The impacts of channelisation on the geomorphology and ecology of the Kuils River, Western Cape, South Africa

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A thesis submitted in partial fulfilment of the requirements for the degree of Magister Scientiae in the Department of Earth Sciences, University of the Western Cape

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September 2003

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Keywords

Kuils River,

Channelisation,

Cross-sectional profiles,

Hydraulic biotopes,

Macro-invertebrates,

Floral characteristics,

Flood effects,

Temporal changes,

Post-project monitoring,

River rehabilitation.

Abstract

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M.Sc. thesis in the Department of Earth Sciences, Faculty of Natural Sciences, University of the Western Cape.

Urbanisation and storm water input in the Kuils River catchment changed the flow of the river from ephemeral to perennial. This led to flooding problems in the Kuilsrivier central business district. The river was channelised in 2000 to increase the carrying capacity of the channel and thus to reduce the flood risk. This study aims to monitor the impacts of channelisation on the geomorphology and ecology of the Kuils River. This was done by selecting representative study sites upstream, within and downstream of the channelised reach. The geomorphological and ecological characteristics of the river were recorded in detail with changes tracked over a year period incorporating channelisation activities and winter floods. The objectives of the study were to determine (1) changes in the cross-sectional area and shape and substrata of the representative study sites; (2) aquatic macro-invertebrate families found and what they indicated about the water quality and general health of the river and their relationship to the hydraulic biotopes found; (3) what plant species occurred at the sites; (4) how the sites responded to the winter floods and (6) what the impacts were of the channelisation on the different parameters.

The cross-sectional area and shape of the channel were measured using the tachometry method of optical distance measurement (Gordon *et al.* 1992) with the aid of an electronic theodolite (Leica TC 307 model) and standard Leica prism fixed on a staff. The substratum and flow types were mapped using the habitat mapping technique of King and Schael (2001). A modified version of the SASS4 biological monitoring method (Thirion *et al.* 1995) was used to determine the macro-invertebrate assemblages while PRIMER V5 (Clarke and Gorley 2001) was used for the analysis. The vegetation data were collected by placing a measuring tape along selected cross-sections. The plant species with their percentage cover were assessed within a $1m^2$ quadrat along the length of the cross-section. PRIMER V5 was also used for the analysis.

The cross-sections showed that the two upstream sites had an active channel within a bigger macro channel. The site within the previously channelised reach had wide banks with a central low flow channel. Hardy macro-invertebrate families were found, indicating a severely impaired ecosystem. The flora consisted of cosmopolitan weed species. The Western Cape received exceptionally high rainfall during the winter of 2001. There was an upstream migration of bank erosion during May 2001 followed by massive bank failure during July 2001. The two upstream sites were subsequently channelised during October – November 2001 to replace a landowners land and to increase the channel's capacity to accommodate larger magnitude flows. The bank collapse during July 2001 could be attributed to the winter floods and downstream channelisation. The presence of the hardy macro-invertebrate families and cosmopolitan weedy plant species could be attributed to the fact that the Kuils River catchment is urbanised and extensively disturbed.

The impacts of the channelisation on the Kuils River were:

Impacts on geomorphology

- Channel widening and straightening resulted in a uniform channel shape.
- This reduced substratum and flow diversity.
- Channelisation was followed by an upstream migration of bank erosion which, in turn, was followed by a massive bank collapse during the following wet season.

Impacts on ecology

- The uniform channel shape and reduced substratum and flow diversities resulted in a reduced diversity of aquatic habitats.
- This correlated with a reduced diversity of aquatic invertebrates.
- Channelisation and bank re-construction disturbed the soil and the vegetation.
- This resulted in a higher diversity of plant species the following year, most of which were alien weeds.

Impacts on infrastructure

- Following channelisation, the upstream progression of bank erosion led eventually to undercutting of the Old Bottelary Road bridge pillars.

Declaration

I declare that *The impacts of channelisation on the geomorphology and ecology of the Kuils River, Western Cape, South Africa* is my own work, that it has not been submitted before for any degree or examination in any other university, and that all the sources I have used or quoted have been indicted and acknowledged as complete references.

Ruth-Mary Corné Fisher

Signed:……………………………………

September 2003

Acknowledgements

This thesis stemmed from a Water Research Commission funded project where the data collected for the project were also used for the thesis. I would like to thank the Water Research Commission for funding. The advisors on the project i.e. Prof. Kate Rowntree – Geomorphology – Rhodes University, Dr. Charlie Boucher – Vegetation – Stellenbosch University and Dr. Neil Armitage – Hydraulics – University of Cape Town are greatly thanked for valuable advise on the data collection and interpretation of the results.

I would also like to thank the project leaders, Dr. Jackie King, University of Cape Town (also advisor for the macro-invertebrates) and Mr. Theo Scheepers, University of the Western Cape, for their expert knowledge and encouragement throughout the project and thesis.

Prof. Lincoln Raiit and Mr. Frans Weitz identified the plant species and also made input into the interpretation of the results.

Mike Luger – Senior environmentalist and Roelof de Haan – Senior Engineer at Ninham Shand Consulting are thanked for the information on the channelisation methods used. They also provided background information on the Kuils River. Mike Luger provided the photograph used in Plate 5.4.

Furthermore, I wish to thank the students, especially Lindie Smith, Tracey van Willingh (Neé Solomons) and Chantel Petersen without whom I wouldn't have been able to do fieldwork in most occasions, and staff of the Earth Science Department for their comments, support, encouragement and willingness to assist.

CONTENTS

LIST OF FIGURES

LIST OF PLATES

LIST OF TABLES

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Rivers have been manipulated and altered to suit the needs of humans for the past few hundred years (Goudie 1981). Rivers and their associated environments were impacted upon when land-use changes occurred. Land-use changes occur when natural vegetation is removed for the cultivation of cropland, land for pasture, commercial forestry and urban development (Richards 1982). Land-use changes affect the runoff and sediment regimes of the catchment by increasing storm water runoff and erosion. This occurs because there is less vegetation to slow the water down as it runs down the hill (Richards 1982; United States Geological Survey (USGS) 2001).

Urban development is hydrologically the most extreme land-use change (Richards 1982). Urbanisation involves the building of houses, roads, pavements and parking areas leading to an increase in impervious area. All these impervious areas limit rainfall from entering the soil through infiltration and the rainfall becomes runoff in a smaller time-frame than in natural conditions. This means that the water will enter the receiving rivers more rapidly and decreases the time for a flood to reach its peak (Terpstra and van Mazijk 2001). Storm water sewers and wastewater treatment plants are built to remove increased runoff from roads and to treat human waste respectively. The storm water and treated effluent are discharged into the nearest river. As a result urban rivers typically experience increased flood frequencies and amplitudes downstream of the receiving rivers (Richards 1982; Fogg and Wells 1998; Terpstra and van Mazijk 2001; USGS 2001).

The increased flood frequency results, in most cases, in flooding problems in urban areas. The flooding problems are usually mitigated by channelisation. Channelisation involves straightening, widening and deepening of rivers to increase their capacity to carry greater floods (Gregory, Hockin, Brookes and Brooker 1985; Newbury and Gaboury 1993). Rivers have also been lined with concrete, wires and revetments to reduce bank erosion (Brown 1992; Luger 1998). Channelisation adversely impacts the natural functioning of river ecosystems. The background and aims of the present study will be discussed in subsequent sections.

1.2 Background to the study

Urbanisation and wastewater inputs in the Kuils River catchment have changed the flow of the river from ephemeral to perennial. Increased storm water runoff has heightened the risk of flooding in the lower parts of the catchment. Ninham Shand Consulting Engineers were contracted to "upgrade" the river section between the Van Riebeeck Road Bridge and the R300 in 2000 in order to reduce the flood risk in the Kuilsrivier central business district and the lower parts of the catchment. The term "upgrading" referred to increasing the carrying capacity of the channel by making it wider and deeper (M. Luger, senior environmentalist, Ninham Shand, pers. comm. 2002). The term "channelisation" describes the same activities, and so this term will be used from now to describe what was done to the Kuils River's channel.

The impacts of channelisation on European and North American rivers are well documented in the international literature. This is not the case in South Africa where in some cases the impacts of channelisation works are not even monitored after completion (M. Luger, senior environmentalist, Ninham Shand, pers. comm. 2000). This provides the rationale for the present study.

The primary focus of the study was to record the impacts of channelisation as described above. However, the Western Cape received exceptionally high winter rains in 2001. The winter floods had to be taken in consideration as it also influenced the outcome of the study and had to be incorporated into the aims and objectives.

1.3 Aims and objectives

This study aims not only to highlight the impacts of channelisation on the geomorphology and ecology of the river, but also to expose the damages to the infrastructure. This study is important for all rivers in the Western Cape since the lessons learnt from the Kuils River can be applied to other rivers, if the same type of work is to be done. It should also lead to recommendations on how to manage urban rivers better and advise on possible rehabilitation methods for the Kuils River.

The second aim of the study is to record in detail the changes to the geomorphological and ecological characteristics of the river. This was done by selecting representative sites within the different reaches upstream, within and downstream of the area of channelisation, and then to track changes over one year of engineering activities and winter floods.

It is difficult to place the present study in the specific discipline of geomorphology or ecology since it is a combination of both. The other difficulty with the study is that it is not purely geomorphology or ecology, and therefore only certain aspects of the two disciplines will be covered. Therefore, key questions were formulated around the different aspects to be covered in this study.

Key questions are:

- *Geomorphology.* What is the cross-sectional area and shape of representative study sites in each reach? What substrata occur in each reach? How do these characteristics change over time and with the different winter floods and channelisation?
- *Invertebrates.* What aquatic macro-invertebrate families occur at each site? What do these indicate about water quality and the general health of the river? How do they relate to hydraulic biotopes? How might they be related to, or correspond to, channelisation activities and winter floods? How does biodiversity differ at the sites?
- *Vegetation.* What species of plants occur in the water and on the banks at each site, and how might they be related to, or respond to, channelisation activities and winter floods? How does biodiversity differ at the sites?

1.4 Structure of the thesis

Chapter 2 outlines the literature reviewed on the different aspects identified, to answer the key questions outlined above. Freshwater ecology (riparian vegetation and macro-invertebrates), fluvial geomorphology (channel types and patterns, and the factors involved riverbank stability and causes of instability), the impacts of urbanisation on river hydrology and channel morphology, and the impacts of channelisation (different types of channelisation and their impact on channel morphology, sediment, flow regimes and ecology) will be discussed. Chapter 3 describes the Kuils River system, catchment characteristics and the anthropogenic impacts on the river, and provides a description of the study sites. The methodology followed to collect or sample and analyse the data necessary to answer the key questions identified above is described in Chapter 4. Chapter 5 outlines the results obtained during the study period, while Chapter 6 discusses the conclusions and recommendations drawn from this research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Chapter 1 gave a brief introduction to how humans have manipulated and altered river environments to suit their own needs. This literature review will focus specifically on the impacts of urbanisation (since the study area falls in an urban area) as well as on the consequent impacts of channelisation on the ecology and geomorphology of rivers. An understanding of the natural ecological and geomorphological processes within river systems is needed in order to determine how humans have impacted on river systems. Thus, an overview of the general ecological and geomorphological concepts relevant to this study will precede sections on the impacts of urbanisation and channelisation.

Only certain aspects of the ecology and geomorphology will be dealt with here. The limitations of the literature review will be given in a short introduction to the respective sections. The aspects dealt with here will help to answer the key questions posed in Section 1.3.

2.2 Freshwater ecology

Freshwater ecology encompasses the disciplines of hydrology, hydraulics, fluvial geomorphology, sedimentology, chemistry (water quality), botany (riparian and in-stream vegetation) and zoology (benthic invertebrates and heptafauna) (King, Brown and Sabet in press). This study will only focus on macro-invertebrates, riparian and in-stream vegetation, and fluvial geomorphology. Fluvial geomorphology is discussed in Section 2.3.

One of the key questions posed for the macro-invertebrates and vegetation assemblages was what families and species occurred in the study area. One way of addressing this was to study the seasonal variations in the two parameters. Another way was to do the sampling during a specific season and to repeat the sampling during the same season the following year. The second option was chosen since sampling during one season would allow for data input and analyses the rest of the year. The macro-invertebrates could also have been related to the physical and chemical water quality parameters, just as the vegetation assemblages could have been related to soil chemistry, slope aspect and angle. However, as this would not have filled with the aims of the study and will thus not be addressed in the literature review.

2.2.1 Macro-invertebrates

The term benthic macro-invertebrate refers to invertebrate organisms that inhabit the bottom substratum (sediments, debris, logs, macrophytes and filamentous algae) of freshwater habitats for at least part of their life cycle. Macro-invertebrates are those retained by mesh sizes more than or equal to 200 to 500 µm (Rosenberg and Resh 1993).

This section will focus on the different macro-invertebrates and where they occur in river systems, how macro-invertebrates can be used to detect changes in the environment through biomonitoring, how changes in the water quality of rivers impact on macro-invertebrate community composition in urban areas, and how disturbances to the channel itself will also impact on the macro-invertebrates.

Vannote, Minshall, Cummins, Sedell and Cushing (1980) proposed the River Continuum Concept (RCC) based on North American rivers. The concept views all rivers as having continuous gradients of physical and chemical conditions that are continuously and progressively modified from the headwaters to the sea. Thus, the structural and functional characteristics of river communities are adapted to conform to the most probable position or average state of the physical system, with invertebrate communities colonising those parts of the river where physical, biological and chemical conditions are suitable for them. Those rivers with similar requirements will exhibit species or family assemblages characteristic of particular reaches of the river (Vannote *et al.* 1980; Davies and Day 1998). The presence of species assemblages in a specific reach will depend on the fluvial geomorphic processes characteristic of that reach. The fluvial geomorphic processes regulate the energy inputs, organic matter transport, storage and use by macro-invertebrate functional feeding groups: i.e. shredders (e.g. mayflies, stoneflies and caddisfly larvae), scrapers or grazers (e.g. snails), collectors or deposit feeders (e.g. worm and worm-like organisms – such as oligochaetes and chironomids), and predators (e.g. damselfly and dragonfly). Shredders utilize coarse particulate organic matter (CPOM > 1mm) such as leaf litter, with a significant dependence on the associated microbial biomass. Collectors filter fine and ultra-fine particulate organic matter (FPOM and UPOM) (FPOM = 50µm – 1mm; UPOM = 0.5 - 50µm) from the transport or gathering of sediments. They also depend on the microbial biomass associated with the particles (primarily on the surface) and products of microbial metabolism for their function. Scrapers (or grazers) are primarily adapted to the shearing ("cutting") of attached algae from surfaces and tend to dominate, following shifts in the primary production in medium-sized rivers.

The macro-invertebrate community characteristics are based on river size according to Strahler (1969). Rivers in headwater zones (orders 1-3) are influenced by riparian vegetation that reduces autotrophic production by shading and by the contribution of large amounts of allochthonous detritus. Rivers in headwater zones interact with the landscape to the greatest extent and therefore invertebrates that are accumulators, processors and transporters of material from the terrestrial system will dominate these systems. Shredders and collectors co-dominate the headwater zones, reflecting the importance of riparian zone CPOM and FPOM – UPOM. Small numbers of predators and grazers are found. However, species diversity tends to be low due to the biological community assemblages consisting of species that can function in a narrow temperature range (as in the headwaters) on a restricted nutritional base (Vannote *et al.* 1980).

According to the RCC the organic input becomes less important as the river order increases (orders 4-6). Autochthonous primary production and organic transport from upstream increases, and algal or rooted vascular plant production occurs. The zone through which the river shifts from heterotrophic to autotrophic is dependent on the degree of shading. Deeply incised rivers with sparse riparian vegetation may be heterotrophic due to side slope (i.e. canyon) shading. Typically, large numbers of collectors and grazers with small numbers of shredders and predators are found in higher order rivers. The total community diversity is the greatest in these river sections because temperature variations tend to be maximised (Vannote *et al.* 1980).

Rivers greater than 6th order receive FPOM from upstream processing of dead leaves and woody debris. The influence of riparian vegetation is insignificant where primary production is often limited by depth and turbidity (Vannote *et al.* 1980). These rivers have low gradients and the channel bed consists of fine alluvial material (Rowntree and Wadeson 1999). Benthic species diversity decreases as bed material size approaches bed loads. Sand beds harbour a macro-invertebrate assemblage characterised by species adapted to shifting sand beds, typically small chironomids (Shields, Knight and Cooper 1995), and densities are low. The low densities are attributed to shifting substrates, siltation and the absence of aquatic vegetation while logs and rocks provide stable substrates for organisms in these environments.

The removal of these latter substrates will result in lower densities of macro-invertebrates that rely on them (Junk, Bayley and Sparks 1989). Collectors are the dominant macro-invertebrates found in higher order rivers, and predators represent a small percentage of invertebrate fauna. The relative dominance of predators tends to change little with stream order as they can be found in all stream orders at more or less the same percentage (Vannote *et al.* 1980).

Winterbourn, Rounick and Cowie (1981) applied the RCC to rivers in New Zealand to ascertain whether New Zealand ecosystems were different than suggested by the RCC, and if so, why, and if not, was there something wrong with the model? They found that New Zealand rivers differed in a number of ways from those the model was based on. The differences were attributed to the generally steep and youthful topography, the heavy and temporally unpredictable rainfall, and the nature of the upland catchments of New Zealand.

It is difficult to find a whole river system, as theorised by the RCC, in South Africa today. This is because humans have degraded most rivers in South Africa. For example, rivers often flow over a concrete bed in urban areas. The degradation is sometimes so severe that the natural communities of organisms often cannot survive (Davies and Day 1998).

Macro-invertebrates, together with riparian vegetation and fish indices, can be used as indicators of environmental health or degradation. Biomonitoring can be defined as: "the systematic use of biological responses to evaluate changes in the environment with the intent to use this information in a quality control programme. These changes are often due to anthropogenic sources." (Rosenberg and Resh 1993:3) Macro-invertebrates are useful for biomonitoring of environmental degradation because of their relative immobility, life-cycle length and ease of sorting and preservation. They also integrate change over time, hence the importance of their immobility (Campbell 1978; Rosenberg and Resh 1993). There are also difficulties in using macro-invertebrates for biomonitoring. These include a lack of knowledge of the species involved and the natural conditions operating (e.g. macro-invertebrate distribution and abundance can be affected by factors other than water quality), and the fact that adequate keys are also not always available for identification purposes (Rosenberg and Resh 1993).

Different countries use different indices for macro-invertebrates. For example the British use the Biological Monitoring Working Party (BMWP) and the Simpson Diversity Index (Ellis *et al.* 1997) method (Thirion, Mocke and Woest 1995; Ellis, Revit and Llewellyn 1997). Dr. F.M. Chutter adapted the BMWP to South African conditions and developed the South African Scoring System (SASS) (Thirion *et al.* 1995). The method used previously (Biotic index) was time-consuming, laborious and required considerable expertise, as the macro-invertebrates had to be identified to species level. SASS was designed not to be too academic, so that field operators with minimal training in aquatic invertebrate taxonomy would be able to recognise these organisms at the family level with the aid of illustrations provided (Thirion *et al.* 1995). The basics of SASS were well established, but were still being refined as new information on invertebrates in different parts of the country became available. The first version of the system became known as 'SASS4' (Dallas and Day 1998), while SASS5 is currently in operation (www.csir.co.za/rhp/).

SASS works on the premises that each taxon (family) of invertebrates from South African rivers is allocated a score. The scores range from 1 for those families most tolerant to organic pollutants, to 15 for those most sensitive to organic pollutants. The combined scores for all the families at a particular site will thus be high if the families are mostly pollution-sensitive, and low if they are mostly pollution-tolerant. High total scores are thus expected for rivers with clean water, and low total scores for severely polluted rivers. To get the Average Score Per Taxon (ASPT), the total score is divided by the number of families present.

SASS has been used extensively in rivers of the Western Cape (H. Dallas, Freshwater ecologist, University of Cape Town, pers. comm. 2003) and as part of the River Health Project (www.csir.co.za/rhp/). Examples of rivers in the Western Cape where SASS has been used include the Lourens and Silvermine (King, Scheepers, Fisher, Reinecke and Smith in press), the Liesbeeck (Davies and Day 1998), Diep, Mosselbank, Eerste, Kuils, Bottelary, and Sand Rivers and rivers of Table Mountain (City of Cape Town, Scientific Services). Table 2.1 provides summarised SASS4 data on selected rivers in the Western Cape.

Table 2.1: SASS4 data on selected rivers in the Western Cape (City of Cape Town, Scientific Services). * Data from Davies and Day (1998)

	River and sampling site	SASS4 score	No. of taxa	ASPT
Mountain streams	Skeleton Gorge Stream	53	6	8.83
	Window Gorge stream-Table Mountain	76	8	9.50
	Diep River-upstream of Rhodes Drive	93	12	7.75
	Disa River-Small tributary	87	12	7.25
Lower reaches/Urban rivers	Kuils River at Bottelary Road	57	13	4.38
	Liesbeeck River-old canal	37	10	3.70
	Diep River-upstream of N7 bridge	32	9	3.56
	Disa River-upstream of Disa River Road bridge	71	16	4.44
	Bottelary River-upstream of Bottelary Road	49	12	4.08
	Liesbeeck River-Canal in Rondebosch*	21	5	4.30

Dallas (2002) provided guidelines for the interpretation of SASS4 data.

Table 2.2: Preliminary guidelines for the interpretation of SASS 4 data for the Western Cape separated on the basis of sub-regions (Dallas 2002).

Sub-region	SASS 4 Score	ASPT	Comments
Mountain stream and foothills (cobble bed)	>140	>8	Water quality natural, biotope diversity high.
	<140	>8	Water quality natural, biotope diversity reduced.
	>140	<8	Borderline case between water quality natural and some deterioration in water quality, interpretation should be based on the extent by which SASS4 exceeds 140 and ASPT is <8.
	100-140	6-8	Some deterioration in water quality.
	<100	<6	Major deterioration in water quality.
Foothills (gravel beds) and lowland floodplains	>110	>7	Water quality natural, biotope diversity high.
	<110	>7	Water quality natural, biotope diversity reduced.
	>110	>7	Borderline case between water quality natural and some deterioration in water quality, interpretation should be based on the extent by which SASS4 exceeds 125 and ASPT is <7.
	70-110	5-7	Some deterioration in water quality.
	<70	<5	Major deterioration in water quality.

SASS scores do not only depend on the water quality, but also on the habitat available to the organisms. Thus, low habitat diversity can also lead to low SASS scores (Thirion *et al.* 1995). This was evident in Skeleton Gorge and Window Gorge streams where low SASS scores were found with high ASPTs. According to Table 2.2 in these streams, water quality was natural, but the habitats were reduced. The Diep and Disa Rivers showed some deterioration in the water quality. The rivers in urban areas all showed major deterioration in water quality.

The macro-invertebrate species or families found at a particular site will indicate the general health of the river, since different species live in water with particular combinations of physical and chemical attributes. Thus, alterations in water quality will affect different species or families to different degrees. Some species will be eliminated while others will be allowed to invade. Changes in water quality may also cause shifts in the physical position of riverine communities (Davies and Day 1998). Gerber and Gabriel (2002) provide information on the different macro-invertebrate families found in South African rivers, as well as a sensitivity scale based on the family's tolerance to pollution. A scale of 1-5 indicates a high tolerance to pollution, 5-10 a moderate tolerance to pollution and 10-15 low tolerances to pollution.

The following section outlines the effects of altered water quality on macro-invertebrate assemblages (families present), especially in urban areas.

Ellis *et al.* (1997) found that rivers receiving runoff from roads in the outer London Metropolitan region showed reductions in the mean Biological Monitoring Working Party (BMWP) taxa scores from 25 to 18, with species richness decreasing from 13 to 8. Biotic scores in the River Roding, London, United Kingdom dropped to a minimum at locations receiving runoff from roads. The Simpson Diversity Index of the River Roding reflected an aquatic community under stress where only well-adapted species would be able to survive (Ellis *et al.* 1997).

Winter and Duthie (1998) and Shieh, Kondratieff, Ward and Rice (1999) studied the effects of different land uses on macro-invertebrate assemblages. Both studies had unimpacted (control) sites, and sites impacted upon by agriculture and urban development. Winter and Duthie (1998) found higher abundances of deposit feeders (i.e. Oligochaeta) and filtering collectors (i.e. Simuliidae and Bivalvia) in urban than in agricultural sites. Shieh *et al.* (1999) found that the most abundant macro-invertebrates in an impacted Colorado plains river were Ephemeroptera, Trichoptera, Chironomidae, Simuliidae and Oligochaeta. Plecoptera and Lepidoptera were only found at the control site. The control site also had the highest species richness, while the lowest species richness was found at the sites downstream of domestic and industrial effluents. The decrease in species richness was accompanied by a substitution of taxa from less to more pollution tolerant. Taxa such as Oligochaeta, Nematoda, Simuliidae and Chironomidae were abundant while other insects were absent or rare in the sites impacted upon by urban effluents.

Beasley and Kneale (2002) studied the impacts of metals and polycyclic aromatic hydrocarbons (PAHs) on macro-invertebrates in urban rivers. They found that the majority of Ephemeroptera (mayflies) and Plecoptera (stoneflies) species were sensitive to metal contamination. There were increased densities of Chironomidae and decreased densities of Baetidae, Heptageniidae and Ephemerellidae in areas exposed to a metal mixture of cadmium, copper, and zinc at chronic criteria levels. A tolerance continuum was also identified in the order of Chironomidae > Trichoptera > Plecoptera > Ephemeroptera. The dominant macro-invertebrate groups shifted from Ephemeroptera at the forested site, to Chironomidae at the agricultural site and Oligochaeta at the urban site. Unique species at the urban sites were limited to the most tolerant groups such as Oligochaeta (55%) and Diptera (24%).

Aquatic ecosystems experience periodic disturbances either as a result of water quality problems as outlined above, through flooding, or due to habitat disturbances. For example, plants in the riparian zone around lakes are periodically inundated, but no damage occurs since the flooding is of short duration. Macro-invertebrates may find shelter under rocks or hang on to vegetation during high flows. Organisms are adapted to these short-term disturbances, but can be adversely affected by catastrophic events (Wydoski and Wick 2000). Catastrophic events considered in this study include the loss of habitats due to flooding and channelisation. Floods impact on macro-invertebrates by removing the available habitat and displacing them (Davies, O'Keeffe and Snaddon 1993; Wydoski and Wick 2000). Floods can also cause extensive bank erosion, resulting in the sediment deposition in the channel (Section 2.3), which affects the substratum. The impacts of channelisation will be discussed in Section 2.5.

Benthic invertebrates re-colonise disturbed river habitats through four mechanisms (Gore 1985). The first one is called drift, where the invertebrates drift from upstream source communities (Gore 1985; Davies *et al.* 1993; Wydoski and Wick 2000). Invertebrates drift in three ways: Catastrophic – due to unpredictable disturbances such as flow fluctuations and habitat disturbances; Behavioural – due to activity patterns; and Constant. Drift mechanisms are used to disperse larvae to downstream reaches. The females lay their eggs in upstream reaches and the larvae will hatch from them as they drift downstream, allowing rapid colonisation throughout the river system (Davies *et al.* 1993). It was found that drift is triggered by solar cues as signals for foraging and internal physiological change, changes in habitat and the depletion of local food sources. Drift also occurs seasonally with the highest rates in early spring and autumn (Gore 1985). The second method of invertebrate dispersal entails the upstream migration of invertebrates to establish communities in degraded river reaches (Gore 1985). The third method entails the invertebrates moving through the substratum (Gore 1985; Wydoski and Wick 2000) or from adjacent bank storage areas (Gore 1985). The latter method of re-colonisation occurs particularly where the substratum and floodplain material are unconsolidated and porous. Non-insect invertebrates and aquatic insect larvae, nymphs and adults migrating from the hyporheos, which is the region within the bed, will accelerate the establishment of a benthic community in degraded reaches (Gore 1985). The fourth method entails colonisation by ovipositing adult female aquatic insects. The adult females emerge from downstream reaches and fly upstream where they deposit their eggs. Ovipositing in upstream reaches is thought to compensate for the general downstream drift of the larval and nymphal stages of their life cycle. Thus, these two methods complement each other and ensure a healthy stock of invertebrates in the whole river system (Gore 1985).

2.2.2 Riparian and in-stream vegetation

The vegetation found along the river corridor is called riparian vegetation (Rowntree 2000), while the vegetation growing in the channel is called in-stream vegetation. This section will focus on the spread of alien plant species, and how disturbances impact on vegetation assemblages. Two disturbances are important in this study: flooding and the disturbance of the soil during channelisation.

The riparian zone includes bottomland (areas receiving surface and subsurface water from a river for at least part of the time), floodplain, and river bank vegetation communities within the 100-year flood lines. The riparian zone functions to: connect to the low-flow channel in such a way that forest vegetation attenuates incoming sunlight, therefore influencing ground surface and water temperatures; contributes organic material providing nutrients and habitat; alter flow hydraulics and sediment movement; and provide low velocity, shallow-water nursery habitat for young fish (Wohl 2000a).

Aquatic plants (macrophytes) play an important role in the structure of in-stream habitat and the processes that occur. Macrophytes provide structural complexity and heterogeneity to the habitat and substratum and provide cover for other organisms as well as energy to the system through primary production. Macrophytes can grow abundantly in the shallow, low-energy streams due to low flow velocities and areas of fine nutrient-rich sediments (Clarke 2002).

Europeans introduced many plant species from elsewhere through agriculture, forestry and early settlement, which proved to be very troublesome in South Africa. This introduced or alien vegetation may out-compete the indigenous species and come to dominate a region in the absence of co-evolved parasites or predators (Lamp and Collet 1976). Alien invaders in the riparian zone of Western Cape rivers in South Africa include *Acacia longifolia, A. cyclops, A. saligna* and *Sesbania punicea* (Henderson 1995; Davies and Day 1998). These plants can also be referred to as weeds where a weed is a "plant growing in the wrong place" (Lamp and Collet 1976: 6). Weeds are found in all areas, but they thrive in urbanised catchments where there is an endless supply of weed species (Moses and Morris 1998). They grow rigorously and rapidly in their new environment since no natural predators are present to keep them within bounds and because they have the ability to produce large quantities of seeds and build up large seed reserves (Lamp and Collet 1976). Roberts (1981) defined seeds to include fruits and true seeds, but exclude spores or propagules that are produced vegetatively. The seed reserves are termed seed banks, which are defined as all the detached viable seeds of a plant species at a specific time present in the soil and on its surface (Roberts 1981; Cavers 1994).

Seeds in the seed bank are subjected to cycles of hydration and dehydration in response to precipitation patterns (Cavers 1994). Their germination is thus dependent on moisture conditions, where the exposed seed will germinate if there is enough moisture input. (Grime 1979). Germination is also dependant on exposure to light and temperature fluctuations (Grime 1979; Roberts 1981), where exposure to periods of low temperature or desiccation may overcome dormancy (Roberts 1981).

Germination is also dependent on soil disturbances (Grime 1979; Roberts 1981). Disturbances are important because they can prevent competitive exclusion by periodic population reduction of dominant species. Species richness is also maintained by environmental disturbances (Brock and Rogers 1998). Grubb (1988) defined a disturbance as any mechanism that limits plant biomass by causing its total or partial destruction. A tight coupling exists between disturbances and germination, where germination should happen immediately after the disturbance event; otherwise little chance is left for establishment. For example, plants in a forest emerge from the seed bank when a fallen tree or fire creates a sufficiently large gap. Different species will be favoured by different disturbance events (Grubb 1988). Two disturbance events are described in this study. One is the physical disturbance of the soil during channelisation, and the other is the disturbance caused by flooding.

The impacts of channelisation are described in Section 2.5, with broad information on how specifically the vegetation is disturbed. The soil is also disturbed during the ploughing of soil in the cultivation of crops. Similar soil disturbances occur during the construction phase when a river is channelised. Therefore, one can relate the two different circumstances of soil disturbance and can use the ploughing of arable land as an example of how the soil is disturbed. The disturbance during ploughing results in the unearthing of buried seeds and the exposure of the seeds to light. These two factors together with moisture inputs initiate germination. The disturbance results in the germination and appearance of large numbers of weed species seedlings, since the main contributors to the seed bank in arable soils are annual weeds (Grime 1979; Roberts 1981). Regnier (1994) found that weed species diversity in the seed bank of cornfields increased as soil disturbance decreased. The weeds identified in Regnier's study included *Sonchus oleraceus, Medicago lupilina, Plantago rugelli, Rumex obtusifolius, Plantago major, Plantago lanceolata, Scirpus* species, *Chenopodium album, Portulaca oleracea, Rumex crispus, Taraxacum officinale, Eleusine indica.* Roberts (1981) also found that the seed bank of arable soils in the United Kingdom included *Amaranthus* species, *Echinichloa crus-galli, Digitaria sanguinalis, Setaria* species, *Sinapsis arvensis, Chenopodium album, Polygonum aviculare,* and *Tribulus terrestris.*

Floods act as transport mechanisms, distributing plant propagules and importing and exporting sediment and nutrients. Floods also provide moisture in dry landscapes and could lead to waterlogged and anoxic soils that produce severe stress for terrestrial plants in other environments (Friedman and Auble 2000). Flood flows effect vegetation by removing the plants through bank failure after fluvial erosion of sediment at the base of the bank; damaging it or burying it under sediment (Brookes *et al.* 2000; Friedman and Auble 2000; Wohl 2000b). Damaged or semi-buried vegetation may die or revive, with complete burial killing plants. Resprouting and regrowth may occur in partially buried vegetation (Brookes *et al.* 2000). High flow velocities during floods rework unconsolidated sediment that decreases substrate stability required for vegetation establishment (Rountree *et al.* 2000). Floods can also create bare, but moist sites necessary for the establishment of seedlings of many plant species, mostly invading plants. Floods disperse the seeds of many bottomland species through floating vegetative propagules such as rhizomes or branch fragments. Flooding often lead to a predictable sequence of herbaceous species along the bottomland (Friedman and Auble 2000).

Timoney *et al.* (1997) compared and contrasted vegetation development after flooding, fire and logging disturbances in the Peace River lowlands, Canada. They found that primary succession was a flood-origin process and that secondary succession might have been autogenic through gap dynamics mediated by nursery logs and buried wood following fire and logging. Flooding and sediment deposition appeared to be the primary process of forest origin and accounted for 72%, with fire-origin accounting for 29% of the undisturbed forests. Certain vegetation species or types were restricted to certain landforms where, for example, the flood-origin pure balsam poplar was found nearer to the active channel than spruce and seldom form extensive stands. Fire origin species were found on alluvium at a distance from the river. Primary succession in the Peace River valley began with the pure willow stage and progressed through either a willow-alder or alder stage before the establishment of trees.

2.2.3 Summary

Macro-invertebrates occupy certain river reaches depending on the fluvial geomorphic processes characteristic of that reach and the feeding methods used. Shredders (mayflies, stoneflies and caddisflies) and collectors (Oligochaeta and chironomids) co-dominate the headwater reaches, while collectors, shredders and grazers (snails) are found in the middle reaches. Collectors dominate the lower reaches with predators (damselflies and dragonflies) found in all the reaches. Macro-invertebrates can also be used as indicators of environmental health, in a process called biomonitoring. The South African Scoring System (SASS) is the method used in South Africa. Each macro-invertebrate family is allocated a score depending on the family's tolerance to organic pollution. Low scores are allocated to families most tolerant to pollution and high score are allocated to families with low tolerance to pollution. High total scores are thus expected for rivers with clean water and low total scores for severely polluted rivers. According to Table 2.1 all the rivers in the lower reaches or urban areas have been subjected to a major deterioration in their water quality.

Europeans introduced many plant species from elsewhere through agriculture, forestry and early settlement in South Africa. This introduced or alien vegetation may out-compete the indigenous species and come to dominate a region in the absence of co-evolved parasites or predators. Alien invaders in the riparian zone of rivers in the Western Cape in South Africa include *Acacia longifolia, A. cyclops, A. saligna* and *Sesbania punicea*. These plants can also be referred to as weeds. Weeds are found in all areas, but they thrive in urbanised catchments where there is an endless supply of weed species. Weeds grow rigorously and rapidly in their new environment since no natural predators are present to keep them within bounds and because they have the ability to produce large quantities of seeds and build up large seed reserves.

Aquatic ecosystems also experience periodic disturbances. The disturbances important here include flooding and channelisation. The impacts of channelisation on aquatic ecosystems are discussed in Section 2.5. Flooding can cause bank erosion and sediment deposition that will remove or cover habitat available to macro-invertebrates. Flooding can also remove the vegetation through bank erosion, damage it or bury it under the sediment. The macro-invertebrates re-colonise disturbed habitats by drifting downstream, upstream migration, movement through the substratum and ovipositing by adult female insects. Floods also act as transport mechanisms by distributing plant propagules. Seeds may be transported downstream with the water and within the sediment. Rapid germination of mostly invading plants usually occur on bare moist sites created by the floods.

2.3 Fluvial geomorphology

Rivers are dynamic and act as agents of erosion and transportation, removing water and sediment supplied to them (Knighton 1984).

This section will give an overview of some concepts of fluvial geomorphology important in this study. An overview of channel types and plan-form patterns and how these patterns change due to environmental factors, factors controlling river bank stability and causes of river bank erosion will be given. Fluvial geomorphology also deals with sediment transport through time, which is directly related to hydrological processes. A basic understanding of these two processes is reported on here without an in-depth and detailed report on the relationship between the two processes.

2.3.1 Channel types and plan-form patterns

This section outlines the types of river channels and plan-forms found, and how these plan-forms change through time.

River channels are classified according to their bed material in two broad types: bedrock and alluvial channels. Channel form in bedrock channels is highly dependant on the geology and its resistance to erosion (Rowntree and Wadeson 1999). Bedrock channels usually occur in short sections in the steep headwater reaches (Knighton 1998). Channel morphology is determined by its confinement between outcrops of rock and the material of the bed and banks. Alluvial channels are formed within the sediment being transported, and acquire their dimensions, shape, pattern and gradient as a response to the hydraulic characteristics of the river. Both the bed and banks are composed of sediment in temporary storage within the system. Channel form in alluvial channels is the result of a balance between the available sediment and the transport capacity of the flow. Bedrock and alluvial channels commonly co-exist in many catchments around the world. These channels are known as bedrock controlled or mixed channels. Some reaches may consist of bedrock within predominant alluvial channels and vice versa. Mixed channels in South Africa include the Sabie, Tugela, Olifants, Buffalo (Rowntree and Wadeson 1999), Sand and Vet Rivers (Gabriel, Grobler and Thirion 1999). Bedrock channels tend to dominate many of the highland areas while alluvial channels dominate the lowland areas (Rowntree and Wadeson 1999).

River zonation concepts of the 1980s viewed the river as a continuum rather than as distinct fragments. For example Vannote *et al.* (1980) argued that river ecosystems respond to the flow of energy and matter through the system rather than to site-specific variables. Classification, however, requires that systems be sub-divided into their component parts. Therefore, longitudinal river zones provide a basis for "within" river classification that can be used to identify geomorphologically similar streams, but also to retain the concept of longitudinal downstream changes. Many long profiles have a natural progression from mountain stream through foothill stream to lowland rivers. Mountain streams are characterised by steep gradients over bedrock and boulders. Foothill streams are characterised by moderate gradients over relatively coarse, but mobile material (small boulders and cobbles). The bed material of lowland rivers tends to be of gravel size or finer (Rowntree and Wadeson 1999).

Alluvial channels can be further divided based on the size of their bed material. Sand, gravel, cobble and boulder bed channels are generally recognised.

Sand beds

Channel beds are dominated by sand and small percentages of gravel (Rowntree and Wadeson 1999). Gravel deposits can also have a significant influence on the sand bed where subsurface gravel deposits become exposed during high flow events (Neil and Hey 1982). Rowntree and

Wadeson (1999) identified two pools separated by a wider, shallower riffle with surface armour of fine gravel in the Olifants River, South Africa. Channel beds are highly mobile and readily moulded into different bed forms under different flow regimes (Knighton 1998; Rowntree and Wadeson 1999). They are also generally more homogenous than other river types (Rowntree and Wadeson 1999).

Gravel beds

Channel beds are dominated by coarse gravel or cobbles and small percentages of sand (Knighton 1998; Rowntree and Wadeson 1999). Sediment transport usually occurs during higher than normal discharges with slow rates of gravel transport. Low sediment loads and relatively large proportions of coarse material are favoured in gravel bed channels (Rowntree and Wadeson 1999).

Cobble and boulder beds

Channel beds are dominated by large clasts (>256 mm), which require high thresholds of stream power before movement takes place (Knighton 1998; Rowntree and Wadeson 1999). Finer material is transported through the spaces between immobile larger cobbles and boulders. These channels have a wide particle size range and are poorly sorted (Rowntree and Wadeson 1999).

The channel types described above can have different plan-forms. The plan- form depends on (1) the discharge regime - depending on climatic and soil conditions; (2) slope or gradient of the channel – providing stream power to erode (Alabyan and Chalov 1998); and (3) the erodibility or resistance of the bed and banks – depending on the size of the sediment being transported (Alabyan and Chalov 1998; Rowntree and Wadeson 1999). The balance between erosion and deposition as well as local flow patterns significantly influences plan-form stability. Bank erosion processes (Section 2.3.2) are also an important factor in driving plan-form changes, meander development (discussed later) and channel width adjustment in alluvial rivers (Casagli, Rinaldi, Gargini and Curini 1999). Vegetation is also important since it may effectively stabilise sediments in the channel either seasonally or for much longer periods (Sear 1996).

Schumm (1963) classified plan-forms as tortuous, irregular, regular, transitional and straight. The meander bends are deformed in most tortuous channels and the typical smoothness of the ideal meander curve is absent. Irregular meanders are irregular only with respect to the smoothly curved meander pattern. Small and large meanders occur. The smaller meanders may be related to periods of low flow, while larger ones occur in response to higher flow perhaps related to the mean annual floods. The regular pattern approximates a regular waveform in plan view. The transitional pattern has very flat curves, which may also approach a regular waveform in plan view. The straight pattern occurs in channels with only minor bends showing no regularity.

Rosgen (1994) classified channel types according to sinuosity. Sinuosity is defined as the length of the active channel divided by the valley length. Meandering channels have a sinuosity of more than or equal to 1.5. Rosgen's classification yielded forty-one channel types. The largest number of channels fall in types A to D, representing relatively straight (A), low sinuosity (B), meandering (C) and multiple (D) channel types (Rosgen 1994; Knighton 1998). Alabyan and Chalov (1998) identified three basic patterns consisting of straight, meandering and braided. Transitional forms or subtypes included anastomosing, split, wandering (meandering channel with braid bar) and meantertal (meandering thalweg). Rowntree and Wadeson (1999) identified two main groups of channel plan-form patterns as single thread and multi thread. Single thread patterns are further divided into straight or sinuous and meandering. Multi thread patterns are further divided into braided and anastomosing or anabranching.

Straight channels

Very few channels are truly uniformly straight (rare actually) with most displaying some degree of sinuosity (Richards 1982; Rowntree and Wadeson 1999). The difference between straight, stable sinuous and meandering channels is the observed degree of sinuosity and lateral mobility of the channel. Straight or stable sinuous channels lack the mobility of a meandering channel and are associated with a low power to resistance ratio. The low sinuosity also reflects relatively immobile sediments (Rowntree and Wadeson 1999).

Meandering channels

Meandering channels are actively migratory as a result of selective bank erosion and point bar development. Sufficient stream power is needed for selective bank erosion and sediment deposition. Meandering is thus the result of a medium to high stream power to resistance ratio (Rowntree and Wadeson 1999). Higher rates of total or potential energy expenditure on steep valley surfaces result in increased total sinuosity. This increases bed area by lengthening the channel and decreasing slope or by increasing channel width. Excess stream power (energy) is dissipated in overcoming extra frictional resistance, where excessive energy in natural rivers is spent on lateral or bed erosion depending on the geological structure of the valley. An incised channel is formed if bed erosion dominates and a wide floodplain is formed in the case of prevalent lateral erosion (Alabyan and Chalov 1998). In general, meandering occurs as a result of bank erosion and sediment transfer where the stream loses its stability, but sufficient bank resistance needs to be in place to prevent over-widening (Alabyan and Chalov 1998; Rowntree and Wadeson 1999). Meandering also tends to increase where both the bed and banks consist of fine material (Rowntree and Wadeson 1999). However, there is as yet no completely satisfactory explanation of how and why meanders develop. Meanders are not simply the result of random disturbances as suggested by the existence and underlying regularity of natural river bends. Meander initiation can be explained by regarding the oscillation of flowing water either as an inherent property of turbulent flow or as a result of the interaction between the flow and the mobile channel bed, an interaction where sediment transport is an essential element (Knighton 1984).

Schumm and Khan (1972) performed a series of experiments in a large flume to determine the effects of slope and sediment load on channel patterns. The channel remained straight at very low slope and sediment load, but a meandertal channel was formed at greater discharges and gradients. The thalweg sinuosity increased with increases in gradient and sediment loads. The meandertal channel was not a truly meandering channel. A truly meandering channel was formed when a suspended sediment load of concentrations of kaolinite was introduced into the flow. The clay stabilised the emerging alternate bars to form point bars. Similar events occurred where a cut-off on the Sutlej River, Pakistan caused the introduction of large sediment loads into a stable irrigation canal.

Ackers (1982) also looked at the initiation of meanders in experimental flumes. It was found that a straight channel alignment in sand bed channels could only be maintained at channel gradients and bed transport rates below some threshold value. The channel would start to meander above this threshold value. Sand bars formed at fairly regular intervals on alternate sides of the channel with deeper sections near the opposite bank along the length of the channel. The sand bars grew in length while migrating downstream. The channel also became wider through general bank erosion, but remained straight. Bank erosion occurred opposite each sand bar. The sequences described above are similar to that observed in the gravel-bed River Ystwyth when the artificially straightened channel regenerated a meander plan-form.

Leopold (1982) studied the initiation of meanders in the East Fork straight reach, Boulder, Wyoming and the Colorado River, near Needles, California in the United States. The study found that the water would circulate in two ways in the long straight reach. The water would converge towards the centreline, while at the same time; it would diverge towards the banks. Bed load would be moving near the channel margins rather than along the centreline. The direction of flow towards the bed would be strengthened if there were an accumulation of bed material. The circulation would increase in the direction of the deposit, which would enhance the accumulation. The reversal of the process occurred just downstream of the deposit. Here the bulk of the flow was diverging against the bank resulting in bank erosion. Sand bars also developed. Surface water was directed away from the sand bar with the flow directed onto the opposite bank. This lead to the development of meander bends in the formerly straight channel by the growth of the sand bars. The meander bends migrated in a downstream direction.

Knighton (1998) agreed that the initiation of meanders requires localised bank retreat that must alternate from one side of the channel to another in a more or less regular fashion, if a series of bends is to develop. The channel bed should also be deformed periodically with the development of a sinuous thalweg as a necessary precursor to erosion of the channel banks.

Braiding

Braiding occurs in a wide range of environments at a range of scales. This channel pattern is favoured by (1) an abundant bed load where the load should contain size fractions that the river is unable to transport as they provide the initial deposits. Bars should also be present to divert flow against the banks contributing to the bank erosion; (2) Steep gradients as the degree of braiding appears to increase as the gradient steepens; (3) High stream power since braiding can persist at low gradients in large rivers. Braiding may be the result of high discharges or high gradients or a combination of both; (4) Highly variable discharge, although not of primary importance, is often associated with high rates of sediment supply that also contributes to bank erosion and irregular bed load movement, both inductive to bar formation; and (5) Erodible bank material as sources of sediment, as well as being necessary for channel widening characteristics of braided reaches (Rowntree and Wadeson 1999).

Anabranching or anastomosing

Rivers are classified as anabranching when stable islands separate the multi thread channel. The islands are formed by vegetated braid bars or due to the divergence of flow around a resistant object. The term anastomosing is used to describe channels with high sinuosity while anabranching is applied to a full range of sinuosities (Rowntree and Wadeson 1999).

2.3.2 Factors controlling river bank stability

The previous section looked at the different channel types, i.e. bedrock, mixed channels, sand gravel, cobble and boulder bed channels and the different plan-forms, i.e. straight, meandering, braided and anastomosing or anabranching. This section focuses on the different factors involved in river bank stability, namely bank material composition and the factors or forces involved in river bank instability and ultimately bank erosion. The factors include flow characteristics, characteristics of the bed and bank material, characteristics of the banks, role of vegetation in bank stability and human-induced factors.

Bank material composition

River channels can also be classified based on their boundary composition (this is a material-related classification). The boundary composition influences the sediment transport characteristics, resistance properties and ultimately the adjustability of the channel form (Knighton 1998). Channels can be classified as cohesive or non-cohesive based on their bed and bank material. Cohesive channels can be further divided into bedrock and silt-clay channels. Bedrock channels are very stable and have no coherent cover of unconsolidated material. The boundaries of silt-clay channels have a high silt-clay content giving it varying degrees of cohesion. Non-cohesive channels can be divided into sand, gravel and boulder bed channels (Knighton 1998).

The bed and banks of a channel are frequently composed of different material, e.g. channels with cohesive banks and non-cohesive beds (Knighton 1998). Channel banks may also be stratified (Simons and Li 1982) or composite (Richards 1982), where layers of cohesive and non-cohesive material are found. For example, imbricated gravel with interstitial sand overlain by sandy silt-clay is found in gravel bed rivers with floodplains (Richards 1982). The stability of composite banks depends on the strength of the weakest material found (Knighton 1998). The measurement of bank material cohesion and internal friction needs laboratory testing, but removal of the soil sample from the field can disturb the sample. The Vicksburg penetrometer can be used as a field estimate of bank strength. The penetrometer measures compaction rather than shear resistance. Bank strength is strongly dependant on a combination of moisture content and percentage of silt and clay. Silt and clay particles provide cohesion, which is the dominant source of shear resistance. Penetrometer readings will be low in wet banks with low silt-clay content and high for dry banks with high silt-clay content (Richards 1982).

2.3.3 Factors controlling river bank instability and bank erosion

Simons and Li (1982) listed the factors and forces involved in bank instability and ultimately bank erosion. The factors are: (1) flow characteristics – discharge magnitude, and mean velocity of the flow; (2) characteristics of the bed and bank material – size, cohesion and tensile strength; (3) characteristics of the banks – geometry, height and gradient; (4) biological factors – vegetation types and (5) human induced factors – urbanisation and channelisation.

(1) Flow characteristics

The hydraulic forces present in a channel depend on the velocity of the flowing water. Velocity and flow make up the discharge or flow at a specific time. How velocity impacts on bank erosion will be discussed later. Little erosion occurs during low flow periods due to low flow velocities. The channel may experience deposition in some reaches during this period. Some bank erosion and deposition may occur during intermediate flows with intermediate flow velocities. High flow velocities occur during high discharge flood events that can be responsible for bank erosion (Simons and Li 1982).

Climatic conditions and the movement and physical state of soil moisture control the processes of weakening and weathering (Thorne 1982). These processes act on intact bank material to influence its strength and bank stability. The most effective processes are directly associated with soil moisture conditions, which operate to decrease bank strength and to loosen and detach particles or aggregates (Petts and Foster 1985). Increases in soil moisture occur during and after heavy or prolonged rainfall, snowmelt and rapid drawdown following a high discharge stage (Thorne 1982; Petts and Foster 1985). The increase in discharge during rainfall and the rising stage due to the rising water table increase the pore water pressure. Pore water pressure refers to the pressure of water filling the voids between solid particles. All the voids are filled with water in fully saturated soils and partly filled with air and water in partially saturated soils. The pore water pressure must always be less than the pore air pressure due to the surface tension at the air-water interface. Pore water pressure is assumed to be in equilibrium with atmospheric pressure. Thus, pore water pressure is negative in the unsaturated (dry) zone above the water table. The difference between the pore water pressure and atmospheric pressure is defined as the matric suction and is positive because pore water pressure is less than zero. The matric suction in unsaturated soil increases the shear strength of the material and allows banks composed of granular soils (soil with fine sand as the dominant proponent) to remain stable during low flow conditions. Negative pore water pressure fluctuates frequently due to rainfall, the rising stages and evaporation (Casagli, Rinaldi, Gargini and Curini 1999). There is an increase in pore water pressure during rainfall and the rising stages due to the rising water table. Positive pore water pressure occurs when the bank material becomes fully saturated, resulting in the decrease in cohesion and bank material strength, and an increase in bank material weight resulting in bank erosion (Thorne 1990; Casagli *et al.* 1999; Abernethy and Rutherfurd 2000). A one in 100 year rainfall event occurred in some parts of the Sabie River catchment during February 2000. Disastrous flooding and massive bank erosion occurred because the catchment was already saturated by the December 1999 rainfall (Smithers, Schulze, Pike and Jewitt 2001). Loss of strength leads to bank failure by liquification in extreme cases (Thorne 1990). Stability can still be maintained in the saturated bank material due to the confining pressure of the water in the river channel and on the bank face. Bank failure is likely to occur during the falling limb of the flood when the bank material is still at, or near, saturation and the confining pressure of the river water is removed (Casagli *et al.* 1999; Simon, Curini, Darby and Langendoen 2000). There are also seasonal variations in bank strength and stability (Richards 1982; Simon *et al.* 2000). Stream banks tend to be stronger with maximum cohesion during dry periods (usually summer) due to the high matric suction values. Summer storms do not deliver sufficient amounts of water over an extended period of time to wet the banks adequately to cause large enough losses or reductions in matric suction and cohesion (Simon *et al.* 2000). Thus, the timing of the flood is more important than the magnitude, since less stress is needed for erosion of wet cohesive banks in winter (Richards 1982). For example, summer storms (July to August) with high intensities and short durations caused little or no bank erosion in the River Bollin-Dean, Cheshire, United kingdom. The winter flows had lower magnitudes than the summer storms, but were more effective in eroding the channel banks. This was because water levels were consistently higher for longer periods with higher water table levels during the winter than during the summer. Bank wetting was increased, which reduced the resistance of the bank material. Thus, the shear stress of the material was less during the winter than during the summer (Knighton 1973).

Channels will respond to rare large floods in different ways. These floods will not have geomorphic effectiveness, which is the modification of landforms (Kochel 1988), if the channel is stable or if floods with similar magnitudes passed through the catchment in the past. Eaton and Lapointe (2001) found that no changes in channel morphology took place in the Sainte Marguerite River, Saquenay region of Quebec, Canada due to the apparent channel stability attributed to the river valley's geomorphologically well-adjusted condition. The well-adjusted condition was due to the passing of a similar magnitude flood event through the catchment in the past.

Channel widening is the most obvious adjustment in channel morphology in those rivers that do respond to large floods. Widening is usually observed in arid and/or alpine environments with sparse riparian vegetation and is also associated with a change in channel pattern from a single thread meander to a braided channel (Eaton and Lapointe 2001). The Eel River, California, United States experienced a one in 100 year flood during December 1964. The flood caused river bank erosion and landslides that produced high sediment yields and substantial alterations to the channel morphology. The sediment produced by the flood was deposited in the channel causing channel bed elevations to rise 1.8 to 2.4m (Patrick, Smith and Whitten 1982). Deposition occurs where sediment supply overwhelms the flow transport capacity. Deposition can occur along the entire length or only in localised reaches of a channel. Rivers in northwestern California, United States experienced infilling along their length due to river bank erosion (Wohl 2000b). Rivers experiencing major geomorphic changes due to large floods appeared to be characterised by flashy hydrographs, high channel gradients, abundant bed load for abrasion against the banks, low bank cohesion and deep, narrow cross-sections that enable high shear stress during floods (Kochel 1988; Wohl 2000b).

The processes of erosion and deposition, as described above, result in cross-sectional changes. Analysis of 45 years of cross-sections showed changes in channel width and bed elevation along the Skokomish River, Washington, United States. The bed of the South Fork Skokomish River incised > 1m between 1940 and 1964. The mainstream Skokomish channel bed was raised through deposition of about 0.5m between 1934 and 1944 (Stover and Montgomery 2001). The difference in successive bed profiles was translated into volumes of eroded or deposited materials. The volumes can be determined by measuring the area across a unit river length and multiplying it with an appropriate factor assessing the changes in bed profiles. The unit horizontal thickness in the cross-section also needs to be considered (Abam and Omuso 2000).

(2) Failure mechanisms

The characteristics of the bed and bank material were discussed previously. The different failure mechanisms found and those operating on the different bank materials will be discussed here. There are three main mechanisms of river bank erosion, which include subaerial weakening and weathering, fluvial entrainment or fluvial scour and mass failure (Rutherfurd, Jerie and Marsh 2000; Couper and Maddock 2001).

Subaerial weakening and weathering

Processes unrelated to stream flow cause subaerial weakening and weathering. These processes include rill erosion, wetting and drying and the associated desiccation and freeze-thaw (Knighton 1998; Rutherfurd *et al.* 2000). Surface runoff occurs when the bank material is fully saturated or the rate of precipitation locally exceeds that of infiltration. This may lead to processes of sheet erosion, rilling and gulleying. Raindrop impact can also detach surface particles and lead to downslope creep on steep banks (Thorne 1982). Cycles of wetting and drying cause swelling and shrinking in cohesive soils. This leads to the development of a ped fabric that is blocks of soil separated by desiccation cracks, where the desiccation cracks provide lines of weakness in the bank face (Thorne 1982, 1990; Petts and Foster 1985; Couper and Maddock 2001). The freezing of water in pores or cracks and fissures heaves apart the soil units and loosens the bank material. This tends to weaken the soil by reducing granular or soil unit interlocking and decreasing cohesion. The movement of water through the bank can lead to leaching through the removal of clay particles by solution or suspension, and softening that will also weaken the bank material by decreasing cohesion (Thorne 1982). Subaerial processes are often viewed as preparatory processes weakening the surface of the bank face prior to fluvial entrainment. Thus, it increases the efficiency of fluvial erosion. Couper and Maddock (2001) showed that subaerial processes were an important agent in the river bank erosion in the River Arrow, Warwickshire, United Kingdom.

Fluvial entrainment or scour

Fluvial entrainment or scour refers to the action of water eroding individual particles off the bank face and is associated with the flow hydraulics in the channel (Thorne 1982; Rutherfurd *et al.* 2000). Individual grains are dislodged from the bank face (Thorne 1982; Simons and Li 1982; Thorne 1990) through pivoting and rolling or sliding in non-cohesive material (Thorne 1982). The rate of particle removal depends on the magnitude and direction of velocity against the bank (Simons and Li 1982). Fluvial entrainment of the bed and bank material occurs from the basal area. The basal area refers to the part of the bed and lower bank that surrounds the bank toe. Bed and bank material may be entrained directly from the bank face and transported downstream or flow may scour the bed at the base of the bank. This will increase the bank angle and height resulting in gravitational failure of the intact bank (Thorne 1982). Slab failure and/or the development of a near-vertical tension crack in the upper part of the bank will occur as a result of the fluvial undercutting (Simon *et al.* 2000). Fluvial entrainment at the bank toe controls the rate of bank erosion. The reason for this is that the other erosion processes tend to decrease bank angle with the slumped material piling up at the toe. The bank angle will eventually be decreased sufficiently to prevent further slumping. Fluvial entrainment, however, removes the collapsed material with the banks remaining steep and unstable (Rutherfurd *et al.* 2000). High velocities during high discharge stages will attack the bank and the whole profile will experience erosion. Thus, the bank line will move landward with the development of new profiles that can produce significant shifting of the channel. The Connecticut River, New England, United States experienced retreat of the whole bank profile due to fluvial entrainment during major floods (Simons and Li 1982).

Mass failure

Mass failure occurs when large sections of the stream bank collapse into the river at the failure plane. The failure plain is the fracture line where the slump block breaks away from the bank (Rutherfurd *et al.* 2000). The susceptibility of the stream bank to mass failure depends on their geometry, structure and material properties. Processes of weakening and weathering and cycles of wetting and drying reduce the strength of the intact bank material and decrease bank stability. Seepage forces decrease cohesion by removing clay particles and promoting the development of soil pipes in the lower bank (Knighton 1998). The loss of matric suction due to infiltrating precipitation was found to be the reason behind the mass stream bank instability in Goodwin Creek, northern Mississippi, United States (Simon *et al.* 2000). Mass wasting is also responsible for channel width adjustments. Width adjustments through mass wasting varied from 1.5m.yr^{-1}, 14m.yr^{-1}, 50m.yr^{-1} and >100m.yr^{-1} in some rivers in the United States (Simon *et al.* 2000).

Many factors are involved in the amount, periodicity and distribution of stream bank erosion. Thus, the processes are not mutually exclusive, but frequently act in combination (Thorne 1982). Subaerial processes dominate the upper reaches of the river, fluvial erosion the middle reaches and mass failure the lower reaches of the river (Couper and Maddock 2001).

Non-cohesive river banks

The driving force for failure is the shear stress on the potential failure plane due to the downslope component of mass. The resisting force against failure is the shear strength of the potential failure plane due to the slope component of mass, friction and granular interlocking (Thorne 1990). Failure in dry river bank material takes place through fluvial entrainment (Thorne 1982; Knighton 1998; Wohl 2000b) or by shallow slip along a plane or very slightly curved surface (Thorne 1982; Knighton 1998). For example, shallow slips occurred in the sandy banks of Wollombi Brook, New South Wales, Australia. The dominant mechanism in banks of low cohesivity seems to be slab-type failure (Knighton 1998). Deep-seated failures are unlikely because the shear strength usually increases more rapidly with depth than does shear stress (Thorne 1982).

Failure mechanisms in saturated or partially saturated materials are similar to those for dry bank materials with the addition that failure may result from an increase in pore water pressure (Thorne 1982, 1990). Thus, mass failure may be triggered by rapid drawdown of heavy and prolonged rainfall (Thorne 1990). Failure by liquification can occur due to a loss of strength in fully saturated and loosely packed material (Thorne 1982). Channel widening of up to 6m occurred via mass failure along the Patuxent River, Maryland, United States (Wohl 2000b).

Cohesive river banks

The driving force for failure is the same as for non-cohesive material. The resisting forces depend on the shear strength, which in turn depends on the frictional forces and cohesion of the material (Simons and Li 1982; Thorne 1990). Cohesive material is less susceptible to grain-by-grain removal in fluvial entrainment (Simons and Li 1982). Aggregates or crumbs of soil will rather be removed during this process (Thorne 1990). Mechanisms of failure are considered to be rotational slip, shallow slip, planar slip and tension cracks. Piping and liquification can lead to failure of the bank toe leading to slip failure higher up the banks (Thorne 1982). The dominant mechanism in banks of high cohesivity seems to be deep-seated rotational slips. Slab failure can also occur in cohesive material where blocks of soil topple forward into the channel (Thorne 1990; Knighton 1998).

Composite river banks

The presence of gravel below a cohesive layer tends to result in oversteepening because the gravel is eroded by fluvial entrainment and loosened to subaerial processes. Mechanisms of failure may be rotational slip or planar slip. The presence of cohesive material below gravel, on the other hand, may result in the formation of a bench that tends to protect the gravel from fluvial erosion and oversteepening (Thorne 1982).

(3) Characteristics of the bank

Channel depth is an indicator of the size of the channel, stability of the banks and shear stress exerted on the channel boundary by the flow. Channels with small width-to-depth ratios have greater than average stability. Thus, erosion is more likely to occur where the channel is narrow relative to its depth (Knighton 1973; Simons and Li 1982), although floods flowing with high velocities along a deep and narrow channel may generate extremely large values of boundary shear stress that will lead to erosion (Wohl 2000b). Velocity is also important for erosion in channels with asymmetrical cross-sections because asymmetry results in locally high velocities and high rates of shear stress close to the face of one bank (Simons and Li 1982), leading to high rates of bank retreat at meander bends (Knighton 1998; Rutherfurd *et al.* 2000). Bank material composition will have less effect on the amount of erosion, but it will influence the type of erosion. For example, discrete particles will be removed from the banks consisting of coarser material or large chunks of material will be removed from banks with high silt-clay contents. The channel gradient is also important in terms of the energy or stream power of the channel. Steeper channels will have higher energy or stream power and thus higher erosive capacities. Flatter channels have low energy and thus lower erosive capacities (Simons and Li 1982).

(4) Biological factor – vegetation types

Channel and floodplain vegetation increase the roughness of the channel (Hickin 1984; Friedman and Auble 2000) and thus increase the resistance to flow and reduce the forces of drag and lift acting on the bank surface (Thorne 1990). The increase in flow resistance decreases the flow velocity close to the bank, thereby reducing scour directly (Rutherfurd *et al.* 2000) while also reducing the shear stress on the bank. However, the stage to where the water will rise at a given discharge will be raised due to the reduced velocity and the water will spread higher on the floodplain. Decreased velocity around vegetation or woody debris results in deposition of fine sediment, which is essential for bank cohesion (Friedman and Auble 2000). The type of vegetation is very important since grasses and shrubs are effective in increasing bank stability at low velocities with their impact decreasing as velocity increases. Their impact is eliminated once the water flattens the stems. Stems of woody species will continue to retard the flow up to very high velocities, but may generate serious bank erosion through the local acceleration of flow around their trunks (Thorne 1990).

Vegetation density is also important since single trees or small groups of trees are obstacles to the flow and can generate large-scale turbulence and severe bank erosion in their wake. Thus, the flow will be able to isolate exposed parts of the bank resulting from the effects of widely spaced trees or groups of trees. Therefore trees must be spaced sufficiently close to the wake zone and one tree must extend to the next for it to be effective in reducing flow attack on the bank (Thorne 1990).

Vegetation increases bank stability directly with roots and rhizomes binding the soil (Thorne 1990). Thus, soil grains that would have been detached will remain bonded to the bank when vegetation is present. When combined, the soil-root matrix produces a type of reinforced earth much stronger than the soil or roots on their own because soil is strong in compaction, but weak in tension and plant roots are weak in compression, but strong in tension. Roots also add tensile strength to the soil and distribute stresses through the soil through their elasticity. However, the reinforcement only extends down to the rooting depth of the vegetation, below which flow could undercut the root zone during significant flow events. The rooting depth is a few centimetres for grasses and tens of centimetres for shrubs (Thorne 1990). Hickin (1984) found that cottonwood and spruce tree roots growing on the floodplains of northern British Columbia, United States provided a strong woody mesh to reinforce the alluvial banks by penetrating to the level of the river bed. Roots will reinforce the bank against failure if the bank height is less than or equal to the rooting depth. Roots will continue to prevent shallow slips and still bind the failure block together during and after collapse so that the failed blocks are more likely to remain at the toe and protect the intact bank from further erosion, but the stabilising effect is lost on deep-seated failures. Vegetation density is also important in bank stability. Generally a species with a dense network of fibrous roots is of more benefit than one with a sparse network of woody roots (Richards 1982; Thorne 1990). Grasses have higher densities than do trees, but woody plants have deeper and larger roots giving wooded banks along large rivers better protection against undercutting (Friedman and Auble 2000). The weight of vegetation, especially trees, reduces bank stability when there is a switch from holding the bank up to dragging it down in response to increased bank height and angles caused by basal lowering and toe erosion. This phenomenon is called surcharging. Surcharge can be beneficial, depending on the position of the tree on the bank and the slope angle (Thorne 1990).

(5) Human-induced factors

The human-induced factors important in this study are urbanisation and channelisation. The impacts of these two factors on channel morphology will be discussed in Section 2.4 and 2.5 respectively.

2.3.4 Summary

Channels are classified into different types, depending on the size of the bed material, channel plan-form and the composition of the bank material. A distinction is made between bedrock and alluvial channels. Bedrock channels are very stable with little, if any, erosion taking place. Alluvial channels are formed within the sediment being transported and can be divided into sand, gravel, cobble and boulder beds. The mobility of the bed material decreases as bed material size increases. The main channel plan-forms identified are straight, meandering, braided and anastomosing or anabranching. River bank stability depends on the bank material composition, where banks consisting of silt-clay material tend to have higher cohesion and tend be more stable. Banks with sand or gravel have less cohesivity. Bank instability and bank erosion occur when the banks become wet during prolonged rainfall events; due to fluvial entrainment or scour during high velocity flow events; and due to processes not related to flowing water. Vegetation increases river bank stability by increasing channel roughness and therefore increasing the channel's resistance to fluvial scour and also through binding the soil with their roots.

2.4 Urbanisation and its impacts on rivers

The previous section addressed the different channel and plan-form types found and the factors involved in river bank stability. This section will look at how urbanisation impacts on catchment hydrology, channel morphology and water quality.

2.4.1 Changes in catchment hydrology

Urban development is hydrologically the most extreme land use change (Richards 1982). The building of roads, pavements, parking lots and houses results in the conversion of natural land to impervious surfaces, a process called catchment hardening (United States Environmental Protection Agency (USEPA) 1998). Impervious surfaces reduce the natural infiltration of rain into the soil. This leads to a higher percentage of rainfall becoming runoff and an increase in overland flow (Hollis 1975). The increased runoff reduces depression storage percolation, soil moisture storage, evapotranspiration and base flows during high and low flow events (USEPA 1998). Impervious surfaces also speed up the rainfall-runoff process. This means that runoff will enter the receiving channels more quickly, and decrease the time taken for the flood discharge to reach its peak (Richards 1982; Campana and Tucci 2001; Terpstra and van Mazjik 2001). The runoff regime becomes quicker resulting in higher and "flashier" flood flows with shorter lag times and time bases and increased peak flows, which increases the hydrograph peak (Hollis 1975; Richards 1982; Fogg and Wells 1998; Terpstra and van Mazjik 2001). Urban areas have problems with waste disposal and a surplus of drainage water gathering from impervious surfaces (Newson 1994). Septic tanks have had to be built for the disposal of human waste. The septic tanks have been replaced with sewers as housing development has increased (United States Geological Survey (USGS) 2001). Storm water drains were built to conduct water from roads that cannot infiltrate into the soil through buried pipes or surface channels to the nearest river, to avoid flooding. The use of storm water drains produces more extensive drainage networks by supplementing natural with man-made channels. The increase in the density of the drainage network also leads to higher peak discharges and decreases in lag times (Gregory and Madew 1982). Storm water and wastewater from houses are taken (via the sewers) to waste water treatment plants. Here the water is treated with chemicals before being discharged into rivers (Morisawa 1985; Newson 1994; USGS 2001). This results in an increased flooding frequency within and downstream of the receiving rivers (USGS 2001). The effect of urbanisation is the greatest for small floods (Hollis 1975) and the recurrence interval is increased by 10 times for smaller floods, since there is an increase in the frequency of less extreme discharges (Gregory and Madew 1982).

Hollis (1975) showed that smaller frequent floods increased up to ten times after 20% of the catchment was urbanized in Harlow, Essex, United Kingdom. Urbanisation increased the magnitude of channel-forming or bankfull flood events (typically 1-3 year recurrence interval) significantly. Flood events that previously occurred once every year or two may occur as often as one or two times monthly (Fogg and Wells 1998).

The reduction of water infiltrating into the soil leads to a reduction in groundwater recharge. This results in a lowering of the groundwater table, which in turn, will reduce base flows in the drier periods (Brun and Band 2000; USGS 2001). A reduction in base flow can cause water quality problems as pollutants become more concentrated, degrade riparian habitats as water levels decrease and interfere with navigable waterways (Brun and Band 2000). The pattern and rates of aquifer recharge and the quality of the recharge are changed due to urbanisation. Land surface impermeabilisation can reduce normal soil infiltration significantly, but water mains leakage, wastewater disposal and excess irrigation of amenity areas, on the other hand, compensate for the reduction with the net effect being increased groundwater recharge (Foster 2001). The changes in recharge influence the groundwater levels and flow regime in the underlying aquifers. The influence on the groundwater levels and flow regimes can take considerable time since the response constants of aquifers are normally the largest of all components of the urban hydrological cycle. Therefore, it can take a long time before aquifers reach equilibrium with the hydrological changes induced by the process of urbanisation (Foster 2001).

2.4.2 Changes in channel morphology

The removal of vegetation within the catchment and along the river bank will increase the sediment yield to the receiving channels and impact on bank stability directly. The removal of the anchoring effect of the root network will reduce the river bank stability, since the roughness provided by the vegetation is removed. A reduced vegetation cover can therefore increase the erosional capacity of the flow at a given discharge, resulting in increased shear stress against the bank. This will favour bank erosion (Richards 1982). Urbanisation causes a complex cyclic variation in sediment yield with sediment yield extremely high during any construction, which declines by the completion of the development. Therefore channels can become choked with sandy sediments as seen in gravel bed rivers becoming sand bed rivers during any construction. The sand wave can migrate downstream with time and the gravel bed channel will be re-established in the post-construction period of low sediment load:discharge ratio (Richards 1982).

River channels within and/or downstream of urbanised areas will become larger to accommodate the larger, more frequent flood peaks as urbanisation progresses (Hammer 1972; Graf 1975; Gregory 1981). Channels will experience a period of sedimentation due to increased land clearance for more houses and roads in the catchment (Graf 1975; Gregory 1981; Richards 1982). This leads to a decrease in channel capacity. New floodplain areas can also be created or existing ones can be enlarged by vertical accretion because the river would not be able to carry the mostly sandy material. Sediment production in the catchment will decrease when development stops, but the flashier flood flows will increase in frequency. Thus, channels will begin to incise (erosion of the channel bed) the newly accumulated floodplain material (Graf 1975). Repeated cross-section surveys along the Watts Branch, Maryland, United States showed that the channel capacity decreased for 12 years due to sedimentation during the construction phase. Channel capacity began to increase again when development stopped (Gregory 1981).

2.4.3 Changes in water quality

Urbanisation can degrade the quality of both surface and subsurface water resources. Storm water runoff from urban areas often contains large amounts of contaminants derived from litter, garbage, car washing, horticulture treatments, vehicle drippings, industry, construction and animal droppings (Goudie 1981; Dallas and Day 1993; Ellis *et al.* 1997; Armitage, Rooseboom, Nel and Townshend 1998; Brun and Band 2000). Almost all pollutants deposited on impervious surfaces, if not removed by street cleaning, wind or decay, will eventually drain towards a river or other aquatic system.

A lot can be said about water quality impairments in river systems and its causes, but that is not the focus of this study. This study focuses chiefly on how water quality affects the macro-invertebrates found in a river and what the macro-invertebrates indicate about the water quality and ecological health of a river. An overview of the types of macro-invertebrates found in urban rivers was given in Section 2.2.1.

2.4.4 Summary

Urbanisation results in the conversion of natural permeable land to largely impervious surfaces. The increase in impervious surfaces results in a decrease in infiltration of rainfall into the soil, and a higher percentage of rainfall becoming runoff. Runoff will also reach the receiving channels faster, since storm water sewers are built as housing development increases. This leads to a flashier runoff regime where the peak and frequency of smaller floods are increased. The reduction in water infiltrating into the soil will also lead to a reduction in groundwater recharge. This can lead to water quality problems in groundwater as pollutants become more concentrated, and can degrade riparian habitats as water levels decrease. However, wastewater disposal and excess irrigation in other parts of the catchment can lead to groundwater recharge.

Channels may become larger due to the increase in the frequency of small to medium magnitude flood events. However, urbanisation also involves the clearing of natural vegetation, resulting in excess sediment production during construction. The channels may then experience increased sedimentation resulting in a decrease in channel capacity. Sedimentation will decrease as development stops, but the frequency and magnitude of the small to medium discharge flow events will still increase. Therefore, channels may become incised in the newly deposited material.

2.5 Channelisation and its impacts on rivers

2.5.1 Introduction

The previous section covered the impacts of urbanisation on catchment hydrology, river morphology and water quality. This section will look at the types of channelisation and their effects on channel morphology, sediment, flow regimes and the ecology.

The creation of new channels, or modification of existing river channels through straightening, narrowing, deepening, widening, or construction of embankments, can collectively be defined as channelisation (Gregory, Hockin, Brookes and Brooker 1985). Other channelisation procedures, including dredging, cutting, and removal of in-stream or bank obstructions, may be classified as river maintenance. Channelisation can be used for flood control, for land drainage to create and maintain agricultural land, for navigation where rivers form part of transport networks, or for reducing or preventing erosion of banks and the riverbed (Keller 1975; Harvey and Watson 1986; Reinfelds, Rutherfurd and Bishop 1995; Nielsen 1996; Schropp and Bakker 1998) (Table 2.3). Channelisation for flood control or land drainage facilitates the rapid removal of excess water to the sea, with the modified channel usually designed to carry a designated flood in order to provide the required drainage (Andersen and Svendsen 1997). Sometimes the terms 'river-regulation works' or 'river-training works' are used to describe much the same kinds of modifications, and all will be considered as channelisation for the purposes of this review. There are two types of channelisation. The first type is called a planned project where engineering design and environmental impacts may or may not form integral parts of the project. The second type is called emergency channel work, which is often done without proper planning and engineering, following catastrophic storms. For example, Hurricane Camille struck Virginia, United States and caused severe storms and floods in 1969. Emergency channelisation was carried out to straighten the channels in the hope of alleviating future floods and to clear rivers of mud, sand and debris (Keller 1980).

Channelisation of a river channel changes its hydraulic geometry or channel morphology. Hydraulic geometry refers to the shape of the channel cross-section at certain discharges, while channel morphology refers to the shape, size and outline of the channel. Channelisation usually transforms the channel into one that is more uniform in shape, usually with a trapezoidal cross-section (Gregory *et al.* 1985; Newbury and Gaboury 1993; Kondolf 1996; Downs and Thorne 1998; Nolan and Guthrie 1998; Eden, Tunstall and Tapsell 1999; Maddock 1999).

The downstream impacts of channelisation can be divided into those effects associated with construction, which are characterised by the release of excess sediment during and directly after construction, and those that occur during the years following completion of the works. Downstream sediment concentrations were at a maximum when disruption to the channel bed and banks was the greatest. For example, sediment concentrations downstream from the realignment of the River Wylye in Wiltshire (done in February 1982) exceeded normal levels by as much as forty times, or a maximum of 560mg l^{-1} (Gregory *et al.* 1985).

2.5.2 Types of channelisation and their impacts on channel morphology, sediment and flow regimes.

Straightening

When a meandering river is straightened, the channel path is shortened, friction at bends is reduced, and the channel gradient (slope) is increased (Brookes 1987; Brookes and Gregory

1988; Luger 1998). As a result the channel will tend to become deeper and wider (Gregory *et al.* 1985; Henderson 1986). Straightening may also involve confining braided systems to a single channel (Wissmar and Beschta 1998). The net effect of straightening is an increase in current speed under both high and low flow conditions (Henderson 1986; Luger 1998). Straightening affects the sediment and flow regimes of the river. The increase in channel slope will result in an increase in flow velocities in the straightened reach. This will enable the transport of more sediment than what is supplied by the natural channel from upstream, because the erosive capacity of the water has been increased. Additional sediment supply is obtained from the bed of alluvial channels through channel incision (bed erosion). The channel slope will increase further upstream because of the incision. The incision will migrate upstream as a knickpoint (Brookes and Gregory 1988; Simon 1989).

Channelisation projects, especially straightening, may induce instability, not only in the altered reach, but also in upstream and/or downstream reaches if their design is based on inadequate background data. The initial response of a reach to imposed channel modifications depends on its location relative to the disturbance. The area of maximum disturbance (AMD) is defined as the furthest point of impact upstream of the channel work, reflecting the area where most erosion (degradation) will take place (Simon 1989). Reaches upstream of the AMD will experience erosion while downstream reaches will experience deposition with material delivered from eroding reaches upstream (Gregory *et al.* 1985; Simon 1989). Simon (1989) found that, during straightening of the Obion River, United States, the maximum amount of degradation occurred just upstream of the AMD because of the significant increase in stream power. Degradation in these reaches continued for 10-15 years, with channel incision lowering the bed levels by as much as 6.1 m (Simon 1989). Briż ga, Craigie and Seymour (1999) reported similar results from straightening the Bunyip River, Victoria, Australia. The straightened part of the river became known as the Bunyip Main Drain. A node of incision migrated for many kilometres upstream from the works, along the main river and its tributaries, eroding bed and banks and causing roads to collapse (Briż ga *et al.* 1999; Shields *et al.* 1995).

Table 2.3: Case studies of channelisation and its purpose.

River and country	Purpose of channelisation	Source
American rivers	Flood control, land drainage	Keller 1975; Harvey & Watson 1986; Wissmar & Beschta 1998
Cape Town rivers, South Africa	Flood control	Brown 1992
Danish rivers	Land drainage	Brookes 1987; Iversen, Kronvang, Madsen, Markman and Nielsen 1993
Danube River, Austria	Flood control	Tockner, Schiemer and Ward 1998
Harper's Brook, U.K.	Flood control	Ebrahimnezhad & Harper 1997
Hout Bay River, South Africa	Flood control, land drainage	Beaumont 1981
Kissimmee River, U.S.A.	Flood control	Dahm, Cummins, Valett and Coleman 1995; Toth, Melvin, Arrington and Chamberlain 1998
Kuils River, South Africa	Flood control	Wiseman & Simpson 1989
Latrobe River, Victoria, Australia	Flood control	Reinfelds *et al.* 1995
Laural Creek, Canada	Flood control, land drainage	Winter & Duthie 1998
Martin Dale Creek and Martin Dale Tributary, Mississippi, U.S.A.	Flood control, land drainage	Shields, Knight and Cooper 1997
Mississippi River, U.S.A.	Flood control, land drainage	Shields *et al.* 1995
Missouri River, U.S.A.	Navigation	Harberg, Remus, Rothe, Becic and Hesse (1994)
Morava River, Czech Republic	Land drainage	Sterba, Mekotora, Krskova, Samsonova and Harper 1997
Raisin River, Ontario, Canada	Land drainage	Watelet & Johnson 1996
Ravensbourne River, U.K.	Flood control	Tapsell 1995
Rhône River, Geneva, Switzerland	Flood control	Henry, Amoros and Giuliani 1995
River Alt, U.K.	Flood control, land drainage	Nolan & Guthrie 1998
River Brede, Denmark	Flood control, land drainage	Nielsen 1996; Vivash, Ottosen, Janes and Sørensen 1998
River Cole, U.K.	Directing of water, flood control and land drainage	Nielsen 1996; Vivash *et al.* 1998
River Elbæk, Denmark	Flood control	Brookes 1990
River Idle, U.K.	Flood control, land drainage	Downs & Thorne 1998
River Lambourn, U.K.	Flood control	Brookes 1990
River Livojoki, Finland	Log transport	Tikkanen, Laasonen, Muotka, Huhta and Kuusela 1994
Rivers Rhine and Meuse, The Netherlands	Navigation	Schropp & Bakker 1998; Van Dijk, Marteijn and Sculte-Wulwer-Leidig 1995
River Skerne, U.K.	Flood control	Eden *et al.* 1999; Nielsen 1996; Vivash *et al.* 1998
River Skjern, Denmark	Flood control and land drainage	Andersen & Svendsen 1997
Rivers in agricultural areas, Finland, Sweden, Denmark, U.S.A.	Land drainage	Petersen, Petersen and Lacoursiére 1992
Wraysbury River, UK	Flood control	Kondolf 1996
Whittle Brook, U.K.	Flood control	Nolan & Guthrie 1998

Simon (1989) and Shields *et al.* (1995) described the morphological nature of incising channels in a conceptual model of channel evolution that recognizes five or six stages of channel response to straightening. The stages are outlined in Figure 2.1.

- *Stage 1: pre-modified.* Characterised by stable, low-gradient and well-vegetated banks as a result of natural fluvial processes and land-use practices. Bank failure by mass wasting does not generally occur. Bank failure occurs when the bank is undercut by the flow of water destabilizing the bank internally.
- *Stage 2: construction (straightening).* Existing banks may be reshaped or the entire channel repositioned during the construction of the new channel. In either case, the banks generally become steeper, higher and straight. Channel width is increased, with vegetation removed to increase channel conveyance. The channel will generally have a trapezoidal shape.
- *Stage 3: degradation.* Characterised by rapid erosion of the channel bed (incision) due to the shortened channel path and increased current velocities, resulting in an increase in bank heights. Bank steepening occurs when moderate flows attack basal surfaces and remove toe material. Stage 3 is probably the most important one as it determines the magnitude of subsequent channel widening because the amount of incision partly controls the bank-failure threshold.
- *Stage 4: threshold.* Continued basal erosion heightens and steepens the banks. Bank failure will occur if the critical bank height is exceeded. Bank retreat and failure will continue developing a vertical bank face and an upper bank of 25-35 degrees. Moderate to high flows generally remove the material deposited at the toe. This retains the over-heightened and over-steepened bank profile, and gives the banks an eroded appearance.
- *Stage 5: aggradation.* Aggradation (deposition or upbuilding) of the channel bed begins, often typified by sand deposits on banks. Previously deposited material on the upper bank also moves down the slopes where it may be re-worked and deposited by river flows. The material deposited on the banks and bed develops into the formation of a floodplain.
- *Stage 6: re-stabilisation.* There is a significant reduction of bank heights, due to channel aggradation on the channel bed and fluvial deposition on the upper bank and slough-line surfaces. Mass-wasting processes are less obvious than in stages 3 to 4 because bank heights no longer exceed critical heights. Woody vegetation extends up the slope towards the base of the vertical face and the former floodplain surface becomes a terrace. Bars gradually form, become vegetated and a meandering plan-form is regained (Simon 1989; Shield *et al.* 1995).

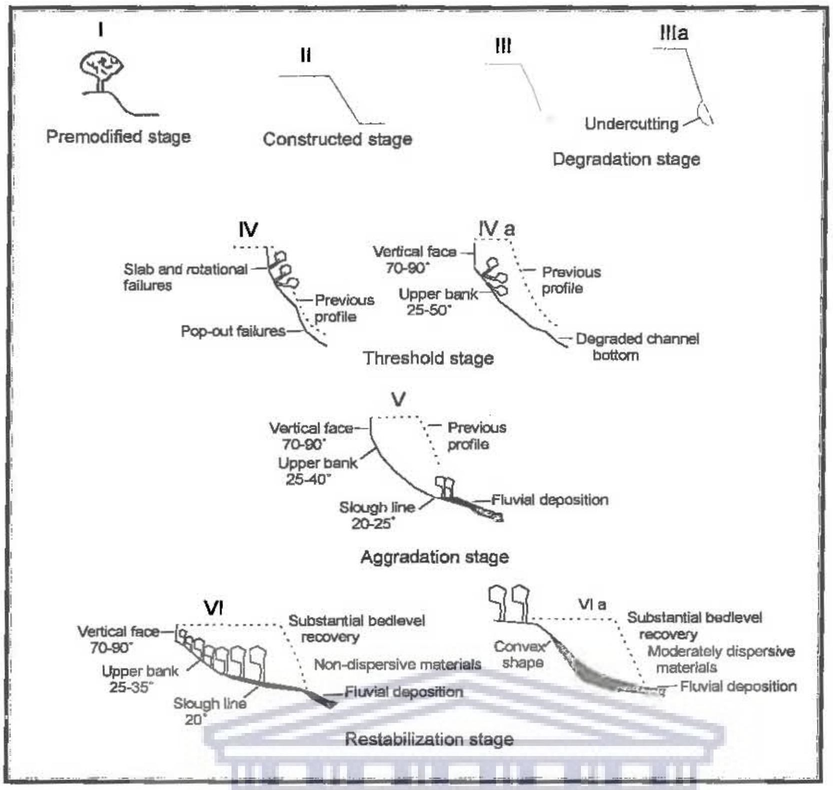

Figure 2.1: Stages of bank retreat and slope development. (From Simon 1989:20).

Embankments

Creation of embankments (also called dykes and levees) along the river channel is usually part of the straightening process. Dykes can also refer to drainage ditches in some parts of the United Kingdom. The dykes referred to in this literature review refer to embankments. They are in general use in European countries such as the Netherlands and Denmark (Admiraal, Van der velde, Smit and Cazemier 1993; Henry *et al.* 1995; Andersen and Svendsen 1997). Embankments are used to restrict the flow in a central channel, to prevent the lateral migration of rivers and to separate the river from its original floodplain, thereby increasing the area available for development outside the narrowed channel.

Moreover, the containment of water in the main channel prevents the overtopping of the banks onto the developed areas, meaning that the natural dissipation of energy is removed. Water with increased energy is then transferred to downstream reaches (causing degradation and aggradation) (Maitland and Morgan 1997). Restriction of water between the embankments leads to increased current speeds in the channel and can result in deepening (incision) of the riverbed. After the river was straightened with embankments built around it, the bed of the Rhine dropped by 7 m at Basel and, 300 km upstream of the engineering works at the port of Duisberg, by 4 m (Pearce 1993).

The isolation of the river from its floodplain also prevents movement of silt from floodplain to river. In this way, sediment supply to the Rhine River decreased and the bed level dropped (Pearce 1993; Maitland and Morgan 1997). The Rhône River in Geneva, Switzerland used to be a braided river. Embankments on the river resulted in some channels becoming blocked and isolated from the main channel. The blocked channels only received seepage water through the embankments during low flows and river water during high flows. The embankments prevented the creation of new channels by impeding the lateral movement of the river (Henry *et al.* 1995).

Deepening

Deepening the riverbed is used to increase the capacity of the channel to carry floodwaters, and also allows easier passage of boats (Brookes and Hanbury 1990). Deepening also affects the sediment and flow regimes of the river. This occurs because deepened reaches can serve as sediment traps affecting sediment supply to downstream reaches. Sediment deposition within the deepened reaches results in the reduction of flow depths and therefore decreasing the capacity of the channel to carry floodwaters (Gregory *et al.* 1985; Brookes and Gregory 1988; Brookes 1992). A deepened channel in the San Lorenzo River, California, U.S.A. was designed to carry a flood with a return period of 100 years. The channel was filled in by 350 000 m^3 of sediment from upstream reaches, reducing the channel capacity to that of a 25-30-year flood (Brookes and Gregory 1988). Deepening also changes the channel long profile by decreasing the bed levels (Simon 1989; Wyżga 1996; Ebrahimnezhad and Harper 1997).

Deepening of the channel will lower the water levels in the channel. This means that the groundwater levels adjacent to the channel will also be lowered. This, in turn, will affect the low flow conditions during the drier periods (Admiraal *et al.* 1993; Shields *et al.* 1997; Sterba *et al.* 1997). Lowering of the water table can result in reduced over-bank flow (Gore and Shields 1995; Schropp and Bakker 1998; Wissmar and Beschta 1998). Over-bank flow occurs when the river is in flood with water levels over the top of the banks. Reduced groundwater levels reduce over-bank flow since the deepened channel will require a flood with bigger magnitude for over-bank flow to occur. The reduction of over-bank flow can also cause decreased infiltration (recharge) to the groundwater and a further reduction in base flow. Base flow is the flow of water entering the rivers from groundwater (Gore and Shields 1995; Schropp and Bakker 1998; Wissmar and Beschta 1998).

Widening

Widening is another method for increasing channel capacity. It results in a decrease in current speeds due to the enlarged cross-sectional area of the channel and the resulting reduction in stream power per unit bed area. The reduced capacity to carry sediments may lead to sedimentation problems, as well as problems of bank erosion within the widened reach if the banks are not stabilised. Flow velocities will increase downstream if the downstream reaches are narrower than the widened reaches upstream. Thus, the downstream reaches may experience increased bed erosion due to the increased flow velocities. Channel capacity will decrease again with time as low flows, which predominate for most of the time, deposit sediment on the channel margins. These may become stabilized with vegetation, to form permanent morphological features. Thus, there will be a tendency for the channel to revert to its original shape. The River Tame near Birmingham was widened for flood control in 1930. In the absence of maintenance, it reverted toward its natural width in less than 30 years (Brookes 1992).

Narrowing

Restriction of flow to a narrower channel will decrease the channel capacity of the river, and result in increased current speeds with local scouring of the bed. Secondary deepening may then occur, increasing the channel capacity again. The localised bed scouring usually causes increased sedimentation in downstream reaches (Admiraal *et al.* 1993; Pearce 1993; Wyź ga 1996).

Maintenance

Brookes and Gregory (1988) group a number of activities, such as weed control, removal of bank vegetation, dredging of accumulated sediments and clearance of rubbish from the channel, as river maintenance. Silt is regularly dredged from silt traps within the Kuils River to protect a downstream wetland area from siltation (Jordaan, Oostenberg Municipality, pers. comm., 2000). This and other rivers within the Western Cape have channels choked with water plants such water hyacinth (*Eichhornia crassipes)* and bulrush (*Typha capensis*). These are removed mechanically and manually in ongoing maintenance programmes (Jordaan, Oostenberg Municipality, pers. comm., 2000). Physical removal of other in-stream features is also common practice to enhance efficient transport of water from farming areas. In Australia, this usually takes the form of manual removal of debris, litter and larger accumulations of wood and other organic matter (Rutherfurd *et al.* 2000).

Bank maintenance is also important where vegetation encroaches into the channel. Henderson (1990) reported that revetments, which are embankment facings such as boulders or riprap, in British rivers that have high sediment loads and flows are completely cleared of all vegetation on a regular basis, since they can become completely overgrown with woody and herbaceous vegetation in a single year. The banks of the River Idle in Nottinghamshire, U.K., are also mown with mechanical mowers on a regular basis, resulting in poor habitat diversity and a uniform mix of species along the channel (Downs and Thorne 1998).

Canalisation

Another form of channelisation is to line the bed and river banks with concrete. The term canalisation is used in this case. Canalisation is most common in the urban landscape, for flood control. Concrete lined channels have smooth surfaces, solid walls and a uniform shape. The solid walls are for the elimination of erosion, the smooth surfaces and uniform shape for better and faster conveyance of floodwaters.

Canalised rivers in South Africa include the Liesbeek River (Luger 1998), Kuils River (Ninham Shand & Chittenden Nicks 1999) Sand, Keyser, Diep and Black Rivers (Brown 1992) in the Western Cape; and the Apies and Jukskei Rivers in Gauteng (Garner 1997). Most rivers in and around Cape Town are canalised, and have few remaining ecological attributes. They now merely act as conduits for storm water runoff and sewage effluent (Brown 1992). Table 2.4 gives a summary of the case studies of the different types of channelisation and the associated changes in channel morphology.

2.5.3 Ecological impacts of channelisation

Channelisation impacts the flow and sediment regimes of rivers. As a result, some hydraulic biotopes (the flow and substratum environment of communities of aquatic species (King and Schael 2001), may be lost. This may lead to a decrease in species diversity, since all species require specific flow and/or substratum conditions and some are highly intolerant of change (Petersen *et al.* 1992 Admiraal *et al.* 1993; Downs and Thorne 1998). Excavation or bulldozing of substrata from the riverbed reduces heterogeneity of the hydraulic biotopes available to aquatic organisms, with natural geomorphological patterns, such as pool-riffle-sequences, lost (King and Schael 2001). Disruption of the substratum may also kill benthic organisms, which are an important source of food for fish (Brookes and Gregory 1988). Loss of meanders and reduced interaction with floodplains due to straightening and embankments, can eliminate fish and wildlife habitat and destroy the complex food web that floodplains once supported (Iversen *et al.* 1993; Pearce 1993; Toth 1993; Shields *et al.* 1997). Channel deepening can lead to changes in the species diversity and distribution of plants and animals in the watercourse, because the deeper water may reduce the amount of light reaching the riverbed and so rooted plants cannot grow (Brookes and Hanbury 1990). Rutherfurd *et al.* (2000) outlined how maintenance practices can impact on diversity. They stated that regular disturbances caused by maintenance activities reduce the chances of diverse habitats being maintained within and along the channels, and thus the chances of a diverse biota. For example, removal of snags, or in-stream obstructions such as tree branches, in Australian rivers, destroys the physical habitat of many aquatic and terrestrial species (Rutherfurd *et al.* 2000). Shelter from fast flow, shade, feeding and spawning sites, nursery areas for juvenile fish, territory markers and refugia from large predators are all lost to fish, as are a host of microhabitats within the complex surface structure of grooves, splits and hollows in the snags. The microhabitats host a diverse range of invertebrates, algae and microbes, which play an important role in the maintenance of water quality of the system as well as being a major food source for organisms higher up the food chain. Snags also provide habitat for reptiles, birds and mammals that use the stumps as nesting, foraging and lookout sites. Their role in habitat provision is especially important in sandy rivers where they provide the only hard substratum available for colonisation.

The impacts of canalisation on the river system are the same as that of channelisation, and more, with a resulting severe impairment of their ability to support life. Canalised rivers are usually isolated from their catchments by their artificial channels, and so receive no surface or groundwater inflows except via drains. They also provide no input to groundwater and so the water table beneath them may drop (Luger 1998). The concrete lining of their beds and banks eliminates all riparian, marginal and rooted aquatic habitat for plants, with the sole remaining plant life possibly being a film of algae on the concrete. Their beds and banks have lost all physical heterogeneity, and so they provide no substrata, food or refugia for aquatic animals because there is little life in them and little turbulence of flow and water quality is not usually markedly enhanced along their length. By contrast, natural river channels and their biotas have a capacity to assimilate pollutants and thus purify water flowing past. This is significant because canalised rivers usually carry an increasing load of point and non-point source pollutants from urban areas. Their reduced assimilative capacity for pollutants results in the water quality of most canalised rivers in urban areas being very poor (Brown 1992; Luger 1998).

Because the canals are designed to carry a range of low and high flows, perhaps up to those with a 20-year return period, floodplains outside the channels will tend to become terrestrial and used for other purposes (Toth 1993). Thus floodplain refugia and nursery areas for fish are lost, as is the interchange of nutrients and sediments between floodplain and river. Floods greater than the 20-year flood period will still overtop the banks, probably causing flood damage to property in the former floodplains (Toth 1993). Table 2.5 provides case studies of the impacts of channelisation on the hydrology, ecology and water quality of river systems.

2.5.4 Summary

Channelisation can involve straightening, deepening, widening or narrowing the channel, maintaining the banks in some desired (unnatural) form, or erecting embankments. Current speeds are increased when the channel is straightened or narrowed, leading to local and upstream scouring of the bed and deposition of eroded sediments downstream. Deepening and widening the channel result in an increased channel capacity, a decrease in current speeds and a subsequent increase in deposition. Canalisation is an extreme form of channelisation, whereby the channel bed and banks are lined with concrete.

The ecological repercussions of channelisation are many and complex. The hydraulic regime and geometry of the channel are changed, with the channel heterogeneity caused by natural flows replaced by homogenous trapezoidal channel forms with near-uniform flow. This loss of heterogeneity inevitably translates into a loss of ecological biodiversity. Rivers become isolated from their banks, floodplains and groundwater, eradicating the interdependence of these in terms of the movement of sediments, water and nutrients. Maintenance of rivers, through mowing and dredging, prevents plants from establishing on the banks and within the channel, while removing natural in-stream features eradicates habitat for a range of aquatic and terrestrial species.

Table 2.4: Case studies of types of channelisation and associated morphological changes.

Source	Types of channelisation									Associated morphological change							
	Straightening	Meander cut-off	Changed to one channel	Decrease in stream length	Embankments	Deepening	Widening	Narrowing	River maintenance	Bank erosion	Channel incision	Bed erosion	Sedimentation	Reduced sedimentation	Uniform channel	Change in channel form	Change in channel slope
Andersen & Svendsen 1997	*				*	*	*							*			
Admiraal *et al.* 1993 River Rhine	*				*	*		*		*	*			*			
River Meuse	*				*			*			*		*				
Beaumont 1981	*		*		*				*	*		*	*				
Brookes 1990 Elbæk River						*			*	*	*						
Brizga *et al.* 1999	*				*					*	*	*					
Downs & Thorne 1998					*	*	*		*	*			*		*		
Ebrahimnezhad & Harper 1997						*									*	*	*
Harberg *et al.* undated		*	*		*	*		*		*					*		
Harvey & Watson 1986					*	*	*			*	*		*				
Henry *et al.* 1995					*								*				
Iversen *et al.* 1993	*				*		*		*								
Koebel 1995 Kissimmee River				*		*		*			*						
Nolan & Guthrie 1998 Whittle Brook	*					*			*	*					*		
Nolan & Guthrie 1998 River Alt	*				*												
Pearce 1993 River Rhine	*	*	*	*	*			*			*	*		*			*
Petersen *et al.* 1992	*	*		*		*				*		*	*		*		
Reinfelds *et al.* 1995		*		*	*		*			*	*	*				*	
Schropp & Bakker 1998	*		*		*												
Shields *et al.* 1995							*			*	*	*	*				
Shields *et al.* 1997	*		*			*				*	*	*					
Simon 1989	*			*		*	*			*	*					*	*
Sterba *et al.* 1997	*		*			*											
Tockner *et al.* 1998	*				*							*					
Toth 1993 Kissimmee River				*	*	*		*			*		*	*			
Wissmar & Beschta 1998			*		*	*			*		*						
Wyzga 1996 Raba River	*		*	*		*		*			*			*			*

Table 2.5: Case studies of the impacts of channelisation on the hydrology, ecology and water quality of river systems.

Source	*Hydrology/Hydraulics*							*Ecology*										*Water quality*				
	Increased runoff	Reduced low flow	Increased peak flow	*Lower water table*	Reduced flood duration	Stabilized water levels	Altered hydrology	Reduced aquatic habitat	Floodplain cut-off	Reduced floodplain Habitat	Reduced species diversity	Reduced riparian vegetation	Reduced aquatic flora	Impacted on fish	Impacted on invertebrates	Reduced interaction with floodplain	Reduced bird & other terrestrial mammals	Vegetation encroachment	Reduced water quality	Increased pollution	Reduced Dissolved Oxygen	Increased water temperature
Admiraal *et al.* 1993 River Rhine				*			*				*	*		*		*			*	*	*	
Admiraal *et al.* 1993 River Meuse				*			*				*	*		*		*			*	*	*	
Beaumont 1981 Hout Bay River		*																				
Brookes, 1990 Elbæk River.																						
Downs & Thorne 1998							*			*	*	*		*					*			
Ebrahimnezhad & Harper 1997		*						*		*		*	*	*	*							
Gore & Shields 1995							*	*	*	*												
Harberg *et al* (undated)		*						*		*			*	*								
Harvey & Watson 1986	*							*														
Henry *et al.* 1995							*		*							*						
Iversen *et al.* 1993								*	*		*		*	*						*		
Koebel 1995 Kissimmee River		*				*	*	*		*	*	*	*	*	*	*	*	*			*	
Nolan & Guthrie 1998 Whittle Brook										*										*		
Nolan & Guthrie 1998 River Alt																			*			
Pearce 1993 River Rhine	*		*	*	*			*	*	*				*		*			*	*		
Petersen *et al.* 1992	*		*	*			*	*	*	*	*	*	*	*	*							*

CHAPTER 3

DESCRIPTION OF THE STUDY AREA

3.1 Introduction

The river was originally named De Kuylen ("kuils" which is Afrikaans for pools) (Burman 1962, 1970) or "River van de Kuylen" (Heap 1993). This was because it often dried up in summer with a series of pools visible. It used to be a non-perennial river flowing only in the winter months (Morant 1991; Ninham Shand 1999; O'Callaghan 1990). "But do not go out tomorrow in search of the Kuils River, for chances are you will not find it. Unlike the other rivers of the Peninsula, the Kuils River is a dry stream bed for ten months of the year, and a roaring torrent during the remaining two months." (Burman 1962:105). The Kuils River also used to discharge directly into False Bay (Harrison 1998).

3.2 Description of the study area

Figure 3.1 shows the Kuils River catchment and study area within the Cape Peninsula, Western Cape. The Kuils River is a major tributary of the Eerste River, joining the latter 5km from the coast. The river used to originate from springs in the Durbanville area. Presently its runoff originates mainly in the storm water system of the Durbanville residential areas. It emerges from a concrete-lined canal near Kanonkop (Ninham Shand 1999). Its catchment size is 261 km^2 from the source to the confluence with the Eerste River (Ninham Shand 1999). The river is in a low-lying area with the highest point only about 100m above sea level. Only the upper foothill, lower foothill and lowland geomorphological zones are present since the river does not originate in mountainous areas as most rivers (Figure 3.1 and 3.2). There are no flow gauging weirs on the Kuils River (Ninham Shand 1994). Mean annual precipitation in the catchment ranges from about 800mm in the eastern hills (Tygerberg Hills) to about 500mm near the coast (Grindley 1982). The area falls within the winter rainfall region of the Western Cape. An annual average rainfall of 555mm was measured at Durbanville for the period 1969-2000 (Figure 3.3).

3.3 Catchment characteristics

3.3.1 Geology and soils

The geology consists of the basement rocks of the Malmesbury Group, which underlie the riverbanks and surrounding slopes in the upper reaches. The Malmesbury Group consists of quartzites, phyllites, greywacke and shales of Pre-Cambrian age. The rocks are covered with recent thin deposits of turf and loamy sands with some alluvial deposition (Grindley 1982; Shand, Granger, Luger and Lee 1994; Ninham Shand and Chittenden Nicks 1999) down to the N1/R300 interchange (Figure 3.1). Clayey slopes occur at the interchange further away from the river and its floodplain. The river course flattens at the footslopes of the Tygerberg. The foothills of the Tygerberg phase into the Cape Flats coastal plain where alluvial soils are clayey, but fine organic matter is also present. The river then enters the coastal plain and passes through acidic sands with some local neutral to calcareous dune sands also present. (Ninham Shand and Chittenden Nicks 1999).

3.3.2 Vegetation

The natural renosterveld vegetation of the Tygerberg Hills has been replaced by agricultural land, urban development and alien vegetation (Grindley 1982; Ninham Shand 1999). Alien vegetation includes *Acacia saligna* (Port Jackson willow), *Acacia Cyclops* (Rooikrans), *Acacia mearnsii* (Black wattle), *Populus canescens* (White poplar) *Sesbania* and other species (Ninham Shand and Chittenden Nicks 1999). A concrete-lined low flow channel in the Durbanville area occurs within a grassed high flow channel. Diversion of some of the low flow water into the high flow channel has resulted in a marshy floodplain. Low grasses and sedges with occasional emergent *Typha* (bulrush) dominate the marshy habitat and plant life. *Cliffortia strobilifera* (Vleibos), a common riverbank vegetation type, is found in one clump near the N1/R300 interchange. The extensively disturbed slopes are covered with weedy indigenous species and numerous alien vegetation. Renosterveld pioneer species are evident with *Elytropappus rhinocerotis* (renosterbos) barely present. Little indigenous vegetation is found in this area other than the renosterveld. Channelisation led to the loss of a fully functional floodplain and other habitats. Diversity is moderate with medium to tall reeds and sedges dominating the area (Ninham Shand 1999; Ninham Shand and Chittenden Nicks 1999).

3.3.3 Aquatic fauna

Macro-invertebrate groups consist of hardy species in the river section between Van Riebeeck Road and the R300. These include damselfly nymphs, diving beetles, dragonfly nymphs, midge larvae, snails and limpets. There are no indigenous fish, with only Carp, an exotic fish, known to inhabit the river (Ninham Shand 1999).

3.3.4 Runoff

The geological features influence the surface runoff characteristics. Runoff is relatively high in the upper reaches with little subsurface flow (Grindley 1982; Shand *et al.* 1994). The natural flow of the river is characterised by high flood peaks and low base flows. The base flow is highly saline in the headwaters. The sandy areas of the lower reaches result in little surface runoff (Shand *et al.* 1994).

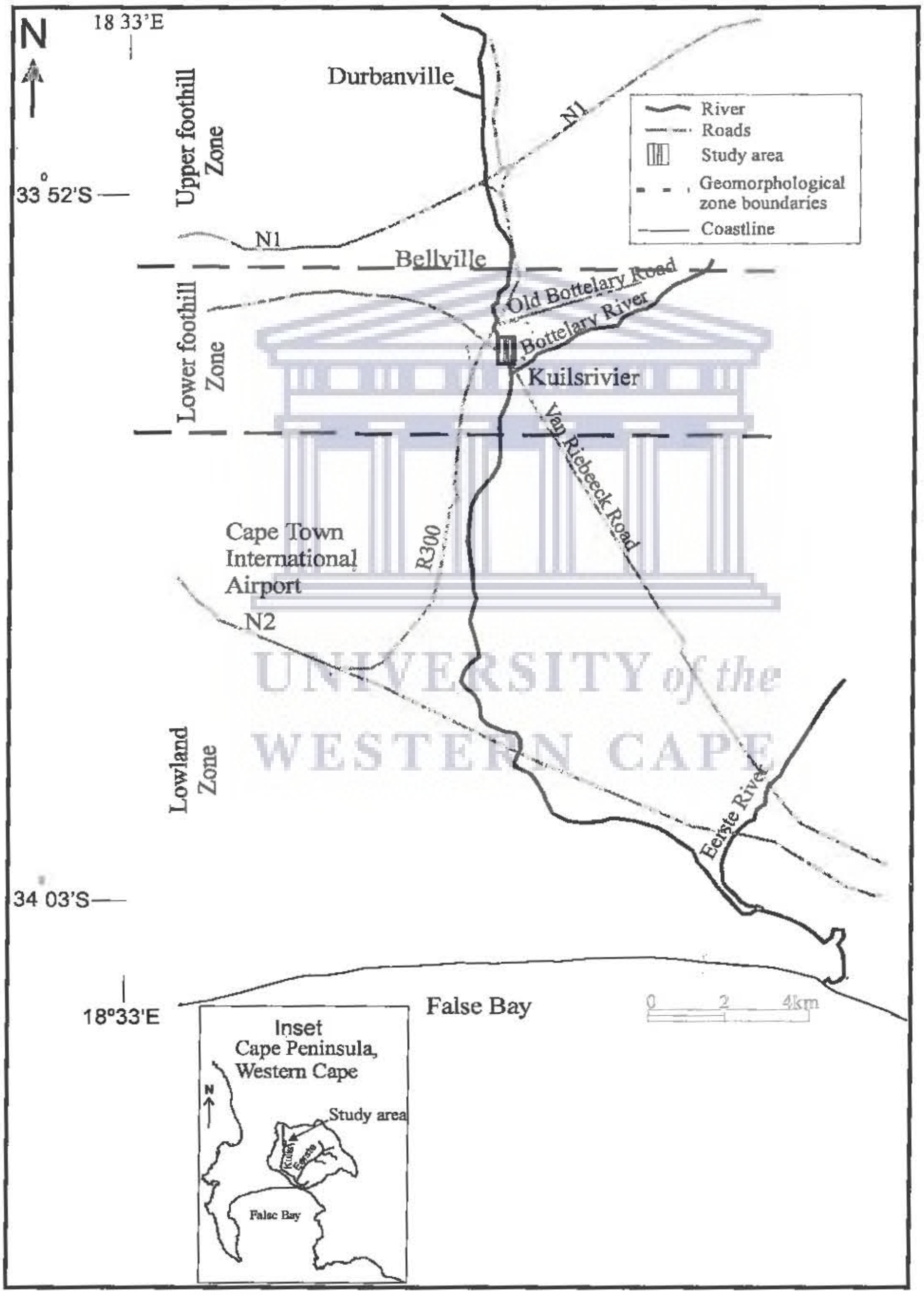

Figure 3.1: Kuils River catchment within the Cape Peninsula, Western Cape showing major suburbs, roads, geomorphological zones and study area. (After Ninham Shand & Chittenden Nicks 1999)

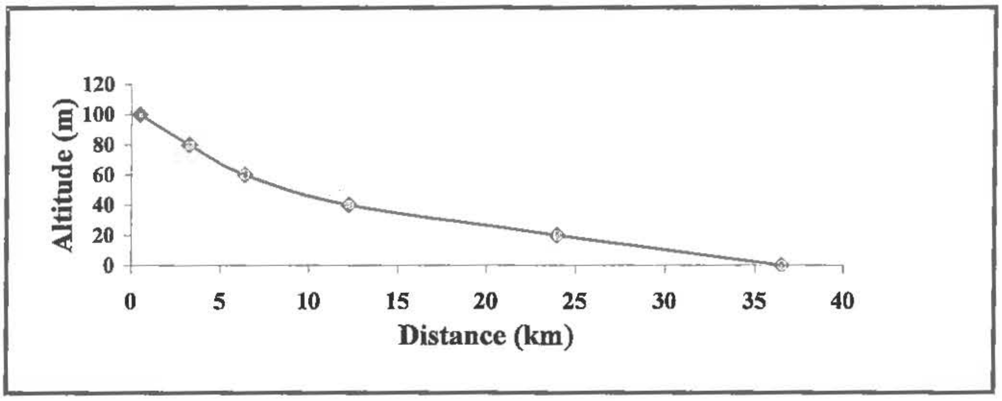

Figure 3.2: Longitudinal profile of the Kuils River.

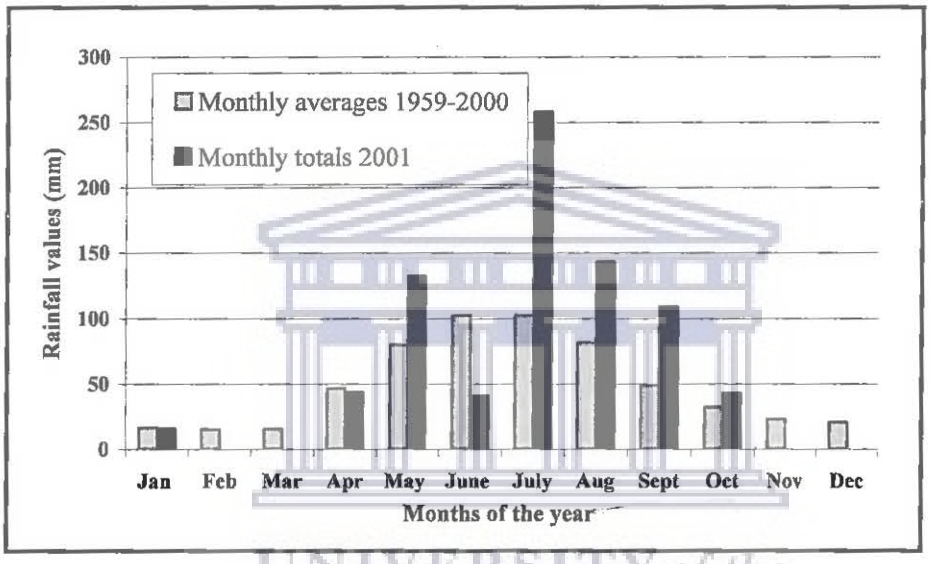

Figure 3.3: Rainfall data measured at Durbanville (T. de Villiers, local farmer, Durbanville area). The Western Cape received exceptionally high rainfall from May to September 2001.

3.4 Impacts on the river

3.4.1 Land-use changes

The Kuils River catchment was not developed extensively until the middle twentieth century. Development had mainly been agricultural, but extensive urbanisation took place with the development of the northern suburbs of Cape Town (i.e. the Durbanville, Bellville and Kraaifontein municipalities) during the twentieth century (Grindley 1982). Urbanisation in the Kuils River Catchment resulted not only in the loss of natural land and vegetation, but also in increased storm water runoff from areas that were previously hydrologically inactive (Brown, Davies and Gardiner 1991; Ninham Shand 1999; Shand, Granger, Luger and Lee 1994). The need for more space resulted in the encroachment of the floodplain in some areas along the river. There are two petrol stations built on the riverbank in Kuilsrivier on the R102 (or Voortrekker Road). There are still some housing developments taking place in the catchment.

The 1995 topographic map (3318DC Bellville) shows that land to the north and northeast of Durbanville is used for agricultural purposes. According to Mr. Scheepers, a resident of Durbanville, large parts of the area have since been developed for housing purposes (Scheepers 2000, University of the Western Cape, personal communication). There are numerous industries in the upper section of the river from the source to the Kuilsrivier municipal boundary (Ninham Shand 1999).

3.4.2 Changes in flow and sediment regimes

Taylor, Boelhouwers, Hendricks, Petersen and Solomons (2000) showed that the Kuils River was a non-perennial river up to 1962. The flow became directed towards the Eerste River by 1962. A series of vegetated dunes forced the river to turn eastward and join the Eerste River (Harrison 1998). The increase in urbanisation and storm water runoff changed it from a non-perennial to a perennial river. This also increased the flood risk in the lower parts of the catchment. There are a number of bridges crossing the river (Figure 3.1) that act as in-stream obstructions, trapping debris behind the pillars, and in this way restricting the flow. Dense *Typha capensis* (bulrush) stands choke the channel and contribute to restricting the flow (Ninham Shand, 1999; Ninham Shand 1994).

3.4.3 Water pollution

Point and non-point sources of pollution result in water pollution in the catchment. Waste Water Treatment Plants and industrial effluent make up the point sources, while litter, oil and other toxic substances from roads and agricultural activities constitute the non-point sources. Treated effluent and runoff from agricultural activities result in eutrophication (increased nutrient levels) in the system. This results in poor water quality and the proliferation of water plants such as *Typha capensis* (bulrush), *Eichornia crassipes* (Water hyacinth) and *Myriophyllum aquaticum* (Parrots feather) (Ninham Shand 1999; Ninham Shand and Chittenden Nicks 1999; Shand *et al.* 1994). Plastic pollution and other types of litter also degrade the system.

3.4.4 Physical disturbance to the banks and channel

Channelisation, canalisation and the construction of berms form part of the physical disturbance to the banks and channel itself. A short section of the river opposite the sewage pump station (Durbanville area) has been channelised (straightened) with a 1 to 2m berm constructed on the west bank mainly to control floods. Channelisation of a minor tributary associated the residential development in Sonstraal Villas resulted in extensive channel erosion and associated downstream sedimentation (Ninham Shand 1994). The channelisation was done for flood control.

3.5 Description of the study sites

3.5.1 Site 1

Site 1, upstream of all planned channelisation activities, served as the control site. It had high, near vertical, eroding sand banks. The banks were covered with *Pennisetum clandestinum* (kikuyu), other grasses and a few alien trees. The site was approximately 46m long with a narrow, confined, slightly meandering channel (Plate 3.1). Three cross-sections were established at the site in the summer of 2000/2001.

There were uncertainties, at the beginning of the project, as to how far upstream the planned channelisation would extend. This created a problem with the selection of Site 1 because the study intended to cover all future channelisation, plus an undisturbed length of river upstream. The upstream reach was important, because it seemed possible that the initial eroded condition of Site 2 might have been caused by the earlier downstream channelisation of Site 3. The water flowing through Site 2 could have been "pulled" downstream faster into Site 3 by the wider, smoother channelised channel. If Site 2 was also to be channelised, it might have been possible to use Site 1 to test this hypothesis. However, if Site 1 was placed too close to Site 2, it might get channelised, and if we placed it too far away it might be beyond the effects resulting from channelisation at Site 2.

Plate 3.1: Site 1 at the beginning of the study period (January 2001). The line indicates the position of the cross-section. Note the narrow confined channel and the banks covered with *Pennisetum clandestinum* (kikuyu) and alien weeds.

3.5.2 Site 2

Site 2, slightly downstream of Site 1 and originally similar to it, also showed signs of severe erosion with a confined macro-channel between high crumbling banks, an active channel meandering within this, and deep erosion dongas entering on either sides (Plate 3.2). It was approximately 104m long, and also due to be channelised. It was located immediately upstream of the reach that was recently channelised (i.e. completed in December 2000). This site was chosen to record how ecological, geomorphological and hydraulic features would be affected as channelisation proceeded. The banks were covered with *Pennisetum clandestinum* (kikuyu), weeds and a few alien trees. Four cross-sections were established at the site in the summer of 2000/2001. After initial data collection at this site, it was widened in January and February 2001, and the banks re-graded to a milder slope and planted with kikuyu.

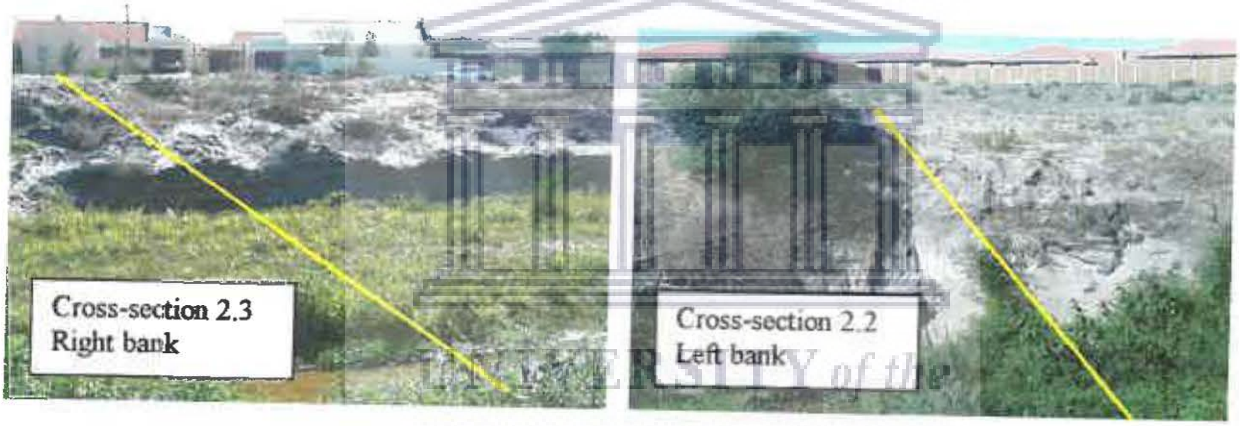

Plate 3.2: Site 2 at the beginning of the study period – January 2001. Lines indicate the position of the cross-sections. Note the crumbling banks and sparse vegetation cover (mostly alien weeds and a few alien trees).

3.5.3 Site 3

Site 3 was in the already-channelised stretch downstream of Site 2. It was 155m long and fairly straight. It fell within the reach stretching from upstream of Van Riebeeck Road Bridge to downstream of Pioneer Street Bridge (Figure 3.4). It was widened and deepened in 2000, (before the study began) and had a wide, shallow, trapezoidal channel 0.5m deep with banks stabilised by kikuyu grass and a central earth-lined gully. The low-flow channel conveyed a discharge of $1.5m^3.s^{-1}$, while the floodplain area could convey a discharge up to $1405m^3.s^{-1}$ (Ninham Shand 1999). Local bank reinforcement, in the form of thin rock mats, was introduced from the top of the slope down to 1m above the low water level. A gabion, designed to dissipate energy, was constructed within the section (Plate 3.3). Five cross-sections were established at this site in the summer of 2000/2001.

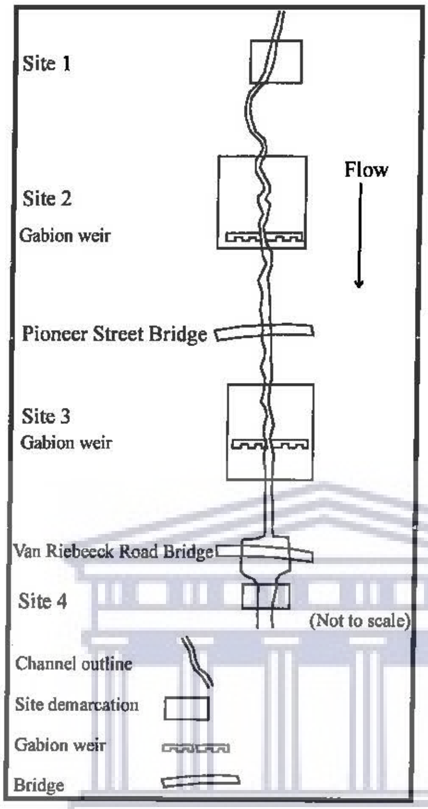

Figure 3.4: Location of the four sites within the study area (December 2000).

Plate 3.3: Site 3 at the beginning of the study period (January 2001).

3.5.4 Site 4

Site 4 was in the most downstream reach, within the commercial district of Kuilsrivier. This section was canalised in 1993/1994. It is now a trapezoidal-shaped concrete channel, with a central gully (Plate 3.4). The concrete lining is 14m wide in the invert and 20m wide across the top. It is 1.175m deep and has side slopes of 1:3 (Roelof de Haan, senior engineer – Ninham Shand, pers. comm., May 2001). Two cross-sections, but no plan map were established at this site in the first summer of data collection.

Plate 3.4: Description of Site 4. The measuring tape indicates the position of cross-section 4.1. This cross-section was used for the discharge-stage modelling (Section 4.5).

CHAPTER 4

METHODOLOGY

Chapter two outlined the different ecological and geomorphological attributes characterising a functional channel. This chapter describes the materials and methods used to sample or measure and analyse the macro-invertebrate and vegetation data; to describe the channel morphology and substratum; and to collect and calculate discharge data. Table 4.1 outlines the dates on which the different parameters were sampled or measured. Most of the sampling or measuring took place during the summer period (December 2000 to May 2001 and repeated January 2002 to March 2002). The substratum and flow maps of Site 2 were re-mapped on 19 April 2001 after the January – February 2001 channelisation.

Table 4.1: Dates on which the different parameters were sampled or measured.

Sampling period	Dates	Cross-sections	Habitat maps	Macro-invertebrates	Vegetation	Discharge
First summer	19-21 December 2001	All sites				
	23 Jan – 20 Feb 2001				All sites	
	07 Feb – 01 Mar 2001		Sites 1 - 3			
	19 Apr 2001		Site 2			
	21 Apr – 14 May 2001			All sites		
Winter	11 May – 12 Jul 2001					All sites
	24 – 26 Jul 2001		Sites 1 - 3			
	27 Jul 2001	Site 1 & 2				
Second summer	15 Jan – 18 Feb 2002				All sites	
	30 & 31 Jan 2002		Sites 1 - 3			
	20 – 23 Feb 2002	All sites				
	12 & 13 Mar 2002			All sites		

4.1 Geomorphology: cross-sections and channel outlines

Cross-sections as well as substratum and flow maps were used to describe channel morphology and the physical habitat available for macro-invertebrates. There are various methods to measure the cross-sections. These include measurement with a tape or rule, levelling, using a clinometer or Abney level to measure slope angles and tachometry using a level or theodolite. The tachometry method of optical distance measurement (Gordon *et al.* 1992) was used to measure the cross-sections. A theodolite (Leica TC307 model) was used to obtain readings reflected off a Standard Leica prism fixed on a staff. The horizontal distance to the staff, the difference in surface elevations and the location in reference to other points were derived (Gordon *et al.* 1992). The theodolite used was electronic, thus the coordinates of all the points along a cross-section were calculated automatically. The cross-sections were surveyed in a straight line between two terminal points. The survey system (points) was fixed to the National Survey Coordinate system using a Global Positioning System (M.C. Briers, Surveyor, pers. comm., Geomatics Department, University of Cape Town 2001).

The theodolite was also used to obtain the channel outline and plan maps when the sites were surveyed for the first time. Tape measures were used to delineate and create channel outlines when the theodolite was not available. The tape measures were laid in a straight line along the length of the channel. Channel widths were measured at right angles to this tape by using a second tape. Substratum and flow maps were also drawn at the same time while the tapes were still in place, using the methods of King and Schael (2001). The surveyors used the Computer Aided Drafting (CAD) programmes Autocad and Allycad to generate the channel outlines and cross-sections.

4.2 Ecology: habitat maps

Two methods could have been used to describe the physical habitat. The first involved using surveyed cross-sections. The method and its application are outlined in King and Schael (2001). This method was not used because the data from one cross-section would have been extrapolated to fit in with the next cross-section. Finer detail could have been lost if the cross-sections were too far apart. The physical heterogeneity and habitat patchiness would thus have been lost with cross-section data. Another reason for not using this method was that the few surveyed points would not have reflected the complex mosaic conditions present in rivers available to aquatic organisms.

The second method entailed habitat mapping, in which habitat maps were derived from substratum and flow type maps. The terms "hydraulic stream ecology" and "ecohydraulics" are also used to describe the method. The concept of, and background to, hydraulic biotopes were described by Rowntree and Wadeson (1999). The variables used in this study to describe habitat were similar to those of King and Schael (2001) to define their hydraulic biotopes. The method relies on visually assessing the substratum and surface flow types.

The previously surveyed channel outlines were used as templates for all hand-drawn maps. Tape measures were also used to guide the mapping of the distribution of the different channel features. The hand-drawn habitat maps were scanned and imported into CorelDraw

V8, a computer-based drawing program, and digitised on screen. Colour codes were added to create the final substratum and flow type maps. The actual areas of the different categories of substratum and flow types were calculated using a digital planimeter and expressed as a percentage of the channel area. The maps were redrawn (Table 4.1) to assess changes due to floods and channelisation.

Table 4.2 and 4.3 outline the categories of the visually distinct flow types and categories of the substrata respectively. Table 4.4 outlines the hydraulic biotopes found at each site during the different sampling periods, while Table 4.5 provides a description of additional features used in the habitat mapping.

Table 4.2: Categories of visually distinct flow types identified in the study (King and Schael 2001)

Flow type	Definition
Broken standing waves (BSW)	Standing waves present that break at the crest (white water).
Undular standing waves (USW)	Standing waves form at the surface with no broken water.
Rippled surface (RS)	Water surface has regular smooth disturbances forming low transverse ripples across the direction of flow.
Smooth boundary turbulent (SBT)	Water surface remains smooth; medium to slow streaming takes place throughout the water profile; turbulence can be seen as the upward movement of fine suspended particles.
Trickle (TR)	Small, slow, shallow flow; when occurring with cobbles, flow is between bed elements with few if any submerged.
Barely perceptible flow (BPF)	Smooth surface flow, only perceptible through the movement of floating objects.
No flow (NF)	No water movement

Table 4.3: Categories of substrata identified in the study (King and Schael 2001)

Category	Size range (mm)
Sand (SA)	0.063-2
Gravel (GR)	2-64
Cobble (C)	64-256
Boulder (B)	> 256

Table 4.4: Hydraulic biotopes identified and sampled during 2001 and 2002.

Hydraulic biotopes	Hydraulic Biotope No. - #	Site 1		Site 2		Site 3		Site 4	
		2001	2002	2001	2002	2001	2002	2001	2002
SA in SM	1			*	*	*			
SA+OM in SM	2				*	*			
SA+OM+A in BF	3			*	*		*		
SA+OM+A in SM	4		*		*				
SA+OM+A+V in SM	5				*				
SA+OM+claybock material in SM	6	*							
MV in SM	7			*		*			
MV in BF	7	*							
MV+A in BF	8		*	*	*	*	*		
V in RS	9	*							
V in BF	9	*		*					
V+A in NF	10			*		*			
V+A in BF	10					*			
C in SM	11								
C+B+A in SM	12			*	*	*	*		
C in SM	13					*			
C+V+A in BF	14						*		
B+OM in BF	15					*			
Slope clayblock material in RS	16						*		
Brown clayblock material+G in RS	17	*							
BR+gabion wiring in SM	18			*					
Concrete+SA+G in SM	19						*		
Concrete in SM	20							*	
Concrete+A in SM	21							*	*
Concrete+A in BF	21								*
Concrete+SA in SM	22								*
Concrete+SA+A in SM	23							*	
Concrete+V+OM+A in SM	24							*	*
Hole in concrete in SM	25							*	*

= Reference number given to biotopes irrespective of flow types. Where SA = Sand; G = Gravel; C = Cobble; B = Boulder (See Table 4 for size ranges); V = Vegetation; MV = Marginal vegetation; SV = Submerged vegetation; ODL = Organic matter; BR = Building rubble; A = Algae (Table 4.5). RS, SM, BF and NF are flow types (Table 4.2).

Table 4.5: Key for additional features used in hydraulic biotope mapping.

Feature	Description
Brown clayblock material	Semi-resistant, organic clayey material found on the channel floor in Site 1.
Clayblock material	Clayey material found on the channel floor in Site 1 and 2.
Slope clayblock material	Semi-resistant, organic clayey material found at the base of the banks. Was removed from the banks during high flows and deposited in the channel.
Grey clayblock material	Clayey material exposed at the bottom of the slopes due to bank erosion in Site 1.
Building rubble (BR)	Material such as bricks, concrete slabs and pipes.
Gabion	Wire mesh baskets filled with rocks. Used as a weir and in the channel to protect the channel against erosion.
Marginal vegetation (MV)	Vegetation growing along the channel margins; may be partially submerged or protrude from the water.
Vegetation (V)	Aquatic vegetation growing in the channel; may be partially submerged or protrude from the water.
Organic matter	Allochthonous plant material from terrestrial sources.
Algae (A)	Epilithic algal growth; attached to the surfaces of substrata and vegetation.

4.3 Ecology: macro-invertebrates

Habitat maps were derived from the substratum and flow maps and completed for three of the four sites surveyed. The different hydraulic biotopes were identified from the habitat maps and sampled.

The samples were taken in summer and the macro-invertebrate communities are thus not representative of the full annual suite of macro-invertebrate families occurring in the river. Sampling during the summer low flows is advantageous to assess water quality since pollution problems will be more marked as there will be no dilution effects due to rains (Tharme *et al.* 1997). A modified version of the South African Scoring System Version 4 (SASS 4) biological method was used for the invertebrate sampling (Thirion *et al.* 1995). SASS 4 requires specific time periods in which to identify the macro-invertebrate families. Longer time periods were taken in identifying the families because the researcher was not familiar with the different families. SASS also requires that specific biotopes be sampled. All the possible biotopes were sampled in this study. This included building rubble, concrete and gabion wiring in the channel. Sediment cores of approximately 0.2m were used to sample the sand bed under all flow types. A 250 μm mesh net was used to sample the marginal and in-channel vegetation. The net was swept in and out through the marginal and in-channel vegetation. The clayblock material substrate, building rubble/wiring within the channel and gravels and boulders were brushed with a commercial dishwashing brush and disturbed to dislodge the organisms into the net. The samples were taken within each hydraulic biotope with their positions marked on the flow maps.

The organisms were placed in a sorting tray and identified in the field by using the user manual for biological monitoring of streams and rivers using SASS 4 (Thirion *et al.*, 1995). Taxa were assigned an abundance rating of 1 to 5 (King and Schael 2001) (Table 4.6). The samples were also fixed and preserved with 4% formalin and 70% ethanol. The preservation of the organisms allowed for further identification in the laboratory and the building of a reference collection.

Freshwater ecologists at the Freshwater Research Unit, University of Cape Town, verified certain samples.

Table 4.6: Abundance ratings for macro-invertebrate families (King and Schael 2001)

Abundance Rating	Number of animals per sample
1	1
2	2-6
3	7-20
4	21-100
5	>100

Data analysis involved entering the data into the Excel software package, and importing it into PRIMER V 5.0 statistical software (Clarke & Gorley 2001; Clarke & Warwick 1994). Prior standardisation of the data was necessary since not all the samples were of the same size. The data were also transformed to Presence/Absence format to give equal weight to all the families, whether rare or abundant. The transformation was used to weight the contributions of the different taxonomic groups and the choice of transformation is biological and not statistical. The Presence/Absence transformation can be regarded as the most severe transformation possible, which down-weighs the contribution of the common species in relation to the rarer ones. One (1) (presence) or 0 (absence) in the Presence/Absence transformation represented the data matrix and the Bray-Curtis similarity was computed. Cluster analysis and Ordination through Multi-Dimensional Scaling (MDS) were then performed on the data (Appendix 1). The cluster analysis produces a dendrogram in which groups of similar samples cluster together. The ordination analysis produces a map of the samples in 2-dimensional space (MDS plot), with the distance between samples reflecting dissimilarities in community structure. Similar samples are thus close together and dissimilar ones far apart. The stress required to produce the plot indicates how accurately the high-dimensional relationships among the samples are represented in 2-dimensional space. The calculated stress value provides a good means of assessing the reliability of the MDS ordination. According to Clarke & Warwick (1994), a stress value of <0.05 gives excellent representation with no prospect of misleading interpretation, and a stress value of >0.3 could give a misleading picture and should therefore be treated with great caution (Clarke and Warwick 1994).

SASS works on the premises that each taxon (family) of invertebrates from South African rivers is allocated a score. The scores are based on the family's tolerance to pollution and range from 1 for those families most tolerant of pollutants to 15 for those most sensitive to pollutants (Thirion *et al.* 1995). The assigned scores per family were added for each sample to give a total score per sample. The average score per taxon (ASPT) was calculated by dividing the total score by the number of families (taxa) found in each sample. These scores were averaged per site per sampling period. The results were interpreted using Table 2.2.

4.4 Ecology: vegetation

The vegetation was sampled along selected cross-sections at each site. First, a measuring tape was laid along selected cross-sections (Table 4.7) and then a $1m^2$ grid was used to delineate successive sampling plots. Plant species present with their respective aerial cover were noted within the sampling plots. In each sampling plot, the cover of each species was defined as the proportion of the ground occupied by a perpendicular projection of the aerial parts of each species, expressed as a percentage. The height of the tallest individual of each species was measured, together with a measure of the vigour of the species from 0 % (dead) to 100 % (very healthy). The vegetation was sampled in a non-destructive manner based on floristic characteristics. Vegetation samples were collected from the surrounding areas for identification (Goldsmith, Harrison and Morton 1986). The collected specimens were pressed in the field and sent to Mr. F. Weitz and Prof. L. Raitt at the Botany Department, University of the Western Cape for identification.

Vegetation data for all the transects were entered into Turboveg V1.99b, a vegetation database (Botany Department, Stellenbosch University 2001) and then exported into an Excel spreadsheet. One Excel sheet per vegetation transect for a specific year was created. The data of the two years per transect were combined in Excel for analysis. The two years were combined and analysed together to ascertain whether the groups or communities formed in year one were still present in year two. PRIMER V5 was used for the analysis, in the same way as described for the macro-invertebrates (Appendix 1), but the data were not transformed or standardised as in Step 3. The reason for this was that all the samples (sampling plots) were the same size. Sampling plots without vegetation (e.g. 100% bare ground) and outliers were excluded from the PRIMER analysis. Outliers were outlying points or samples that lay far apart from the rest of the data set and had a disproportionate effect on the data. These were removed to allow for better examination of the remaining clusters. It was also important to see, when changes occurred, if the different groups identified occupied similar positions on the cross-section in year two compared to year one. The positions of the groups were indicated on the cross-section by copying the created cross-section from Allycad into CorelDraw V8. Lines and text were added in CorelDraw V8 to demarcate the different groups and their positions on the cross-section.

Table 4.7: The number of vegetation sampling plots surveyed per cross-section.

Site	Cross-section	Number of sampling plots 2001	2002
1	1.1	30	30
	1.2*	24	30
	1.3	23	26
2	2.1	43	33
	2.2*	40	42
	2.3	45	45
3	2.4	45	47
	3.3*	46	50
	3.5	43	43
4	4.1*	38	39

The * indicates the vegetation transects used for analysis.

4.5 Rainfall and Discharge

Discharge readings were taken to develop an understanding of how the river reacted to rainfall events. The winter discharge sampling programme entailed field observations during rain events, starting on the first day of rain with depth readings at Site 4 cross-section 4.1. The field observations continued until it was safe to take discharge readings in all the sites. Discharge readings were taken on three dates during the winter. The discharge and depth data were used by Mr Jateen Bhana (under the supervision of Dr. Neil Armitage), a fourth year Civil Engineering student in the Department of Civil Engineering, University of Cape Town, for his project (CIV436D Thesis 17: Using PCSMM GIS to model the Kuils River catchment). The aim of the project was to use the Kuils River catchment as a model to produce a discharge-stage rating curve for the river. Site 4, cross section 4.1 (Plate 3.4), was used because it was the most stable of all the sites. Detailed plan, substratum and flow maps were drawn when it was safe to do so. A photographic record was also compiled.

The velocity-area method of calculating discharge and a pygmy-type current meter for measuring velocity was used. A top-setting wading rod helped to facilitate setting the current meter at 60% depths (Gordon *et al.* 1992).

Discharge data were collected during the months of May, June and July 2001. Depth measurements at cross-section 4.1 were taken continuously throughout the study period.

CHAPTER 5

RESULTS

5.1 Introduction

Chapter 4 reported on the materials and methods used to measure, sample and analyse the different parameters covered in this study. This chapter will address the results of the analyses of the different parameters. A brief description of the events occurring during the study period is presented chronologically in Figure 5.1 together with a set of photographs helping to visually orientate the reader. This introduction provides an outline of the changes that occurred in the cross-sections (Section 5.2) and the habitat maps (5.3). Changes in the macro-invertebrates and vegetation will be discussed in Sections 5.4 and 5.5 respectively.

Site 2 was channelised after the initial data collection exercise, in January and February of 2001. This involved straightening of the channel and widening of the banks (Figures 5.1 and Plate 5.1). Bank erosion occurred within the widened section of Site 2 and between Sites 1 and 2 during May 2001 (Plate 5.2) at the beginning of the winter rains. The Western Cape had unusually high rainfall from May to September 2001 (Figure 3.3). Further extensive bank erosion occurred at Sites 1 and 2, upstream of Site 1, and on the outer bends of meanders between Site 1 and 2 during the July 2001 floods (Plates 5.3 and 5.4). The bank erosion resulted in channel widening and deposition of eroded sediment in the channel further downstream. Site 3, not indicated on Figure 5.1, was also heavily silted up due to upstream bank erosion (Plate 5.5). The owner of the horse farm adjacent to Site 1 lost about 250 m^2 of land during the floods. This is equivalent to about 1250 m^3 of bank sediment from the right bank alone. The Oostenberg Municipality re-structured the banks to replace this land, using sediment from the channel. After the July 2001 floods, the channel was straightened and widened from Site 2 upstream past Site 1 towards the Old Bottelary Road Bridge during October and November 2001 (Figure 5.1 and Plate 5.6). The straightening resulted in a decrease in channel length from 113m at the beginning of the study period to 108m after the January – February 2001 channelisation to 104m after the October – November 2001 channelisation. This was done to eradicate the slight meandering of the channel in order to prevent future erosion on the outer bends and to accommodate floods of similar or larger magnitude. Those reaches straightened during October and November 2001 and referred to above remained stable during the 2002 winter rainfall period, but bank erosion occurred at the

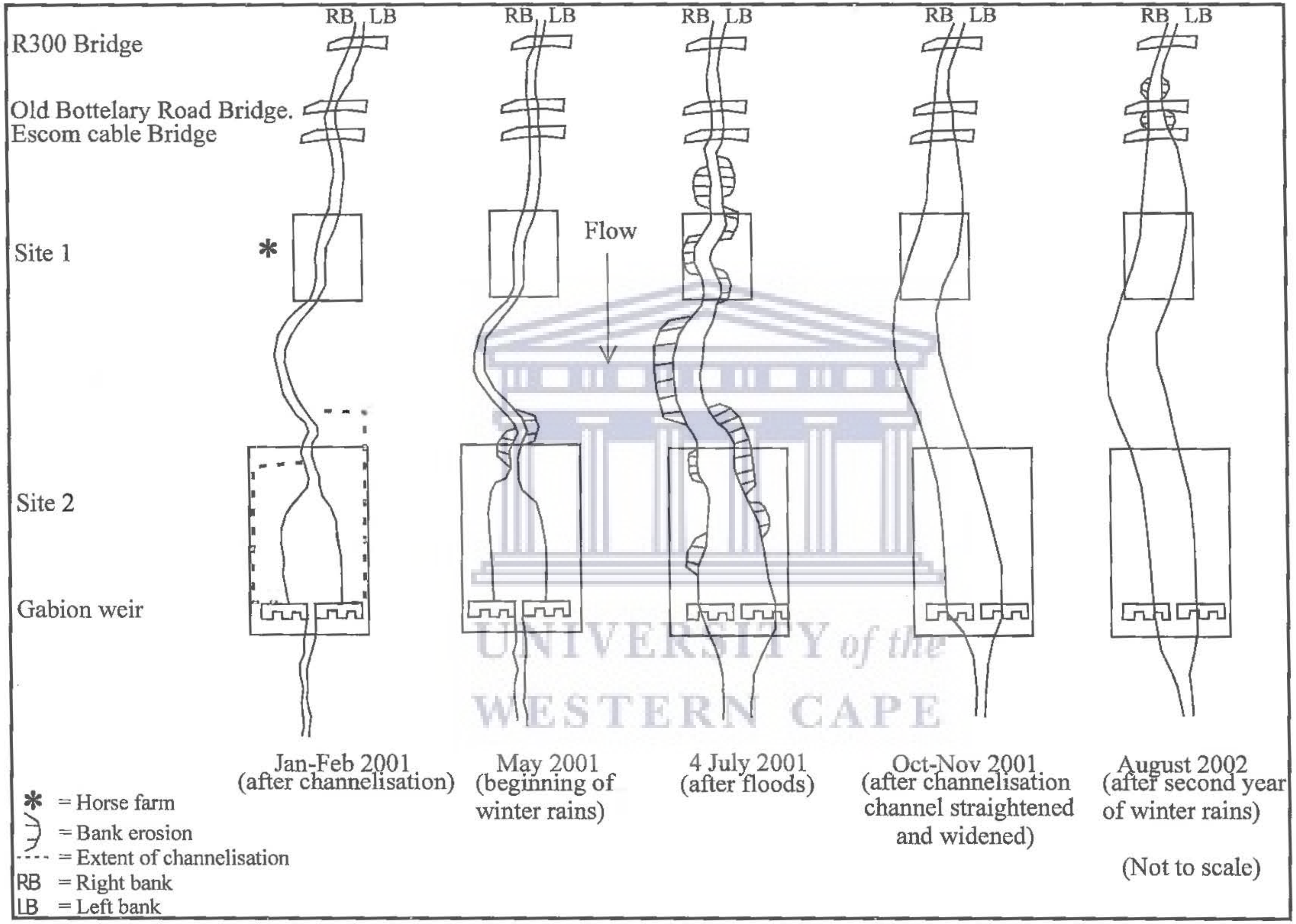

Figure 5.1: Channel changes through the study period as a result of the channelisation and winter floods.

Old Bottelary Road Bridge upstream of Site 1 with undercutting of bridge pillars. The impacts of the channelisation are discussed in Chapter 6 (Plate 6.2).

Plate 5.1: Cross-section 2.3 on the right bank before and after the channelisation. Flow was from the right to the left.

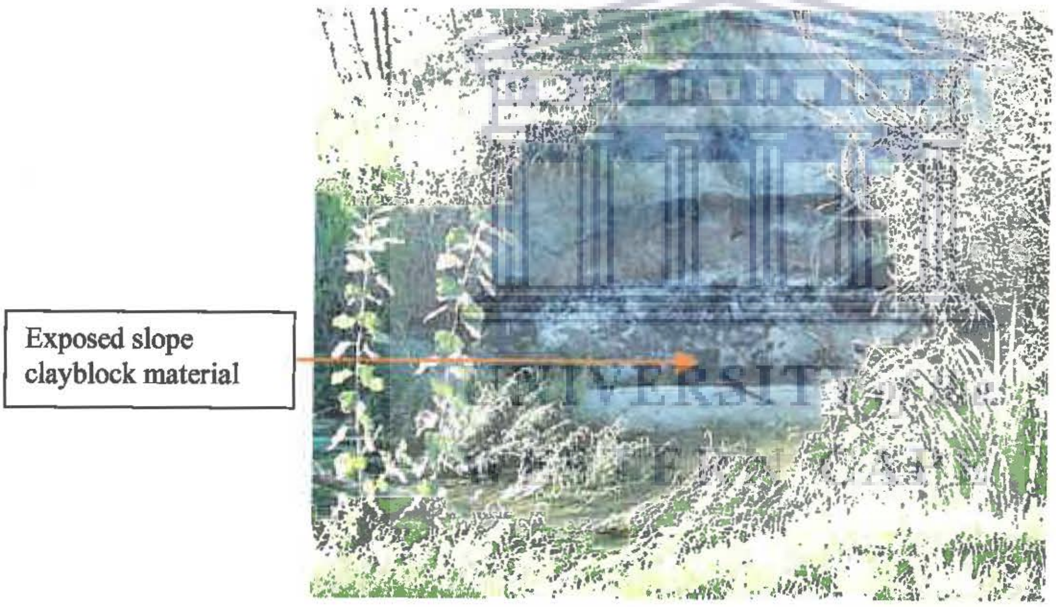

Plate 5.2: Bank erosion on the left bank (flow was from the left to the right) between Site 1 and 2 during May 2001. Note the exposed resistant slope clayblock material (black colour) at the bottom of the slope.

5.2 Geomorphology: cross-sections

5.2.1 Site 1

The cross-sections of Site 1 (Figure 5.2) indicate that the channel was fairly narrow at the beginning of the study period (December 2000), with an active channel or thalweg slightly incised into a bigger macro channel. The water's edge at all three measurement times is indicated with arrows on Figure 5.2. The definition of the active channel was more pronounced on the right bank (looking downstream) than on the left bank. The bank collapse during July 2001 (Plates 5.3 and 5.4) resulted in more than 5m of land being washed away on the left bank at cross-sections 1.1 and 1.3. The active channel of cross-section 1.2 widened by 2.5m and the midslope of the right bank (macro-channel) receded by 6.5m (indicated by arrows on Figure 5.2). The bank collapse also resulted in sediment being deposited in the channel as recorded at cross-section 1.1. The channelisation during October and November 2001 was an attempt to stabilize the banks of the river by re-grading them to an angle of about thirty degrees and furthermore resulted in a uniform straight channel. The channel was filled in on the right bank at cross-sections 1.2 and 1.3 and on the left bank at cross-section 1.1, resulting in a more or less trapezoidal cross-section (Figure 5.2 and Plate 5.5).

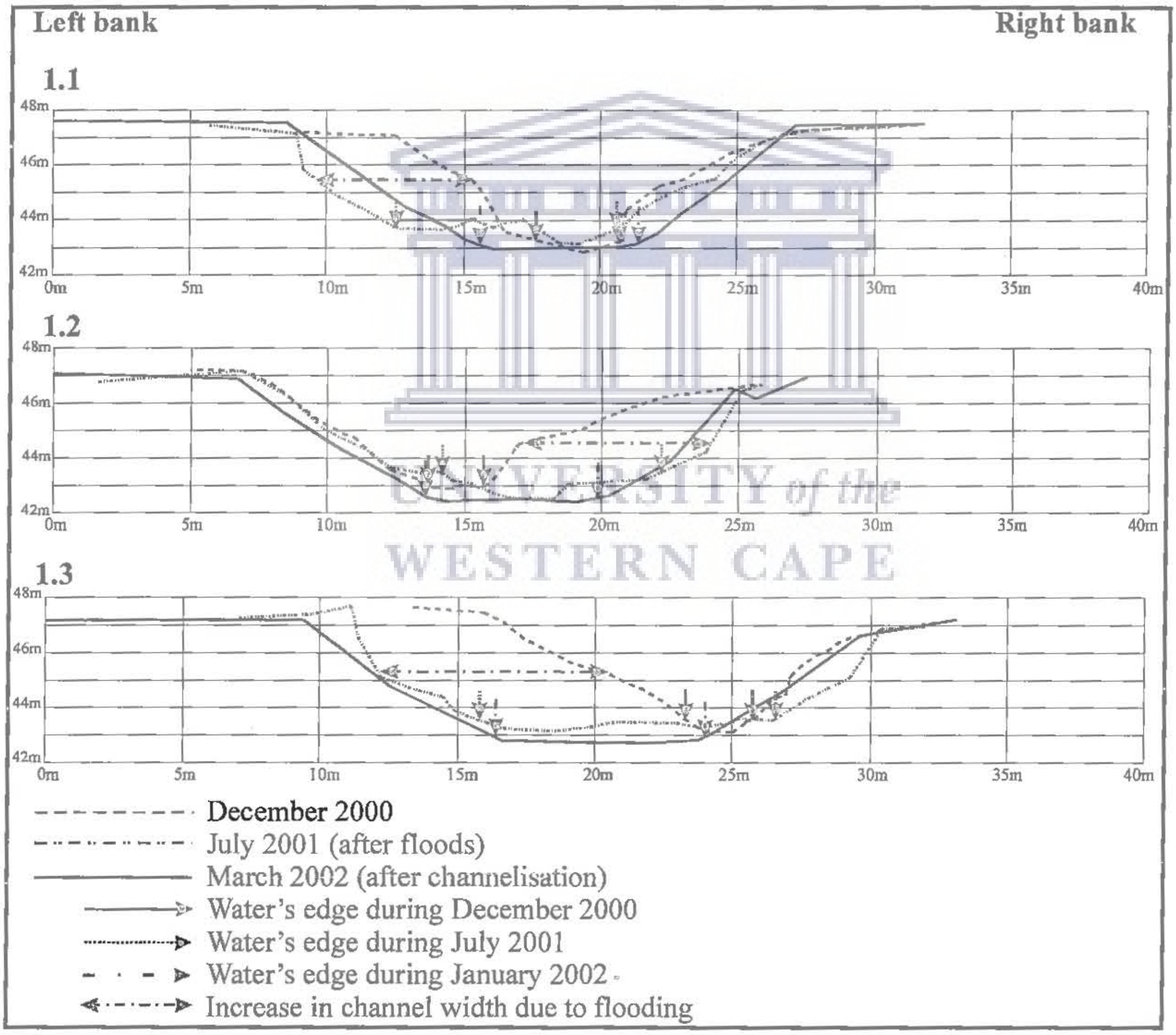

Figure 5.2: Cross-sections of Site 1 during the first and second summer after channelisation and intervening winter floods.


During the floods on 03 July 2001.

After the floods on 04 July 2001.

Plate 5.3: Water levels in Site 1 (looking upstream towards Site 1) during and after the floods. Photograph on the left was taken on 03 July 2001. Channel changes on right were noticed on 04 July, but the photograph was taken on 05 July 2001. The photograph on the left was taken at about 1pm while the water levels were still rising and before it reached a maximum at about 5pm, as reported by the horse farm owner. The telephone poles on the left bank (on the right of the photographs) were used as reference points.

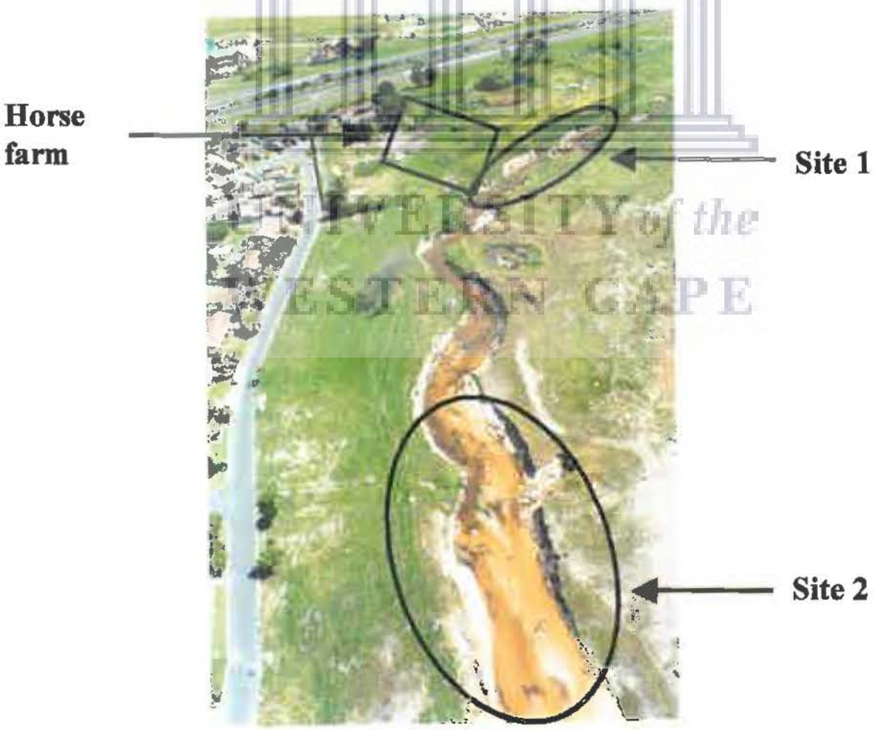

Plate 5.4: Bank erosion within Sites 1 and 2, upstream of Site 1 and on the outer bends of meanders between Site 1 and 2 after the July 2001 floods. Note the sediment deposited in the channel. Photograph was taken on 27 September 2001 – courtesy of Ninham Shand Consulting Engineers.


Looking downstream from Site 1.

Looking upstream from Site 2.

Plate 5.5: The straightened channel of Sites 1 and 2 after the October – November 2001 channelisation. The channelisation involved bulldozing the channel to straighten it. The banks were also straightened and widened.

5.2.2 Site 2

The channel of Site 2 was wider than that of Site 1 at the beginning of the study period, but the active channel itself was relatively narrow. The water's edge at all three measurement times is indicated with arrows on Figure 5.3. The channel also became wider in a downstream direction with cross-section 2.1 the narrowest and cross-section 2.4 the widest. The winter floods resulted in bank retreat on the left bank of more than 7.5m at cross-sections 2.1 and 2.3, and ± 10m at cross-section 2.2. Bank retreat was less severe on the right bank with a retreat of ± 1.5m at cross-section 2.1 and ± 5m on cross-section 2.2, while the right bank of cross-section 2.3 experienced minimal erosion. Cross-section 2.4 experienced no bank erosion. The floods also resulted in sediment deposition within the channel as shown on cross-sections 2.2, 2.3 and 2.4 (Figure 5.3 and Plate 5.4). The channel bed was raised by ± 1m at cross-section 2.3 and 2.4 and by 1.5m at cross-section 2.2 (Figure 5.3). Due to the channelisation the right bank receded a further 1.5m and 2m at cross-section 2.1 and 2.2 respectively. Reshaping of the left side of the channel at the last two cross-sections resulted in infilling and build up of about 2m of the bank (Figure 5.3 and Plate 5.5).

5.2.3 Site 3

The channelisation of Site 3 during 2000 resulted in a wide trapezoidal shaped channel with a relatively narrow active channel and floodplain areas. The water's edge is indicated with arrows on Figure 5.4. There was no bank erosion as a result of the winter floods, but some deposition did occur on the floodplains (Plate 5.5). The active channel was lowered as shown on cross-sections 3.4 and 3.5 (Figure 5.4).

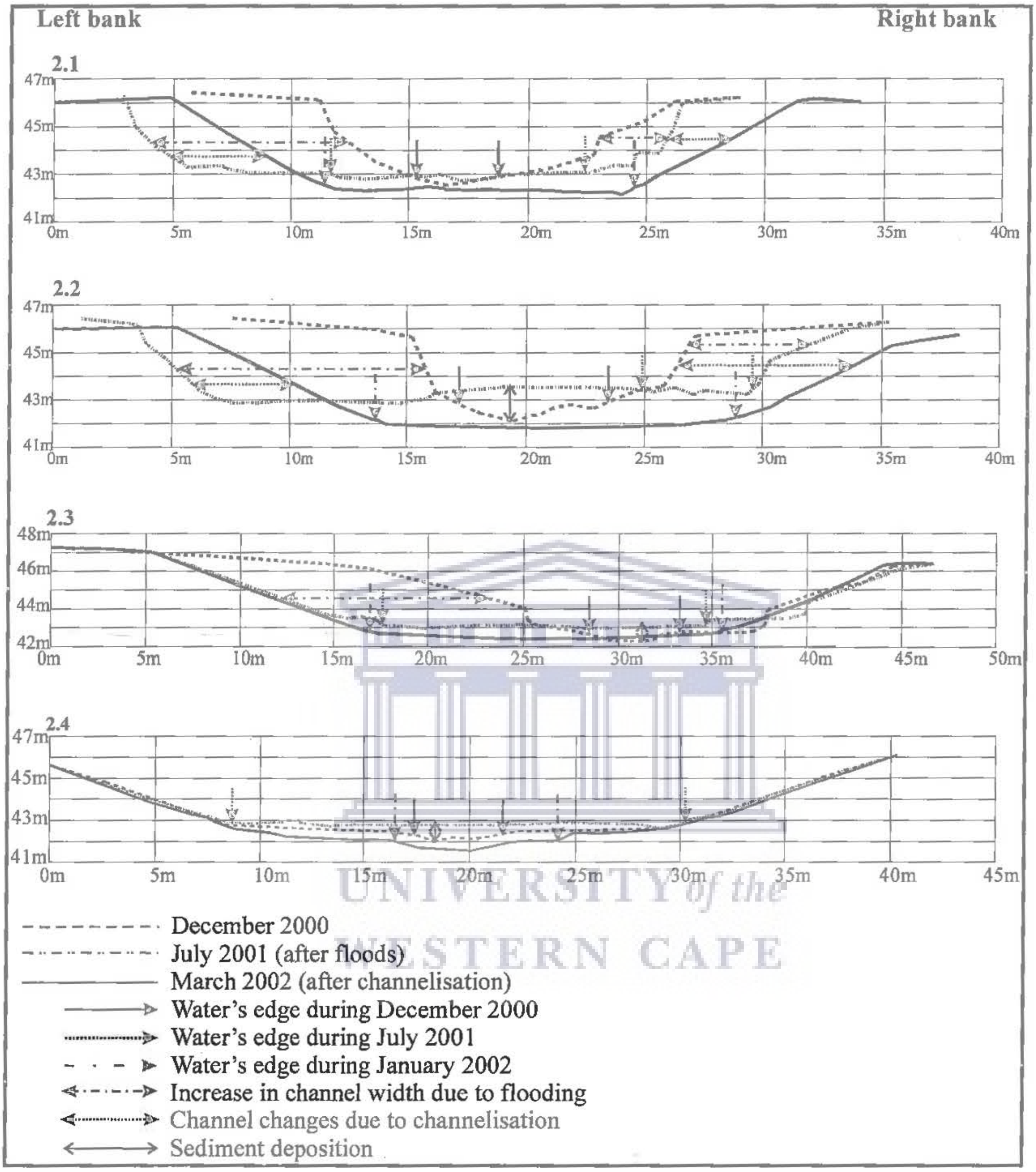

Figure 5.3: Cross-sections of Site 2 during the first and second summer after channelisation and intervening winter floods.

5.2.4 Site 4

The channel of Site 4 is a typical trapezoidal shaped concrete channel (Figure 5.5). Sediment was deposited in the channel during and after the floods. Some of the sediment was removed from the channel during maintenance works after the winter floods. The sediment was dumped on the right bank, as shown on cross-section 4.1, and remained there until the second survey was done (Figure 5.5).

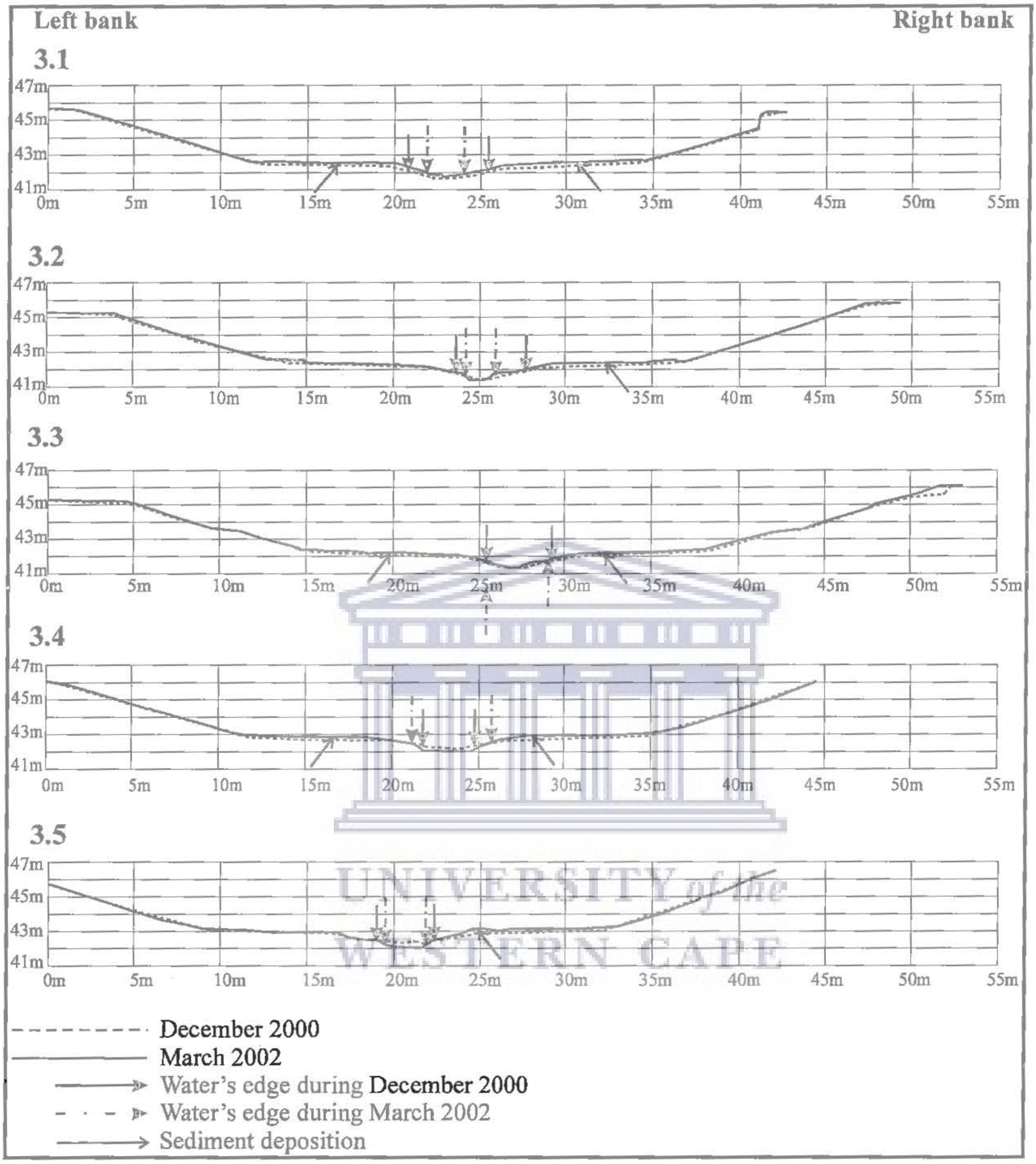

Figure 5.4: Cross-sections of Site 3 during the first and second summer after intervening winter floods.

Plate 5.6: Sediment deposited on the floodplain area, within the channel and behind the gabion weir in Site 3 after the floods. The vegetation on the floodplain areas was completely buried under the sediment.

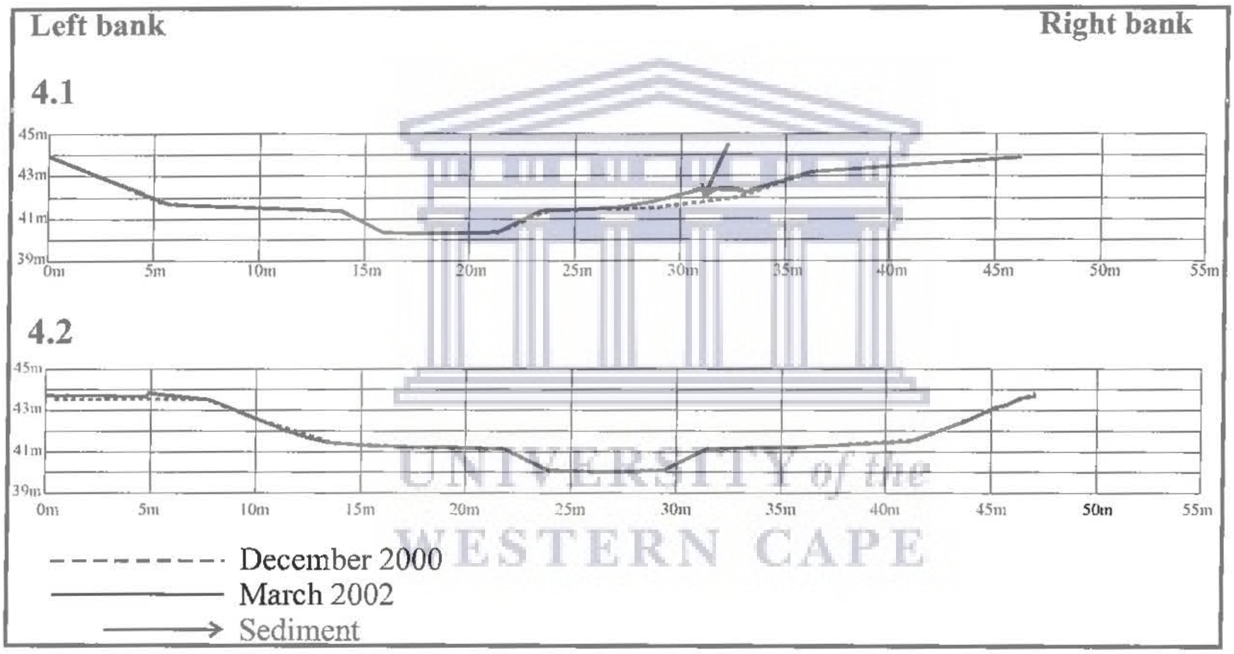

Figure 5.5: Cross-sections of Site 4 during the first and second summer after intervening winter floods.

5.3 Ecology: habitat maps

The following sections provide an overview of the habitats/biotopes (combination of substratum and flow types) present in the study area during the study period and the changes that took place. The first section deals with the habitats during the first summer sampling period. The second section covers the period after the channelisation of Site 2 during January and February 2001. The third section covers the period during and shortly after the winter floods in July 2001 while the last section looks at the habitats in the second summer sampling period. Reference should be made to Tables 4.2, 4.3, 4.4 and 4.5 for definitions of the flow types, categories of the substrata, hydraulic biotopes identified and key for additional features used for the mapping, respectively.

5.3.1 Habitats during the first summer

Site 1

During the first summer, Site 1 was approximately 4m wide at cross-section 1.1, <2m at cross-section 1.2 and 2m at cross-section 1.3 (Figure 5.6a). The active channel meandered slightly within the macro-channel as discussed in Section 5.2.1. Marginal vegetation was present throughout the active channel and accounted for ± 42% of the channel area coverage. A pool with vegetation occurred at the upstream end of the site near cross-section 1.1. From there, downstream for about 12m, the channel bed consisted of sand, organic matter and clayblock material. From about 10m upstream of cross-section 1.2 to a downstream position halfway between cross-sections 1.2 and 1.3, the middle of the channel was dominated by a semi-resistant organic clay layer referred to as brown "clayblock material" and gravel. A pool with a substrate of sand, organic matter and clayblock material was also present over the last 10m at the downstream end of Site 1 (Figure 5.6a and Table 5.1)

Typical summer base flow conditions characterised the flow patterns of Site 1 during the first summer. Barely perceptible flow dominated 79% of the site, not only in the upstream 15m and downstream 7m of the site, but also where marginal vegetation occurred. Rippled surface flow was associated with the brown colour clayblock material and gravel substrates in the middle of the channel and accounted for about 7% of the channel area. Smooth boundary turbulent flow occurred on the upstream and downstream sides of the rippled surface flow covering about 14% (Figure 5.6b and Table 5.2).

Table 5.1: Channel area, average channel width, and substratum coverage (%) at Site 1 during the study period.

	First summer	After floods	Second summer
Average channel area (m^2)	140	405.5	308
Average channel width (m)	1.5-4	7.6	5.5-7
Marginal vegetation	42.28	3.82	
Marginal vegetation+algae			13.32
Vegetation	12.00	4.76	
Sand		60.15	0.84
Sand+organic matter+clayblock material	32		78.89
Iron stained sand			2.79
Sand bar			4.16
Brown colour clayblock material+gravel	13.72	12.92	
Grey colour clayblock material		18.35	

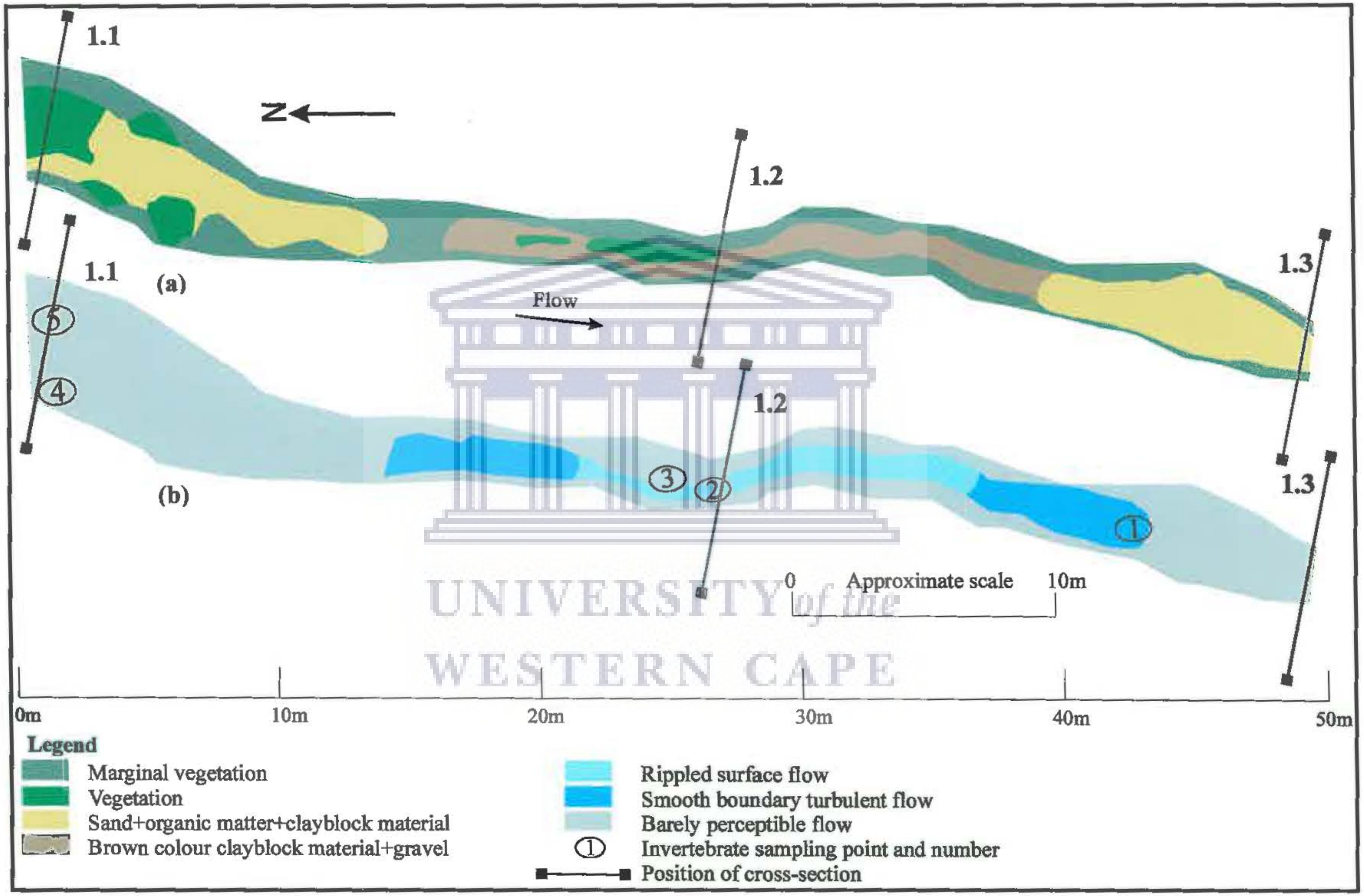

Figure 5.6: Substratum (a) and flow types (b) of Site 1 during the first summer – February 2001. The length of the lines indicating the position of the cross-sections are not to scale.

Table 5.2: Flow type coverage (%) at Site 1 during the study period.

Flow types	First summer	After floods	Second summer
Broken standing waves		1.52	
Rippled surface flow	6.82	20.23	
Smooth boundary turbulent flow	14.12	66.33	79.78
Barely perceptible flow	79.06	5.99	15.32
No flow			0.12
Dry areas		5.93	4.78

Site 2

During the first summer the channel was on average 2-4m wide and showed some sinuosity. Marginal vegetation was present in a fragmented manner along the channel margins. A high diversity of substrate was present for the upper 30m of the site between cross-section 2.1 and 2.2. The channel bed consisted of sand, sand+organic matter+algae, building rubble, clayblock material and vegetation. Downstream of cross-section 2.2 the centre of the channel consisted predominantly of sand, comprising about 34% of the channel bed. Patches of building rubble, clayblock material, vegetation and cobble were also found (Figure 5.7a and Table 5.3). A vegetated island occurred about halfway between cross-sections 2.2 and 2.3 (Figure 5.7a).

In February 2001 most of the channel (68%) consisted of smooth boundary turbulent flow. Rippled surface flow occurred along the bends in the channel and also where the marginal vegetation restricted the flow. Broken standing waves associated with the building rubble about 12m downstream of cross-section 2.1 accounted only for 1% of the channel area. Barely perceptible flow was mainly associated with the marginal vegetation, but also occurred where clayblock material was found. Some areas where vegetation occurred were dry (Figure 5.7b and Table 5.4).

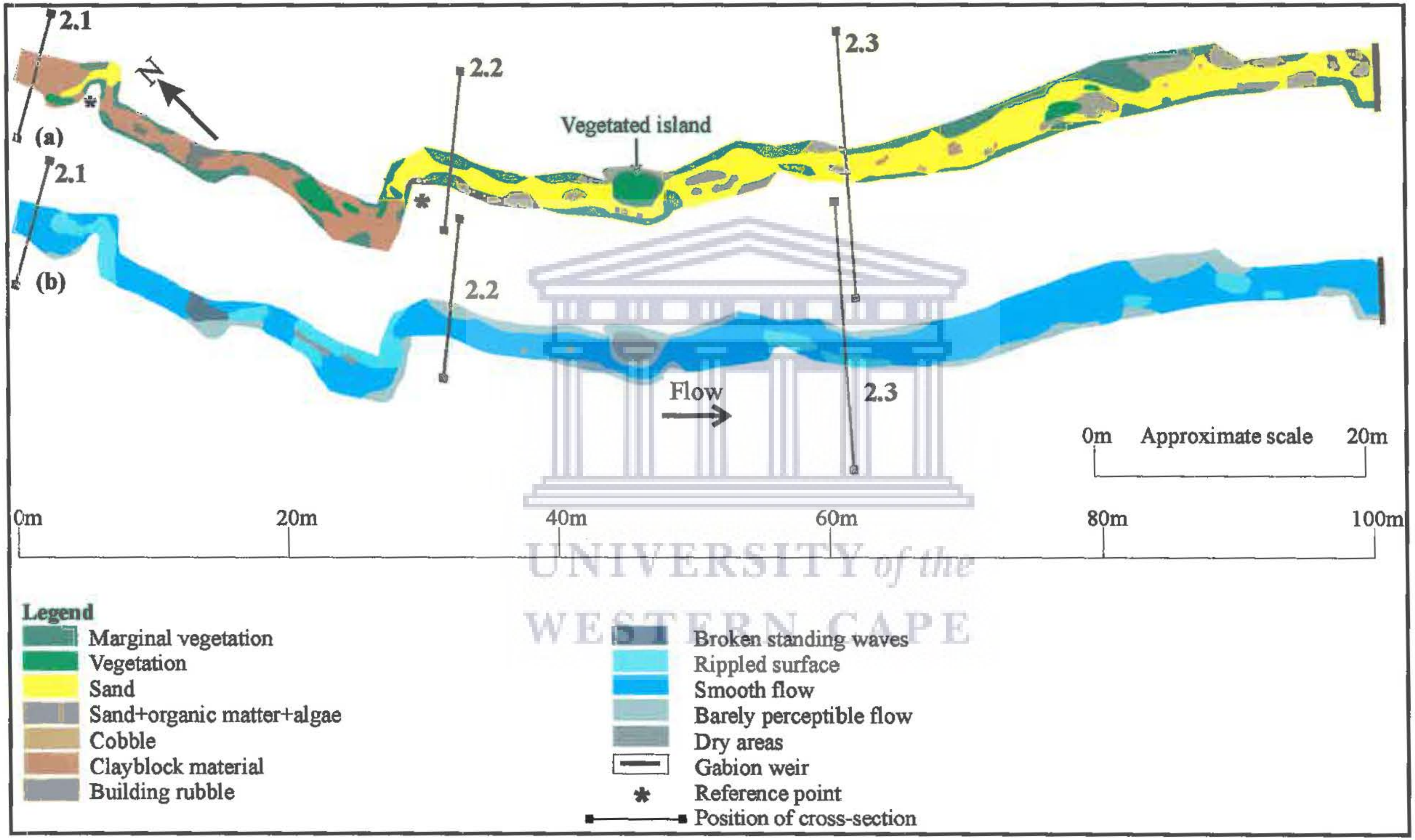

Figure 5.7: Substratum (a) and flow types (b) of Site 2 during the first summer – February 2001. The length of the lines indicating the position of the cross-sections is not to scale.

Table 5.3: Channel area, average channel width, and substratum coverage (%) at Site 2 during the study period.

	First summer	After channelisation	After floods	Second summer
Channel area (m^2)	317.56	803	1546.4	1697.2
Average channel width (m)	2-4	6-16	10-23	12-24
Marginal vegetation	18.63	11.82	1.22	0.91
Marginal vegetation+Algae	6.09	2.74		8.24
Vegetation	5.53	27.83	1.48	4.37
Sand	33.78	25.09	80.44	7.71
Sand+Organic matter			12.75	
Sand+Organic matter+Algae	7.05	29.96		47.01
Sand+Organic matter+Algae+Vegetation				20.41
Iron stained sand				5.04
Clayblock material	26.15		0.92	1.46
Slope clayblock material			1.94	
Cobble	1.03	1.32		0.04
Old alluvial fan				4.81
Building rubble	1.74	1.24	1.25	

Table 5.4: Flow type coverage (%) at Site 2 during the study period.

Flow types	First summer	After channelisation	After floods	Second summer
Broken standing waves	1.22			
Rippled surface flow	13.14	1.42	0.24	
Smooth boundary turbulent flow	67.98	53.38	87.01	29.05
Barely perceptible flow	15.33	34.27	4.23	69.12
No flow		0.68		0.15
Dry areas	2.334	10.25	8.52	1.68

Site 3

The mapping was done in March 2001, two months after the channel was straightened. The channel therefore had a very straight plan form (Figure 5.8a and b) and was mostly 1.5-2m wide except for the section downstream of the gabion weir. Marginal vegetation and algae (mostly *Pennisetum clandestinum*) occurred along the channel margins down to the gabion weir making up about 60% of the channel area. Eighteen percent of the channel bed consisted of sand (Figure 5.8a and Table 5.5). Small patches of sand, organic matter and cobbles also occurred. Gabion wires were found on the channel floor just upstream of cross-sections 3.2 and 3.3. A pipe across the river was found downstream of cross-section 3.1. The channel floor beneath the pipe was lined with concrete to stabilise and support it. The concrete was covered with sand on the downstream side of the pipe and cobbles and vegetation on the upstream end. The channel floor was also lined with concrete where a footbridge (not shown on the map) crossed the channel downstream of cross-section 3.3 on the upstream end of the gabion weir. Downstream of the gabion weir, the channel width increased to 8m where the channel bed consisted of gabion wiring+vegetation. The gabion opening was sand covered with sand+organic matter on the downstream side of the sand patch. From a position just upstream of cross-section 3.4, down to the end of the site, the channel was overgrown with marginal vegetation (*Pennisetum clandestinum*) and choked with algae. Only small patches of the channel bed were visible through the vegetation and algae (Figure 5.8a).

Barely perceptible flow dominated just over 72% of the site along the channel margins and downstream of the gabion weir until the end of the site. Smooth boundary turbulent flow occurred along the centre of the channel covering about 20% of the channel area. Rippled surface flow covered only 2% and was usually associated with narrowing of the channel or occurrence of obstructions. It was visible about 22m downstream of cross-section 3.1, and just upstream of the gabion opening where narrowing occurred, and over the gabion wires and cement block under the footbridge (Figure 5.8b and Table 5.6).

Table 5.5: Channel area, average channel width, and substratum coverage (%) at Site 3 during the study period.

	First summer	After floods	Second summer
Channel area (m^2)	515.3	1148.2	648.3
Average channel width	1.5-2	6	1.2-4
Marginal vegetation		12.01	
Marginal vegetation+algae	58.91		12.20
Vegetation	0.30	5.63	0.18
Sand	18.44	64.39	18.47
Sand+organic matter	6.88	5.11	12.24
Sand+cobble+boulder+organic matter+algae			2.15
Cobble	0.80	0.09	4.01
Boulder			0.25
Slope clayblock material		10.11	18.6
Sand bar+vegetation			25.34
In-channel cement block+sand+gravel	1.77		1.74
In-channel gabion wire+vegetation	7.51		0.48
Gabion weir	5.12	1.31	4.07
Pipe	0.27		0.27

Table 5.6: Flow type coverage (%) at Site 3 during the study period.

Flow Types	First summer	After floods	Second summer
Broken standing waves	0.82	1.98	
Undular standing waves		16.27	
Rippled surface flow	2.01	67.34	17.24
Smooth boundary turbulent flow	19.76		42.53
Barely perceptible flow	72.24	8.33	30.08
Dry areas		3.78	5.19
Pipe	0.26		0.25
Gabion	4.91	2.30	4.71

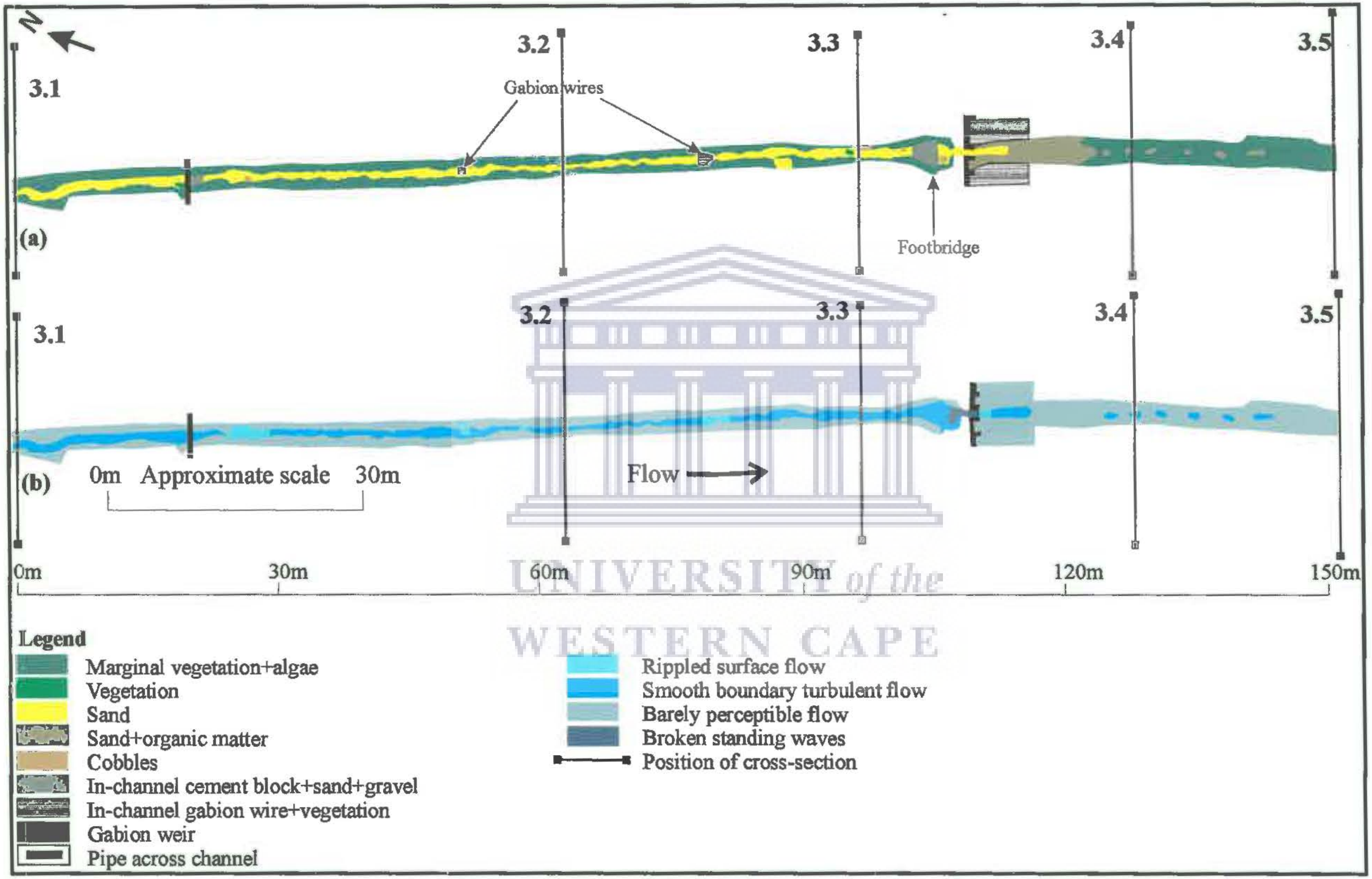

Figure 5.8: Substratum (a) and flow types (b) of Site 3 during the first summer– March 2001.

5.3.2 Habitats after the January – February 2001 channelisation – Site 2

Channelisation resulted in a 3-fold widening of the channel (Figure 5.9a and b and Table 5.7). The channel width for the first 9m of the site remained the same as that mapped during February 2001 (Figure 5.7). The channel bed here consisted of clayblock material and building rubble. Left bank marginal vegetation about 10m downstream of cross-section 2.1 comprised of terrestrial trees (*Acacia saligna*) that were forced into the channel during the grading process. Two vegetated islands, the first on the bend just downstream of cross-section 2.1 and the other at cross-section 2.2 were not part of the channel as mapped during February 2001. These vegetated islands were part of the floodplain then and were responsible for the sinuosity seen at the mentioned positions indicated by an asterisk on Figure 5.7a. The increase in channel width was a direct result of this. Damaged stormwater pipes from the Soneike Development entering the river from the left bank were repaired during the grading process, but patches of building rubble (in the form of concrete slabs and pipes) were still visible further downstream. To the left side of the upstream vegetated island the channel consisted mainly of sand. To the right of the vegetated island the channel consisted of clayblock material and building rubble. The channel bed consisted of 25% sand with patches of vegetation, building rubble and clayblock material from upstream of cross-section 2.2 to about cross-section 2.3. Marginal vegetation occurred in a fragmentary manner along the channel margins in this part of the channel. Sand+organic matter+algae and vegetation dominated the channel downstream of cross-section 2.3. The vegetation found in this part of the channel was previously part of the marginal vegetation growing on the floodplain (Figure 5.7a). Sand, sand+organic matter+algae, vegetation and cobbles formed the substrata of the lower 15m of the site with marginal vegetation as well as marginal vegetation+algae spread out in a fragmentary manner along the margins (Figure 5.9a and Table 5.3).

Table 5.7: Channel width (m) at certain points along the channel in Site 2 before (07 February 2001) and after (19 April 2001) the channelisation.

Points along the channel (m)	07 Feb 01	19 Apr 01
10	2	6
15	2	10
65	3	9.5
85	4	15.5
100	2.5	6.5

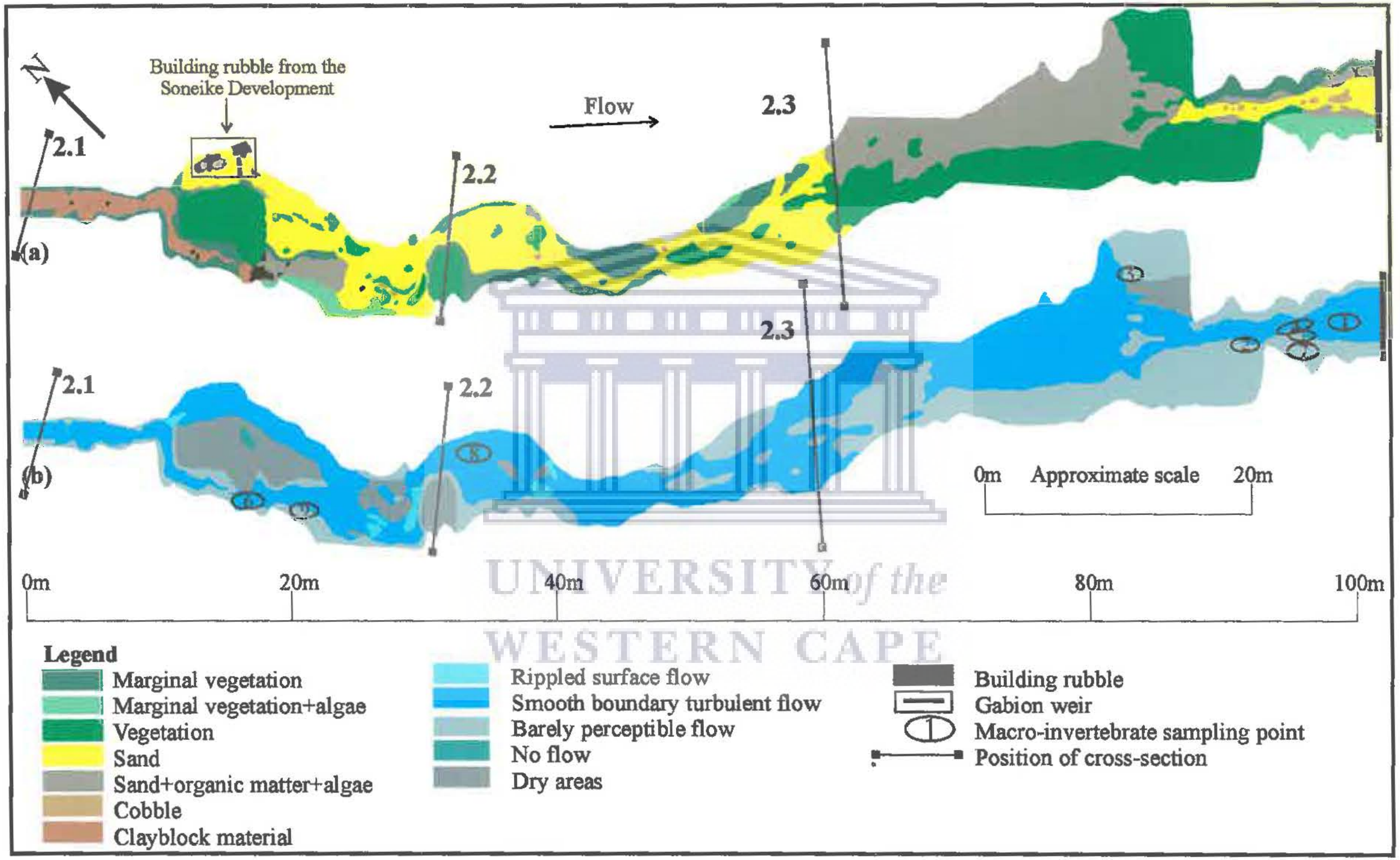

Figure 5.9: Substratum (a) and flow types (b) of Site 2 after the channelisation – April 2001. The length of the lines indicating the position of the cross-sections is not to scale.

5.3.3 Habitats after the July 2001 floods

Site 1

The habitats mapped during the winter of 2001 (Figure 5.10 and 5.11) showed a completely different picture to those mapped during the previous summer. The winter floods resulted in bank erosion and consequent increased meandering of the active channel as discussed in section 5.2.1. The active channel at cross-section 1.1 widened from 4 to 7.6m, from <2 to 7.6m at cross-section 1.2 and from 2 to 7.6m at cross-section 1.3. The widest section of the channel was halfway between cross-section 1.2 and 1.3 where the channel was 15.5m wide. Marginal vegetation was found infrequently with patches of vegetation along the channel. The bank erosion on the right bank at cross-section 1.2 exposed more resistant clayblock material (indicated as grey colour clayblock material on Figure 5.10) at the bottom of the slope. The exposed clayblock material extended from about 6m downstream of cross-section 1.1 to about halfway between cross-sections 1.2 and 1.3. The same type of resistant clayblock material was also exposed on the left bank at cross-section 1.1 and near cross-section 1.3. The channel itself was mostly sand-covered (about 60% of the channel) with occasional small gravel patches. Gravel also covered the resistant brown clayblock material in places (Figure 5.10 and Table 5.1).

The winter flow pattern (Figure 5.11) was also more diverse than mapped previously in February 2001. The site consisted of 66% smooth boundary turbulent flow. Some of the marginal and emergent vegetation nearest to the left bank were dry. These dry patches formed a restriction to the flow and resulted in rippled surface flow between the dry areas and beyond them. The vegetation patch in the middle of the channel upstream of cross-section 1.3 was also dry. The dry areas made up 6% of the channel area, while the exposed clayblock material had barely perceptible flow, covering about 6%. The vegetation found downstream of the clayblock material halfway between cross-sections 1.2 and 1.3 was dry. The two vegetation clumps near the left bank and just downstream of cross-section 1.2 (Figure 5.11), also formed a restriction forcing the flow over the submerged vegetation and between the two dry vegetation patches. This resulted in broken standing waves with rippled surface flow further downstream. Broken standing waves covered 2%, while rippled surface flow covered 20 % of total channel area. (Figure 5.11 and Table 5.2).

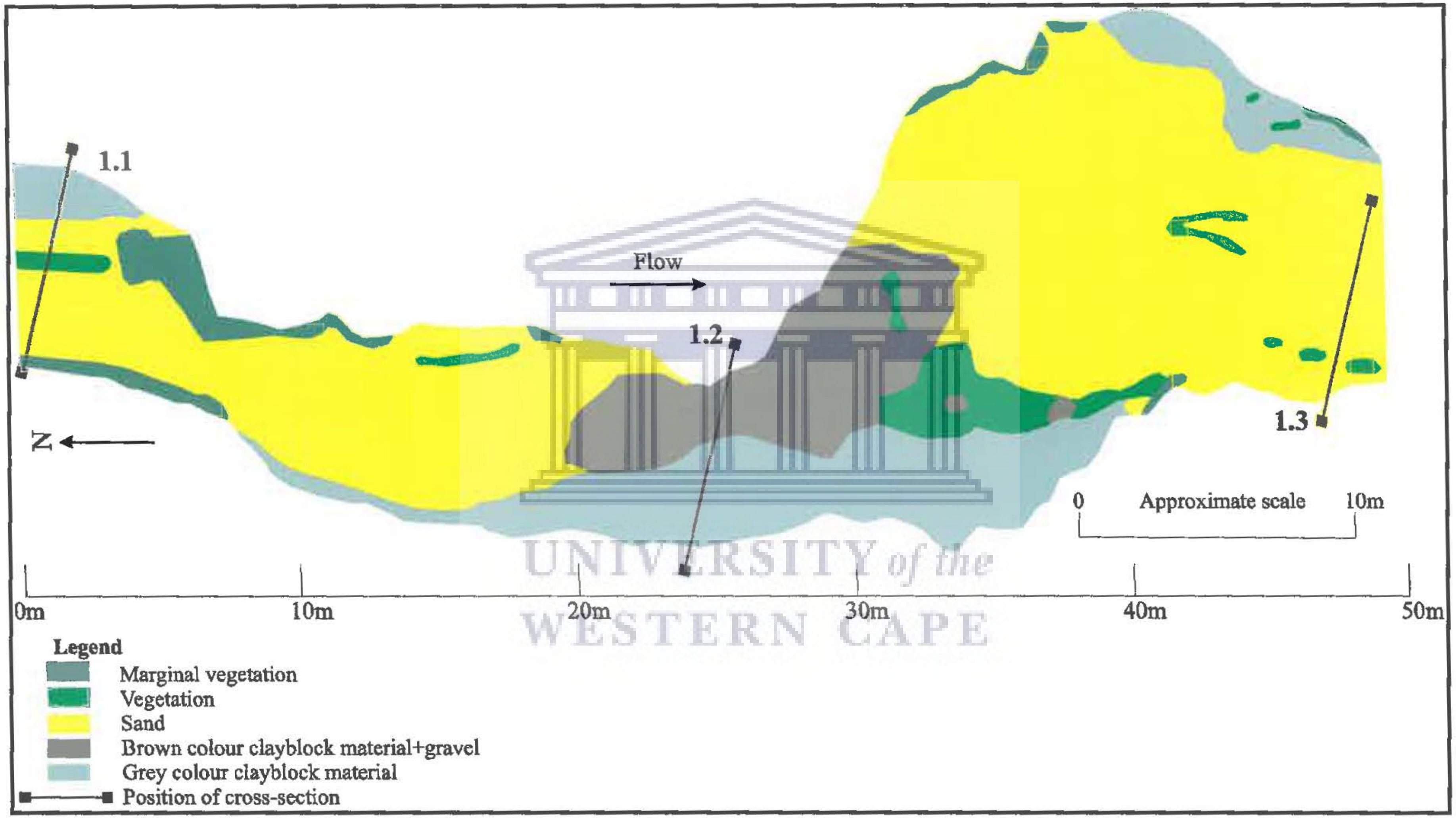

Figure 5.10: Substratum map of Site 1 after the floods– July 2001. The length of the lines indicating the position of the cross-sections is not to scale.

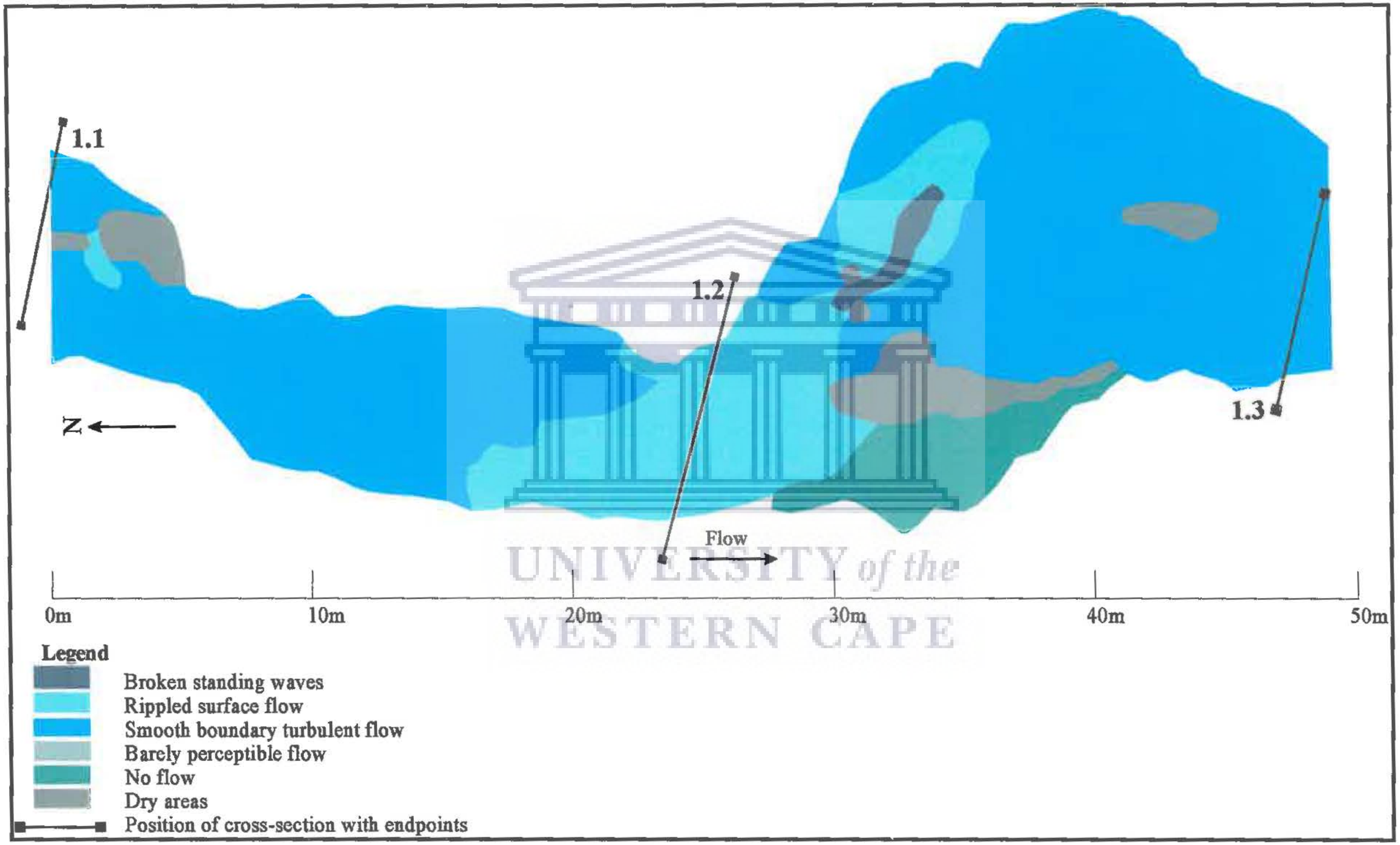

Figure 5.11: Flow map of Site 1 after the floods– July 2001. The length of the lines indicating the position of the cross-sections is not to scale.

Site 2

The channel width increased further after the floods with the channel being 10m at the narrowest point and 23m at the widest point. The channel was fairly straight with sand as the dominant substrate (about 80%). Various sized patches of sand+organic matter, vegetation, slope clayblock material and building rubble occurred more concentrated upstream of cross-section 2.2, but sand was the dominant substratum type. Damaged stormwater pipes from the Soneike Development were found within the channel about halfway between cross-section 2.1 and 2.2. Scattered patches of slope clayblock material, marginal vegetation and vegetation were found downstream of cross-section 2.2 to the end of the site. A relatively large sand+organic matter patch was found in the centre of the channel of the last 40m of the site. The sand was approximately 90cm deep in the last 10m of the site (Figure 5.12 and Table 5.3).

Flow diversity after the floods was low. Smooth boundary turbulent flow dominated 87% of the site. Barely perceptible flow was found in small patches and associated with the sand+organic matter. The sand+organic matter patch found in the last 20m of the site and some of the vegetation patches were dry (Figure 5.13 and Table 5.4).

Site 3

The channel bed consisted mostly of sand, which made up about 65% of the channel area (Figure 5.14a and Table 5.5). The concrete blocks and gabion wires on the channel floor and the pipe across the channel (indicated on Figure 5.8) were covered with sand and thus not visible on Figure 5.14a. The flooding also caused a widening of the channel from an average width of between 1.5 and 2m to 5.5m upstream of the gabion weir, but the channel remained straight. Marginal vegetation was present along the channel margins, but it was not as extensive as shown on Figure 5.8 and tabulated in Table 5.5. Small patches of vegetation, sand, organic matter and slope clayblock material also occurred (Figure 5.14a). Sand bars occurred on the floodplain areas upstream and downstream of the gabion weir. The vegetation could be seen through the sand in some places and (Plate 5.5), but they were not indicated on Figure 5.14.

Undular standing waves covered about 16% of the flow surface and could be seen in the centre of the channel with rippled surface flow around it.

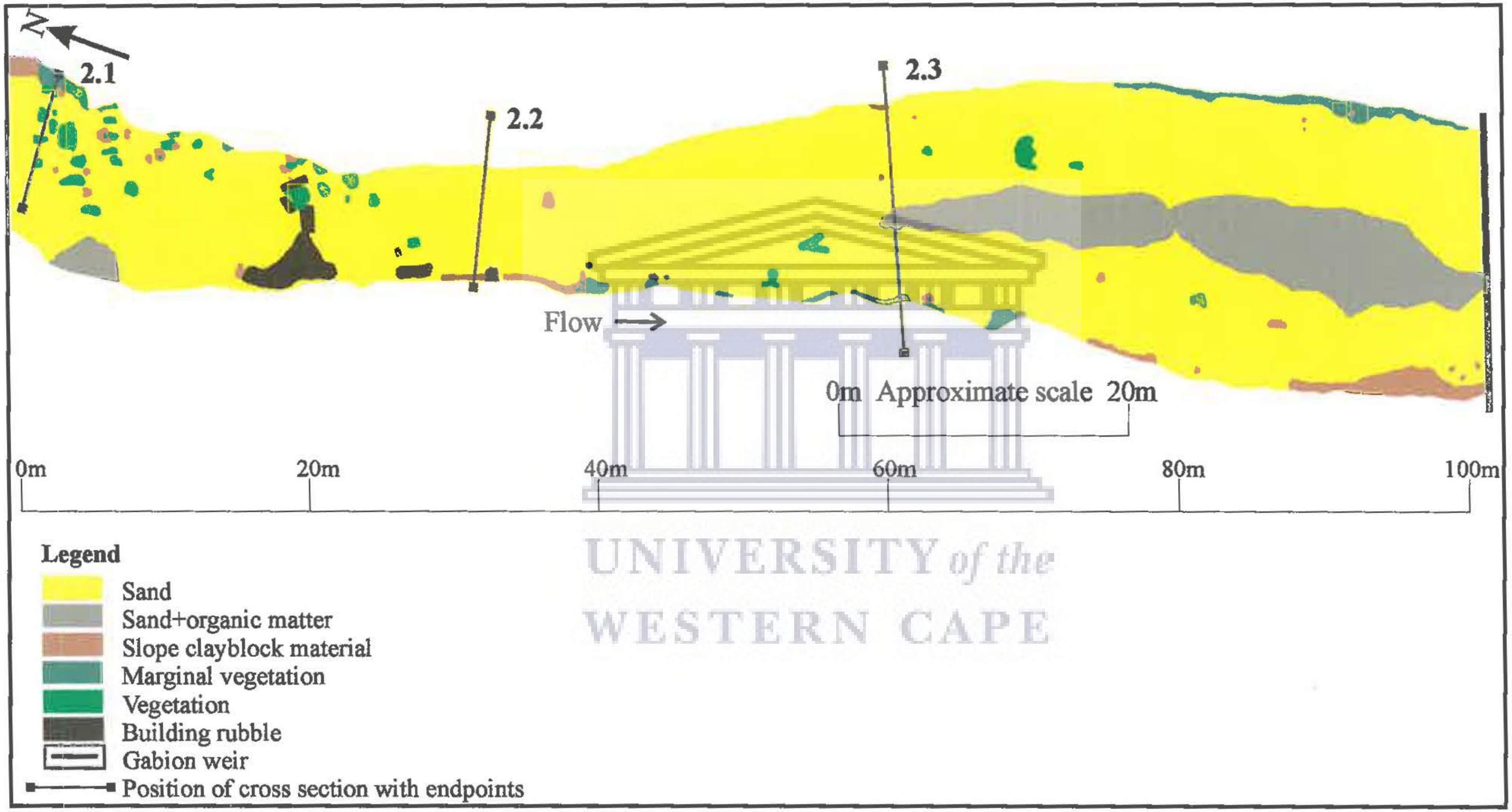

Figure 5.12: Substratum map of Site 2 after the floods– July 2001. The length of the lines indicating the position of the cross-sections is not to scale.

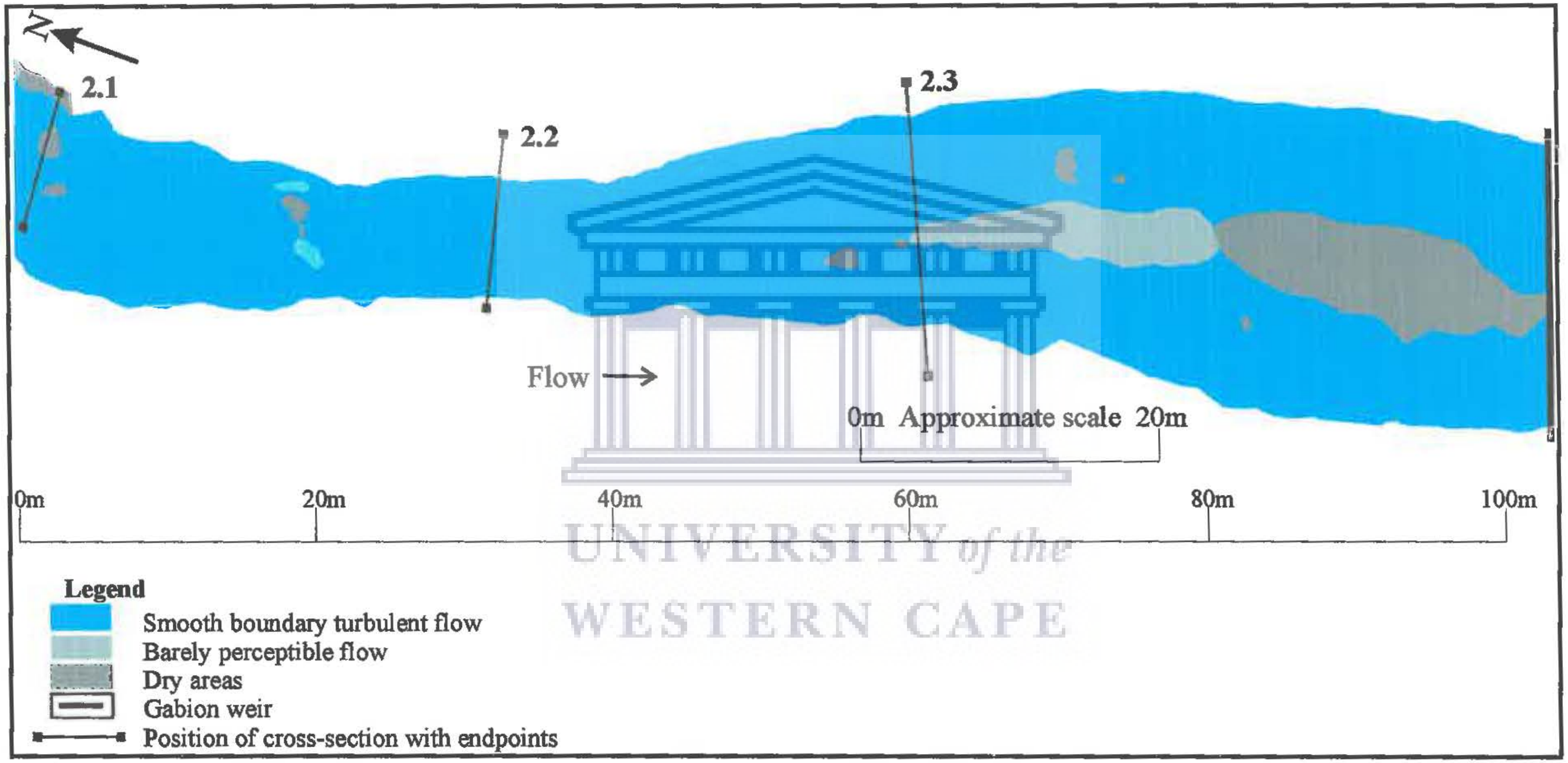

Figure 5.13: Flow map of Site 2 after the floods – July 2001. The length of the lines indicating the position of the cross-sections is not to scale.

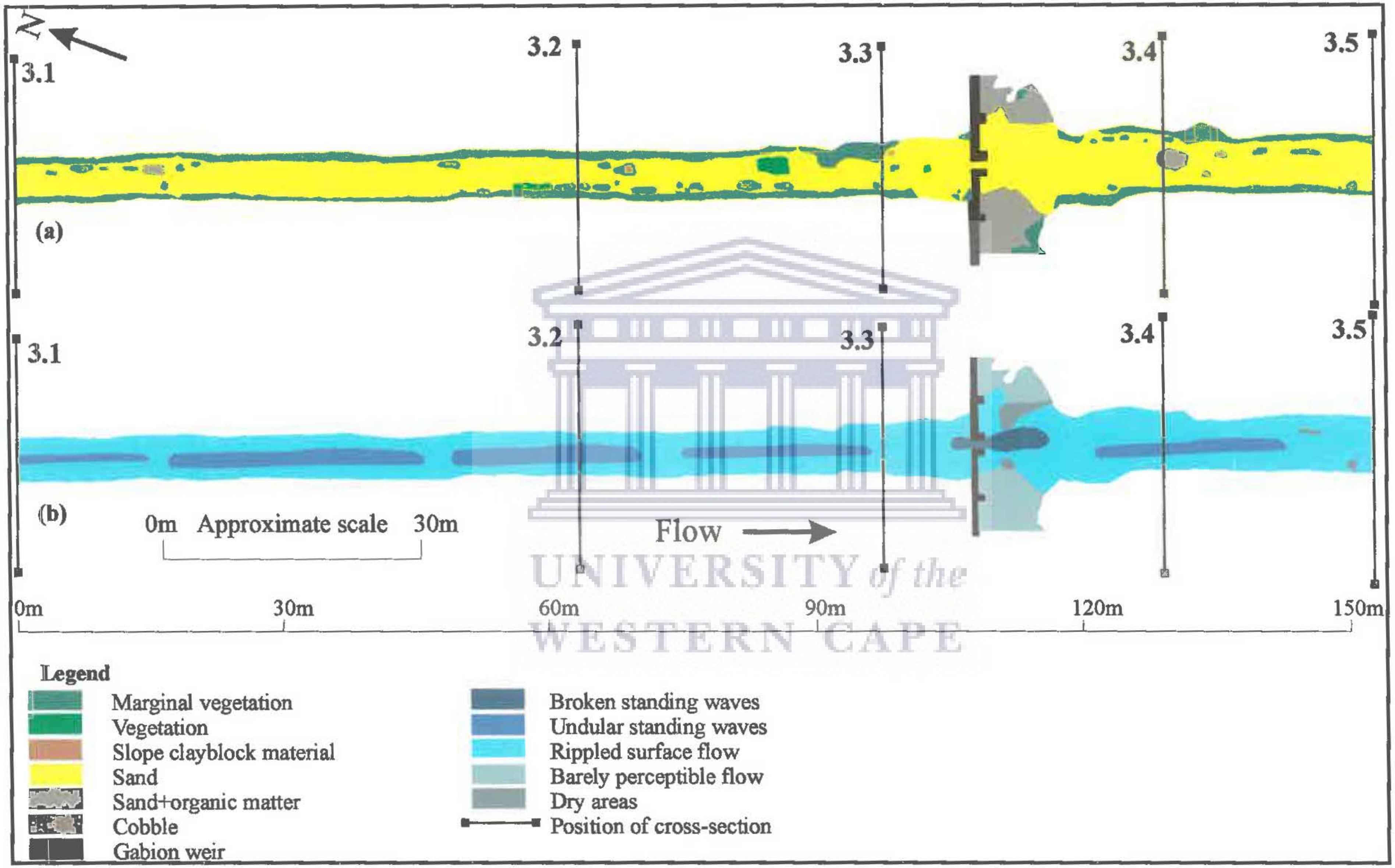

Figure 5.14: Substratum (a) and flow types (b) of Site 3 after the floods– July 2001.

About 67% of the site was dominated by rippled surface flow. Broken standing waves were visible in the gabion weir opening and beyond it and accounted for about 2% of the flow surface. Barely perceptible flow was found in the widened sections of the gabion weir and accounted for ± 8% of the channel area. A few patches of sand and vegetation were exposed near the downstream end of the site (Figure 5.14b and Table 5.6).

5.3.4 Habitats during the second summer

After the channelisation - Site 1

The restructuring of the banks and straightening of the channel between October and November 2001 resulted in a fairly straight and wide (± 5.5 - 7m) active channel (Figure 5.15a and Table 5.1). Vegetation, organic matter and algae were found along the channel margins. The channel bed consisted mostly of sand+organic matter+algae (about 80%). A patch of iron stained sand occurred in the middle of the channel about 6m upstream of cross-section 1.3. Vegetated sand bars occurred infrequently along the channel margins.

The reduction in channel width downstream of cross-section 1.2 was the result of a small alluvial fan that formed along the left bank due to the slope failure resulting from seepage that followed abnormally high rainfall in early January 2002 (Figure 5.15a).

There was very little flow diversity (Figure 5.15b) after the channelisation. Barely perceptible flow was associated with the marginal vegetation, while the vegetated sand bars were dry. Smooth boundary turbulent flow was found along the centre of the channel and there was also a small area with no flow upstream of cross-section 1.3. Barely perceptible flow made up 15%, smooth boundary turbulent flow 80%, dry areas 4.8% and no flow 0.2% of the total site area (Figure 5.15b and Table 5.2).

After the channelisation - Site 2

The channel was fairly straight with channel widths ranging from 12 to 23.5m. Marginal vegetation+algae was found infrequently along the channel margins. Sand+organic matter+algae+vegetation and iron stained sand occurred in a fragmentary manner along the left and right bank channel margins respectively. The iron stained sand was vegetated in some places. Dense vegetation from the right bank had established itself onto the exposed sand over the last 15m of the site. A sand bar consisting of sand+organic matter and sparse vegetation was found along the centre of the channel at, and immediately downstream, of cross-section

2.1. Sand and patches of sand+organic matter, cobble+gravel+sand and vegetation were found in the centre of the channel down to cross-section 2.2. Sand+organic matter+algae+vegetation formed most of the substratum between cross-section 2.2 and 2.3, while sand+organic matter was the dominant substratum downstream of cross-section 2.3 and made up 45% of the channel area. Patches of vegetation were found within this substratum (Figure 5.16 and Table 15.3).

A stormwater pipe that used to exit into a gabion (Plate 5.7) entering the river from the right bank was stabilised and reinforced with concrete when the channel sides were graded in October-November 2001 (Plate 5.8). The stabilised pipe concentrated the flow and formed a small alluvial fan halfway between cross-section 2.1 and 2.2. The fan became vegetated with time (1). On the opposite side of the channel another fan (2) formed where the Soneike Development stormwater pipe entered from the left bank. The fan material consisted of sand+organic matter+algae, but it was not vegetated. Water from the pipe was still visible in a trickle and was forced to flow in the opposite direction of flow (Figure 5.17) by the alluvial fan (2) on the downstream end. A new alluvial fan (3) that consisted of sand only was formed (Figure 5.16).

The flow map (Figure 5.17) indicated that smooth boundary turbulent flow was found in the centre of the channel down to about halfway between cross-section 2.2 and 2.3 and accounted for about 18% of the channel area. Barely perceptible flow dominated the channel and made up 69% of the site. It was mainly associated with the marginal vegetation at the upstream end of the site and the sand+organic matter+algae and sand+organic matter+algae+vegetation substrates in the centre of the channel. Smooth boundary turbulent flow was again visible near the opening of the gabion weir at the end of the site. Some parts of the channel margins on the left bank were exposed due to lower water levels during the summer period. This was indicated as sand+organic matter+algae+vegetation on Figure 5.16. The channel margins were also exposed on the right bank where the iron stained sand was found. The sand bars and alluvial fans were also dry (Figure 5.17 and Table 5.4).

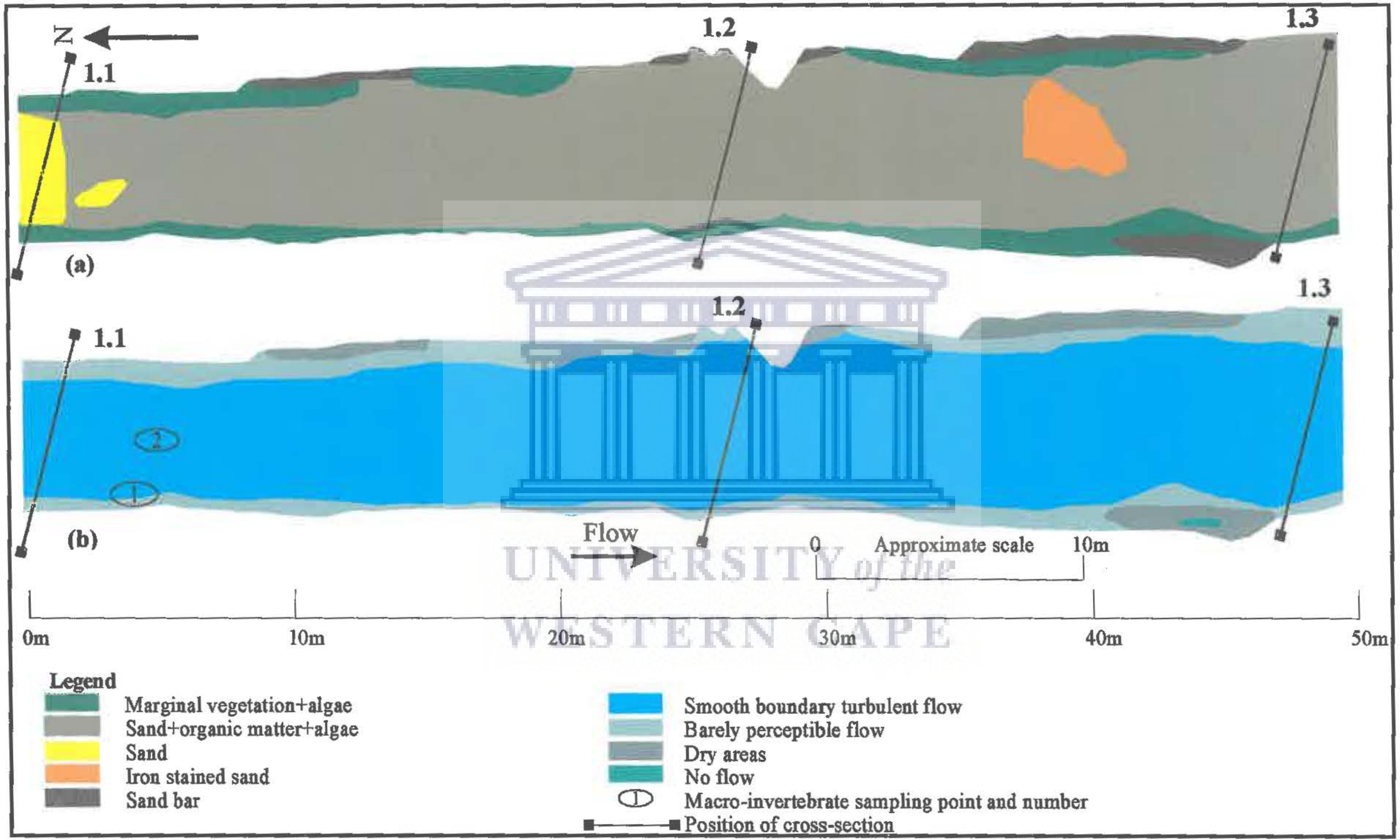

Figure 5.15: Substratum (a) and flow types (b) of Site 1 after the channelisation– January 2002. The length of the lines indicating the position of the cross-sections is not to scale.

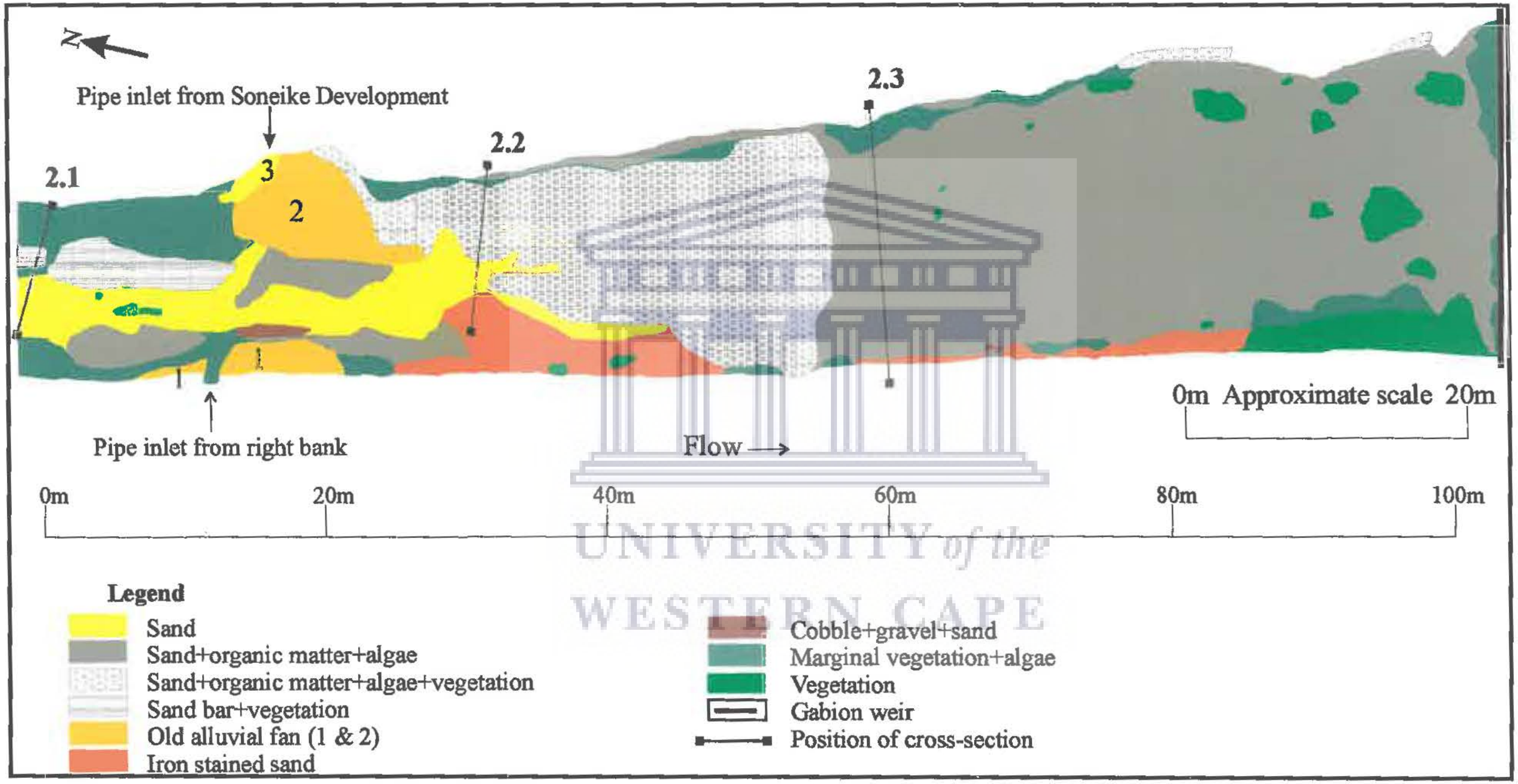

Figure 5.16: Substratum map of Site 2 after the channelisation– January 2002. The length of the lines indicating the position of the cross-sections is not to scale.

Plate 5.7: Depression with a storm water outlet filled with rubbish on right bank of Site 2 before the October – November 2001 channelisation. The presence of the pipe in the gabion was only noticed during the winter when water was seen coming from the outlet.

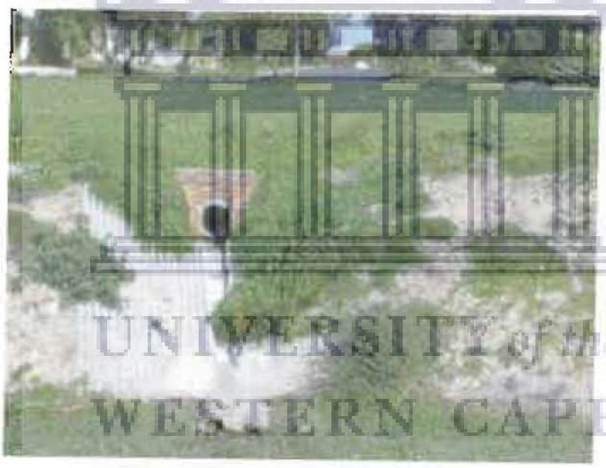

Plate 5.8: Storm water outlet pipe stabilised and reinforced with concrete after the October – November 2001 channelisation

Habitats during the second summer - Site 3

Since the previous assessment in July 2001, the channel has narrowed from an average width of 6m to an average of 1.2m at the narrowest point and an average of 4m at the widest point upstream of the gabion (Figure 5.18a and b and Table 5.5). The channel plan form developed signs of meandering (Plate 5.9) about halfway between cross-section 3.1 and 3.2 down to the gabion, although true meandering has not developed yet. Marginal vegetation+algae occurred almost continuously along the margins and accounted for 12% of the channel area. The channel bed consisted of sand+organic matter down to the pipe across the river. Slope clayblock material with vegetation behind it was found on the upstream end of the pipe.

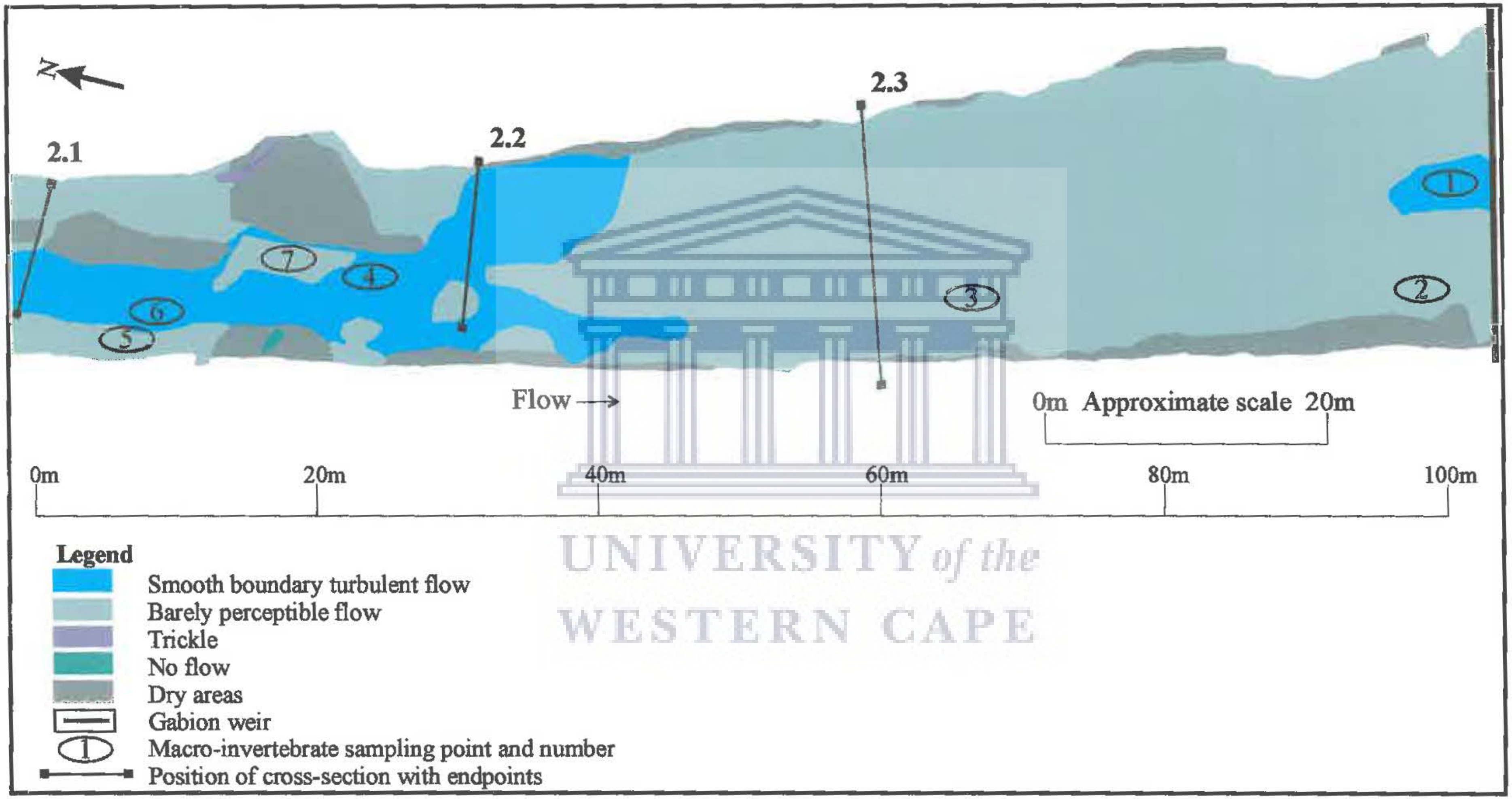

Figure 5.17: Flow map of Site 2 – January 2002. The length of the lines indicating the position of the cross-sections is not to scale.

The channel bed consisted mainly of sand+organic matter with various sized patches of slope clayblock material, vegetation and sand from downstream of the pipe down to the gabion weir. Vegetated sand bars were found infrequently on both banks halfway between cross-sections 3.1 and 3.2. Gabion wire+vegetation was found halfway between cross-sections 3.2 and 3.3. The cement block under the footbridge near the gabion weir was covered with sand and gravel. The channel widened downstream of the gabion weir. Sand was found from the middle of the gabion weir opening and beyond it. The channel bed consisted of sand+cobbles+boulders+organic matter+algae on the inside of the gabion. A cobble bar and a few boulders were found halfway between cross-sections 3.3 and 3.4. The channel bed consisted of sand+organic matter for the last 10m of the site (Figure 5.18a and Table 5.5).

The flow in the river was low due to the summer conditions. Smooth boundary turbulent flow occurred throughout most of the channel and was mostly associated with the sandy substrates. It accounted for about 43% of the channel area. Rippled surface flow was associated with the slope clayblock material substrates in the middle of the channel. Barely perceptible flow was found along the channel margins, in the widened part of the gabion weir and in the channel behind the cobble bar. The vegetated sand bars were dry. The dry areas made up 5% of the channel area (Figure 5.18b and Table 5.6).

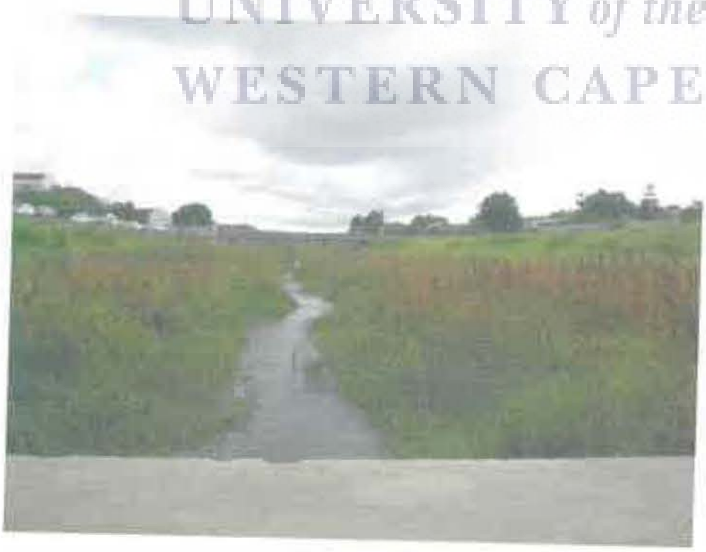

Plate 5.9: Channel plan-form of Site 3 upstream of the gabion weir – Photograph taken on 15 February 2002.

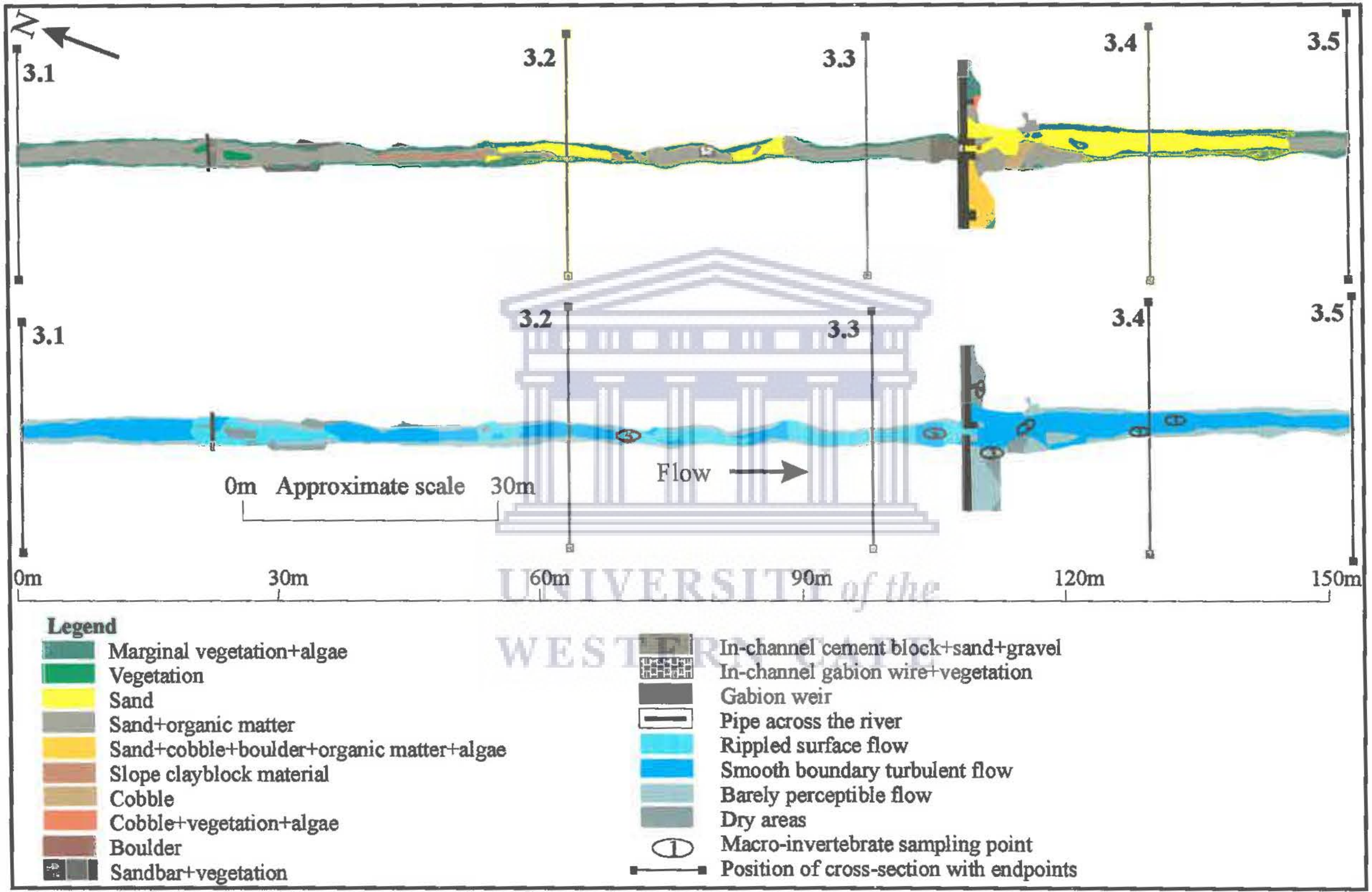

Figure 5.18: Substratum (a) and flow types (b) of Site 3 – January 2002.

5.4 Ecology: macro-invertebrates

The cross-sections and habitat changes documented in Sections 5.2 and 5.3 respectively impacted on the composition of macro-invertebrate assemblages in the study area. Data on these assemblages in both sampling periods were analysed together per site. A full list of the sample codes used, sample size, community compositions, and abundance ratings is given in Appendix 2.

5.4.1 Site 1 – 2001&2002

The dendrogram (Figure 5.19a) separated the nine samples into two groups with 20% similarity. The first group of samples was collected in emergent vegetation. Sample S1-1-02 was not closely related to the other two samples in the group (Figure 5.19b) because it consisted of Coenogrionidae, Dytiscidae, Veliidae, Naididae and Physidae and only had Physidae and Coenagrionidae in common with the other samples. The second group consisted of samples collected in a mixture of biotopes including sand, emergent vegetation and brown clayblock material. The first two of these formed a pair at 80% similarity and had Chironomidae and Naididae in common. Sample S1-2-02 contained Physidae in addition, while sample S1-1-01 contained Naididae only.

The number of biotopes sampled decreased drastically during 2002 (Table 4.4) because the channelisation resulted in a very uniform channel-bed with only the biotopes marginal vegetation and sand+organic matter+algae available. The family composition remained similar between the years (Tables 5.8 and 5.9), but some families present during 2001 were absent during 2002 and vice versa. There were fewer families in 2002 than in 2001 (Table 5.8).

5.4.2 Site 2 – 2001&2002

Three groups were identified on the dendrogram and MDS plot (Figure 5.20a and b). The first group consisted of samples collected in sand and contained Naididae only. The two samples were 100% similar. The second group consisted of samples collected in sand, organic matter and algae. Invertebrates found included Physidae, Chironomidae, Simuliidae and Naididae. All the samples in this group had Physidae in common. Group 3 consisted of a mixture of biotopes sampled, including marginal vegetation, vegetation, building rubble, sand, sand+organic matter+algae and sand+organic matter+algae+vegetation.

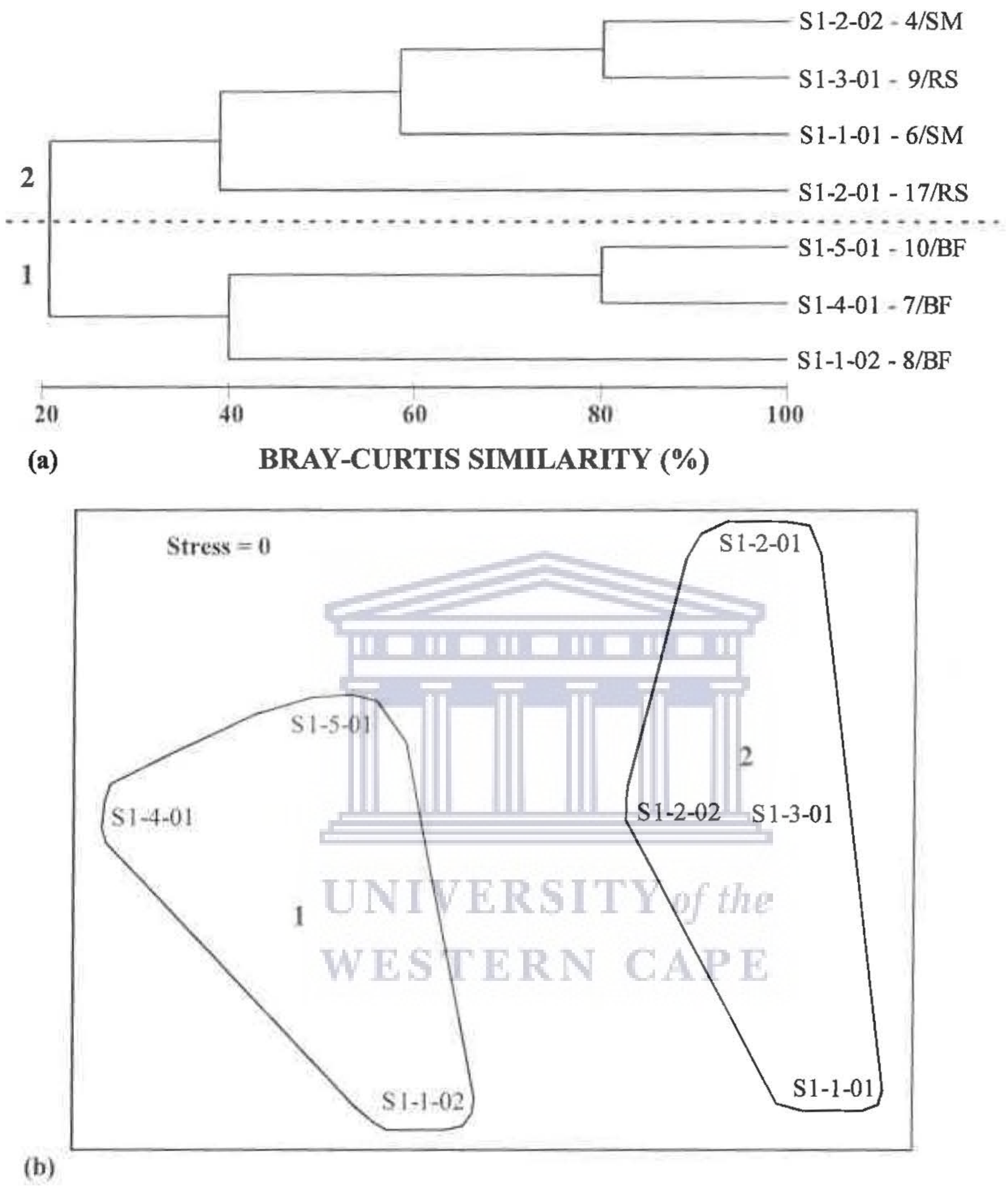

Figure 5.19: Dendrogram (a) and MDS (b) ordination of macro-invertebrate data from Site 1 for 2001 and 2002. Code: S1-1-01 – 6/SM = Site, sample number, year – hydraulic biotope number (Table 4.4) and flow type (Table 4.2).

The MDS plot (Figure 20b) showed that sample S2-2-01 was not closely related to the other samples in the group because it only contained five of the thirteen families found in this group (Appendix 2). All the samples in this group had Coenagrionidae in common.

Groups 2 and 3 were more closely related to each other than to Group 1 because the latter consisted of samples that contained Naididae only. Tables 5.8 and 5.9 show there was a decrease in community composition and abundance ratings during 2002, except at Site 4. The number of biotopes sampled also decreased from nine in 2001 to eight during 2002, except for Site 4 where it remained the same (Table 4.4).

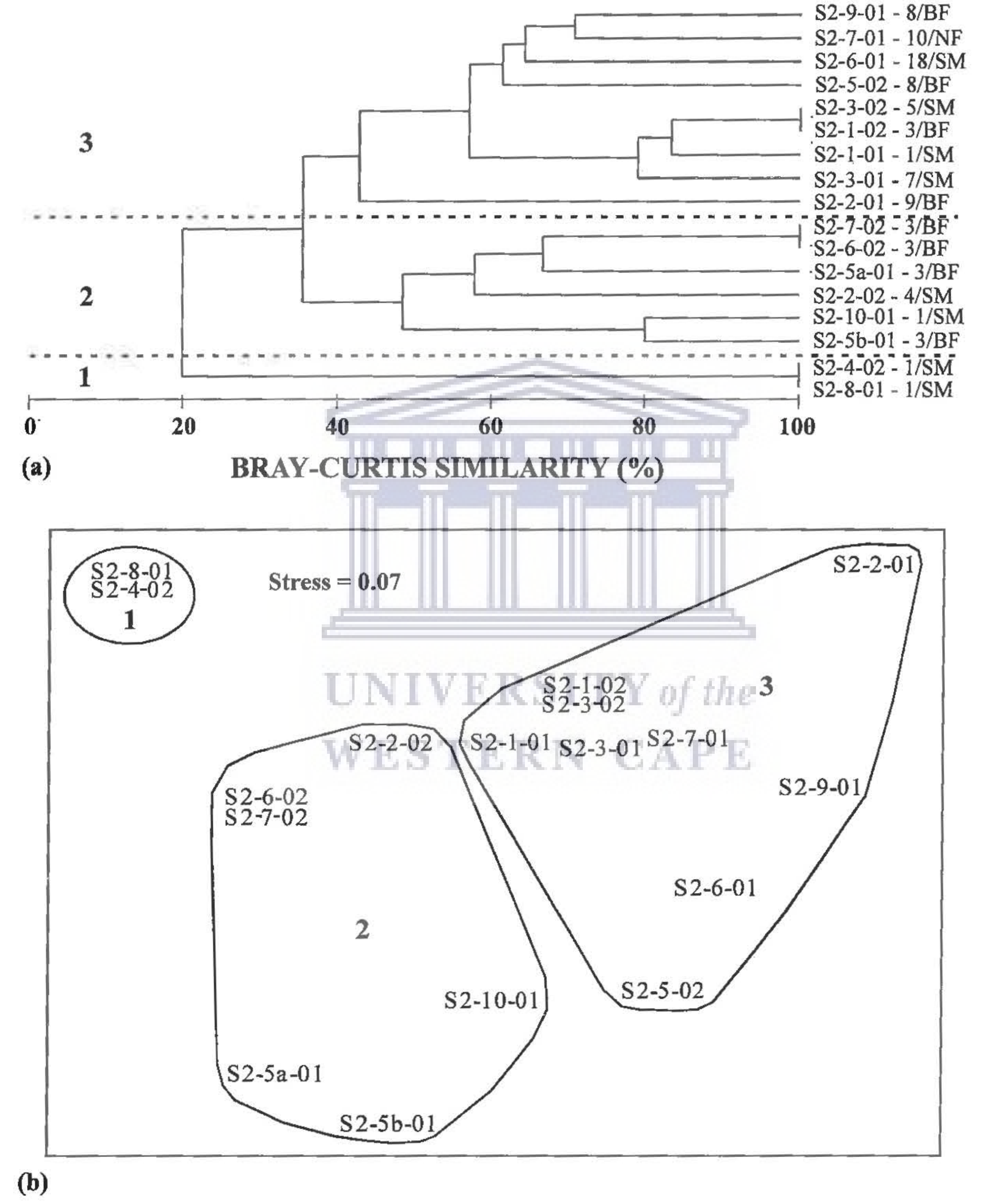

Figure 5.20: Dendrogram (a) and MDS (b) ordination of macro-invertebrate data from Site 2 for 2001 and 2002. Code: S2-1-01 – 6/SM = Site, sample number, year – hydraulic biotope number (Table 4.4) and flow type (Table 4.2).

5.4.3 Site 3 – 2001&2002

Five groups were formed (Figure 5.21). Group 1 was formed at 57% similarity. The samples were taken in sand+organic matter, and cobbles+organic matter+algae. The families found included Naididae, Physidae and Corixidae. Group 2 consisted of samples collected in cobble+boulder+organic matter+algae, gravel+slope clayblock material+organic matter, a concrete slab, and sand+organic matter. Sample S3-3-02 was 57% similar to the rest of the samples in the group. The remaining samples were 85% similar to each other. Samples S3-2-02, S3-5-02 and S3-6-02 had Chironomidae, Naididae, Physidae and Simuliidae in common with sample S3-2-02 having Dytiscidae in addition and sample S3-6-02 having Coenogrionidae in addition. Sample S3-3-02 contained Gomphidae, Chironomidae and Physidae. Group 3 consisted of samples taken in a mixture of biotopes including sand+organic matter, marginal vegetation, marginal vegetation+algae, and boulder+organic matter. The samples had Physidae and Corixidae in common (Appendix 2). The samples in Group 4 were taken in marginal vegetation, vegetation and algae biotopes. These samples contained Corixidae and Physidae, but had Baetidae in addition. Samples S3-2-01 and S3-8-01 made up Group 5, which were sampled in marginal vegetation and cobbles respectively (Figure 5.21a). These samples had Gerridae, Baetidae, Physidae and Hirudinae in common, but were not closely related as indicated on Figure 5.21b.

5.4.4 Site 4 – 2001&2002

The dendrogram and MDS plot (Figure 5.22) separated into three groups. Group 1 consisted of one sample, which was taken in smooth turbulent flow in vegetation with algae. The sample had the highest number of families (11) present of all the sites during both sampling periods (Appendix 2). Group 2 consisted of the rest of the samples taken in 2002. The samples were 78% similar and had Naididae, Baetidae, Chironomidae and Physidae in common. Group 3 consisted of samples taken in 2001. The samples were 64% similar and had Gomphidae, Simuliidae and Chironomidae in common. These samples had the highest concentration of Simuliidae and Chironomidae with ratings of three to five (Appendix 2).

Samples S4-2-01 and S4-2-02 were taken in vegetation, but the former had families present similar to the rest of the samples in Group 3. The latter was the only sample that contained families that did not occur in the other samples. The two years separated into two groups with different community compositions. The samples in Group 2 were more closely related to each other than those in Group 3.

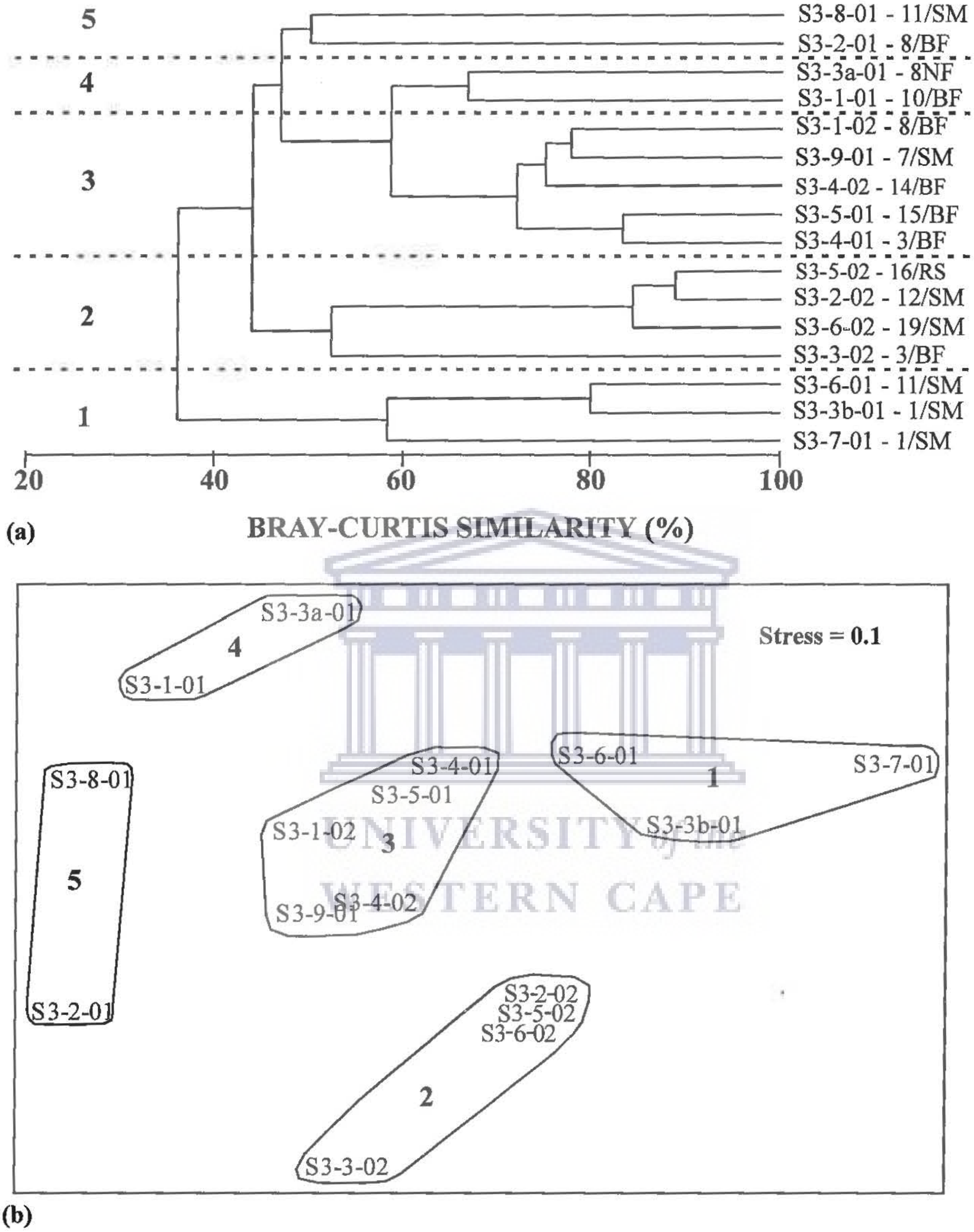

Figure 5.21: Dendrogram (a) and MDS (b) ordination of macro-invertebrate data from Site 3 for 2001 and 2002. Code: S3-1-01 – 6/SM = Site, sample number, year – hydraulic biotope number (Table 4.4) and flow type (Table 4.2).

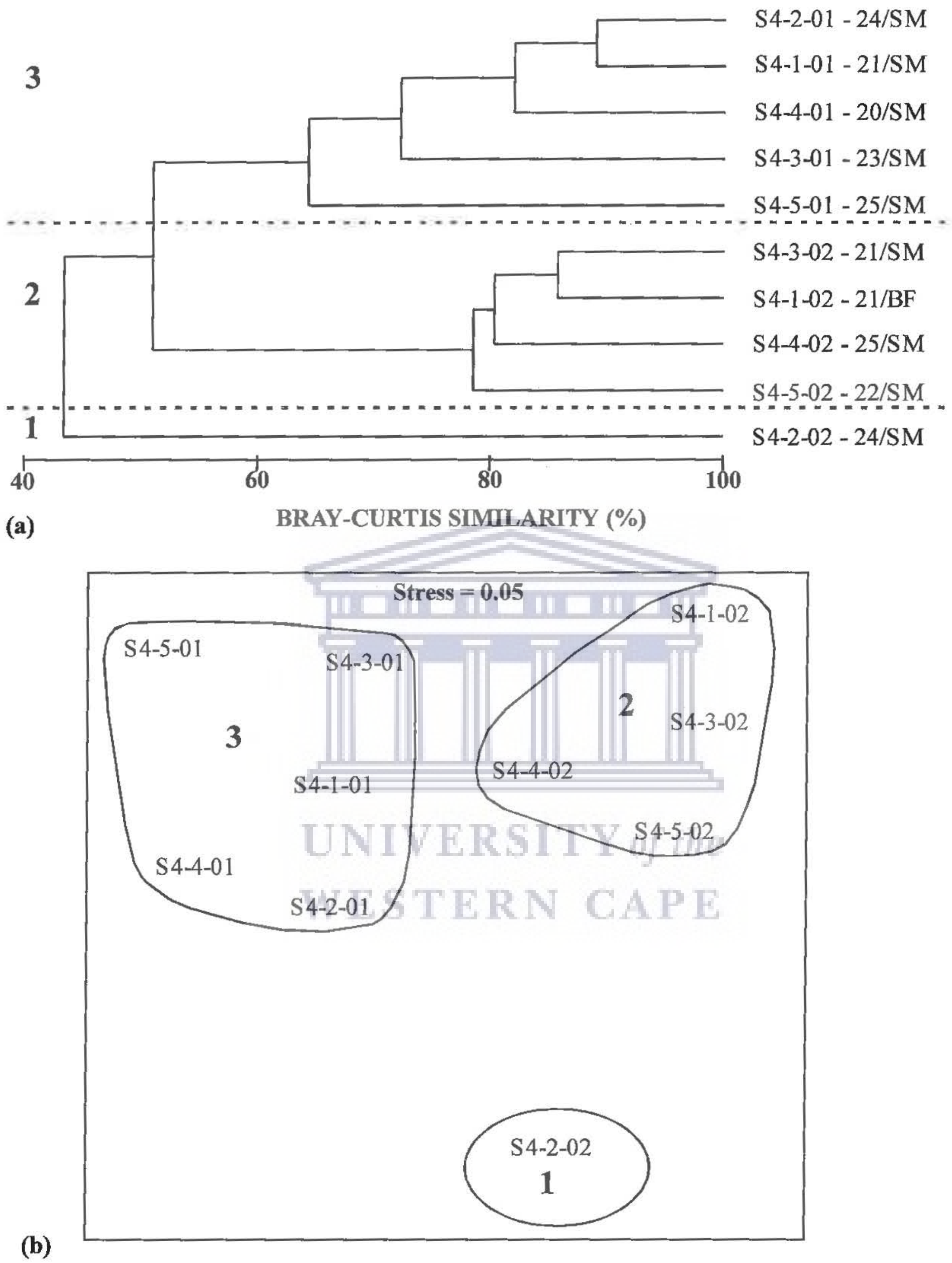

Figure 5.22: Dendrogram (a) and MDS (b) ordination of macro-invertebrate data from Site 4 for 2001 and 2002. Code: S4-1-01 – 6/SM = Site, sample number, year – hydraulic biotope number (Table 4.4) and flow type (Table 4.2).

5.4.5 Sites 1 to 4 – 2001&2002

The data of all four sites were analysed together to ascertain if there was a difference in the macro-invertebrate composition between the sites.

Three main groups were identified on the dendrogram and MDS plot (Figure 5.23a and b). Group 1 was 57% similar and consisted of samples taken in sandy substrates. The samples had Physidae in common (Appendix 2). Group 2 was further divided into three subgroups. The samples in Subgroup 2a were 100% similar, consisted of Hirudinae only and were taken in sand. The samples of Subgroup 2b had Physidae in common and were taken in sand, cobbles and marginal vegetation. The samples of Subgroup 2c had Naididae and Chironomidae in common and were taken in clayblock material, sand, concrete, cobbles, boulders and vegetation. Group 3 consisted of samples taken in a mixture of habitats including marginal vegetation, vegetation, cobbles, boulders, sand, building rubble, concrete and clayblock material (Figure 5.23a). All the families found in the study area were present in this group. The most common families were Naididae, Coenogrionidae, Gomphidae, Baetidae, Chironomidae and Physidae. Aeshnidae was only found in sample S3-2-01, Libelullidae only in S2-3-01, Veliidae only in S3-2-01, S1-1-02 and S2-5-02, Gyrinidae only in S2-2-01, Culicidae in S2-9-01 and S3-2-01. Sample S4-2-02 was the only sample that contained Pleidae, Naucoridae and Athericidae (Appendix 2).

In summary, there seemed to be no distinction between macro-invertebrate compositions between the sites, since similar macro-invertebrate families were found in all the sites (Table 5.8). There also seemed to be no distinction based on the biotopes sampled as certain groups consisted of a variety of biotopes sampled (Figure 5.23a). Site 1 was an exception, as there was a difference between samples from vegetation biotopes and those collected in sandy biotopes (Figure 5.19). The channelisation of Sites 1 and 2 and the sediment deposition in Site 3 resulted in a loss of biotopes in 2002. This led to a change in community composition and decreased abundances at most sites, except for Site 4 (Table 5.8 and Appendix 2). The samples within all the sites were also very closely related to each other (Figure 5.23b)

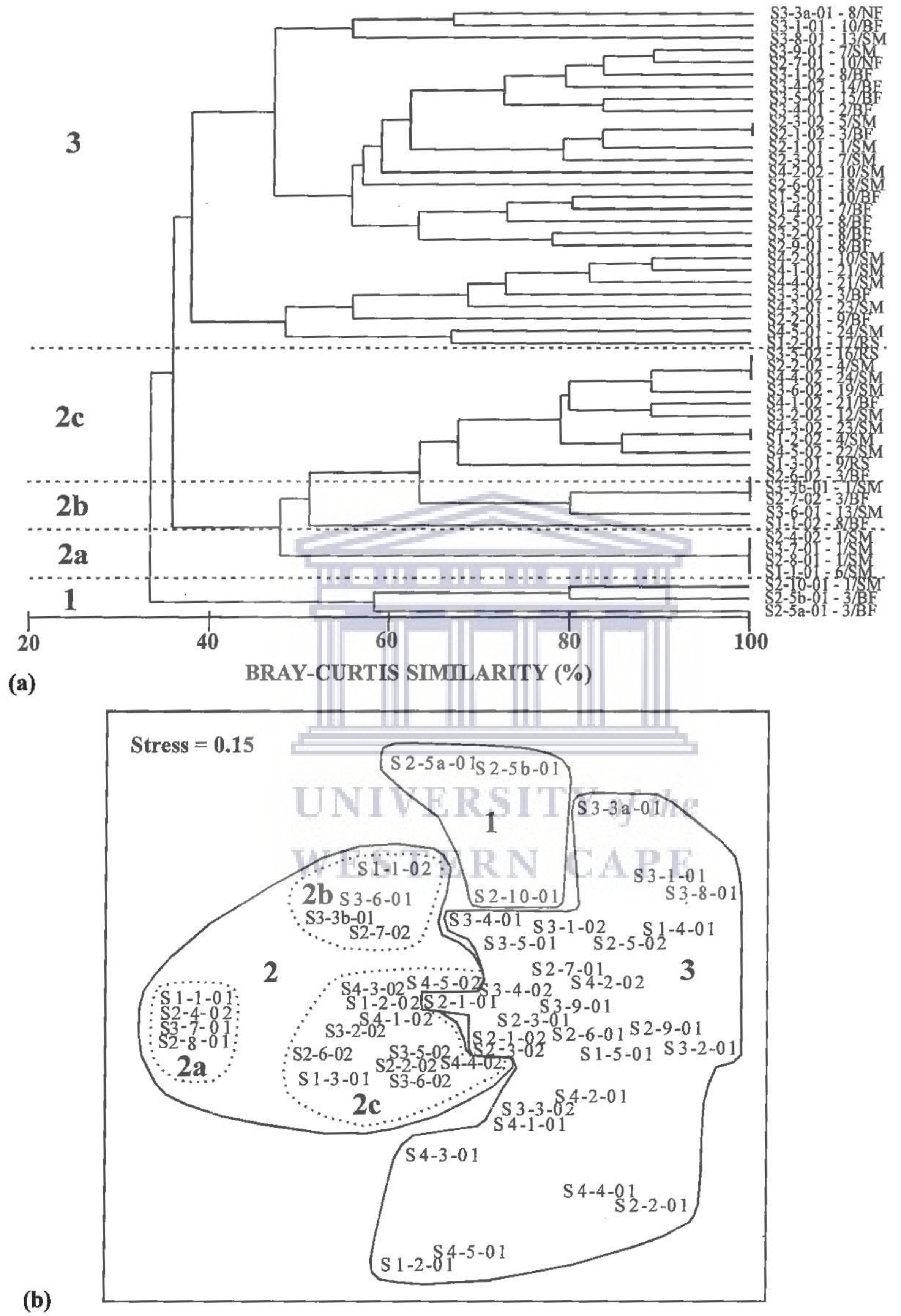

Figure 5.23: Dendrogram (a) and MDS (b) ordination of macro-invertebrate data from Sites 1 to 4 for 2001 and 2002. Code: S1-1-01 – 6/SM = Site, sample number, year – hydraulic biotope number (Table 4.4) and flow type (Table 4.2).

Table 5.8: Summary table of invertebrate families present and their sensitivity scale according to Gerber and Gabriel (2002) in all sites during 2001 and 2002.

Invertebrate Order	Invertebrate Families	Sensitivity scale	Site 1 2001	Site 1 2002	Site 2 2001	Site 2 2002	Site 3 2001	Site 3 2002	Site 4 2001	Site 4 2002
Annelida	Hirudinae	3			*	*	*			*
	Naididae	1	*	*	*	*	*	*	*	*
Odonata	Coenagrionidae	4	*	*	*	*	*	*		
	Gomphidae	6	*		*	*	*	*	*	
	Aeshnidae	8					*			
	Libellulidae	5			*					
Ephemeroptera	Baetidae	4	*		*	*	*	*	*	*
Hemiptera	Corixidae	3			*		*	*		
	Pleidae	4								*
	Naucoridae	7								*
	Veliidae	5		*		*	*			
	Gerridae	5			*		*	*		
Coleoptera	Gyrinidae	5			*					
	Dytiscidae	5		*	*	*		*		*
Diptera	Simuliidae	5			*	*	*	*		*
	Chironomidae	2	*	*	*	*	*	*	*	*
	Culicidae	1			*		*			
	Athericidae	10								*
Gastropoda	Lymnaeidae	3	*		*	*	*	*		
	Physidae	3	*	*	*	*	*	*	*	*
	Total		7	6	15	11	14	11	5	10

Average SASS 4-type scores and ASPTs were calculated, as outlined in Section 4.3, for all the Sites during both sampling periods. All the SASS4 scores were less than 20, and the ASPTs were less than 5 (Table 5.10). A full list of SASS 4-type scores and ASPTs per sample is given in Appendix 3.

Table 5.9: Average SASS 4-type scores and ASPT (score/no. of taxa) per site during 2001 and 2002.

		SASS 4-type score	No. of taxa	ASPT
2001	Site 1	9.00	2.80	2.46
	Site 2	15.30	4.70	2.80
	Site 3	17.20	5.20	2.91
	Site 4	14.80	3.80	3.85
2002	Site 1	12.00	4.00	2.80
	Site 2	12.71	4.14	2.59
	Site 3	17.83	5.50	3.23
	Site 4	15.80	5.00	2.69

5.5 Ecology: plant assemblages

The previous section covered the macro-invertebrates found in the study area. Hardy macro-invertebrate families were found, indicating that the water quality and general health of the Kuils River are severely impaired. This section will cover the plant assemblages found and the changes that occurred due to the changes documented in Sections 5.2 and 5.3.

The results of one vegetation transect per site will be presented here as indicated on Table 4.7. The data for all the vegetation transects are found in Appendix 4 to 11.

5.5.1 Vegetation Transect 1.2

Six groups of plant assemblages were identified on the dendrogram and MDS plot (Figure 5.24 and 5.25). Groups 5 and 6 occurred in 2001 only, while groups 1 and 4 only occurred in 2002. Group 1 consisted of 92% and group 4 of 38% of the species found in 2002, while 75% of the species found in 2001 were not present in 2002 and 83% of the species in 2002 were new. In 2001, *Bromus diandrus* and *Pennisetum clandestinum* were the only species of Group 2. The dominant species in Group 3 was *Pennisetum clandestinum* and in most of the sampling plots it was the only species (Appendix 4b). Group 6 consisted of *Cyperus longus*, *Cyperus* species, *Polygonum aviculare*, *Isolepis fluitans* and *Xanthium strumarium* (Table 5.10). The latter two species were unique to the group (Appendix 3b). According to the MDS plot (Figure 5.24b) the plant species in Groups 2 and 3 were more closely related than those in Group 1. Groups 1 to 4 formed a cluster of relatively close relationship with Group 6 further removed from the rest of the groups.

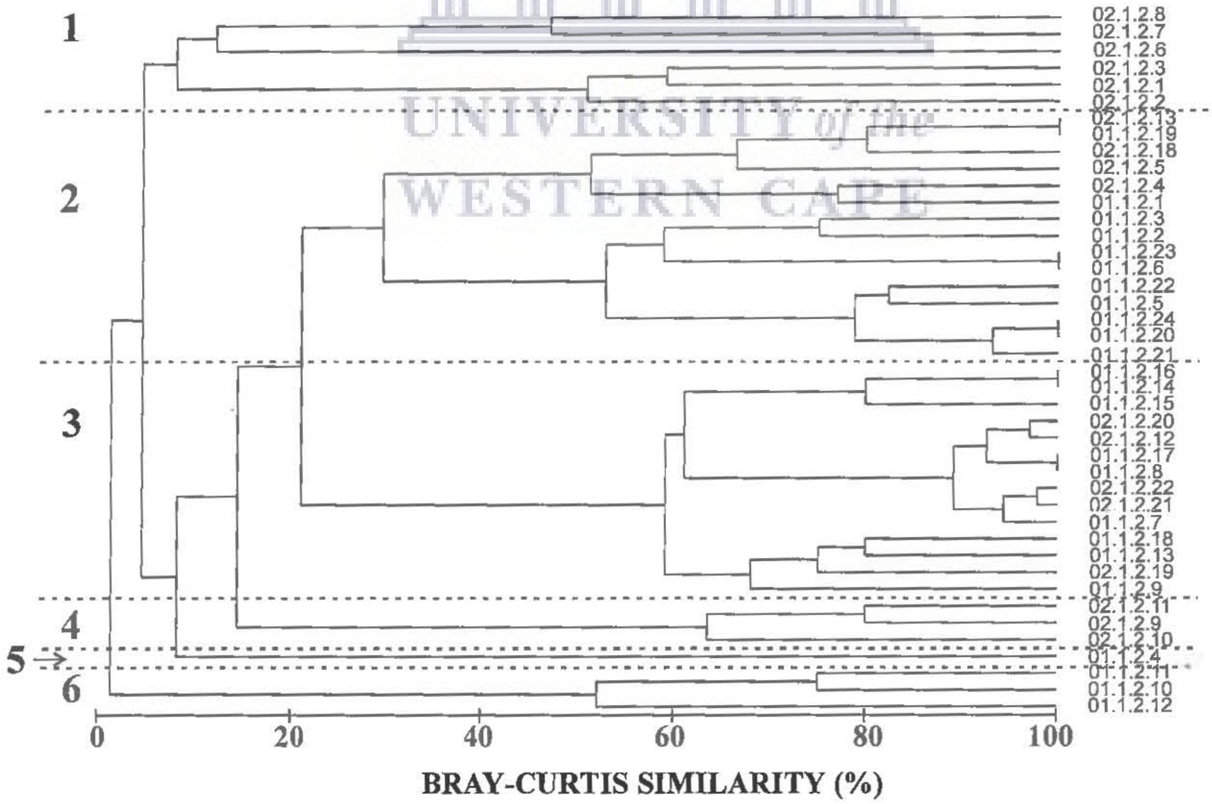

Figure 5.24: Dendrogram of the plant assemblages of vegetation transect 1.2 for 2001 and 2002. The bold numbers represent the groups identified while 01.1.2.1 is a code used for the sampling plots and represents year, site, vegetation transect and sampling plot.

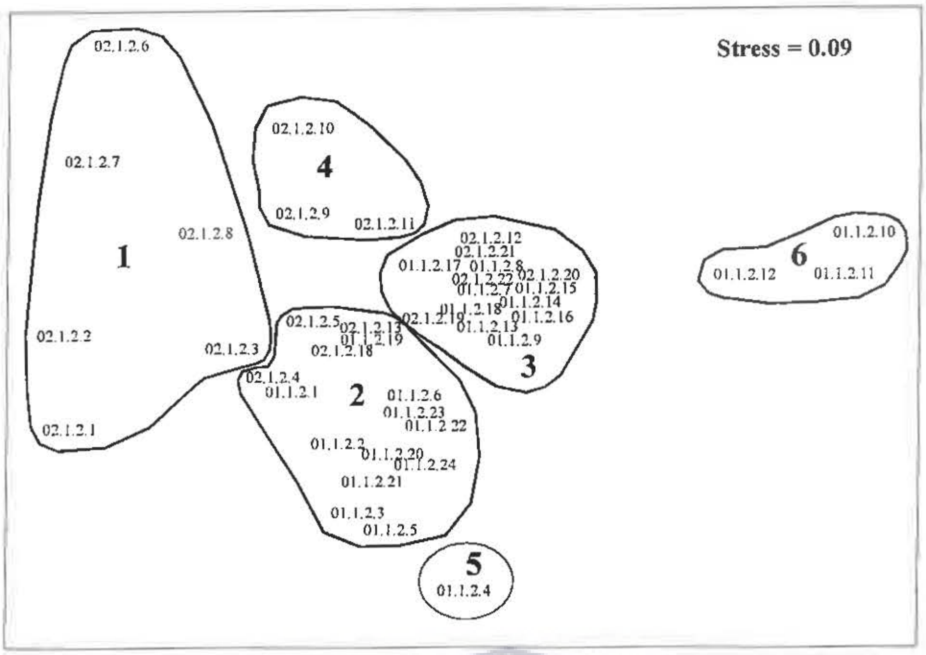

Figure 5.25: MDS plot of the plant assemblages of vegetation transect 1.2 for 2001 and 2002. The bold numbers represent the groups identified while 01.1.2.1 is a code used for the sampling plot and represents year, site, vegetation transect and sampling plot.

Table 5.10: Plant species $^{\text{per group}}$ present along vegetation transect 1.2 for 2001 and 2002.

2001	2002
Pennisetum clandestinum^{2,3,5}	*Amaranthus deflexus* (sl)^{1}
Bromus diandrus^{2,5}	*Echium plantagineum*^{1,2}
Chenopodium album^{3}	*Raphanus raphanistrum* (sl)^{1}
Cyperus species^{3,6}	*Tribulus terrestris*^{1,4}
Polygonum aviculare^{3,6}	*Amaranthus deflexus*^{1}
Isolepis fluitans^{6}	*Cynodon dactolyn*^{1,4}
Xanthium strumarium^{6}	*Acacia saligna* (sl)^{1,2}
Cyperus longus^{3,6}	*Pennisetum clandestinum*^{1,2,3,4}
	Raphanus raphanistrum^{1}
	Paspalum distichum^{1}
	Cyperus rotundus^{1,4}
	Datura stramonium^{1}
	Hibiscus species^{1,4}
	Cyperus species^{3}

The position of the different groups identified in Figure 5.25 is illustrated on the profile line in Figure 5.26. Group 1 was found on the bank and along the midslopes of the right bank on the profile of 2002, but did not occur in 2001. Group 2 was found on both banks to about 6m down the slope in 2001, and to a much lesser extent on the right bank in 2002. Group 3 was found along the midslopes on the right bank and within the channel and about halfway along the left bank in 2001. In 2002, the position of Group 3 on the left bank remained the same compared to that of 2001, but covered a slightly smaller area. Its position shifted from along the midslopes in 2001 to within the channel in 2002 on the right bank. Group 4 was found along the lower slopes and within the channel on the right bank on the profile of 2002, but did not occur in 2001. Group 6 occurred along the lower slopes on the right bank in 2001. Group 4 seemed to have replaced Group 6 in 2002 (Figure 5.26). Group 3 was found along the midslopes from 6-9m on the right bank and within the channel up to about 18m on the left bank in 2001, while Group 5 was found on top of the right bank.

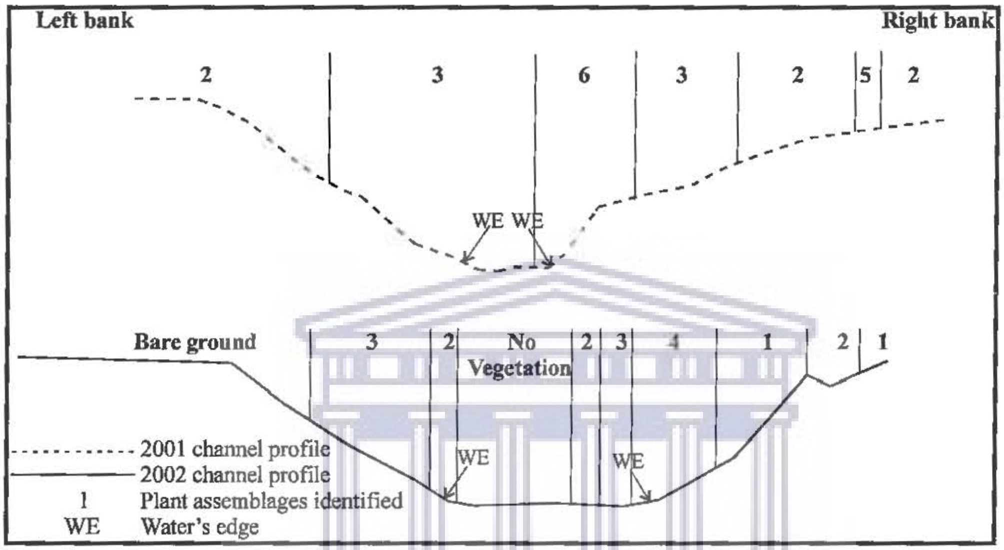

Figure 5.26: Position of the different groups identified according to Figures 5.24 and 5.25 on vegetation transect 1.2 for 2001 and 2002. See section 5.2.1 for a description of the changes documented in the cross-sections of Site 1.

5.5.2 Vegetation transect 2.2

Five groups were identified on the dendrogram and MDS plot (Figure 5.27a and b). Group 1 was only found in 2001 and it had *Bromus diandrus* and *Pennisetum clandestinum* in common with Group 3, but the other plant species were unique to it (Table 5.11). Group 2 only occurred in 2002 and had *Acacia saligna* (seedling) unique to it. The other species were common to the other groups. Group 3 occurred in both years, but the species composition between the years was not the same (Table 5.11). Sixty nine percent of the plant species of Group 3 was new in 2002. Group 4 was found in both years with *Cynodon dactolyn* the dominant species in most cases (Appendix 5a and 9a), while Group 5 was only found in 2001. The MDS plot (Figure 5.27b) showed that all five groups were relatively closely related. The sampling plots of Groups 2,3 and 4 were more closely related than those of Group 1.

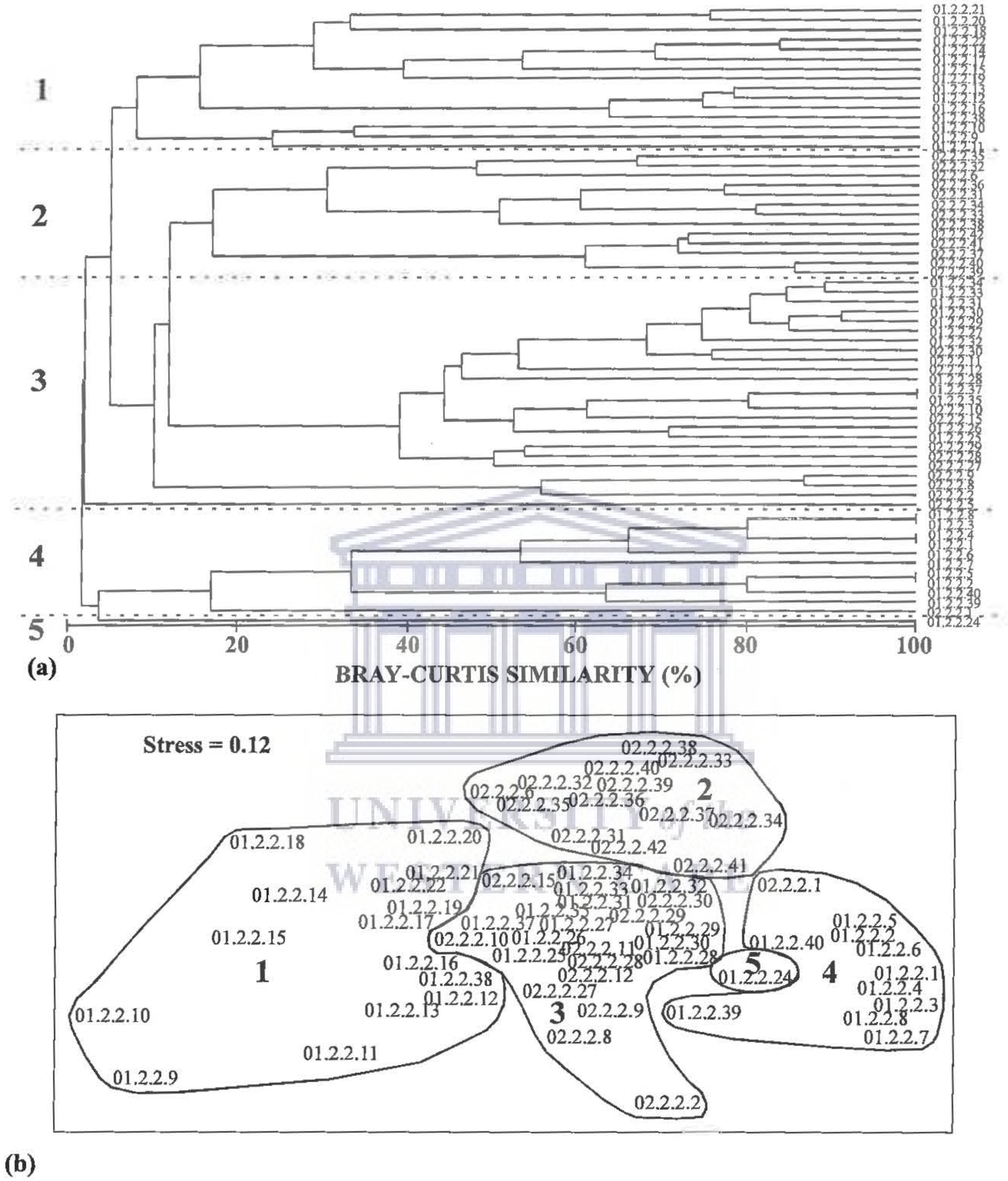

Figure 5.27: Dendrogram (a) and MDS plot (b) of the plant assemblages of vegetation transect 2.2 for 2001 and 2002. The bold numbers represent the groups identified while 01.2.2.1 is a code used for the sampling plots and represents year, site, vegetation transect and sampling plot.

Table 5.11: Plant species $^{per\ group}$ present along vegetation transect 2.2 for 2001 and 2002.

2001	2002
Cynodon dactylon^{4}	*Brachiaria serrata*$^{3, 4}$
Carpobrotus edulis^{1}	*Cynodon dactylon*$^{2, 3, 4}$
Bromus diandrus$^{1, 3, 4}$	*Echium plantagineum*^{4}
Pennisetum clandestinum$^{1, 3}$	*Paspalum distichum*^{4}
Lolium temulentum^{1}	*Tribulus terrestris*^{4}
Cleome monophylla^{1}	*Xanthium strumarium*$^{2, 3}$
Salsola kali^{1}	*Pennisetum clandestinum*$^{2, 3}$
Chenopodium album^{1}	*Acacia saligna*^{3}
Erucastrum strigosum^{1}	*Medicago polymorpha*^{3}
Avena fatua^{1}	*Carpha glomerata*^{3}
Acacia saligna$^{3, 5}$	*Isolepis fluitans*^{3}
Polygonum aviculare^{3}	*Lolium perenne*^{3}
Sonchus oleraceus^{3}	*Polypogon* species$^{2, 3}$
Typha species^{3}	*Amaranthus deflexus*$^{2, 3}$
Xanthium strumarium^{3}	*Cyperus denudatus*^{3}
Carpha glomerata^{3}	*Acacia saligna* (sl)^{2}

Figure 5.28 shows the positions of the different groups on the profile as identified on Figure 5.27. Group 1 occurred on top of and along the midslope of the left bank. Group 2 replaced Groups 1 and 4 on top of and along the midslopes on the left bank in 2002. Group 3 remained in similar positions, namely along the midslopes of the left bank and water's edge on both banks, but its aerial extent was reduced in 2002. Group 4 was found on top of both banks in 2001, but occurred only on top of the right bank in 2002 (Figure 5.28).

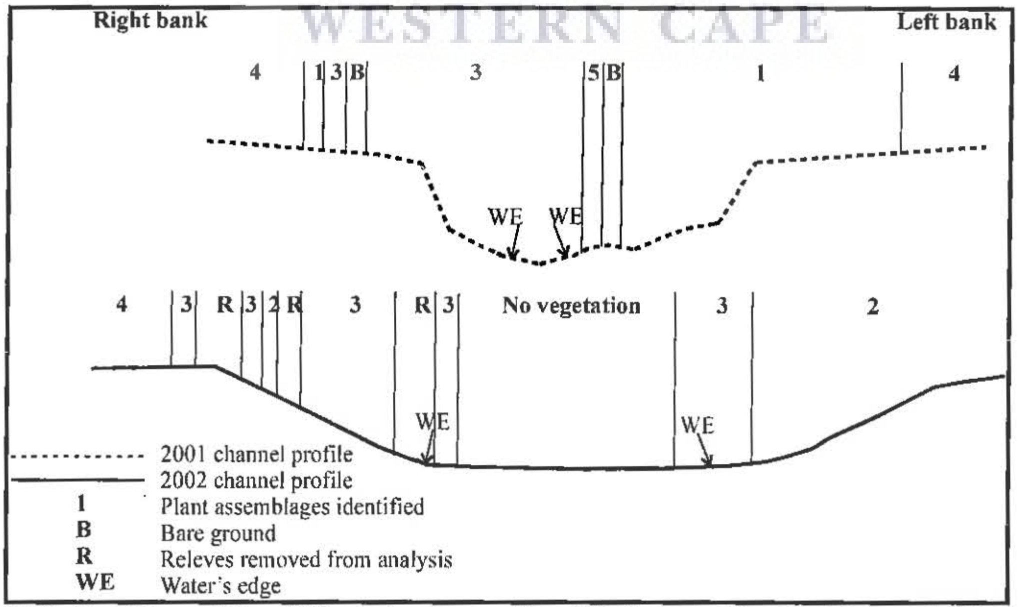

Figure 5.28: Position of the different groups identified according to Figure 5.27 on vegetation transect 2.2 for 2001 and 2002. See section 5.2.1 for a description of the changes documented in the cross-sections of Site 2.

5.5.3 Vegetation transect 3.3

Four groups were identified on the dendrogram (Figure 5.29) and MDS plot (Figure 5.30). Group 1 only occurred in 2002. The group had various species in common with the other groups but *Xanthium strumarium*, *X.* species, *Brachiaria serrata*, *Hibiscus* species, *Isolepis fluitans*, *Cyperus* species, *C. rotundus*, *C. denudatus*, *Carpha glomerata*, *Picris* species, *Nemesia versicolor* and *Fallopia convolvulus* were unique to it. Groups 2 to 4 occurred in both years with many of the species common to all the groups (Appendix 6b and 10b and Table 5.12). According to the MDS plot (Figure 5.30) the plant species in Group 3 were very closely related to each other. This was not the case with Group 4. In Group 4 the sampling plots were scattered on the MDS plot (Figure 5.30).

Table 5.12: Plant species $^{\text{per group}}$ present along vegetation transect 3.3 for 2001 and 2002.

2001	2002
Acacia saligna (sl)^{2,3,4}	*Pennisetum clandestinum*^{1,2,3,4}
Chenopodium album^{4}	*Cynodon dactolyn*^{2,3,4}
Euphorbia peplus^{4}	*Dittrichia graveolens*^{1,2,4}
Pennisetum clandestinum^{2,3,4}	*Fuirena coerulescens*^{1,2,4}
Portulaca oleracea^{3,4}	*Portulacaria* species^{2}
Tribulus terrestris^{4}	*Acacia saligna* (sl)^{1,2,4}
Cynodon dactolyn^{2,3,4}	*Plantago lanceolata*^{1,2,3,4}
Medicago polymorpha^{3,4}	*Lolium perenne*^{2,3,4}
Polygonum aviculare^{3,4}	*Medicago polymorpha*^{1,4}
Chenopodium multifidum^{3}	*Polypogon* species^{1,3,4}
Conyza canadensis^{3}	*Xanthium strumarium*^{1}
Cyperus longus^{2,3,4}	*Amaranthus deflexus*^{1,2,3,4}
Taraxacum officinale^{3}	*Rumex acetosella*^{1,4}
Xanthium strumarium^{3}	*Helichrysum cochleariforme*^{1,2,4}
Rumex species^{3}	*Brachiaria serrata*^{1,4}
Brachiaria serrata^{3,4}	*Hibiscus* species^{1}
Lolium temulentum^{3}	*Isolepis fluitans*^{1}
Isolepis fluitans^{3,4}	*Cyperus* species^{1}
Polygonum species^{4}	*Carpha glomerata*^{1}
Eragrostis species^{3}	*Cyperus rotundus*^{1,4}
	Picris species^{1}
	Cyperus denudatus^{1,4}
	Xanthium species^{1,4}
	Cyclopia species^{3,4}
	Nemesia versicolor^{4}
	Fallopia convolvulus^{1}
	Poa species^{2,3}
	Rumex species^{2,3}
	Taraxacum officinale^{3}
	Hypochaeris radicata^{2,4}
	Nicotiana glauca^{2}

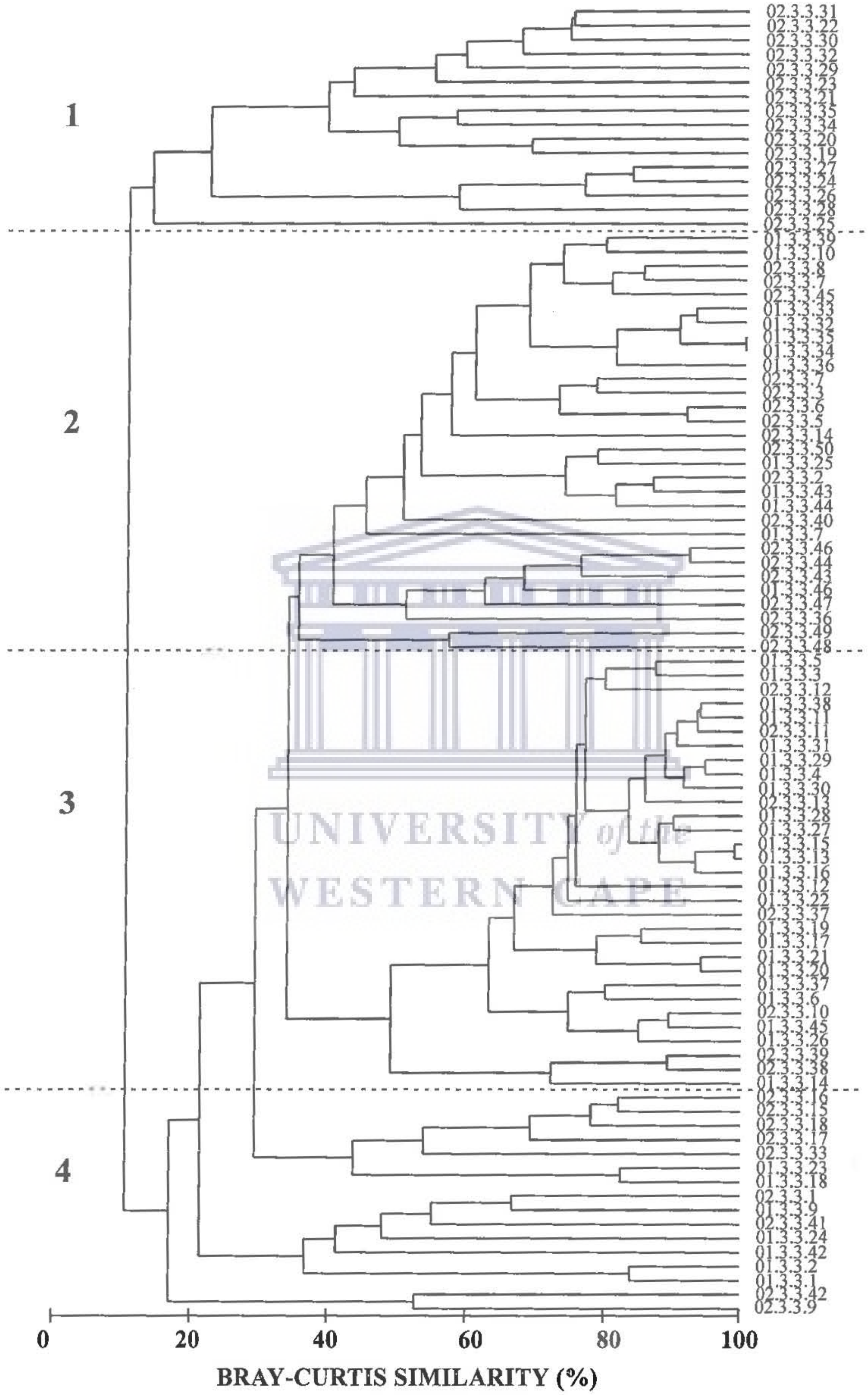

Figure 5.29: Dendrogram of the plant assemblages of vegetation transect 3.3 for 2001 and 2002. The bold numbers represent the groups identified while 01.3.3.1 is a code used for the sampling plots and represents year, site, vegetation transect and sampling plot.

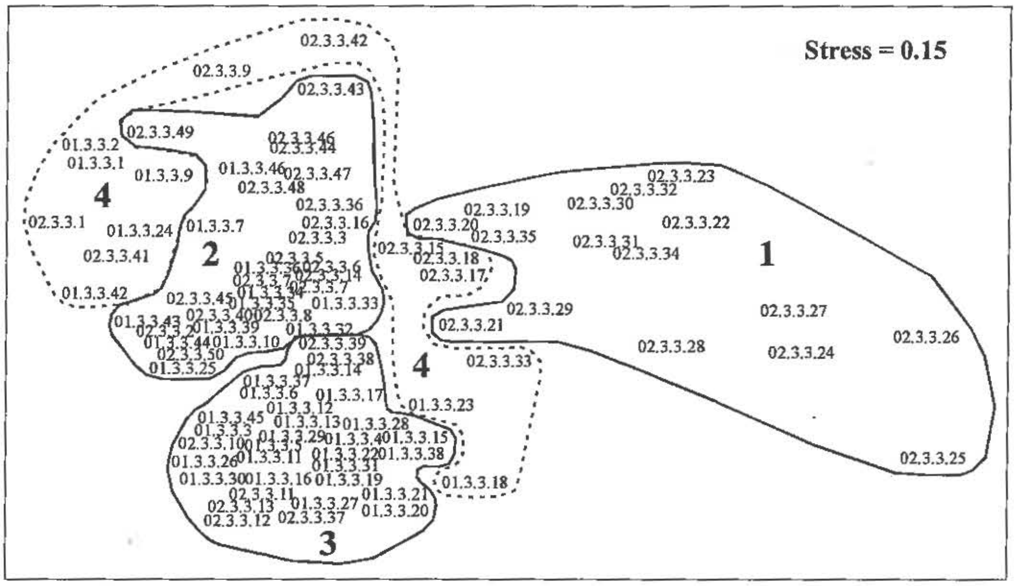

Figure 5.30: MDS plot of the plant assemblages of vegetation transect 3.3 for 2001 and 2002. The bold numbers represent the groups identified while 01.3.3.1 is a code used for the sampling plots and represents year, site, vegetation transect and sampling plot.

Figure 5.31 illustrates the position of the different groups on the profile line as identified in Figure 5.29 and 5.30. There seemed to be no specific order or pattern of grouping along the profile in 2001 (Figure 5.31). The pattern remained more or less similar in 2002 with no order on the midslopes. However, the position of groups 2 to 4 remained more or less similar in both years, but their aerial extent changed slightly in 2002. A big difference in 2002 was the presence of Group 1, which replaced groups 2 to 4 on the floodplain areas (Figure 5.31).

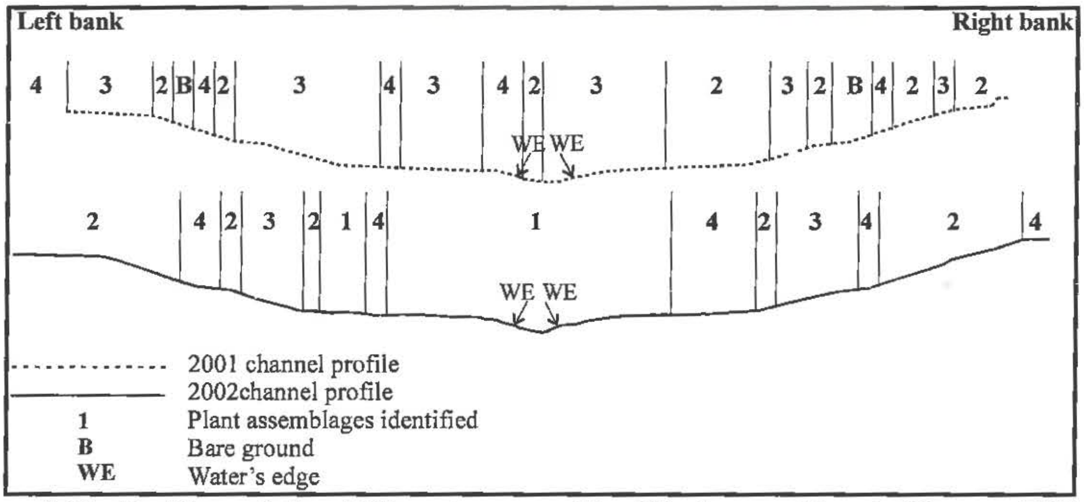

Figure 5.31: Position of the different groups identified according to Figures 5.29 and 5.30 on vegetation transect 3.3 for 2001 and 2002. See section 5.2.1 for a description of the changes documented in the cross-sections of Site 3.

5.5.4 Vegetation transect 4.1

Four groups were identified on the dendrogram and MDS plot (Figure 5.32 and 5.33). Most of the plant species found in a particular group in 2001 occurred in the same group in 2002. Fifty eight percent of the plant species found in 2001 were also found in 2002. The plant species found in 2001 made up 64% of the plant species found in 2002. The remaining species of 2001 were replaced with new species in 2002. Group 4 tended to be divided into two groups of sampling plots namely the sampling plots found on top of the banks consisting of *Chenopodium multifidum* (both years) and *Plantago lanceolata* (2002) and the sampling plots with *Carpha glomerata* (both years) within the concrete canal section of the channel (Appendix 7 and 11 and Table 5.13). This was also visible on the MDS plot in Figure 5.33 where the sampling plots of Group 4 were rather far apart.

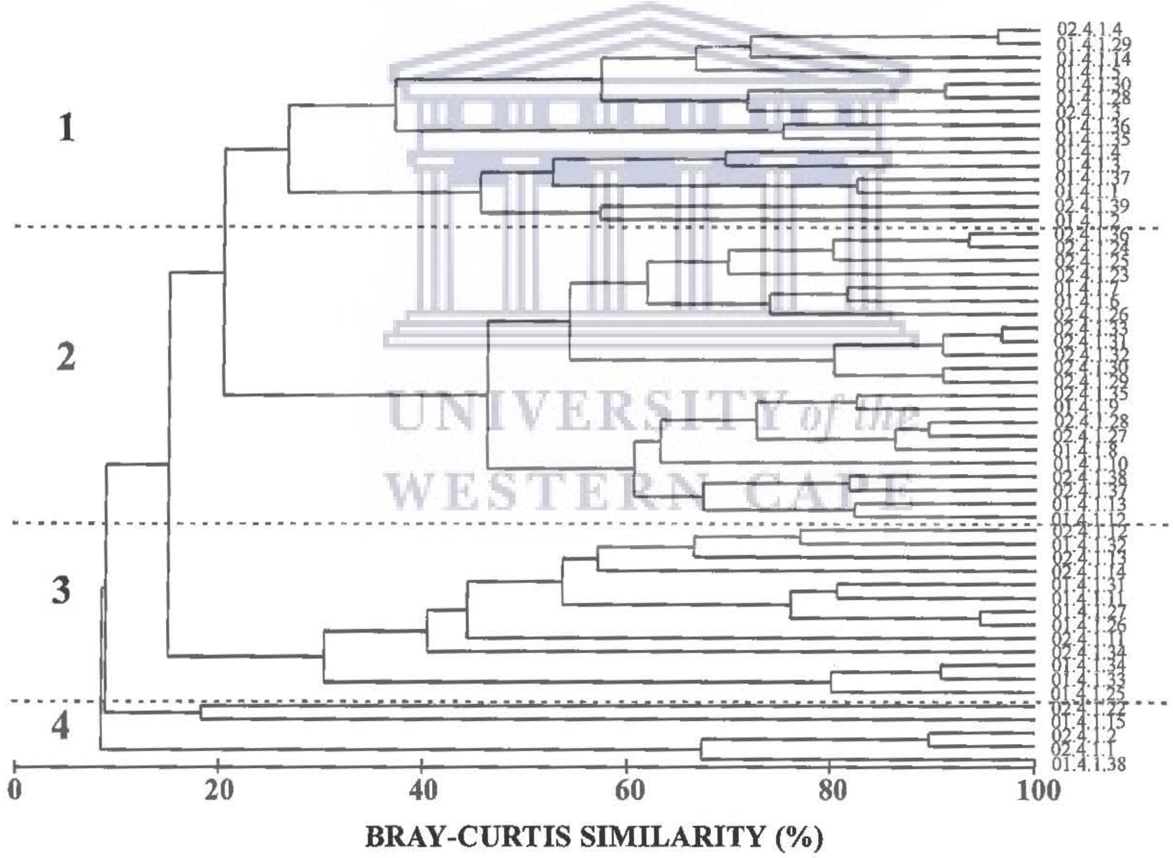

Figure 5.32: Dendrogram of the plant assemblages of vegetation transect 4.1 for 2001 and 2002. The bold numbers represent the groups identified while 01.4.1.1 is a code used for the sampling plots and represents year, site, vegetation transect and sampling plot.

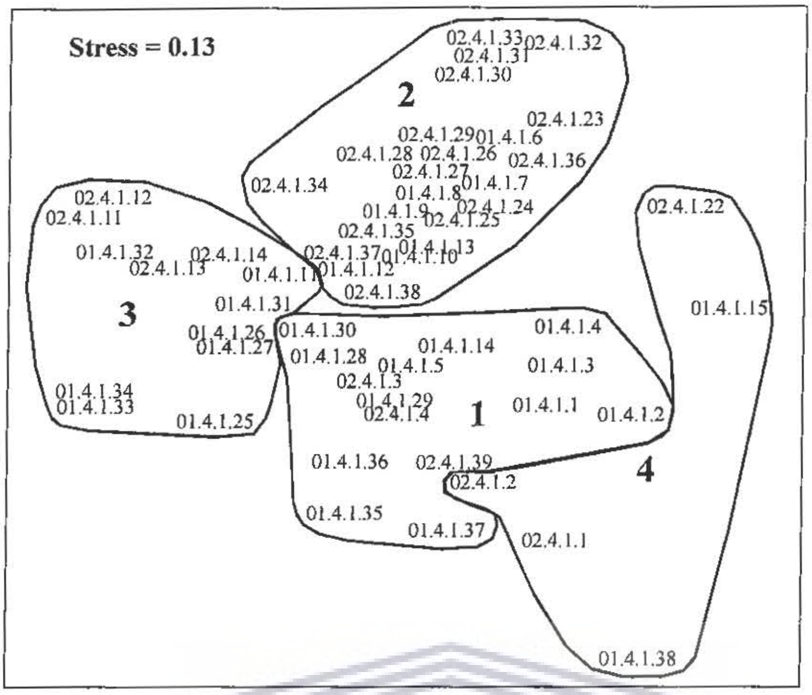

Figure 5.33: MDS plot of the plant assemblages of vegetation transect 4.1 for 2001 and 2002. The bold numbers represent the groups identified while 01.4.1.1 is a code used for the sampling plots and represents year, site, vegetation transect and sampling plot.

Table 5.13: Plant species $^{\text{per group}}$ present along vegetation transect 4.1 for 2001 and 2002.

2001	2002
Chenopodium multifidum^{1,4}	*Chenopodium multifidum*^{1,4}
Pennisetum clandestinum^{1,2,3}	*Plantago lanceolata*^{1,2,3,4}
Plantago lanceolata^{1,2,3}	*Echium plantagineum*^{1}
Echium plantagineum^{1,2}	*Citrullus lanatus*^{3}
Taraxacum officinale^{1}	*Cynodon dactolyn*^{2,3}
Acacia saligna^{2}	*Dittrichia graveolens*^{3}
Medicago polymorpha^{1,2,3}	*Carpha glomerata*^{2,4}
Sonchus oleraceus^{2}	*Pennisetum clandestinum*^{2,3,4}
Cynodon dactolyn^{1,2,3}	*Hypochaeris radicata*^{1,2}
Carpha glomerata^{4}	*Medicago polymorpha*^{2}
Cleome monophylla^{1}	*Lactuca serriola*^{2}
Tribulus terrestris^{3}	

Figure 5.34 shows that Groups 1 and 3 were scattered along the profile in 2001, but Group 1 was confined to the top of the banks in 2002, while Group 3 remained in the same position in both years. Group 2 occurred only on the left bank in both years, but increased in aerial extent in 2002. Group 4 remained in the same position in both years, namely on the right bank and within the concrete section of the channel on the left bank.

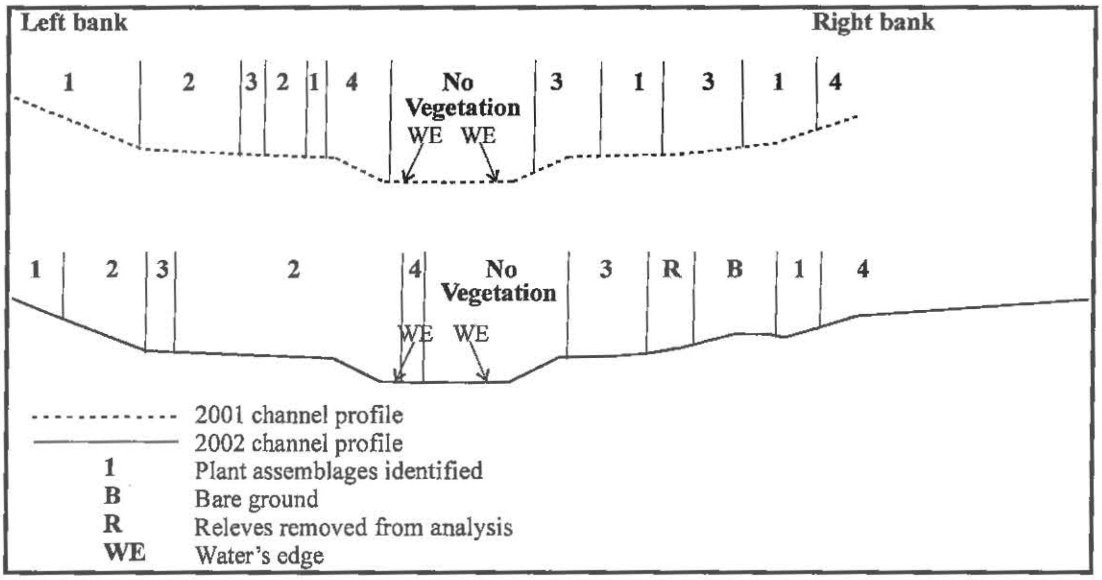

Figure 5.34: Position of the different groups identified according to Figures 5.32 and 5.33 on vegetation transect 4.1 for 2001 and 2002. See section 5.2.1 for a description of the changes documented in the cross-sections of Site 4.

In summary, most of the plant species found occurred in most of the sites. Site 1 had the lowest number of species (12) with Site 3 having the highest number (46) in 2001. The number of species found in Site 1 increased to 24, while those in Sites 2 and 3 decreased to 24 and 36 respectively. The number of species in Site 4 remained more or less the same during both years (Table 5.14). Sixty percent of the plant species found at all the sites were alien while 72% were weeds (alien and indigenous) (Table 5.15).

In 2001 the plant assemblages of Sites 1 and 2 were characterised by species adapted to wetter conditions found near the water's edge and along the lower slopes of the banks for example, Group 5 of vegetation transect 1.2 and Group 3 of vegetation transect 2.2. The slopes were covered with species adapted to drier conditions. The pattern outlined above was not found in Site 3 where the plants were scattered along the profile and not confined to a specific position. Site 4 had plants adapted to wetter conditions on the left bank only. In 2002, the reversal occurred in Sites 1 to 3. Sites 1 and 2 did not have the specific groups with plants adapted to wetter conditions confined close to the water. Instead, the plants adapted to wetter conditions were scattered across the profiles. Site 3 on the other hand had one group with plants adapted to wetter conditions on the floodplain areas near the water. The plant assemblages of Site 4 remained the same in both years.

Table 5.14: Plant species found in the study area during 2001 and 2002.

Plant species names	Site 1		Site 2		Site 3		Site 4	
	2001	2002	2001	2002	2001	2002	2001	2002
Acacia saligna		*	*	*	*	*	*	
Amaranthus deflexus		*		*	*	*		
Avena fatua			*					
Brachiaria serrata		*		*	*	*		
Bromus diandrus	*		*					
Carex glomerabilis			*					
Carpha glomerata		*	*	*	*	*		*
Carpobrotus edulis			*	*				
Chenopodium album	*		*		*			
Chenopodium multifidum			*		*		*	*
Citrullus lanatus		*	*	*				*
Cleome monophylla	*	*	*	*			*	
Conicosia pugioniformis			*					
Conyza canadensis			*		*			
Cyclopia species				*	*	*		
Cynodon dactylon	*	*	*	*	*	*	*	*
Cyperus denudatus		*		*	*	*		
Cyperus longus	*		*		*			
Cyperus rotundus		*			*	*		
Cyperus species	*	*		*	*	*		
Datura stamonium		*	*	*				
Dittrichia graveolens					*	*		*
Echium plantagineum	*	*	*	*	*	*	*	*
Ehrharta villosa					*			
Eragrostis species					*			
Erucastrum strigosum			*	*				
Euphorbia peplus		*			*			
Fuirena coerulescens					*	*		
Helichrysum cochleariforme			*		*	*		
Hibiscus species					*	*		
Hypochaeris radicata					*	*		*
Isolepis fluitans	*	*	*	*	*	*		
Lactuca serriola								*
Lolium perenne		*		*	*	*		
Lolium temulentum	*		*		*			
Lotononis species					*	*		
Medicago polymorpha		*	*	*	*	*	*	*
Nemesia versicolor					*	*		
Nicotiana glauca				*	*	*		
Pennisetum clandestinum	*	*	*	*	*	*	*	*
Picris species					*	*		
Plantago lanceolata					*	*	*	*
Poa species			*		*	*		
Polygonum aviculare	*		*		*			
Polygonum species		*	*	*	*	*		

Table 5.14 continued

Portulaca oleracea					*			
Portulacaria species					*	*		
Raphanus raphanistrum		*		*				
Rumex acetosella					*	*		
Rumex species		*			*	*		
Salsola kali			*					
Setaria species		*						
Sonchus oleraceus		*	*				*	
Tamus communis					*	*		
Taraxacum officinale					*	*	*	
Tragus racemosus					*	*		
Tribulus terrestris		*	*	*	*	*	*	
Typha species			*	*	*	*		
Xanthium species					*	*		
Xanthium strumarium	*	*	*	*	*	*		
Total	12	24	30	24	46	36	12	11

Table 5.15: Plant species present in all sites of the study area during 2001 and 2002, with growth patterns, origin and weed status (Bond and Goldblatt 1984; Bromilow 1995; Henderson 2001; Levyns 1966; Goldblatt and Manning 2000). All the plants are herbs. A=Annual, B=Biannual, P=Perennial, AL=Alien, IN=Indigenous, * =Information not available.

Plant species name	Annual/Perennial	Origin (e.g. alien)	Weed?
Acacia saligna	P	AL	Yes
Amaranthus deflexus	P	AL	Yes
Avena fatua	A	AL	Yes
Brachiaria serrata	P	IN	Yes
Bromus diandrus	A	AL	Yes
Carex glomerabilis	P	*	*
Carpha glomerata	P	AL	Yes
Carpobrotus edulis	P	IN	No
Chenopodium album	P	AL	Yes
Chenopodium multifidum	P	AL	Yes
Citrullus lanatus	A	IN	Yes
Cleome monophylla	A	IN	Yes
Conicosia pugioniformis	P and B	*	*
Conyza canadensis	*	AL	Yes
Cyclopia species	*	IN	No
Cynodon dactylon	P	IN	No
Cyperus denudatus	P	AL	Yes
Cyperus longus	P	AL	Yes
Cyperus rotundus	P	AL	Yes
Cyperus species	P	AL	Yes
Datura stamonium	A	AL	Yes
Dittrichia graveolens	*	*	*
Echium plantagineum	A/B	AL	Yes
Ehrharta villosa	A or P	IN	Yes

Table 5.15 continued

Eragrostis species	P	IN	Yes
Erucastrum strigosum	*	*	*
Euphorbia peplus	A	AL	Yes
Fuirena coerulescens	*	*	*
Helichrysum cochleariforme	*	IN	Yes
Hibiscus species	A	AL	Yes
Hypochaeris radicata	*	AL	Yes
Isolepis fluitans	P	IN	No
Lactuca serriola	A and P	AL	Yes
Lolium perenne	P	AL	Yes
Lolium temulentum	A	AL	Yes
Lotononis species	P	*	*
Medicago polymorpha	A or P	AL	Yes
Nemesia versicolor	A	*	*
Nicotiana glauca	A	AL	Yes
Pennisetum clandestinum	P	AL	Yes
Picris species	*	*	*
Plantago lanceolata	P	AL	Yes
Poa species	A/P	AL	No
Polygonum aviculare	A	AL	Yes
Polygonum species	A	AL	Yes
Portulaca oleracea	A	AL	Yes
Portulacaria species	A	AL	Yes
Raphanus raphanistrum	A or B	AL	Yes
Rumex acetosella	P	AL	Yes
Rumex species	A, P or B	Al	Yes
Salsola kali	A	AL	No
Setaria species	A and P	IN	Yes
Sonchus oleraceus	A	AL	Yes
Tamus communis	*	*	*
Taraxacum officinale	P	AL	Yes
Tragus racemosus	A	IN	Yes
Tribulus terrestris	A	IN	Yes
Typha species	P	IN	No
Xanthium species	A	AL	Yes
Xanthium strumarium	A	AL	Yes

5.6 Rainfall and Discharge

Discharge readings were taken on three occasions during the winter of 2001. On two occasions, May and July, this was done shortly after rainfall events. The May readings were taken after approximately 57mm fell in the Durbanville area (week prior to 11 May), while 183mm fell in the week prior to 12 July. Only 39mm fell during the 27 days of June prior to the 28th of June (Unofficial record, A.C.T. Scheepers pers. comm. 2003) (Table 5.13.). Discharge was calculated by averaging the two or three different readings taken through the study area on any one day. Discharge at Site 4 on 11 May was 0.091m^3 s^{-1} (Table 5.14). This increased to an average of $0.257m^3\ s^{-1}$ by 28 June 2001. The highest reading was taken on 12 July 2001, when $0.756m^3\ s^{-1}$ was measured at Site 3 (Table 5.14). No readings were taken on 3 July 2001 when the banks started to collapse at Sites 1 and 2, because flows were too high to access the river following heavy falls of 122mm in the preceding three days in the Durbanville area (Unofficial record, A.C.T. Scheepers pers. comm. 2003) (Table 5.13). From the above-mentioned discharge events, it can be seen that the considerable volumes of water in the Kuils River after rains can erode the channel and banks, changing the course of the river.

The discharge-rating curve produced by Mr. Bhana (UCT, Department of Engineering) could not be used for the thesis because these were large discrepancies between the measured data and modelled data.

Table 5.16: Rainfall in millimetre measured in the Durbanville area prior to the discharge readings taken. * Indicates the day when the banks started to collapse in Sites 1 and 2. No discharge readings were taken (Unofficial record, A.C.T. Scheepers).

Date of discharge reading	Rainfall (mm)
11 May 2001	57
28 June 2001	39
03 July 2001*	122
12 July 2001	183

Table 5.17: Discharge ($m^3.s^{-1}$) measured on three dates during winter 2001.

Location of measurement	11 May 01	28 Jun 01	12 Jul 01
Site 1			
Cross-section 1.1	0.083	0.396	0.749
Cross-section 1.3	0.098	0.505	0.729
Site 2			
2.5m downstream of cross-section 2.1	0.090	0.396	0.529
Cross-section 2.3	0.089	-	0.588
Site 3			
28.4m upstream of pipe	0.106	0.383	0.756
10.2m upstream of gabion weir	0.099	-	-
14m downstream of gabion weir	0.067	0.547	0.732
Site 4			
Cross-section 4.1	0.087	0.090	0.622
Cross-section 4.2	0.098	-	0.670
Min	0.067	0.090	0.529
Max	0.106	0.547	0.756
Avg.	0.091	0.257	0.597

CHAPTER 6

DISCUSSION AND CONCLUSIONS

Chapter 5 outlined the events that occurred at the study sites and the impacts these had on the different parameters. This chapter will provide possible explanations for the observed changes in the parameters. The outline will follow that of Chapter 5.

6.1 Geomorphology: cross-sections

Factors that could be responsible for changes in the river width include excessive and prolonged rainfall, soil properties, vegetation cover, and downstream channelisation.

According to Thorne (1990), Casagli *et al.* (1999), Abernethy and Rutherfurd (2000) pore water pressure increases during rainfall due to the rising water table. Positive pore water pressure occurs when the bank material becomes fully saturated resulting in a decrease in cohesion and bank material strength and an increase in bank material weight resulting in bank erosion. When loss of strength is complete as may happen in extreme cases, bank failure due to liquification may result (Thorne 1990). Stability can still be maintained in the saturated bank material due to the confining pressure of the water in the river channel and on the bank face. Bank failure is likely to occur during the receding limb of the flood when the bank material is still at or near saturation and the confining pressure of the river water is removed (Casagli *et al.* 1999; Simon *et al.* 2000). Figure 5.4 shows the stage of the water during the flood. The higher water stage later in the afternoon, as reported by the horse farm owner (pers. comm. 2001), resulted in the full saturation of the bank material and increased the positive pore water pressure. The increased positive pore water pressure led to decreased cohesion and bank material strength and an increase in bank material weight. Bank failure could thus be expected after the confining pressure of the water disappeared during the receding limb of the flood.

The soil properties of the bank material also play a role in the occurrence of bank erosion and the type of erosion found. The bank material of the Kuils River consists of cohesionless sand material with little clay. According to Thorne (1982) the types of failure found in non-cohesive riverbanks include fluvial entrainment or scour and mass failure. Field observations during the rising limb of the flood on 3 July 2001 revealed that chunks of bank material were eroded from the bare banks at Site 2 due to dislodgement by fluvial scour. Mass failure occurs when large sections of the riverbank collapse into the river at the failure plane. The failure plane is the fracture line where the slump block breaks away from the bank. Plate 6.1 shows a failure plane where a slump block had not yet broken away from the bank. This is evidence of how mass failure occurred in Site 1, where the other slump blocks were removed from the bank. The prolonged rainfall was probably the reason behind the mass failure. The increase in pore water pressure due to the infiltration of rainfall was found to be the reason behind the mass failure in Goodwin Creek, northern Mississippi, USA (Simon *et al.* 2000).

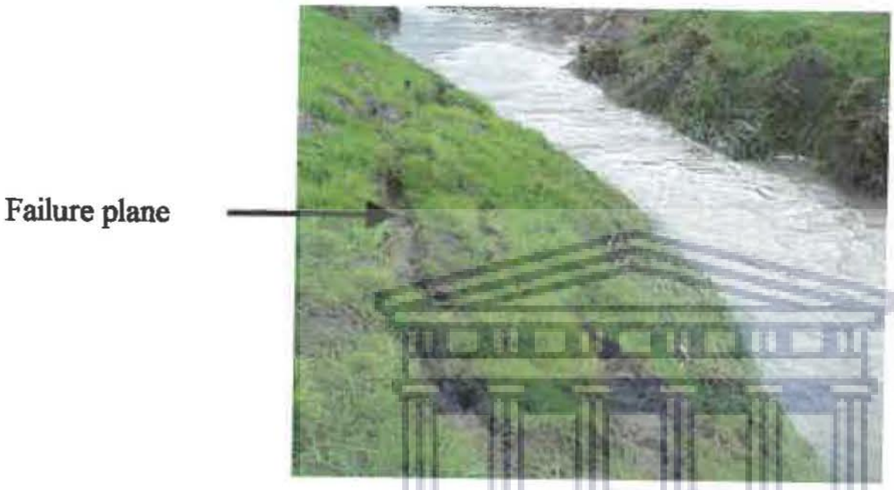

Plate 6.1: Failure plane along which the bank material on the right bank failed. The remaining material was still intact.

The most obvious channel adjustment due to floods is widening, which is often associated with a change in channel pattern, usually from single thread meander to braided channel (Eaton & Lapointe 2001). Deposition can occur along the entire channel or in isolated reaches where sediment supply is higher than the flow transport capacity (Wohl 2000b). The floods in the Kuils River caused extensive channel widening at Sites 1 and 2, with sediment deposited subsequently along the entire length of the channel downstream of the Old Bottelary Road Bridge as shown on Plates 5.4 and 5.5 and Figures 5.10, 5.12 and 5.14. Similarly, the Eel River, California, USA experienced a 1-in-100 year flood during December 1964 (Patrick *et al.* 1982). The flood caused bank erosion and landslides, producing high sediment loads. Channel morphology was altered substantially with the sediment produced by the flood deposited in the channel, causing the riverbed to rise by 1.8 to 2.4 m. Other rivers in northwestern California, USA also experienced infilling along their lengths due to riverbank erosion (Wohl 2000b).

The processes of erosion and deposition, as described above, can also result in cross-sectional changes (Stover and Montgomery 2001). Changes due to erosion and deposition were evident in the cross-sections of Sites 1 and 2 after the July 2001 floods (Plate 5.5 and Figures 5.2 and 5.3) where the banks widened by more than 5m in some cases and the channel bed was raised by almost 1m. Changes in the cross-sections of Site 3 also occurred due to deposition (Figure 5.4 and Plate 5.6). Studies by Stover and Montgomery (2001) showed changes in channel width and bed elevation along the Skokomish River, Washington, USA. The bed of the South Fork Skokomish River incised more than 1m between 1940 and 1964. The mainstream Skokomish channel bed was raised through deposition of about 0.5m between 1934 and 1944 (Stover and Montgomery 2001).

Vegetation increases bank stability directly, with roots and rhizomes binding the soil. Thus, grains that would have been detached will remain bonded to the bank when vegetation is present. Roots also add tensile strength to the soil and distribute stresses through the soil by their elasticity. However, the reinforcement only extends down to the rooting depth of the vegetation, with flow undercutting the root zone below the rooting depth during significant flow events. The rooting depth is a few centimetres for grasses and tens of centimetres for shrubs (Thorne 1990). The type of vegetation is very important since grasses and shrubs are effective at binding the soil at low velocities with their impact decreasing as velocity increases. Bank height is also important, since roots will reinforce the bank against failure if bank height is less than or equal to the rooting depth. Roots will continue to prevent shallow slips and still bind the failure block together during and after collapse, so that the failed blocks are more likely to remain at the toe and protect the intact bank from further erosion. Vegetation density is also important in bank stability. Generally a species with a dense network of fibrous roots is of more benefit than one with a sparse network of woody roots (Richards 1982; Thorne 1990). Grasses have higher densities than do trees, but woody plants have deeper and larger roots, giving wooded banks along large rivers better protection against undercutting (Friedman and Auble 2000). The banks of Sites 1 and 2 were covered by herbaceous plant species (weeds and annual grasses) with shallow root systems (Table 5.15). The shallow root systems did not provide the necessary stability when the banks were saturated after the excessively high and prolonged rainfall, aiding in the bank erosion.

The literature review in Chapter 2 provides a comprehensive description of the impacts of channelisation on channel morphology. The types of channelisation important in this study are straightening and widening. In summary, when a river is straightened the channel path is shortened. This increases the channel gradient, which in turn increases flow velocities in the straightened reach. The erosive capacity of the water is also increased, and can accommodate larger amounts of sediment supplied from upstream reaches. The imbalance in the sediment regime leads to bed erosion or incision of alluvial channels. The increase in channel gradient within the straightened reach initiates erosion in the upstream reaches. The erosion will migrate further upstream in the form of knickpoints (Brookes & Gregory 1988; Simon 1989; Shields *et al.* 1995). The process of upstream migrating erosion was evident in the Kuils River in 2001 (Figure 5.1).

Simon (1989) and Shields *et al.* (1995) described the morphological nature of incising channels in a conceptual model of channel evolution in six stages of channel response to straightening (Section 2.5). Stages one to three were evident in the Kuils River. Plate 5.2 shows the exposed toe material as flows attacked the basal surfaces and removed toe material during moderate flows in Stage three. The later stages were not observed in the study because there was extensive bank erosion after the initial erosion as well as a second round of channelisation during the following summer (Figure 5.1). No bank erosion occurred in the study area during 2002, but bank erosion occurred upstream of the channelised Site 1, undercutting bridge pillars of the Old Bottelary Road bridge (Plate 6.2).

Plate 6.2: Undercutting of the Old Bottelary Road bridge pillars upstream of Site 1 – Photograph taken 02 September 2002.

The Bunyip River in Australia was also straightened in order to drain the Koo-Wee-Rup swamp. This resulted in the upstream migration of a zone of bed incisions along the main river and tributaries, eroding bed and banks and causing roads to collapse (Brizga *et al.* 1999).

Table 2.4 provides a list of case studies with the types of channelisation and the associated morphological changes documented.

The straightening and widening of Site 3 during 2000 resulted in a straight channel (Figure 5.8), and a uniform and wider channel in Sites 1 and 2 during January 2002 as seen on Figures 5.15, 5.16 and 5.17. Straightening resulted in channel incision and bank erosion similar to that of the Rivers Rhine and Meuse, The Netherlands (Admiraal *et al.* 1993) and Whittle Brook, United Kingdom (Nolan and Guthrie 1998). Nolan and Guthrie (1998) also documented a uniform channel after straightening of Whittle Brook, United Kingdom, while Petersen *et al.* (1992) documented the same phenomenon in agricultural areas in Finland, Sweden, Denmark and the USA.

6.2 Ecology: habitat maps

The changes documented in Sections 5.1 and 5.2 and discussed in Section 6.1 had profound effects on the habitats.

The initial Site 1 showed a fairly natural channel with the substrates present representing the geology of the catchment. There was very little variety in the flow types with barely perceptible flow dominating the channel (Table 5.2). The channel was also slightly sinuous. The initial habitats of Site 2 were not natural, as building rubble occurred in the channel (Figure 5.7a). The channel outline was more sinuous than that of Site 1. The channel in Site 3 was the least natural of the three sites since it was channelised the previous year. The channelisation resulted in a straight channel with very little variety in substratum and flow types (Figure 5.8). Artificial habitats in the form of in-channel cement blocks and gabion wires had also been created to support infrastructure crossing the river.

Following the floods, the channel was widened and filled with sand at all three sites as discussed in Section 6.1. Faster flows and a variety of flow types were found in Sites 1 (Figure 5.11) and 3 (Figure 5.14b) after the floods. This was not the case in Site 2, as uniform flow with smooth turbulent boundary flow was the dominant flow type (Figure 5.13 and Table 5.4). The uniform flow type could be explained by the fact that the channel was widened in the January – February 2001 channelisation (discussed later) before the floods occurred. The floods resulted in an even wider channel. Thus, the velocity of the flow was slowed down further within the widened section.

The October – November 2001 channelisation resulted in a straight uniform channel as seen on Figures 5.15-5.17. According to Brookes (1992) widening of a channel results in a decrease in flow velocities due to the enlarged cross-sectional area of the channel and the resulting reduction in stream power per unit bed area. This could probably explain the slower flowing water in Site 1 (Figure 5.15b) and in Site 2 during July 2001 (as discussed above) (Figure 5.13) and during January 2002 (Figure 5.17). The slower flowing and shallow water was probably also responsible for the accumulation of organic matter and algae on the channel bed in Site 1 (Figure 5.15a) and in the latter part of Site 2 (Figure 5.16).

The straightened and widened channel resulting from the October – November 2001 channelisation was not found in Site 2 after the January – February 2001 works. Figure 5.9 shows that the channel was widened, but still fairly narrow relative to that of January 2002. The difference in channel width could be explained by the degree of disturbance of the water's edge during the works. The October – November 2001 works involved the complete disturbance of the water's edge during the construction of the new channel. The water's edge was the least disturbed during the January – February 2001 works. Thus the channel retained more or less the same shape as that before the channelisation. This could also explain why the width of the first nine metres of the site's length remained the same as before the channelisation.

The changes in the habitats of Site 3 were the reversal of those documented for Site 1. Site 1 was more natural and was altered due to the floods and subsequent channelisation. Site 3, on the other hand, was channelised earlier and also changed due to the floods. Then a configuration similar to meandering developed, although true meandering did not develop yet (Prof Kate Rowntree, pers. comm. 2003). Schumm and Khan (1972), Ackers (1982) and Leopold (1982) studied the initiation of meanders. The study of Leopold (1982) is more relevant to explaining what happened in Site 3 than the other two studies.

The flow map (Figure 5.8b) showed no organised flow types during March 2001. Stronger flows (undular standing waves) were found after the July 2001 floods (Figure 5.14b). The strong flows resulted in the development of bedforms that would resist flow (Prof Kate Rowntree, pers. comm. 2003). Not only sand was deposited in the channel during the floods, but chunks of slope clayblock material were also deposited. The slope clayblock material was not visible on Figure 5.14a as the sand covered it. It was visible on Figure 5.18a as the sand was removed by the flow. The presence of the slope clayblock material in the channel would have resulted in the strengthening of the circulation cell on the opposite side of the slope clayblock material. Thus, the super-elevation of the water surface against the opposite bank could have resulted in bank erosion. The presence of the slope clayblock material could thus provide the deformity in the channel bed as pointed out by Knighton (1998) as a necessary precursor to bank erosion. Sand bars also developed, as indicated on Figure 5.30a, and in a similar way as described by Leopold (1982), the surface water was directed away from the sand bar with super-elevation against the opposite bank. Meander bends, developing with the growth of the incipient point bars, migrated in a downstream direction in the East Fork River straight reach (Leopold 1982). True meandering would probably have developed in Site 3 if more floods had occurred (Prof. Kate Rowntree pers. comm. 2003). Plate 5.9 shows the potential meanders in Site 3 during February 2002.

6.3 Ecology: macro-invertebrates

The changes documented in the habitat maps in Sections 5.3 and 6.2 had profound impacts on the macro-invertebrate family assemblages found. This section will provide possible explanations for the changes in the macro-invertebrates documented in Section 5.4. The discussion will follow the sequence as outlined in the key questions posed for the macro-invertebrates in Section 1.3. Firstly, the types of macro-invertebrate families found and what they indicate about water quality followed by a discussion on the general health of the river. Secondly, the relationship between the macro-invertebrate families and the hydraulic biotopes will be discussed, followed by a discussion on the impact of the disturbances on the macro-invertebrate families and their abundances.

According to Gerber and Gabriel (2002) most of the families found (Table 5.8) had a sensitivity ranging from 1 to 5 and were thus highly tolerant to pollution. Four families had sensitivities ranging from 6 to 10 and were thus moderately tolerant to pollution. The families found in the Kuils River were typical of lowland rivers in summer (Davies and Day 1998). They were also similar to those found in the urban areas of the Lourens River, Western Cape (Tharme *et al.* 1997; King *et al.* in press). Urban areas are impacted upon by garden runoff and stormwater flow, with its associated wide range of pollutants (Tharme *et al.* 1997), and by industrial and municipal waste (Shieh *et al.* 1999).

High abundances of Chironomidae (all sites) and Simuliidae (Site 4) were also found (Appendix 2). According to Tharme *et al.* (1997) high numbers of these two families are indicative of poor water quality. Chironomidae thrive in conditions of nutrient enrichment, while the filter feeding Simuliidae populations will increase with increases in suspended organic particles in the water column (Tharme *et al.* 1997). Simuliidae usually occur in faster flowing water where they are attached to the substrate, usually cobbles, with suckers (Thirion *et al.* 1995) to feed on the suspended particles in the water column (Tharme *et al.* 1997). These substrates were rarely available in the Kuils River. Site 4 was the only site that could provide stable substrates, and this would explain the high abundance of Simuliidae in Site 4. Shieh *et al.* (1999) also found high abundances of Oligochaeta, Nematoda, Simuliidae and Chironomidae in urban rivers, while Winter and Duthie (1998) found higher abundances of Oligochaeta and Simuliidae in urban rivers than in rural rivers.

The South African Scoring System (SASS) was developed as a rapid bioassessment tool where macro-invertebrates are used to assess the degree of impairment of water quality and general ecosystem health (Tharme *et al.* 1997). According to Table 2.2 the water quality and general health of the river at all the sites (Table 5.9 and Appendix 3) were severely impaired with major deterioration in water quality. This study shows that the water quality and general health of the Kuils River are even worst than other urban rivers in the Western Cape (Table 2.1).

SASS scores and ASPTs are not only dependent on water quality, but also on the availability of habitats in the sites sampled (Thirion *et al.* 1995). According to Wydoski and Wick (2000), habitats in aquatic ecosystems are limited. The most important factors in the distribution of macro-invertebrates are water velocity and substrate size. Habitats in riffles with large cobble substrates produce a higher diversity of species and generally larger numbers of organisms than river reaches composed of sand and silt (Wydoski and Wick 2000). Urban rivers in the Western Cape are not only impaired by water quality problems, but also by the limitation in habitats since most of them are canalised (Brown 1992).

When comparing Site 4 with the canalised section of the Liesbeeck River (Table 2.1; Davies and Day 1998) it can be seen that the total SASS score for the Liesbeeck River was higher, but the number of taxa and ASPTs were similar in the two cases. The Kuils River as a whole has limited available habitats since it is a sand bed river. Sand bed rivers are not very hospitable environments due to shifting substrate and siltation (Junk *et al.* 1989) and due to the grinding effect of moving sand (Davies and Day 1998). Very few organisms can therefore survive in these conditions.

Whether there was any relationship between the community composition and habitats available was also one of the key questions asked at the start of the study. Site 1 was the only site that showed a correlation between macro-invertebrate community composition and habitats sampled. Two groups of habitats and corresponding macro-invertebrates were identified. Group 1 consisted of macro-invertebrates adapted to life in vegetation (although many of these animals can live in sand and rocky substrates too) such as snails (Physidae and Lymnaeidae), dragonflies (Gomphidae), damselflies (Coenogrionidae), beetles or water bugs (Dytiscidae) and mayflies (Baetidae). Some of the macro-invertebrates, for example the predators, Gomphidae, Coenogrionidae, Aeshnidae and Libelullidae (Vannote *et al.* 1980) can hide in vegetation to catch their prey. The vegetation also provided shelter from the predators to the other animals found there. Group 2 consisted of those invertebrates typically adapted to life in sand, for example worms (Naididae) and wormlike animals (Chironomidae) since they are collectors or deposit feeders which gather organic matter from the substratum (Vannote *et al.* 1980). The other sites showed no clear correlation between community composition and habitats, and the groups that formed on the basis of the similarity between the animals (Figures 5.19-5.22). There was also no distinct difference between the sites since many of the sites grouped together (Figure 5.23). This could be explained by the fact that the sites had similar animals (Table 5.8) and that all the sites were in the same geomorphological zone (Figure 3.1).

According to Davies and Day (1998) semi-submerged bankside vegetation (marginal) is the main refuge for aquatic animals where both the predator and prey find shelter in sand bed rivers. This was an example in this study where a higher number of families were found in the vegetation. The snails (Physidae and Lymnaeidae), referred to as scrapers or grazers (Vannote *et al.* 1980; Davies and Day 1998), shear ("cut") attached algae from surfaces. This could explain their presence in all the habitats that had algae.

It was also that biodiversity would decrease in a downstream direction with Site 4 having the lowest diversity and Site 1 the highest. This was not the case. Sites 1 and 4 had almost the same number of families (seven and five respectively) in 2001. Sites 2 and 3 had the highest diversity, with 11 and 14 families respectively in 2001 (Table 5.8 and Appendix 2). The higher diversity in sites 2 and 3 could be attributed to the higher biotope diversity (Table 4.4).

The biodiversity in 2002 was influenced by two disturbances in the study area during 2001. The first disturbance in the study area was the July 2001 floods that resulted in the infilling of the channel with sediment in all the sites. The second disturbance occurred during October - November 2001 when Sites 1 and 2 were channelised. According to Wydoski and Wick (2000), such catastrophic events can adversely affect aquatic organisms. Shieh *et al.* (1999) found that changes in physical habitats were the most important factor affecting the macroinvertebrate assemblages in their study. Thus, these two disturbances could have been responsible for the loss in biotope availability and variability in Sites 1 to 3 (Table 4.4) during 2002. This could also explain the decrease in the number of families in these sites during 2002. The sedimentation of the channel in Site 3 after the floods could be responsible for the decrease in available habitats and consequent decrease in community composition in 2002. Alternatively, the decrease in community composition might be related to the fact that the samples were taken too soon after the disturbances, when suitable habitats were not available yet and the invertebrates had not colonised. This could also explain why no animals were found in the sand in smooth boundary turbulent flow biotope in Site 3 in 2002 and why they were not listed in Table 4.4.

The channelisation in the Kuils River during October – November 2001 involved the bulldozing of the riverbed. Such activities lead to the reduction in hydraulic biotope heterogeneity available to aquatic organisms (King and Schael 2001). A reduction in hydraulic biotopes was clearly evident in Site 1 where the number of available habitats decreased from seven in 2001 to only two in 2002 (Table 4.4). Ebrahimnezhad and Harper (1997), Gore and Shields (1995), Harberg *et al.* (1994), Harvey and Watson (1986), Pearce (1993) (Table 2.5) also recorded reduction in aquatic habitats due to channelisation. The reduction in habitats may lead to a decrease in species diversity (Petersen *et al.* 1992; Admiraal *et al.* 1993; Downs and Thorne 1998). Reductions in the community composition were recorded in Sites 1 to 3 in 2002 (Table 5.8). Such a loss in biotope availability and variability due to channelisation and the subsequent reduction in species diversity also occurred in the Danube River, Austria (Tockner *et al.* 1998), rivers in agricultural areas in Finland, Sweden, Denmark and the USA (Petersen *et al.* 1992), Rivers Rhine and Meuse, The Netherlands (Admiraal *et al.* 1993) and the Kissimmee River, USA (Koebel 1995).

The macro-invertebrates of Site 4 responded differently to expected. It was expected that this site would support the least or no life because it was a concrete canal. Concrete canals are usually severely impaired in their ability to support life (Luger 1998). The concrete lining of their beds and banks eliminates all riparian, marginal and rooted aquatic biotopes for plants, with the sole remaining plant life being possibly a film of algae on the concrete. The concrete beds also lose all physical heterogeneity, and thus provide no substrata, food or refugia for aquatic animals (Brown 1992; Luger 1998). The opposite happened in Site 4 as it supported more or less the same number of families as in Site 1 in 2001, and was the only site where there was an increase in the number of families in 2002 (Table 5.8). Drift is a process where macro-invertebrates re-colonize disturbed areas by drifting from upstream reaches (Gore 1985; Davies *et al.* 1993). The drift process could explain the higher abundance and number of families in Site 4 in 2002. Site 4 is not a particularly suitable environment, but it could have received invertebrates drifting from disturbed areas upstream. Drift could also explain the presence of Athericidae in Site 4 in 2002, which usually occur in mountain streams (Gerber and Gabriel 2002).

6.4 Ecology: vegetation

The aim of the vegetation section was to give a description of the plant species found in the study area, and the assemblages that they formed, and to relate the changes to the winter floods and channelisation. Thus, this section will firstly cover the types of plant species found and give possible explanations to why they occurred in the study area. Secondly, the changes in the plant assemblages will be related to the floods and channelisation.

The Kuils River catchment is extensively urbanised and the natural vegetation was replaced with alien plant species (Ninham Shand and Chittenden Nicks 1999). Most of the species found in the study area consisted of alien and indigenous weeds. Many weed species are introduced through agriculture and early settlement with no natural predators to keep them within bounds. Weeds also reproduce rapidly due to their ability to produce large quantities of seeds (Grime 1979; Lamp and Collett 1983). Weeds are also found in urbanised catchments where there is an endless supply of weed species (Moses and Morris 1998). Thus, the presence of alien weeds in all the sites during both sampling periods was not unusual since the catchment itself is extensively disturbed. The species found in this study during both sampling periods are similar to those found in arable soils. The plant species found in this study are similar to those found in the study by Regnier (1994) and Roberts (1981)

In 2001, the plant assemblages found in Sites 1 and 2 were influenced by the plants present in the catchment, as outlined above. The plant assemblages of Site 3 in 2001 were influenced by the channelisation prior to the onset of the study period. The channelisation involved bulldozing the channel to create a new channel, and the complete removal of the vegetation. *Pennisetum clandestinum* was planted on the slopes and created floodplain areas to stabilise the newly created channel. The channelisation can be classified as a disturbance event according to Grime 1979 and Grubb 1988. Usually, the soil is left bare after a disturbance, with germination taking place soon afterwards. Species should germinate immediately after the disturbance otherwise little chance is left for establishment (Grubb 1988). The soil was not left bare after the channelisation in this study because the banks and channel floor were planted with *Pennisetum clandestinum*. Little opportunity was thus available for other plants to establish amongst the *Pennisetum clandestinum*. Other plants could only establish if there was a gap or opening to do so. This could explain why the plant assemblages did not occur on specific positions along vegetation transect 3.3 in 2001 (Figure 5.30).

The plant assemblages found in Site 4 did not change much between the two sampling periods and the groups tended to occupy similar positions along the cross-section in both years. There is a stormwater outlet on the left bank The readily available moisture could explain why the is more vegetation on the left bank.

In 2002, the plant assemblages of Sites 1 and 2 were influenced by the July 2001 floods and consequent channelisation during October – November 2001. The floods removed not only the vegetation, but also the sediment containing seeds. Concerning the vegetation, the channelisation of Sites 1 and 2 in 2001 was different to the channelisation of Site 3 in 2000. The difference was that *Pennisetum clandestinum* was planted in the newly created channel of Site 3, while the banks were left bare with only a thin strip of *P. clandestinum* planted along the water's edge in Sites 1 and 2. The channelisation of Sites 1 and 2 in 2001 involved taking sediment deposited in the channel, which originated from the collapsed banks, to fill in the banks. The soil was disturbed during the construction phase, unearthing seeds in the seed bank, bringing them closer to the soil surface and exposing them to light. The banks remained bare until January (normally the driest time of the year) 2002 when the Western Cape received unexpected rainfall. The moisture input and readily available seeds beneath the soil surface resulted in the rapid germination of annual alien weeds. Different plant species were found in 2002, resulting in the presence of the different groups identified as seen in Figures

5.24 and 5.26. The plants that were established in Sites 1 and 2 in 2002 usually invade riverbanks, roadsides and are frequent in disturbed soils (Bond and Goldblatt 1984; Bromilow 1995; Levyns 1966; Goldblatt and Manning 2000; Henderson 2001).

There were not many studies on the impacts of channelisation on vegetation patterns (Section 2.5). Thus, it is difficult to compare the findings of the present study with similar studies done elsewhere. However, Friedman and Auble (2000) reported that channel narrowing along the South Platte River, USA resulted in the establishment of indigenous and introduced woody bottomland pioneer species on the former channel bed. The opposite happened in the present study, since the channel of Sites 1 and 2 was widened. The widening and complete restructuring of the channel resulted in the absence of vegetation on the channel bed as seen on vegetation transects 1.2 and 2.2 in 2002 (Figures 5.25 and 5.26 respectively).

The sediment containing the seeds that originated from the collapsed banks of Sites 1 and 2, upstream of Site 1 and between Sites 1 and 2 was deposited on the floodplain areas of Site 3 as shown on Plate 5.6 and on Figure 5.4. The existing vegetation was completely buried beneath the sediment. The deposited sediment also remained bare until the January 2002 rains as already described. The moisture input and readily available seed within the deposited sediment resulted in the rapid germination of different plant species on the floodplain areas. Thus, the floods acted as transport mechanisms distributing plant propagules (Friedman and Auble 2000). The plant species found in 2002, even if different to those found in 2001, were found within the catchment. Similar events as described for Site 3 occurred in the Lourens River, Western Cape, South Africa. The July 2001 floods also caused bank erosion and sediment deposition on floodplain areas and resulted in the establishment of herbaceous weeds after the January 2002 rains (King *et al.* in prep.). Timoney *et al.* (1997) also found that flooding and sediment deposition appeared to be the primary process for forest origin in the Peace River valley, Canada.

6.5 Conclusions and recommendations

The following conclusions can be drawn from the study. The results from the cross-sectional data showed that the beginning of the study period Site 1 had a relatively narrow active channel within a bigger macro channel. The channel was wider at Site 2 than in Site 1, but also had an active channel within a macro channel. Site 3 was channelised in 2000 and had a wide trapezoidal channel with a central low flow channel. Site 4 was canalised and also had a trapezoidal shaped channel. The Kuils River channel consisted of sand as the main substratum type in all three mapped sites.

The flow was typical of summer low-flow periods with smooth boundary turbulent flow dominating. The macro-invertebrate and vegetation data showed that the Kuils River is a severely impaired and extensively disturbed urban river with only hardy macro-invertebrate families and cosmopolitan weed plant species present.

The Western Cape received exceptionally high winter rains in 2001. The winter floods were accompanied by an upstream migration of bank erosion between Sites 1 and 2 during May 2001. This was followed by massive bank collapse downstream of the Old Bottelary Road bridge during July 2001. Sediment was deposited at the sites where the bank erosion occurred and at downstream reaches. Sites 3 and 4 remained stable with no bank erosion, but sediment deposition also occurred. Channel width also increased in Sites 1 and 2 due to the floods. The upstream migration of bank erosion and massive bank collapse could be attributed to both the winter floods and downstream channelisation. The river section upstream of Site 2 and downstream of the Old Bottelary Road bridge was channelised during October and November 2001. These emergency channelisation works were undertaken to replace the horse farm owner's land adjacent to Site 1 and to increase the channel capacity to carry similar or larger magnitude flows than those of July 2001. These reaches remained stable with no bank erosion during the winter of 2002. Bank erosion was observed upstream of these reaches, with undercutting of the Old Bottelary Road bridge pillars.

The channelisation of Sites 1 and 2 resulted in a wider, uniformly straight trapezoidal channel with reduced substratum and flow variability. This reduced the available hydraulic biotopes, which resulted in the reduction of the number of macro-invertebrate families found in 2002. Site 3 also had lower numbers of macro-invertebrate families in 2002. This could be attributed to the reduced hydraulic biotopes following the sediment deposition during the floods. Another possible reason for the decrease in family numbers could be that the samples were taken too soon after the channel was disturbed and as such was not fully adjusted. Site 4 had higher macro-invertebrate family numbers in 2002 compared to 2001. The increase was attributed to the downstream drift of the invertebrate families and the fact that Site 4 was the only site that provided some stability after the disturbances of the upstream sites. The October – November 2001 channelisation involved disturbances of the soil, which resulted in the establishment of different, but still cosmopolitan weedy, plant species in Sites 1 and 2. The sediment deposited on the floodplain areas of Site 3 contained seeds from upstream reaches. This would explain the establishment of different plant species with some of them similar to those of Sites 1 and 2 on the floodplain areas in 2002.

The impacts of channelisation on the Kuils River can thus be summarised as follows:

Impacts on geomorphology

- Channel widening and straightening resulted in a uniform channel shape.
- This reduced substratum and flow diversity.
- Channelisation was followed by an upstream migration of bank erosion, which in turn, was followed by massive bank collapse during the following wet season.

Impacts on ecology

- The uniform channel shape and reduced substratum and flow diversities resulted in a reduced diversity of aquatic habitats.
- This correlated with a reduced diversity of aquatic invertebrates.
- Channelisation and bank re-construction disturbed the soil and the vegetation.
- This resulted in a higher diversity of plant species the following year, most of which were alien weeds.

Impacts on infrastructure

- Following channelisation, the upstream progression of bank erosion eventually led to undercutting of the Old Bottelary Road bridge pillars.

In light of the events and impacts of the channelisation outlined above, the following recommendations are made. Most of these were made with the help of the WRC project advisors. The recommendations should serve the purposes of potential river rehabilitation activities of the October – November 2001 channelised reaches. King *et al* (in press.) covered the different river rehabilitation concepts available. According to these authors, river rehabilitation refers to the partial return towards a pre-disturbance condition. Rehabilitation would not be possible for the Kuils River since the catchment has been disturbed extensively. Thus, a better term to use would be "remediation or enhancement" (King *et al.* (in press.). The public needs to be aware of the river in order for remediation to work; thus the first step is to increase public awareness of the river as part of an urban green space. Other methods can then be used to increase the biodiversity of the ecosystem. They are summarised as follows:

Increase public awareness:

- Landscape the area to attract people to the river;
- Have 'soft walls' in the form of trees or taller shrubs to block sound and vision from roads and houses;
- Have a path close to the river where people can walk;
- Plant *Pennisetum clandestinum* (Kikuyu) in places where people would like to sit.

Increase biodiversity:

- Demarcate a zone around the river where no development is to take place;
- Reshape the channel the way Site 3 was designed, to both accommodate higher flows and to allow the river to meander within a bigger floodplain area. Make sure the monotony of the banks is addressed. For example have steeper, terraced or low banks in some places;
- Re-vegetate the banks with indigenous plants. Plant sedges around the wet bank area. The vegetation will also help to stabilise the banks and attract birds and insects;
- Install wetlands in the channel to improve the water quality. The wetlands will also serve to attenuate floods where stormwater can be discharged in. Ponds and weirs can also be installed to slow down the flow.

The recommendations made above could help the City of Cape Town to manage the river better. They would also help with possible remediation of other urban rivers in the Western Cape where similar activities occurred. Continual monitoring is also very important since the long-term effects of the channelisation need to be established. Long-term monitoring will also serve an academic need in order to understand how the river will respond to channelisation if further channelisation is planned.

The study only covered certain aspects of geomorphology and ecology, as indicated in the key questions posed (Section 1.3). There is tremendous scope to study other aspects also. For example, study the long-term changes in channel outlines and substrates and relate them to discharge. The macro-invertebrates could also be related to the chemical and physical water quality parameters or to the seasonal variations. The vegetation data could be related to the soil properties and slope aspect. Again, long-term monitoring of the different aspects would be crucial in understanding ecosystem functioning.

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Appendix 1: Steps in the analysis of macro-invertebrate data

Step 1: Enter macro-invertebrate data into Excel as in Appendix 1. Leave the first row open. Only family names, sample codes and abundances are entered. No additional data are needed.

Step 2: In PRIMER V5: File-Open-Select Excel files-select the created file-Open. Make sure that the correct worksheet is selected. Tick Sample data, include title and row labels. Give the new file a title-OK. New PRIMER file is created with the given title.

Step 3: Data-Similarity. Tick analyse between samples, Bray-Curtis similarity measure, transform to Presence/Absence, standardise-OK. Similarity matrix is created.

Step 4: To create dendrogram-Analyse-Select group average for cluster mode. Tick plot dendrogram-OK. Dendrogram is created. The orientation of the dendrogram can be changed by selecting Graph-Properties-Change orientation to Horizontal. Save created file as type Windows metafile (*.wmf) -Close file and accompanying results.

Step 5: To create MDS plot-Analyse-MDS. Tick plot graph-OK. MDS plot is created. Save as for Dendrogram in Step 4. No need to change the orientation of the graph-Close file. The results file underneath MDS plot will provide information of the stress factors-Note Best 2-D configuration (stress given between brackets). Close file.

Labels can be created for the sample codes in the PRIMER spreadsheet created as in Step 2. To do that-Edit-Labels-Samples. A box will open with the different sample codes. Double-click on the sample code to add a label. E.g. 9/RS to represent the hydraulic biotope and flow type. Add labels for all the sample codes-OK. Can use the new PRIMER sheet for the creation of the Dendrogram as in Steps 1 to 4. Not advised for MDS plot.

PRIMER V5 produces the Dendrogram and MDS plot. The graphs were modified, i.e. line thicknesses changed in CorelDraw V8. The lines to separate the groups in the dendrogram and the circles in the MDS plot to delineate the different groups were added in CorelDraw V8.

In CorelDraw V8: Open new graphic. New file is created with a page to work on. The page size can be changed as preferred. File-Import-Choose files of type Windows metafile – will look like a balloon-Select your created file-Import – The name of the file to be imported will appear-Click only once anywhere on the page. You'll have to Zoom out until you can see the Dendrogram or MDS plot. Choose Ungroup all to separate the Dendrogram or MDS plot from the back page and titles. Delete the back page. Now you can edit the graphs by increasing the line thickness, changing the font types and sizes and inserting new lines or text.

Appendix 2 **Macro-invertebrate abundance ratings for Sites 1 to 4.** (Table 4.4 for Hydraulic biotope number and 4.6 for ratings.) Where S1-1-01 refers to Site (S1), sample number (1) and year (01).

Sample code	S1-1-01	S1-2-01	S1-3-01	S1-4-01	S1-5-01	S2-1-01	S2-2-01	S2-3-01	S2-5a-01	S2-5b-01	S2-6-01	S2-7-01	S2-8-01	S2-9-01	S2-10-01	S3-1-01	S3-2-01	S3-S3a-01	S3-3b-01	S3-4-01	S3-5-01	S3-6-01	S3-7-01	S3-8-01	S3-9-01	S4-1-01	S4-2-01	S4-3-01	S4-4-01	S4-5-01
Habitat	6/SM	20/RS	10/RS	8/BF	12/BF	1/SM	8/BF	8/SM	1/BF	1/BF	21/SM	11/NF	1/SM	8/BF	14/SM	11/BF	9/BF	11/NF	1/SM	2/SM	18/SM	15/SM	1/SM	14/SM	9/SM	24/SM	27/BF	26/SM	23/SM	28/SM
Sample size (m)	0.8x0.6	1.4x0.4	3x0.4	1.6x0.3	3x1	1.5x0.4	2.5x1.4	2.3x0.3	Core	Core	2.7x1	2.3x1	Core	1.6x0.7	1.5x0.5	1x0.5	1.2x0.5	2x1	Core	0.5x0.5	0.5x0.2	1.5x0.5	Core	1.5x0.5	2.7x0.5	1.5x0.5	1.5x0.6	1.3x0.4	2x0.2	
Hirudinae	2	0	1	0	0	2	0	2	0	0	0	2	2	0	0	0	0	0	4	4	1	1	1	0	1	0	0	3	0	0
Naididae	0	0	0	0	0	1	0	1	0	0	0	0	0	0	0	2	1	0	0	4	0	0	0	1	0	0	0	0	0	0
Coenogrionidae	0	0	0	3	2	1	1	4	0	0	1	2	0	2	0	0	2	0	0	0	0	0	0	0	2	0	0	0	0	0
Gomphidae	0	0	0	4	2	0	3	2	0	0	0	2	0	1	0	2	4	0	0	0	0	0	0	0	2	2	3	1	1	0
Aeshnidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Libellulidae	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Baetidae	0	0	0	2	2	0	0	0	0	0	0	2	0	1	0	1	5	2	0	0	2	0	0	1	2	0	1	0	2	0
Corixidae	0	0	0	0	0	0	0	0	0	0	2	4	0	2	0	3	0	4	0	4	1	2	0	0	2	0	0	0	0	0
Veliidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0
Gerridae	0	0	0	0	0	0	1	0	0	0	0	0	0	1	0	0	3	0	0	0	0	0	0	1	0	0	0	0	0	0
Gyrinidae	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Dytiscidae	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Simuliidae	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	3	5	4	3	5	5	3
Chironomidae	0	4	4	0	4	4	4	3	0	0	3	4	0	4	4	0	2	0	0	2	3	0	0	0	5	5	3	5	5	3
Culicidae	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
Lymnaeidae	0	0	0	1	0	0	0	3	0	1	0	2	0	0	2	2	0	0	0	2	2	0	0	2	2	0	0	0	0	0
Physidae	0	0	0	2	3	3	0	2	3	2	3	2	0	3	4	3	3	3	2	2	1	3	0	2	3	2	2	0	0	0

Sample code	S1-1-02	S1-2-02	S2-1-02	S2-2-02	S2-3-02	S2-4-02	S2-5-02	S2-6-02	S2-7-02	S3-1-02	S3-2-02	S3-3-02	S3-4-02	S3-5-02	S3-6-02	S4-1-02	S4-2-02	S4-3-02	S4-4-02	S4-5-02
Habitat	9/BF	4/SM	3/SM	4/SM	5/SM	1/SM	9/BF	3/SM	3/BF	9/BF	17/SM	2/BF	7/BF	19/RS	26/SM	26/BF	27/SM	25/SM	28/SM	25/SM
Sample size (m)	1X0.5	Core	0.5x0.5	2x0.5	0.5x0.5	Core	1x0.5	Core	Core	1.5x0.5	1.5x0.3	Core	2.5x0.6	1.5x0.4	1x0.2	1.4x0.4	2x0.2	1x0.2		0.8x0.2
Hirudinae	0	0	5	0	5	4	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Naididae	2	3	4	4	3	0	0	3	4	2	2	0	2	2	2	2	4	3	3	2
Coenogrionidae	2	0	2	0	1	0	3	0	0	2	0	0	0	0	1	0	2	0	0	0
Gomphidae	0	0	2	0	1	0	0	0	0	0	0	1	2	0	0	0	0	0	0	0
Pleidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Naucoridae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
Baetidae	0	0	0	0	0	0	3	0	0	3	0	0	4	0	0	0	3	0	0	2
Corixidae	0	0	0	0	0	0	0	0	0	1	0	0	2	0	0	0	0	0	0	0
Veliidae	1	0	0	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0
Gerridae	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0
Dytiscidae	3	0	2	0	1	0	0	0	0	3	2	0	3	0	0	3	0	0	0	0
Simuliidae	0	0	0	2	0	0	0	0	0	0	2	0	0	2	2	0	2	0	2	0
Chironomidae	0	2	5	4	3	0	3	0	0	4	4	1	3	5	4	4	5	4	4	4
Athericidae	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	0	0	0
Lymnaeidae	0	0	0	0	0	0	2	0	0	3	0	0	0	0	0	0	2	0	0	0
Physidae	5	1	4	3	3	0	3	2	2	2	2	3	4	4	3	4	3	2	1	4

Appendix 3: SASS4-type scores, number of taxa and ASPT per sample. Where S1-1-01 = Site number-sample number-year

Sample code	SASS score	No. of taxa	ASPT
S1-1-01	1	1	1.00
S1-2-01	2	1	2.00
S1-3-01	3	2	1.50
S1-4-01	20	5	4.00
S1-5-01	19	5	3.80
S2-1-01	13	5	2.60
S2-2-01	27	6	4.50
S2-3-01	26	8	3.25
S2-5a-01	1	1	1.00
S2-5b-01	6	2	3.00
S2-6-01	12	4	3.00
S2-7-01	31	9	3.44
S2-8-01	1	1	1.00
S2-9-01	28	8	3.50
S2-10-01	8	3	2.67
S3-1-01	22	6	3.67
S3-2-01	41	10	4.10
S3-3a-01	10	3	3.33
S3-3b-01	4	2	2.00
S3-4-01	15	6	2.50
S3-5-01	16	6	2.67
S3-6-01	7	3	2.33
S3-7-01	1	1	1.00
S3-8-01	23	6	3.83
S3-9-01	33	9	3.67
S4-1-01	16	4	4.00
S4-2-01	20	5	4.00
S4-3-01	14	4	3.50
S4-4-01	17	4	4.25
S4-5-01	7	2	3.50
S1-1-02	18	5	3.60
S1-2-02	6	3	2.00
S2-1-02	24	7	3.43
S2-2-02	11	4	2.75
S2-3-02	24	7	3.43
S2-4-02	1	1	1.00
S2-5-02	21	6	3.50
S2-6-02	4	2	2.00
S2-7-02	4	2	2.00
S3-1-02	30	9	3.30
S3-2-02	16	5	3.20
S3-3-02	11	3	3.67
S3-4-02	24	7	3.43
S3-5-02	11	4	2.75
S3-6-02	15	5	3.00
S4-1-02	6	3	2.00
S4-2-02	46	11	4.18
S4-3-02	6	3	2.00
S4-4-02	11	4	2.75
S4-5-02	10	4	2.50

Appendix 4a: Percentage cover of plant species data of transect 1.1 for 2001. All species are herbs.

	Right bank														Wet Channel				Left bank											
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	N	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Bromus diandrus	20	15	8	5	2	5	5															2	2	30	35	30	2	20	25	8
Echium plantagineum	5	2																												
Fennisetum clandestinum	5					5	2	2	25	55	95	95	60	50	10		5	20	98	99	99	96	70	15	10	5	5	10	10	2
Cleome monophylla				2	2																									
Lolium temulentum				5	10		5	2	5	5												2								
Cynodon dactylon								5																						
Polygonum aviculare													40	50	30															

Appendix 4b: Percentage cover of plant species data of transect 1.2 for 2001. All species are herbs.

	Right bank											Wet Channel		Left bank										
Group number	2	2	2	5	2	2	3	3	3	6	6	6	3	3	3	3	3	3	2	2	2	2	2	2
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Pennisetum clandestinum	5	5	2	5	2	20	80	99	41				40	50	70	50	99	50	15	10	5	20	20	10
Bromus diandrus		10	15	5	40	10														30	30	40	10	30
Chenopodium album									2															
Cyperus species									2	30	20	5												
Polygonum aviculare									20	10	10													
Isolepis fluitans										30	55	55												
Xanthium strumarium											5													
Cyperus longus												40	10	50	30	50								

Appendix 4c: Percentage cover of plant species data of transect 1.3 for 2001. All species are herbs.

	Right bank										Wet Channel				Left bank								
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Bromus diandrus	40	33	60	30	10		2												5	10	20		15
Pennisetum clandestinum	5	2	5	10	5	15	73	65	50	45	20	5	15	55	49	63	85	20	15	10	5	10	10
Polygonum aviculare										15	30	10			2								
Xanthium strumarium										15	30	5											
Cyperus longus														5									
Chenopodium album															2								
Echium plantagineum															2	2							

Appendix 5a: Percentage cover of plant species data of transect 2.2 for 2001. All species are herbs except for *Acacia saligna* that is a tree. BG = Bare ground

	Left bank																									Wet Channel			Right bank											
Group number	4	4	4	4	4	4	4	4	1	1	1	1	1	1	1	1	1	1	1	1	1	1	BG	5	3	3	3	3	3	3	3	3	3	3	3	BG	3	1	4	4
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
Cynodon dactylon	3	10	2	3	10	5	1	2																															10	10
Carpobrotus edulis									2	10	1				5	2	3																							
Bromus diandrus											3	30	40			25	1		5		3				10	5												30	10	
Pennisetum clandestinum												2				1	1		2	5	5	2			15	25	50	40	60	60	65	40	75	63	30		30	25		
Lolium temulentum													5	5	5	5	5	5	10	5	10	5																		
Cleome monophylla															5						2																			
Salsola kali																4																								
Chenopodium album																		5		30	20																			
Erucastrum strigosum																		11																						
Avena fatua																			5																					
Acacia saligna																								10	15	10														5
Polygonum aviculare																									5		15	90	10	20	30	15	15	15						
Sonchus oleraceus																												10												
Typha species																													10	5										
Xanthium strumarium																															5	5	10	20						
Carpha glomerata																																5								

Appendix 5b: Percentage cover of plant species data of transect 2.3 for 2001. All species are herbs except for *Acacia saligna* that is a tree. BG = Bare ground; R = Removed from analysis; N = No vegetation; sl = seedling

	Left bank																										Wet Channel			Right bank															
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Chenopodium album	5	5													5				2		6		20	5																			1		1
Xanthium strumarium	1	10															5	3	5	10	20	10								15													2		5
Cynodon dactylon		5	5		3	8				3		3					2				10	1													5				2		5		1		10
Bromus diandrus			10										10	15		1	2	3																		2	10	5		5	5	30	2	20	10
Acacia saligna (sl)					2																	1																							
Pennisetum clandestinum						2						3	4		1	3		2	5	12				3													2	2		5				3	
Citrullus lanatus							15	38	45																																				
Echium plantagineum										2	2		40	8	3	1	3	60	2																			5	10	40	20		5	2	
Avena fatua												2	1					2	2																										
Conicosia pugioniformi													1	2																															
Lolium temulentum													10	20	15	5	5			3																		10				20	5		
Carpobrotus edulis																1	3				3	3																							
Salsola kali																5	5		5	6		5																							
Polygonum aviculare																				4	1	5	25	25	15	25				5	5	2	2				5	10							
Conyza canadensis																							5																						
Helichrysum cochleariforme																							5																						
Polygonum species																							15																						
Chenopodium species																								10																					
Cyperus longus																								2						5															
Isolepis fluitans																								25		25	10		40	15	5	10	40	50	5										
Carpha glomerata																									5	10			5			10	15	15											
Carex glomerabilis																															5				5										
Acacia saligna																																				3	5	5							
Erucastrum strigosum																																							5						

Appendix 6a: Percentage cover of plant species data of transect 2.4 for 2001. All species are herbs except for *Acacia saligna* that is a tree. N = No vegetation; sl = seedling

	Left bank																							Wet			Right bank																		
	Slopes													Floodplain										Channel			Floodplain										Slopes								
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	N	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Acacia saligna (sl)	2																																												
Cynodon dactylon	5		15	10		3	10				5	5																										10	15	5		5	65	90	75
Lolium temulentum	5																																												
Medicago polymorpha	5		2							2				10	10	10	25	30	38	20	20	4				15	55	40	40	65	60	10	80	75	80	70	5								
Pennisetum clandestinum	20	35	48	15	45	30	10	30	45	48	30	20	15	30	60	70	65	50	40	64	60	87	95	25		20	40	59	55	33	33	87	15	20	18	28	72	15	5	12	25	57	15	10	20
Tribulus terrestris	10		2																																										
Acacia saligna			3																																										
Ehrharta villosa								5																																					
Carpha glomerata																			10		3	3				10		1																	
Polygonum species																				1	2																								
Brachiaria serrata																								15		10																			
Cyperus species																																	5	5		2	5		5	5					
Portulaca oleracea																																											5		

Appendix 6b: Percentage cover of plant species data of transect 3.3 for 2001. All species are herbs except for *Acacia saligna* that is a tree. BG = Bare ground; sl = seedling

	Left bank																							Wet Channel			Right bank																			
	Slopes												Floodplain														Floodplain										Slopes									
Group number	4	4	3	3	3	3	2	BG	4	2	3	3	3	3	3	3	3	4	3	3	3	3	4	4	2	3	3	3	3	3	3	2	2	2	2	2	3	3	2	BG	BG	4	2	2	3	2
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46
Acacia saligna (sl)	5	5	3		5	10	10		2	5			2		2	2													1			2					2	3	10					3	2	5
Chenopodium album	2	2																																												
Euphorbia peplus	2																																													
Pennisetum clandestinum	5	4	53	80	60	43	10		5	25	75	60	70	39	70	70	40	30	50	60	63	54	20	7	20	40	68	65	80	78	70	25	25	20	20	15	43	70	20			10	13	17	40	5
Portulaca oleracea	2											5																																		
Tribulus terrestris	2	2																																												
Cynodon dactylon			2	5	5	5	5		3	5	5	20	8	30	10		10					3	5					5	10	10	10	20	25	20	20	15	10	7	2							15
Medicago polymorpha				3		3							10	10	10	10	35	60	40	30	25	10	55	2			20	15	2																	
Polygonum aviculare				3	2																																					10				
Chenopodium multifidum					3		5																																							
Conyza canadensis						2																																								
Cyperus longus						2										3	3		5			2	5	2	5	15				5	2												2	2	5	2
Taraxacum officinale												2						2																												
Xanthium strumarium														1																																
Rumex species																				5	2	2								2																
Brachiaria serrata																						2	5					3																		
Lolium temulentum																						5									5						5									
Isolepis fluitans																								2			2																			
Polygonum species																								2																						
Eragrostis species																																							1							

Appendix 6c: Percentage cover of plant species data of transect 3.5 for 2001. All species are herbs except for *Acacia saligna* that is a tree. sl = seedling

	Left bank																		Wet						Right bank																	
	Slopes									Floodplain									Channel						Floodplain									Slopes								
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Acacia saligna (sl)	1		2	2	2												2	2													2						5	2	2	2		5
Chenopodium multifidum	3						3				2																											3				
Pennisetum clandestinum	73	57	25	56	58	40	20	55	55	20	33	40	35	35	30	35	28	40	53	30	35	20	45	40	50	42	57	60	15	10	61	70	65	74	80	63	35	60	63	40	70	5
Cynodon dactylon		5		5														5									15	15								10	10	15	10	10		
Polygonum aviculare		10	2																											5												
Tribulus terrestris		3																																	3				5	8		
Brachiaria serrata				5	10												10	5	5	5	2		5	40	15																	
Lolium temulentum				2																														5								
Polygonum species						2																				3	3															
Medicago polymorpha									20	65	60	55	60	55	56	60	45	30	30	10			3	10	15						2	20	25	10				8				
Taraxacum officinale										5																								1								
Cyperus longus															1																											
Carpha glomerata																		1																								
Cyperus species																			5	5			2	5	10	35	25	10	15	30	20	10	5		2	7	15	5	5	5		

Appendix 7: Percentage cover of plant species data of transect 4.1 for 2001. All species are herbs except for *Acacia saligna* that is a tree. R = Removed from analysis; Co = Concrete channel with no vegetation

	Left bank																	Wet Channel					Right bank															
Group number	1	1	1	1	1	2	2	2	2	2	3	2	2	1	4	4	4	Co	Co	Co	Co	Co	Co	Co	3	3	3	1	1	1	3	3	3	3	1	1	1	4
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38
Chenopodium multifidum	5	10	5											5														2	2								5	90
Pennisetum clandestinum	3	3	5	5	2	45	48	20	20	15	5	10	15	5	2																							
Plantago lanceolata	2		2	2	10	5	10	20	15	10	10	25	30	10											2	5	5	15	10	15	10				3	5	2	
Echium plantagineum		2	5	2			2																															
Taraxacum officinale					5																																	
Acacia saligna						10																																
Medicago polymorpha						5	5	15	10	2	2			1																								
Sonchus oleraceus						5																																
Cynodon dactylon									5	2	15	5													5	15	13	5		7	20	25	5	5				
Carpha glomerata																2	5																					
Cleome monophylla																													1									
Tribulus terrestris																																	1					

Appendix 8a: Percentage cover of plant species data of transect 1.1 for 2002. All species are herbs except for *Acacia saligna* which is a tree. sl = seedling

	Right bank												Wet Channel						Left bank											
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	12	16	17	18	19	20	21	22	23	24	25	26	27	28	BG	BG
Acacia saligna (sl)	1		2	5	10	2	2	2	5	5	2													1	5	2				
Echium plantagineum (sl)	1						1																							
Pennisetum clandestinum			3	2	30	20	10		5	10	20	25	60					30	70	30	10	10	30	5	8	8	5	2		
Cynodon dactylon					8	5																	3					5		
Cleome monophylla									2																					
Isolepis fluitans									1	20	10																			
Rumex species									2																					
Cyperus denudatus										3	3																			
Echium plantagineum										5																				
Setaria species										3																				
Sonchus oleraceus										8																				
Amaranthus deflexus											5																			
Brachiaria serrata											20	50								25										
Cyperus species											2																			
Lolium perenne											3		5	5																
Polygonum species											1																			
Raphanus raphanistrum											1																			
Medicago polymorpha												10	20																	

Appendix 8b: Percentage cover of plant species data of transect 1.2 for 2002. All species are herbs except *Acacia saligna which is a tree*. sl = seedling N = No vegetation; B = Bare ground

	Right bank										Wet Channel									Left bank										
Group number	1	1	1	2	2	1	1	1	4	4	4	3	2	N	N	N	N	2	3	3	3	3	B	B	B	B	B	B	B	B
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Amaranthus deflexus (sl)	2																													
Echium plantagineum	15	8	10	2	2																									
Raphanus raphanistrum (sl)	3																													
Tribulus terrestris	10	2					10	50	20																					
Amaranthus deflexus		5	5																											
Cynodon dactylon		10					5	15	5																					
Acacia saligna (sl)			3		5	8	15																							
Pennisetum clandestinum			5	5	10			3	8	2	30	85	15					10	30	88	75	72								
Raphanus raphanistrum			1	1																										
Paspalum distichum						3																								
Cyperus rotundus							5	10		3																				
Datura stramonium							30	15																						
Hibiscus species								8	52	95	55																			
Cyperus species																				2										

Appendix 8c: Percentage cover of plant species data of transect 1.3 for 2002. All species are herbs except *Acacia saligna which is a tree*. sl = seedling

	Right bank											Wet Channel						Left bank								
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26
Acacia saligna (sl)	3	3	2	1	3	2		1																		
Amaranthus deflexus	3	5		1																						
Cynodon dactylon	5		5		3	5																				
Echium plantagineum	5	5																								
Tribulus terrestris	8	2	5	3	2																					
Euphorbia peplus		3		5																						
Pennisetum clandestinum		1		10	20	5		5	5		15	35							5	30	5			3	8	15
Brachiaria serrata				8							10															
Xanthium strumarium									3																	
Carpha glomerata												15														

Appendix 9a: Percentage cover of plant species data of transect 2.2 for 2002. All species are herbs except for *Acacia saligna* that is a tree. BG = Bare ground; R = Removed from analysis; N = No vegetation; sl = seedling

	Right bank													Wet Channel														Left bank														
Group number	4	3	R	R	3	2	R	3	3	3	3	3	R	R	3	N	N	N	N	N	N	N	N	N	N	N	3	3	3	3	2	2	2	2	2	2	2	2	2	2	2	2
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Brachiaria serrata	4	21						10	10		15	45																15	10													
Cynodon dactylon	35																												15	3				5							5	
Echium plantagineum	6																																									
Paspalum distichum	5																																									
Tribulus terrestris	6																											1								2	35	8	65	55	35	31
Xanthium strumarium					1	2																						2	10		32	15	45	60	8	35		20	5	15		
Pennisetum clandestinum						3		3	5	45	65	45			15												27	32	36	75	20	3			5	5	1		3	2	5	15
Acacia saligna									2																																	
Medicago polymorpha											2																8	30	10													
Typha species													15																													
Carpha glomerata																											8															
Isolepis fluitans																											10															
Lolium perenne																											5	20	3													
Polypogon species																											4			5	3											
Amaranthus deflexus																													7	7	10					8		4	8	8	15	4
Cyperus denudatus																													1													
Acacia saligna (sl)																																2	3	1		2	4		3			

Appendix 9b: Percentage cover of plant species data of transect 2.3 for 2002. All species are herbs except for *Acacia saligna* and *Nicotiana glauca* that are trees. sl = seedling

	Right bank													Wet Channel															Left bank																
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45
Brachiaria serrata	3				5			20	8	5			10	10																			10												
Citrullus lanatus	50	30	60	50	15	20	15	10	8	8																																			
Cynodon dactylon		10	10																																										
Pennisetum clandestinum			5	3			10	5		15	84	53	5																	10	67	80	48	8	3	15	30	87	53	34	32	40	30	15	5
Amaranthus deflexus				2																																									
Xanthium strumarium				5	10																													5	25										
Polypogon species					3	2	2	30	5	10																				2	5		5	10											
Acacia saligna (sl)								3																															1	3	3	1			
Cyperus denudatus										3	3																						2											1	
Medicago polymorpha											8	45																				5	20												
Carpha glomerata													8															15		3	10														
Cyperus species													2																																
Isolepis fluitans													15	10																															
Lolium perenne																															10	15	5						8		3				
Echium plantagineum (sl)																																				1									
Echium plantagineum																																						8	8	3			15	60	10
Cyclopia species																																							5	5					
Cleome monophylla																																									2			1	
Carpobrotus edulis																																											1		
Nicotiana glauca																																													10

Appendix 10a: Percentage cover of plant species data of transect 2.4 for 2002. All plants are herbs.

	Right bank																Wet												Left bank																		
	Slopes									Floodplain							Channel												Floodplain										Slopes								
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47
Cynodon dactylon	15	30	37	82	60	47	45	48	51	53	10	15			10	20																		59	72	40	20	35			40	40	57	25	55	39	15
Pennisetum clandestinum	5	20	12	10	20	25	25	25	15	20	27	42	40	30	60	12	8											5	8	10	40	60	35	30	15	10	10	8	75	80	40	40	10	8	5	8	
Cyclopia species							2	5	5					5																																	
Cyperus rotundus										4	10	3	8	7																3	5	5	11	1													
Lolium perenne											8	5	5	8	10	10	2																			3	3	1									5
Medicago polymorpha											5	15	45	25	70	40															8		15														
Brachiaria serrata												10	10	5	10	10													5	5		7	3														
Polypogon species												5	30	8	2		5												8	30	25	30	8	3													
Paspalum distichum															10																																
Carpha glomerata																	8											2	5	8	5																
Cyperus denudatus																	3													5	8																
Isolepis fluitans																	8												15	5	8	15	15														
Cyperus species																														3			5														
Rumex species																																	3														
Xanthium strumarium																																	5	5													
Nemesia versicolor																																		2													
Echium plantagineum																																													5	3	

Appendix 10c: Percentage cover of plant species data of transect 3.5 for 2002. All species are herbs except for *Acacia saligna* that is a tree. sl = seedling

	Left bank																			Wet				Right bank																		
	Slopes									Floodplain										Channel				Floodplain									Slopes									
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43
Acacia saligna (sl)	1		5		2	5	5																						1	3	8					3	2	3			2	2	
Cynodon dactylon	3			3	8						8			5													5	10	10		7			10	45	47	50	30	25	15	15	10	
Dittrichia graveolens	3	15	5	2					1					2																1								2		10		5	5
Echium plantagineum	8							3																																			
Pennisetum clandestinum	20	25	20	45	40	45	35	50	65	95	65	10	12	5		20	55	30	20	30	10	30	45	55	65	85	69	47	45	53	40	65	80	75	45	50	33	8	8	10	8	3	
Brachiaria serrata					5												20	8		30	10	35	40	10																			
Plantago lanceolata					3																									2													
Cyclopia species							10	15	15		5																																
Lolium perenne							2	3																	10	3						8	10	3									
Hypochaeris radicata								5	4																																		
Medicago polymorpha								5	15	5	5																																
Isolepis fluitans											15	62	65	50	70	10	2	7	36	15				5	15		2	10	10		10												
Tragus racemosus											2			1				10	3							2	1	5		2								2					
Carpha glomerata												5		2				2	7							3		5	5	5													
Cyperus species												8		8					2									8	7														
Polygonum species												3					5	7	5	2			15	20		1	5	10	2	3		4											
Rumex acetosella												2																															
Cyperus rotundus													3	8	8	8	3	23	15								7	3	5	4	7	13	5	2	5				2				
Polypogon species													5	8		8															8												
Nemesia versicolor														1																													
Amaranthus deflexus															1															1													
Xanthium strumarium																5	5	3						5	5	1	8		3	5		3											
Typha species																		3	2	3																							
Helichrysum cochleariforme																												2	2	3													
Lotononis species																														10	20												
Tribulus terrestris																																										8	30

Appendix 11: Percentage cover of plant species data of transect 4.1 for 2002. BG = Bare ground; Co = Concrete channel without vegetation R = Removed from analysis

	Right bank																	Wet Channel					Left bank																
Group number	4	4	1	1	BG	BG	BG	BG	R	R	3	3	3	3	Co	Co	Co	Co	Co	Co	Co	4	2	2	2	2	2	2	2	2	2	2	2	3	2	2	2	2	1
Sampling plot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
Chenopodium multifidum	50	50		2																																			10
Plantago lanceolata	3	15	18	10									5	15										5	20	10	20	20	10						15	5	18	20	5
Echium plantagineum			2																																				
Citrullus lanatus									5	10	20	3																											
Cynodon dactylon											15	35	50	25																				10	7		10	8	
Dittrichia graveolens												2	5	20																									
Carpha glomerata																						15	15																
Pennisetum clandestinum																						5	30	30	30	40	25	20	20	20	40	30	40	10	20	30	10	5	
Hypochaeris radicata																										10	5	5							5		5	7	5
Medicago polymorpha																										15	20	30	30	30	35	35	30						
Lactuca serriola																																				5	5		