.26	Easy	0	
HE10	3.75	1.64	Easy	0	

Table 7.4 Status of Reference sites for long-term monitoring

Site	Ave. form ratio	Ave. cross-sectional area (m^2)	Accessibility	% pegs disrupted	Additional comments
REF1	5.09	0.30	Easy	0	
REF2	2.92	0.46	Easy	0	
REF3	4.84	0.44	Easy	0	Limited mobility within site
REF4	5.12	0.57	Easy	0	Limited mobility within site
REF5	3.15	1.10	Limited	0	Downstream of major road crossing
REF6	3.81	0.90	Easy	0	Upstream of major road crossing
REF7	3.49	0.84	Limited	0	Limited mobility within site
REF8	2.62	0.22	Difficult	0	Limited mobility within site
REF9	2.31	0.31	Difficult	0	Limited mobility within site
REF10	3.09	0.32	Difficult	0	Limited mobility within site

Table 7.5 Site groups based on similarity of channel form variables (key sites in red)

Baviaans	**BV8**, **BV9**, BV10	BV3, **BV4**, BV5, BV6, BV7	BV1, **BV2**	
Heuningnes	**HE2**, HE4, HE9, HE10	**HE6**, HE7	HE1, **HE3**	**HE5**, HE8
Reference	REF5, REF6, **REF7**	**REF2**, REF8, REF9, REF10	REF1, **REF3**, REF4	

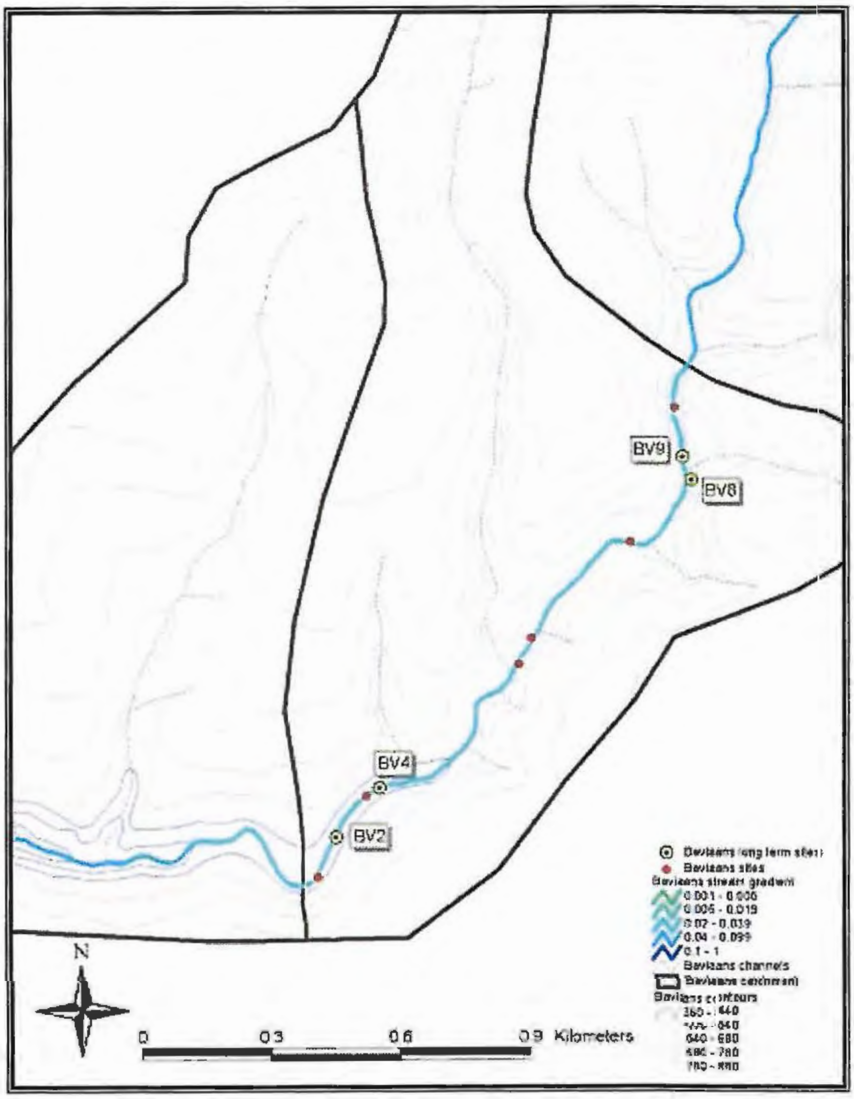

Figure 7.2 Location of Baviaans long-term monitoring sites (key sites labelled)

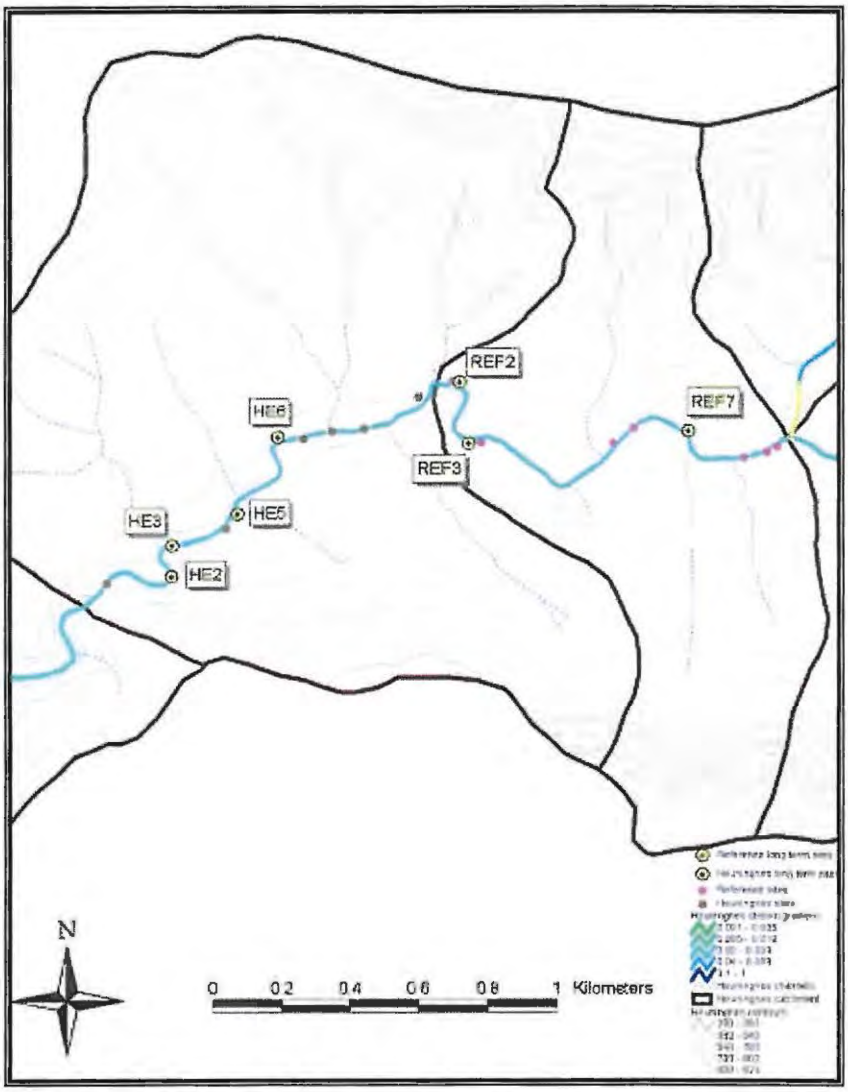

Figure 7.3 Location of Heuningnes and Reference long-term monitoring sites (key sites labelled)

Table 7.6 Geographic coordinates of Baviaans study sites

BV1	-33.81385	24.42754
BV2	-33.81202	24.42891
BV3	-33.81200	24.42892
BV4	-33.81216	24.42877
BV5	-33.80890	24.43298
BV6	-33.80943	24.43275
BV7	-33.80690	24.43541
BV8	-33.80561	24.43693
BV9	-33.80513	24.43672
BV10	-33.80410	24.43654

Table 7.7 Geographic coordinates of Heuningnes study sites

HE1	-33.78200	24.39906
HE2	-33.73184	24.40110
HE3	-33.78103	24.40113
HE4	-33.78058	24.40281
HE5	-33.78020	24.40317
HE6	-33.79280	24.40445
HE7	-33.77825	24.40527
HE8	-33.77806	24.40620
HE9	-33.78010	24.40722
HE10	-33.77717	24.40893

Table 7.8 Geographic coordinates of Reference study sites

REF1	-33.77677	24.40999
REF2	-33.77679	24.41021
REF3	-33.77839	24.41048
REF4	-33.77836	24.41087
REF5	-33.77842	24.41501
REF6	-33.77801	24.41564
REF7	-33.77810	24.41734
REF8	-33.77879	24.41905
REF9	-33.77865	24.41977
REF10	-33.77851	24.42009

7.3 THEORETICAL DISCUSSION

The various KRRP steering committee meetings attended while conducting this research have highlighted the need to also approach the long-term monitoring as a question of resource economics i.e. looking at it from a watershed services perspective. Thus, in addition to measuring if geomorphological improvements are taking place in the river channel as defined by the RQOs, it was emphasised that long-term monitoring should also provide insight into soil loss i.e. comparing impacted and unimpacted sites as well as possible soil loss post wattle clearing. Understanding the difference in impacted and unimpacted channel form and the potential sediment that may have been lost due to the wattle invasion is important from a resource economics viewpoint. This is an attribute that has an economic value attached to it and is also largely relevant to the KRRP because of the importance of the Kouga Dam which ultimately catches all the study catchment's runoff. The existing infrastructure of the citrus farms below the dam and the dam's importance as a supply of water for the Nelson Mandela Metropole would both be affected by excess sediment silting up the dam and reducing its capacity.

Essentially, the long-term monitoring needs to be carried out by bearing in mind the criteria for an ecologically successful rehabilitation project emphasised by Palmer *et al.* (2005) in Chapter 2. After some time, monitoring needs to answer important questions such as whether the rehabilitated rivers have returned or are returning to the envisaged dynamic end state? Have ecological conditions been measurably enhanced? Is the river increasing in self-sustainability and resilience? The long-term monitoring system suggested in this chapter that uses the RQOs as criteria for success will help to answer these important questions. It is then also important to integrate this geomorphological monitoring with other monitoring programmes e.g. riparian vegetation, stream biota, water quality, etc.

Finally, it is imperative that an outcome of long-term monitoring should be the clarification and explanation of both the positive and negative aspects of the rehabilitation project. The importance of monitoring and the sharing of project successes and failures cannot be underestimated. With the support of the funding and implementing agencies, there exists an incentive to assess and report the outcomes of a rehabilitation project. As was already emphasised, this chapter is only a recommendation and decisions about the criteria of the long-term monitoring should be made at that point in time by the relevant graduate geomorphologist or field technician appointed by the monitoring & evaluation unit.

CHAPTER 8

CONCLUSION

8.1 INTRODUCTION

The primary focus of this thesis was the study of fluvial geomorphology. It examined the geomorphological processes and characteristics relating to the rehabilitation of the riparian zones of the Heuningnes and Baviaans tributary catchments. The thesis described and compared an invaded river system, a recently cleared but reinvaded river system and a more 'natural' reference. It did this by comparing the channel morphology of the three systems so as to characterise the possible effects that the woody alien invasive *Acacia mearnsii* may have had on the channel morphology. The short-term effects of clearing were also examined. This chapter serves to summarize and conclude the findings of this research. It also reflects on the contribution to the literature and comments on any limitations. Finally it also provides future recommendations for similar research.

8.2 SUMMARY OF FINDINGS

The aim of the research was to characterise the effects that the woody alien invasive *Acacia mearnsii* has had on the channel morphology of the Baviaans and Heuningnes Rivers. It began with a complete analysis of the relevant study area so as to determine a workable sampling framework.

Comparing the channel morphology of the various study reaches was another objective that was met and it was found that the Heuningnes and Baviaans catchments were similar and exhibited a marked difference in comparison to the Reference. The Heuningnes and Baviaans channels are impacted with severe wattle infestations along their riparian zones in comparison to the natural Reference channels covered with dense fynbos vegetation. The Reference channels have a significantly smaller form ratio (width-depth ratio) in comparison to the invaded channels. In relation to the channel form variables that were measured, the Reference channels were homogenous in comparison to the invaded channels i.e. they exhibited less variability. This heterogeneity of the invaded channels is assumed to be a direct result of the severe wattle invasion's effect on channel processes and channel form. Statistical analysis of all the variables measured emphasised three separate groups (i.e. study reaches) and showed the Reference reach as unique in comparison to the impacted channels of the Baviaans and Heuningnes.

The four key controls on channel morphology (gradient, flow, sediment, bank resistance) were all examined, compared and discussed in relation to impacted and unimpacted channels. The lack of any clear relationship or explanation between channel form and the other channel controls points to vegetation as the primary control on channel form.

Resource quality objectives (RQOs) were then established so as to define a 'successful' river rehabilitation from a fluvial geomorphological perspective. They were based on available literature and on what seemed appropriate to the rivers of this study region. This was followed by a long-term monitoring protocol that was recommended so as to assess whether or not these RQOs are being achieved. As a result, a long-term programme to monitor change to channel morphology post wattle clearance and rehabilitation measures was successfully recommended.

Another objective that was met, but would have benefited given more time, was the examination of the short-term effects of removing *Acacia mearnsii* from the riparian zones of the Baviaans and Heuningnes Rivers. Monitoring the short-term changes to the study reaches within the study period (<2yrs) was done so as to compare any changes that may have occurred post wattle clearance from the Baviaans catchment. It was discovered that bed material and channel form changed very minimally over this period. Thus, it seemed that no real significant change took place within the channel over this period. For this reason, it is difficult to understand the extent to which clearing has so far affected channel processes and channel form within the Baviaans, especially after such a short period of time.

The final objective of this research was the interpretation of the differences in terms of the effect of *Acacia Mearnsii* on channel form i.e. how the processes are affected by the wattle invasives. This was perhaps the most problematic objective to meet and form was somewhat easier to assess than processes. In retrospect, a much more detailed assessment of vegetation was necessary that examined the surrounding channel vegetation to a greater level. This should not be viewed as new research in the future but would merely be adding to what has already been done. This will benefit the understanding of how the vegetation affects channel form. A greater level of vegetation data would then also benefit and improve on the various statistical analyses that were done. This may require that fewer sites be assessed with a much higher level of accuracy. However, this will affect the accuracy of sampling/comparison as fewer sites will be examined. Future researchers need to consider these aspects and try and find a balance between the number of sites and a level where a more detailed assessment can be carried out.

Thus, two concerns are emphasised: data limitation (see Section 6.5) and a more detailed assessment of vegetation. Without these concerns, conclusions made while carrying out this objective would have been more reliable.

8.3 CONTRIBUTION TO THE SUBJECT

This research is a result of the need to fully understand the impacts of invasive alien vegetation, specifically along the riparian zone and the river channel. Furthermore, research such as this is also important with regards to furthering the practice and understanding of river rehabilitation. Understanding how alien vegetation has affected the river channel will benefit future rehabilitation efforts which are often expensive and labour-intensive. The importance of continuous further research and monitoring cannot be underestimated. The successes and failures of each rehabilitation effort should be shared for the progress of river rehabilitation as a science.

From a fluvial geomorphological viewpoint this research supports much of the available literature in showing how *Acacia mearnsii* acts as an impact on the river channel by invading the riparian zone and covering it with a dense canopy. There are various consequences to this invasion: 1) sunlight is reduced along the river channel because of the mono-specific canopy that also reduces biodiversity along the channel; 2) a significant increase in large woody debris and debris dams; 3) tree collapse resulting in weaker banks; 4) undercutting and weakening of the banks because of a disruption to flow dynamics; 5) a change in channel form resulting in wider channels and an increase in channel form ratios.

8.4 LIMITATIONS OF RESEARCH

This research was limited by a lack of accurate flow measurement data. Most field trips coincided with periods of low flow that could not be measured. It is for this reason that the slope-area method was used as a technique to estimate discharge indirectly. As previously mentioned, a gauging weir is planned for construction between sites BV8 and BV9 but will only be built after the construction of additional weirs in the Heuningnes. Towards the end of the study period, a rain gauge was installed by the KRRP within the study area to collect long-term rainfall data rather than relying on a variety of rainfall data from other areas close by.

This research was restricted to headwater mountainous streams with relatively small catchments and steep stream gradients in comparison any reach further downstream or elsewhere. As such, this research cannot simply be applied or extrapolated to other reaches in catchments that might vary significantly in size, gradient, geology, climate, vegetation, etc. Each catchment is uniquely affected by a set of controls and variables and the impact and direction of channel change brought on by an alien invasion will vary from one catchment to another.

This research was also limited by its research period. In fluvial geomorphological terms, two years is not very long. Greater changes or trends may have become apparent if this research was conducted over a longer time period. This merely emphasises the importance of the long-term monitoring which should pick up on these trends and understand if the RQOs are being achieved and thus the rehabilitation was a success. This research also focussed more on measuring an array of *variables* relevant to fluvial geomorphology rather than trying to measure the *processes* taking place within the river channel.

8.5 RECOMMENDATIONS FOR FUTURE RESEARCH

Future research could calculate the amount of sediment being removed downstream due to the erosion brought on by the *Acacia mearnsii* invasion. The effects and costs of an *Acacia mearnsii* invasion on various ecosystem services within the river ecosystem could also be assessed.

8.6 CONCLUSION

Rehabilitation research is important. Not only does it help in understanding the conditions of an impacted ecosystem, but if it is done properly and accurately it also justifies further interest, funding and research of other areas that require rehabilitation efforts. However, for rehabilitation as a science to progress, the sharing of project successes and failures is essential.

In that context, the contribution of this thesis to the larger KRRP is important because it showed the manner in which the wattle invasion affected channel form. It revealed the condition and channel form of a 'natural' reference stream which should directly benefit rehabilitation efforts by providing a form towards which cleared and rehabilitated streams should progress. Thus, this research was only one part of a larger rehabilitation project and was essentially more about establishing starting points than the actual rehabilitation itself. This research shows where the impacted channels lie along the rehabilitation continuum. It emphasises that the invaded catchments are moderately impacted and require *passive* rehabilitation efforts e.g. the removal of alien invasives and re-planting of indigenous vegetation. This should allow the river to return to a more natural form without any *active* detailed repair measures e.g. gabions.

The research itself was interesting and challenging, especially due to the limited amount of comparable research within a South African context. Thus, circumstances required innovative thinking, approaches and techniques. Future long-term monitoring within the KRRP and other relevant and similar research should ideally build upon this research.

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