

**LINKS BETWEEN VALLEY CONFINEMENT,
LANDFORMS AND VEGETATION DISTRIBUTION IN
A SEMI-ARID VALLEY FLOOR ENVIRONMENT,
BAVIAANSKLOOF, SOUTH AFRICA**

A thesis submitted in fulfilment of the
requirements for the degree of

DOCTOR OF PHILOSOPHY

of

RHODES UNIVERSITY

by

LINDIE B. SMITH-ADAO

Supervisor: Prof. K. Rowntree

Co-supervisor: Dr. J. Nel

January 2016

Abstract

Although a large body of international literature has advanced our understanding of river systems, a considerable amount of gaps exist in the knowledge of dryland systems. River systems reflect complex interactions between biophysical processes and patterns. Understanding how processes generate observed patterns and, in turn, how patterns influence processes is crucial to understanding river structure and function. It requires an interdisciplinary approach in both research and resulting applications. The aim of this thesis was to examine the relationship between valley confinement, fluvial style, valley floor morphology and vegetation in the semi-arid environment of the Baviaanskloof river catchment, South Africa.

This interdisciplinary investigation used a mixed method approach that involved desktop analyses and field surveys to understand dynamics at multiple scales, from the whole catchment to local (site, reach and quadrat or sample plot) scales. The desktop analyses included historical rainfall patterns and climate extremes, aerial photograph time-series and remote sensing greenness indices, and the field surveys focussed on cross-valley landform profiles, groundwater depth levels, sediment size distribution and soil chemistry, and vegetation distribution patterns. Based on the integrative assessment of these techniques a framework was developed of the links between valley confinement, surface-groundwater interaction, hydrogeomorphic processes and landforms, vegetation and human activities. Study findings highlighted the fact that very strong links exist between these factors.

In this semi-arid area water availability (groundwater and streamflow conditions) was the primary control on valley floor vegetation composition and patterning. One group of species was associated with the wetted channel reaches at confined and semi-confined valley settings, while the other was associated with dry bed channel reaches at unconfined valley settings. The analyses also indicated that the environmental variables which best explained the variation in vegetation at the differing geomorphic landforms were related to landform position (elevation and distance), sediment size (fine and coarse sand) and available phosphorus (i.e. human impacts). The different plants, in turn, also affected landforms through their influence on sediment erosion, transport and deposition. Specially, they build, maintained or modified geomorphic landforms at confined, semi-confined and unconfined valley settings across the valley floor. Valley confinement was a primary control influencing hydrogeomorphic processes and their associated landforms. Alluvial fans and terraces acted as critical additional controls at especially the unconfined valley setting.

Implications for restoration efforts in the catchment included strategies that took cognisance of: active revegetation on floodplain surfaces related to former agricultural fields; channel switching associated with the highly dynamic and unpredictable nature of geomorphic

features; unstable multi-thread braided channels in the unconfined valley setting; and the selection of representative monitoring sites.

Key words

Valley confinement settings, hydrogeomorphic processes and landforms, surface-groundwater interactions, vegetation composition and patterning and human disturbance.

Declaration

I declare that the entirety of the work contained therein is my own, original work and that I am the sole author thereof (save to the extent explicitly otherwise stated). Neither the whole, nor any part of the thesis, has been, is being, or will be submitted for a higher degree from any other university.

Signature 

Lindie B. Smith-Adao

January 2016

Acknowledgements

I sincerely thank my supervisors, Prof. K. Rowntree and Dr. J. Nel. Thank you for your time, support and constructive feedback. Each of you has stepped in at different times when I have needed your specific expertise and guidance. We overcame a lot over the years.

Thank you for the financial and logistic assistance provided by the following institutions: the Council for Scientific and Industrial Research (CSIR), the National Department of Science and Technology (DST), and the National Research Foundation (NRF).

The following past and present staff members at the CSIR in Stellenbosch are thanked for their valuable contributions and assistance during this research: Mr. R. Vonk, Dr. R. Bugan, Mrs. L. Soltau, Dr. M. Lück-Vogel, Dr. D. Lotter, Dr. D. Le Maitre, Dr. P. O'Farrell, Dr. Luthando Dziba, Prof. B. Reyers, Mr. G. Forsyth and Prof. B. van Wilgen. Mr. J. Raath and Dr. K. Reinecke are acknowledged for their botanical guidance during this study. The Agricultural Research Council (ARC), especially Mrs. M. Fritz, and the South African Weather Bureau (SAWB) are also thanked for providing the rainfall data for this study, often at short notice.

Members of the “Sweatshop”, both past and present, are thanked for their support and all the laughs and conversations throughout my studies. It was a comfort to know that I was not alone on this emotional PhD journey. In particular, Dr. R. Blanchard, Ms. I. Kotzee and Mr. T. Yapi are thanked for their assistance with data preparation and presentation. A special word of thanks also to all my field assistants, especially Mr. E. Swartbooi who assisted me with field surveys for two years.

Thank you to my special colleagues and friends, Mrs. M. Levendal, Ms. C. Petersen, Mrs. L. Williams, Dr. B. Egoh and Dr. P. Ngani for their encouragement, invaluable help and telling me to never give up, that tomorrow is another day and that there is an end to everything. Ms. C. Petersen really came through for me in the end.

I am grateful to the Baviaanskloof community, including the farmers, Living Lands who acts as a secretariat for the PRESENCE network, Eastern Cape Parks, Mrs. R. Powell and Dr. J. Glenday for information pertaining to the Baviaanskloof River valley. I am enormously appreciative to all of you for your time and willingness to share your knowledge and experience. The farmers and Eastern Cape Parks are also thanked for allowing access to the Baviaanskloof River and the Baviaanskloof Nature Reserve respectively. Mr P. Kruger (Zandvlakte) was especially very helpful.

I acknowledge and thank Ms. R. Wright, Mrs. M. Anthony, Mrs. G. Fortuin, Mrs. A. September and Mrs V. van Rhyn for their administrative support and encouragement. Ms. L. Van der Merwe and Mrs. K. Burns are also thanked for librarian assistance and the compilation of this thesis respectively. In addition, Mr. R. Newman and Mr F. Hartogh are acknowledged for computer and printing support throughout my study period. The staff members of the Geography Department at Rhodes University, who helped me in one way or another over the years, are acknowledged.

To Mr. C. Marais, my geography high school teacher, who unbeknown to him, was the catalyst for me taking geography at university and from the beginning of my studies thinking about embarking on the PhD journey one day - thank you for inspiring young school pupils to know more but to also do more.

Most importantly, I want to acknowledge my family and my extended family. I could not have done this without all of you. In particular, Mr. J. Manuel Adão (my husband), Dr. V. McGhie (my mother) and Mr. E-R Smith (my brother) are thanked for their love, incredible support, enthusiasm and encouragement. Thank you for believing in me. This thesis is dedicated to my husband for his endless love, patience, prayers and for keeping me motivated. The best is yet to come.

Finally, thank you to my Heavenly Father for providing me with the health and strength to complete this research.

Table of Contents

	PAGE
Abstract	i
Declaration	iii
Acknowledgements	iv
Table of Contents	vi
List of Figures	x
List of Tables	xiii
List of Appendices	xv
List of Acronyms.....	xvii

Chapter 1: Introduction..... 1

1.1 Background	1
1.2 Key concepts and terminology.....	2
1.2.1 Classification according to hierarchically-nested scales.....	2
1.2.2 Connectivity across spatiotemporal scales	5
1.2.3 Valley confinement and river behaviour	7
1.2.4 Existing knowledge and gaps	9
1.3 Research aim, objectives and approach	11
1.4 Thesis structure and overview.....	13

Chapter 2: Study area and site selection 15

2.1 Location and topography	15
2.2 Geology, geomorphology and soils	17
2.3 Geomorphological zones of the Baviaanskloof River	20
2.4 Climate	22
2.4.1 Rainfall	23
2.4.2 Temperature.....	25
2.4.3 Wind and humidity	25
2.4.4 Evaporation.....	25
2.5 Water sources	26
2.5.1 Surface water	26

2.5.2	Groundwater	27
2.5.3	Overall status and water use of the Baviaanskloof River	29
2.6	Vegetation	29
2.7	Land use	33
2.7.1	Human occupation	33
2.7.2	Protection and management of the Baviaanskloof River catchment	38
2.8	Study site selection and description	41
Chapter 3: Historical rainfall and streamflow changes.....		45
3.1	Introduction.....	45
3.2	Methods: Data collection, analysis and presentation	47
3.2.1	Rainfall patterns and climate extremes	47
3.2.2	Modelled streamflow	54
3.2.3	Floods and droughts: Documentary records and interviews	55
3.3	Results.....	56
3.3.1	Rainfall patterns and climate extremes	56
3.3.2	Modelled streamflow	68
3.3.3	Floods and droughts.....	70
3.4	Discussion and conclusion	73
3.4.1	Rainfall, modelled streamflow and known major floods.....	73
3.4.2	Rainfall, modelled streamflow and known droughts	75
3.4.3	Flow variability.....	76
3.4.4	Concluding remarks.....	76
Chapter 4: Historical river valley changes.....		78
4.1	Introduction.....	78
4.2	Methods: Data collection, analysis and presentation	79
4.2.1	Image acquisition, processing and accuracy	79
4.2.2	Geomorphic classification and mapping.....	81
4.2.3	Land cover classification and mapping	84
4.2.4	Data manipulation and analysis	85
4.3	Results.....	85
4.3.1	Landscape geomorphic change, 1944-2007.....	85
4.3.2	Quadrat geomorphic change, 1944-2010.....	98
4.3.3	Land cover change, 1944-2007.....	104
4.4	Discussion and conclusion	115
4.4.1	Valley floor changes and their controls	115
4.4.2	Concluding remarks.....	119

Chapter 5: Physical river valley dynamics.....	120
5.1 Introduction.....	120
5.2 Methods: Data collection, analysis and presentation	122
5.2.1 Valley cross-section survey	123
5.2.2 Groundwater table depth: Electrical resistivity survey	127
5.2.3 Land surface-groundwater interactions: Earth observation assessment	130
5.2.4 Grain size distribution and soil chemistry: Sediment sampling.....	133
5.3 Results.....	135
5.3.1 Valley floor landforms.....	136
5.3.2 Surface-groundwater interactions and vegetation relations.....	142
5.3.3 Grain size distribution and soil chemistry	162
5.4 Summary	179
 Chapter 6: River valley vegetation patterns	 181
6.1 Introduction.....	181
6.2 Methods: Data collection, analysis and presentation	183
6.2.1 Plant community distribution patterns: Vegetation sampling.....	183
6.3 Results.....	187
6.3.1 Plant community distribution patterns.....	187
6.4 Summary	208
 Chapter 7: River valley inter-relationships discussion.....	 212
7.1 Introduction.....	212
7.2 Physical controls on valley floor vegetation patterns	213
7.2.1 Surface-groundwater and valley form influences	214
7.2.2 Hydrogeomorphological influences: Processes and landforms	217
7.2.3 Anthropogenic influences.....	226
7.3 Vegetation controls on valley floor process-form dynamics	227
7.3.1 Vegetation and landform formation.....	228
7.3.2 Vegetation and landform morphodynamics.....	231
7.4 Concluding remarks	234
 Chapter 8: General conclusions and recommendations	 235
8.1 Key research findings	235
8.1.1 Objective 1: To examine historic rainfall patterns and climate extremes (Chapter 3).....	235
8.1.2 Objective 2: To investigate historic geomorphological (i.e. fluvial morphology), land cover and vegetation changes (Chapter 4 with inputs from Chapters 2 and 3).	237

8.1.3	Objective 3: To determine the two-way links between hydrogeomorphic processes and landforms, including surface-groundwater interactions, and vegetation distribution patterns on the valley floor (Chapters 5-7 with inputs from Chapters 2-4).....	239
8.2	Implications for river restoration efforts in the Baviaanskloof.....	245
8.3	Future research.....	247
REFERENCES		249
APPENDICES		280

List of Figures

	PAGE
Figure 1.1: A hierarchical geomorphological framework for South Africa.	3
Figure 1.2: Outline of objectives and links associated with the different thesis chapters.	12
Figure 2.1: Location of the study area within the south-western region of the Eastern Cape Province, South Africa.	15
Figure 2.2: Locations of the 13 study sites within the Baviaanskloof River catchment.	16
Figure 2.3: The Baviaanskloof landscape with its steep mountains (foreground), flat valley floor (middle) and rugged topography (background).	17
Figure 2.4: Fault (a) and intricate fold structures (b) in Table Mountain sandstone.	17
Figure 2.5: Baviaanskloof River longitudinal profile with locations of geomorphological zones and study sites.	21
Figure 2.6: Semi-confined (a), broad unconfined (b) and narrow confined (c) sections alternating in the Baviaanskloof.	22
Figure 2.7: Baviaanskloof meteorological data.	24
Figure 2.8: River flow data showing seasonal variation (after Glenday, 2015).	27
Figure 2.9: Groundwater sources in the Baviaanskloof.	28
Figure 2.10: Examples of typical Baviaanskloof vegetation.	30
Figure 2.11: Vegetation types, Baviaanskloof River catchment (Euston-Brown 2006).	31
Figure 2.12: Land use in the Baviaanskloof River catchment (de Jong, 2013).	36
Figure 2.13: Human related affects or activities in the Baviaanskloof River catchment.	37
Figure 2.14: Main channel bed and bank erosion on the farm Rus en Vrede, study site 9.	38
Figure 2.15: Examples of restoration activities in the Baviaanskloof.	41
Figure 2.16: The 13 study sites selected on the Baviaanskloof River.	42
Figure 3.1: Locations of the rain gauge stations used in the study.	49
Figure 3.2: Surface flow at the unconfined Baviaanskloof River after heavy rains.	59
Figure 3.3: Rainfall intensity in the Baviaanskloof.	61
Figure 3.4: Magnitude and frequency of daily rainfall events, Baviaanskloof (1926-2010).	62
Figure 3.5: Average monthly rainfall amounts for the Baviaanskloof (1926-2010).	63
Figure 3.6: Wet and dry years linked to possible floods and droughts at 1-to 12-month. SPI time periods.	64
Figure 3.7: Annual rainfall for the Baviaanskloof.	67
Figure 3.8: Average naturalised river flows showing seasonal variation, 1920-2004.	69
Figure 3.9: Annual modelled river flow, Baviaanskloof (Middleton and Bailey, 2009).	70
Figure 4.1: Study sites selected to assess historical valley floor changes, Baviaanskloof.	81
Figure 4.2: Geomorphic change for confined study sites 2, Verlatenrivier (a) and 6, Beacosnek (b), 1944 and 2007.	87

Figure 4.3:	Geomorphic area change between 1944 and 2007, confined study sites.	88
Figure 4.4:	Geomorphic change for semi-confined study sites 1, Nuwekloof (a) and 8, Zaaimeanshoek (b), 1944 and 2007.	90
Figure 4.5:	Geomorphic area change between 1944 and 2007, semi-confined study sites.	91
Figure 4.6:	Geomorphic change for unconfined study site 4, Verlorenrivier (1944-2007).	93
Figure 4.7:	Geomorphic area change between successive years, unconfined study sites.	94
Figure 4.8:	Geomorphic change for unconfined study site 9, Rus en Vrede (1960-2007).	97
Figure 4.9:	Land cover change for confined study sites 2, Verlatenrivier (a) and 6, Beacosnek (b), 1944 and 2007.	105
Figure 4.10:	Land cover area change between 1944 and 2007, confined study sites.	106
Figure 4.11:	Land cover change for semi-confined study sites 1, Nuwekloof (a) and 8, Zaaimeanshoek (b), 1944 and 2007.	108
Figure 4.12:	Land cover area change between 1944 and 2007, semi-confined study sites.	109
Figure 4.13:	Land cover change for unconfined study site 4, Verlorenrivier (1944-2007).	111
Figure 4.14:	Land cover area change between successive years, unconfined study sites.	112
Figure 4.15:	Land cover change for unconfined study site 9, Rus en Vrede (1960-2007).	114
Figure 5.1:	Surveyed cross-valley profile locations in the Baviaanskloof with an aerial view of six sites from Google Earth.	124
Figure 5.2:	A rectangular quadrat, site 6.	126
Figure 5.3:	An acquisition system with a resistivity profile, site 1 (a) and pit, site 4 (b).	129
Figure 5.4:	A sediment grid, site 6.	134
Figure 5.5:	Valley floor cross-sections, geomorphic surfaces and quadrats, confined study sites 2 and 6.	137
Figure 5.6:	Valley floor cross-sections, geomorphic surfaces and quadrats, semi-confined study sites 1 and 8.	140
Figure 5.7:	Valley floor cross-sections, geomorphic surfaces and quadrats, unconfined study sites 4 and 9.	141
Figure 5.8:	Electrical resistivity profiles, confined study site 2. Modified from Soltau <i>et al.</i> (2011). Profile locations as per Table 5.2.	143
Figure 5.9:	Electrical resistivity profiles, semi-confined study sites 1 (a) and 12 (b).	147
Figure 5.10:	Electrical resistivity profiles, unconfined study sites 4 (a) and 10 (b).	150
Figure 5.11:	NDVI and TC transformation resistivity profile data during the dry periods.	151
Figure 5.12:	NDVI and TC transformation correlations per resistivity profile condition during the dry periods, Baviaanskloof.	152
Figure 5.13:	Monthly rainfall for the 12 months preceding the respective Landsat acquisition dates and resistivity survey.	153
Figure 5.14:	Relations between water table depth, NDVI and TC transformation data.	153
Figure 5.15:	NDVI and TC transformation resistivity profile data during the wet periods.	155
Figure 5.16:	NDVI and TC transformation resistivity correlations per profile during the wet periods, Baviaanskloof.	156
Figure 5.17:	Rainfall totals summed since the last dry season.	157

Figure 5.18:	Relations between rainfall, the NDVI and TC transformation quadrat data at the confined study sites.	159
Figure 5.19:	Relations between rainfall, the NDVI and TC transformation quadrat data at the semi-confined study sites.	160
Figure 5.20:	Relations between rainfall, the NDVI and TC transformation quadrat data at the unconfined study sites.	162
Figure 5.21:	Grain size cumulative curves for coarse sediments, confined sites 2 and 6:.....	164
Figure 5.22:	Grain size percentage visual estimates for geomorphic landforms, confined sites 2 and 6.....	168
Figure 5.23:	Grain size cumulative curves for fine sediments, confined sites 2 and 6.....	170
Figure 5.24:	Grain size cumulative curves for coarse sediments, semi-confined sites 1 and 8.....	172
Figure 5.25:	Grain size percentage visual estimates for geomorphic landforms, semi-confined sites 1 and 8.....	173
Figure 5.26:	Grain size cumulative curves for fine sediments, semi-confined sites 1 and 8.....	174
Figure 5.27:	Grain size cumulative curves for coarse sediments, unconfined sites 4 and 9.....	176
Figure 5.28:	Grain size percentage visual estimates for geomorphic landforms, unconfined sites 4 and 9.....	177
Figure 5.29:	Grain size cumulative curves for fine sediments, unconfined sites 4 and 9.....	178
Figure 6.1:	Vegetation characteristics in the study area.	188
Figure 6.2:	Vegetation growth forms associated with geomorphic landforms.	192
Figure 6.3:	Cluster dendrogram (a) and MDS ordination (b) of Bray-Curtis similarity between species composition at all the sites.	194
Figure 6.4:	Photographs of typical species occurring on differing geomorphic landforms, Group 1.	198
Figure 6.5:	Photographs of typical species occurring on differing geomorphic landforms, Group 2.	206
Figure 7.1:	Links between valley confinement, surface-groundwater interactions, hydrogeomorphic processes and landforms, human activities and vegetation.	213
Figure 7.2:	Structure, growth and landform building at the confined valley setting, 2010 field study.....	229
Figure 7.3:	Vegetation and landform formation at the unconfined valley setting, 2010 field observations.	231
Figure 7.4:	Vegetation and channel form dynamics in the Baviaanskloof, 2010 field campaign.	232

List of Tables

	PAGE
Table 1.1: Geomorphic river classification level definitions.	3
Table 1.2: Flow regimes in dryland rivers.	9
Table 2.1: Vegetation in the Baviaanskloof River catchment (Euston-Brown 2006).	32
Table 2.2: Timeline of key human activities or events, Baviaanskloof.	35
Table 2.3: Description of study sites.	43
Table 3.1: Rainfall stations selected for the study.	48
Table 3.2: Rainfall indices used in the study (adapted from Zhang and Yang, 2004).	51
Table 3.3: SPI classification scale and corresponding event probabilities of occurrence.	53
Table 3.4: Daily rainfall distribution in the Baviaanskloof River catchment.	57
Table 3.5: Heavy and extreme daily rainfall, Baviaanskloof (1926-2010).	58
Table 3.6: Seasonality of heavy and extreme rainfall in the	59
Table 3.7: Moderate to extreme rainfall events in the Baviaanskloof.	60
Table 3.8: Comparison of daily rainfall prior to and after 1963 at station 10483.	60
Table 3.9: Years of extreme wetness and dryness using the SPI, Baviaanskloof.	65
Table 3.10: Annual rainfall statistics for the selected rain stations, Baviaanskloof.	66
Table 3.11: Wet and dry years linked to possible floods and droughts in the Baviaanskloof.	68
Table 3.12: A flood and drought chronology for the Baviaanskloof, 1847- 2009.	71
Table 3.13: A summary of known floods and droughts in the Baviaanskloof.	72
Table 4.1: Aerial photography data sets analysed in the study.	80
Table 4.2: Adapted key for geomorphic features mapped, Baviaanskloof.	82
Table 4.3: ArcGIS data layers used in the study.	83
Table 4.4: Adapted key for vegetation and land cover features mapped, Baviaanskloof.	85
Table 4.5: Area (ha) and frequency of occurrence (brackets) of geomorphic features, confined sites.	88
Table 4.6: Area (ha) and frequency of occurrence (brackets) of geomorphic features, semi-confined sites.	91
Table 4.7: Area (ha) and frequency of occurrence (brackets) of geomorphic features, unconfined sites.	95
Table 4.8: Quadrat geomorphic change, confined study sites (1944-2010).	98
Table 4.9: Quadrat geomorphic change, semi-confined study sites (1944-2010).	100
Table 4.10: Quadrat geomorphic change for unconfined study site 4, Verlorenrivier (1944- 2010).	101
Table 4.11: Quadrat geomorphic change, unconfined study site 9 (1960-2010).	103

Table 4.12:	Land cover percentages and percentage change, confined study sites.....	106
Table 4.13:	Land cover percentages and percentage change, semi-confined study sites.....	109
Table 4.14:	Land cover percentages, unconfined study sites.....	113
Table 4.15:	Land cover percentage change between successive years, unconfined sites.	113
Table 5.1:	Geomorphic landform or feature type, Baviaanskloof.....	126
Table 5.2:	Resistivity profile and pit or well localities with water level information.	128
Table 5.3:	Sediment size classes.	134
Table 5.4:	Geomorphic landforms or features recognised within the study sites and their associated number of quadrats.	138
Table 5.5:	Groundwater table depth summary statistics. mbd = meters below datum (i.e. the ground level).	144
Table 5.6:	Downstream variation of geomorphic landform or feature mean grain size within the Baviaanskloof.	165
Table 5.7:	Downstream variation in geomorphic landform or feature coarse grain size within the Baviaanskloof.	166
Table 5.8:	High soil nitrogen, phosphorus, organic carbon and pH per confinement setting, Baviaanskloof.....	171
Table 6.1:	Frequency of occurrence of plant species, Baviaanskloof. After Küchler and Zonneveld (1988) and J. Raath, July 2010.....	184
Table 6.2:	Plant age categories for trees, shrubs and herbs.....	184
Table 6.3:	Growth form definitions.....	185
Table 6.4:	Comparison of herb, shrub and exotic vegetation categories, Baviaanskloof.....	189
Table 6.5:	Species richness (i.e. plant numbers) per study site, Baviaanskloof.....	189
Table 6.6:	R ² values for pair-wise tests of differences between factor groups or geomorphic landforms at Group 1.	195
Table 6.7:	Geomorphic landforms of Table 6.6 and their associated site information	195
Table 6.8:	Typical species on each geomorphic landform, Group 1, as identified by PRIMER.....	197
Table 6.9:	Characteristics of selected species from Groups 1 and 2 occurring on differing geomorphic landforms.	199
Table 6.10:	Differentiating species between geomorphic landforms, Group 1.....	201
Table 6.11:	R ² values for pairwise tests of differences between factor groups or geomorphic landforms at Group 2	203
Table 6.12:	Geomorphic landforms of Table 6.11 and their associated site information.	204
Table 6.13:	Typical species on each geomorphic landform, Group 2.....	205
Table 6.14:	Differentiating species between geomorphic landforms, Group 2.....	207

List of Appendices

	PAGE
Appendix 5.1: Quadrats and their geomorphic landforms or features per valley confinement setting.....	280
Appendix 5.2: Valley floor cross-sections, geomorphic surfaces and quadrats, confined study sites 7 and 11.....	283
Appendix 5.3: Valley floor cross-sections, geomorphic surfaces and quadrats, semi-confined study sites 3 and 12.	284
Appendix 5.4: Valley floor cross-sections, geomorphic surfaces and quadrats, unconfined study sites 5, 10 and 13.	285
Appendix 5.5: NDVI and TC transformation summary statistics for the dry periods, Baviaanskloof.....	286
Appendix 5.6: NDVI and TC transformation summary statistics for the wet periods, Baviaanskloof.....	287
Appendix 5.7: Colour composite images of NDVI and TC bands for quadrats at sites 1, 2, 4, 6, 8 and 9 during a dry period.	288
Appendix 5.8: Colour composite images of NDVI and TC bands for quadrats at sites 1, 2, 4, 6, 8 and 9 during a wet period.....	289
Appendix 5.9: Grain size cumulative curves for coarse sediments, confined sites 7 and 11.....	290
Appendix 5.10: Grain size percentage data for coarse sediments, confined study sites.	291
Appendix 5.11: Coarse sediment summary statistics for confined study sites.	293
Appendix 5.12: Grain size percentage visual estimates for geomorphic landforms, confined sites 7 and 11.....	295
Appendix 5.13: Grain size cumulative curves for fine sediments, confined sites 7 and 11.....	296
Appendix 5.14: Grain size percentage data for fine sediments, Baviaanskloof.....	297
Appendix 5.15: Fine sediment summary statistics for confined study sites.	300
Appendix 5.16: Soil nitrogen, phosphorus, organic carbon and pH per confinement setting, Baviaanskloof.....	302
Appendix 5. 17: Grain size cumulative curves for coarse sediments, semi-confined sites 3 and 12.....	305
Appendix 5.18: Grain size percentage data for coarse sediments, semi-confined sites.....	306
Appendix 5.19: Coarse sediment summary statistics for semi-confined study sites.	308
Appendix 5.20: Grain size percentage visual estimates for geomorphic landforms, semi-confined sites 3 and 12.....	310
Appendix 5.21: Grain size cumulative curves for fine sediments, semi-confined sites 3 and 12.....	311
Appendix 5.22: Fine sediment summary statistics for semi-confined study sites.	312
Appendix 5.23: Grain size cumulative curves for coarse sediments, unconfined sites 5, 10 and 13.....	314

Appendix 5.24:	Grain size percentage data for coarse sediments, unconfined study sites.	316
Appendix 5.25:	Coarse sediment summary statistics for unconfined study sites.	319
Appendix 5.26:	Grain size percentage visual estimates for geomorphic landforms, unconfined sites 5, 10 and 13.....	322
Appendix 5.27:	Grain size cumulative curves for fine sediments, unconfined sites 5, 10 and 13.....	324
Appendix 5.28:	Fine sediment summary statistics for unconfined study sites.	326
Appendix 6.1:	Presence/absence of species in the Baviaanskloof per confinement setting.	329
Appendix 6.2:	Descriptions of plant species in the study area.	336

List of Acronyms

ARC	Agricultural Research Council
ANOSIM	Analysis of Similarities
ANOVA	Analysis of Variance
BNR	Baviaanskloof Nature Reserve
BMRP	Baviaanskloof Mega Reserve Project
BIO-ENV	Is the method of the best routine in PRIMER
BVSTEP	A stepwise search of environmental variables in PRIMER
CWD	Consecutive wet days
DLA-CDSM	Department of Land Affairs Chief Directorate: Surveys and Mapping
DEA	Department of Environmental Affairs
Diss/SD	Dissimilarity Coefficient/Standard Deviation
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
FAO	Food and Agriculture Organization
GIS	Geographical Information Systems
GCPs	Ground Control Points
GPS	Global Positioning System
IAP	Invasive alien plant
Ma	million years
MAP	Mean annual precipitation
MAR	Mean Annual Runoff
Mbd	Meters below datum
MS	Microsoft
mS/m	Millisiemens per meter
Mcm	million cubic meters
MDS	Multi-Dimensional Scaling
NOAA	National Geographic Data Center
NDVI	Normalized Difference Vegetation Index

PRESENCE	Participatory Restoration of Ecosystem Services and Natural Capital in the Eastern Cape
PES	Ecosystem Services System
RMSE	Root Mean Square Error
SAC	Satellite Applications Centre
SIMPER	Similarity Percentages
Sim/SD	Similarity Coefficient/Standard Deviation
SANSA	South African National Space Agency
SAWS	South African Weather Service
SPI	Standard Precipitation Index
SPOT-5	Centre National d' Etudes Spatiales
TC	Tasselled Cap
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USGS	United States Geological Survey
WR2005	Water Resources of South Africa, 2005
WR90	Water Resources of South Africa, 1990
WRSM2000	Water Resources Simulation Model 2000
WfW	Working for Water

Chapter 1: Introduction

1.1 Background

River systems reflect complex interactions between physical and biological processes. Hydrogeomorphic processes provide the physical habitat template that controls the type of vegetation communities that are able to establish, while vegetation is a key geomorphological control that modifies flow, and influences sediment erosion and deposition (e.g. Francis, 2006; Corenblit *et al.*, 2007; Osterkamp and Hupp, 2010; Gurnell *et al.*, 2012; Bendix and Stella, 2013; Gurnell, 2014). Understanding the underlying processes and how they interact is crucial to understanding river structure and functioning, and how rivers are likely to respond to natural or human disturbances. This information, in turn, is critical for effective river management and restoration (Gilvear, 1999; Newson, 2002; Sear *et al.*, 2003; Wohl, 2005; Newson and Large, 2006; Renschler *et al.*, 2007; Fryirs and Brierley, 2013).

Developing an improved understanding of the interacting physical and biological processes is challenging. It requires integration across at least three disparate disciplines of science: geomorphology, hydrology and ecology (Dollar *et al.*, 2007; Parsons and Thoms, 2007; Renschler *et al.*, 2007; Vaughan *et al.*, 2009) to improve understanding of how biophysical patterns and processes are connected across multiple spatiotemporal scales (e.g. from entire catchments to instream habitats; from days to millions of years). The complexities of interdisciplinary river science have resulted in scientific investigations being largely discipline-bound. This has resulted in discipline interface knowledge gaps and disciplines focusing on specific levels of organization (Renschler *et al.*, 2007; Vaughan *et al.*, 2009).

This thesis contributes to an evolving body of interdisciplinary river science data and other key knowledge gaps in the field (view Section 1.3). This is done by investigating the relations between valley confinement, hydrogeomorphic process and form, surface-groundwater interaction and vegetation distribution in a semi-arid environment of the Baviaanskloof River catchment of South Africa. The research findings are also intended to advance research on dryland river dynamics, which to date lag behind similar research in more humid-temperate environments, and to inform river restoration efforts in the Baviaanskloof.

This chapter begins with a brief overview of the current understanding of the factors governing the structure and functioning of rivers. It then outlines some knowledge gaps that were used to inform the research aim and objectives of this thesis. The chapter ends by describing the intended research approach to address the aim and objectives, and the thesis structure.

1.2 Key concepts and terminology

This section summarizes concepts relevant to this study, providing further detail in subsequent chapters.

1.2.1 Classification according to hierarchically-nested scales

This study examined river dynamics at both the catchment and local scales. Geomorphologists have long since recognized a hierarchical organization within catchments, based on the premise that river structure and function are determined by the surrounding catchment and its variables. A hierarchical system helps deal with the complexity and variability of river systems and the importance of bottom-up and top-down linkages across multiple spatiotemporal scales (Montgomery and Buffington, 1998; Thomson *et al.*, 2001; Poole, 2002; Naiman *et al.*, 2005; Dollar *et al.*, 2007), discussed in Section 1.2.2 (Montgomery and Buffington, 1998; Thomson *et al.*, 2001; Poole, 2002; Naiman *et al.*, 2005; Dollar *et al.*, 2007) (Montgomery and Buffington, 1998; Thomson *et al.*, 2001; Poole, 2002; Naiman *et al.*, 2005; Dollar *et al.*, 2007). Several hierarchically-nested frameworks have been developed for rivers over the years (e.g. Frissel *et al.*, 1986; Gregory *et al.*, 1991; Rosgen, 1994; Van Niekerk *et al.*, 1995; Rowntree and Wadeson, 1999; Brierley *et al.*, 2002; Brierley and Fryirs, 2005). These frameworks provide spatially-nested levels of resolution (e.g. catchment, stream, valley segment, reach and microhabitat), where structure and functioning at one level determines the characteristics of the lower levels, and is constrained by that at higher hierarchical levels (Frissel *et al.*, 1986; Poff and Ward, 1990; Montgomery and Buffington, 1998; Dollar *et al.*, 2007; Schmitt *et al.*, 2007; Grabowski *et al.*, 2014). Traditionally, more emphasis has been placed on the importance of the physical structure and function controlling biological systems, even though there was a growing realization that these systems (e.g. vegetation) also controlled fluvial geomorphic form and process, especially at lower levels of the hierarchy.

Wadeson and Rowntree (1994) and Rowntree and Wadeson (1999) produced a hierarchical classification framework for South African rivers which is based on and coherent with a Northern Hemisphere model by Frissel *et al.* (1986). The framework uses a combination of desktop and field surveys and aims to provide a cascading system with six nested hierarchical levels (Figure 1.1 and Table 1.1) where each level provides input into the lower one, linking the catchment to the instream habitats of the river channel. Most activities are directed at the reach scale because it reflects both influences from larger (e.g. segment) and smaller (e.g. geomorphic units, plants and sediments) scales (Grabowski *et al.*, 2014). However, studies have shown that a catchment scale perspective that considers the complete fluvial landscape is critical for river management and restoration (Kondolf *et al.*, 2007; Benda *et al.*, 2011). The research here focusses on multiple levels of organization that includes the catchment, reach and morphological or geomorphic unit (Figure 1.1 and Table 1.1).

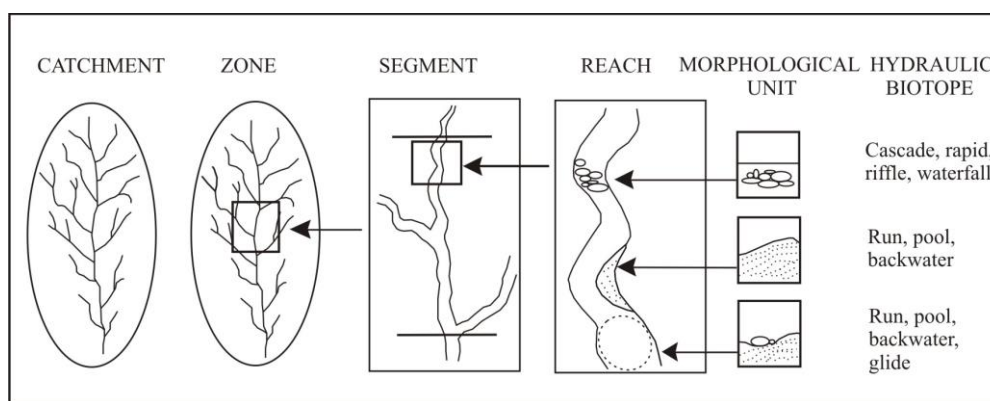


Figure 1.1: A hierarchical geomorphological framework for South Africa.

After Rowntree and Wadeson (1999) and Freeman and Rowntree (2005).

Table 1.1: Geomorphic river classification level definitions.

Modified from Rowntree and Wadeson (1999) and (Rowntree *et al.*, 2000).

Hierarchical level	Description and scale
Catchment	The land surface which contributes water and sediment to any given stream network. Can be applied to the whole river system or to a catchment above a specific point of interest.
Zone	Areas within a catchment which can be considered as homogeneous with respect to flood runoff and sediment production. Sections of the river long profile.
Segment	A length of channel along which there is no significant change in the imposed flow discharge or sediment load. It is classified in terms of an index of sediment/discharge ratio and average channel gradient. Boundaries will tend to co-incide with major tributary junctions.
Reach	A length of channel within which the local constraints on channel form are uniform so that a characteristic assemblage of channel pattern and morphology or morphological units occurs. Can be several meters or kilometres of length.
Morphological unit	The basic structures recognised by fluvial geomorphologists as comprising the channel morphology and may be either erosional or depositional features. Occur at a scale of an order similar to that of the channel width.
Hydraulic biotope	Hydraulic biotopes (pools, runs, riffles) which can be equated to morphological units are determined by the temporally variable hydraulic and substrate characteristics associated with each morphological unit. Occur at a spatial scale of the order of 1 m ² to 100 m ² and are discharge dependent.

According to Brierley *et al.* (2013) the geomorphic unit scale is critical to landform identification and interpretation of their morphodynamics based on process-form relationships. Morphological units typically comprise features located within the channel (e.g. pools, scour features) and along the channel margin (e.g. bars, depositional features) (Rowntree and Dollar, 1999). Intermediate discharges appear to result in the greatest diversity for all these morphological units (Rowntree and Wadeson, 1999). However, they have also been regarded by researchers as geomorphic landforms occupying the entire valley floor including, for example, floodplains and terraces (Hupp and Osterkamp, 1985; Van Niekerk *et al.*, 1995; Hupp and Osterkamp, 1996; Moon *et al.*, 1997; Brierley and Fryirs, 2005). This view has been adopted in the present study.

The valley cross-sectional form takes into account the full suite of geomorphic features across the valley floor. The valley floor is classified according to the absence or presence of sedimentary deposits and their relationship to the main or active channel (Rowntree and Wadeson, 1999). The main channel is typically marked by well-defined channel banks and is that part of the river which receives water flow most often. Sediment entrainment and transport is directly related to stream power and shear stress, the product of channel gradient and discharge, and to the calibre of the sediment load (Church, 2002; Cowie and Brierley, 2008; Fryirs and Brierley, 2013). In this study riparian zones represent narrow strips directly along rivers within bank and around bankfull discharge (Hupp and Osterkamp, 1996; Steiger *et al.*, 2005).

The word riparian refers to biotic communities occupying river banks (Naiman *et al.*, 1993; Naiman *et al.*, 2005). Riparian areas are ecotones (Swanson *et al.*, 1982) that occupy a transitional zone between aquatic and terrestrial ecosystems (Gregory *et al.*, 1991; Richardson *et al.*, 2007), linking the systems by exchange of materials and energy flows (Malanson, 1993; Décamps *et al.*, 2004). Fluvial landform extent, across the aquatic and terrestrial interface among other factors, varies with landscape evolution and geological control, deliberated on in Section 1.2.3 (Rowntree and Wadeson, 1999). Distinctive hydrogeomorphic processes, sediment and plant species are associated with fluvial valley landforms, as detailed in Chapters 4 to 7 (Hupp and Osterkamp, 1985; Gregory *et al.*, 1991; Bendix and Hupp, 2000; Latterell *et al.*, 2006; Hupp and Rinaldi, 2007; Sandercock *et al.*, 2007; Osterkamp and Hupp, 2010; Bendix and Stella, 2013; Gurnell, 2014).

Natural river systems are constantly changing because of the interactions that occur between geomorphic landforms and processes (i.e. sediment erosion and deposition) at a range of spatiotemporal scales (Clarke *et al.*, 2003; Brierley and Fryirs, 2005). Temporal and spatial considerations are fundamental to river science as it relates to the distinction between cause and effect (Dollar, 2000; Couper, 2004; Brierley and Fryirs, 2005; Wohl *et al.*, 2005). Information appears different at different scales, such that what is derived at one scale might

not be relevant at another (Couper, 2004). Causation and clarification in geomorphology especially are highly scale-dependent (Newman and Large, 2006).

It is essential to note the uncertainties in our knowledge at each level of the hierarchical classification and the problems of escalating uncertainty encountered when switching scales (Newman and Large, 2006; Slaymaker, 2009). Furthermore, according to Turnbull *et al.* (2008), because hierarchical classification does not explicitly present a means of transcending scales (i.e. since it cannot account for spatiotemporal connectivity between scales), which is crucial in semi-arid environments, existing hierarchical frameworks need to be refined over the years or, alternatively, new approaches need to be developed with continued experience and knowledge.

1.2.2 Connectivity across spatiotemporal scales

The semi-arid Baviaanskloof River valley provides a good example of biophysical controls (e.g. vegetation, hydrology, geomorphology and human activities) on connectivity of both water and sediment. The concept of connectivity is increasingly being applied within an array of disciplines such as geomorphology (Hooke, 2003; Brierley *et al.*, 2006; Kuo and Brierley, 2014), hydrology (e.g. Western *et al.*, 2001; Michaelides and Chappell, 2009; Bracken *et al.*, 2013) and ecology (e.g. Merriam, 1984; Pringle, 2003; Freeman *et al.*, 2007) because it allows integration of ecosystem structure and function across multiple time periods and spatial dimensions (Bracken and Croke, 2007; Turnbull *et al.*, 2008; Parsons *et al.*, 2015). Poole *et al.* (2002) and Fryirs *et al.* (2007a) defined connectivity as the transfer of energy and matter or materials (e.g. water, sediment, organic matter and nutrients) between system components or within a system as a whole. The concept was first introduced through landscape ecology as a means of explaining species distribution (Taylor *et al.*, 1993).

Connectivity is described in terms of structural and functional connectivity. The former is the extent to which landscape elements are physically linked to one another and is related to morphology while the latter is process related and refers to the movement of material fluxes among resource patches (Lake *et al.*, 2007; Turnbull *et al.*, 2008). Structural and functional connectivity among spatial units is a key determinant of nonlinear dynamics in a system (Peters and Havstad, 2006; Fryirs *et al.*, 2007a; Turnbull *et al.*, 2008). Bracken and Croke (2007) also identified three main types of connectivity: landscape connectivity, which relates to the physical coupling of landforms within a catchment; hydrological connectivity, which describes how well runoff-producing areas interconnect to yield continuous flows (i.e. the passage of water across and through the landscape); and sedimentological or sediment connectivity, which concerns the physical transfer of sediments through a catchment or between landscape compartments. Sediment connectivity is also used to describe the degree of coupling within a river system (Harvey, 2001; 2002a; 2012). This includes local scale coupling (e.g. hillslope-channel coupling) and larger scale coupling (e.g. zonal or regional

coupling). The coupling concept, linked to landscape sensitivity, has spatiotemporal aspects (Harvey, 2002a). Each of these types of connectivity can be conceptualized along interacting dimensions: longitudinal, lateral, vertical and temporal (Ward, 1989).

The movement of materials along the river channel; upstream-downstream and tributary-trunk relationships (longitudinal linkages), between the river channel and its adjacent floodplain or hillslope-valley floor (lateral linkages), and between the channel bed and underlying hyporheic zone or surface-groundwater (vertical linkages), comprises three dimensional connectivity and variation over multiple timescales the fourth (Ward, 1989; Harper *et al.*, 1999; Ward *et al.*, 2001; Amoros and Bornette, 2002; Thoms and Sheldon, 2002; Wohl *et al.*, 2005; Brierley *et al.*, 2006; Fryirs *et al.*, 2007a). The maintenance of natural patterns of longitudinal, lateral and vertical connectivity is especially crucial to fluvial styles and the viability of plant communities (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013). The temporal dimension of connectivity is also very important. For example, the recovery of lost linkages or disconnections is temporally dynamic (Kondolf *et al.*, 2006; Grabowski *et al.*, 2014). Small scale channel adjustments within individual reaches often operate over short timeframes (daily, weekly, decades); in contrast, large scale river long profile or across catchment changes usually occur over longer timeframes (centuries) (Clarke *et al.*, 2003; Brierley and Fryirs, 2005).

Longitudinal, lateral and vertical linkages at any position in the landscape may be connected (coupled) or disconnected (decoupled) (Świąchowiec, 2002; Brierley *et al.*, 2006; Fryirs *et al.*, 2007a; Fryirs, 2013). Well-coupled robust systems tend not to involve major thresholds (abrupt changes), exhibiting adjustability and better recovery potential; whereas decoupled or poorly coupled systems can operate near major thresholds, exhibiting vulnerability to disturbance (Harvey, 2001; 2002a; Fryirs *et al.*, 2007a). Studies have highlighted various forms of landscape decoupling in different settings. For example, in hillslope-channel decoupling sediments eroded on slopes are stored in alluvial fans at the base of slopes or on the valley floor (Harvey, 2001; Świąchowiec, 2002). Hooke (2003) through her coarse sediment connectivity framework noted that (dis)connectivity in downstream coarse sediment movement may result from limited competence along a channel reach. An example includes sediment deposited on a bar. Five classes (unconnected, partially connected, connected, potentially connected and disconnected) of channel connectivity were identified (Hooke, 2003; Jain and Tandon, 2010).

Brierley *et al.* (2006) and Fryirs *et al.* (2007a) advocated for four landforms (buffers, barriers, blankets and boosters) of landscape (dis)connectivity that affect sediment stored, eroded and transported (i.e. sources, stores and sinks). Buffers such as alluvial fans, floodplains or intact valley fills and floodouts prevent sediment from entering the channel and disrupt lateral and longitudinal linkages. Floodouts are unchannelled features at the terminus of rivers where flow dissipates often with a barrier (e.g. bedrock outcrops) to the flow (Nanson *et al.*, 2002;

Tooth *et al.*, 2004). Barriers such as bedrock steps or valley constrictions disrupt longitudinal linkages through their effect on the base level or bed profile of a channel. Dams are artificial barriers trapping sediment. Blankets such as floodplain sand sheets or bed armour smother other landforms promoting temporary inactivity whereas boosters such as gorges may enhance sediment connectivity (Brierley *et al.*, 2006; Fryirs *et al.*, 2007a). Buffers, barriers, and blankets are present in the Baviaanskloof (view Section 2.3) and will almost certainly affect sediment dynamics. Fryirs (2013) using spatiotemporal variability in a conceptual framework of (dis)connectivity then related sediment storage and sporadic remobilization; which is linked to the sediment delivery problem, to a conveyor belt where sediment is removed or added at any given time. The term “switches in catchments” was adopted. This is analogous to switching on and off sediment sources in different parts of a catchment under various magnitude-frequency conditions. In natural river systems (dis)connectivity (i.e. sediment storage) can be as important as connectivity, i.e. sediment transport (Fryirs *et al.*, 2007a; Fryirs, 2013).

Recently, Bracken *et al.* (2015) presented a sediment connectivity framework across multiple scales with three key elements. These included: (1) the frequency-magnitude distributions of sediment detachment and transport processes; (2) the spatiotemporal feedbacks between sediment detachment and transport processes and; (3) the mechanisms of sediment detachment and transport. These authors emphasized the codependency (feedbacks and relationships) of each of the elements. These feedbacks are very relevant to this research.

Anthropogenic impacts often alter hydrological connectivity along the longitudinal, lateral, vertical and temporal dimensions of river landscapes. This include human activities such as channel straightening, levee or dam construction, road or railway building, water abstraction and agriculture that frequently disrupt connectivity. In the Baviaanskloof past human activities (view Section 2.7.1, Table 2.2) disrupted natural processes and hence, connectivity. These activities transform river landscapes and necessitate restoration action which should take connectivity into account (Wohl *et al.*, 2005; Kondolf *et al.*, 2006; Lake *et al.*, 2007; Blanton and Marcus, 2009).

1.2.3 Valley confinement and river behaviour

This study investigated links between hydrogeomorphic processes and landforms, surface-groundwater interaction and vegetation distribution at three alternating valley confinement settings. Valley confinement describes the degree to which the river channel abuts the valley margin reflecting the channel's position on the valley floor (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013). It is a crucial metric in the differentiation of sediment source, transfer and accumulation zones along rivers, and by so doing controls river form and process (Tooth *et al.*, 2004; Fotherby, 2009). Valley confinement is usually described by the ratio of the channel width to the valley bottom width. This study adopted the guidelines by Brierley *et al.*

(2002) and Brierley and Fryirs (2005) in defining valley confinement settings, which ranges from confined or entrenched (> 90% of the channel impinges on the valley margin), to partly-confined or semi-controlled (10-90% of the channel impinges on the valley margin) and unconfined or alluvial (< 10% of the channel impinges on the valley margin).

In confined valley settings, geological controls seriously limit channel migration and avulsion (Ward, 1998; Brierley and Fryirs, 2005). Valley sidewalls restrict changes in both channel width and floodplain sediment storage, and increase channel discharge by limiting overbank flow (Schumm, 1977; Montgomery and Buffington, 1997). Confined river channels generally have higher unit stream power and sediment transport capacities, especially during extreme flooding events (i.e. channels are strongly coupled to the adjacent hillslopes which act as major sources of sediment). This is often reflected in the deep narrow cross-sections of these rivers (Wohl, 2000b; Fryirs and Brierley, 2013; Kuo and Brierley, 2013). They typically also exhibit strong affinity for longitudinal exchange (Ward *et al.*, 2002; Hauer and Lorang, 2004).

Although semi-confined river reaches are key transitional elements along longitudinal profiles in river landscapes, they have received less attention than unconfined rivers in alluvial valleys (Brierley and Fryirs, 2005; Fryirs and Brierley, 2010). These transition zones can result in higher sediment storage rates which promote enhanced channel-valley connectivity and hence increased fluvial valley landforms (Benda *et al.*, 2011). Semi-confined rivers have variable capacity to adjust in lateral and vertical dimensions which, in part, depends on accommodation space or confining features in the river valley (Fryirs and Brierley, 2010).

Unconfined, low gradient rivers in broad valleys with terraces have continuous floodplains with deep alluvial deposits across which over-bank flood waters spread. Reduced stream power linked to limited flow depths result in much of the flow energy being dissipated across the floodplain. This limits the consequences of high discharges on channel morphology and promotes sediment deposition (Lecce, 1997; Montgomery and Buffington, 1998; Brierley and Fryirs, 2005). These rivers show strong affinities for longitudinal, lateral and vertical exchange (Ward *et al.*, 2002; Hauer and Lorang, 2004). Connectivity of the river network to the catchment land surface is also weakly coupled in that these rivers are buffered against hillslope processes (Montgomery, 1999; Sear *et al.*, 2003).

Alternating narrow and broad mountain valleys can result in river reaches switching between confined and unconfined variants within the space of a few kilometres (Stanley *et al.*, 1997; Fryirs, 2002; Tooth and Nanson, 2004; Fryirs and Brierley, 2010; Keen-Zebert *et al.*, 2013). This pattern, often referred to as “pearls on a string”, promotes high heterogeneity in fluvial processes and physical habitat (Stanford and Ward, 1988; Yu *et al.*, 2013) but is poorly studied. This research will contribute to this field of study by examining hydrogeomorphic process-form relationships at confined, semi-confined and unconfined valley settings.

1.2.4 Existing knowledge and gaps

While good progress has been made in addressing the integration of the above concepts in recent times, there remain some important knowledge gaps. Firstly, most studies seeking to understand river structure and function are done on perennial rivers in temperate, humid regions in the Northern Hemisphere. There are far fewer studies in the dryland environments that characterise the Southern Hemisphere (Davies *et al.*, 1994; Tooth and Nanson, 2004; Sandercock *et al.*, 2007; Shaw and Cooper, 2008; Sandercock and Hooke, 2010; Tooth, 2013). Dryland rivers – whether perennial, seasonal, intermittent or ephemeral (Table 1.2) – are arguably more challenging to study owing to their spatial remoteness, harsh climates, limited resources, and high spatial and temporal variability (Tooth, 2000b; Bull and Kirkby, 2002; Young and Kingsford, 2006). They flow through hyper-arid, arid, semi-arid and dry-subhumid regions of the earth (Bull and Kirkby, 2002; Thoms and Sheldon, 2002; Kingsford and Thompson, 2006). Long-term streamflow data used to deduce geomorphic effects (Juracek and Fitzpatrick, 2009) are also mostly lacking in these regions (Benito *et al.*, 2010). The scant dryland river research that does exist (e.g. Tooth, 2000a; Nanson *et al.*, 2002; Sandercock and Hooke, 2010; Yu *et al.*, 2013) focuses mainly on upland catchments and therefore seldom provide a whole catchment perspective of cross-scale process interactions involving for example floods, droughts, groundwater and disconnection.

Table 1.2: Flow regimes in dryland rivers.

After Uys and O'Keefe (1997) and Gordon *et al.* (2004).

River flow regime	Description
Perennial	Rivers essentially flow year round.
Seasonal	Rivers flow only seasonally.
Intermittent	Rivers only flow during the times when they receive water from springs or surface runoff.
Ephemeral	Rivers are above the water table at all times and only flow during unpredictable high rainfall events.

Hence, there is a need to develop theory applicable to unique systems from a range of dryland settings instead of relying on pre-existing perceptions from humid and temperate environments (Van Niekerk *et al.*, 1995; Tooth, 2000b). New river management paradigms for drylands need to be formulated to avoid adopting solutions resulting from inappropriate research (Davies *et al.*, 1994; Nanson *et al.*, 2002; Thoms and Sheldon, 2002).

Secondly, even in the Northern Hemisphere, integration between hydrogeomorphology and vegetation has been largely unidirectional, focusing on how fluvial landforms and processes

influence riparian vegetation (Corenblit *et al.*, 2007; Osterkamp and Hupp, 2010; Bendix and Stella, 2013). Fewer studies have considered the bi-directional relationships, seeking to understand how plants both affect and respond to fluvial processes (Hupp and Rinaldi, 2007; Osterkamp and Hupp, 2010; Bendix and Stella, 2013).

Thirdly, linked to this, integration between hydrogeomorphology and vegetation has been narrow in its focus, considering only the active river channel and associated riparian vegetation. Relatively little attention has been directed towards broader linkages between the valley floor and its aquatic, riparian and upland vegetation (e.g. Hupp and Osterkamp, 1985; Hupp, 1990; 2000; Latterell *et al.*, 2006), especially in dryland systems (Shaw and Cooper, 2008; Sandercock and Hooke, 2010; Tooth, 2013). Broadening the scope to include the valley floor and its upland vegetation is essential for gaining a whole catchment perspective that includes landscape connectivity.

Fourthly, with some exceptions (e.g. Tooth *et al.*, 2004; Keen-Zebert *et al.*, 2013; Yu *et al.*, 2013), studies that do exist on the broader valley floor generally study one type of valley confinement setting and not alternating patterns. Understanding alternating valley settings can shed light on, for example, channel planform pattern dynamics on the valley floor. According to Yu *et al.* (2013) different river patterns occur upstream and downstream of confined sections. River styles in dryland settings can vary markedly from low-sinuosity single-thread channels to braided or anabranching channels (Tooth, 2000b; Nanson *et al.*, 2002; Tooth and Nanson, 2004). To date, our understanding of alluvial channel patterns remains incomplete (Church, 2002) because accurate determination of controlling factors of patterns are difficult (Tooth and Nanson, 2004).

Fifthly, few studies have investigated trends in sedimentary characteristics of geomorphic surfaces such as bars (Hassan *et al.*, 2009) and benches (Rowntree, 1991), specifically for river systems with marked geological controls (Heitmüller and Hudson, 2009) and highly variable flow regimes (Hassan, 2005). These landforms are highly stochastic, being subject to frequent and rapid changes (Bendix and Hupp, 2000; Sandercock *et al.*, 2007). Even in humid areas little attention has been paid to benches and they are therefore poorly understood. Benches are important for preventing basal erosion of channel banks, i.e. undercutting and incision (Rowntree, 1991; Fryirs and Brierley, 2013). Similarly, despite their significance, studies on floodplains are limited (Dollar, 2002; Grenfell *et al.*, 2009; Mouw *et al.*, 2009), especially with respect to arid and semi-arid environments and small catchments worldwide (Daniels, 2003). The research that has been undertaken has tended to focus on major meandering or anastomosing rivers in the Northern Hemisphere (Daniels, 2003; Dollar, 2004; Grenfell *et al.*, 2009). The dynamic habitat mosaics of floodplains support high levels of species diversity owing to their continual soil enrichment and ability to act as nutrient sinks (Naiman *et al.*, 1993; Tockner and Stanford, 2002; Hauer and Lorang, 2004).

Finally, there are gaps in the consideration of valley floor landform changes both spatially (vertically, laterally and longitudinally) and temporally (e.g. years to decades). Such spatio-temporal connectivity linkages account for variation in vegetation distribution, amongst other environmental variables (Bendix and Hupp, 2000; van Coller *et al.*, 2000; Brierley and Fryirs, 2005; Merritt, 2013). Detailed information on vegetation patterns and their relations with groundwater levels (i.e. vertical gradient) in water-deficient areas are almost non-existent (Chen *et al.*, 2006; Hao *et al.*, 2009; Osterkamp and Hupp, 2010). There is a need to understand surface-groundwater interactions better since they influence the availability of key limited resources in semi-arid areas (Newman *et al.*, 2006). Plants play a key role in these interactions because of their direct and indirect influence on recharge (Le Maitre *et al.*, 1999; Rebelo *et al.*, 2015). Changes in water table depths also directly affect vegetation survival and ultimately plant species diversity (Stromberg *et al.*, 2007; Hao *et al.*, 2009).

1.3 Research aim, objectives and approach

Given the knowledge gaps described above, the following aim and objectives are identified. The principal aim of this thesis is to examine the relationship between valley confinement, fluvial style, valley floor morphology and vegetation in the semi-arid environment of the Baviaanskloof river catchment, South Africa. It is intended to provide a theoretical and applied understanding of dryland river structure and function – to better understand the underlying processes, and to inform river restoration efforts.

Thesis chapters are interrelated. With the exception of Chapters 1 and 8, all address one or more of the three key objections (Figure 1.2). These objectives by means of which the aim is achieved are:

1. To examine historic rainfall patterns and climate extremes (Chapter 3).
2. To investigate historic geomorphological (i.e. fluvial morphology), land cover and vegetation changes (Chapter 4 with inputs from Chapters 2 and 3).
3. To determine the two-way links between hydrogeomorphic processes and landforms, including surface-groundwater interactions, and vegetation distribution patterns on the valley floor (Chapters 5-7 with inputs from Chapters 2-4).

This study has a research (Chapters 3-7) focus. Limitations, uncertainties/errors and comprehensive literature reviews were covered in each chapter rather than summarized in Chapter 8. Where possible, mitigation measures were considered. The research approach involved a combination of desktop analyses and field surveys (Chapters 3-5) at study sites (Chapter 2). The desktop study examined historical data related to rainfall trends and geomorphic and land cover changes, thus extending the spatial and temporal coverage of the study. The desktop analyses also included an earth observation assessment examining vegetation and surface-groundwater interaction. Datasets from a wide range of sources were

integrated (e.g. rain gauge records, documentary evidence, aerial photography, topographical maps and remote sensing). This is where a geographical information system (GIS) became very useful as datasets were queried and analysed using several techniques, and valley floor changes were visualized (ESRI, 2012).

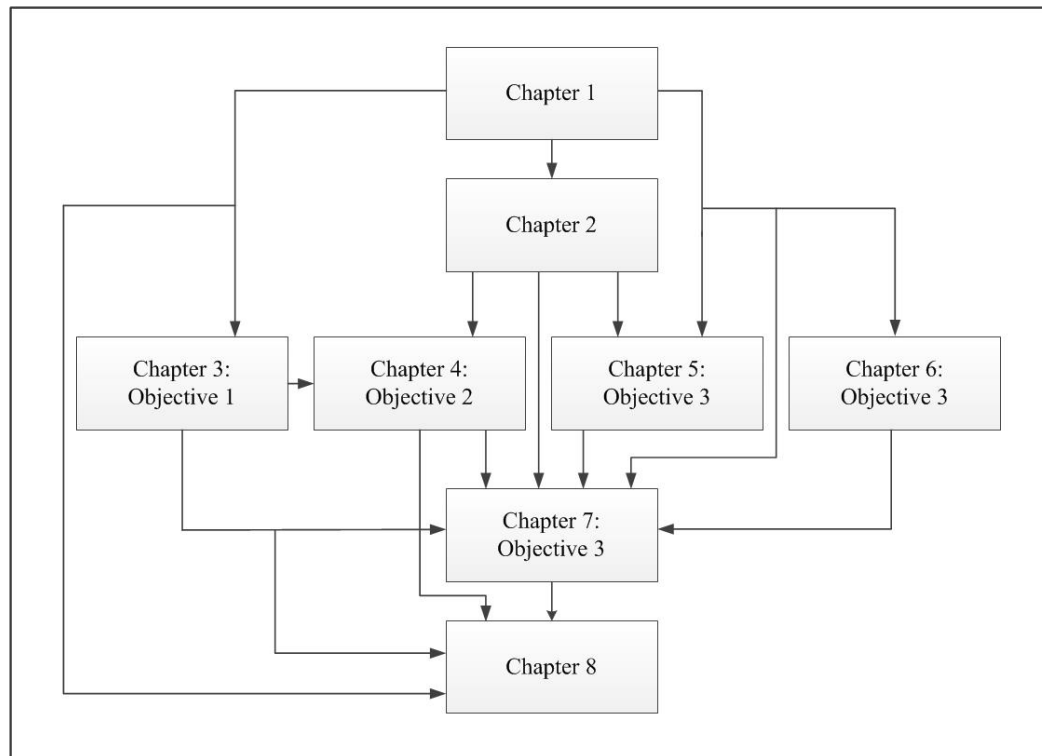


Figure 1.2: Outline of objectives and links associated with the different thesis chapters.

The field surveys mainly involved valley cross-section and resistivity surveys. Thirty-nine cross-valley profiles were linked to 289 quadrats which were set up along profiles. These quadrats represented geomorphic features where mainly sediment distribution and chemistry, and vegetation distribution data were recorded. Groundwater depth levels were obtained from resistivity surveys. Field observations, notes and a photographic record also complemented the data collected at the study sites. Comparisons were then made between study sites and between the three alternating valley confinement settings in the Baviaanskloof River catchment.

Due to the extensive interdisciplinary datasets required in this integrative study, assistance from experienced professionals in the study was allowed (view Section 1.5 for chapter specific details). The nature and extent of their contributions are acknowledged and deliberated on in the relevant chapters. This improved data quality and contributed to the thesis findings. For example, the subjectivity of visual estimates of plants was reduced by using an experienced botanist (Chapter 6). The development and writing of the chapters were

the principle responsibility of the author of this thesis (save to the extent explicitly otherwise stated).

1.4 Thesis structure and overview

This thesis is composed of eight chapters: four of these are synthesis chapters (Chapters 1-2 and 7-8) and four are data analysis chapters (Chapters 3-6) (Figure 1.2). There is some inevitable overlap between the literature review in Chapter 1 and the introductions to the data analysis chapters. Where applicable there are cross-referencing between chapters. The eight chapters are briefly described in the section below.

Chapter 1: Introduction – This chapter presents the context within which the study was undertaken. It gives a general overview of the research topic and reviews the broader literature base to set the scene for the chapters that follow. Key knowledge gaps are also described. The chapter then outlines the research aim, objectives and approach as well as the structure of the thesis.

Chapter 2: Study area and site selection – This chapter introduces the Baviaanskloof River catchment. It provides an in-depth view into its biophysical, anthropogenic and socio-economic setting, as well as some of the most important issues in the area. The chapter also gives a synopsis of the selected study sites.

Chapter 3: Historical rainfall and streamflow changes – This chapter assesses historic rainfall (daily, monthly and yearly) and modelled streamflow (monthly and yearly) data. It specifically looks at trends and provides a flood and drought chronology for the Baviaanskloof (1847-2009) using documentary evidence and interviews.

Chapter 4: Historical river valley changes – This chapter examines historical valley floor changes at six selected study sites. Geomorphic and land cover changes in the Baviaanskloof are assessed over the last 63 years. Time-tested methods (e.g. aerial photo interpretation) are employed. The chapter also uses the data obtained in Chapter 3 and incorporates it with inputs from Chapter 2 on human activities.

Chapter 5: Physical river valley dynamics – This chapter examines the physical river valley dynamics in the study area at 13 study sites through: surveying (valley cross-sections and resistivity profiles); an earth observation assessment (the Normalized Difference Vegetation Index and Tasseled Cap transformation) and sediment sampling (grain size distribution and soil chemistry). In this chapter, contributions were made by the following researchers from the Council for Scientific and Industrial Research (CSIR), Stellenbosch: R. Vonk, a surveyor, who processed the cross-section point data acquired in the field; R. Bugar, a hydrogeologist, who assisted with resistivity data collection; L. Soltau, a geophysicist, who interpreted the

acquired resistivity data and M. Lück-Vogel, a remote sensor, who processed and interpreted the acquired satellite imagery data.

Chapter 6: River valley vegetation patterns – This chapter shifts focus and scale. It investigates plant community distribution patterns in the Baviaanskloof River valley at site and geomorphic landform scales. An area-based vegetation sampling method was used to obtain valley floor vegetation data from a series of variable-sized quadrats. In this chapter, contributions were made by J. Raath, an independent botanical consultant, who undertook field work with the assistance of the author and identified most of the plant species in the study area.

Chapter 7: River valley inter-relationships – This chapter interprets the physical (Chapter 5) and biological (Chapter 6) results collectively by examining hydrogeomorphic process-form and vegetation relationships on the valley floor. In addition, it presents an explanation of the observed valley floor changes within the three valley confinement settings (confined, semi-confined and unconfined). Introductory information in Chapter 2 and historical data obtained from Chapters 3 and 4 also provided significant input into this chapter.

Chapter 8: General conclusions and recommendations – This concluding chapter summarizes the major findings of this thesis by synthesising the key findings of Chapters 3-7. Specifically, it discusses the results in light of the research objectives and knowledge gaps identified in Chapter 1. Implications for river restoration efforts in the Baviaanskloof and recommendations for future research are also presented.

Chapter 2: Study area and site selection

This chapter is an introduction to the Baviaanskloof River catchment. It summarizes the available past and present biophysical, anthropogenic and socio-economic information relevant to this study. These implications are explained and outlined within the sections where applicable. Key information is drawn from: De Villiers (1941), Taljaard (1949), Boshoff *et al.* (2000), Illgner and Haigh (2003), Euston-Brown (1995), McCarthy and Rubidge (2005), Crane (2006), Boshoff (2008), Jansen (2008), Ellery and Rowntree (2011), Hattingh (2011), Knight (2012) and de Jong (2013).

2.1 Location and topography

The Baviaanskloof, meaning valley of baboons, is located in the south-western region of the Eastern Cape Province of South Africa (Figure 2.1). It is situated between the Karoo in the north and the Langkloof in the south. The valley is south-east of Willowmore and approximately 95 km north-west of Port Elizabeth with its most southern point 50 km from the Indian Ocean. The catchment area is approximately 1233 km² between latitudes 33° 30' and 33° 45' south and longitudes 23° 35' and 24° 25' east. The 75 km long river valley is flanked by the parallel east-west running mountain ranges of the Baviaanskloof (north) and Kouga (south) (Figure 2.1).

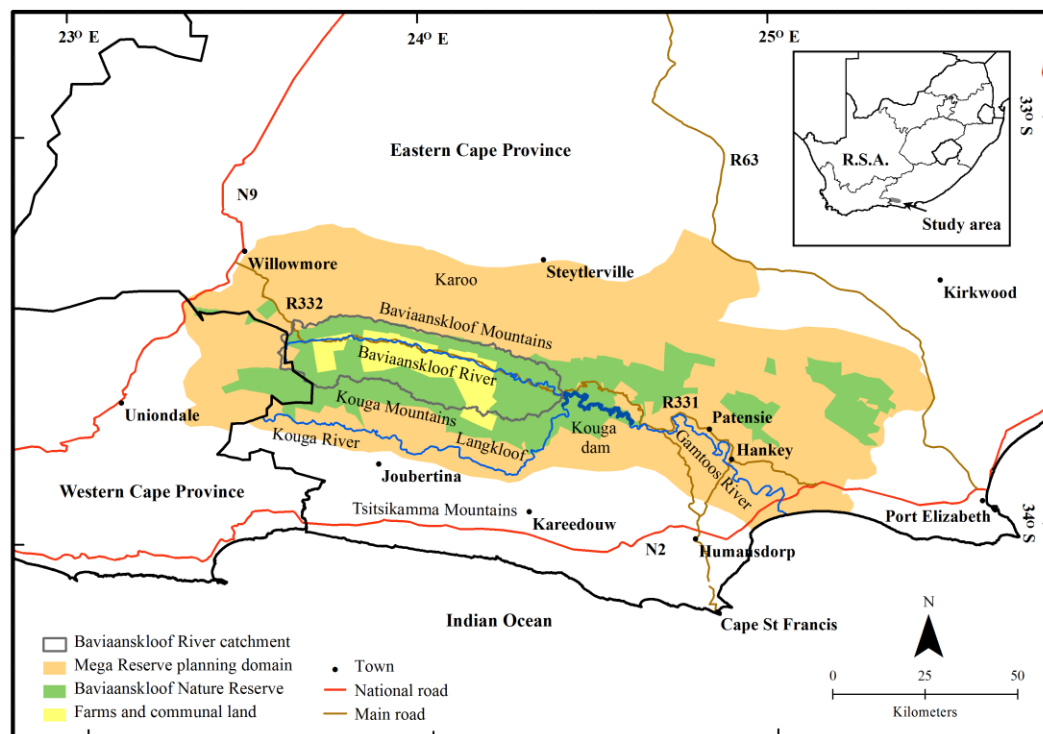


Figure 2.1: Location of the study area within the south-western region of the Eastern Cape Province, South Africa.

The position of some places or features mentioned in the text is also indicated.

The 106 km Baviaans River rises at an altitude of approximately 1400 to 1406 metres above sea level (masl) at Quaggas Berg (Figure 2.2). Approximately 62% of its 1233 km² catchment falls within a protected area (Figure 2.1), the Baviaanskloof Nature Reserve, discussed further in Section 2.7.2. Thirteen sites were chosen in the study area (Section 2.8) for the collection of field data (Chapters 5 and 6). These study sites were located alongside the Baviaanskloof River at elevations ranging from 863 to 303 m (Figure 2.2). Sites 2-10 were on private land whereas sites 1 and 11-13 were on state land (Figure 2.1).

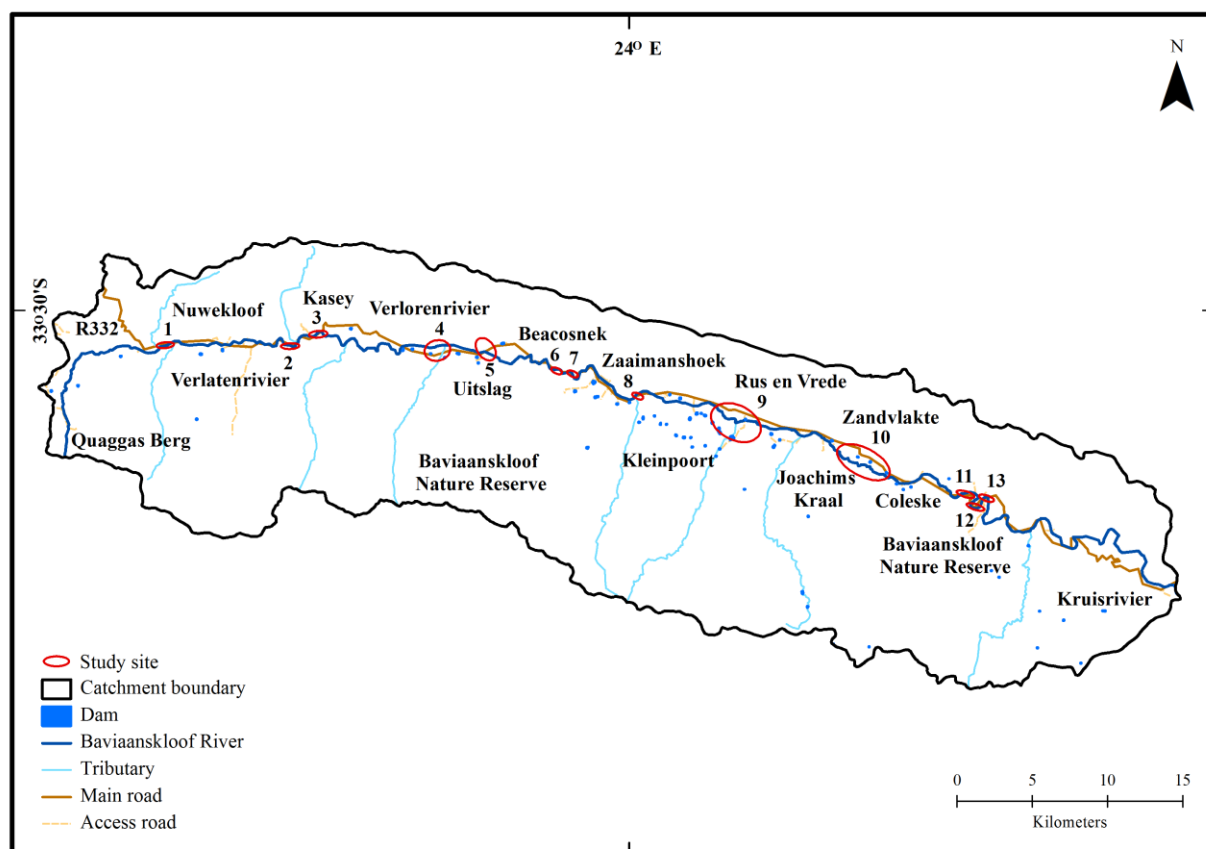


Figure 2.2: Locations of the 13 study sites within the Baviaaskloof River catchment.

The landscape in this remote study area is very rugged with the exception of the elevated plateaus of subdued relief and flat valley floor. The valley floor contrasts markedly with the surrounding topography dominated by very steep slopes (Figure 2.3). It has a constant slope of about 1% from west to east. The altitude of the valley floor ranges from 700 to less than 200 masl. Only one third of the area has mountain slopes of less than 30%. Slope gradients usually range between 30-40% but slopes of 60% prevail in some areas (Illgner and Haigh, 2003; Knight, 2012). The north facing Kouga Mountains are less steep and higher than the south facing Baviaanskloof Mountains (Ellery and Rowntree, 2011; Knight, 2012). The peaks of Scholtzberg (1625 masl) and Smutsberg (1758 masl) are the highest points on the Baviaanskloof and Kouga mountain ranges. The lowest point in the catchment is the

confluence of the Baviaanskloof and Kouga rivers at < 160 masl, Figure 2.1 (Illgner and Haigh, 2003).

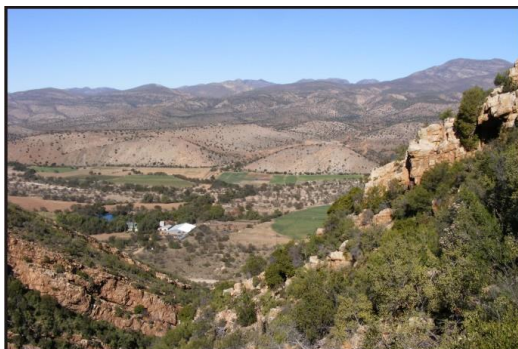


Figure 2.3: The Baviaanskloof landscape with its steep mountains (foreground), flat valley floor (middle) and rugged topography (background).

Photograph by J. Raath.

2.2 Geology, geomorphology and soils

The diverse landscape of the Baviaanskloof (Figure 2.3) is the result of geological and geomorphological processes which began approximately 500 million years (Ma) ago, continuing until today (Moon and Dardis, 1988; McCarthy and Rubidge, 2005; Johnson *et al.*, 2006; Maud, 2008). Rifting, massive upheaval (Partridge and Maud, 1987; Maud, 2008), active faulting (Figure 2.4a), complex folding (Figure 2.4b) (De Villiers, 1941; Taljaard, 1949) and river development (Hattingh, 2008) in particular played a major role in the evolution of this drainage basin. The area is mainly underlain by sedimentary rocks of the Cape Supergroup which were deposited, folded and uplifted some 450 to 330 million years ago during the formation of the supercontinent of Gondwana to form the Cape Fold Belt of mountains (Maud, 2008), one of the 34 geomorphic provinces of South Africa (Partridge *et al.*, 2010).

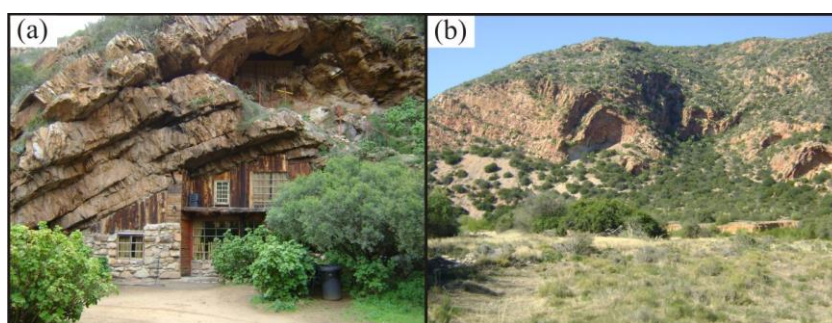


Figure 2.4: Fault (a) and intricate fold structures (b) in Table Mountain sandstone.
Note the upward-arching anticlines and downward-arching synclines in the latter.

The Baviaanskloof landscape is also dominated by quartzitic sandstones, shales and tillites of the oldest layer of the Palaeozoic Cape Supergroup, the Table Mountain Group (Mills and Cowling, 2010) with its network of joints and fractures. These joints and fractures promote both rainfall infiltration and groundwater recharge and storage in the Table Mountain Group quartzitic sandstones (Meyer, 1998; Wu, 2005). However, because the fractures tend to close at relatively shallow depths, most of the infiltrated rainfall exits as interflow (Wu, 2005). The geology of the study area includes all six formations of the Table Mountain Group namely, the Sardinia Bay (oldest), Peninsula, Cedarberg, Goudini, Skurweberg and the Baviaanskloof (youngest). The last three formations constitute the Nardouw Subgroup (Thamm and Johnson, 2006). The mountainous areas of the study area comprise the erosion-resistant Skurweberg and Peninsula Formations; the softer Goudini rocks underly the Baviaanskloof valley and the gentle, upland plateaux (Toerien and Hill, 1991; Euston-Brown, 1995). These formations are associated with poor soil development (Rust and Illenberger, 1989), quite resistant to erosion and yield predominately nutrient-poor substrata (Rust and Illenberger, 1989; Rebelo *et al.*, 2006). Soils are very shallow, stony, sandy and acidic (Rebelo *et al.*, 2006). The remaining two formations of the Table Mountain Group (Sardinia Bay and Cedarberg) are subordinate in the landscape (Euston-Brown, 1995).

Cretaceous weathering of the Cape Folded Belt, exhumed after the separation of the African and Falkland plates, infilled the valley with predominately Enon sediments. These were subsequently eroded to reveal the ancient Cretaceous valley, as a consequence of Cenozoic (Neogene) uplift after a prolonged period of stasis that produced the numerous plateaux throughout the region. Further upheaval and massive tearing caused the formation of both large and small faults which ultimately lead to new river courses and basins (McCarthy and Rubidge, 2005; Ellery and Rowntree, 2011). De Villiers (1941) and Illgner and Haigh (2003) noted the extensive faulting in the Baviaanskloof which resulted from the break-up. A major east-west tensional fault, the Baviaanskloof-Kouga fault, runs through the valley. It is at least 100 km long with a vertical displacement of some two to three kilometres. Several secondary transverse fault lines also occur (Rust and Illenberger, 1989; Illgner and Haigh, 2003). Two minor faults terminate south of the Baviaanskloof-Kouga fault fracture. The western one ends on Beacosnek, while the one in the east ends on Joachimskraal, Figure 2.2 (De Villiers, 1941; Illgner and Haigh, 2003). Recent seismic information (2001, 3.4-3.7 M and 2006, 2.7 M) on the Baviaanskloof faults indicate that they are under strain and potentially capable of producing earthquakes (Goedhart and Booth, 2009).

The alternating valley confinement settings (confined, semi-confined and unconfined) are assumed to be the product of the extensive faulting and varied rock formations (i.e. hard erosion-resistant rocks versus easily erodible rocks) in the Baviaanskloof (K. Reddering, Council for Geoscience, Port Elizabeth, pers.comm., 2010). Valley confinement controls fluvial geomorphic form and process (Fryirs and Brierley, 2013) which ultimately affect vegetation distribution patterns (Osterkamp and Hupp, 2010), a theme central to this study

(Chapters 6 and 7). Historically, the Baviaanskloof faults presented weak points which were exploited by the short steep tributaries that drained the mountain ranges. These tributaries eroded the early Baviaanskloof rock away forming the present-day northern V-shaped valleys and deeply incised slot canyons or “kloofs” which are at times no more than a meter across (Taljaard, 1949; Ellery and Rowntree, 2011).

Concerning river development, before the break-up of Gondwana Eastern Cape rivers flowed northwards. Afterwards, the newly formed southern Cape Coastline caused a complete rejuvenation and reversed river drainage, producing new steep-gradient energetic river systems of which the Baviaanskloof River was one. These rivers were associated with rapid landscape denudation (Rust and Illenberger, 1989; Hattingh, 2008). The 90° river turns along weak fault or joint planes of the Cape Fold Belt give a good indication of stream capture or river piracy which also took place in the vicinity of the study area. For example, the Kouga-Krom river was intercepted by a tributary of the Baviaanskloof River which in turn, captured the Kouga River (Rust and Illenberger, 1989; Hattingh, 2008).

Minor amounts of fine-grained Bokkeveld shale (Cape Supergroup) mainly from the Ceres Subgroup, Enon conglomerates and alluvial deposits (sand, mud and gravel) are restricted to the centre of the valley floor and border the Baviaanskloof-Kouga fault line (Taljaard, 1949; Mills and Cowling, 2010). Fault-fractured quartzite also occurs on the valley floor. All of these deposits weather comparatively easily (Rust and Illenberger, 1989; Vlok, 1989). Red and white Enon conglomerate outcrops are exposed sporadically from Nieuwekloof to Kruisrivier, Figure 2.2 (Illgner and Haigh, 2003). They consist of densely packed pebbles and rocks in a sandy matrix (Toerien and Hill, 1991; Shone, 2006). The deposition of Enon conglomerates from the Uitenhage Group by the high-energy palaeo-Baviaanskloof River (De Villiers, 1941; Hattingh, 2008) represent the last major rock forming period in the valley (Ellery and Rowntree, 2011). However, geological processes continued in the form of two periods of uplift events 20 and 5 million years ago. Erosion surfaces such as the Post Africa I and II found at the valley floor margin is a product of these uplift events. These surfaces are associated with a hard band of silcrete (McCarthy and Rubidge, 2005).

The quaternary deposits occurring along the mainstem and its major tributaries are the youngest sediments in the Baviaanskloof, dating back to the last 1.5 million years (Boshoff *et al.*, 2000). The geology has given rise to deep, nutrient-rich sandy soils with some clay on the lower lying areas (Rust and Illenberger, 1989; Vlok, 1989). A soil survey conducted by Knight (2012) indicated that the valley floor soils consist largely of sand, sandy loam or loamy sand with fine to coarse gravel. The survey data were mainly obtained from profile pits but river cuttings or banks, erosion dongas and hand auger drillings were also used to gain additional soil information. As described by Brierley and Fryirs (2005) and Fryirs and Brierley (2013) soils such as these are an indication of a river valley system driven by erosional and depositional processes. They are slightly acidic to alkaline, low in organic

carbon and clay and high in phosphorus and potassium. These soils can also be compacted and have low water retention (i.e. high drainage) and mostly moderate to rapid permeability (i.e. medium to high porosity). Furthermore, alluvial layering in the soils is associated with the Dundee soil form which dominates in the Baviaanskloof. Dark layering (i.e. black peat), the result of accumulation of organic matter under wetland conditions, is also present at some river cuttings (Knight, 2012). The above-mentioned soil characteristics usually influence surface runoff, soil erosion, stormflow production and vegetation structure.

2.3 Geomorphological zones of the Baviaanskloof River

The Baviaanskloof River mainly consists of two geomorphological zones (Rowntree *et al.*, 2000) as illustrated by its longitudinal profile (Moolman, 2008). The longitudinal profile is strongly concave (Partridge *et al.*, 2010) with a progressive decrease in slope in a downstream direction (Ellery and Rowntree, 2011). The geomorphological zones comprise the mountain stream and foothill (upper and lower) zones (Figure 2.5). The channel gradient in the mountain streams is steep to very steep (> 0.01). In the foothills, it is moderately steep, ranging between 0.005 and 0.009 (Rowntree *et al.*, 2000; Moolman, 2008). This has implications for the erosion and transport of sediment by the Baviaanskloof River. The steeper the slope, the greater the potential energy for sediment reworking (Rowntree *et al.*, 2000; Rowntree, 2012). The two geomorphological zones differ in terms of valley floor morphometry and hydraulic characteristics.

In the mountain stream zone, the single thread Baviaanskloof River channel is constrained by steep valley sidewalls and lined with narrow flood benches. The channel bed is composed of bedrock, boulders and cobbles with step pool sequences, or cascades and rapids. The valley floor in the foothills consists of alternating unconfined (wider) and confined (narrower) sections of between 16 and 7 km in length. Semi-confined sections are also present (Figure 2.6). Unconfined sections are approximately 900 m in width (occasionally this is exceeded) whereas confined sections are 30-100 m in width (Rowntree, 2012). These variations in valley width are thought to be the result of past faulting which force erosion-resistant rocks together (in the narrow sections) and the lateral erosion of weaker rocks during flooding (wide sections) (K. Reddering, Council for Geoscience, Port Elizabeth, pers.comm., 2010). The alternating confined and unconfined nature of the valley floor has a marked influence on river form and process (Brierley and Fryirs, 2005; Fotherby, 2009) and connectivity (Ward, 1989; Fryirs *et al.*, 2007a; Fryirs, 2013), and is an important focus area of this study (Chapters 4, 5, 7 and 8 especially).

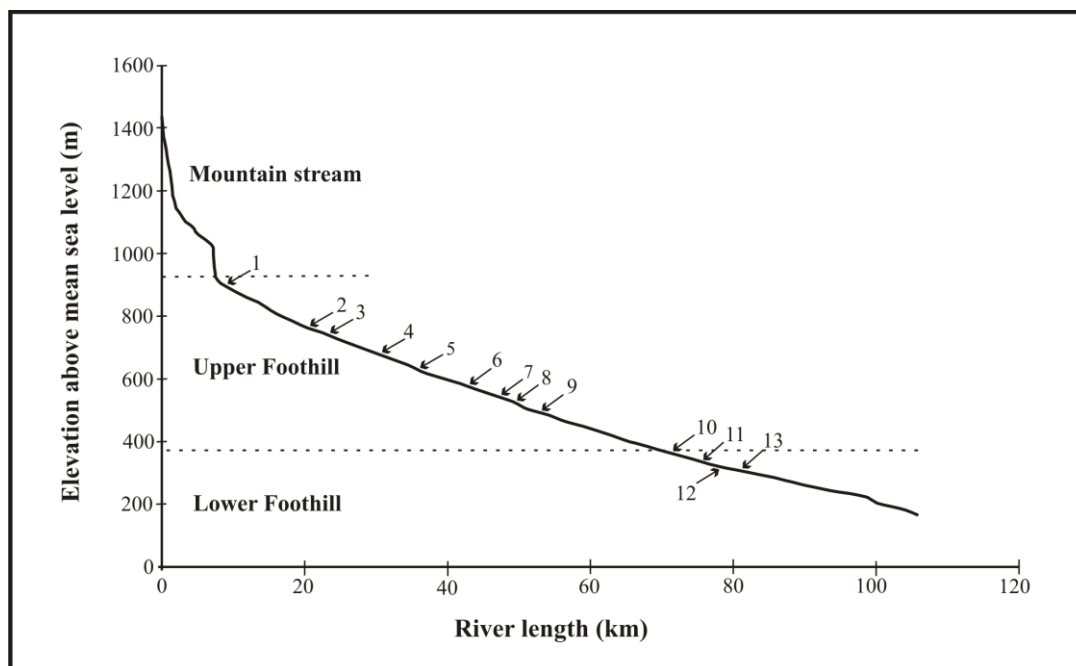


Figure 2.5: Baviaanskloof River longitudinal profile with locations of geomorphological zones and study sites.

The longitudinal profile is based on contour and spot height information (after Moolman, 2008).

In the unconfined sections, floodplain development is maximal with the Baviaanskloof River adopting a braided channel planform characterized by shifting inherently unstable multi-thread channels (Ellery and Rowntree, 2011). A dominant main channel is also present with a typical width of 10-40 m (Figure 2.6c). Bars, islands, broad multi-level terraces and alluvial fans are usually common here. Terraces are often paired (i.e. alongside both main channel banks) and confine the main channel. Fans act as buffers between the hillslopes and the valley floor, trapping sediment from the steep hillslopes (Harvey, 1996; 2002b). They also attenuate floods and promote groundwater recharge (Houston, 2002; Grenfell *et al.*, 2009). In the Baviaanskloof they are subject to erosion and frequent truncation by the main channel (Bobbins, 2011). Sometimes opposing fans meet on the valley floor, forming a barrier across the river (e.g. at site 4).

In contrast, in the confined sections, floodplain development is limited and the straight Baviaanskloof River channel is single thread (1-5 m wide) with a distinct stepped form (Figure 2.6b). A narrow low-flow channel is inserted within a wider flood channel that may occupy the entire width of the narrow section, or may be bounded by narrow floodplain surfaces (Rowntree, 2012). Flood benches are usually present.

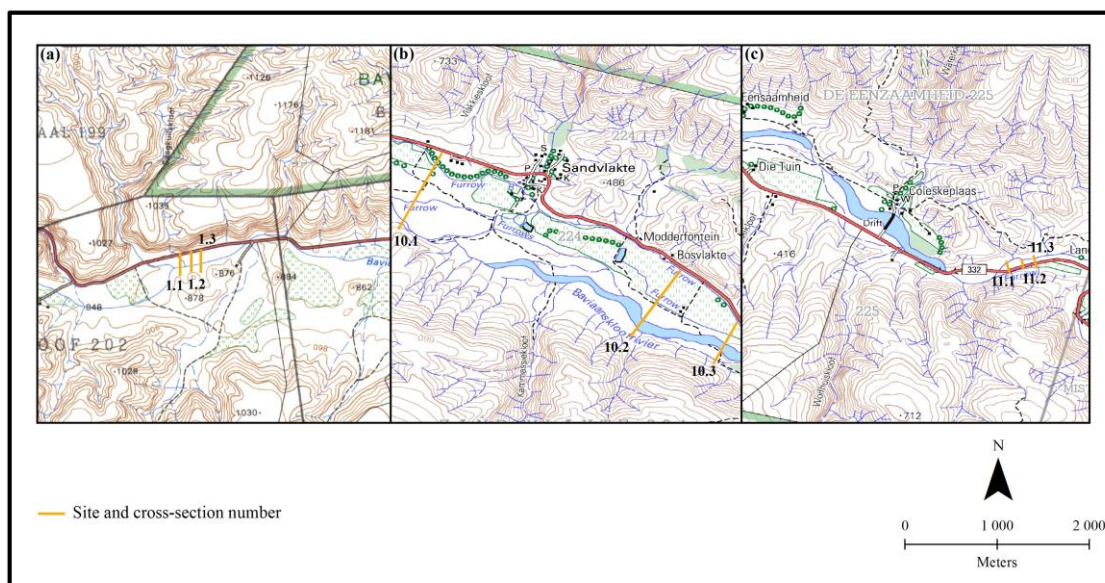


Figure 2.6: Semi-confined (a), broad unconfined (b) and narrow confined (c) sections alternating in the Baviaanskloof.

Topographical maps (1:50 000) supplied by the DLA-CDSM (1985, 2000).

The Baviaanskloof River channel bed in the foothill zone is dominated by coarse material made up largely of gravels, cobbles and boulders (Ellery and Rowntree, 2011), forming pools, runs and riffles. The channel banks (low to very high) have an abundance of fine sand and gravels with cobbles and boulders being sparse to common. There is evidence from organic rich layers exposed in channel banks that wetlands were a common feature throughout the wide sections at some point in the past. The loss of wetlands is thought to be a result of incision of the main channel through fans and the reduced buffering function of the incised fans (Rowntree, 2012).

2.4 Climate

The Baviaanskloof is an inland river valley, cut off by two mountain ranges from the Indian Ocean (Figure 2.1). Hence, the resulting climate is drier than the coastal region. The general climate of the study area is regarded as semi-arid and highly variable (both in space and time). The topography especially results in considerable climatic differences between the high altitudes and the valley floor (Hattingh, 2011). To date, there are limited detailed studies on the climate of the Baviaanskloof although various data sources exist. This thesis will examine historical rainfall patterns and climate extremes in Chapter 3 which will build on the information outlined in this section and Section 2.5, water in the river valley. Climate data are available through the South African Weather Service, the Agricultural Research Council, Lynch (2004), Schulze (2007) and Middleton and Bailey (2009). The most comprehensive climate dataset obtained for the study area is for the weather station 20237 (Baviaanskloof).

This dataset is managed by the Agricultural Research Council's Agromet division of the Institute for Soils, Climate and Water.

2.4.1 Rainfall

Studies by Jansen (2008) and Knight (2012) indicate that whilst the rainfall is erratic and non-seasonal (i.e. rainfall occurs throughout the year), there is a tendency for more rainfall during the summer. The data showed a bimodal rainfall pattern with late spring/summer and autumn maxima (Figure 2.7a). During this study's field campaign year (Chapter 5, Section 5.2) it was very dry during July - October 2010. The higher rainfall during June 2010 displayed the natural variability of the rainfall in the valley. A catchment-wide rainfall distribution analysis (i.e. using a national dataset) indicated that the mountainous areas have a mean annual precipitation (MAP) of between 500 and 800 mm but on the highest peaks it can exceed 900 mm. At the valley floor and adjoining flats annual precipitation averages between 200 and 500 mm but it can also be less than 150 mm (Middleton and Bailey, 2009).

Jansen (2008), using rainfall data from eight stations in the valley, reported that the average annual rainfall in the Baviaanskloof River catchment is 300 mm. From this 188 mm can be expected in summer and 112 mm in winter. In general, rainfall is the source of alluvial groundwater, river baseflows and flood flows (Lite *et al.*, 2005). Increased or heavy rainfall is also important in determining river channel form and process because it affects vegetation and flow hydrology (Goudie, 2006; Grenfell *et al.*, 2014). Figure 2.7b demonstrates that the annual rainfall may vary from less than 80 mm to more than 600 mm with a number of consecutive years below average rainfall. These rainfall extremes are associated with prolonged droughts and devastating flooding events (Urquhart, 1990; Illgner and Haigh, 2003).

Severe droughts occurred in 1933, 1966 and 1987 (Figure 2.7b). During drought years, the groundwater resource tend to be stressed when abstraction for irrigation remains at normal levels and total failure of water sources has occurred at a few places in the Baviaanskloof (Knight, 2012). For instance, during the 1987 drought, the furrows leading water from the tributaries dried up completely (P. Kruger, Zandvlakte, Baviaanskloof, pers.comm., 2010). Direct effects of severe droughts can include connectivity disruption or cessation in river systems (Boulton, 2003), groundwater table lowering (Newman *et al.*, 2006) major channel changes (Gasith and Resh, 1999), as well as habitat and vegetation reduction (Lake, 2003).

On average, major floods tend to occur at roughly 10-year intervals in the valley (Boshoff *et al.*, 2000; Hattingh, 2011). For example, major floods were recorded in 1931, 1944, 1953, 1963, 1979, 1981, 1996 and 2005 (Figure 2.7b). Flood flows can be extremely damaging to human assets, carry large amounts of sediment and cause major river channel adjustments (Hooke, 2007). River channel adjustments take place through changes in cross-section (depth and width), channel gradient and channel pattern (Rowntree and Dollar, 1996; Downs and

Gregory, 2004; Labbe *et al.*, 2011). Flooding events may also re-establish or augment upstream-downstream connectivity (Lake, 2000). The study area did not experience high rainfall during the 2010 fieldwork year. The annual rainfall was only 320 mm (Figure 2.7b).

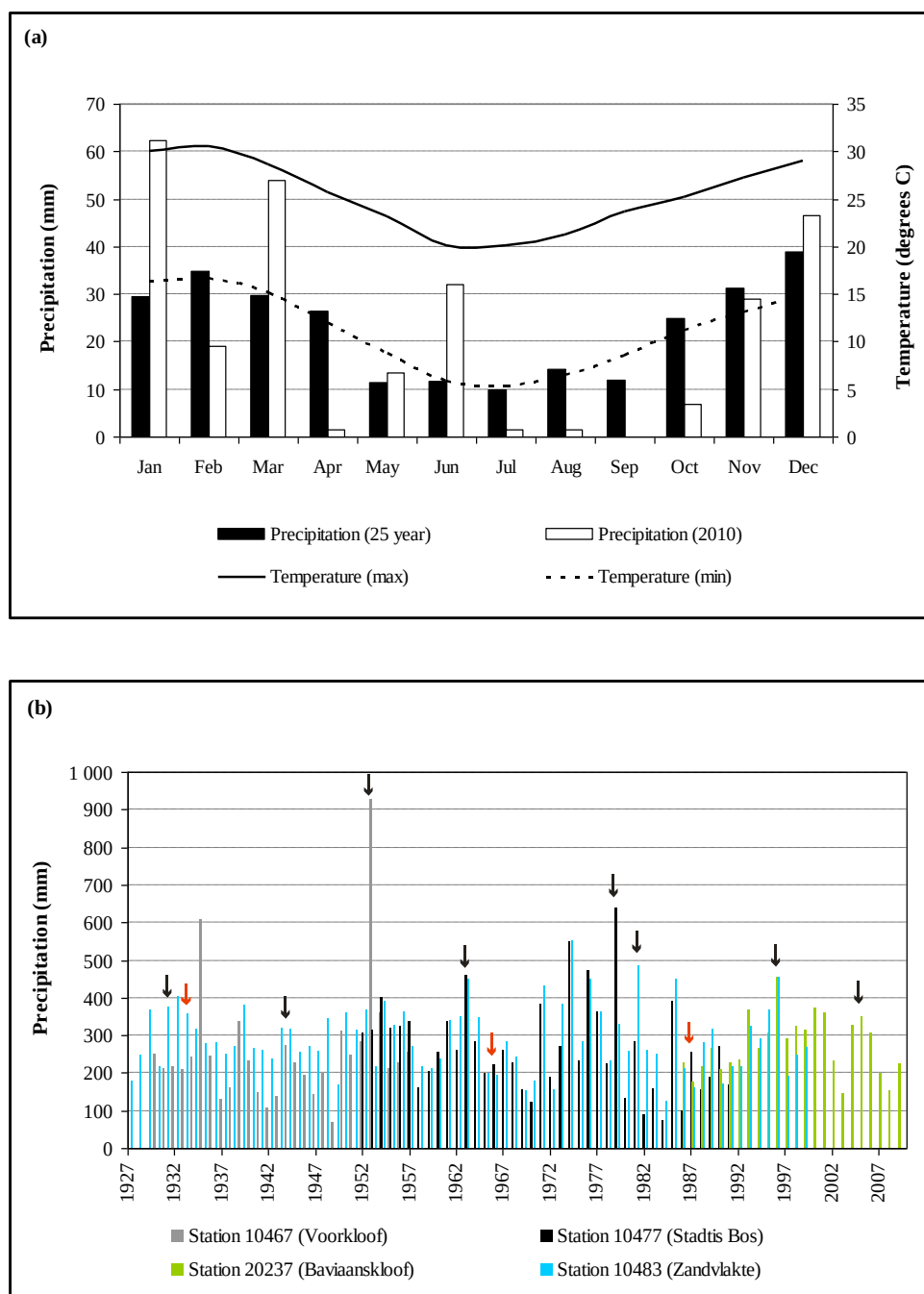


Figure 2.7: Baviaanskloof meteorological data.

Climodiagram showing monthly temperature and rainfall for 2010 and 25 year average values at station 20237, Baviaanskloof (a). Annual rainfall at stations 10467, 10477, 20237 and 10483, (b). Black and red arrows represent major floods and droughts respectively. Data sources: Agricultural Research Council and South African Weather Service.

Most rainfall events are orographic (ECPB, 2007; Jansen, 2008) or associated with post-frontal circulation. The largest rainstorm intensities, however, result from cut-off lows (Tyson and Preston-White, 2000; Mander *et al.*, 2010; Engelbrecht and Landman, 2015). These intense infrequent storms of longer duration can cause widespread flooding on the whole valley floor (Ellery and Rowntree, 2011). Intense convective storms or thunderstorms also occur (Jansen, 2008). These storms are often localized, of relative short duration and can cause rapid surface runoff associated with short-lived, high streamflows and flash floods (Jansen, 2008; Ellery and Rowntree, 2011). These unstable summer thunderstorms accompanied by rain, lightning and hail are common (Boshoff *et al.*, 2000). There are generally 10-20 thunderstorms per year (ECPB, 2007).

2.4.2 Temperature

Baviaanskloof is characterised by warm to hot summers and cool to cold winters. Temperature as well as temperature-related factors such as frost will generally change with altitude (Knight, 2012). The average monthly maximum and minimum temperatures, respectively, are 32°C and 16°C in January/February (i.e. warmest months) and 20°C and 5°C in June/July (i.e. coldest months) (Figure 2.7a). However, warm winds from the high plateau can push temperatures up to 44°C in summer, while winter extremes can vary between 5°C and -3°C (ECPB, 2007).

Temperatures at or close to 0°C do occur and frost is common in most parts of the catchment (Knight, 2012) between June to August. The high mountain peaks are also often covered in snow (ECPB, 2007; Jansen, 2008). Within limits, warm temperatures are conducive to vigorous plant growth but more frequent severe frost and early or late frost can be fatal resulting in reduced growth (Knight, 2012; Duker *et al.*, 2015).

2.4.3 Wind and humidity

The prevailing wind direction is south to southeast in summer and northwest in winter (ECPB, 2007; Jansen, 2008). The average annual wind speed is moderate to high at 6.1 km/h. The highest wind speeds occur during the summer months with average monthly wind speeds reaching up to 7.4 km/h. Wind speeds during storm events are expected to be much higher (Knight, 2012). The average maximum annual humidity is between 75% and 80%. The minimum humidity is the lowest during the winter months (21%) and only slightly higher during the summer months, 24% (Knight, 2012).

2.4.4 Evaporation

Evaporation is usually influenced by rainfall, temperature, wind and humidity. The average annual FAO reference evaporation is 1694 mm, exceeding rainfall in the catchment all year (Knight, 2012). According to Schulze (2007) the FAO reference evaporation in the valley amounts to roughly 2100 mm per annum, approximately 400 mm higher than presented

above. Knight (2012), using data from station 20237, reported that only a small fraction (43 mm) of the average annual rainfall in the Baviaanskloof is considered to be effective and available for use. Most of the rainfall is lost to evapotranspiration (Jansen, 2008).

2.5 Water sources

The high mountain ranges surrounding the Baviaanskloof (Figure 2.1) create a catchment that drains towards the centre, thereby creating a wetter environment than proposed by the rainfall alone (Knight, 2012). There are two main water sources in the study area: (1) surface flow in the Baviaanskloof River and its tributaries and (2) groundwater in rock and alluvial aquifers (Jansen, 2008; Ellery and Rowntree, 2011).

2.5.1 Surface water

The stream network in the catchment displays a rectangular trellis drainage pattern controlled by the underlying geological structure as described above in Section 2.2 (Moon, 1988; Rust and Illenberger, 1989). It is also characterized by a high drainage density. Steep low-order tributaries flow via ravines to the valley floor and intersect with the Baviaanskloof River which winds through the valley, Figure 2.2 (Boshoff, 2008). Flash floods promptly move down tributaries. These are often ephemeral on the south side of the valley. Tributaries in the northern slot canyons are, however, perennial because of surface-groundwater interactions related to the Table Mountain Group. The slot canyons are also home to numerous fountains or springs (Ellery and Rowntree, 2011).

Mean Annual Runoff (MAR) in the catchment is between 20-50 mm (Middleton and Bailey, 2009). The Baviaanskloof River can be described as an undammed, interrupted perennial river, meaning a river with alternating reaches of perennial (confined valley sections) and intermittent or ephemeral flow (unconfined valley sections) (Stromberg *et al.*, 2007). In the narrow valley sections, surface flow is continuous for much longer periods of time, with the river channel and flood channel being fed by baseflow and surface runoff respectively (Rowntree, 2012). In the wider valley sections, the groundwater aquifer does not intersect the channel surface under normal conditions during a dry cycle. Water flow proceeds via subsurface flow. The river channel only carries surface water during or immediately after floods (Ellery and Rowntree, 2011). During wet cycles the river can flow for significant periods after rainfall, being fed by groundwater (R. Powell, Rhodes University, Grahamstown, pers.comm., 2015). This suggests high surface-groundwater interaction in the valley, a topic that will be explored in Chapters 5 and 7 of this thesis.

Unfortunately no long-term flow records exist for the study area. Simulated naturalised monthly streamflow data for ungauged catchments are, however, available from the Water Resources of South Africa 2005 study (WR2005) (Middleton and Bailey, 2009). This study will make use of the WR2005 dataset in Chapter 3 to support the assessment of extreme

events. Limited discharge measurements during low flow conditions and modelled flow data are also available from an Ecological Reserve assessment for the Baviaanskloof Mega Reserve, Figure 2.1 (Jordaan, 2010). However, studies generally focus on high discharges that are typically associated with sufficient energy to erode and transport channel sediments resulting in significant river morphological changes (Rowntree and Dollar, 1999; Wohl, 2000b; Fryirs and Brierley, 2013). A study by PhD student, R. Powell, measuring flows over longer periods in the valley is currently underway (R. Powell, Rhodes University, Grahamstown, pers.comm., 2015). River flow data (Figure 2.8) by Glenday (2015) mirror that of the variability of the rainfall data (Figure 2.7).

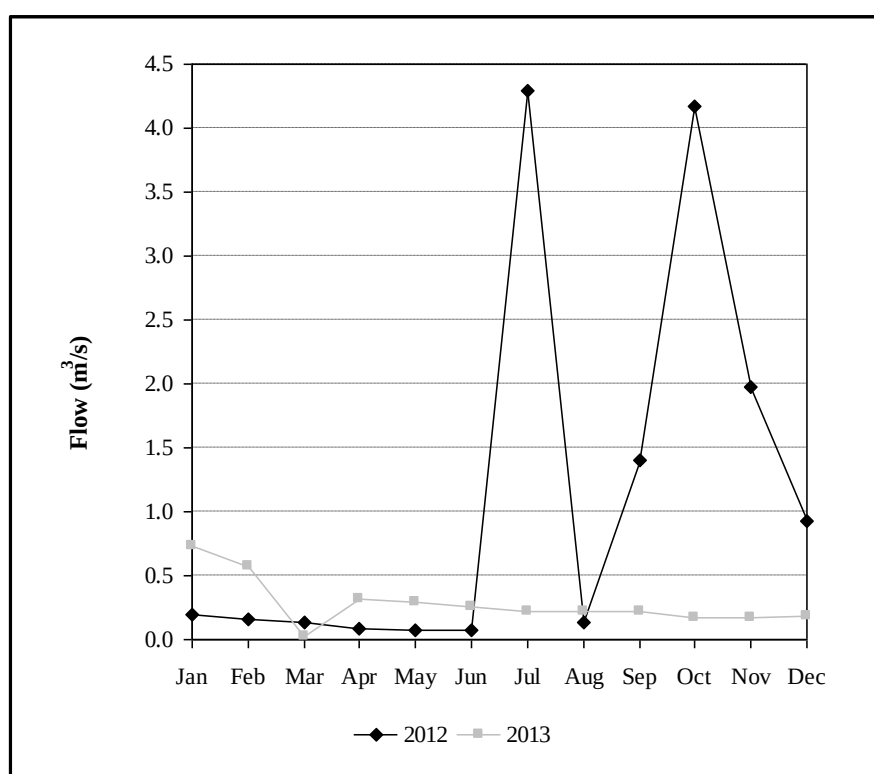


Figure 2.8: River flow data showing seasonal variation (after Glenday, 2015).

2.5.2 Groundwater

There are two primary groundwater systems in the Baviaanskloof, the Table Mountain Group aquifer and the alluvial aquifer (Jansen, 2008). The Table Mountain Group aquifer refers to the water movement in the fractures and joints of the Table Mountain Group quartzitic sandstones in the mountainous areas (Wu, 2005; Knight, 2012). It is a secondary aquifer usually affiliated with good water quality and high yields. However, groundwater storage in this aquifer is often limited, and deep groundwater drilling is very costly (Meyer, 1998; Wu, 2005). Nonetheless, this rock aquifer provides a near constant source for domestic water supply in the Baviaanskloof through springs in the slot canyons (Ellery and Rowntree, 2011).

Groundwater recharge was estimated at 2-5% of the total rainfall (Jansen, 2008). This represents 6-15 mm/a. The Table Mountain Group aquifer is also associated with a 110 m deep artesian borehole drilled on 16 February 1937 at Sewefontein which discharges 49 500 litres of water per hour (P. Ruiters, Sewefontein Tourist Information Office, Baviaanskloof, pers. comm., 2010) (Figure 2.9 a). Fountains also commonly originate from the Table Mountain Group quartzitic sandstones (Meyer, 1998). An example in the Baviaanskloof includes the seven natural fountains at Sewefontein which deliver 108 000 litres of water per hour, Figure 2.9b (Webley, 2011b).



Figure 2.9: Groundwater sources in the Baviaanskloof.

An artesian borehole (a) and fountain water (b) at Sewefontein. A pit on the farm Rus en Vrede (c).

The alluvial aquifer is located on the valley floor along (under) the Baviaanskloof River and is in direct contact with it (Jansen, 2008). Reworked Enon conglomerates mixed with coarse material derived from the Table Mountain Group quartzitic sandstones and Bokkeveld shales form the conducting material of this aquifer. It varies in thickness from a few meters at the valley margins to > 50 m in some of the central positions. This primary aquifer which is mainly recharged by surface runoff from the mountain slopes helps to sustain mainstem baseflow during the dry periods (Jansen, 2008). Additionally, water stored in the alluvial fans is assumed to percolate vertically and laterally to recharge the alluvial aquifer (Bobbins, 2011).

The net average groundwater recharge of the alluvial aquifer is in the order of 25-40 mm per year (Jansen, 2008). Hence, this aquifer stores much larger volumes of water than the secondary aquifer (Ellery and Rowntree, 2011). The alluvial aquifer usually also has good water quality. Electro-conductivity (EC) ranges from 20-40 mS/m which mirrors that of the Baviaanskloof River (Jansen, 2008). The water can be extracted through pumping and taken from springs, shallow pits (Figure 2.9c) or windmills (i.e. wells) (Illgner and Haigh, 2003; Jansen, 2008). These structures or actions all lower the groundwater table. Farmers use almost all of the water extracted for irrigation purposes (e.g. centre-pivots and quick coupling moveable systems) (Jansen, 2008; Knight, 2012). According to Jansen (2008) the interconnectivity between the rock and the alluvial aquifers is uncertain, but possible.

Due to the absence of a long-term groundwater monitoring system in the study area, detailed recharge, flow and groundwater level data are lacking. This study made use of an electrical resistivity survey to determine groundwater table depth at selected study sites in the Baviaanskloof (Chapter 5, Section 5.2.2). Likewise, Glenday (2015) developed a conceptual hydrologic model for the Baviaanskloof using various data sources. These included groundwater level data from pits and 18 piezometers installed at selected study sites in the valley.

2.5.3 Overall status and water use of the Baviaanskloof River

Although little is known about the Baviaanskloof River or its biota, recent assessments revealed that the river's overall ecological status is good to fair, i.e. largely natural to moderately modified (Jordaan and Brand, 2010). It provides many important ecosystem services, both locally and regionally (Janssen, 2008; Powell and Mander, 2009). For example, the river water is of a high quality (Boshoff, 2008; Jordaan and Brand, 2010) that is used mainly for agricultural activities and human consumption (Boshoff, 2005; Jansen, 2008). Local occupants of the valley currently rely on the pools, springs and wells or pits linked to the river system as a source of water (Ellery and Rowntree, 2011). In addition, it is a critical water resource for downstream users (Boshoff, 2008). On average the Baviaanskloof River delivers about 35-40 million m³/a to the Kouga Dam (Figure 2.1), roughly 20% (Jansen, 2008). The Kouga Dam in turn provides water to the Nelson Mandela Metropole ($\pm$ 23 million m³/a) (Boshoff, 2008) and the farmers in the fertile Gamtoos River valley, $\pm$ 50 million m³/a (Mander *et al.*, 2010).

The water use by the Baviaanskloof farmers for irrigation has been estimated at 1.75 million m³/a (Jansen, 2008), 2 million m³/a (DWAF, 2004a) and 3.3 million m³/a (Knight, 2012). The latter is 1.2 m³ more than the volume estimated by the Department of Water Affairs. It takes into account an allowable annual groundwater abstraction of 16.3 million m³ in the Baviaanskloof under the General Authorisations in terms of section 39 of the National Water Act, 1998 (Act no 36 of 1998) (Knight, 2012).

2.6 Vegetation

The Baviaanskloof supports a diverse plant life (Figure 2.10a-j) which has adapted to the physical conditions in the catchment (van Jaarsveld, 2011). The rich levels of plant species and vegetation types can be ascribed to the topography which results in several different habitats with varying soil types, micro-climates and fire regimes (Vlok, 1989; Boshoff, 2005). The Baviaanskloof Nature Reserve (Figure 2.1) in particular has about 1199 species (138 families and 570 genera) (Boshoff, 2005; 2008). The area is also well-known for its high number of endemic plants such as the threatened Willowmore cedar (*Widdringtonia schwarzii*), the cliff ox-tongue (*Gasteria rawlinsonii*) and *Stapelia baylissii* which are usually found growing in the narrow slot canyons (Boshoff, 2008; van Jaarsveld, 2011).

The river valley has complex vegetation (Vlok, 1989) because it is situated in an area where at least five biomes (Fynbos, Albany Thicket, Grassland, Savanna and Forest) converge (Euston-Brown, 2006; Mucina and Rutherford, 2006). This produces complicated vegetation patterns and unique plant assemblages (Euston-Brown, 2010) which change rapidly over short distances (Vlok, 1989; van Jaarsveld, 2011). Many of these were not captured in national scale vegetation mapping and classification studies completed by, for example, Acocks (1953; 1988), Low and Rebelo (1996) and Mucina and Rutherford (2006).

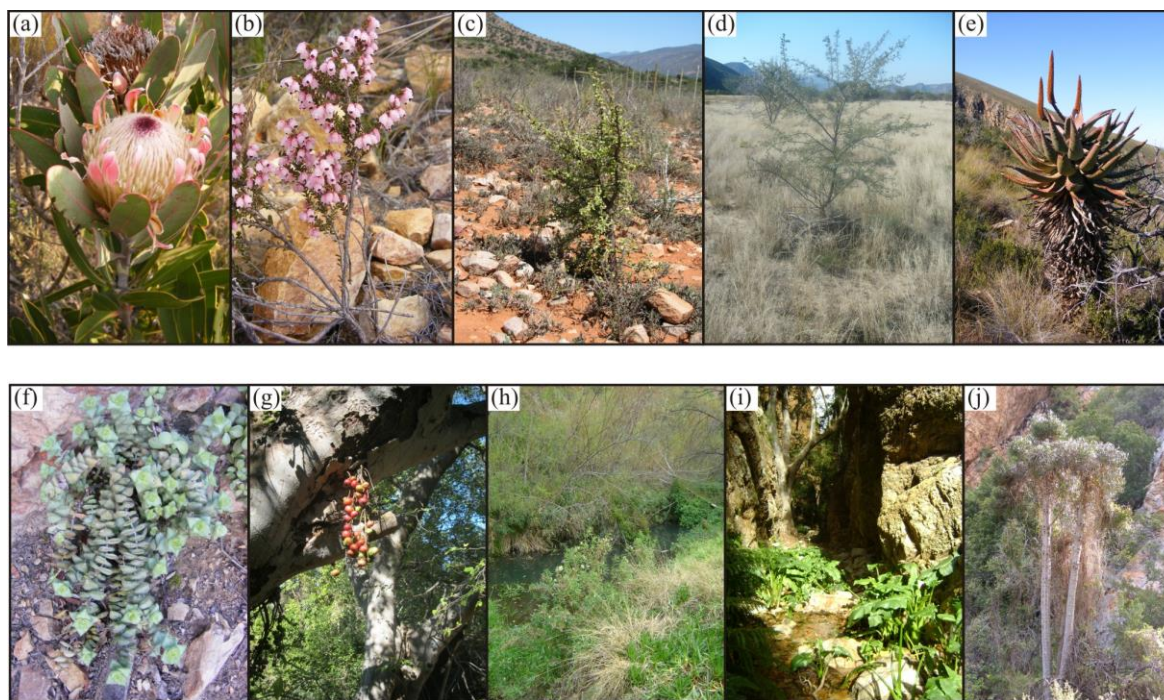


Figure 2.10: Examples of typical Baviaanskloof vegetation.

Fynbos components include proteas (a) and ericas (b). Baviaanskloof Spekboom Thicket (c) and Thicket Savanna (*Vachellia karroo*) (d) are found on the lower mountain slopes and valley floor respectively. Succulents include *Aloe ferox* (e) and *Crassula rupestris* (f). Riparian vegetation includes, for example, wild fig trees (g), sedges (h) (e.g. *Cyperus longus*) and grasses (e.g. *Pennisetum clandestinum*). The kloof areas support species such as arum lilies (*Zantedeschia aethiopicum*) (i) and *Euphorbia tetragona* (j). Photographs by J. Raath.

Although earlier initiatives (e.g. Vlok and Euston-Brown, 2002; Driver *et al.*, 2003) produced finer scale maps, the vegetation map (1:50 000) by Euston-Brown (2006) depicts more accurately the diverse nature of the Baviaanskloof flora. Figure 2.10 and Table 2.1 display the vegetation within the Baviaanskloof River catchment. Twenty different vegetation types are recognised. The study area is dominated by fynbos vegetation types (69 883 ha) found at the higher altitude areas (e.g. Figure 2.10a-b). They are generally well managed and in a good condition. This is followed by biome-transitional vegetation types (25 606 ha) and thicket, 22 983 ha, (e.g. Figure 2.10c-d) which are mostly restricted to the lower lying areas. The fynbos and thicket vegetation types are present in both solid and mosaic form (Figure 2.11).

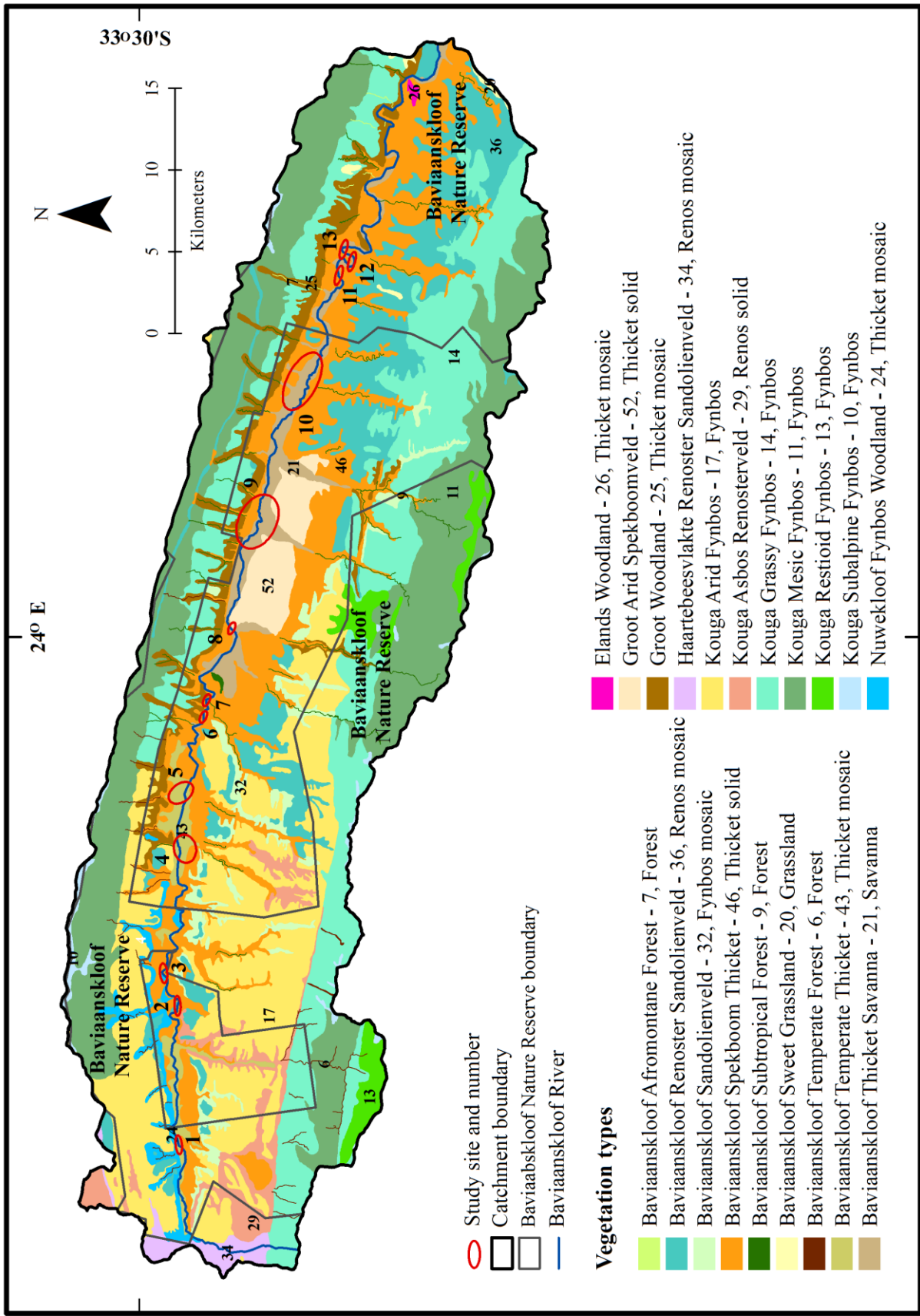


Figure 2.11: Vegetation types, Baviaanskloof River catchment (Euston-Brown 2006).

Overstocking and subsequent overgrazing (discussed in Section 2.7.1) has especially degraded the subtropical thicket vegetation (e.g. *Portulacaria afra* or spekboom, *Schotia afra*, etc.) in the area (Euston-Brown, 1995; de Jong, 2013). Dense closed-canopy vegetation has been transformed into an open savanna-like system dominated by grasses (e.g. *Cynodon dactylon*), dwarf karroid shrubs (e.g. *Atriplex lindleyi*) and umbrella shaped trees like *Pappea capensis*. The majority of degraded thicket occurs on private land, Figure 2.1 (Lechmere-Oertel *et al.*, 2005). Savanna, forest, and grassland are in the minority (Euston-Brown, 2006).

Table 2.1: Vegetation in the Baviaanskloof River catchment (Euston-Brown 2006).

Vegetation type	Area (ha)	Cover (%)
Baviaanskloof Afromontane Forest	50.6	0.04
Baviaanskloof Renoster Sandolienveld	11 591.3	9.4
Baviaanskloof Sandolienveld	3 060.1	2.48
Baviaanskloof Spekboom Thicket	18 781.7	15.23
Baviaanskloof Subtropical Forest	855.1	0.69
Baviaanskloof Sweet Grassland	219.8	0.18
Baviaanskloof Temperate Forest	372.1	0.3
Baviaanskloof Temperate Thicket	1 654.4	1.34
Baviaanskloof Thicket Savanna	3 361.4	2.73
Elands Woodland	69.2	0.06
Groot Arid Spekboomveld	2 547.7	2.07
Groot Woodland	4 928.5	4
Haartebeesvlakte Renoster Sandolienveld	1 134.2	0.92
Kouga Arid Fynbos	19 568.1	15.87
Kouga Asbos Renosterveld	3 358.9	2.72
Kouga Grassy Fynbos	21 777.6	17.66
Kouga Mesic Fynbos	25 198.0	20.43
Kouga Restioid Fynbos	2 380.9	1.93
Kouga Subalpine Fynbos	958.5	0.78
Nuweekloof Fynbos Woodland	1 464.2	1.19
Total	123 332.3	100

Even though relatively little is known about the riparian vegetation on the valley floor, the biome-mixing in this transitional area would most likely create varied species composition and distribution patterns. The channels in the narrow confined sections are lined with sedges, reeds, grasses and fig trees (Figure 2.10g-h). As discussed in Section 2.5.1, these channels usually have permanent surface water (a near-surface groundwater table), which promotes dense riparian vegetation growth. This, in turn, contributes to channel stability. For example, channel widening is inhibited (Rowntree, 2012). While several of the riparian areas are somewhat modified (e.g. destabilized banks or overgrazed) the vegetation is generally intact (Euston-Brown, 2010). The vegetation along the channels in the broad unconfined sections is more terrestrial in nature, with sweet thorn (*Vachellia karroo*) being dominant, (Figure 2.10d). These channels are typically associated with intermittent or ephemeral flow (i.e. indicating a deeper groundwater table) (Ellery and Rowntree, 2011) which promotes sparse

vegetation and channel instability. These process-form and vegetation relationships will be examined in more detail in Chapters 6 and 7 of this thesis.

The aridity of the area has largely prevented the successful establishment of exotic species in the Baviaanskloof. Invasive alien plant (IAP) infestation in the valley is limited to scattered or isolated low density populations of species such as the succulent shrubs *Opuntia ficus-indica* (prickly pear) and *Bryophyllum delagoense*. They occur in the fynbos vegetation on the mountain slopes (Mander *et al.*, 2010) and along the drainage channels, particularly in the riparian zones (Euston-Brown, 2010). Consequences of invasions can include: habitat loss and fragmentation; indigenous vegetation replacement with dense monocultures (Brock and Green, 2003; Richardson *et al.*, 2007); river channel changes (Rowntree, 1991; Birken and Cooper, 2006); reduction in water table levels (Tickner *et al.*, 2001); and reduced streamflows (Richardson *et al.*, 2007; Meek *et al.*, 2010). Present-day control measures in the valley are containment, local eradication of emerging weeds, riparian restoration and the development of a payment for ecosystem services system (PES) for listed IAP removal (Mander *et al.*, 2010).

Fires occur naturally every 8-16 years on the mountains of the Baviaanskloof (van Jaarsveld, 2011). According to Euston-Brown (2006) sites such as the sheltered kloofs and very arid vegetation are generally protected against fire. In contrast, grassland and fynbos vegetation burns regularly. Fire-prone vegetation occupies 81% of the study area (mostly fynbos species in the mountainous areas), making fire management indispensable in biodiversity and ecosystem service maintenance (Euston-Brown, 2006). Some plants depend on it for their survival while others are killed or degraded by it. Fynbos (Figure 2.10a-b), for example, is a fire-adapted vegetation that requires regular burning for its persistence (Rebelo *et al.*, 2006; Le Maitre *et al.*, 2014). Thicket vegetation does not burn, but is at risk when it is fragmented by clearing, allowing grasses and other flammable vegetation to invade (Le Maitre *et al.*, 2014). Wild fire affects fluvial landforms and processes by increasing runoff and sediment supply from the surrounding hillslopes (Bendix and Cowell, 2010). Post-fire storms in burnt catchments can also result in elevated streamflows and higher discharges (Legleiter *et al.*, 2003). Although this study will mainly focus on valley floor dynamics, hillslope fire impacts may influence the vegetation and hydrogeomorphic outputs of this study. This is an issue that is beyond the scope of this study.

2.7 Land use

2.7.1 Human occupation

Hoffman and Rohde (2007) noted that present natural environments are as much a result of human interference over the last few millennia, especially the past few hundred years, as they are of their climatic and evolutionary histories. In other words, natural environments are also cultural (Binneman, 1989) or socio-economic landscapes (Cowling *et al.*, 2007). The

Baviaanskloof has been culturally and economically used for perhaps 120 000 years, first by prehistoric humans, and in recent times by European colonists (Binneman, 1989).

Evidence in both the archaeological and historical record suggests that the first anatomically modern humans emerged in the study area during the Middle Stone Age, 120 000 to 30 000 years ago (Cowling *et al.*, 2007; Webley, 2011b). During the Later Stone Age (20 000 years ago) the hunter-gatherer San (Bushmen) people flourished. They are believed to be the direct descendants of the early humans (Boshoff, 2008; Webley, 2011b). This period was marked with technological innovations such as rock art, stone or bone artefacts, containers and decorative items (e.g. Binneman, 2000; Webley, 2011a). Thereafter, the San were displaced and eventually eliminated in the Baviaanskloof by the Khoekhoen or Khoikhoi, Iron Age agro-pastoralists and the early European farmers. When the 19th century ended the San had ceased to live as independent people in the valley (Boshoff, 2008; Webley, 2011b).

The Khoekhoen pastoralists or herders settled in the region about 2000 years ago while the Bantu-speaking Iron Age agro-pastoralists followed 1700 years ago (Boshoff, 2008). The people of the latter group were the first food producers and introduced domesticated animals (e.g. goats, cattle and sheep). Hence, this period signified the start of major socio-economic landscape changes in the catchment (Cowling *et al.*, 2007; Webley, 2011b).

European settlers, first hunters and then trekboere, with their domestic ungulates, moved into the area during the 18th century, (Table 2.2) (Urquhart, 1990). The valley was never intensively settled due to its remoteness and inaccessibility. The human population of the Baviaanskloof reached a maximum of about 2000 between the mid-19th and 20th centuries, after which it began to decline (Boshoff, 2008; Webley, 2011b). Today, only between 1000 and 1300 people reside in the Baviaanskloof (Webley, 2011b). Migration out of the area is due to limited opportunities (employment, education and housing), the attraction of towns, and a lack of cost-effective basic services such as public transport or supply stores (Boshoff *et al.*, 2000).

A public gravel road linking Patensie to Willowmore was built between 1885 to 1890 with extensions done in the 1930s and 1940s (Urquhart, 1990; Webley, 2011b). The road crosses the active channel more than 20 times (Figure 2.2) (Illgner and Haigh, 2003). Sections of the road in the Baviaanskloof Nature Reserve are currently in a very bad condition. This gravel road endures much flood damage, cutting off permanent residents from the outside world for long periods (Webley, 2011b).

The area is facing growing socio-economic pressures and an overall decline in the regional economy (Crane, 2006). The government controls 62% (75 871 ha) of the catchment in the form of the Baviaanskloof Nature Reserve while free-hold titles and private commercial farmers own 36% (44 304 ha). The remaining 2% (2 204 ha) is communal land at

Zaaimanshoek and Sewefontein, and Tchnuganoo (Noirtin, 2008; Powell and Mander, 2009; Mander *et al.*, 2010). Zaaaimanshoek (study site 8, Figure 2.2), consists of 40 households, a church and primary school occupying 179 ha. This settlement is largely dependent on social security grants and external working opportunities (Powell and Mander, 2009; Webley, 2011b). A third communal area of about 125 individuals lives within the eastern portion of the state-owned Baviaanskloof Nature Reserve (Coleske), just above study sites 11-13 (Figure 2.2). Currently the community is facing a lot of tension caused by loss of employment, access to natural resources and possible resettlement (Crane, 2006; Hough and Prozesky, 2010).

Table 2.2: Timeline of key human activities or events, Baviaanskloof.

Year	Activity or event description	Source
1817	First farms in the western Kloof granted, domestic stock farming (e.g. cattle, goats, sheep, etc.) and crop growing (e.g. maize, wheat, vegetables, etc.)	Hattingh (2011)
1850-1900	Construction of water furrows. Water is directed to small dams (by gravity).	Illgner and Haigh (2003)
1926	Land use mainly seed production. Baviaanskloof was a major producer of vegetable seed (e.g. onions, carrots and pumpkins).	Bobbins (2011)
1939	Overstocking with sheep.	Illgner and Haigh (2003)
1950	Soil erosion due to overgrazing.	Illgner and Haigh (2003)
1960	Levee or berm construction.	Illgner and Haigh (2003)
1962	Forced stock reductions (i.e. veld recovery).	Illgner and Haigh (2003)
1970-1987	Angora goat boom, overstocking. Reduced hillslope vegetation due to overgrazing. Hillslope sheet and gully erosion.	J. Buckle, South African Biodiversity Institute, Port Elizabeth, pers.comm., 2011
1982-early 1990s	Extensive river-floodplain engineering (e.g. berm and furrow construction; stream channelization and diversions) in response to government agricultural subsidies after major floods. Subsidies ceased in 1994.	Jansen (2008); de Jong (2013)
1982-1986	Introduction of centre pivot irrigation.	P. Kruger, Zandvlakte, Baviaanskloof, pers.comm., 2010; de Jong (2013)
1986	Change in veld burning policy. Block burning was replaced with a natural burning regime. Since then increased run-off due to uncontrolled fires reported.	Boshoff <i>et al.</i> (2000); Jansen (2008)

The family-owned farms and community properties on the valley floor are entirely encircled by the western sector of the Baviaanskloof Nature Reserve, Figure 2.1 (Crane, 2006). The private farming community consists of traditional farmers and newcomers. The former group generate most of their income from agriculture and some tourism (e.g. through accommodation, game viewing or hunting and off-road tours) while the latter group mainly practice tourism, catering and hobby farming (de la Flor Tejero, 2008; De Paoli, 2008). Land use data for the catchment are available from de la Flor Tejero (2008), Janssen (2008), Noirtin (2008), Mander *et al.* (2010), Knight (2012) and de Jong (2013).

The catchment consists mostly of natural vegetation (69%) found in the Baviaanskloof Nature Reserve and on farm land that is not in use or set aside for conservation (i.e. “nature”). Degraded land (i.e. sparsely vegetated areas) is associated with mixed livestock production (e.g. Dorper sheep, Angora goats and cattle) (27%) and an assortment of various uses (e.g. tourism and hobby farming), 3%. Cultivation (e.g. irrigated and dryland) accounts for only 1%, Figure 2.12 (de Jong, 2013). It is normally restricted to the alluvial soils along the Baviaanskloof River. Irrigated crops comprise, for example, wheat and maize; vegetable seed production (e.g. onions and pumpkins); citrus fruit and pasture legumes like lucerne and barley (Illgner and Haigh, 2003; Webley, 2011b).

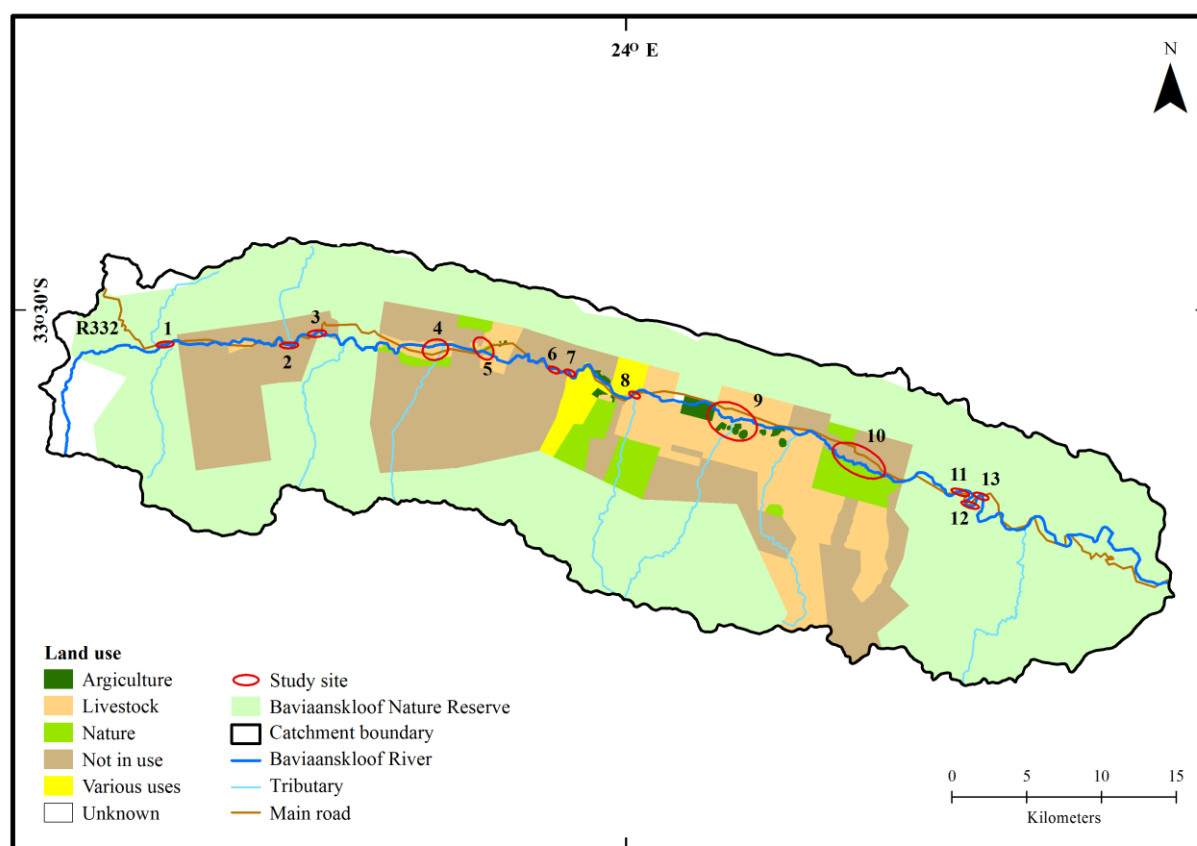


Figure 2.12: Land use in the Baviaanskloof River catchment (de Jong, 2013).

Several changes to farming conditions in recent decades resulted in drastic changes in the land use patterns of the Baviaanskloof. Land use change is driven typically by economic reasons, not by ecological or sustainability motives (Crane, 2006). Extensive small stock farming in the mountainous areas has largely been terminated. There has also been a reduction in cultivation and vegetable seed production which used to be a flourishing industry in the past (Table 2.2) (Knight, 2012). Commercial agriculture in general has become less viable with growth in this sector limited (Crane, 2006). Main reasons for the downscaling in agricultural activities included high input costs, low producer prices and predation (Knight, 2012).

Extreme droughts and floods (Section 2.4.1) combined with poor land and water resource management in the past have led to landscape degradation which is highly problematic for the sustainable supply of important ecosystem services (Section 2.5.1). Extensive farming activities have proven to be not viable and depended on flood damage protection (de la Flor Tejero, 2008; Jansen, 2008; Mander *et al.*, 2010) that altered the hydrological connectivity. Historic overstocking (e.g. goats and sheep) on the hillslopes resulted in overgrazing accompanied by numerous stock paths (Illgner and Haigh, 2003; Boshoff, 2008; de Jong, 2013; van Luijk *et al.*, 2013). This reduced the hillslope vegetation (Figure 2.13a) leading to increased downslope runoff and soil erosion (Draaijer, 2010; van Luijk *et al.*, 2013) with increased streamflow and sedimentation on the valley floor (Table 2.2) (Jansen, 2008). Common erosion features in the valley include rills (at slopes 3-21° and vegetation cover 4-14%) and deep gullies or dongas (Figure 2.13c) (at slopes < 4° and vegetation cover 32%) (Draaijer, 2010). Access roads are also a source of erosion (Boshoff *et al.*, 2000). High siltation rates pose a serious threat to river water quality (Boshoff, 2008). In addition, overgrazing depletes natural capital by reducing biodiversity and ecosystem services, ecosystem carbon stocks, plant productivity (Mills and Cowling, 2010) and soil quality (e.g. less organic matter, nutrients and moisture) (Mander *et al.*, 2010).



Figure 2.13: Human related affects or activities in the Baviaanskloof River catchment.

Reduced hillslope vegetation (a). Gully erosion (b). The construction of levees or artificial embankments alongside the Baviaanskloof River on the farm Rus en Vrede, site 9 (c). Human activity timeline and study site locations as per Table 2.2 and Figure 2.2.

Farming activities also necessitated the construction of berms or levees along both the main and side channels (Figure 2.13c) (Rowntree, 2012), the artificial straightening of unstable fan channels (Bobbins, 2011) and stream channelization and diversions to protect the cultivated fields and infrastructure from flooding (Table 2.2). Numerous farm dams (Figure 2.2) and diversion structures (e.g. furrows or canals) were also built to supply water (Jansen, 2008; de Jong, 2013). Generally, tributary flood water is redirected straight into the main channel preventing the natural attenuation or water retention function of the floodplain. This causes high flow velocities associated with river bed and bank erosion. Channel erosion has increased since the 1980s and caused major incision (down cutting) of the Baviaanskloof River in especially the unconfined valley sections (Figure 2.14). Channel incision then triggered groundwater table lowering (a 3 m drop at times) which impacts negatively on the available water sources (Figure 2.9b-c) (Jansen, 2008; de Jong, 2013). In the Baviaanskloof river-floodplain engineering was at the expense of sustained groundwater recharge and baseflow (Jansen, 2008; Mander *et al.*, 2010). This study will map past geomorphic and land cover changes on the valley floor in Chapter 4 expanding on the information detailed in this section.



Figure 2.14: Main channel bed and bank erosion on the farm Rus en Vrede, study site 9.

Here the river is about two meters incised. The incision of the Baviaanskloof River is one of the main causes of groundwater table lowering in the study area.

2.7.2 Protection and management of the Baviaanskloof River catchment

The Baviaanskloof Nature Reserve, previously known as the Baviaanskloof Forest Reserve, occupies over half of the catchment (Figures 2.1 and 2.11) and therefore its management is very important. Historically, it was managed for water purposes by the national Department of Forestry from 1923 to March 1987 under the Forest Act. The Department's policy of mountain protection was aimed at promoting a constant yield of high quality water by maintaining vegetation cover and abating soil erosion (Boshoff *et al.*, 2000; Boshoff, 2008). To this end, livestock trespassing on state land were impounded, and fire control (i.e. firebreaks and prescribed burns) was accepted as an essential management tool (Boshoff *et al.*, 2000). In 1970 the Mountain Catchment Areas Act was proclaimed and the forestry policy expanded to include nature conservation and public recreation (Boshoff *et al.*, 2000; Boshoff,

2008). The reserve became managed according to wilderness principles and became part of the provincial government, Cape Nature Conservation, from April 1987 to 1993. Fire control ceased (Table 2.2) and an ecosystem approach to catchment management was adopted (Boshoff *et al.*, 2000).

In 1994 the Department of Economics Affairs, Environment and Tourism (DEDEA), Eastern Cape Government assumed management of the Baviaanskloof Nature Reserve (Boshoff *et al.*, 2000; Boshoff, 2008). There was a proposal in 1997 to consolidate the western sector of the reserve (Boshoff, 2008) through expropriation of all private land within the valley. Under the new democratic order of 1994 this proposition was met with fierce resistance. A viable solution had to take into account the local community and existing land use adjacent to the reserve, a concept later termed “living landscapes” by the Baviaanskloof Mega Reserve project (BMRP) which started in late 2002 (Boshoff, 2005; Crane, 2006; Boshoff, 2008). This concept is also used by de Jong (2013) on a common vision for the Baviaanskloof Hartland. This project investigated sustainable land uses that are supported by and applicable to the people in the Baviaanskloof. The BMRP project seeks to expand and consolidate the existing protected area network (i.e. formal protected areas and privately owned land) and create a Mega Reserve (Figure 2.1) in which the conservation of the regional biodiversity and natural resources are aligned with rural and agricultural development needs. Concerning the former, the goal is to eventually obtain 500 000 ha of land (Ashwell *et al.*, 2006; Boshoff, 2008). Currently, 160 000 ha of private land (including five conservancies) is managed as part of the Mega Reserve’s Proud Partner Programme through a range of agreements or contracts with landowners (Boshoff, 2008; Hattingh, 2011).

The Baviaanskloof Nature Reserve (400 000 ha in 2011) (Hattingh, 2011) has been managed by the Operations Directorate of the Eastern Cape Parks (ECPB, 2007) since 2004. More importantly, the reserve was proclaimed by the United Nations Educational, Scientific and Cultural Organisation (UNESCO) as a World Heritage Site in 2004 (Boshoff, 2005; 2008). This means that not only is the area of regional significance, it is also an international node of conservation importance. Its national and international conservation status demands that sufficient resources are made available to ensure its integrity. To this end, its management must conform to a plan approved by UNESCO (Boshoff, 2005; 2008). Although there is a draft Integrated Management Plan for the Baviaanskloof Mega Reserve which includes the Baviaanskloof Nature Reserve, a spatially explicit restoration and monitoring plan is lacking (ECPB, 2007). This thesis through its research on valley confinement setting, hydrogeomorphic process-form and vegetation relationships (Chapter 7), will inform this plan (Chapter 8).

In the Baviaanskloof the reduction of water retention capacity and lowered groundwater table has affected the livelihoods of the farmers. Tourism and payments for ecosystem services like carbon sequestration are now seen as opportunities for an alternative way of income for

farmers (de Jong, 2013). The Subtropical Thicket Restoration Project (STRP) was started to restore the degraded areas of thicket at various scales, starting at farm scale. Active intervention is required as severely degraded thicket is unable to recover naturally (Mills *et al.*, 2007; Mills *et al.*, 2015). Although this project was launched in January 2004 by the Department of Water Affairs and Forestry (DWAF), now the Department of Water and Sanitation (DWS), it has its origins in 1999 from the Conservation Farming Project. It falls under the DWS/Working for Woodlands Programme, with funding provided by the government's Expanded Public Works Programme (EPWP). The project's aim is to investigate the feasibility of thicket restoration for carbon farming (Powell, 2007; Noirtin, 2008; Mills *et al.*, 2015). This involves reforestation of the degraded areas with indigenous vegetation. Presently, cuttings of spekboom, obtained from a propagation nursery at the Kouga Dam (Figure 2.1) or harvested from the wild, are being planted, for example, in the Cambria area of the Baviaanskloof (Powell, 2007; Noirtin, 2008).

Several non-profit organizations are active in the Baviaanskloof. Living Lands acts as a secretariat for the PRESENCE network which was set up in 2007. PRESENCE (Participatory Restoration of Ecosystem Services and Natural Capital in the Eastern Cape) evolved from a research based network to a communication platform (Hattingh, 2011; Van den Broek *et al.*, 2012). In 2011 an early implementation phase started which included erosion mitigation, indigenous reforestation with assistance from the STRP, fan restoration, etc. (Living Lands, 2011; Van den Broek *et al.*, 2012). Living Lands together with PRESENCE network partners such as the Working for Wetlands programme also initiated several restoration activities (Figure 2.15a-f) on private land in the Baviaanskloof River catchment (Van den Broek *et al.*, 2012). This government programme was initiated in 2004 and is currently managed by the South African National Biodiversity Institute (SANBI) on behalf of the Department of Environmental Affairs (DEA). It is an offspring of the Working for Water (WfW) programme which was administered previously through the DWAF and now the DEA. The programme's primary focus is wetland rehabilitation and the protection and sustainable use of wetlands (Turpie *et al.*, 2008).

Recently, work also started on the restoration of the Baviaanskloof River and its wetlands that have been lost through flood protection activities. The aim of this restoration is to increase the water retention in the landscape and restore the base flow. Gabion weirs have been placed in the Baviaanskloof River (e.g. site 10, Zandvlakte, Figure 2.15e-f) to stop the incision of the river bed and to raise the groundwater level. It is hoped that the water behind these structures will be retained, hence restoring the wetlands (de Jong, 2013; Rowntree, 2014). Likewise, the levees on the sides of the fan channels are currently being removed by Water for Food and Ecosystems and Living Lands to allow the water to spread over fan surfaces (Figure 2.15c-d). Newly constructed levees (i.e. blocking structures) placed perpendicular to the old channel will then force the water to spread out, instead of following the anthropogenic channel (Living

Lands, 2011; de Jong, 2013). This thesis will also inform the above mentioned restoration efforts (Chapter 8).

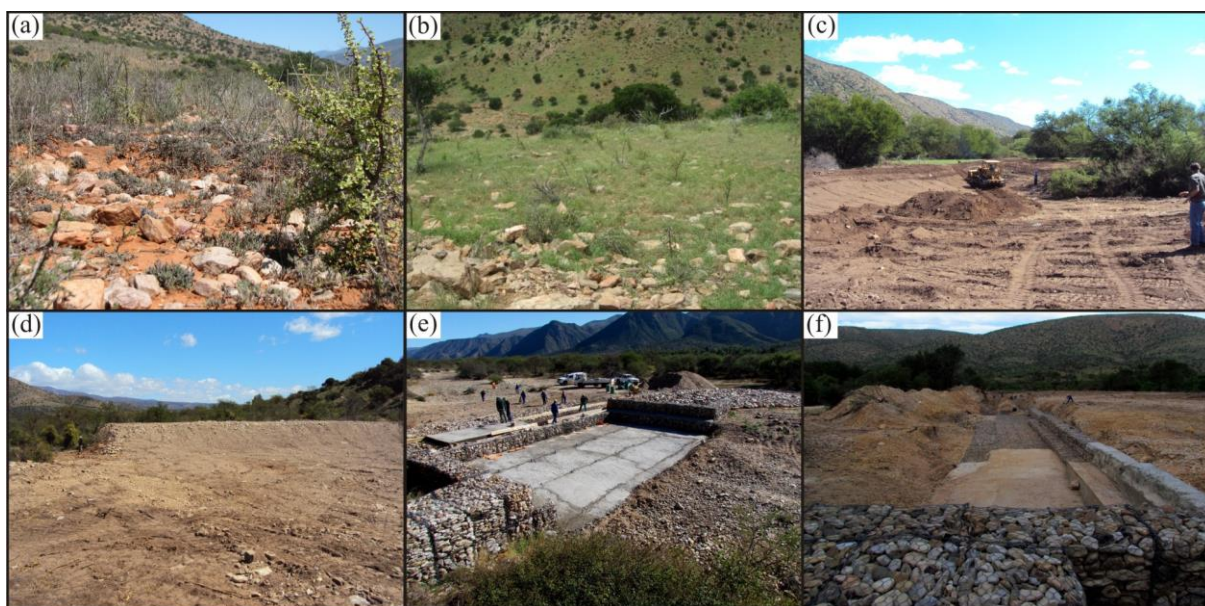


Figure 2.15: Examples of restoration activities in the Baviaanskloof.

Replanting of degraded thicket areas with spekboom (a-b). Levee removal on alluvial fans to allow the water to spread out onto floodplain and fan surfaces (c-d). The construction of gabion weirs across the Baviaanskloof River at Joachimskraal and Zandvlakte by Working for Wetlands (e-f). Sites as per Figure 2.2. Photographs by N. Blanksma, J. Broekman, J. Buckle and L. Smith-Adao.

2.8 Study site selection and description

A desktop analysis employing Google Earth, digital 1:50 000 topographical maps (DLA-CDSM, 1967, 1985, 1986, 2000) and SPOT-5 imagery (Centre National d' Etudes Spatiales, 2012) displayed in GIS facilitated the selection of potential sites. Criteria for site selection were:

1. Valley confinement setting representation. All three valley confinement settings (confined, semi-confined and unconfined) had to be represented.
2. Degree of disturbance (i.e. low human and natural impacts). It was not possible to do this for all the sites, and sites 2, 6 and 9 were located in close proximity to engineering structures (e.g. levees), agricultural fields and human settlement.
3. Site suitability or representivity. This involved capturing the diverse geomorphic features, morphometric characteristics and relative uniformity of hydrological conditions within reaches.
4. Accessibility (e.g. land owner permission and site access).

Highly impacted sites (e.g. with channelization, diversions, degraded vegetation, etc.) were generally avoided but this was not always possible. Since Baviaanskloof is a remote area with difficult access, the chosen sites had to be located close to the public gravel road. However, they were situated as far as possible from any road bridges or crossings to minimize their negative effects.

Final study sites were selected based on field verification. The 13 selected sites (Figure 2.16) were restricted to the foothill zone and reflected the range of biophysical conditions that occur over the length of the Baviaanskloof River valley. These sites can be classified into wet (year-round surface flow) and dry (channel bed dry for part or most of the year) sites. Streamflow permanence was employed as an indicator of low flow hydrology which is a suitable indicator of long-term variations in depth to groundwater (Lite and Stromberg, 2005). Basic site characteristics are summarized in Table 2.3.

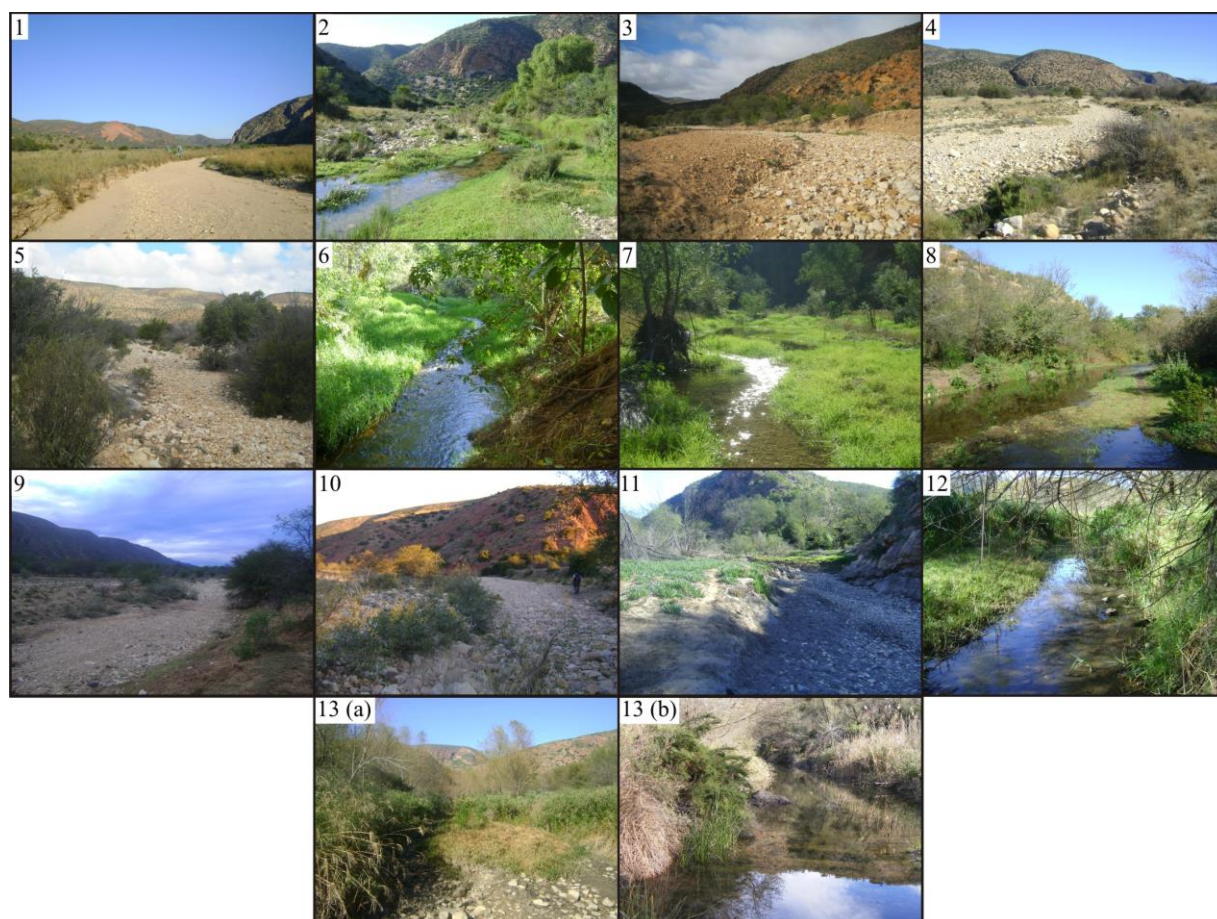


Figure 2.16: The 13 study sites selected on the Baviaanskloof River.

Each photograph is labelled with its respective site number which corresponds to Table 2.3. Note that study site 13 had both a dry bed channel (a downstream view, 13a) and a wetted channel (an upstream view, 13b). Study site locations within the Baviaanskloof River catchment and along the longitudinal profile as per Figures 2.2 and 2.5 respectively.

Table 2.3: Description of study sites.

Study site locations within the Bavaanskloof River catchment and along the longitudinal profile as per Figures 2.2 and 2.5 respectively. Geomorphic zones after Rowntree *et al.* (2000). masl = metres above sea level.

Study site (altitude, masl)	Co- ordinates (dd)	Geomorphic zone	Gradient (%)	Distance downstream (km)	Confinement setting	Cross-valley geomorphic characteristics	Vegetation characteristics	Disturbance characteristics
1, Nuwekloof (863)	-33.517506° 23.640048°	Upper foothill	0.0097 (1.0)	11.43	Semi-confined	Steep hillslopes; wide single main channel with high banks; low sinuosity; channel width > 10 m; surface flow absent; river bed substratum coarse with fines; landforms include bars, a high narrow terrace and floodplain with secondary channels.	Open grassy area with scattered young trees and shrubs.	Instream woody debris.
2, Verlatenrivier (763)	-33.527253° 23.749145°	Upper foothill	0.0076 (0.8)	20.16	Confined	Steep hillslopes; narrow single main channel with low to moderately high banks; low sinuosity; channel width 1-3 m; surface flow; reach morphology run-riffle; river bed substratum coarse with fines; landforms include flood benches, point bars, a high terrace and an alluvial fan at the bottom of the reach.	Open grassy areas alternate with densely vegetated areas; aquatic plant species; open tree canopy.	Degraded area, grazing, windmill (well 2 m deep), woody debris.
3, Kasey (743)	-33.513433° 23.773396°	Upper foothill	0.0094 (0.9)	22.78	Semi-confined	Steep rock cliffs for valley sides; wide main channel with high, steep banks (right bank modified); channel slightly more sinuous; channel width vary between 5-10 m; surface flow absent; river bed substratum coarse with fines; landforms include floodplain, bars and flood benches.	Scattered mature tree, shrub and grass species.	Very degraded area, artificial embankments, woody debris.
4, Verlorenrivier (663)	-33.514253° 23.842647°	Upper foothill	0.0085 (0.9)	32.07	Unconfined	Steep hillslopes; wide main channel with very high to low banks; channel more sinuous (i.e. meandering); channel width > 10 m; surface flow absent; river bed substratum coarse with fines; landforms include a wide floodplain with secondary channels, dunes and alluvial fan deposits, bars and flood benches.	Open grassy area with scattered young trees and shrubs.	Farm dams, pits, agricultural fields, grazing, woody debris.
5, Uitslag (623)	-33.514634° 23.885580°	Upper foothill	0.0082 (0.8)	36.24	Unconfined	Steep hillslopes; wide main channel with high, steep banks; single and multi-channelled, channel more sinuous (i.e. meandering); channel width > 10 m; surface flow absent; river bed substratum coarse with fines; landforms or features include a wide floodplain with incised secondary channels and coarse alluvial fan deposits (boulders and cobbles); tributaries, flood benches.	Open grassy areas alternating with densely vegetated areas; mature to old plant species.	Farm dams, furrows, artificial embankments, agricultural fields, grazing, woody debris.
6, Beacosnek (583)	-33.561152° 23.899210°	Upper foothill	0.0080 (0.8)	41.77	Confined	Steep rock cliffs for valley sides; narrow single main channel with low to moderately high banks; low sinuosity; wetted perimeter 1-5 m; surface flow; river bed substratum coarse with fines; reach morphology pool-run-riffle; landforms include narrow floodplain surfaces and flood benches, bars and a high terrace.	Dense riparian plants; aquatic plants; open grassy areas alternating with densely vegetated areas; tree canopy both open and closed.	In-channel wood jams, woody debris.
7, Beacosnek (563)	-33.548538° 24.007749°	Upper foothill	0.0075 (0.7)	44.26	Confined	Steep rock cliffs for valley sides; narrow single main channel with low to moderately high banks; low sinuosity; wetted perimeter 1-5 m; surface flow; river bed substratum coarse with fines; reach morphology pool-run-riffle; landforms include narrow floodplain surfaces, flood benches and bars.	Open grassy areas alternating with densely vegetated areas; aquatic plants; tree canopy open.	Degraded area; in-channel wood jams; woody debris.
8, Zaaimanshoek (523)	-33.557962° 24.017054°	Upper foothill	0.0122 (1.2)	49.45	Semi-confined	Steep hillslopes; upstream ravine; narrow to wide single main channel with low to high banks; channel slightly more sinuous; wetted perimeter 1-6 m; surface flow; reach morphology pool-riffle; riverbed substratum coarse with fines; landforms include broader floodplain surfaces with dunes and former channels, flood benches, an island, bars and a high narrow terrace.	Dense riparian vegetation with exotics; aquatic plants; open grassy areas alternate with densely vegetated areas; tree canopy both open and closed.	Degraded area, furrows, grazing, human settlement, wood cutting, footpaths; woody debris.

Table 2.3: Continued from previous page.

Study site (altitude, masl)	Co- ordinates (dd)	Geomorphic zone	Gradient (%)	Distance downstream (km)	Confinement setting	Cross-valley geomorphic characteristics	Vegetation characteristics	Disturbance characteristics
9, Rus en Vrede (483)	-33.577352° 24.101346°	Upper foothill	0.0088 (0.9)	54.15	Unconfined	Steep hillslopes; wide main channel with well-developed high banks; higher channel sinuities (i.e. meanders); single and multi-channelled (i.e. braid pattern); channel width > 10 m; surface flow absent; river bed substratum very coarse with some fines; landforms or features include wide floodplain surfaces with coarse alluvial fan deposits (boulders and cobbles); bars; islands; tributaries; multiple broad terraces.	Dense vegetation with mature to old plant species alternating with open grassy areas; tree canopy both open and closed.	Farm dams, pits, agricultural fields, artificial embankments, paths, grazing, woody debris.
10, Zandvliakte (363)	-33.592881° 24.169158°	Lower foothill	0.0058 (0.6)	70.83	Unconfined	Steep hillslopes; wide main channel with low to high banks; single and multi-channelled (i.e. braid pattern); river bed substratum coarse with fines; channel width > 10 m; surface flow absent; landforms or features include wide floodplain surfaces with coarse alluvial fan deposits (boulders and cobbles); bars; islands; tributaries; multiple broad terraces.	Dense vegetation with mature to old plant species alternating with open sandy areas; tree canopy mostly open.	Farm dams, pits, furrows, old agricultural fields, diversion pipe line, woody debris.
11, Bavianskloof Nature Reserve (343)	-33.604479° 24.226564°	Lower foothill	0.0068 (0.7)	74.27	Confined	Steep rock cliffs for valley sides; narrow single main channel with low to very high banks; channel width 1-2 m to > 10 m; surface flow absent but shallow groundwater table; river bed substratum very coarse with fines; landforms include narrow floodplain surfaces with dunes; flood benches; bars; secondary channels.	Densely vegetated areas alternating with open sandy areas.	Degraded area, grazing, furrows, woody debris.
12, Bavianskloof Nature Reserve (323)	-33.650049° 24.228020°	Lower foothill	0.0046 (0.5)	77.20	Semi-confined	Steep rock cliffs for valley sides; main channel with moderate to high banks; channel slightly more sinuous; wetted perimeter 1-5 m; surface flow: river bed substratum coarse with fines; reach morphology pool-run-riffle; landforms include broader floodplain surfaces; flood benches; a wider lower terrace.	Dense riparian vegetation, aquatic plant species; open areas alternating with densely vegetated areas; tree canopy both open and closed.	Woody debris, signs of a fire.
13, Bavianskloof Nature Reserve (303)	-33.678238° 24.370664°	Lower foothill	0.0047 (0.5)	81.54	Unconfined	Steep hillslopes; meandering single main channel with low to high banks; channel width 2-10 m; surface flow; reach morphology pool-riffle; river bed substratum coarse with fines; landforms include floodplains with dunes; secondary channels; flood benches.	Dense riparian vegetation, aquatic plant species; open areas alternating with densely vegetated areas; tree canopy both open and closed; mature to old plant species.	Furrows, woody debris.

Chapter 3: Historical rainfall and streamflow changes

3.1 Introduction

Rainfall (i.e. amount and timing) is one of the most important controlling factors in determining fluvial style because it affects both the flow regime and vegetation (Goudie, 2006; Cadol *et al.*, 2011; Grenfell *et al.*, 2014). The components of the flow regime that regulate geomorphological and ecological processes in rivers are: magnitude, frequency, duration, seasonal timing, predictability and rate of change (flashiness) of flow conditions (Poff *et al.*, 1997; Naiman *et al.*, 2008). Natural flow variability creates and maintains the dynamics of in-channel as well as overbank conditions and habitats (e.g. floodplains are frequently inundated) (Poff *et al.*, 1997; Naiman *et al.*, 2008; Fryirs and Brierley, 2013). This plays a vital role in the functioning of riparian plants (Francis, 2006; Gurnell, 2014) and upland terrestrial plants (Bendix and Hupp, 2000; Osterkamp and Hupp, 2010). Very high rainfall often leads to flood discharges (Goudie, 2006). Increased discharge can result in river instability, for example, channel widening, incision and pattern change (Friedman *et al.*, 1996; Wohl, 2000b). Plant communities are also affected by hydrogeomorphic controls (Hupp and Osterkamp, 1996; Lite *et al.*, 2005; Francis, 2006; Sandercock *et al.*, 2007; Bendix and Stella, 2013). In general, extreme floods reset physical habitats (Naiman *et al.*, 2008) while moderate and small or minor floods remove in-channel vegetation and recharge groundwater for shallow rooted plants respectively. Normal low flows sustain or maintain plant communities and provide recruitment opportunities (Naiman *et al.*, 2005).

Semi-arid and arid regions are characterised by cycles of wet and dry periods linked to scarce and erratic rainfall, and intermittent or ephemeral channels (Figure 1.2). River flows in semi-arid and arid rivers are sporadic with fewer observed floods because flow is highly variable (Tooth, 2000b; Bull and Kirkby, 2002). During years of low rainfall, zero flow periods or periods of significantly low but persistent flow are normal in rivers, especially if they are not perennial (Bull and Kirkby, 2002; Gordon *et al.*, 2004). Extremely low rainfalls over prolonged periods, however, often lead to devastating droughts. Just like floods, droughts are considered an integral part of the flow regime of a river system, shaping and maintaining many aquatic communities and ecosystems (Humphries and Baldwin, 2003; Lake, 2003). A shortage in rainfall typically results in reduced runoff, soil moisture, groundwater levels and streamflow (Lake, 2000). Likewise, the physical direct effects of droughts on a river include a complete drying of the channel, habitat area reduction (Lake, 2003) and in-stream vegetation encroachment and sedimentation. Ultimately, the result is river stability associated with single-channel patterns (Goudie, 2006).

Continuous long-term streamflow records used to perform a flood analysis and to infer associated geomorphic effects (Juracek and Fitzpatrick, 2009) are limited (Benito *et al.*,

2010), especially in semi-arid areas. Numerous approaches to this problem have been considered over the years (see Blazkova and Beven, 1997; Benito *et al.*, 2010; Gericke and du Plessis, 2013). For example, one approach is to use flood records from comparably-sized, adjacent catchments with similar rainfall regime and land use to estimate the flood history in the ungauged catchment (Kondolf and Larson, 1995; WMO, 2008). This is often difficult because these rivers are also rarely gauged, meaning that there is a lack of river flow monitoring stations collecting routine hydrological data (Hooke, 2007; Benito *et al.*, 2011). Another approach is to estimate flood frequency distribution on the basis of more readily available long-term rainfall records (Blazkova and Beven, 1997). Rainfall is usually one of the few meteorological measurements made in dryland regions (Karimi-Googhari, 2011). This study adopted the latter approach since discharge data in the Baviaanskloof River catchment were lacking. Furthermore, although discharge records are available from the neighbouring Kouga River catchment (Figure 2.1), the two catchments are too different in both natural and anthropogenic characteristics.

Generally, the analysis of observed rainfall records provides insight into rainfall variability and patterns. Increases in extreme rainfall can also result in increased flood frequencies (Suppiah and Hennessy, 1998). However, the conversion of rainfall into streamflow is complex. Several factors can independently influence the cause and effect relationship between rainfall and streamflow. Examples include factors such as the extent of rainfall in the catchment; soil saturation before the rainfall event; and the relation between the size of the catchment and the duration of the rainfall event (Blazkova and Beven, 1997). For instance, different rainfall intensities may be superimposed on different sub-catchments during the same rainfall event (Moody *et al.*, 2008).

This chapter is primarily designed to meet objective one of the study (Section 1.4) and in doing so partially addresses objectives two to three (Figure 1.2). Objective one examines historic rainfall patterns and climate extremes while objective two investigated historic geomorphological, land cover and vegetation changes. Objective three determines the two-way links between hydrogeomorphic processes and landforms, including surface-groundwater interactions, and vegetation distribution patterns on the valley floor. Objective one is addressed by examining and interpreting hydrological information obtained through:

- 1: Rainfall records (daily, monthly and yearly).
- 2: Modelled streamflow records (monthly and yearly).
- 3: A flood and drought chronology (documentary evidence and interviews).

The chapter aims to deduce historical wet and dry periods and flood frequencies associated with climate extremes in order to explain past (Chapter 4) and present (Chapters 5-7) morphological and vegetation changes of the ungauged semi-arid Baviaanskloof River valley. Valley floor changes observed today reflect an integrated history of former floods or droughts (this chapter) and land use impacts (Chapter 4).

The chapter is divided into three main sections: methods (Section 3.2), results (Section 3.3) and discussion and conclusion (Section 3.4). The methods section deals with data collection, analysis and presentation. The results section first considers the analysis concerning rainfall patterns and climate extremes (Section 3.3.1). An analysis related to published modelled streamflow data is presented next (Section 3.3.2), followed by the flood and drought analyses (Section 3.3.3). The discussion and conclusion section examine the results collectively, interpreting key chapter findings.

3.2 Methods: Data collection, analysis and presentation

This study made use of secondary data sources to obtain hydrological information for the Baviaanskloof River valley. Data sources included: (1) daily, monthly and yearly rainfall records (1926-2010); (2) published modelled monthly and yearly streamflow (1920-2004); (3) documentary evidence (1840-2010) and (4) two informal interviews in 2009. Rainfall data from five rain gauge stations were used to examine changes in rainfall pattern and its implication for flood and drought occurrence. The overlapping timeframes between the rainfall records of the different stations enabled cross-checking, which enhanced data interpretation.

In addition, there was a specific focus on extreme wet and dry periods. Characteristics of extreme daily rainfall that were analysed include magnitude, frequency and seasonality. River flows (flood and low flows) were then deduced from modelled streamflow records. Information from available documentary records and interviews were also used to construct a flood and drought chronology.

In terms of the data analyses, unless otherwise stated, basic statistical techniques such as computation of totals, averages and percentages were performed using functions (e.g. filter, custom sort, sum, average and percentage) in Microsoft (MS) Excel. The results were then either charted or tabulated.

3.2.1 Rainfall patterns and climate extremes

Data verification

All the available daily and monthly station rainfall records for the Baviaanskloof area were obtained from the Agricultural Research Council (ARC) and the South African Weather Service (SAWS) climate databases. The ARC provided most of the rainfall records. All of the records had missing data and the record duration varied considerably. There was some overlap of station data time series which allowed for verification during the quality assurance procedure. Initial station selection criteria included station location, sufficient record length and minimal data gaps. All stations that were selected in the catchment were in close

proximity to the study sites, with at least 30 years of data and no more than 10% missing data. Data availability limitations, however, necessitated the selection of additional stations with shorter time series, higher percentages of missing data or located outside of the catchment. Seven rain gauge stations were finally chosen providing rainfall data for the period 1926-2010 (84 years) (Table 3.1). The positions of these stations are shown in Figure 3.1.

Table 3.1: Rainfall stations selected for the study.

Data sources: the Agricultural Research Council and South African Weather Service. The asterisk indicates the stations making up the combined dataset.

Station name (coding number)	Time series	Record (years)	Altitude (m)	Co-ordinates (dd)	Missing monthly data
Voorkloof (10467)	1930-1957	27	915	-33.516666° 23.716667°	1931-1932, Mar & Oct 1933, Feb-Dec 1938, Jan-Jul 1939, Feb 1942 & Feb-Dec 1957.
Stadtis Bos (10477)	1952-1991	39	760	-33.533332° 23.950000°	Jan-Jul 1952, Jul 1958, Sep 1959, Aug 1990 & Sep-Dec 1991.
Stadtis Police Station (22272) *	1994-2010	16	765	-33.549999° 23.066667°	Only scattered missing daily data.
Rust en Vrede (10480) *	1978-1991	13	432	-33.566665° 23.083333°	Jan-Jul 1978 & Dec 1991.
Baviaanskloof (20237) *	1985-2010	25	411	-33.578800° 23.105380°	Jan-Mar 1985.
Zandvlakte (10483)	1927-1999	72	457	-33.583332° 23.166666°	Jan-Mar & Nov 1927, Apr 1939, Sep-Dec 1977, Jan-May 1978, 1980-1991, Jan-Apr & Oct-Nov 1994, Oct 1995, Nov 1997, Jun-Jul 1998 & Jan-Feb & May-Dec 1999.
Koeifontein (10774)	1926-1993	67	732	-33.500000° 23.149999°	Oct-Dec 1940, Jul 1990 & Sep-Dec 1993.

All of the gauge stations (with the exception of station 10774, Koeifontein) are located on the valley floor alongside the Baviaanskloof River, accessible to farm houses. Koeifontein, a mountain station, is located outside the study area. It is in a rain shadow and therefore does

not represent high altitude areas of the Baviaanskloof catchment. This implies that the research was limited because of the absence of rainfall data from the upland and mountainous areas.

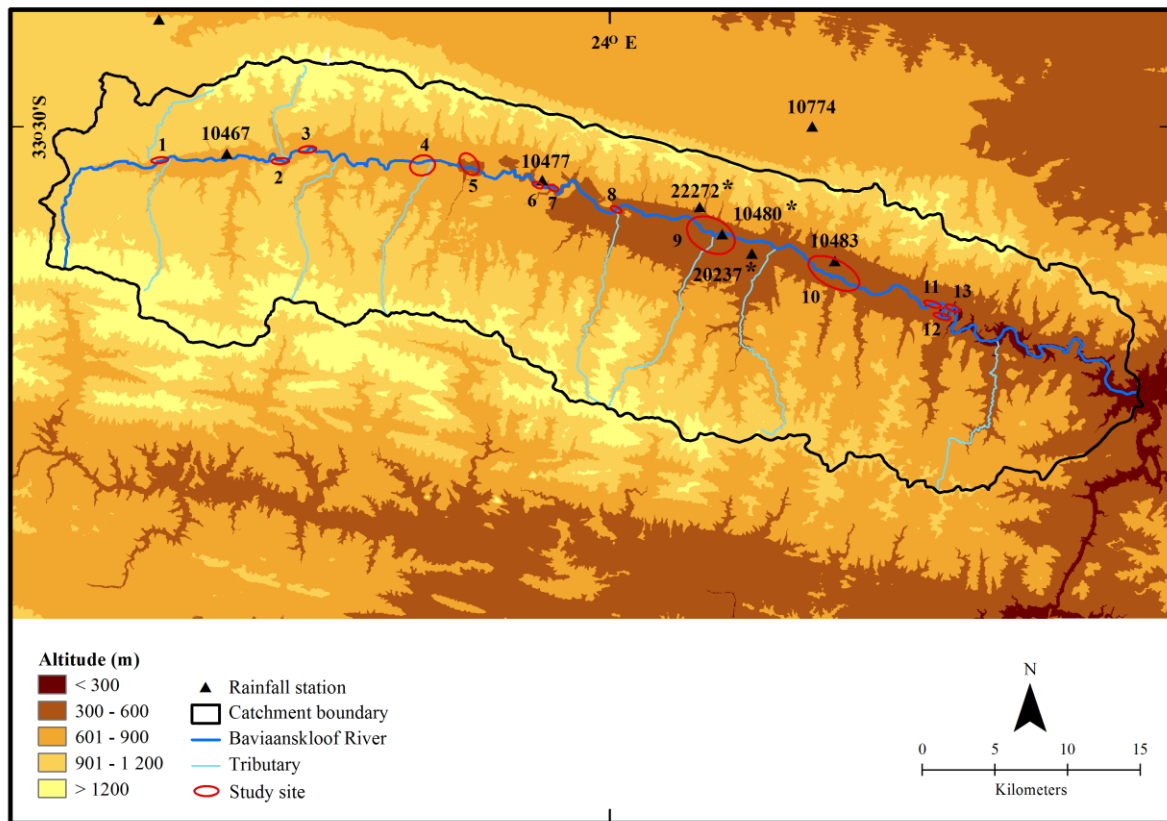


Figure 3.1: Locations of the rain gauge stations used in the study.

The shading indicates height in meters while the asterisk points out the stations making up the combined dataset.

The raw rainfall station records were further analysed to ensure that they were of adequate quality. Where possible obvious data errors were corrected and data quality was improved. The data were mostly accepted, relying on quality control procedures that were in place at the ARC and the SAWS.

Since accurate results are dependent on a complete as possible data set, existing data gaps were dealt with as follows. Firstly, the rainfall records of three neighbouring stations (from west to east: Stadtis Police, Rust en Vrede and Baviaanskloof), which were approximately 2.4 km apart, were combined. This involved the calculation of averages and data pooling. The combined dataset was sufficiently complete and covered a period of 31 years (1979-2010). From here onwards this dataset is referred to as “combined stations” (Table 3.1 and Figure 3.1). Records for the year 1978 were excluded from the analysis because of missing monthly data (Table 3.1). Secondly, complete records were created for the remaining stations using rainfall values extracted from the infilled daily rainfall database by Lynch (2004). Missing

records (Table 3.1) were coded as -99.9 and excluded from further analysis. This missing data should have minimal impact on the results and overall conclusions because it is not extensive.

Daily rainfall

Preliminary treatment of all the station rainfall data involved calculating the number of rain days and rainfall amounts per year. Taking 1963 as a central point in time, all the records at station 10483 (Zandvlakte) were also examined with respect to rainfall before and after this period. This station was selected because it had the longest rainfall time series (Table 3.1). A wet day was defined as a day with 1 mm or more rains while a dry day had less than 1 mm of rain. These thresholds are considered appropriate because studies have found that with lower thresholds, inaccuracies associated with measurement errors can arise (Kruger, 2006; Costa and Soares, 2009). Also, lesser rainfall amounts are not absorbed by the soil but are evaporated off directly (Ceballos *et al.*, 2004).

This analysis made use of rainfall indices that were calculated in the RClimDex V1 software package (Kruger, 2006) in addition to the above-mentioned rainfall computations. These climate extreme indices were originally developed for climate change monitoring and detection. Input files were prepared according to the steps outlined in the RClimDex user manual by Zhang and Yang (2004). The rainfall indices used in this study are listed in Table 3.2. The program and user manual are freely available from the Expert Team on Climate Change Detection, Monitoring and Indices (ETCCDMI) webpage: <http://cccma.seos.uvic.ca/ETCCDMI/software.shtml> (Kruger, 2006). This MS Excel-based program requires the base package of R and graphic user interface Tc1Tk, also freely downloadable from the above-mentioned webpage. It generates results centred on an annual level, fixed- or user-defined threshold values and other percentiles (Zhang and Yang, 2004). Processed index data were stored in spreadsheet files. The results were then either tabled or charted to make rainfall distribution deductions.

The frequency of rainfall intensities was also analysed, with a focus on moderate to extreme rainfall events. The following class intervals over a 24-hour period were considered for rainfall intensities: moderate rainfall, 5 to < 25 mm; good rainfall, 25 to < 50 mm; heavy rainfall, 50 to < 100 mm and extreme rainfall, ≥ 100 mm (modified from the South African Weather Bureau, 1996; Gong *et al.*, 2004). Generally, forecasters at the South African Weather Service issue warnings for heavy rainfall when the rainfall at any weather station exceeds 50 mm (Dyson, 2009). In addition, this analysis looked into the seasonality of heavy to extreme rainfall events. Seasons were defined as follows: summer, December to February; autumn, March to May; winter, June to August, spring; September to November (after Kruger and Shongwe, 2004).

Table 3.2: Rainfall indices used in the study (adapted from Zhang and Yang, 2004).

RR indicates the daily rainfall amount.

Acronyms	Index name	Definition	Units
R10	Number of moderate rainfall days	Annual count of days when rainfall totals above or equal to 10 mm	Days
R20	Number of moderate rainfall days	Annual count of days when rainfall totals above or equal to 20 mm	Days
R25	Number of good rainfall days (Rnn)	Annual count of days when rainfall totals above or equal to 25 mm. Rnn is a user defined threshold.	Days
R40	Number of good rainfall days (Rnn)	Annual count of days when rainfall totals above or equal to 40 mm. Rnn is a user defined threshold.	Days
R50	Number of heavy rainfall days (Rnn)	Annual count of days when rainfall totals above or equal to 50 mm. Rnn is a user defined threshold.	Days
R70	Number of heavy rainfall days (Rnn)	Annual count of days when rainfall totals above or equal to 70 mm. Rnn is a user defined threshold.	Days
R100	Number of extreme rainfall days (Rnn)	Annual count of days when rainfall totals above or equal to 100 mm. Rnn is a user defined threshold.	Days
CDD	Consecutive dry days	Annual maximum number of consecutive dry days ($RR < 1$ mm)	Days
CWD	Consecutive wet days	Annual maximum number of consecutive wet days ($RR \geq 1$ mm)	Days
PRCPTOT	Annual total wet-day rainfall	Annual total rainfall from wet days ($RR \geq 1$ mm) summed	mm
SDII	Simple daily intensity index	Ratio between the total yearly rainfall on wet days and the number of wet days ($RR \geq 1$ mm)	mm/day
RX1day	Max 1-day rainfall amount	Annual maximum rainfall in one day	mm
RX5day	Max 5-day rainfall amount	Annual maximum rainfall in five consecutive days	mm

The magnitude and frequency of moderate to extreme daily rainfall, that is recurrence intervals or return periods (years), were then determined using the annual series. This was accompanied by exceedance probabilities. The annual series involves the selection of the highest rainfall values in each year (Ologunorisa and Tersoo, 2006). This study employed annual 1-day and 5-day maximums generated in RCLimDex (Table 3.2). The general

procedure adopted was similar to what was described by Walker (2007) with the addition of examining the synoptic circulation during climate extremes. Synoptic weather maps were obtained from the “Daily Weather Bulletins” available from the SAWS library as well as the National Geographic Data Center (NOAA) Central Library webpage: http://docs.lib.noaa.gov/rescue/data_rescue_south_africa.html (1950-1982).

Rainfall records were analysed using MS Excel custom sort functions with a ranking system of observed falls. The return period is the average interval in years between events equalling or exceeding a certain magnitude. It equals $(n + 1) / m$, where m is ranked so that the highest rainfall value gets a rank of 1 and n is the length of the record in years. The probability is the probability that rainfall of that much or higher will occur in a given year. It was computed by dividing the rank by the total number of years of data plus 1, $p = m / (n + 1) * 100$, where p , n , and m are defined above (Kennedy and Neville, 1986; Rowntree and Wadeson, 1999). The end results were plotted and the return periods for the rainfall were cross-checked against the dates of known extreme event incidences (Section 3.4)

Monthly rainfall

Average monthly rainfall values were calculated and plotted for all the stations to determine seasonal patterns. Abnormally dry or wet rainfall conditions and short- to long-term rainfall patterns were also investigated using the Standard Precipitation Index (SPI) developed by McKee *et al.* (1993). It is an index based only on historic monthly rainfall data, ideally 30 consecutive years without missing data. However, longer periods do result in better SPI outputs. Even though the SPI was mainly designed for defining and monitoring drought, it measures dry and wet events equally effectively. It is spatially invariant in its interpretation and quantifies rainfall anomalies for multiple time scales (1-month to 48-months). This is very useful in water availability and water use applications (McKee *et al.*, 1993; Guttman, 1999).

The SPI is basically the transformation of the rainfall time series into a standardized normal distribution. This facilitates comparisons across regions or rainfall stations. It also presents climate extreme frequencies in the same manner. Rainfall is normalized using a probability distribution so that values of SPI are actually seen as standard deviations from the median (Lloyd-Hughes and Saunders, 2002; Karavitis *et al.*, 2011). A SPI value of zero corresponds to the median while positive SPI values indicate greater than median rainfall (wet conditions). Negative values indicate less than median rainfall and dry conditions, see Table 3.3 (Hayes *et al.*, 2000; Sönmez *et al.*, 2005; Kumar *et al.*, 2009). This table also comprises the corresponding probabilities of occurrence of each anomaly class. A detailed procedure for calculating the SPI is provided by Guttman (1999) and Lloyd-Hughes and Saunders (2002).

Table 3.3: SPI classification scale and corresponding event probabilities of occurrence.
Modified from Edwards and McKee (1997) and Lloyd-Hughes and Saunders (2002).

SPI values	Category	Probability %
$\geq +2$	Extremely wet (extreme flooding possible)	2.3
+ 1.50 to + 1.99	Very wet (severe flooding possible)	3.4
+ 1 to + 1.49	Moderately wet (moderate flooding possible)	9.2
-0.99 to + 0.99	Near normal (mildly wet or dry)	68.2
-1 to -1.49	Moderately dry (moderate drought possible)	9.2
-1.50 to -1.99	Severely dry (severe drought possible)	3.4
≤ -2	Extremely dry (extreme drought possible)	2.3

This study computed SPI values for 1-month, 3-month, 6-month and 12-month rainfall time periods for all the selected stations (Table 3.1). The station data for each time period were combined. Average values for the entire rainfall record were then calculated for all the SPI time periods. These values represented conditions conducive to extreme floods and droughts. A time period using a 3-month SPI allows for a comparison of the rainfall over a specific 3-month period (e.g. January to March) with the rainfall totals from the same 3-month period for all the years included in the historical record. It reflects short-term rainfall conditions and provides a seasonal estimation. A 12-month SPI in comparison reflects long-term rainfall patterns with the SPI responding more slowly to rainfall changes (McKee *et al.*, 1993). Lloyd-Hughes and Saunders (2002) cautioned against applying the SPI at short time scales (e.g. 3-months) in areas with low seasonal rainfall. Misleadingly large SPI values can result (Hayes *et al.*, 2000).

A freely downloadable PC-version of the SPI program with documentation explaining its operation can be found at the University of Nebraska-Lincoln's National Drought Mitigation Centre webpage:

<http://www.drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx>. Input and output files were prepared according to the procedures outlined on the above webpage and a method document downloadable from <http://drought.unl.edu/portals/0/docs/spi-program-alternative-method.pdf>. The SPI values were then imported into MS Excel and graphed.

Yearly rainfall

Yearly rainfall values were computed and charted for all the stations to determine long-term rainfall patterns. The following parameters were analysed: total rainfall (i.e. summed monthly totals), average or mean rainfall as well as wet and dry years linked to potential floods and droughts. Dry years were viewed as less than 75% of mean annual rainfall while wet years were viewed as more than 125% of mean annual rainfall. Slightly dry or wet years were between the mean and these values (after Laing, 1992; Vogel *et al.*, 2000). Extreme annual

totals were considered > 500 mm (i.e. possible floods) and < 100 mm (i.e. possible droughts). Annual rainfall statistics were derived using the summary statistics function in Instat Plus V3.37, a MS Windows interactive statistical package. The program with documentation explaining its operation is freely available from the University of Reading's Statistical Services Centre webpage: http://www.reading.ac.uk/ssc/n/n_instat.htm. The data were then tabulated.

The Mann-Kendall two-tailed test (Kendall, 1970) was employed to detect trends in the annual time series data using TREND Version 1.0.2 software (Chiew and Siriwardena, 2005). Input data were prepared according to Podger and Argent (2006). The software and supporting documentation can be downloaded from the eWater Toolkit webpage: <http://www.toolkit.net.au/Tools/TREND>. This non-parametric test is a rank-based procedure. The test statistic (Z value), which is a normal approximation, tests the null hypothesis of no trend (H_0) at a chosen level of significance, $\alpha = 0.10, 0.05$ or 0.01 . The significance level $\alpha = 0.05$ was used in this study. The observations are either randomly ordered or indicate a monotonic increasing or decreasing trend over time. The latter represent an alternative hypothesis, H_1 . A positive output value indicates an upward trend, and vice versa (Kendall, 1970; Chiew and Siriwardena, 2005).

3.2.2 Modelled streamflow

Simulated streamflows were used as surrogates or proxies for rains that converted into high streamflows and subsequent flooding. However, low river flows which are often associated with dry conditions were also noted. The streamflow data were extracted from the Water Resources of South Africa, 2005 Study (WR2005) information system which operates through a dashboard menu linked to a database. The database includes all the WR2005 data and information up to September 2005, parameters used and metadata (Middleton and Bailey, 2009). The WR2005 study is an improvement and update of the Surface Water Resources of South Africa 1990 (WR90) study (Midgley *et al.*, 1994). It focussed on investigating integrated water resources. The analysis for the WR90 study was aimed at providing past and present hydrological information for all catchments, gauged and ungauged, in South Africa. The project relied on quaternary catchment simulations generated from the enhanced Water Resources Simulation Model 2000 (WRSM2000) computer model, a 2002 Windows version (Middleton and Bailey, 2009).

Other uses of the model generally include: (1) calibration of streamflow records by comparing the observed flows from gauging stations against the simulated flows; (2) estimating flows in ungauged catchments by transferring calibrated model parameters, based on similarities of the biophysical environment (e.g. vegetation, geology and climate) and (3) producing naturalised flow records (i.e. flows without any human land use effects such as dams, irrigation and towns). WRSM2000 is of a modular construction with five different types of modules (runoff,

reservoir, irrigation, channel and mine) linked by a network of routes. Routes containing source (tail) and sink (head) modules can be visualised as river reaches or pipelines connecting the various modules to one another. The network's main function is to specify the order in which the modules must be solved. The model was first developed in 1969 and has since been subjected to several enhancements (Pitman *et al.*, 2008). For WRSM2000 V3 (the latest version) a number of new alternative methodologies have been introduced. Of particular importance is the surface-groundwater interaction (both the Hughes and Sami method have been included). All the methodologies available in V2 have been retained as options (Pitman *et al.*, 2008; Middleton and Bailey, 2009).

Data processing and handling

The WR2005 study generated synthetic hydrology for the ungauged Baviaanskloof River catchment from the adjoining gauged catchments. WRSM90 networks (Midgley *et al.*, 1994) were aligned with the WRSM2000 model input requirements (Middleton and Bailey, 2009). They were updated using an extended patched rainfall time series, water use data (e.g. patched observed flows, abstractions and return flows) and land use data (e.g. afforestation, dryland crops, alien vegetation, etc.). Wetland and reservoir data were also updated. Rainfall stations employed in the hydrological analysis of the WR2005 project were the same as those used in this study's rainfall analysis. Calibrations of observed versus simulated streamflows were considered in conjunction with the comparison between WR90 and WR2005 naturalised flows (Middleton and Bailey, 2009). Naturalised flows were produced using the tickbox feature in the runoff module of the WRSM2000 model. Outflow route streamflows were then added. See Pitman *et al.* (2008) for further details.

The river flow analyses used the WR2005 time series of naturalised monthly flows available from 1920-2004 for the Baviaanskloof. This dataset represented the total flow in million cubic meters (Mcm) produced by the catchment, not the total flow leaving the catchment. Long-term characteristics were also investigated by calculating yearly flows. The data generated line diagrams and histograms that were then examined to assess variability and extreme event occurrence. Comparisons were made (Section 3.4) with the results described in Sections 3.3.1 (rainfall data) and 3.3.4 (flood and drought chronology). It must be emphasized that this modelled dataset does not represent real data.

3.2.3 Floods and droughts: Documentary records and interviews

Historical accounts, both written and oral, have been recognised as invaluable proxy sources for the reconstruction of hydroclimatic chronologies (e.g. Nash, 1996; Nash and Endfield, 2008; Benito *et al.*, 2011). They were used to document flood and drought years related to exceptionally high and below-average rainfall in the Baviaanskloof River catchment. The timing of the flood or drought event was the main focus here. Only clearly dry or wet

conditions were noted. Vague references to conditions were disregarded. In addition, extreme, great, heavy, severe or big events were highlighted. These accounts complemented the above-mentioned rainfall and simulated river flows. Documentary evidence was obtained via a literature search using phrases such as “historical flood or drought events”, “damaging rainstorms or floods”, “very dry periods” and “severe flooding or droughts” in the former Cape Province, southern Cape, Eastern Cape Province and Baviaanskloof.

The data obtained during the search were mainly sourced from Google and the PRESENCE learning network. Climate related publications were also obtained from the SAWS library as well as two online webpages. The first was that of the NOAA Central Library: http://docs.lib.noaa.gov/rescue/data_rescue_south_africa.html containing freely available records from the 1920s. The second, the Sabinet Reference platform, at: http://reference.sabinet.co.za/sa_epublication/cssa holds records from 2006 onwards with access subject to subscription. Unfortunately newspaper accounts, archival records and annual reports acquired through various other sources did not produce any useful information relevant to this study. Ultimately the literature search (excluding the SAWS records) rendered only a small number of publications. These publications were then read in sequence.

An oral account of perceived climatic extremes was also provided by the owner of the farm Zandvlakte (site 10, Figure 2.2), P. Kruger. The information was obtained and recorded verbatim during two informal interviews conducted on 16 June 2009 and 28 July 2009 respectively. The documentary and interview results were combined and presented in chronological order in table format. The confidence level of a reported year/event increased with the number of sources, a description of the impacts, a specific place mentioned and where accurate dates were given. The results were then tested against the available rainfall and modelled streamflow data to ascertain their reliability or accuracy (Section 3.4).

3.3 Results

3.3.1 Rainfall patterns and climate extremes

Daily rainfall

Daily rainfall records for the selected stations were examined to assess variability or extreme event occurrence. For all the rain gauge stations the number of no-rain days exceeded that of the number of rain days (Table 3.4), a typical semi-arid situation. The rain days were < 12% for the total rainfall series. However, there was a reduction in the number of consecutive dry days (CDD) over the years. The shorter the period of no-rain days, the lower the drought stress. Likewise, the maximum number of consecutive wet days (CWD) has decreased slightly. The most CWD occurred during autumn. In general, CWD is an indicator of whether an area has come to experience more extremes in rainfall during the wet season (Kruger,

2006). The longest annual dry spells in the catchment occurred in 1942 (station 10467, Voorkloof) whilst the longest annual wet spells transpired in 1935 (station 10483, Zandvlakte) respectively (Table 3.4). The most rainfall per day (i.e. the largest single extreme event) occurred at stations 10467 (1953) and 10477 (Stadtis Bos, 1979) (Table 3.4). According to Kruger (2006) flood producing rains are usually associated with extreme weather systems. For example, during these two extreme events the circulation over South Africa was what Tyson and Preston-White (2000) described as a composite synoptic weather type. A mid-latitude system (a cold front and cut-off low or intense westerly trough) accompanied a ridging anticyclone. Stations 10467 and 10477 also had the highest 5-day maximum rainfall values (Table 3.4).

Table 3.4: Daily rainfall distribution in the Baviaanskloof River catchment.

RR indicates the daily rainfall amount while CDD and CWD and indicate the maximum number of consecutive dry and wet days respectively (Table 3.2). Combined dataset as per Table 3.1. MAR indicates Mean Annual Runoff (Middleton and Bailey, 2009).

Variable	Station 10467 (Voorkloof)	Station 10477 (Stadtis Bos)	Combined stations	Station 10483 (Zandvlakte)	Station 10774 (Koeifontein)
Time period (years)	1930-1957	1952-1991	1979- 2010	1927-1999	1926-1993
Years	27	39	31	72	67
MAR	46.8	28.1	30.7	30.7	3.1
No-rain days (RR < 1 mm)	9506	13535	10458	24181	22928
Rain days (RR ≥ 1 mm)	721	1075	1228	2482	1909
CDD (year)	188 (1942)	166 (1983)	104 (1995)	109 (1970)	296 (1989)
CWD (month & year)	5 (Mar 1931 & Sep 1932)	6 (Apr 1967)	6 (Feb 1995, Oct 1996 & Mar 1999)	7 (May 1935)	7 (Mar 1963)
Daily maximum rainfall, mm (date)	322.6 (16 Feb 1953)	225 (11 Jun 1979)	96.5 (25 Mar 1981)	107.7 (11 Jan 1951)	85 (25 Mar 1981)
5-Day maximum rainfall, mm (month & year)	322.6 (Feb 1953)	245 (Jun 1979)	120.5 (Sep 1993)	178.4 (Jan 1932)	148 (Oct 1953)
Daily rainfall amount (mm)	Total number of days ≥ to given rainfall amount (number of days per year)				
10	199 (7.4)	360 (9.2)	323 (10.4)	701 (9.7)	564 (8.4)
20	82 (3)	150 (3.8)	115 (3.7)	244 (3.4)	213 (3.2)
25	59 (2.2)	88 (2.3)	69 (2.2)	157 (2.2)	133 (2)
40	20 (0.7)	32 (0.8)	21 (0.7)	47 (0.7)	47 (0.7)
50	9 (0.3)	19 (0.5)	10 (0.3)	22 (0.3)	26 (0.4)
70	2 (0.07)	6 (0.2)	1 (0.03)	6 (0.08)	6 (0.09)
100	2 (0.07)	1 (0.03)	0 (0)	1 (0.01)	0 (0)

As expected, for all the stations the rainy days with moderate (10-25 mm) and good (40 mm) rains were the most frequent. The analysis further showed that there were far more heavy (50-70 mm) rainfall days than extreme (100 mm) rainfall days (Tables 3.4 and 3.5). According to R. Powell (Rhodes University, Grahamstown, pers.comm., 2015) the unconfined reaches of the Baviaanskloof River flow for significant periods after intense rainfall events of > 50 mm (i.e. above average seasonal rainfall). For example, reaches in the wider valley sections flowed for around eight months after heavy rainfall in July of 2012 (Figure 3.2). Table 3.6 demonstrated that the most intense storm days (events) are in the summer and autumn months. March had the highest frequency of 12 heavy rainfall days (events).

Table 3.5: Heavy and extreme daily rainfall, Baviaanskloof (1926-2010).

Rainfall classes after the South African Weather Bureau (1996) and Gong *et al.* (2004). Station time periods and combined dataset as per Table 3.1.

Daily maximum heavy (50 to < 100 mm) or extreme (≤ 100 mm) rainfall per year				
Station 10467 (Voorkloof)	Station 10477 (Stadtis Bos)	Combined stations	Station 10483 (Zandvlakte)	Station 10774 (Koeifontein)
1930-1957	1952-1991	1979- 2010	1927-1999	1926-1993
16 Feb 1953 (322.6)	11 Jun 1979 (225)	25 Mar 1981 (96.5)	11 Jan 1951 (107.7)	25 Mar 1981 (85)
19 Jan 1951 (67.3)	23 Mar 1981 (99)	1 Dec 1985 (69)	14 Sep 1952 (80.5)	2 Jan 1932 (82.6)
1 May 1954 (52)	1 Nov 1978 (85)	23 Sep 1993 (67.5)	23 Sep 1993 (79)	12 Aug 1964 (77)
11 Nov 1950 (51.6)	21 Feb 1955 (74.5)	29 Feb 2000 (56)	20 Aug 1971 (76)	26 Jul 1951 (76.7)
13 Mar 1948 (51.3)	9 Jan 1976 (58)	11 Nov 2005 (55.5)	9 Apr 1967 (73.1)	20 Oct 1953 (72.5)
	12 Aug 1964 (57)	13 Dec 1998 (53.5)	22 Oct 1996 (71)	25 Jul 1983 (72)
	15 Jan 1974 (55)	31 Dec 2007 (52.5)	31 Dec 1931 (67.6)	30 Jan 1957 (69.5)
	15 Sep 1952 (53.6)	7 Dec 2009 (51.3)	25 Mar 1981 (64.8)	21 Aug 1971 (69)
	17 Feb 1977 (53)		25 Jul 1983 (64.5)	11 Nov 1950 (65.3)
	22 Aug 1971 (52)		20 Mar 1961 (61.5)	29 Aug 1933 (64.3)
	20 Mar 1961 (51)		21 Mar 1946 (58.9)	23 Mar 1946 (60.2)
	16 Jan 1960 (50.7)		28 Aug 1933 (58.2)	21 Mar 1961 (60)
			25 Mar 1974 (58)	25 Mar 1974 (60)
			13 Aug 1964 (57.5)	22 Feb 1955 (59)
			23 Feb 1939 (57.2)	30 Apr 1954 (56)
			1 Jan 1932 (56.6)	28 May 1944 (55.9)
			25 Jun 1945 (54.1)	23 Nov 1943 (55.6)
			17 Feb 1955 (53)	14 Nov 1989 (54)
			16 Dec 1937 (50.8)	24 Feb 1939 (53.3)
				4 Dec 1927 (50.8)

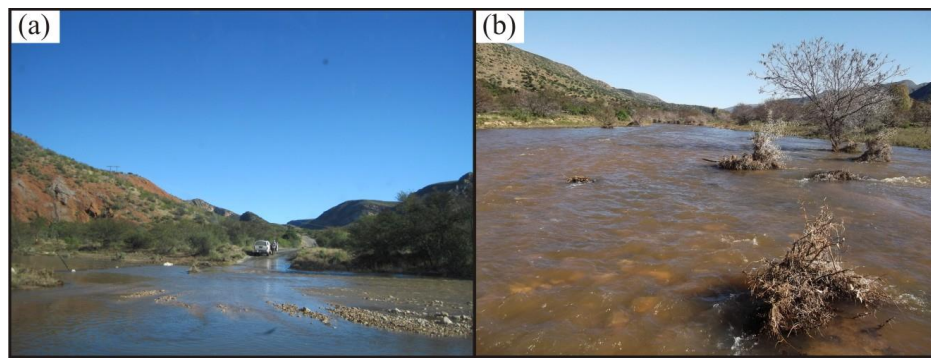


Figure 3.2: Surface flow at the unconfined Baviaanskloof River after heavy rains.

Photographs taken by J. Glenday and R. Powell on the farms Verlorenrivier, site 4 (a) and Zandvlakte, site 9 (b). Site locations as per Figure 3.1.

Table 3.6: Seasonality of heavy and extreme rainfall in the

Baviaanskloof. Rainfall events as per Table 3.5. Stations making up the combined dataset are indicated in Table 3.1.

Station name (coding number)	Frequency (number of days)											
	Summer			Autumn			Winter			Spring		
	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov
Voorkloof (10467)		1	1	1		1						1
Stadtis Bos (10477)		3	2	2			1		2	1		1
Combined stations	4		1	1						1		1
Zandvlakte (10483)	2	2	2	4	1		1	1	3	2	1	
Koeifontein (10774)	1	2	2	4	1	1		2	3		1	3
Total days		23			16			13			12	

The results indicated that $> 80\%$ of rainfall comes as moderate events. These heavy to extreme rainfall events tend to be sporadic and infrequent (Table 3.7). Although the moderate rain days (events) accounted for most of the total number of rain days (events) but the good to extreme rain days (events) contributed most of the actual rainfall amount (Table 3.7).

Taking 1963 as the break point, it can be seen in Table 3.8 that the rainfall differences (increase and decrease) are not significant (i.e. only 3%). It can hence be concluded that there is no change in the pattern of daily rainfall between the two periods (i.e. pre- and post-1963).

Table 3.7: Moderate to extreme rainfall events in the Bavianskloof.

Rainfall classes after the South African Weather Bureau (1996) and Gong *et al.* (2004). Combined stations as per Table 3.1.

Station name (coding number)	Number of moderate rainfall events, 5 to < 25 mm (%)	Number of good rainfall events, 25 to < 50 mm (%)	Number of heavy rainfall events, 50 to < 100 mm (%)	Number of extreme rainfall events, ≥ 100 mm (%)
Voorkloof (10467)	346 (85)	50 (12)	7 (2)	2 (1)
Stadtis Bos (10477)	496 (85)	69 (11.8)	18 (3)	1 (0.2)
Combined stations	546 (89)	59 (10)	10 (1)	0 (0)
Zandvlakte (10483)	1118 (87.6)	135 (10.6)	21 (1.7)	1 (0.1)
Koeifontein (10774)	898 (87)	107 (10)	26 (3)	0 (0)

Table 3.8: Comparison of daily rainfall prior to and after 1963 at station 10483.

RR indicates the daily rainfall amount while CDD and CWD and indicate the maximum number of consecutive dry and wet days respectively (Table 3.2).

Variable	Station 10483 (Zandvlakte)	
Time period (years)	1927-1963 (36)	1964-1999 (36)
No-rain days (RR < 1 mm)	12289	11892
Rain days (RR ≥ 1 mm)	1225	1257
CDD (year)	88 (1955)	109 (1970)
CWD (month & year)	7 (May 1935)	6 (Aug 1981, Apr 1982, Oct & Nov 1985)
Daily maximum rainfall, mm (date)	107.7 (11 Jan 1951)	73.1 (9 Apr 1967)
5-Day maximum rainfall, mm (month & year)	178.4 (Jan 1932)	154.1 (Aug 1971)
Daily rainfall amount (mm)	Total number of days ≥ to given rainfall amount (number of days per year)	
10	367 (10.2)	334 (9.3)
20	128 (3.5)	116 (3.2)
25	76 (2.1)	81 (2.2)
40	26 (0.7)	21 (0.5)
50	11 (0.3)	11 (0.3)
70	2 (0.05)	4 (0.1)
100	1 (0.02)	0 (0)

Figure 3.3 revealed that over the last 84 years the daily rainfall intensity fluctuated, displaying no dominant trend. Peaks in the rainfall record occurred in 1953 (station 10467) and 1979 (station 10477). This coincided with two extreme rainfall events which made up much of the annuals totals.

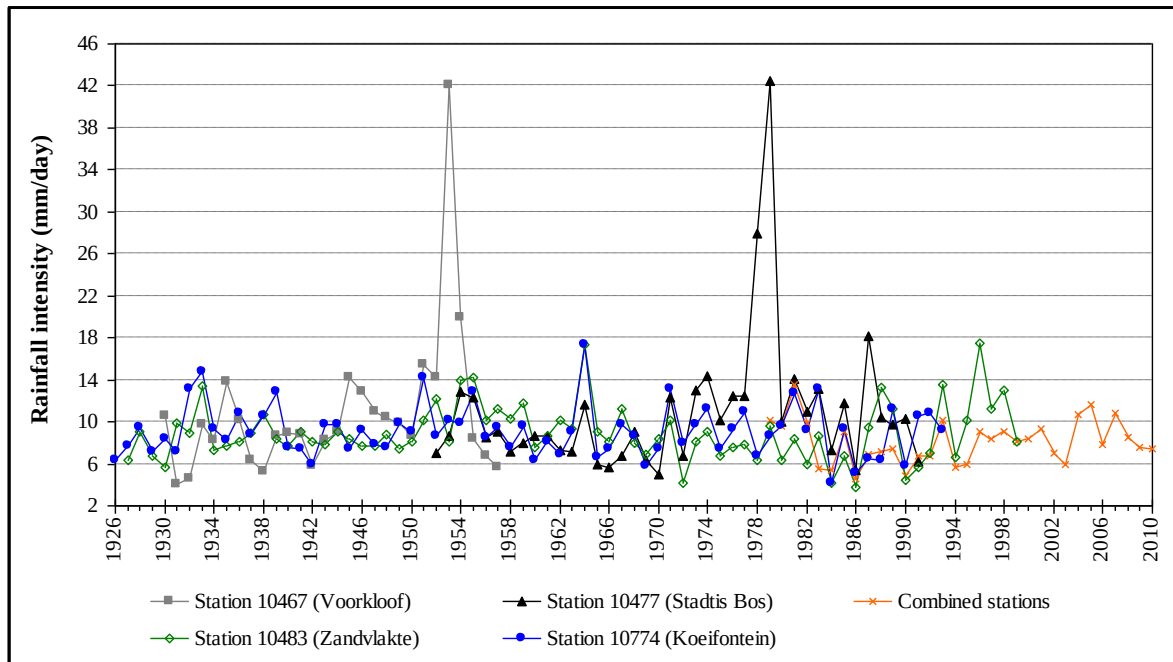


Figure 3.3: Rainfall intensity in the Baviaanskloof.

The values represent the total yearly rainfall divided by the number of rainy days, i.e. the SDII (Table 3.2).

Figure 3.4 depicts the return periods of moderate to extreme daily rainfall in the Baviaanskloof River catchment. A 1-day annual maximum rainfall event of 322.6 mm at station 10467 can be expected to occur once in 28 years (probability = 0.036), whereas the 5-day annual maximum amount of 245 mm at station 10477 can be expected to occur once in 40 years (Figure 3.4) with a probability of 0.03.

At station 10483 1-day and 5-day less frequent rainfall events of high magnitude had return periods of over 70 years (probability = 0.014). In contrast, a 40.25 mm (combined stations) rainfall event has a recurrence interval of 2 years (Figure 3.4). However, it must be noted that the maximum recurrence interval for each graph depends on the length of record. The high rainfall at Station 10467 undoubtedly would have had a much longer return period if the record had been longer.

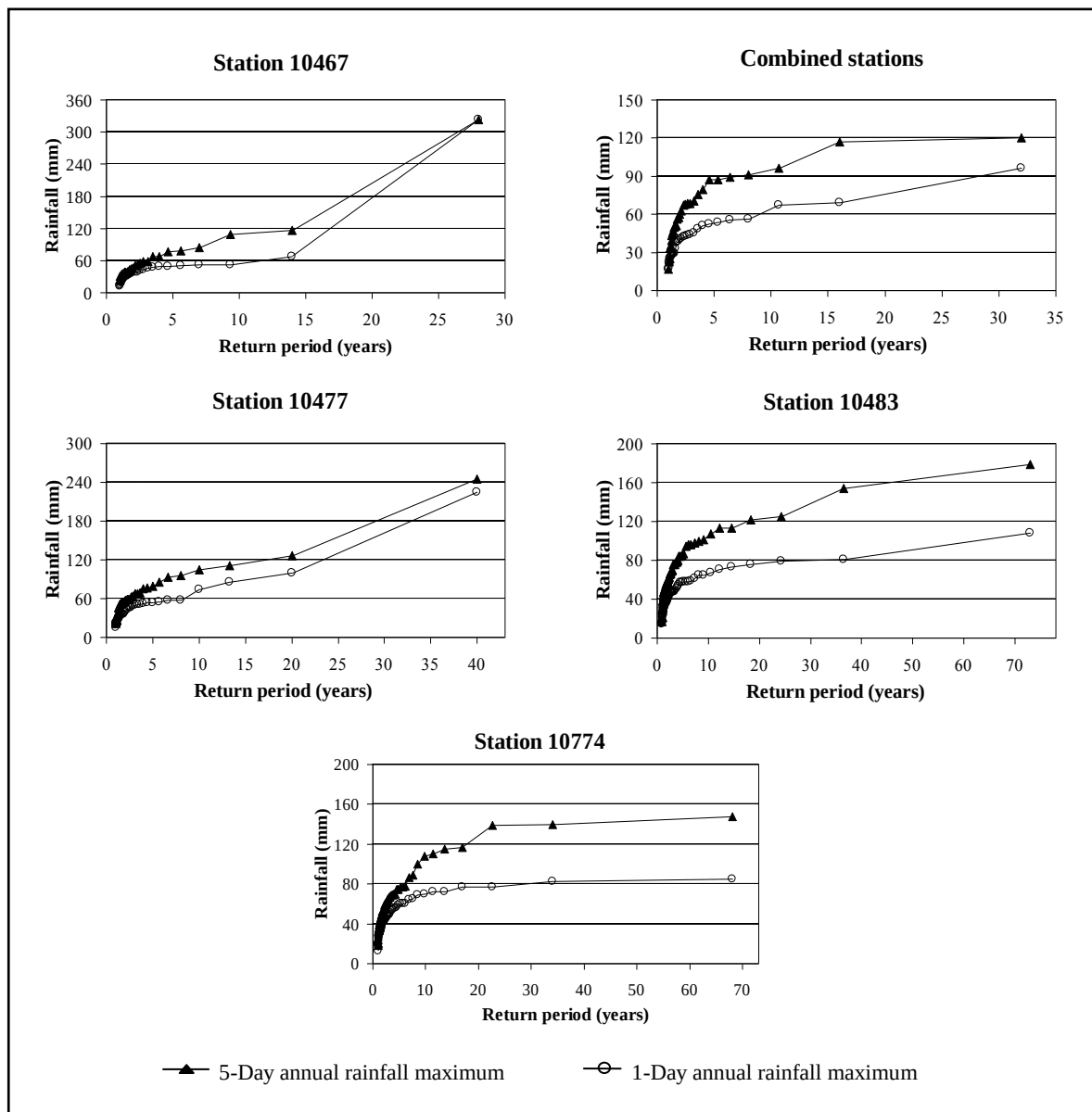


Figure 3.4: Magnitude and frequency of daily rainfall events, Baviaanskloof (1926-2010).

Station time periods as per Table 3.1.

Monthly rainfall

Seasonal rainfall characteristics in the Baviaanskloof were determined from average monthly rainfall values (Figure 3.5). Rainfall occurs all year, with peaks in summer and autumn (Figure 3.5 and Table 3.6). The remainder of the year received < 30 mm of rainfall each month, May to October. The driest season is winter. The highest average monthly rainfall (53 mm) was during February, station 10467 (Voorkloof). This implies that the summer season in the upper catchment is possibly wetter than that of the lower catchment. The lowest

rainfall occurred during June at station 10774 (Koeifontein), a mountain station located outside the catchment in the rain shadow of the Baviaanskloof Mountains (Figure 3.1). The average rainfall was 9 mm (Figure 3.5).

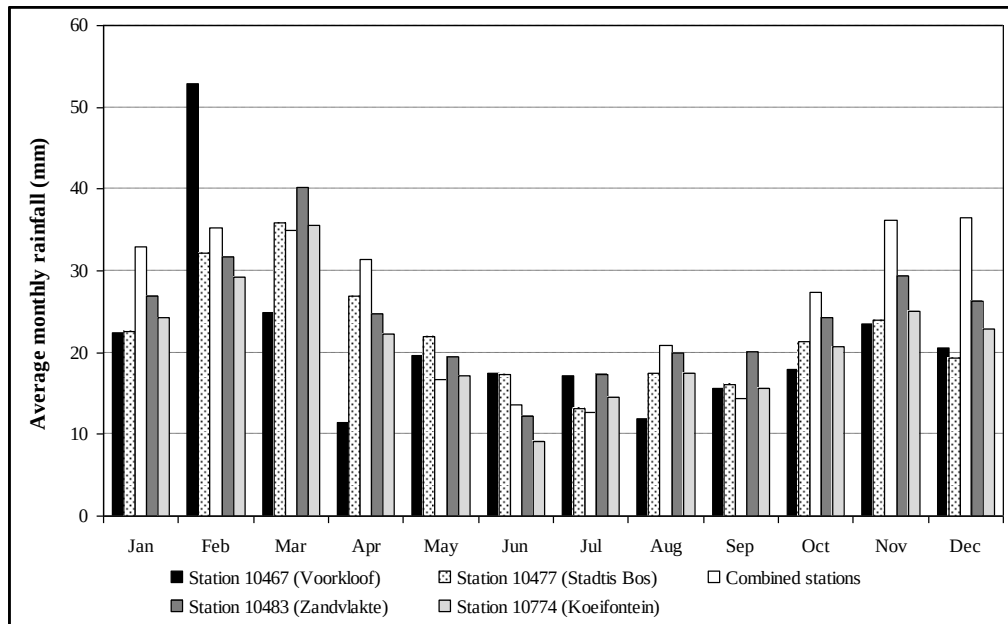


Figure 3.5: Average monthly rainfall amounts for the Baviaanskloof (1926-2010).

Extremely wet and dry periods over the valley were also ascertained from 1- to 12-month SPI time scale analyses (Figure 3.6). Here extreme refers to SPI values of $\geq +2$ (extreme flooding possible) and ≤ -2 (extreme drought possible) (Table 3.3). The 1-month SPI time period showed that although extremely wet conditions occurred in each decade (excluding the 1920s), the 1970s, 1980s and 2000s experienced the most wetness. Furthermore, periods of very low rainfall were lacking. It is also evident from the 3-month SPI time period that the possibility of extreme flooding was the highest in the 1970s with four very wet years implicated. The most extreme dry periods occurred in the 1920s, 1950s and 1980s (Figure 3.6 and Table 3.9). At the medium-term 6-month SPI time period excess rainfall was mostly associated with the 1970s, three years were implicated. Extreme wetness, however, also occurred in the 1950s and 1990s. In addition, the possibility of droughts was the highest in the 1920s and 1980s. Longer-term 12-month SPI values indicating extremely wet conditions were detected in 1974 and 1997. The 12-month analysis also identified extreme dryness during the 1920s, 1949, 1970, the 1980s and 1991 (Figure 3.6 and Table 3.9). Moreover, the SPI outputs revealed that the 1970s (1971, 1974 and 1979) experienced the most intense storm events across time periods. The driest years across SPI time periods were 1926/27, 1983/84 and 1991 (Table 3.9). The chance of extreme floods and droughts occurring were very high in these years.

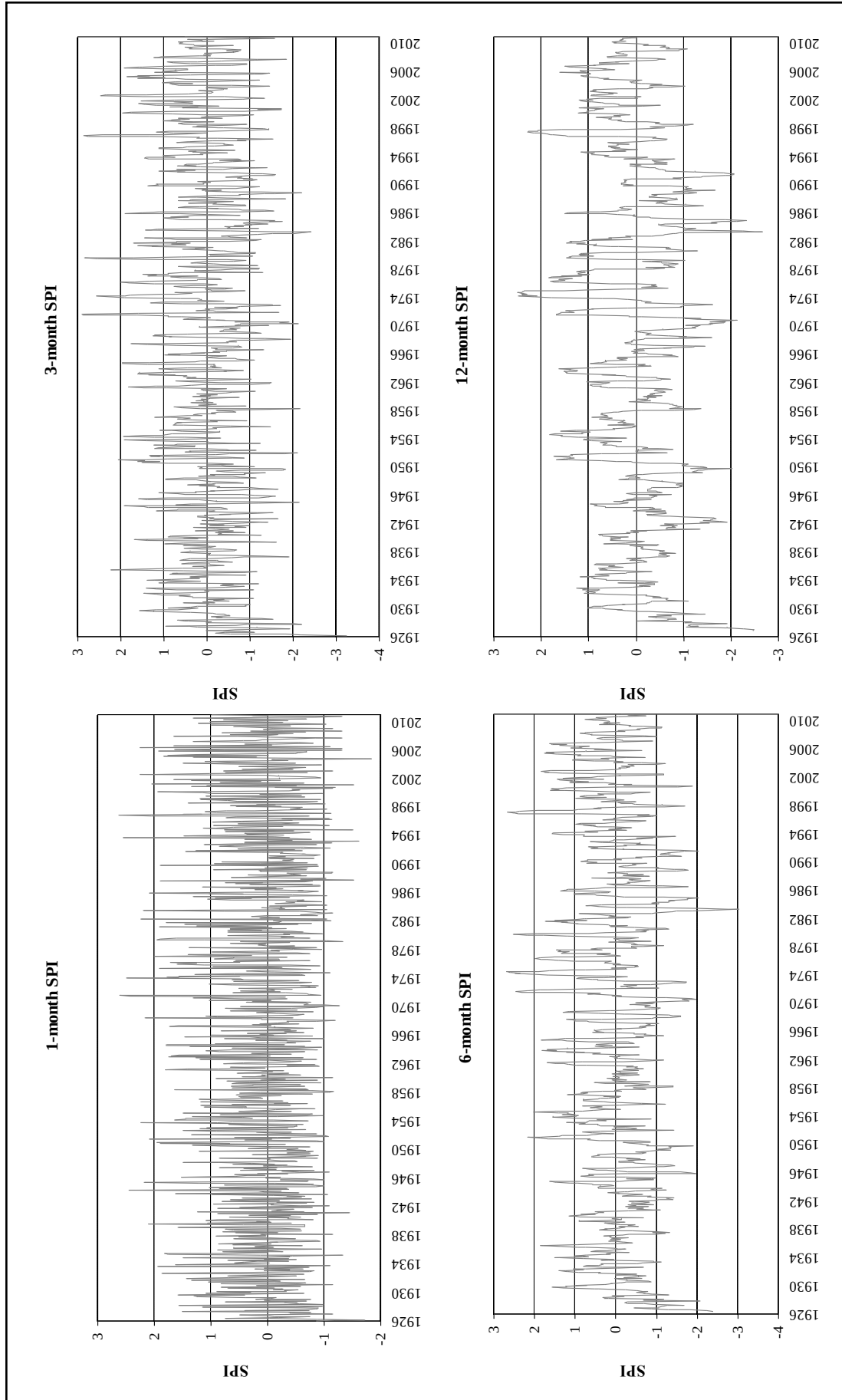


Figure 3.6: Wet and dry years linked to possible floods and droughts at 1-to 12-month. SPI time periods.
SPI classification scale as per Table 3.3.

Table 3.9: Years of extreme wetness and dryness using the SPI, Baviaanskloof.

SPI classification and values as per Table 3.3 and Figure 3.5. Years are linked to possible flood and drought occurrences. The years in bold are repeated at two or more SPI time periods.

SPI time period	Extremely wet periods	Extremely dry periods
1-month	1939, 1944, 1945, 1951 , 1953, 1968, 1971 , 1974 , 1977, 1982, 1983, 1985, 1993, 1996 , 2001, 2002 & 2006.	Absent
3-month	1935, 1935, 1951 , 1971 , 1974 , 1976, 1979 , 1996, 1997 & 2002 .	1926 , 1927 , 1945, 1952, 1958, 1970, 1983 & 1988.
6-month	1951 , 1954, 1971 , 1974 , 1979 , 1996 & 1997 .	1926 , 1927 , 1983 , 1984 & 1991 .
12-month	1974 & 1997 .	1926 , 1927 , 1949, 1970, 1983 , 1984 & 1991 .

Yearly rainfall

The wide range in annual rainfall values demonstrates considerable inter-annual variability (Table 3.10 and Figure 3.7). Standard deviations ranged from 88 mm (station 10483, Zandvlakte) to 164 mm (station 10467). The coefficients of variation ranged from 30% (station 10483) to 63% (station 10467). The rainfall records also clearly illustrated the inter-station variability between the upper, middle and lower catchment. However, in the lower catchment there is not much difference between the rainfall results of the high- and low-altitude stations. For example, there is no consistent change in the coefficient of variation (Table 3.10).

When comparing the time series of wet and dry years between the stations, one can see that in some instances similar years are showcased. Across stations the most wet years were found in the 1970s and 1980s while the most dry years were found in the 1940s. Considering only the extreme conditions, the years 1974 (extreme wetness) and 1984 (extreme dryness) were noted at most stations (Table 3.11). This was mirrored in Table 3.5 with, for example, intense daily rainfall (> 50 mm) recorded at three stations during 1974. Hence, the probability of extreme floods and droughts occurring were very high during these two years. Also, the wettest year on record occurred in 1953 at station 10467, in which annual rainfall reached 925.9 mm. The driest year on record was 1949, when only 69 mm was recorded at the same station (Table 3.10 and Figure 3.7). The results further indicated that the distinct spatial-temporal variation of rainfall in the Baviaanskloof resulted in a mixed pattern in some cases. This refers to wet and dry conditions in different places at the same time. An example includes a comparison

between stations 10467, 10477 and 10483 where in 1953 both wet and dry periods occurred (Table 3.11).

Table 3.10: Annual rainfall statistics for the selected rain stations, Baviaanskloof.
Station locations as per Figure 3.1.

Variable	Station 10467 (Voorkloof)	Station 10477 (Stadtis Bos)	Combined stations	Station 10483 (Zandvlakte)	Station 0774 (Koeifontein)
Dates	1930-1957	1952-1991	1979-2010	1927-1999	1926-1993
Minimum, mm (year)	69 (1949)	74 (1984)	88 (1983)	124 (1984)	83 (1988)
Maximum, mm (year)	926 (1953)	638 (1979)	573 (1981)	550 (1974)	553 (1974)
Average (mm)	256	268	313	293	254
Standard deviation (mm)	164	123	116	88	92
Coefficient of variation (%)	63	46	37	30	37

The Mann-Kendall test results indicated that only station 10477 and the combined stations displayed statistically significant annual trends. The remainder of the stations were therefore trend free. However, the different time periods must be noted. Station 10477 had a decreasing trend (-2.06) while the combined stations had an increasing trend (2.19). Both trends were statistically significant at > 0.05 .

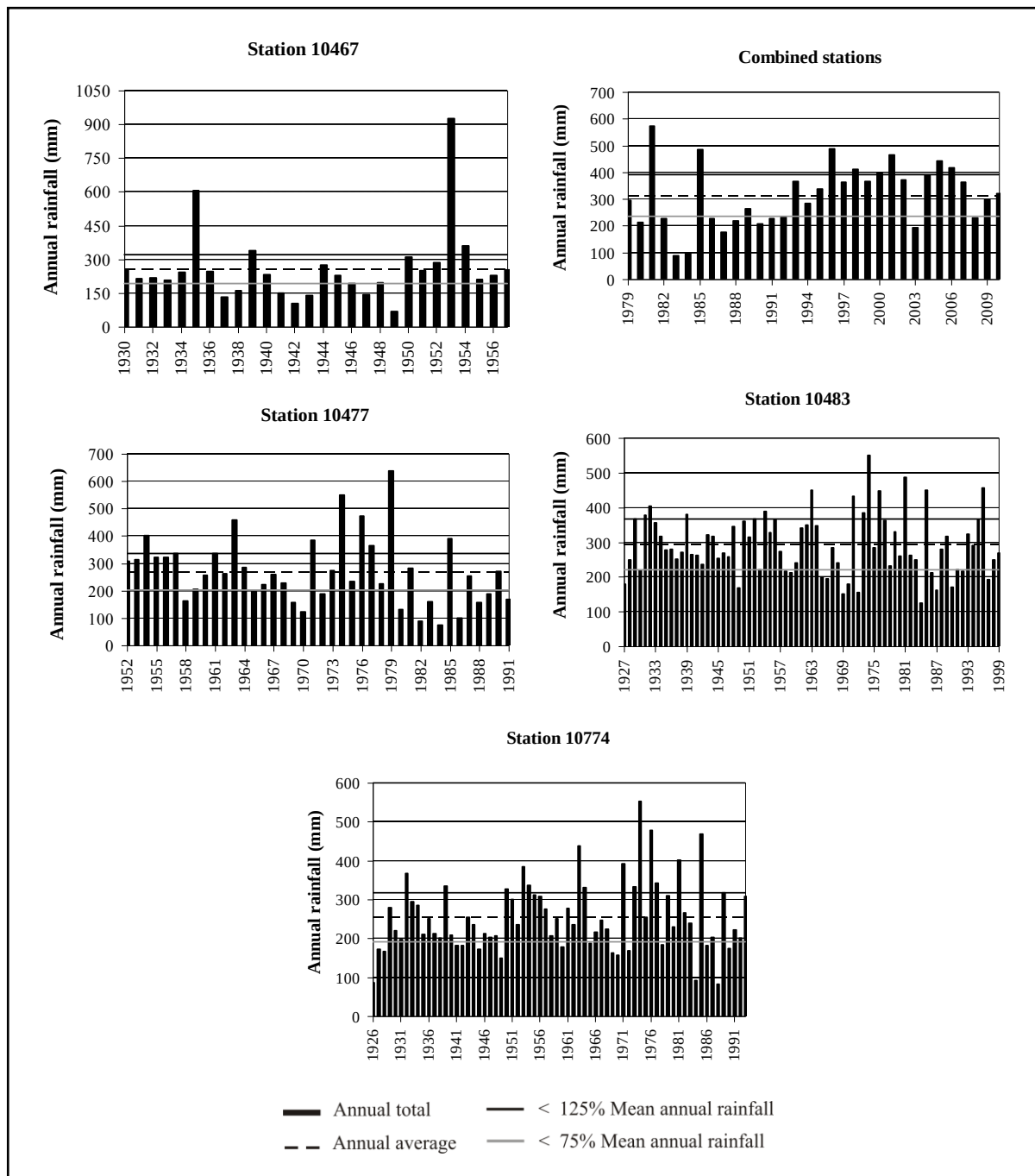


Figure 3.7: Annual rainfall for the Baviaanskloof.

Note that < 75% of mean annual rainfall (i.e. dry years) suggests droughts while > 125% of mean annual rainfall (i.e. wet years) suggests floods (after Laing, 1992; Vogel *et al.*, 2000).

Table 3.11: Wet and dry years linked to possible floods and droughts in the Baviaanskloof.

Annual rainfall as shown in Figure 3.7. The years in bold are repeated at two or more stations. Combined dataset as per Table 3.1.

Station name (coding number)	Wet years	Extremely wet years (rainfall amount in mm)	Dry years	Extremely dry years (rainfall amount in mm)
Voorkloof (10467)	1939 & 1954.	1935 (606.7) & 1953 (925.9).	1937, 1938, 1941, 1942 , 1943 & 1947.	1949 (69)
Stadtis Bos (10477)	1954, 1957, 1961, 1963, 1971, 1976, 1977 & 1985.	1974 (548) & 1979 (637.5).	1958, 1965, 1969, 1970, 1972, 1980 , 1983, 1988, 1989 & 1991.	1982 (88), 1984 (73.6) & 1986 (98.3).
Combined stations	1985, 1996 , 1998, 2000, 2001, 2005 & 2006.	1981 (572.5)	1980 , 1982, 1986 , 1987, 1988, 1990 , 1991, 1992 , 2003 & 2008.	1983 (88.4) & 1984 (98).
Zandvlakte (10483)	1929, 1931, 1932, 1939 , 1952, 1954, 1963, 1971, 1973, 1976, 1981, 1985 & 1996.	1974 (550.3)	1927, 1930, 1949 , 1953, 1958 , 1959, 1965 , 1966, 1969 , 1970, 1972 , 1984, 1986 , 1987, 1990, 1992 & 1997.	Absent
Koeifontein (10774)	1932, 1939 , 1950, 1953, 1954, 1963 , 1964, 1971, 1973, 1976, 1977, 1981, 1985 & 1989.	1974 (552.5)	1927, 1928, 1941, 1942 , 1945, 1949, 1960, 1965, 1969, 1970, 1972 , 1978, 1986 & 1990.	1926 (85.4), 1984 (91.5) & 1988 (82.9).

3.3.2 Modelled streamflow

The naturalised monthly flow analysis for this all-year rainfall area identified spring and summer as high streamflow seasons (Figure 3.8). The highest average modelled river flows occurred during November (4.62 Mcm) and December (4.22 Mcm). In this record, the autumn months of April (2.14 Mcm) and March (2.41 Mcm) had the lowest average modelled river flows. Overall, these results differed somewhat from the rainfall seasonality data (Figure 3.6) and could therefore be considered questionable.

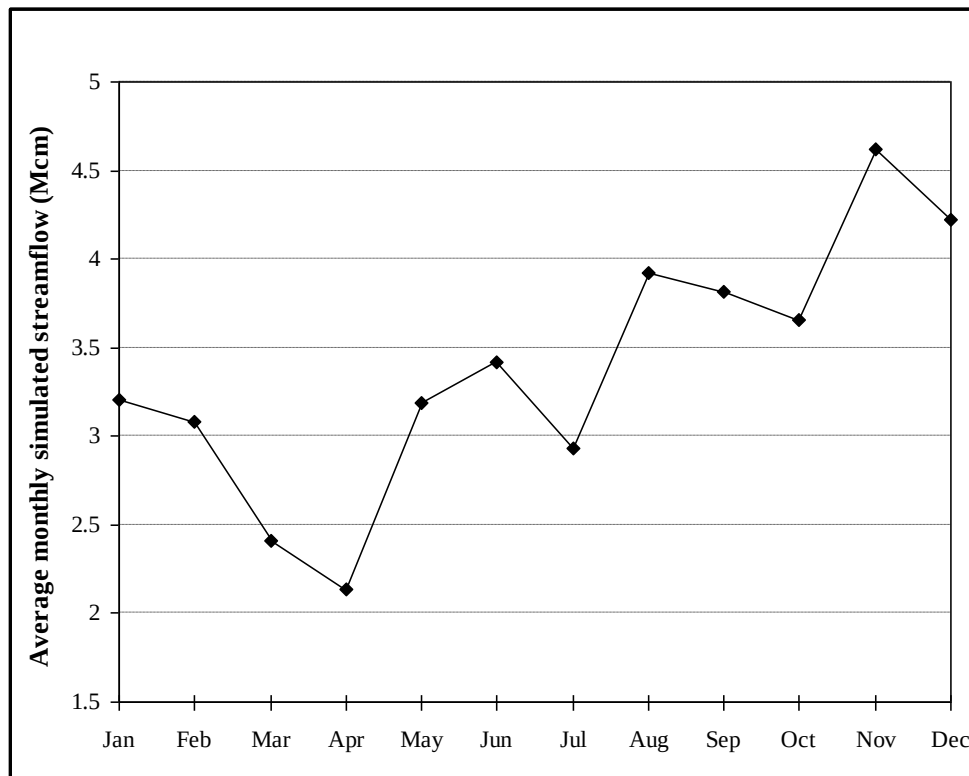


Figure 3.8: Average naturalised river flows showing seasonal variation, 1920-2004.
After Middleton and Bailey (2009).

From an annual perspective, the analysis indicated that the inter-annual variability of the rainfall in the Baviaanskloof was reflected in the modelled river flow which was also highly episodic and flashy. Annual naturalised simulated flows ranged from low flows to flood flows. Most of the very low river flows (< 15 Mcm/a) occurred in the 1940s, in which three years were implicated. The lowest flows (i.e. extremely dry periods) were observed in 1948, 1969 and 1990 (Figure 3.9).

High magnitude modelled flows (50 to < 100 Mcm/a) were encountered 14 times, mostly twice a decade. Moreover, extreme river flows (> 100 Mcm/a) which are typically associated with likely damaging flood events, were predicted only six times in 84 years. These wet years included 1931, 1952, 1970, 1973, 1980 and 1996. There was also a tendency for two flood years to follow one another (Figure 3.9).

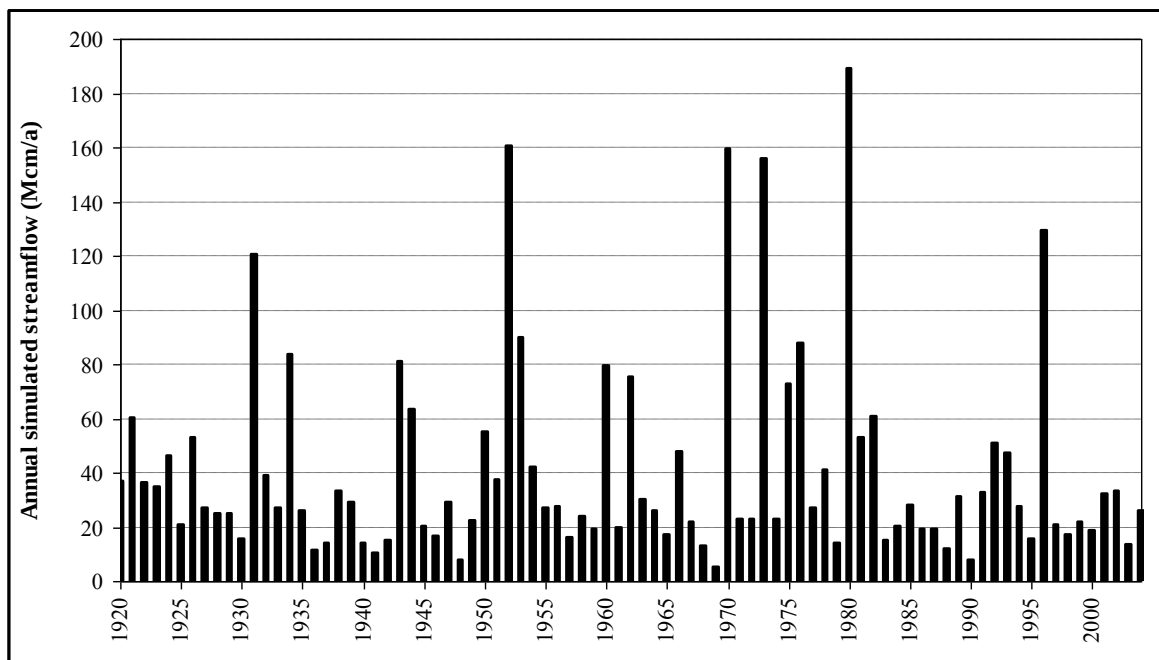


Figure 3.9: Annual modelled river flow, Baviaanskloof (Middleton and Bailey, 2009).

3.3.3 Floods and droughts

A historical documentary and verbal account of floods and droughts was used to construct a climatic chronology for the Baviaanskloof River catchment (Table 3.12). The oldest written reference to a flooding event in the catchment was in 1847. The oral history only started in 1972. This refers to when P. Kruger (the interviewee) started to keep record of climate extremes in the Baviaanskloof. Overall, the analysis revealed that at least 34 flooding events occurred in the study area since 1847. These were for the most part inter-annual floods. Detailed information on intra-annual floods were mostly lacking because of missing monthly data in the chronology. Most of the floods were noted in the 1970s and 1980s. Nine of the 34 floods were major or extreme with devastating effects described for six events. These six flooding events were restricted to 1916, 1931/32, 1972, 1981 and 1996. The remainder of the severe flood years included 1953, 1963 and 2005. In general, major floods tended to occur at least once in each decade (Tables 3.12 and 3.13).

In terms of data verification (between documented sources and interviews) some flood years only had one source. Flooding in these years could therefore be considered questionable. Most years, however, had a number of sources or additional information provided. In this analysis they represented the periods when there could be little question. For example, although no rainfall (Table 3.1) and streamflow (Figure 3.9) data are available to corroborate the 1916 flood, this flood was linked to an accurate place and date while a thorough description of the impacts was given. This extreme event did occur. Documentary records also indicated floods (e.g. 1850-1900 and 1931) that occurred in the broader Cape area which included the

Baviaanskloof. The flood that transpired in December 1931 was particularly disastrous. Because of the detailed information provided, the confidence rating for this record was also thought to be high although only one source was given.

Table 3.12: A flood and drought chronology chronology for the Baviaanskloof, 1847-2009.

The date (when known), the number of events, comment on the events and source are shown.

Year	Description of event	Source
1847	First recorded flood in Baviaanskloof.	Boshoff <i>et al.</i> (2000); Hattingh (2011)
1850-1900	Five recorded floods in the southern Cape.	Illgner and Haigh (2003)
1867	Flood event	Boshoff <i>et al.</i> (2000)
1905	Flood event	Boshoff <i>et al.</i> (2000)
1915	Drought event	Scheltema (2007)
1916	An extreme or great flood on 5 May 1916 caused by catchment-wide heavy rainfall (500 mm) resulted in the loss of several lives and flood damage. The flood was preceded by an almost 18-month long drought event. Floodwaters collected behind debris trapped in a thick growth of prickly pears on the valley floor. This flood was widespread in the southern Cape.	Nortje (1984); Boshoff <i>et al.</i> (2000), Scheltema (2007); Jansen (2008); Hattingh (2011)
1921	Widespread flood in December 1921.	Illgner and Haigh (2003)
1931	Heavy and disastrous floods over an extensive area of the southeast Cape and the whole eastern half of the Cape Province during the last four days of December 1931. The heaviest falls were on the 31 st with over 10 inches (i.e. 254 mm) at some stations. There were serious wash aways and damage to crops.	Union of South Africa (1935)
1932	Great flood on 1 January 1932. It was said that this flood was bigger than the 1916 flood. However, because the prickly pears were cleared away, the flood had a less detrimental impact. This flood was also widespread.	Boshoff <i>et al.</i> (2000); Illgner and Haigh (2003); Hattingh (2011)
1933	Drought event. Rainfall was below normal during the period January to October over the greater part of South Africa. Nearly all of the rivers where running very low or had stopped flowing, springs or storage dams were dry, grazing was absent and stock was dying. In November 1933 the drought was broken.	Union of South Africa (1935); Illgner and Haigh (2003)
1940	Flooding events in February 1940. Prickly pears invade cleared areas.	Illgner and Haigh (2003)
1944	Flood event	Boshoff <i>et al.</i> (2000)
1948	Flood event	Illgner and Haigh (2003)
1951	Flood event	Illgner and Haigh (2003)
1953	Severe flood event. Rainfall 176% to over 200% above normal in 1953 for the Baviaanskloof area.	Union of South Africa (1955); Illgner and Haigh (2003)
1961	Flood event	Boshoff <i>et al.</i> (2000); Illgner and Haigh (2003)
1963	Severe flood in April 1963. This event was thought to be bigger than the 1932 flooding event.	Boshoff <i>et al.</i> (2000), Illgner and Haigh (2003)
1964	Floods during September and December 1964.	Illgner and Haigh (2003)
1966	Drought event	Illgner and Haigh (2003)
1971	Flood in August 1971.	Boshoff <i>et al.</i> (2000), Illgner and Haigh (2003)
1972	Big flood, extensive damage in the valley.	P. Kruger, Zandvakte, Baviaanskloof, pers.comm., 2009
1974	Flood in March 1974.	Illgner and Haigh (2003)
1976	Flood in February 1976 during a drought period.	Illgner and Haigh (2003)
1977	Flooding twice during this year	Boshoff <i>et al.</i> (2000)
1979	Flooding twice during this year. One flood in August 1979.	Boshoff <i>et al.</i> (2000)
1981	According to P. Kruger a big flood with damage to the floodplain fields. Records show extreme discharge. A devastating flood occurred during May 1981.	Boshoff <i>et al.</i> (2000), Illgner and Haigh (2003); P. Kruger, Zandvakte, Baviaanskloof, pers.comm., 2009

Year	Description of event	Source
1983	Flood event	Boshoff <i>et al.</i> (2000)
1984	Flood event	P. Kruger, Zandvlakte, Baviaanskloof, pers.comm., 2009
1987	Severe drought event. Furrows transporting water from the tributaries starting to dry up for the first time.	P. Kruger, Zandvlakte, Baviaanskloof, pers.comm., 2009
1993	Flood event	Boshoff <i>et al.</i> (2000)
1996	Severe or big flood, serious flood damage in the valley and several places in the Eastern Cape Province.	South African Weather Bureau (1996); Boshoff <i>et al.</i> (2000); Illgner and Haigh (2003); P. Kruger, Zandvlakte, Baviaanskloof, pers.comm., 2009
1998	Flood event	Boshoff <i>et al.</i> (2000)
2000	Flood event	Boshoff <i>et al.</i> (2000)
2005	Moderately big flooding event	P. Kruger, Zandvlakte, Baviaanskloof, pers.comm., 2009
2009	Localized flash floods in February 2009 close to Bo-kloof and from June 2009 onwards extending from Kamerkloof to the Baviaanskloof Nature Reserve.	P. Kruger, Zandvlakte, Baviaanskloof, pers.comm., 2009

Table 3.13: A summary of known floods and droughts in the Baviaanskloof.

The flood and drought events in bold were extreme.

Month/Year	Wet and dry periods	
1915		Drought
May 1916	Flood	
Dec 1921	Flood	
Dec 1931	Flood	
Jan 1932	Flood	
1933		Possible drought
Feb 1940	Flood	
1944	Flood	
1948	Flood	
1951	Flood	
1953	Flood	
1961	Flood	
April 1963	Flood	
Sept & Dec 1964	Flood	
1966		Drought
Aug 1971	Flood	
1972	Flood	
March 1974	Flood	
Feb 1976	Flood	Drought
1977	Flood	
Aug 1979	Flood	
May 1981	Flood	
1983	Flood event	
1984	Flood event	
1987		Drought
1993	Flood	
1996	Flood	
1998	Flood	
2000	Flood	
2005	Flood	
Feb & June 2009	Flood	

On further examination of Tables 3.12 and 3.13 it is apparent that there is an under-reporting of drought events in the chronology. The most prolonged dry periods in the study area were noted in 1942, 1983, 1989 and 1995 (Table 3.4). The driest periods were also observed in 1926, 1949 and the 1980s with five years implicated (Table 3.11). The oldest written reference to a drought in the Baviaanskloof was in 1915. Since that time only three other drought episodes were noted. Droughts occurred as well in 1933, 1966 and 1987 (an oral account). Only the 1987 drought was considered extreme. All of these dry periods (except 1933 and 1987) only had one source with no additional information given (Tables 3.12 and 3.13). They could therefore be considered questionable with a low to moderate confidence rating.

According to Kelso and Vogel (2007) drought errors can result for example when drought effects are felt when it rains in the wrong season or time of the year for farming. The 1933 drought year had a higher confidence rating because additional information from two sources accompanied this record. Similarly, since detailed information was provided for the 1987 drought, the confidence rating for this record was also thought to be high although only one source was given (Table 3.12).

3.4 Discussion and conclusion

The objective of this section is to synthesise the results by exploring the links between the rainfall, modelled streamflow and the known floods and droughts. Where possible, explanations are provided for irregularities in the data. In addition, there is a specific focus on extreme event occurrence and flood frequency in the Baviaanskloof.

3.4.1 Rainfall, modelled streamflow and known major floods

When data on rainfall, modelled streamflow and major floods were cross-checked, there was a general concurrence. Support was found for all but one (1972) of the nine major flooding years (Table 3.13). Although no rainfall (Table 3.1) and streamflow (Figure 3.9) data are available to corroborate the 1916 flood, results from the flood chronology indicated that this extreme event did take place (Table 3.12).

The daily (Table 3.4) and yearly rainfall results at Zandvlakte (station 10483) showed that the December 1931-January 1932 period was very wet (Table 3.11). These results were mirrored at Koeifontein (station 10774) for the 1932 flood year (Figure 3.5). The SPI time period analysis demonstrated moderately wet conditions for these two years (Figure 3.6), while extreme river flow was simulated in 1931 (Figure 3.9). An exception at Voorkloof (station 10467) were related to missing data during this period (Table 3.1) which was infilled with synthetic data (Lynch, 2004).

The 1953 flood year was corroborated with extreme daily and yearly rainfall at stations 10467, 10483 and 10774 (Figure 3.7). At station 10467 322.6 mm was recorded on 16 February alone (Table 3.5). This was the largest rainfall amount on record (Table 3.4). Furthermore, extreme wetness was noted in 1953 with regards to the 1-month SPI time period (Table 3.9). High magnitude river flow was also detected for the same year (Figure 3.9). At

Evidence for the 1963 flood year were related to high annual rainfall at stations 10477 (Stadtils Bos), 10483 and 10774 (Figure 3.7). Table 3.11 validated this year as being wet for all three rain gauge stations. The SPI outputs revealed moderately wet conditions in 1963 (Figure 3.6). Moderate simulated river flow was also noted in this year. Possible explanations for this result are linked to the modelling procedure (i.e. the averaging effect of patchy rainfall data across large sized sub-catchments) and input data (Middleton and Bailey, 2009).

Concerning the 1981 flood year, very high daily (Figure 3.5) and annual (Table 3.7) rainfall events were recorded at stations 10774 and 10483. The 3- to 6-month SPI values also indicated very wet conditions during 1981. Moderately wet conditions were associated with the 12-month SPI time period (Figure 3.6). Figure 3.9 indicated that the river flow in 1981 was not extreme but it was still high (52.96 Mcm/a).

The rainfall records for the combined stations and station 10483 showed moderate to heavy rains during October-December 1996 (Table 3.5). The annual rainfall at these stations also indicated wet conditions in 1996 (Figure 3.7). Similar results were presented by the flood chronology analysis (Table 3.11). This was supported by the 1- to 6-month SPI analyses which showed extreme wetness during the same year. The modelled streamflow record also revealed extreme flow for 1996 (Figure 3.9).

At the combined stations the daily rainfall data demonstrated moderate to good rain showers during 2005 (Table 3.4). The annual rainfall outputs also showed that this was a wet year (Figure 3.7 and Table 3.11). The 3- to 12-month SPI data also identified very wet conditions for this year (Figure 3.6). There are no modelled streamflow data available to back the 2005 flooding event. The record ended in 2004 (Figure 3.9). However, since the rainfall data corresponded with the written account, it is argued that a large flooding event did occur in 2005.

The oral evidence for the major flood in 1972 (Table 3.12) did not correspond directly with the rainfall (Figure 3.7) and modelled steam flow data (Table 3.9). However, since this flood year only has one source it could be considered questionable (Table 3.12). Good to heavy rains during March 1972 at stations 10477 and 10483 could have resulted in severe flooding during this year. The 12-month SPI time period also indicated moderately wet conditions for 1972 (Figure 3.6). However, the river flow was not high (Figure 3.9). As discussed above, likely reasons could be related to the modelling method and input data. The annual rainfall at

stations 10477, 10483 and 10774 was also below the annual mean (Figure 3.7). Table 3.11 demonstrated that 1972 was a dry year at all three stations.

This comparison also showed instances (e.g. in 1971 and 1974) where the flood chronology differed from the rainfall data in terms major flooding events. For example, whilst the flood record had limited data regarding the severity of the August 1971 flood event (Table 3.12), the remainder of the historical results displayed extreme conditions. During August 1971 heavy rainfalls occurred at stations 10477, 10483 and 10774 (Table 3.5). Likewise, the 1- to 6-month SPI results (Figure 3.6 and Table 3.9) indicated that 1971 was extremely wet. Table 3.11 further illustrated that this year was wet at all three above mentioned stations. These outcomes were, however, not supported by the modelled streamflow data (Figure 3.9).

3.4.2 Rainfall, modelled streamflow and known droughts

When examining the evidence, there are no rainfall (Table 3.1) and modelled streamflow (Figure 3.9) data available to verify the drought in 1915. However, in the written record it was noted that the extreme flood in 1916 was preceded with an 18-month long drought event (Table 3.12). This confirmed that 1915 was a drought year.

Concerning the 1933 drought year, rainfall records for stations 10483 (Zandvlakte) and 10774 (Koeifontein) indicated above-average rainfall. Although below mean annual rainfall was recorded at station 10477 (Stadtis Bos), the rainfall was not < 75% of the mean annual rainfall (Figure 3.7). Nonetheless, it is possible that a seasonal drought could have occurred during a season that was important for farming activities (Wilhite, 2000). In the written record it was observed that grazing was absent and livestock were dying (Table 3.12). The 1- to 6-month SPI time periods indicated moderately dry conditions for this year (Figure 3.6). The modelled streamflow analysis also did not display high flow for 1933 (Figure 3.9).

The rainfall records for stations 10477, 10483 and 10774 indicated that 1966 was a below mean annual rainfall year (Figure 3.7). Table 3.11 further showed that this was a dry year for station 10483. For the remaining two stations slightly dry conditions are revealed (Figure 3.7). The SPI results did not support dryness in 1966 (Table 3.9). This is mirrored by the river flow analysis which indicated flow above 40 Mcm/a (Figure 3.9). However, since the rainfall data mostly agreed with the written account, it is contended that 1966 was a drought year.

Yearly rainfall data from station 10483 and the combined stations clearly demonstrated that 1987 was a drought year with below mean annual rainfall linked to very dry conditions (Figure 3.7). Table 3.11 also indicated that 1987 was associated with dryness. At stations 10477 and 10774 slightly dry conditions are shown with rainfall below the mean annual rainfall (Figure 3.7). Severely dry conditions were detected by the 1- to 3-month SPI time periods. The 12-month SPI time period displayed moderately dry conditions (Figure 3.6). In

addition, Figure 3.9 did show reasonably low river flow for 1987. In the written record it was observed that the furrows dried up for the first time during this extreme drought year (Table 3.12).

It is apparent in Tables 3.12 and 3.13 that data on drought events are lacking in the chronology. The lack of known droughts, in part, may be due to the fact that it is very difficult to define an actual drought event. Hence, insufficient understanding and limited empirical knowledge of dry spells can be accountable for this data limitation (Vogel *et al.*, 2000; Wilhite, 2000).

3.4.3 Flow variability

In this study, an attempt was made to assess flood frequency using the most relevant information available from the rainfall, modelled streamflow and flood chronology analyses. This was done to make broad statements regarding the frequencies of flood flows in the Baviaanskloof River catchment.

As expected, the rainfall results indicated that high magnitude (i.e. extreme) rainfalls (≤ 100 mm) have longer return periods (mostly > 40 years) and a much lower frequency of occurrence than small magnitude (i.e. moderate) rainfalls (Figure 3.4 and Table 3.7). This trend was also visible in the extreme modelled flood flows which were infrequent (Figure 3.9). In general, moderate rainfalls (5 to < 25 mm) had return periods of less than one year. At the good rainfall events (25 to > 50 mm) it was above one year. From the analysis of rainfall magnitudes and estimated return periods (Figure 3.4), it was found that available records of major inter-annual floods (Table 3.12) generally disagreed with the rainfall events of high return periods. For example, the flood event of 31 December 1931 (Table 3.5) did not correspond to rainfall with a 10.4 year return period. Table 3.12 further showed that these major or large floods had frequencies ranging from 9-21 years. They were typically associated with heavy rainfall events (50 to > 100 mm) (Table 3.5) with return periods, which mostly exceeded 3 years but were < 40 years (Table 3.4). The remainder of the moderate flooding events which were associated with good rainfalls tended to have flood frequencies ranging from 1-3 years. Unfortunately, the flood chronology analysis did not reveal information about intra-annual floods (Tables 3.12 and 3.13).

3.4.4 Concluding remarks

This study presented a historical analysis based on available secondary data sources for the ungauged Baviaanskloof River catchment. The aim was to obtain information on rainfall patterns, floods and droughts, extreme event occurrence and flood frequency in order to explain past (Chapter 4) and present (Chapters 5-7) hydrogeomorphic process-form and vegetation relationships in the catchment.

The results revealed that when data on rainfall, modelled streamflow and flood and drought incidences were cross-checked, there was mostly a positive correlation. Despite the various limitations of the long-term flood and drought history derived for the valley it is felt that this data set is valuable since it extends the climatic record and partially fills the streamflow gap in the study area. This aggregated record will provide an initial point of departure for further detailed environmental studies in the Baviaanskloof.

Chapter 4: Historical river valley changes

4.1 Introduction

Many modern-day problems in fluvial geomorphology require a historical view. Dealing with these problems necessitates a solid place-based understanding of how a system has adjusted and evolved over space and time (Spink *et al.*, 2010), otherwise the ultimate controls on and changes to the system will not be fully captured (Dollar, 2004). Yet, most river system studies provide only arbitrarily-timed snapshots of the system because the studies extend less than five years (Gurnell *et al.*, 2003). Browning *et al.* (2009) noted that historical perspectives enable investigators to clarify patterns and trends of change and to unravel interactions among variables shaping change trajectories. Only by understanding the past can we place recent and continuing channel changes into perspective and thus begin to disentangle the complex factors which affect rivers today (Winterbottom, 2000; Dollar, 2004).

Understanding the past also allows forecasting of likely future trajectories of change. This promotes proactive rather than reactive practices. The historical record therefore affords vital insights with which to guide management practice (Brierley *et al.*, 2010; Spink *et al.*, 2010). Recent geomorphic investigations have benefited from advances in fields such as historical geography, archaeology and paleohydrology (Gurnell *et al.*, 2003; Keen-Zebert *et al.*, 2013; Grenfell *et al.*, 2014). Historical information is useful in river restoration (Greco *et al.*, 2007; Fryirs *et al.*, 2013; Arnaud *et al.*, 2015) or rehabilitation work (Brierley and Fryirs, 2009; Spink *et al.*, 2010), human impact studies (Boix-Fayos *et al.*, 2007; Fryirs *et al.*, 2009; Stromberg *et al.*, 2010b; Rebelo *et al.*, 2015), climate change (Goudie, 2006; Hoffman and Rohde, 2011), and channel (Winterbottom, 2000; Cadol *et al.*, 2011; Hupp *et al.*, 2013) and catchment or valley floor changes (Parsons and Gilvear, 2002; Fryirs *et al.*, 2009; Grenfell *et al.*, 2009; Kuo and Brierley, 2014).

This chapter investigates historic geomorphological, land cover and vegetation changes (objective two, Section 1.4) and in doing so partially addresses objective three (Figure 1.2). Objective three examines the two-way links between hydrogeomorphic processes and landforms, including surface-groundwater interactions, and vegetation distribution patterns on the valley floor. This is done at selected sites in the Baviaanskloof River catchment. Furthermore, comparisons are made within and between confined, semi-confined and unconfined valley settings. Valley floor changes observed today (Chapters 5-7) reflect an integrated history of former events and impacts (this chapter).

The chapter is divided into three main sections: methods (Section 4.2), results (Section 4.3) and discussion and conclusion (Section 4.4). The methods section deals with data collection, analysis and presentation. The results section first considers the analysis concerning landscape geomorphic change (Section 4.3.1). An analysis related to quadrat geomorphic change is

presented next (Section 4.3.2), followed by the land cover change analysis (Section 4.3.3). The discussion and conclusion section examine the results collectively, interpreting key chapter outputs.

4.2 Methods: Data collection, analysis and presentation

The methodology related to the historical mapping included two main procedures: data acquisition and data handling. Data acquisition consisted of stereoscopic interpretation of multi-temporal aerial photographs for selected study sites. This process was also aided by several existing ArcGIS data layers. These sequential sets of aerial photographs or photo comparisons provided a time-series from which valley floor changes could be mapped. Data handling involved capturing, analysing and generating geomorphic and land cover data in ArcGIS 10.1 (ESRI, 2012). This process facilitated both statistical and graphical analysis of the data. The analysis was conducted at two scales: a landscape scale (examining valley confinement settings) and a quadrat or sampling plot scale (examining within valley confinement settings) (Section 4.2.2). These quadrats will be used in later analyses. This time series data will assist with the interpretation of morphological and vegetation data in subsequent chapters (Chapters 5 and 6). A number of studies have found GIS useful in analysing river morphology (e.g. Winterbottom, 2000; Cadol *et al.*, 2011; Arnaud *et al.*, 2015) and valley floor change (e.g. Parsons and Gilvear, 2002; Kuo and Brierley, 2014) in aerial photographs.

In addition, a timeline of key human activities or events in the valley (deliberated on in Section 2.7.1, Chapter 2) and historical rainfall data for selected rain gauge stations (Table 3.1) combined with modelled streamflow data and a chronology of climate extremes (discussed in Sections 3.3 and 3.4, Chapter 3) assisted with explaining the resultant historical valley floor changes.

4.2.1 Image acquisition, processing and accuracy

Image acquisition

An initial enquiry to the Department of Land Affairs, Chief Directorate: Surveys and Mapping (DLA-CDSM) concerning aerial photograph availability for the Baviaanskloof River catchment revealed aerials at various scales covering different years and sections of the catchment. A variety of scales was considered necessary since fine scales lose detail while coarse scales involve a sacrifice in terms of synoptic view (Rossouw, 1997). The aerial photograph coverage for the study area was incomplete. These factors influenced the selection of the aerial photographs analysed in the study since the interpretation was directly tied to the 13 selected study sites (Figure 2.16 and Table 2.3) and 2010 field surveys (detailed in Sections 5.2 and 6.2.1, Chapters 5 and 6 respectively). In the end, stereoscopic pairs of hard copy aerial photos were acquired from the DLA-CDSM for the years 1944, 1960-1961, 1972,

1986 and 2007. This was used in conjunction with digital 2007 orthorectified colour images, also acquired from the DLA-CDSM (Table 4.1).

Table 4.1: Aerial photography data sets analysed in the study.

Data source: DLA-CDSM. GCPs = ground control points, RMSE = root mean square error and - = information not available, ortho-rectified imagery.

Year	Date	Scale	Film and print type	Average GCPs	Average RMSE (m)
1944	No date	1: 20 000	Black and white contact print	26.2	3.2
1960-1961	Dec-Jan	1: 34 500 and 1: 36 100	Black and white contact print	30.5	1.6
1972	4 Jul	1:40 000	Black and white contact print	54.5	2.3
1986	8 Jun	1:50 000	Black and white contact print	70	0
2007	11 and 14 Sep	1:32 000	Colour contact print	-	-

0

Processing and accuracy

Using a high resolution scanner, one aerial photo of each stereo pair was digitized (i.e. 1000 dots per inch or dpi) and then georeferenced using the 2007 orthorectified images as base layers for the co-registration in ArcGIS 10.1. Nineteen images were corrected for scale, tilt and distortion of the ground surface. Using a combination of low root mean square error RMSE values (GCPs with high errors were deleted) (Table 4.1) and the selection of GCPs mainly on the valley floor and valley margins improved accuracy. The latter also focused the correction process and reduced errors related to the steep topography of the Baviaanskloof (Figures 2.3 and 3.1). RMSE values are measures of the difference between GCPs on the base layer (2007 orthorectified image) and the georeferenced image (scanned image). Hence, it measures the accuracy of the GCPs (Hughes *et al.*, 2006; Schmitz *et al.*, 2009). Points that minimize RMSE values are generally seen as an indication of best fit (ESRI, 2012). The RMSE values were the lowest for 1986 and 1960-1961, less than 2 m horizontally (Table 4.1).

At least 30 GCPs for fine scales and 20 for coarse scales were employed. Using more GCPs also improved overall georectification accuracy (Table 4.1). However, it must be noted that georeferenced imagery has inherent locational error. Although there was a focus on selecting hard GCPs, it was impossible to avoid also selecting a couple of soft GCPs (e.g. persistent vegetation) as some of the air photos offered few GCP choices. Hard GCPs included artificial features such as corners of buildings, road junctions and field boundaries in addition to rocky outcrops. They are usually fixed in the landscape for long periods of time and their locations can be pinpointed (Hughes *et al.*, 2006). The spline method of transformation was then followed by the Nearest Neighbour resampling approach which does not alter the original

pixel values. This transformation is a true rubber sheeting method and optimizes for local accuracy (ESRI, 2012). The images were rectified using the same projection as the 2007 imagery (projected as Universal Transverse Mercator, WGS1984).

Study site selection linked to rectified imagery

Although randomization of study site selection would have been ideal to access changes, selection was hampered by the existing aerial photographs (Table 4.1). It was also influenced by the available 2010 field-based data (e.g. the resistivity sites), geomorphic representation, degree of disturbance and confinement. Six alternating confined, semi-confined and unconfined sites were paired along the Baviaanskloof River (Figure 4.1). Site characteristics (e.g. a reduced valley floor width) and time constraints resulted in limited data capturing and analysis for the confined and semi-confined sites. Only 1944 and 2007 images were interpreted. This contrasted with mapping of all the selected images for the unconfined study sites. This should have minimal impact on the results and overall study conclusions, as it is expected that at the unconfined study sites increased human activity (de Jong, 2013) and river instability (Rowntree, 2012) are more likely to result in valley floor changes.

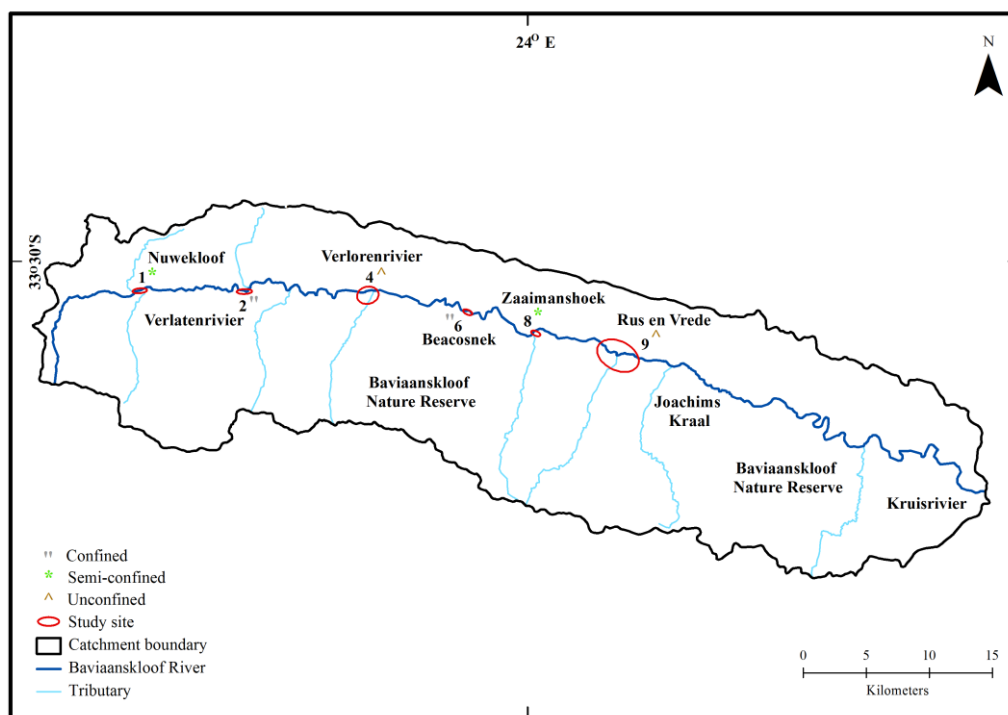


Figure 4.1: Study sites selected to assess historical valley floor changes, Baviaanskloof.

4.2.2 Geomorphic classification and mapping

The objective of the geomorphic mapping was to adopt a classification interpretable at a simple landscape scale. Mapping involved 12 features defined according to geomorphological

criteria (Table 4.2) and the presence or absence of natural vegetation. Stereoscopic interpretation and supplemental ArcGIS data layers (Table 4.3) assisted with distinguishing the different fluvial surfaces. Image interpretation was based on texture, colour, shape, size, pattern and association with geomorphic features (Bishop *et al.*, 2012).

Table 4.2: Adapted key for geomorphic features mapped, Baviaanskloof.

Modified from Hickin (1984), Rowntree and Wadeson (1999), Simon and Castro (2003), Burge (2004), Gordon *et al.* (2004), Latterell *et al.* (2006) and Fryirs and Brierley (2013).

Feature	Description
Main channel	Active trunk or primary channel containing the thalweg that carry most of the flow.
Tributary channel	A smaller active channel or stream flowing into a larger channel. Lateral tributary inputs at confluences.
Secondary channel	An abandoned former main or tributary channel (i.e. old channel) on the floodplain. This inactive sediment filled side-channel can be briefly reactivated to hold floodwaters.
Point bar	A bar formed on the inside of meander bends. It is associated with erosion on the opposite bank and meander migration across the floodplain.
Lateral, side or alternate bar	Accumulation of sediment attached to the side of the channel, often occurring sequentially downstream as alternate bars.
Scroll bar	A point bar on which the accumulation of a slight convex upward gravel basement is topped with finer material eventually forming scroll ridges.
Mid-channel bar	A bar forming within the middle of the channel, with strong flow on either side.
Island	A large vegetated mid-channel bar that is rarely inundated. It is however, submerged at high flows.
Flood bench or channel shelf	Narrow terrace-like lateral feature (best developed along steep-gradient reaches) formed at the edge of the active channel abutting on to the macro-channel bank.
Floodplain	A flat area adjacent to the river channel created by the present river in the current climate and subject to overflow during high flow events.
Terrace	Abandoned former floodplain. This flat valley marginal feature is no longer active.
Alluvial fan	Sedimentary deposits that accumulate at the junction between mountains and valley floor surfaces. This transitional feature is usually conically shaped.

Concerning the extent of the mapped area for each site, it was decided to map a certain distance upstream and downstream of the first and last surveyed cross-section. For the confined and semi-confined sites it was 50 m and 200 m respectively. For the unconfined

Verlorenrivier and Rus en Vrede sites, it was 1 km and 1.5 km. These distances were considered to be adequate to capture the spatial and temporal variability within each valley confinement setting (confined, semi-confined and unconfined). Their selection depended mostly on the existing aerial photograph coverage as well as the characteristics of the confinement setting (e.g. extent, degraded areas and hillslope edge location) which in turn determined the area (including the river reach length) available for mapping. For instance, at the confined sites the limited extent (i.e. short narrow valley floor sections) was directly related to the reduced mapping area.

It must be mentioned that in several of the historical aerial photographs, delineating the main channel was difficult. Most of the times the channel was dry or there was a lack of dense marginal vegetation. This uncertainty was accounted for by delineating lines that bound the area that unquestionably would be within the main channel and was the best estimate of the channel at the time of the aerial photo (Dean and Schmidt, 2011). Sandercock *et al.* (2007) noted that landform distinction in semi-arid environments can be problematic because landforms do not always have a regular arrangement.

Table 4.3: ArcGIS data layers used in the study.

Data layer	Scale	Source
Cross-sections	Image specific	ArcGIS 10.1 (ESRI, 2012), obtained during 2010 Baviaanskloof field campaign
Quadrats (i.e. representing geomorphic landforms)	Image specific	ArcGIS 10.1 (ESRI, 2012), selected during 2010 Baviaanskloof field campaign
Square area boundary	Image specific	ArcGIS 10.1 (ESRI, 2012)
Alluvial fans	90 m	Bobbins (2011)
Geology	1:250 000	Council for Geoscience (1979 and 1991)
2007 SPOT-5 satellite imagery	2.5 m	Centre National d' Etudes Spatiales (2012)
Topographical maps	1:50 000	DLA-CDSM (1967, 1985, 1986, 2000)
Farm dams	1:50 000	DLA-CDSM (2005)
Relief lines (contours)	20 m	DLA-CDSM (2006)
Rivers	1:50 000	DWAF (2004b)
Rivers	1:500 000	DWAF (2006)

Other common mapping problems (e.g. difficulty in distinguishing between subtle differences) were related to the varying scales and different viewing angles of the aerals, object shadows and the poor clarity of a few of the older images. For example, the quality of some of the photo sets was not good enough to distinguish the surface composition of alluvial fans, hence, their distribution and boundaries. For this reason fans were not mapped in great detail. They were, however, represented using a ArcGIS data layer produced by Bobbins (2011) (Table 4.3).

To clarify the role that vegetation had in causing recent change, the vegetation in channels and on bars or flood benches were also estimated and described. Three categories were used: vegetated (dense vegetation), partially vegetated (scattered vegetation) and unvegetated (very little to no vegetation). On-screen digitizing then resulted in mapped polygons. In all cases an underestimate of the extent was chosen rather than an overestimate (Ridefelt *et al.*, 2009). Each georeferenced image was then appended to others pertaining to a particular year set (Table 4.1), to produce one map with polygons depicting the various geomorphic landforms for that year (ESRI, 2012).

Field surveys during 2010 aided the delineation of the 2007 geomorphic landforms which was used to cross-check historical identifications. For example, recent photographs and surveyed cross-sections using a differential GPS with an accuracy of 2 cm were used to identify geomorphic features (Table 4.2). This included relatively stable landforms such as terraces. Although sediment reworking may occur on terraces, their boundaries remain generally unchanged over decadal timescales (Fryirs and Brierley, 2013). No distinction was made between multiple terraces (e.g. site 9). A single polygon encompassed all multi-level terraces since delineation was limited to all visible fluvial surfaces.

Cross-sections were linked to sample plots or quadrats that represented geomorphic landforms (Table 4.3), which were set-up along cross-sections (Section 5.2.1, Chapter 5 for further details). In addition, the occurrence and characteristics of these landforms were marked on sketches in the field and used in conjunction with the rectified aerial photographs. Geomorphic changes linked to study quadrats were also analysed. Unfortunately these quadrats had GPS measurement errors and in some instances are associated with inaccuracies of between 4-15 m. This limitation was, however, mitigated by verifying the quadrat data with the cross-section data.

4.2.3 Land cover classification and mapping

Seven vegetation and land cover classes were identified and mapped (Table 4.4). These classes are similar to the vegetation classes described previously (Section 4.2.2). A greyscale density slicing method (e.g. Callow and Smettem, 2007) using four broad vegetation classes was chosen to facilitate consistent and easy interpretation from the aerial photographs. Dark tonal areas were easier to map than light tonal areas. Various data layers (Table 4.3) also assisted with distinguishing the different land cover features. The land cover mapping process followed a similar procedure (i.e. stereoscopic interpretation, on-screen digitizing and map generation) as was described for the geomorphic mapping. It was also associated with similar mapping issues. Field surveys (e.g. field observations, vegetation sampling and recent photographs) validated the resultant 2007 vegetation and land cover maps which were also used to cross-check delineations made from the historical aerial photographs.

Table 4.4: Adapted key for vegetation and land cover features mapped, Baviaanskloof.

Feature	Description
High density vegetation	Dense trees, shrubs and some grasses with limited bare ground. Mostly a closed canopy where understorey plants cannot be seen. Dark tonal areas.
Medium density vegetation	Patches of trees, shrubs and grasses spread apart with visible bare ground. Canopy can be open or closed or both. Dark tonal areas.
Low density vegetation	Scattered or sparse trees or shrubs with lots of grasses and bare ground in between. An open canopy. Lighter tonal areas.
No vegetation	Bare ground or patches of bare ground. Visible open white spaces.
Active agricultural field	A field with obvious signs of recent cultivation or a current crop. These fields form part of the production system.
Old agricultural field	Former or abandoned cultivated area. Obvious signs of regrowth which can include shrubs and trees. Assumed that it was not cultivated recently due to non-viability.
R322 road	A public gravel road that runs through the valley.

4.2.4 Data manipulation and analysis

Data handling involved polygon analysis in ArcGIS 10.1 (ESRI, 2012). The attribute tables for each classified image contained information on the number of polygons, the geomorphic and land cover classification, the description of each polygon and the area (ha) of each polygon. The data were then exported as txt files into Microsoft Excel. Area and percentage calculations resulted in numerous tables and bar graphs. These were used to illustrate how the valley floor has changed over the mapped period.

4.3 Results

4.3.1 Landscape geomorphic change, 1944-2007

Confined study sites

The results of the geomorphic mapping for the confined sites are presented in Figures 4.2 and 4.3 and Table 4.5 respectively. The partially vegetated main channel at both sites is narrower than it was six decades ago based on the aerial photograph comparisons between 1944 and 2007. Secondary channels at site 6 (Beacosnek) are also narrower and only partially vegetated (Figure 4.2 and Table 4.5). The in-channel morphology of the Baviaanskloof River in 1994 was dominated by point, lateral (site 2, Verlatenrivier, only) and mid-channel bars (site 6 only) totalling four at site 2 and five at site 6. Site 2 had bars with low to medium density

vegetation and an absence of former channels. The bars at site 6 had low to high density vegetation (Table 4.5). These fluvial surfaces were reflected in the river's single thread medium sinuosity planform or pattern. Over the years the active main channel displayed small lateral displacement at both study sites (Figure 4.3).

In 1944 the average channel width at study sites 2 and 6 was 6 m and 16 m respectively. In 2007 it was 4 m at site 2 and 5 m at site 6 (Figure 4.3). There was also a reduction in the number of bars (site 6) and bar area (site 2) which were replaced by flood benches and an increased floodplain area (Figures 4.2 and 4.3). Medium to high density vegetation occupied the flood benches (Table 4.5). While alluvial fan deposits covered a large section of the terrace area at site 2, fans were completely absent at site 6. Terraces at site 2 also occurred on both sides of the main channel but at site 6 only one high terrace was present. It was noticeable that tributary channels were lacking at both study sites (Figures 4.2).

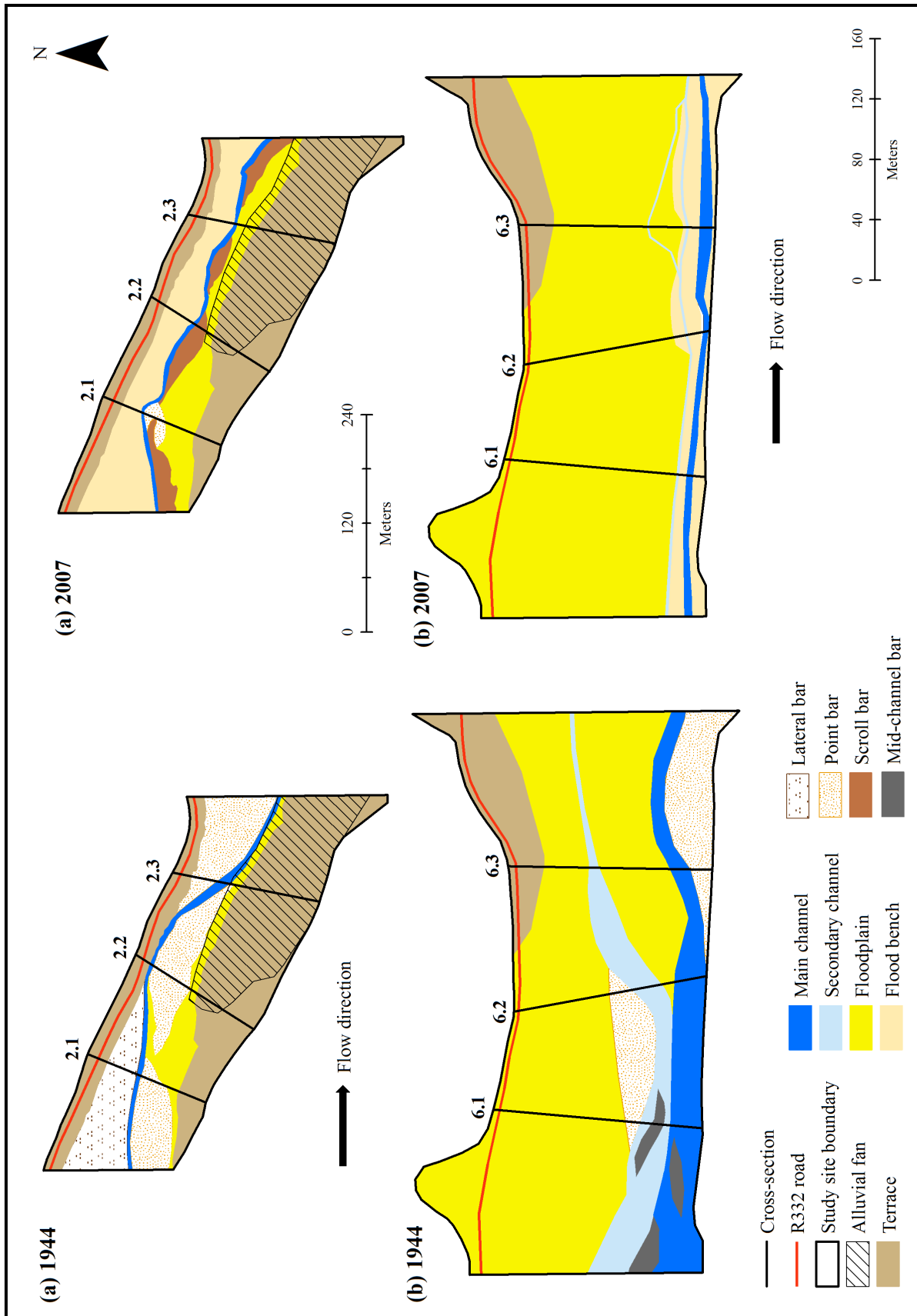


Figure 4.2: Geomorphic change for confined study sites 2, Verlatenrivier (a) and 6, Beacosnek (b), 1944 and 2007.

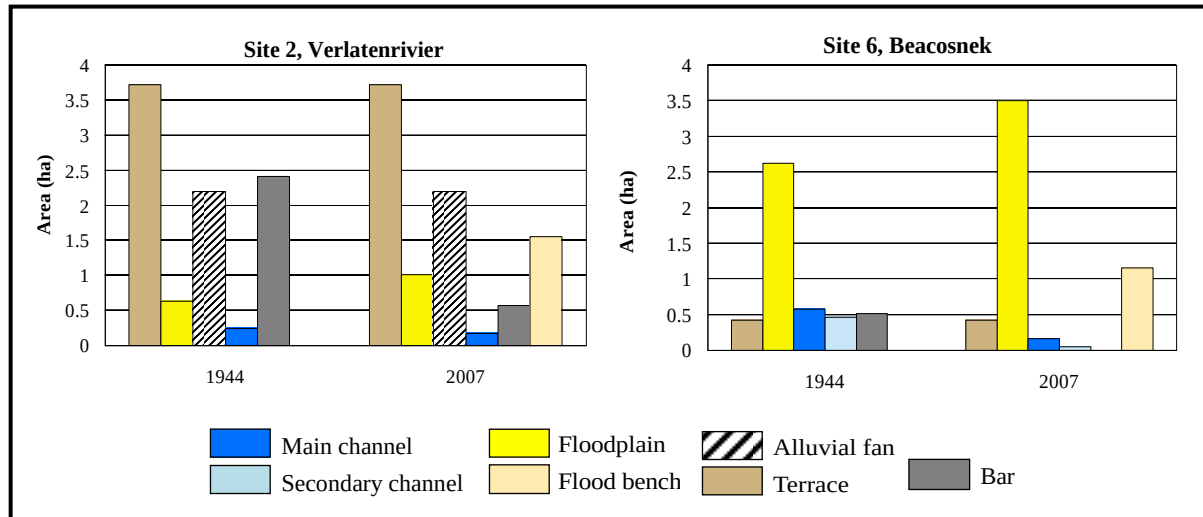


Figure 4.3: Geomorphic area change between 1944 and 2007, confined study sites.

Table 4.5: Area (ha) and frequency of occurrence (brackets) of geomorphic features, confined sites.

Vegetation density descriptions as per Table 4.4.

Site 2, Verlatenrivier	1944	2007
Terrace	3.72 (1)	3.72 (1)
Floodplain	0.63 (1)	1.01 (1)
Alluvial fan	2.20 (1)	2.20 (1)
Flood bench	-	1.55 (1)
Lateral bars with high density vegetation	-	0.06 (1)
Lateral bars with medium density vegetation	0.77 (1)	-
Scroll bars with low density vegetation	-	0.43 (5)
Scroll bars with high density vegetation	-	0.06 (1)
Point bars with medium density vegetation	1.05 (2)	-
Point bars with low density vegetation	0.60 (1)	-
Partially vegetated main channel	0.25 (1)	0.17 (1)
Total geomorphic features	8	11
Site 6, Beacosnek		
Terrace	0.42 (1)	0.42 (1)
Floodplain	2.63 (1)	3.50 (1)
Flood benches	-	0.57 (5)
Lateral bars with low density vegetation	-	0.01 (1)
Mid-channel bars with low density vegetation	0.07 (2)	-
Mid-channel bars with no vegetation	0.04 (1)	-
Point bars with high density vegetation	0.31 (1)	-
Point bars with low density vegetation	0.20 (1)	-
Partially vegetated main channel	0.58 (1)	0.17 (1)
Vegetated secondary channels	0.47 (2)	-
Partially vegetated secondary channels	-	0.05 (2)
Total geomorphic features	10	11

Semi-confined study sites

The analysis indicates that the channel planform of the partially vegetated Baviaanskloof River at the semi-confined sites over the time interval 1944-2007 changed from a wide wandering braided channel flowing around numerous mid-channel bars to a narrow single thread sinuous channel with a reduced number of bars (Figure 4.4 and Table 4.6). The average channel area at site 8 (Zaaimanshoek) for example, decreased from 29 to 9 m (Figure 4.4). Similarly, in the 1944 air photos there were five and seven mid-channel bars at study sites 1 (Nuwekloof) and 8 respectively. This decreased to one (site 1) and two (site 8) in the 2007 air photos. At site 8 this came with the establishment of an island. Also, lateral bars totalled four in 1944 at this site. In 2007 there were none. However, at site 1 their numbers remained constant through time. Bars were mostly overgrown with low to medium density vegetation (Table 4.6). At site 1 the valley tended to be relatively open and straight (Figure 4.4).

Channel narrowing and bar area reduction has resulted in an increased floodplain area (both sites) and has converted some surfaces into flood benches (site 8). At site 8 for instance, the floodplain area increased from 8.8 to 13.09 ha (Figures 4.4 and 45 and Table 4.6). Partially vegetated secondary channels at this site also underwent narrowing and were associated with vegetation establishment as well as fewer bars. In conjunction with this, tributary channels (i.e. mostly unvegetated) remained stable but the total number of geomorphic features was reduced (Figure 4.4 and Table 4.6). This contrasted with the unchanged geomorphic feature numbers at site 1 as shown in Table 4.6. While alluvial fan deposits were limited to this study site, abandoned secondary channels were mostly absent here (Figures 4.4 and 4.5). The remnant perched terrace at site 8 covered a very small area (0.11 ha) whereas at site 1 it occupied a larger area (1.95 ha) (Table 4.6).

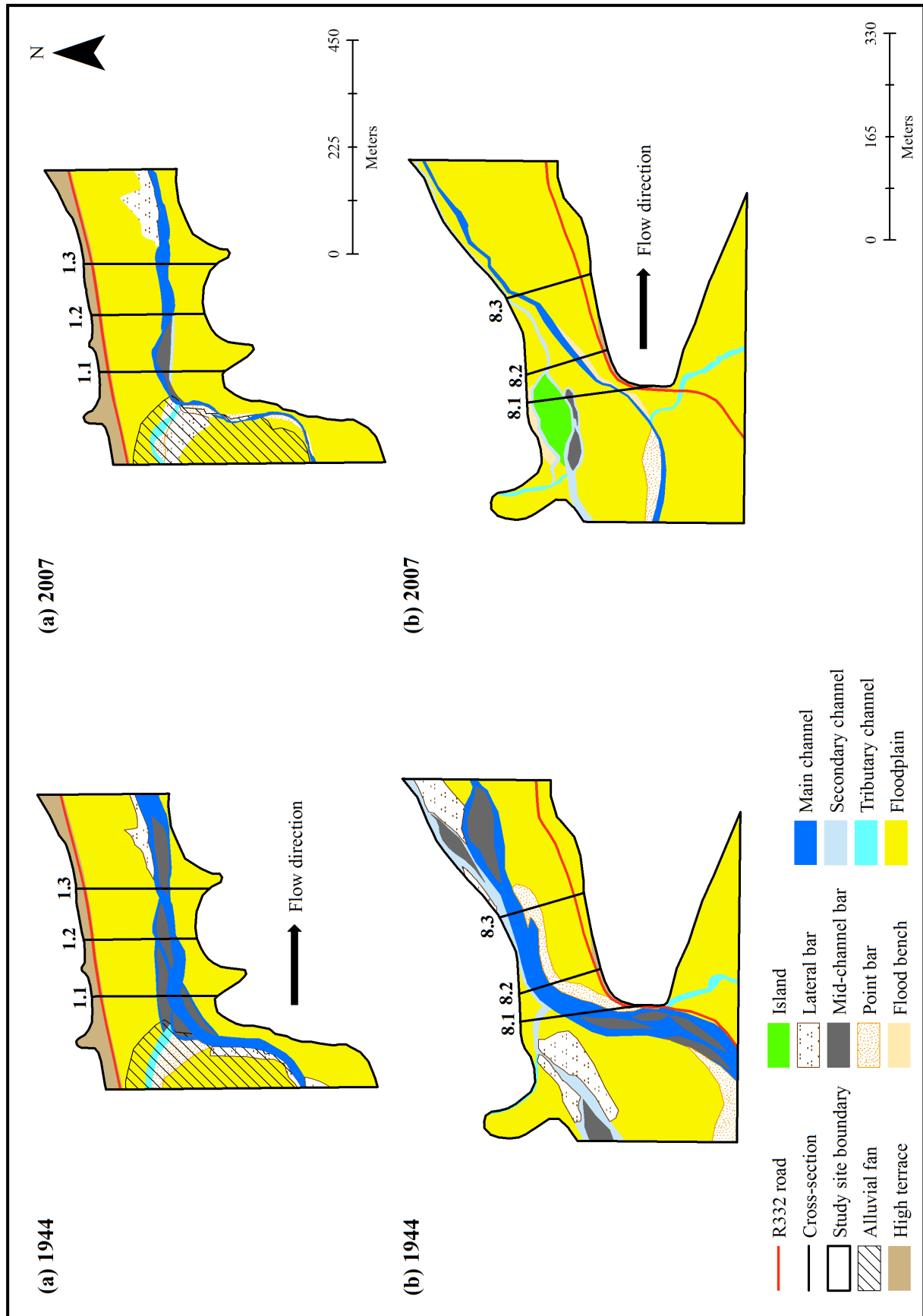


Figure 4.4: Geomorphic change for semi-confined study sites 1, Nuwekloof (a) and 8, Zaaimanshoek (b), 1944 and 2007.

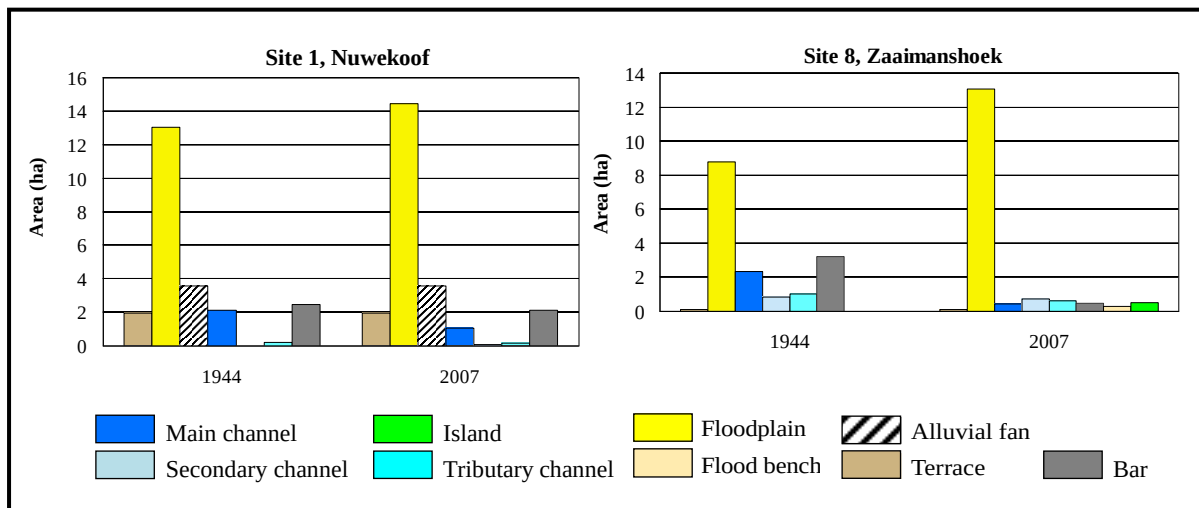


Figure 4.5: Geomorphic area change between 1944 and 2007, semi-confined study sites.

Table 4.6: Area (ha) and frequency of occurrence (brackets) of geomorphic features, semi-confined sites.

Vegetation density descriptions as per Table 4.4.

Site 1, Nuwekloof	1944	2007
High terrace	1.95 (1)	1.95 (1)
Floodplain	13.07 (1)	14.46 (1)
Alluvial fan	3.60 (1)	3.60 (1)
Lateral bars with medium density vegetation	0.34 (1)	1.28 (2)
Lateral bars with low density vegetation	0.39 (3)	0.09 (1)
Lateral bars with no vegetation	-	0.03 (1)
Mid-channel bars with medium density vegetation	0.35 (1)	-
Mid-channel bars with low density vegetation	0.79 (4)	0.30 (1)
Point bars with medium density vegetation	0.59 (1)	-
Point bars with low density vegetation	-	0.42 (4)
Partially vegetated main channel	2.01 (1)	0.44 (1)
Unvegetated main channel	0.12	0.63
Partially vegetated secondary channels	-	0.07 (1)
Partially vegetated tributary channels	0.21 (1)	0.16 (1)
Total geomorphic features	15	15
Site 8, Zaaimanshoek		
High terrace	0.11 (1)	0.11 (1)
Floodplain	8.80 (1)	13.09 (1)
Flood benches	-	0.29 (2)
Lateral bars with medium low density vegetation	0.19 (1)	-
Lateral bars with low density vegetation	1.04 (3)	-
Mid-channel bars with medium density vegetation	0.56 (3)	0.15 (2)
Mid-channel bars with low density vegetation	0.52 (4)	-
Point bars with medium density vegetation	0.53 (1)	0.31 (1)
Point bars with low density vegetation	0.39 (1)	-

Site 1, Nuwekloof	1944	2007
Islands with high density vegetation	-	0.51 (1)
Partially vegetated main channel	2.36 (1)	0.43 (1)
Partially vegetated secondary channels	0.85 (3)	0.32 (1)
Vegetated secondary channels	-	0.42 (3)
Partially vegetated tributary channels	0.04 (1)	0.05 (1)
Unvegetated tributary channels	0.11 (1)	0.12 (1)
Total geomorphic features	21	15

Unconfined study sites

Over the 63 years studied, the single thread Baviaanskloof River at site 4 (Verlorenrivier) maintained a medium sinuosity character. However, a section of the partially vegetated main channel was multi-thread in 2007 (Figure 4.6). On average, the channel width along the main channel varied from 10 m to over a 100 m over the full time interval. Although lateral channel migration had continued over this period, the main channel did not shift from one side of the valley to the other. It was constrained by the alluvial fans present on the valley floor (Figure 4.6). However, channel widening still took place with the active channel area increasing from 5.82 ha in 1944 to 8.85 ha in 2007 (Figure 4.7 and Table 4.7). This was associated with a reduction in the number of mid-channel bars. The most evident shift occurred during 1972 and 1986. In contrast, the total lateral bar area and number increased over the decades. The greatest increase of new bar area occurred in the 1986 image (Figure 4.6 and Table 4.7).

The secondary channel area (i.e. associated with both main and tributary channels) increased by 7 ha between 1944 and 1972. Although it decreased steadily after this period, it was still more than it was in 1944, 11.12 ha in 2007 (Table 4.7). These former channels were mostly partially vegetated through time. The tributary channel area slightly increased from 1944 to 1961, thereafter it mostly decreased. This was also accompanied by a reduction of mid-channel bars. Tributaries were mainly partially vegetated over the years (Figure 4.6 and Table 4.7). For all periods floodplain areas mostly fluctuated, hence displaying no dominant pattern. Flood benches with low density vegetation were present only in 2007 and covered a small area. Terrace surfaces were absent at site 4 (Figure 4.7 and Table 4.7). Table 4.7 shows that the number of geomorphic features over the five time intervals increased from 26 to 41.

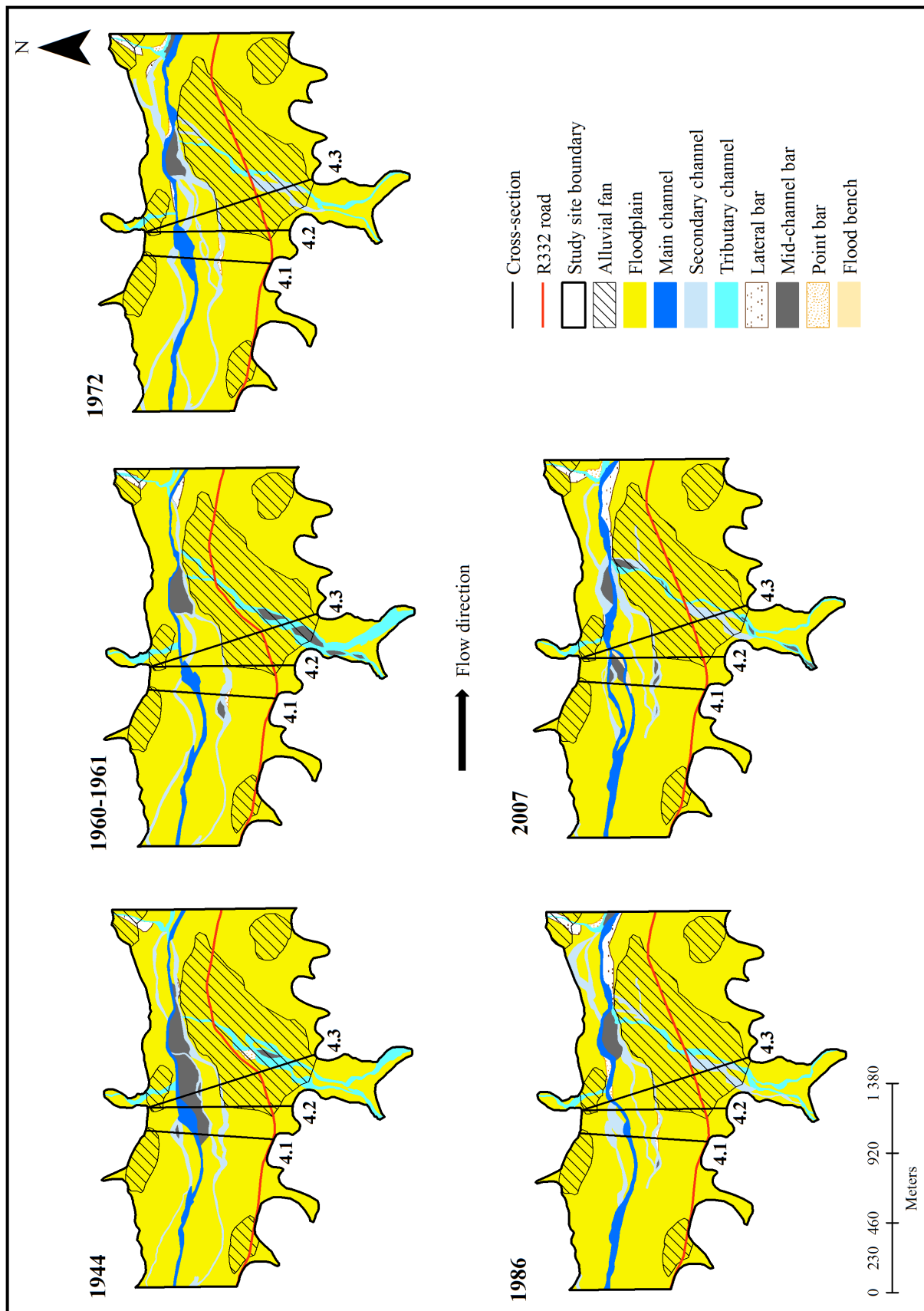


Figure 4.6: Geomorphic change for unconfined study site 4, Verlorenrivier (1944-2007).

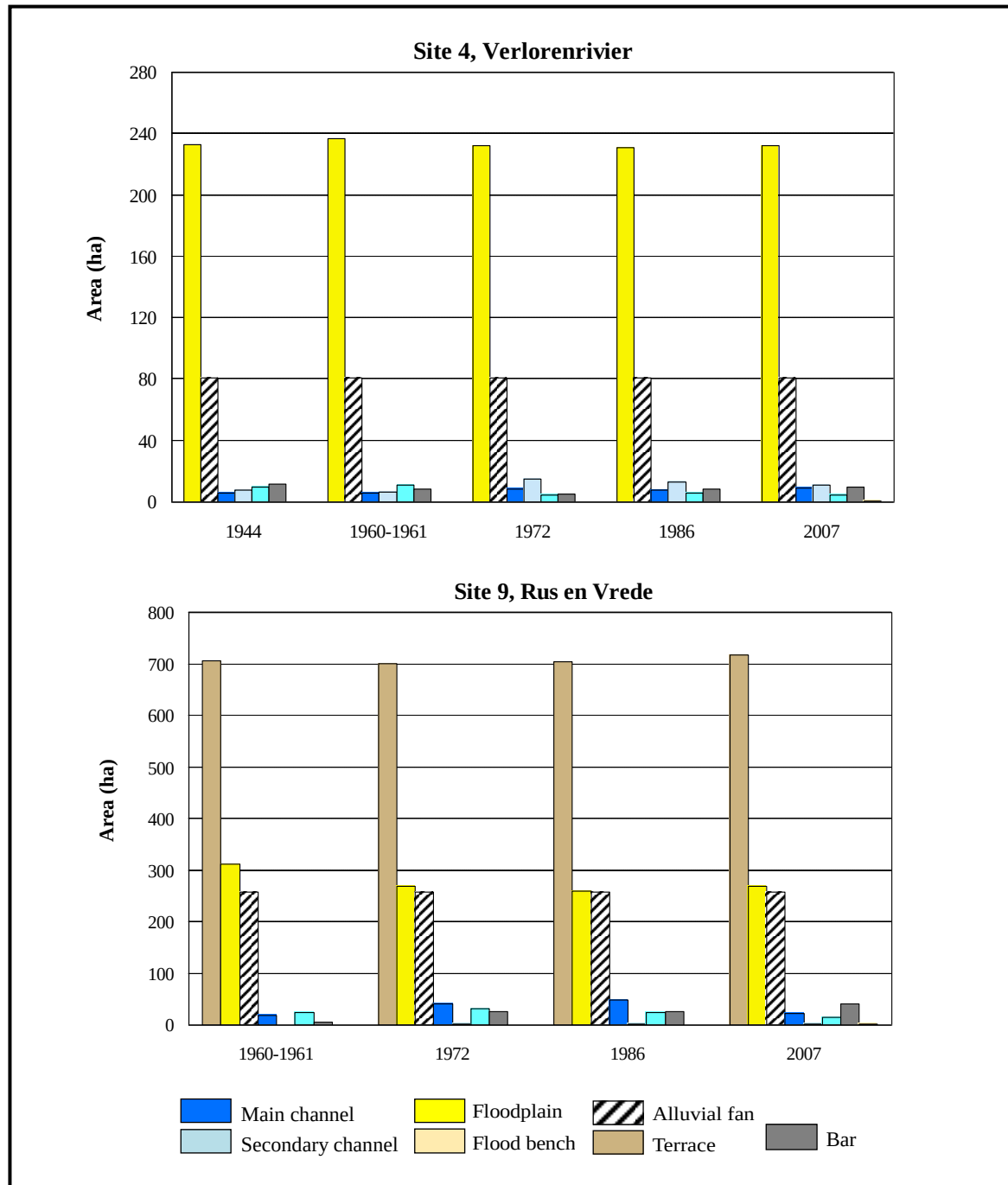


Figure 4.7: Geomorphic area change between successive years, unconfined study sites.

Table 4.7: Area (ha) and frequency of occurrence (brackets) of geomorphic features, unconfined sites.

Vegetation density descriptions as per Table 4.4.

Site 4, Verlorenrivier	1944	1960-1961	1972	1986	2007
Floodplain	233.29 (1)	236.62 (1)	232.60 (1)	231.07 (1)	232.56 (1)
Alluvial fans	80.68 (6)	80.68 (6)	80.68 (6)	80.68 (6)	80.68 (6)
Lateral bars with medium density vegetation	1.08 (2)	0.90 (2)	1.31 (3)	4.04 (3)	3.79 (4)
Lateral bars with low density vegetation	-	0.75 (1)	0.23 (1)	-	-
Mid-channel bars with high density vegetation	0.16 (1)	-	-	-	0.18 (1)
Mid-channel bars with medium density vegetation	3.68 (3)	5.02 (5)	0.30 (1)	0.10 (1)	2.10 (6)
Mid-channel bars with low density vegetation	6 (2)	1.34 (1)	2.60 (1)	3.11 (2)	3.17 (5)
Point bars with medium density vegetation	-	-	-	0.93 (3)	0.53 (1)
Point bars with low density vegetation	-	0.26 (1)	1.06 (4)	0.40 (2)	-
Flood benches with low density vegetation	-	-	-	-	0.41 (2)
Partially vegetated main channel	5.82 (1)	5.61 (1)	8.21 (1)	7.52 (1)	8.85 (1)
Vegetated secondary channels	0.35 (1)	-	3.51 (2)	2.89 (2)	5.48 (3)
Partially vegetated secondary channels	7.01 (3)	6.70 (5)	9.27 (5)	9.94 (6)	4.65 (5)
Unvegetated secondary channels	0.83 (1)	-	2.42 (1)	0.28 (1)	0.99 (2)
Partially vegetated tributary channels	5.58 (3)	3.94 (2)	3.55 (2)	4.79 (2)	3.78 (3)
Vegetated tributary channels	4.21 (2)	7.02 (3)	0.83 (1)	0.94 (1)	0.93 (1)
Total geomorphic features	26	28	29	31	41
Site 9, Rus en Vrede					
Terrace	-	707.08 (1)	701.09 (1)	705.43 (1)	717.53 (1)
Floodplain	-	311.24 (1)	268.66 (1)	259.22 (1)	269.28 (1)
Alluvial fans	-	257.25 (10)	257.25 (10)	257.25 (10)	257.25 (10)
Lateral bars with high density vegetation	-	1.41 (2)	2.02 (1)	-	0.52 (2)
Lateral bars with medium density vegetation	-	2.58 (2)	12.2 (8)	-	8.81 (8)
Lateral bars with low density vegetation	-	0.12 (1)	0.58 (1)	1.56 (1)	3.35 (5)
Lateral bars with no vegetation	-	-	-	0.65 (1)	-
Mid-channel bars with high density vegetation	-	-	0.98 (2)	0.44 (2)	2.55 (2)
Mid-channel bars with medium density vegetation	-	-	8.28 (4)	7.52 (5)	2.40 (2)
Mid-channel bars with low density vegetation	-	-	-	2.90 (2)	0.78 (2)
Point bars with high density vegetation	-	-	-	-	1.55 (1)
Point bars with medium density vegetation	-	0.86 (1)	0.91 (1)	4.94 (2)	17.53 (10)
Point bars with low density vegetation	-	-	1.47 (1)	7.89 (5)	3.77 (6)
Flood bench with medium density vegetation	-	-	-	-	2.10 (1)
Vegetated main channel	-	18.36 (1)	-	-	-
Partially vegetated main channel	-	-	40.70 (1)	47.71 (1)	21.37 (1)
Unvegetated main channel	-	-	-	-	0.23
Vegetated secondary channels	-	-	1.40 (1)	-	-
Partially vegetated secondary channels	-	-	0.14 (1)	2.52 (4)	2.50 (5)
Vegetated tributary channels	-	12.68 (4)	22.13 (7)	9.29 (4)	4.78 (3)
Partially vegetated tributary channels	-	12.49 (4)	9.03 (4)	14.63 (6)	9.94 (8)
Unvegetated tributary channels	-	-	-	0.38 (1)	-
Total geomorphic features	-	27	44	46	68

The time series of geomorphic maps displays a high degree of variability at site 9 (Rus en Vrede). However, the active channel morphological change shown in Figures 4.7 and 4.8 has not occurred at a constant rate. The history of channel change can be divided into three

periods: (1) narrowing observed during the 1960s, (2) a subsequent period of progressive widening during the 1970s and 1980s maintained by extreme flooding events (view Table 3.12, Chapter 3) and (3) again a period of narrowing during 2007 almost to the 1960s' situation. The channel area from period to period ranged from 18 ha to 48 ha to 22 ha respectively (Figure 4.7 and Table 4.7). Furthermore, visual inspection of the available aerial photograph sets showed that the upper and middle reaches of the Baviaanskloof River at site 9 differed considerably from its lower reaches. In the case of the former, a single sinuous vegetated channel shifted from one side of the floodplain to the other (upstream and downstream of cross-section 9.1). The capacity for channel adjustment was still there. In contrast, the latter displayed a multi-thread channel pattern with constrained lateral displacement on the floodplain (mostly downstream of cross-section 9.3). These braided channels were also partially vegetated. The average channel width varied from < 20 m to > 110 m over the years (Figure 4.8).

Over the 47 year study period at study site 9 (Rus en Vrede) the number of geomorphic features more than doubled (Table 4.7). Newly generated areas were particularly related to secondary channels and channel bars which increased. For example, in the 1960s the bar area was 4.97 ha whereas in 2007 it was 41.25 ha (Figures 4.7 and 4.8). Point and lateral bars with mostly low to medium density vegetation dominated over the decades. Only one medium density vegetation flood bench was observed (2007) and covered an area of 2.10 ha. The number of vegetated and partially vegetated tributary reaches was almost equal (Table 4.7). Tributary area expansion was the highest in 1972 and the lowest in 2007. The floodplain area was reduced from 311.24 ha (1960s) to 269.28 ha (2007) (Figures 4.7 and 4.8). Terraces and alluvial fans present on both floodplain and terrace surfaces, acted as confining features at this study site (Figure 4.8).

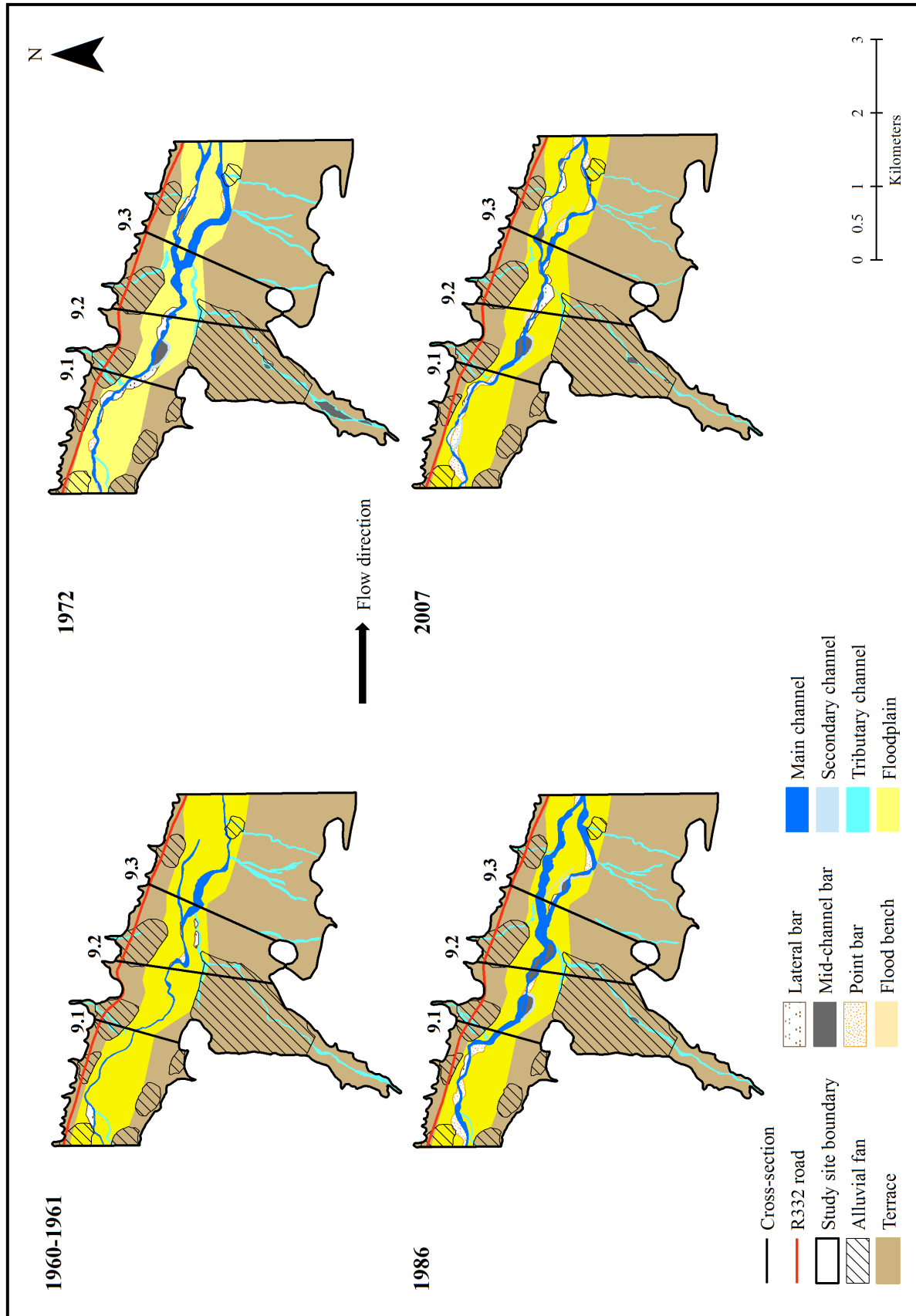


Figure 4.8: Geomorphic change for unconfined study site 9, Rus en Vrede (1960-2007).

4.3.2 Quadrat geomorphic change, 1944-2010

Tables 4.8 to 4.10 show the geomorphic changes linked to the study quadrats (outlined in Section 5.2.1, Chapter 5) for the six selected study sites over the study period. Although this analysis was mainly undertaken for descriptive purposes, the results were intended to indicate possible patterns or trends associated with past (this chapter) and present (discussed in Chapter 5) fluvial surfaces.

Confined study sites

Comparison of the 1944 to 2010 data at study site 2 (Verlatenrivier) illustrates that an active main channel reach can be filled and become an established floodplain (e.g. 2.3.E). Furthermore, point bars either developed into a floodplain surface (e.g. 2.1.F) or changed into scroll bars (e.g. 2.2.E). At study site 6 (Beacosnek) main channel reaches transformed into various flood benches (e.g. 6.1.A) or were abandoned (e.g. 6.3 E) (Table 4.8). Sediment filled secondary channels also became part of the floodplain (e.g. 6.1.D) and vice versa (e.g. 6.2.D). Moreover, point bars were replaced by either the main channel (e.g. 6.3.C) or flood benches (e.g. 6.3.A). However, at both sites geomorphic units such as the terrace (e.g. 2.1 G), floodplain (e.g. 2.2.F and 6.2.F) and main channel (e.g. 2.3.D and 6.1.C) also persisted (i.e. remained stable) throughout the study period (Table 4.8).

Table 4.8: Quadrat geomorphic change, confined study sites (1944-2010).

Quadrat code e.g. 2.1.A = study site number (2), cross-section number (1) and quadrat (A). Landform descriptions as per Table 4.2.

Quadrat code	Latitude	Longitude	1944	2007	2010
Site 2, Verlatenrivier					
2.1.A	-33.521083	23.756583	Lateral bar	Flood bench	Flood bench
2.1.B	-33.521194	23.756361	Lateral bar	Main channel	Main channel left bank
2.1.C	-33.521194	23.756417	Lateral bar	Main channel	Main channel bed
2.1.D	-33.521306	23.756389	Main channel	Point bar	Point bar
2.1.E	-33.521278	23.756056	Point bar	Scroll bar	Scroll bar
2.1.F	-33.521500	23.756222	Point bar	Floodplain	Floodplain
2.1.G	-33.521861	23.755944	Terrace	Terrace	Terrace
2.2.A	-33.521583	23.757472	Point bar	Flood bench	Flood bench
2.2.B	-33.521361	23.757139	Main channel	Flood bench	Main channel left bank
2.2.C	-33.521556	23.757278	Point bar	Main channel	Main channel bed
2.2.D	-33.521639	23.757222	Point bar	Scroll bar	Lateral bar
2.2.E	-33.521639	23.757194	Point bar	Scroll bar	Scroll bar
2.2.F	-33.521833	23.757083	Floodplain	Floodplain	Floodplain
2.2.G	-33.522500	23.756722	Terrace	Terrace	Terrace
2.3.A	-33.521361	23.757139	Main channel	Flood bench	Flood bench
2.3.B	-33.521556	23.757278	Point bar	Scroll bar	Scroll bar
2.3.C	-33.521639	23.757222	Floodplain	Main channel	Main channel bed
2.3.D	-33.522139	23.758639	Main channel	Main channel	Main channel right bank
2.3.E	-33.522417	23.759000	Main channel	Floodplain	Floodplain

Quadrat code	Latitude	Longitude	1944	2007	2010
2.3.F	-33.522444	23.758611	Terrace & fan	Terrace & fan	Terrace & fan
Site 6, Beacosnek					
6.1.A	-33.536667	23.946556	Main channel	Flood bench	Flood bench
6.1.B	-33.536472	23.946556	Main channel	Secondary channel	Main channel right bank
6.1.C	-33.536556	23.946417	Main channel	Main channel	Main channel bed
6.1.D	-33.536306	23.946583	Secondary channel	Floodplain	Floodplain
6.1.E	-33.536028	23.946667	Floodplain	Floodplain	Floodplain
6.1.F	-33.535722	23.946694	Floodplain	Floodplain	Floodplain
6.2.A	-33.536556	23.947889	Main channel	Flood bench	Main channel right bank
6.2.B	-33.536694	23.947556	Main channel	Main channel	Main channel bed
6.2.C	-33.536528	23.947583	Main channel	Flood bench	Flood bench
6.2.D	-33.536417	23.947639	Floodplain	Secondary channel	Secondary channel right bank
6.2.E	-33.536472	23.948417	Floodplain	Secondary channel	Secondary channel bed
6.2.F	-33.535694	23.947361	Floodplain	Floodplain	Floodplain
6.3.A	-33.536556	23.948667	Point bar	Flood bench	Flood bench
6.3.B	-33.536556	23.948444	Point bar	Main channel	Main channel right bank
6.3.C	-33.536528	23.948611	Point bar	Main channel	Main channel bed
6.3.D	33.536444	23.948500	Main channel	Secondary channel	Secondary channel right bank
6.3.E	-33.536472	23.948417	Main channel	Secondary channel	Secondary channel bed
6.3.F	-33.535806	23.948444	Floodplain	Floodplain	Floodplain

Semi-confined study sites

Table 4.9 demonstrates that at study site 1 (Nuwekloof) the main channel either remained unaltered (e.g. 1.2.D) or was abandoned (e.g. 1.3.C). In addition, the 1944 mid-channel bars became occupied by former main channels (e.g. 1.1.C and 1.1. D) in 2007 and 2010. Sections of the 1944 floodplain also changed into bars (e.g. 1.1. E), new main channel reaches (e.g. 1.3.F), secondary channels (e.g. 1.2.C) or remained the same during 2007 and 2010. Over the years at study site 8 (Zaaimanshoek) main channel reaches stayed unchanged (e.g. 8.3.E), were abandoned (8.2.C) and became part of the floodplain (e.g. 8.1.E) or formed a flood bench (8.1.A). Likewise, the lateral bars transformed either into an island (8.1.F), secondary channel (8.1.G) or flood bench (8.1.I). A point bar was also reworked into a main channel reach (8.2.D). At this study site the floodplain largely remained the same geomorphic unit (e.g. 8.2.G and 8.3.F) (Table 4.9).

Table 4.9: Quadrat geomorphic change, semi-confined study sites (1944-2010).

Quadrat code e.g. 1.1.A = study site number (1), cross-section number (1) and quadrat (A).
Landform descriptions as per Table 4.2.

Quadrat code	Latitude	Longitude	1944	2007	2010
Site 1, Nuwekloof					
1.1.A	-33.522694	23.665917	Floodplain	Floodplain	Floodplain
1.1.B	-33.521778	23.665694	Main channel	Floodplain	Floodplain
1.1.C	-33.521611	23.665806	Mid-channel bar	Secondary channel	Secondary channel right bank
1.1.D	-33.521583	23.665833	Mid-channel bar	Secondary channel	Secondary channel bed
1.1.E	-33.554667	23.665722	Main channel	Floodplain	Mid-channel bar
1.1.F	-33.521250	23.665528	Floodplain	Main channel	Main channel bed
1.1.G	-33.521333	23.665472	Floodplain	Main channel	Main channel left bank
1.1.H	-33.520889	23.665472	Floodplain	Floodplain	Floodplain
1.1.I	-33.520278	23.665194	Terrace	Terrace	Terrace
1.2.A	-33.521944	23.666889	Floodplain	Floodplain	Floodplain
1.2.B	-33.521833	23.667194	Floodplain	Floodplain	Floodplain
1.2.C	-33.521889	23.667139	Floodplain	Floodplain	Main channel bed
1.2.D	-33.521639	23.667028	Main channel	Main channel	Main channel bed
1.2.E	-33.521528	23.667028	Mid-channel bar	Main channel	Main channel bed
1.2.F	-33.521361	23.667111	Main channel	Main channel	Main channel left bank
1.2.G	-33.520083	23.666556	Terrace	Terrace	Terrace
1.3.A	-33.522028	23.668222	Floodplain	Floodplain	Floodplain
1.3.B	-33.521694	23.668194	Main channel	Floodplain	Secondary channel right bank
1.3.C	-33.521667	23.668111	Main channel	Floodplain	Secondary channel bed
1.3.D	-33.521500	23.667917	Mid-channel bar	Main channel	Main channel bed
1.3.E	-33.52125	23.667944	Floodplain	Main channel	Main channel bed
1.3.F	-33.521222	23.668083	Floodplain	Floodplain	Main channel left
1.3.G	-33.520444	23.667972	Floodplain	Floodplain	Floodplain
Site 8, Zaaimeanshoek					
8.1.A	-33.552306	24.004528	Main channel	Flood bench	Flood bench
8.1.B	-33.552194	24.004500	Main channel	Main channel	Main channel bed
8.1.C	-33.552278	24.004417	Main channel	Main channel	Main channel left
8.1.D	-33.552111	24.004361	Mid-channel bar	Floodplain	Floodplain
8.1.E	-33.551722	24.004333	Main channel	Floodplain	Floodplain
8.1.F	-33.551417	24.003750	Lateral bar	Mid-channel bar	Island
8.1.G	-33.551333	24.003611	Lateral bar	Secondary channel	Secondary channel
8.1.H	-33.551306	24.003667	Lateral bar	Secondary channel	Secondary channel left bank
8.1.I	-33.551306	24.003889	Lateral bar	Island	Flood bench
8.2.A	-33.550861	24.004611	Floodplain	Secondary channel	Floodplain
8.2.B	-33.551056	24.004806	Main channel	Secondary channel	Secondary channel left bank
8.2.C	-33.551056	24.004806	Main channel	Secondary channel	Secondary channel
8.2.D	-33.551139	24.005556	Point bar	Main channel	Main channel bed
8.2.E	-33.551444	24.005028	Point bar	Main channel	Main channel right bank
8.2.F	-33.551556	24.005139	Floodplain	Flood bench	Flood bench
8.2.G	-33.551694	24.005139	Floodplain	Floodplain	Floodplain
8.3.A	-33.550444	24.005972	Floodplain	Secondary channel	Secondary channel
8.3.B	-33.550583	24.006167	Main channel	Secondary channel	Secondary channel right bank
8.3.C	-33.550583	24.006167	Floodplain	Floodplain	Floodplain
8.3.D	-33.550722	24.006361	Main channel	Main channel	Main channel left
8.3.E	-33.550667	24.006222	Main channel	Main channel	Main channel bed
8.3.F	-33.551333	24.006111	Floodplain	Floodplain	Floodplain

Unconfined study sites

The time series analysis (Table 4.10) for study site 4 (Verlorenrivier) revealed that the main channel reaches underwent various changes over the study period. After 1944 they either became part of the floodplain (4.2.D) or were abandoned (4.3.B). Subsequent to 1972 they then reverted to a main channel (e.g. 4.2.D and 4.3.B) or floodplain surface (4.2.E). After 1986 these reaches were either reworked into flood benches (e.g. 4.1.J and 4.2.C) or mid-channel bars which later formed islands (4.2.B and 4.3.A). However, reaches also remained completely unchanged (4.1.H and 4.1.I). Additionally, since 1960 mid-channel bars (e.g. 4.3.C and 4.3.D) were reworked into secondary channels which then became active channel reaches in 2007 (Table 4.10). Over the years the secondary channels either remained the same (e.g. 4.1.C and 4.2.F), developed into the floodplain (4.2.H) or formed bars (e.g. 4.1.F). They were also reoccupied (e.g. 4.1.E). At site 4 some tributary reaches after 1961 were abandoned and resulted in secondary channels (e.g. 4.3.H and 4.3.I). The latter then became part of the floodplain during 2007 (4.3.G). Floodplain surfaces (i.e. at times covered with fan deposits) also persisted throughout the study period, e.g. 4.1.A and 4.2.J (Table 4.10).

Table 4.10: Quadrat geomorphic change for unconfined study site 4, Verlorenrivier (1944-2010).

Quadrat code e.g. 4.1.C = study site number (4), cross-section number (1) and quadrat (C). Landform descriptions as per Table 4.2.

Quadrat code	Co-ordinates	1944	1960-1961	1972	1986	2007	2010
4.1.A	-33.520111 23.860833	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain
4.1.B	-33.521528 23.860806	Secondary channel	Secondary channel	Secondary channel	Secondary channel	Secondary channel	Secondary channel left bank
4.1.C	-33.521556 23.860833	Secondary channel	Secondary channel	Secondary channel	Secondary channel	Secondary channel	Secondary channel bed
4.1.D	-33.521694 23.860861	Secondary channel	Secondary channel	Secondary channel	Secondary channel	Main channel	Secondary channel left bank
4.1.E	-33.521722 23.860833	Secondary channel	Secondary channel	Secondary channel	Secondary channel	Main channel	Secondary channel bed
4.1.F	-33.521861 23.860556	Secondary channel	Floodplain	Secondary channel	Secondary channel	Mid-channel bar	Mid-channel bar
4.1.G	-33.522500 23.860611	Main channel	Main channel	Main channel	Main channel	Main channel	Floodplain
4.1.H	-33.522611 23.860583	Main channel	Main channel	Main channel	Main channel	Main channel	Main channel left bank
4.1.I	-33.522667 23.860611	Main channel	Main channel	Main channel	Main channel	Main channel	Main channel bed
4.1.J	-33.522806 23.860750	Main channel	Main channel	Main channel	Main channel	Flood bench	Flood bench
4.1.K	-33.524361 23.860833	Floodplain	Floodplain	Point bar	Floodplain	Floodplain	Floodplain
4.1.L	-33.525722 23.860361	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain
4.2.A	-33.520083 23.861278	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain
4.2.B	-33.522028 23.861611	Main channel	Main channel	Main channel	Secondary channel	Mid-channel bar	Island
4.2.C	-33.522556 23.861694	Main channel	Main channel	Main channel	Main channel	Flood bench	Flood bench

Quadrat code	Co-ordinates	1944	1960-1961	1972	1986	2007	2010
4.2.D	-33.522639 23.861750	Main channel	Floodplain	Floodplain	Main channel	Main channel	Main channel bed
4.2.E	-33.522694 23.861750	Main channel	Floodplain	Floodplain	Floodplain	Main channel	Main channel right bank
4.2.F	-33.524389 23.862139	Secondary channel	Secondary channel	Secondary channel	Secondary channel	Secondary channel	Secondary channel left bank
4.2.G	-33.524417 23.862167	Secondary channel	Secondary Channel	Secondary Channel	Secondary channel	Secondary channel	Secondary channel bed
4.2.H	-33.524611 23.862056	Secondary channel	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain
4.2.I	-33.526139 23.862389	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan
4.2.J	-33.528056 23.862694	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan
4.3.A	-33.522056 23.862250	Main channel	Main channel	Main channel	Main channel	Mid-channel bar	Island
4.3.B	-33.522222 23.862278	Main channel	Secondary channel	Secondary channel	Main channel	Flood bench	Flood bench
4.3.C	-33.522278 23.862306	Mid-channel bar	Secondary channel	Secondary channel	Main channel	Main channel	Main channel bed
4.3.D	-33.522389 23.862417	Mid-channel bar	Secondary channel	Secondary channel	Floodplain	Main channel	Main channel right bank
4.3.E	-33.525000 23.863806	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan
4.3.F	-33.525861 23.864278	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan	Floodplain & fan
4.3.G	-33.527333 23.864944	Tributary channel & fan	Tributary channel & fan	Secondary channel & fan	Secondary channel & fan	Floodplain & fan	Floodplain & fan
4.3.H	-33.528278 23.864972	Tributary channel & fan	Tributary channel & fan	Secondary channel & fan	Secondary channel & fan	Secondary channel & fan	Secondary channel bed & fan
4.3.I	-33.528333 23.864944	Tributary channel & fan	Tributary channel & fan	Secondary channel & fan	Secondary channel & fan	Secondary channel & fan	Secondary channel right bank & fan

Table 4.11 indicates that at study site 9 (Rus en Vrede) the main channel reaches over the decades either remained unaltered (e.g. 9.1.H and 9.3.D), became part of the floodplain (9.3.C) or were reworked into mid-channel bars (e.g. 9.2.I and 9.3.I). They also formed islands (e.g. 9.1.G) or were transformed into flood benches (9.2.I). Tributary reaches generally stayed the same (e.g. 9.1.C and 9.2.B). At this study site the floodplain underwent various changes over the study period (Table 4.11). After 1960 parts of it were reworked into active channel reaches (9.2.F and 9.3.J) and mid-channel bars (e.g. 9.2.H). Subsequent to 1986 sections of the floodplain were also transformed into lateral bars (9.2.E and 9.2.G) and sediment filled secondary channels (9.3.G and 9.3.H). Over the years the mid-channel bars either became stable islands (e.g. 9.3.I) or flood benches (9.2.H and 9.2.I). However, parts of the floodplain (e.g. 9.1.I and 9.3.L) and terrace areas (e.g. 9.1.J and 9.3.M) also remained unchanged. In addition, a few of the terrace surfaces (9.1.D and 9.2.L) and tributaries (e.g. 9.1.B) were overlain with fan deposits (Table 4.11).

Table 4.11: Quadrat geomorphic change, unconfined study site 9 (1960-2010).

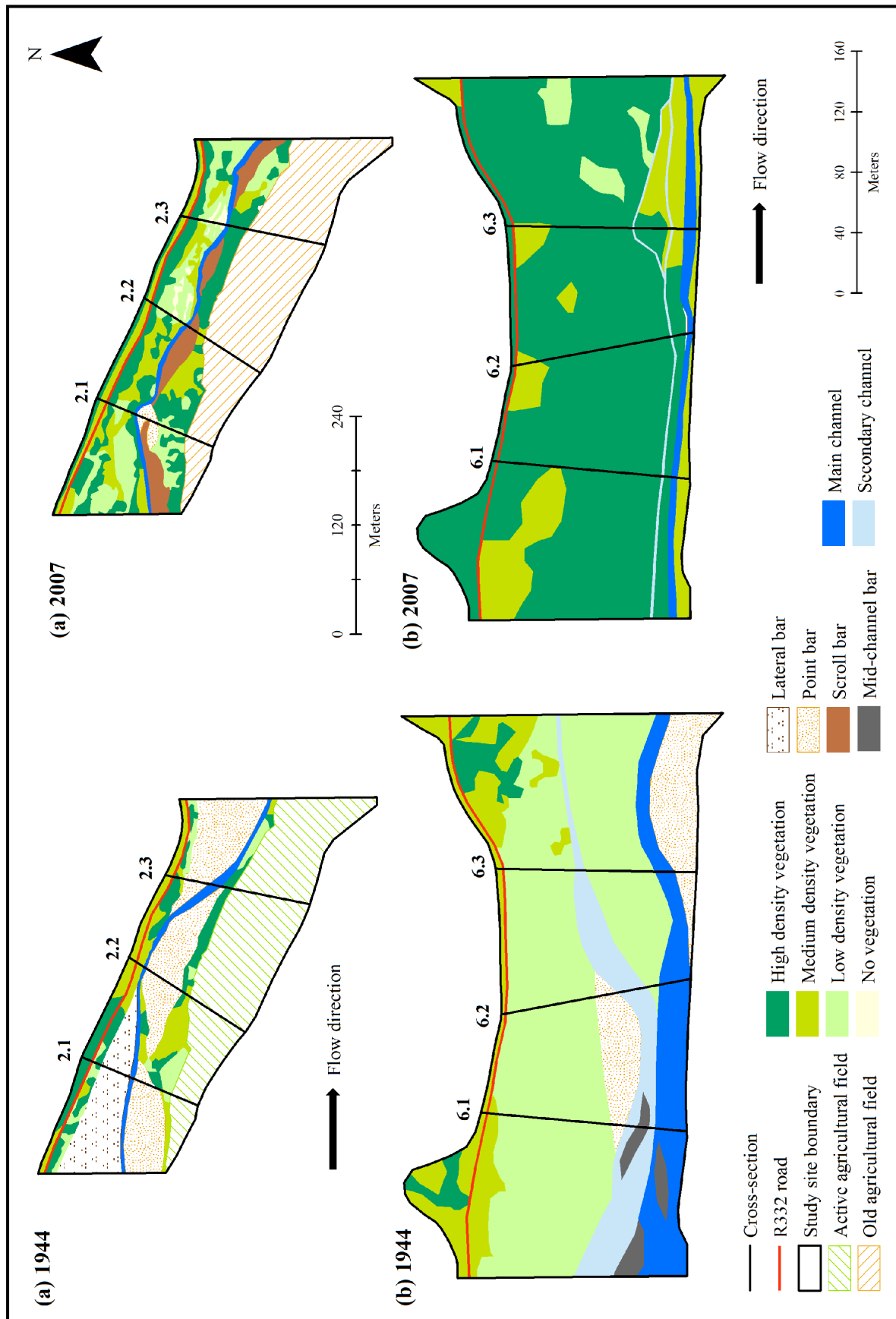
Quadrat code e.g. 9.1.A = study site number (9), cross-section number (1) and quadrat (A). Landform descriptions as per Table 4.2.

Quadrat code	Co-ordinates	1960-1961	1972	1986	2007	2010
9.1.A	-33.558028 24.067889	Terrace & fan	Terrace & fan	Terrace & fan	Terrace & fan	Terrace & fan
9.1.B	-33.558667 24.067833	Tributary channel & fan	Tributary channel & fan	Tributary channel & fan	Tributary channel & fan	Tributary channel bed & fan
9.1.C	-33.558694 24.067917	Tributary channel & fan	Tributary channel & fan	Tributary channel & fan	Tributary channel & fan	Tributary channel left bank & fan
9.1.D	-33.559667 24.067472	Terrace & fan	Terrace & fan	Terrace & fan	Terrace & fan	Terrace & fan
9.1.E	-33.561222 24.067472	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain
9.1.F	-33.560667 24.066194	Floodplain	Floodplain	Floodplain	Floodplain	Main channel left bank
9.1.G	-33.562167 24.066667	Main channel	Main channel	Main channel	Main channel	Island
9.1.H	-33.562333 24.066556	Main channel	Main channel	Main channel	Main channel	Main channel bed
9.1.I	-33.563694 24.065694	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain
9.1.J	-33.566556 24.051389	Terrace	Terrace	Terrace	Terrace	Terrace
9.2.A	-33.573167 24.074722	Terrace & fan	Terrace & fan	Terrace & fan	Terrace & fan	Terrace & fan
9.2.B	-33.570278 24.074861	Tributary channel & fan	Tributary channel & fan	Tributary channel & fan	Tributary channel & fan	Tributary channel right bank & fan
9.2.E	-33.566972 24.074917	Floodplain	Floodplain	Floodplain	Lateral bar	Main channel right bank
9.2.F	-33.566667 24.075083	Floodplain	Floodplain	Main channel	Main channel	Main channel bed
9.2.G	-33.566472 24.074917	Floodplain	Floodplain	Mid-channel bar	Lateral bar	Lateral bar
9.2.H	-33.566167 24.075194	Floodplain	Main channel	Mid-channel bar	Flood bench	Flood bench
9.2.I	-33.566056 24.075389	Main channel	Main channel	Mid-channel bar	Flood bench	Flood bench
9.2.J	-33.565472 24.075750	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain
9.2.K	-33.564111 24.075556	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain
9.2.L	-33.560667 24.076111	Terrace & fan	Terrace & fan	Terrace & fan	Terrace & fan	Terrace & fan
9.3.A	-33.571389 24.083833	Terrace	Terrace	Terrace	Terrace	Terrace
9.3.B	-33.570750 24.084250	Terrace	Terrace	Terrace	Terrace	Terrace
9.3.C	-33.569750 24.084861	Main channel	Floodplain	Floodplain	Floodplain	Floodplain
9.3.D	-33.568972 24.085056	Main channel	Main channel	Main channel	Main channel	Main channel right bank
9.3.E	-33.568944 24.085222	Main channel	Main channel	Main channel	Main channel	Main channel bed
9.3.F	-33.568278 24.085722	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain
9.3.G	-33.567639 24.085750	Floodplain	Floodplain	Secondary channel	Secondary channel	Secondary channel bed
9.3.H	-33.567722 24.085750	Floodplain	Floodplain	Secondary channel	Secondary channel	Secondary channel left bank
9.3.I	-33.567139 24.086028	Main channel	Main channel	Main channel	Mid-channel bar	Island
9.3.J	-33.566528 24.086361	Floodplain	Floodplain	Main channel	Main channel	Main channel bed
9.3.K	-33.566583 24.086694	Floodplain	Floodplain	Main channel	Main channel	Main channel left bank
9.3.L	-33.566056 24.086778	Floodplain	Floodplain	Floodplain	Floodplain	Floodplain
9.3.M	-33.564944 24.087333	Terrace	Terrace	Terrace	Terrace	Terrace

4.3.3 Land cover change, 1944-2007

Confined study sites

Scrutiny of Figures 4.9 and 4.10 and Table 4.12 show that all the vegetation density classes have increased at study site 2 (Verlatenrivier) between 1944 and 2007. High density vegetation has increased twofold, the low density vegetation threefold and the medium density vegetation only marginally (Figure 4.10). This was reflected in the positive percentage change values for these three vegetation density classes (Table 4.12). Vegetation cover increase resulted from a marked reduction in both lateral and point bar surface areas which became available (Figures 4.9 and Table 4.5). Through time agricultural activities were abandoned leaving behind only old fields (Figures 4.9 and 4.10 and Table 4.12). Moreover, a few small bare surface areas appeared in the middle to lower sections of site 2 (Figure 4.9).



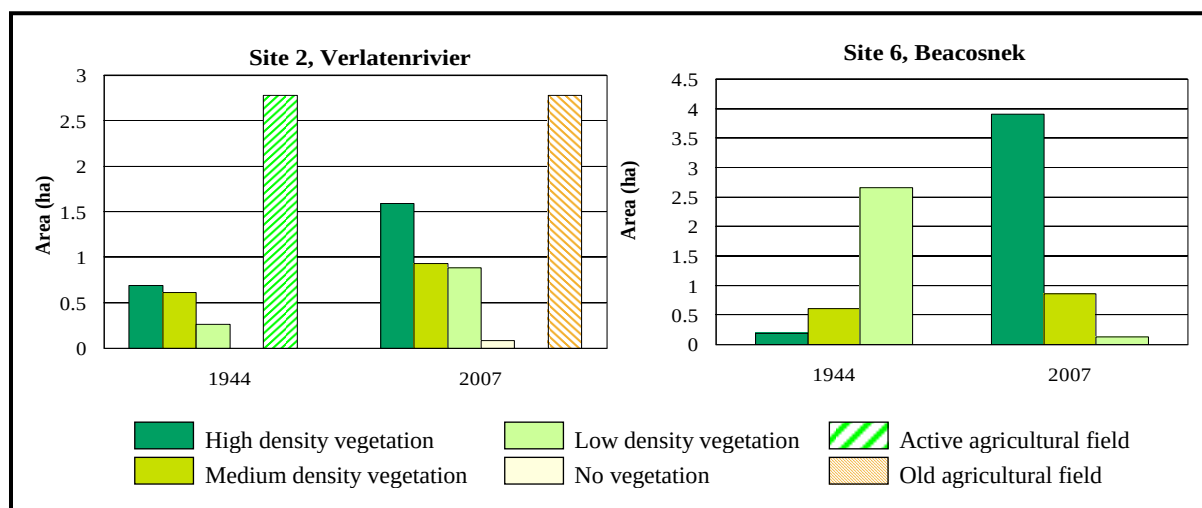


Figure 4.10: Land cover area change between 1944 and 2007, confined study sites.

At study site 6 (Beacosnek) the vegetation cover became denser (Figures 4.9 and 4.10) over the study period. In 2007, low density vegetation was only 3% while high density vegetation accounted for 79%. This was also reflected by the percentage change results (Table 4.12). Essentially, the vegetation change coincided with a loss in river channel (main and secondary channels) and bar area. The increased vegetation may also have been the cause of channel reduction since these processes overlapped in time (Figures 4.3 and 4.9 and Table 4.5). Table 4.12 demonstrates that the medium density vegetation basically remained unchanged at study site 6. This is also shown by the slight increase presented by the percentage change analysis (Table 4.12).

Table 4.12: Land cover percentages and percentage change, confined study sites. Feature descriptions as per Table 4.4.

Land cover feature	Percentage		Percentage change
	1944	2007	1944-2007
Site 2, Verlatenrivier			
High density vegetation	16	25	+60
Medium density vegetation	14	15	+5
Low density vegetation	6	14	+134
No vegetation	-	1	+100
Active agricultural field	64	-	-100
Old agricultural field	-	44	+100
Site 6, Beacosnek			
High density vegetation	5	79	+1332
Medium density vegetation	18	18	+0.2
Low density vegetation	77	3	-96

Semi-confined study sites

The analysis has shown that study site 1 (Nuwekloof) was dominated by low density vegetation from 1944 to 2007 (Figures 4.11 and 4.12 and Table 4.13). In 1944, medium density vegetation occurred in a fragmentary manner along the valley margins (only 3%) while high density vegetation was totally absent. By 2007 the former has increased to 8% while the latter accounted for only 6% (Figure 4.11 and Table 4.13). Over the decades agricultural activities were reduced (Figures 4.11 and 4.12). Agricultural fields were either totally overgrown with low density vegetation or abandoned. Floodplain vegetation also increased (Figure 4.11) because the main channel and mid-channel bars occupied less area over the years at site 1 (Figure 4.11 and Table 4.6). However, some open ground areas surfaced in the vicinity of cross-section 1.1 (Figures 4.11 and 4.12). Table 4.13 mirrored the above-mentioned results.

In 1944, the valley floor at study site 8 (Zaaimanshoek) was dominated by low to medium density vegetation. This contrasted with the 20% of fragmented high density vegetation (Figure 4.11 and Table 4.13). By 2007 the vegetation cover became a lot denser with high and medium density vegetation prevailing (Figures 4.11 and 4.12 and Table 4.13). Table 4.13 also shows that low density vegetation decreased. The connectivity between the high density areas has also increased over the years (Figure 4.11). Between 1944 and 2007 agricultural areas were either occupied by medium to high density vegetation or replaced by old agricultural fields (Figures 4.11 and 4.12 and Table 4.13). Similar results were indicated by percentage change analysis (Table 4.13). Valley floor vegetation at site 8 increased mainly because there was a noticeable decrease in bare geomorphic surfaces (i.e. river channel and bar surface areas were reduced) (Figure 4.11 and Table 4.6).

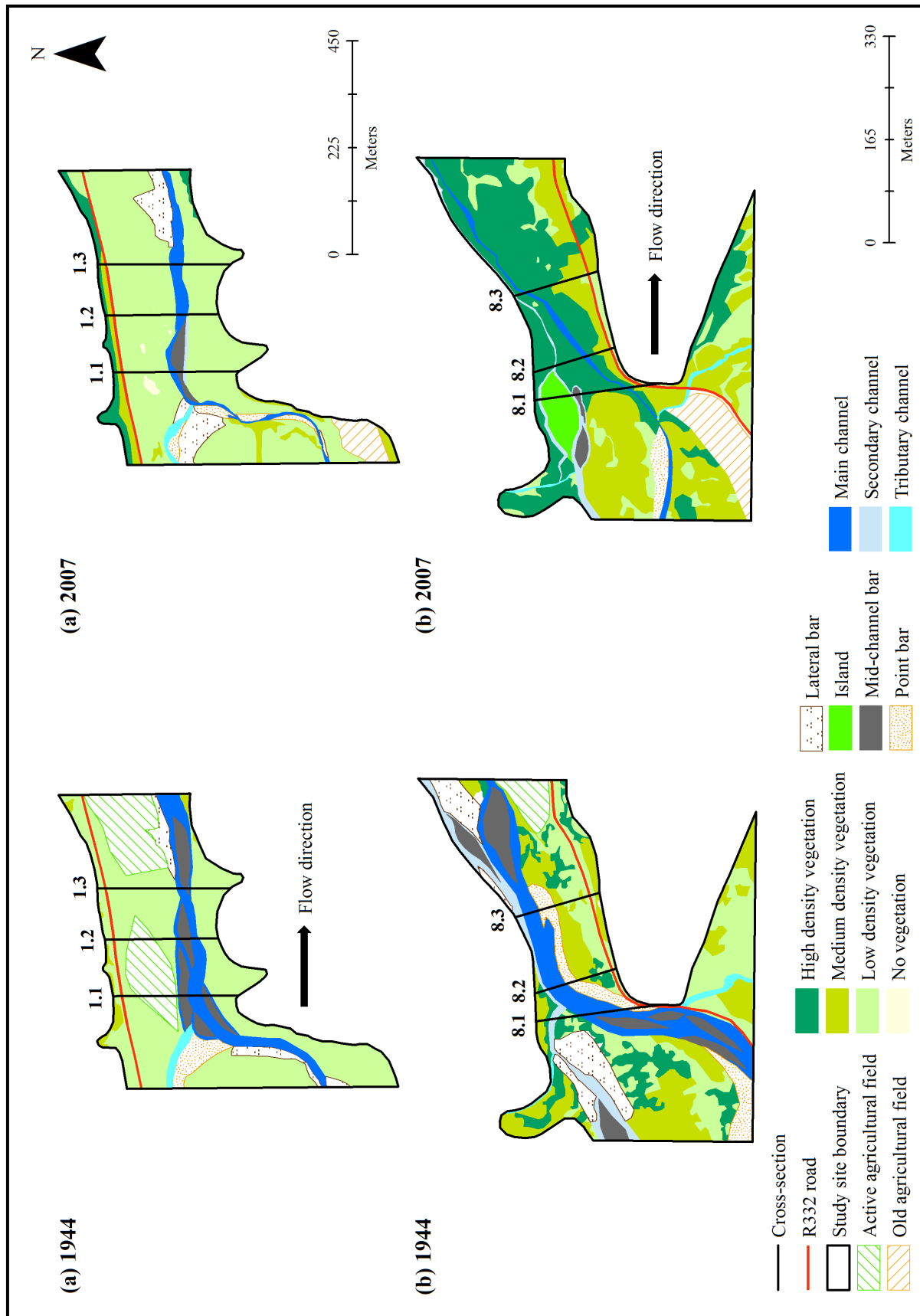


Figure 4.11: Land cover change for semi-confined study sites 1, Nuwekloof (a) and 8, Zaaimanshoek (b), 1944 and 2007.

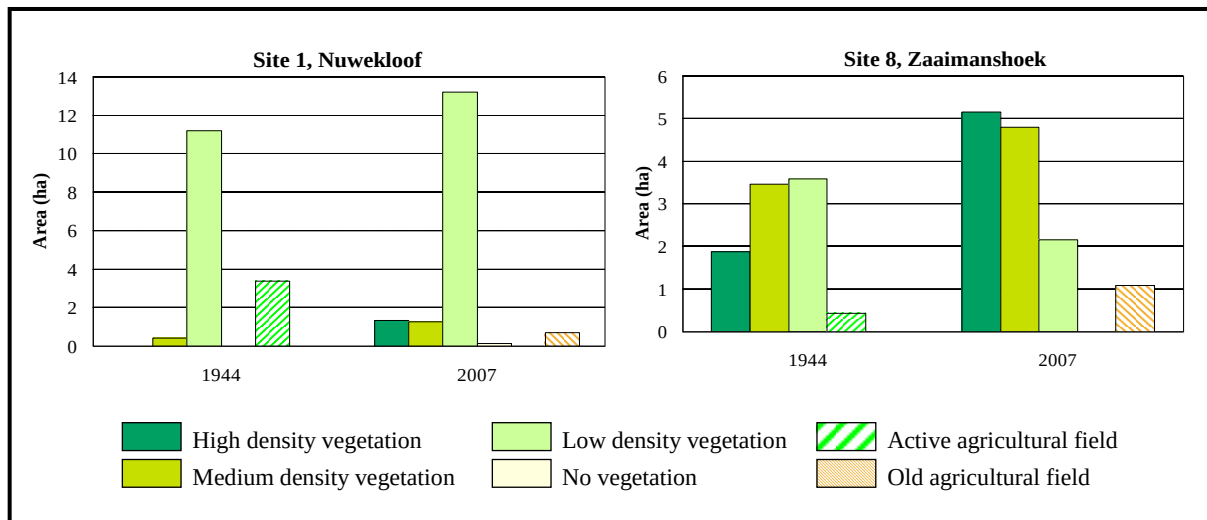


Figure 4.12: Land cover area change between 1944 and 2007, semi-confined study sites.

Table 4.13: Land cover percentages and percentage change, semi-confined study sites.

Feature descriptions as per Table 4.4.

Land cover feature	Percentage		Percentage change
	1944	2007	1944-2007
Site 1, Nuwekloof			
High density vegetation	-	6	+100
Medium density vegetation	3	8	+183
Low density vegetation	75	81	+8
No vegetation	-	1	+100
Active agricultural field	22	-	-100
Old agricultural field	-	4	+100
Site 8, Zaaimanshoek			
High density vegetation	20	40	+95
Medium density vegetation	37	36	-2
Low density vegetation	38	16	-57
Active agricultural field	5	-	-100
Old agricultural field	-	8	+100

Unconfined study sites

At study site 4 (Verlorenrivier), the vast majority of the valley floor was covered by well-connected low density vegetation during all five time intervals (Figure 4.13). This density class however mostly decreased over the years (Figure 4.14). It peaked in 1960-1961 (55%) and in 2007 reverted to the 1944 coverage (49%). The second highest land cover type was related to agriculture (Table 4.14). Active agriculture remained relatively similar from 1944 to

1972. Thereafter, this land cover type decreased (Figures 4.13 and 4.14 and Table 4.14). Agricultural areas on the floodplain were abandoned and were no longer in use (i.e. old farm lands increased). This occurred mainly between the years 1986 and 2007. Medium to high density disconnected vegetation covered most of the remainder of the floodplain during all five time periods (Figure 4.13 and Table 4.14). These vegetation density classes mostly varied showing no particular pattern over the years (Table 4.14). The vegetation change over the 63-year period concurred with tributary channel and mid-channel bar area reduction (Figure 4.13 and Table 4.7). Bare ground areas were essentially insignificant and were scattered over the valley floor at site 4 (Figure 4.13). This land cover type peaked in 1986 (Table 4.14). Table 4.15 displayed similar results.

The analysis indicated that from 1960-2007 low density vegetation and active agriculture dominated the valley floor at study site 9, Rus en Vrede (Figures 4.14 and 4.15). Low density vegetation decreased over the decades while active agriculture mostly increased (Figure 4.14 and Table 4.14). Active agriculture replaced the natural valley floor vegetation. However, abandoned cultivated areas also increased through time. Over the four time intervals the remainder of the valley floor was mostly covered by medium to high density vegetation which increased over the years and became more connected (Figures 4.14 and 4.15 and Table 4.14). Medium density vegetation peaked in 2007 while high density vegetation peaked in 1986 (Table 4.14). The vegetation change over the full time period coincided with main channel and mid-channel bar area loss (Figure 4.15 and Table 4.7). Scattered bare ground areas were only present during 1960-1961. They were in the vicinity of cross-sections 9.1 and 9.2 (Figure 4.15). The above mentioned results were reflected in Table 4.15.

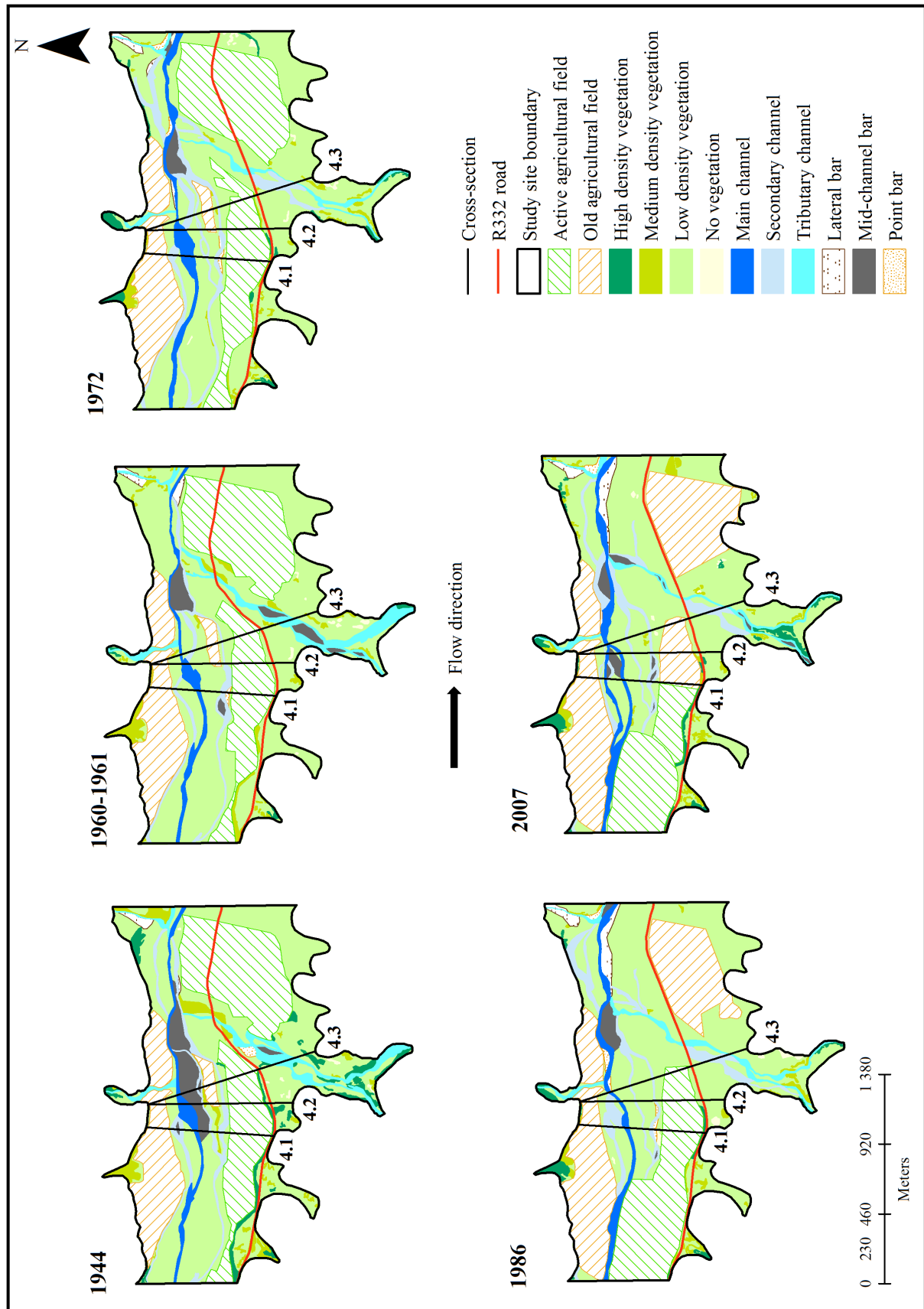


Figure 4.13: Land cover change for unconfined study site 4, Verlorenrivier (1944-2007).

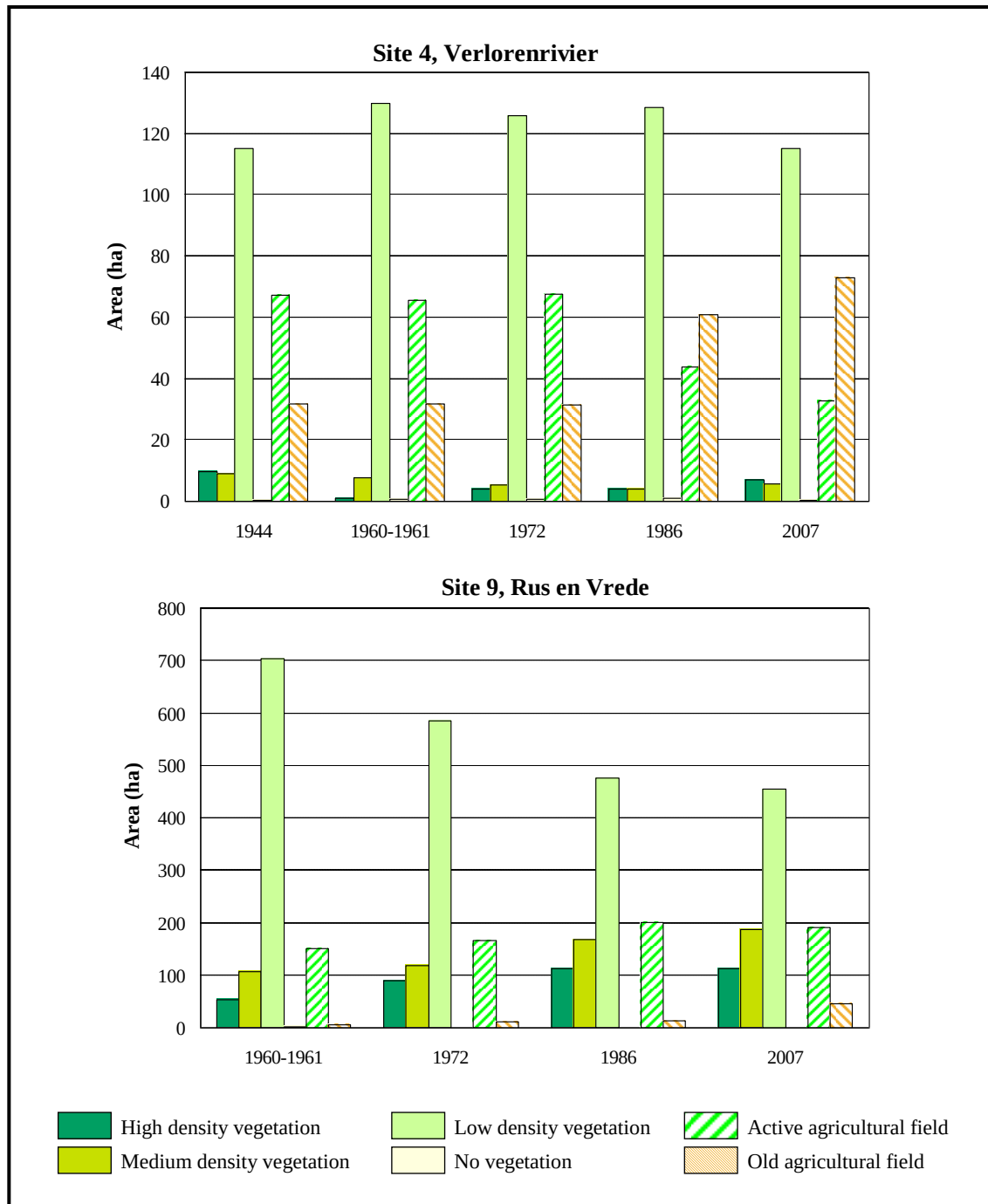


Figure 4.14: Land cover area change between successive years, unconfined study sites.

Table 4.14: Land cover percentages, unconfined study sites.

Feature descriptions as per Table 4.4.

Land cover feature	1944	1960-1961	1972	1986	2007
Site 4, Verlorenrivier					
High density vegetation	4	0.4	2	2	3
Medium density vegetation	3.9	3	2	1.6	2.4
Low density vegetation	49	55	54	53	49.2
No vegetation	0.1	0.2	0.3	0.4	0.1
Active agricultural field	29	28	28.7	18	14.1
Old agricultural field	14	13.4	13	25	31.2
Site 9, Rus en Vrede					
High density vegetation	-	5	9	12	11
Medium density vegetation	-	10.5	12	17	19
Low density vegetation	-	69	61	49	46
No vegetation	-	0.2	-	-	-
Active agricultural field	-	14.8	17	21	19
Old agricultural field	-	0.5	1	1	5

Table 4.15: Land cover percentage change between successive years, unconfined sites.

Feature descriptions as per Table 4.4.

Land cover feature	1944-1961	1961-1972	1972-1986	1986-2007
Site 4, Verlorenrivier				
High density vegetation	-91	+345	+0.2	+72
Medium density vegetation	-16	-32	-24	+38
Low density vegetation	+11	-3	-1	-7
No vegetation	+71	+46	+20	-71
Active agricultural field	-4	+5	-37	-22
Old agricultural field	-2	+0.2	+88	+24
Site 9, Rus en Vrede				
High density vegetation	-	+76	+26	-1
Medium density vegetation	-	+17	+42	+8
Low density vegetation	-	-12	-19	-6
No vegetation	-	-100	-	-
Active agricultural field	-	+15	+21	-7
Old agricultural field	-	+146	+13	+231

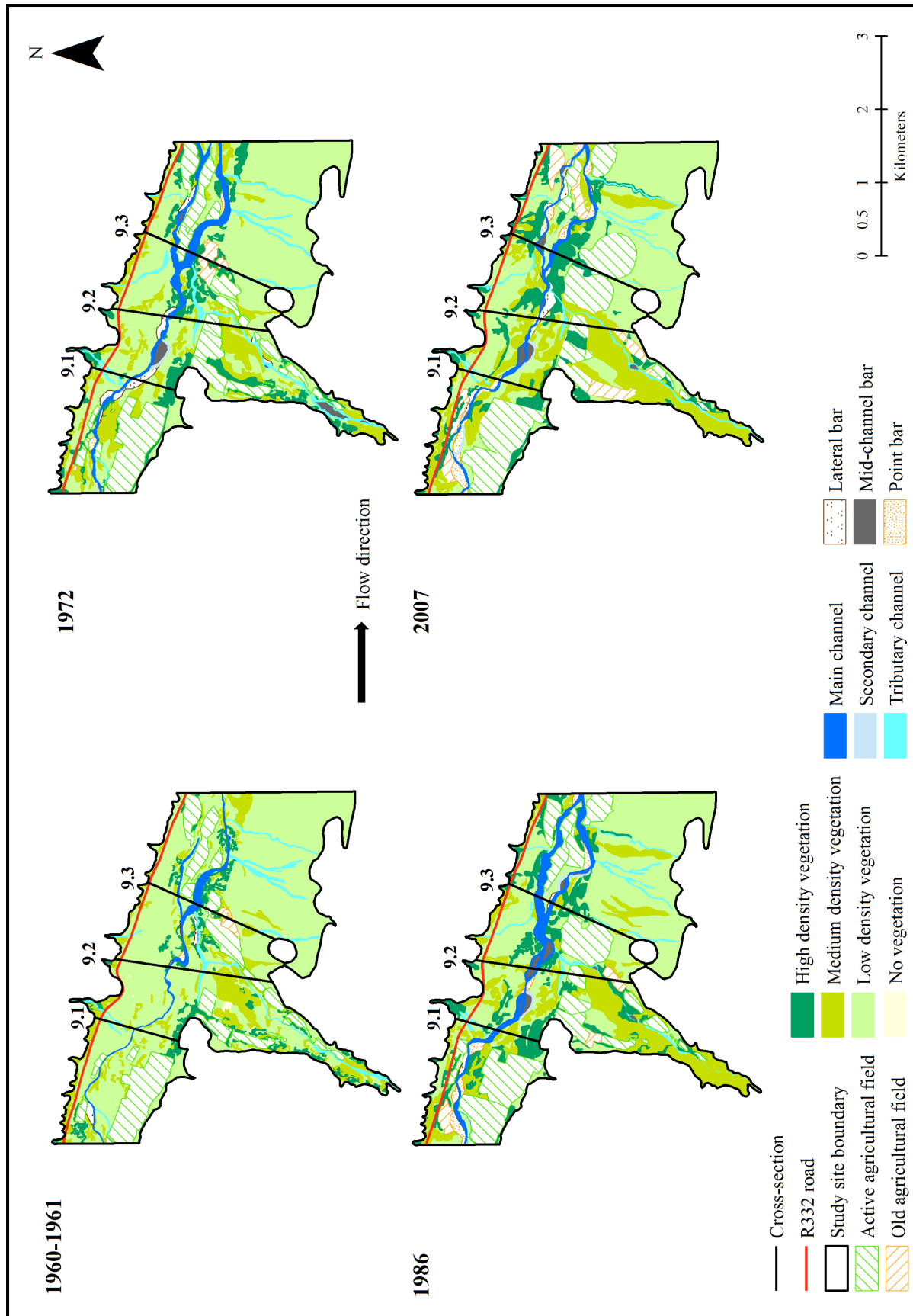


Figure 4.15: Land cover change for unconfined study site 9, Rus en Vrede (1960-2007).

4.4 Discussion and conclusion

4.4.1 Valley floor changes and their controls

This analysis shows that valley confinement is a primary control influencing river processes and resulting forms. Moreover, secondary confining features such as alluvial fans and terraces which formed under former flow and sediment regimes acted as additional controls at 50% of the study sites. Secondary control was dominated by terraces which were sometimes discontinuous. The above is in agreement with Fryirs and Brierley (2010) who suggest that these antecedent controls dictate river adjustment or activity on the valley floor. This in turn impacts upon the function and structure of river systems (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013).

Aerial photograph comparisons over 63 years show that, at the confined valley setting, simple single thread river channels (i.e. main and secondary) narrowed and were associated with limited lateral channel migration. Terrace and alluvial fan materials (site 2, Verlatenrivier only) located along one or both valley margins further constrained or imposed morphology. In addition, the number and area of bars decreased. Bar areas evolved into narrow flood benches and poorly developed elongated floodplains (Figure 4.2). These fluvial features were colonized by vegetation which had constricted riparian and terrestrial associations (Figure 4.9), a trend typically common to confined valleys (Gregory *et al.*, 1991; Montgomery, 1999). Vegetation cover thus increased, so that dense to medium density vegetation dominated (Figure 4.10) and exerted a significant influence upon process-form relationships. At the confined sites (Table 2.3) narrow valley floors were associated with limited accommodation space which restricted channel adjustments and sediment storage or reworking (i.e. landform formation). Until now, only a few studies (e.g. Fryirs, 2002; Keen-Zebert *et al.*, 2013; Kuo and Brierley, 2013) have documented similar results.

At the semi-confined valley setting, the Baviaanskloof River experienced a planform change over the time interval 1944-2007, from braided to sinuous single thread. This was accompanied by channel narrowing (main and secondary channels) and a reduction in mainly mid-channel and point bars. These areas were then reworked into larger floodplain surfaces which had an irregular shape. Furthermore, high narrow terraces lined one valley margin while alluvial fan deposits were limited to site 1, Nuwekloof (Figure 4.4). Here, the vegetation density either remained low (site 1) or increased substantially (site 8, Zaaimanshoek) (Figures 4.11 and 4.12). At the semi-confined study sites, the wider valley floors were associated with increased accommodation space which resulted in river reaches being less constrained. However, shifts in channel position from one valley side to another varied while sediment stores and features still remained to some extent restricted (Figure 4.4). Similar conclusions were made by Brierley and Fryirs (2005) and Fryirs and Brierley (2010) for partly confined valleys in New South Wales, Australia.

Aerial photograph interpretation at the unconfined valley setting revealed that the partially vegetated Baviaanskloof River was constrained either by alluvial fan sediments (site 4, Verlorenrivier) or both terrace and fan sediments (site 9, Rus en Vrede). These secondary confining features lined both valley margins (Figures 4.6 and 4.8). At site 9 extensive terrace surfaces were perched above continuous floodplain areas (Figure 4.8). In addition, reaches of the Baviaanskloof River changed from single thread to multi-thread (i.e. a braided morphology). These river reaches generally had higher sinuosity along with highly variable widths. Main channel area increases and decreases over the years corresponded to a widening (sites 4, 1944-2007 and 9, 1960-1986) and narrowing (site 9, post-1986) of the active channel reaches (Figures 4.6 and 4.8). The secondary channel area also increased at site 9 but mostly decreased at site 4. In contrast, tributary area initially increased (1944 and 1960s) and subsequently decreased (1972-2007) (Figure 4.7 and Table 4.7).

At the unconfined valley setting secondary and tributary channel widths were very variable while bars were larger after 1972 (Figures 4.6 and 4.8). Likewise, sediment reworking and preservation induced floodplain expansion and contraction (site 9 only). With regard to vegetation, the valley floor was mostly covered by low density vegetation which decreased over the years (Table 4.14). However, through time the vegetation also locally became denser (site 9 only) (Figure 4.14). Although increased accommodation space was associated with the broad valley floors at the unconfined sites, secondary control resulted in the main channel only adjusting laterally across floodplain surfaces at the upper section of site 9 (Figure 4.8). However, there was a positive relationship between sediment storage and the wide valley floor with more features being observed at both sites (Table 4.7). Comparable trends were reported by for example Brierley and Fryirs (2005), Fryirs and Brierley (2013) and Kuo and Brierley (2013). The latter authors examined the influence of valley width, channel slope, and landslides upon the downstream pattern of sediment storage in the Liwu basin, eastern Taiwan. This study showed that sediment conveyance is very effective within this highly connected basin.

The above-mentioned spatial and temporal changes at the three valley confinement settings in the Baviaanskloof can also be ascribed to several additional controlling variables. It appears that the main channel contraction at the study sites (excluding site 4) was associated with low-energy conditions which also promoted sediment deposition in the form of narrow benches, bars and floodplains. These landforms provided new pioneer habitat for vegetation colonization. The reduction in high flows may be attributed to the dry periods (Table 3.11) and drought events (1966 and 1987) on record from 1944 (Table 3.12). The driest periods were observed in 1949 and the 1980s. Furthermore, the more permanent river flow (i.e. shallow groundwater table) at confined and semi-confined sites 2, 6 and 8 (Figure 2.14 and Table 2.3) also supported vegetation establishment and expansion on the bare moist surfaces. This in turn stabilized the channel banks and presumably also contributed to channel narrowing. This relationship has been confirmed by many studies (e.g. Scott *et al.*, 1996;

Hession *et al.*, 2003; Cadol *et al.*, 2011; Labbe *et al.*, 2011). For instance, Cadol *et al.* (2011) showed how narrowing of channels in Canyon de Chelly National Monument, north-eastern Arizona, coincided with the establishment and expansion of woody riparian vegetation (e.g. non-native tamarisk and native cottonwood).

However, channel narrowing could also have occurred as a response to former flood induced widening (Friedman and Auble, 2000; Dean and Schmidt, 2011). Main channel reaches were much wider in 1944 at the confined (Figure 4.2) and semi-confined valley settings (Figure 4.4). The substantial vegetation increase at the above mentioned sites can also be attributed to the total absence or abandonment of agricultural activities over the years (Figures 4.9 and 4.11 and Tables 4.12 and 4.13). Hoffman and Rohde (2007) argued that present natural environments are as much a result of past human interference as they are of their evolutionary and climatic histories. Likewise, the river pattern and sediment storage changes at site 8 was almost certainly a consequence of channel narrowing linked to reduced high flows, an issue highlighted by Kleinhans (2010).

In contrast, the intermittent or ephemeral flow (i.e. indicating a deeper groundwater table) at the semi-confined and unconfined sites 1, 4 and 9 (Figure 2.14 and Table 2.3) gave rise to mostly sparse vegetation. The low density vegetation in turn was associated with landform instability. However, vegetation changes (increases and decreases) at these sites were also related to agriculture. Agricultural areas were abandoned (Figures 4.12 and 4.14), decreased (sites 1 and 4, Tables 4.13 and 4.14) or increased (site 9, Table 4.14). These former agricultural areas were mostly covered by grass species during the 2010 field campaign (pers. obs.). They will probably contribute to the instability at these study sites in the long-term. Typically, a mixture of woody and grass species are expected to provide the most bank protection (Simon and Collison, 2002). The valley floor at the unconfined sites has especially been heavily impacted and transformed as natural vegetation was converted to crop production and pastures (Figures 4.13 and 4.15).

At the unconfined valley setting main channel expansion over time was linked to high-energy conditions which promoted channel bed and bank erosion (e.g. Figure 2.12). Increased peak discharges could have resulted from the extremely wet periods (Table 3.11) and major floods (Table 3.12) on record from 1944. The wettest periods were detected in 1953 as well as the 1970s and 1980s. Major floods occurred in 1953, 1963, 1972, 1981, 1996 and 2005. These disturbance events had frequencies ranging from 9-15 years. Channel widening at this valley setting correlated well with the identified large floods and supplied the sediments needed to also develop new landforms (e.g. bars and benches), a trend reported on by numerous researchers (see Tooth, 2000b; Brierley and Fryirs, 2005; Kleinhans, 2010). However, sediment delivery could equally have been related to the lateral shifts in main channel position (site 9 only) or historic overstocking and subsequent soil erosion due to overgrazing (Table 2.2).

Past management interventions such as levee construction (i.e. artificial embankments) and river channelization (i.e. realignment) (Table 2.2), which are associated with elevated river flows, most likely also confined the channel and caused narrowing at site 9. These engineering structures resulted in major incision of the main channel since the 1980s at the broad valley sections. Channelization also caused headcut erosion and downstream sedimentation (Jansen, 2008; de Jong, 2013). Levees generally disrupt the connection between the river and its valley removing or dampening dynamic fluvial processes and affecting lateral biodiversity gradients (Van Looy *et al.*, 2003; Hohensinner *et al.*, 2004; Leyer, 2005). Channel width increases also resulted in shifting inherently unstable multi-thread braided reaches with bars (see for example Beechie *et al.*, 2006; Eaton *et al.*, 2010; Kleinhans, 2010). Conversely, the channel narrowing observed in 2007 at site 9 can conceivably be ascribed to the denser riparian vegetation (Figure 4.14) linked to increased water availability from flooding (Table 3.12) or decreased sediment loads related to a drastic reduction in small stock farming after 1987 (Knight, 2012).

The quadrat-scale analysis further demonstrated that the fluvial features at the three valley confinement settings are highly dynamic and the direction of change is very variable and therefore unpredictable (Tables 4.8 to 4.11). This reflects the inter-annual variability of the rainfall (Figure 3.7). It produces a complex and shifting mosaic of habitats, landforms and related vegetation community patterns (Ward *et al.*, 2002; Steiger *et al.*, 2005). Spatial variability, in particular, controls geomorphic processes and disturbance regimes (Montgomery, 1999; Fryirs and Brierley, 2013). This has important implications for how floodplains and terraces in unconfined valley settings are managed.

Over the decades fluvial action (erosion, transport and deposition) resulted in both positive and negative bio-physical (i.e. vegetation and hydrogeomorphic) feedbacks. According to Chorley and Kennedy (1971) positive feedbacks are mechanisms that reinforce or aggravate progressive change while negative feedbacks are mechanisms of self-regulation that prevent progressive change in one direction. In this study, bio-physical feedbacks manifested themselves, for example, where existing features were abandoned (i.e. old channels, Table 4.9), transformed into new landforms (e.g. bars and benches, Table 4.8) or became densely vegetated (stable islands, Tables 4.10 and 4.11).

Positive feedbacks were related to sediment accumulation and vegetation establishment creating landform heterogeneity, with features at times also reverting back to previous geomorphic units (Table 4.10). However, at all the valley confinement settings several features (e.g. terraces) or parts of features (e.g. floodplain surfaces) are not readily reworked and remained unchanged (Tables 4.8 to 4.11). The existence of bio-physical feedbacks is well known (e.g. Bendix and Hupp, 2000; Murray *et al.*, 2008; Dean and Schmidt, 2011). Dean and Schmidt (2011) for example demonstrated how large floods in the lower Rio Grande, Texas, acted as negative feedbacks by maintaining a historically wide, sandy channel.

Channel narrowing by vertical accretion also occurred at the same time with a rapid invasion of non-native riparian vegetation (e.g. *Arundo donax*) which created a positive feedback.

4.4.2 Concluding remarks

This study demonstrated that in the Baviaanskloof River catchment the degree of valley confinement is a primary control influencing river ecosystem structure and function. Furthermore, alluvial fans and terraces acted as an additional secondary control. Differences in the physical structure, geomorphic process domains and disturbance regimes of narrow and wide valley floor sections also assisted in explaining the spatial and temporal changes on the valley floor. In this study area, for example, unconfined sites often had sparse vegetation adjacent to the channel resulting from dry conditions and a lowered groundwater table. This causes flooding on the valley floor and leads to channel instability (e.g. high discharges and sediment loads). In contrast, confined sites had dense riparian vegetation because the groundwater table is closer to the surface and they accommodated minimal lateral expansion during flooding. Therefore, the channel is more stable during flooding events. These findings suggest that the valley confinement settings have different, but perhaps complementary functions.

Moreover, various additional controlling factors related to anthropogenic activities such as agriculture and management interventions (e.g. levees and river channelization) also contributed to the observed valley morphological changes from 1944-2010.

The study further showed that the geomorphic features at the three valley settings are highly dynamic and the direction of change is very variable and hence, mostly unpredictable. Variability within rivers creates landform and habitat heterogeneity important for different life stages of many plant species. This research has important implications for floodplain rehabilitation or restoration programmes or efforts in semi-arid and dryland environments in general. For example, reference river reaches selected in these programmes should be long enough to accurately represent this variability. In summary, conditions set in the past continue to exert a key influence upon modern rivers.

Chapter 5: Physical river valley dynamics

5.1 Introduction

A large body of literature exists on the importance of hydrogeomorphic controls on vegetation composition and distribution patterns (e.g. Malanson, 1993; Hupp and Osterkamp, 1996; van Collier *et al.*, 1997; Lite *et al.*, 2005; Francis, 2006; Hupp and Rinaldi, 2007; Sandercock *et al.*, 2007; Osterkamp and Hupp, 2010; Bendix and Stella, 2013). Vegetation dynamics vary along river systems with hydrological processes, geomorphic setting, sediment supply and surface-groundwater interaction (Tabacchi *et al.*, 1998; Gurnell *et al.*, 2012). Moreover, vegetation is largely governed by the river flow regime (Bendix and Hupp, 2000; Bertoldi *et al.*, 2011; Gurnell, 2014). Secondary controls include biological and chemical processes (Naiman *et al.*, 2008; Gurnell *et al.*, 2012; Bendix and Stella, 2013). Plant species have different tolerance ranges and growth responses (Grime, 2002) to inundation and flood disturbance (i.e. magnitude and frequency) and its associated erosional and depositional processes (Bendix and Hupp, 2000; Osterkamp and Hupp, 2010); drought stress (Amlin and Rood, 2003; Lite and Stromberg, 2005); water table depth which affects soil moisture (Amlin and Rood, 2002; Lite *et al.*, 2005; Chalmers *et al.*, 2012), hyporheic fluxes (Micheli and Kirchner, 2002; Mouw *et al.*, 2009) and landforms and their characteristics (e.g. elevation and sediment texture and size) (Bendix and Hupp, 2000; van Collier *et al.*, 2000; Hupp and Rinaldi, 2007).

Flood disturbances influence plant communities through multiple mechanisms. Floodwaters related to peak discharges can uproot, remove or physically damage plants and inundate areas causing reduced growth or mortality (Friedman and Auble, 2000; Brock *et al.*, 2006; Francis, 2006; Bendix and Stella, 2013; Gurnell, 2014). Prolonged inundation typically results in oxygen depletion in the root zone (Friedman and Auble, 2000; Brock *et al.*, 2006). Upland terrestrial plants are particularly stressed by waterlogged and anoxic soils. Floods also function as transport vectors displacing vegetation, dispersing seeds or propagules (e.g. rhizomes) and exchanging nutrients and sediments between landforms (Bendix and Hupp, 2000; Friedman and Auble, 2000; Brock *et al.*, 2006). In riparian zones dispersal of propagules or seeds in water, hydrochory, is very important for plant species structure and richness (Naiman *et al.*, 2005; Richardson *et al.*, 2007). Flood damage also encourages species establishment by providing bare freshly deposited moist sediment or removing plants from pre-existing surfaces, opening up gaps in the vegetation (Bendix and Hupp, 2000; Friedman and Auble, 2000; Richardson *et al.*, 2007). The patchy environment in arid and semi-arid regions is especially effective at trapping and retaining resources. It is characterized by resource-rich units or patches such as in large trees, clumps of shrubs or woody debris that are dispersed across the landscape and separated by more open, resource-poor zones. These patches act as sinks by filtering and concentrating nutrients lost from source areas (Ludwig and Tongway, 1995).

River channel changes such as channel migration and abandonment (Gurnell, 1995; Scott *et al.*, 1996; Steiger *et al.*, 2005) and post-flood channel narrowing (Scott *et al.*, 1996; Friedman and Auble, 2000; Friedman and Lee, 2002) can also lead to species establishment. Generally, the rate of substrate recolonization is rapid after floods. Exceptions result where flooding is very severe or occurs out of season (Lake, 2000). Wolman and Gerson (1978) however, stress that the slow rate of vegetative re-establishment in arid or semi-arid areas prohibits rapid recovery. Although establishment sites are often ample in these areas, the rate of decline of the water table and water availability restrict vegetation establishment (Richardson *et al.*, 2007). Vegetation in arid and semi-arid areas is usually limited by water stress, hence water availability is expected to be closely related to vegetation patterning (Lite *et al.*, 2005; McLendon *et al.*, 2008; Chalmers *et al.*, 2012). Water availability and flood disturbance also vary significantly over time in drylands, with dry years or droughts producing conditions of high water stress and low disturbance. However, when water is available growth can be rapid with sufficient temperatures and nutrients (Lite *et al.*, 2005). Typically, seedling regeneration depends on flooding as a disturbance while adult survival mechanisms are more related to groundwater depth and other surface water resources (O'Connor, 2001).

Interactions between streamflow and sediment erosion and deposition often result in distinct landforms of different ages occupied by specific plant communities (Gurnell, 1995; Friedman and Auble, 2000; Hupp and Rinaldi, 2007; Osterkamp and Hupp, 2010; Chalmers *et al.*, 2012). Site suitability and environmental conditions determine the likelihood of a given species growing on a particular geomorphic landform (Hupp and Osterkamp, 1996; Bendix and Hupp, 2000). Therefore, it is the hydrogeomorphic processes operating differently on different landforms that actually affect plant distributional patterns, not the landforms *per se* (Hupp, 1990; Bendix and Hupp, 2000). Hupp and Osterkamp (1996) further suggested that specific processes operating at the severe end of a stress equilibrium gradient in combination with competition with other species at the other end, can possibly be major drivers of vegetation zonation across landforms. It is important to note that species may be present where floods are severe, not because they can survive floods, but because they have the ability to rapidly colonize flood-cleared alluvial surfaces (Hupp and Osterkamp, 1996; Gurnell, 2014). Landform position becomes even more critical in arid and semi-arid environments because it affects the flood regime as well as access to moisture (Bendix and Hupp, 2000). Flow variability tends to increase landform distribution complexity and related vegetation patterns (Bendix and Hupp, 2000; Sandercock *et al.*, 2007).

This chapter examines the two-way links between hydrogeomorphic processes and landforms, including surface-groundwater interactions, and vegetation distribution patterns on the valley floor. It intends to partially meet objective three of this study (Figure 1.2) by investigating the physical river valley dynamics in the Baviaanskloof through:

- 1: Surveying (valley cross-sections and resistivity profiles). It was hypothesized that the groundwater table at the confined sites is very shallow (i.e. intersecting the channel

surface) whereas under natural conditions the opposite is true at the unconfined sites. The resulting permanent surface water at the confined sites promotes good riparian vegetation growth which contributes to channel stability (Rowntree, 2012).

2: An earth observation assessment (the Normalized Difference Vegetation Index and Tasseled Cap transformation). It was hypothesized that if the valley floor vegetation remains green during the dry period, then there is a groundwater influence.

3: Sediment sampling (grain size distribution and soil chemistry).

Comparisons of valley floor changes are made within and between confined, semi-confined and unconfined study sites. The results will then be employed in Chapter 7 to interpret process-form and vegetation relationships on the valley floor.

The chapter is divided into three main sections: methods, results and an overall summary. The methods section (Section 5.2) deals with data collection, analysis and presentation. Under the results section (Section 5.3), the analysis pertaining to valley floor landforms are considered first (Section 5.3.1). An analysis related to surface-groundwater interactions and vegetation relations are presented next (Section 5.3.2). This is then followed by the grain size distribution and soil chemistry analyses (Section 5.3.3). The summary section (Section 5.4) highlights key chapter findings.

5.2 Methods: Data collection, analysis and presentation

A pilot study involving four sites (3, 5, 7 and 12) during the winter of 2009 was used to develop and refine the study methodology. Fieldwork then commenced systematically down the valley at 13 study sites along the Baviaanskloof River (Figures 2.2 and 2.16) during a winter sampling programme, late June to mid-August 2010. Field data were collected mainly during the dry period when baseflow is the dominating contribution to streamflow. The sampling area comprised 81.5 km along an elevation gradient ranging from 863 to 303 m (Table 2.3).

Four field activities and one desktop analysis were completed at all or selected study sites. First, valley cross-sections were acquired through surveying. These were then linked to quadrats which were set-up along cross-sections. Second, groundwater depth levels were obtained from a resistivity survey. An earth observation assessment then followed involving the Normalized Difference Vegetation Index and Tasseled Cap transformation. Third, sediment size distribution and soil chemistry data were recorded at quadrats. This information was used to infer plant community distribution patterns from quadrat vegetation sampling (Chapter 6).

5.2.1 Valley cross-section survey

Valley cross-section surveying involves measuring horizontal and vertical distances of a series of points in relation to a benchmark or starting point (Harrelson *et al.*, 1994). Different surveying techniques can be used depending on the level of accuracy desired, the study purpose, the site conditions, the equipment available and how easy it is to transport, and time constraints. These include: measurement with a tape, optical distance measurement or tachometry using a dumpy level or theodolite, and electronic distance measurement using a total station and/or a differential real-time GPS (Global Positioning System) (Gordon *et al.*, 2004). The latter technique was employed in this study to obtain topographic cross-valley profiles. This method was deemed appropriate because measurements could be done rapidly over long distances on the valley floor whilst maintaining high accuracy (± 2 cm). A disadvantage of this method is, however, that obstructions of any sort (e.g. dense vegetation or a remote, rugged terrain) can result in a weak signal (Gordon *et al.*, 2004).

To mitigate this issue, specific cross-section locations were selected at each site while walking the study reach length. An attempt was made to avoid locations on meander bends, through deep pool hydraulic biotopes or features such as debris dams that have altered the channel form. Most importantly, locations had to exhibit an accurate representation of the geomorphic surfaces of the site. It was also important to establish a line-of-sight, using danger tape (also known as barricade tape), in-between the vegetation to position cross-profiles. This was often associated with cutting or chopping a clear path through dense vegetation. However, impassable terrain was encountered at some of the semi-confined (i.e. site 8) and unconfined study sites, i.e. site 9 (Figure 5.1). Likewise, the narrow valley sections with their steep rock faces (i.e. site 6) caused interruptions in satellite-GPS signal reception. Although high survey accuracy was maintained at these sites, obtaining these cross-valley profile measurements was very challenging and time consuming.

Data collection and interpretation

Three cross-sections per site (12 sites; Figure 5.1) were surveyed with the assistance of a professional surveyor (R. Vonk, June 2010). A Leica TCRP 1205 total station and a Leica 1200 RTK GPS base station were used. A CNAV 3000 GPS unit was also utilised to set up a control network. Standard surveying procedures were followed with reference to work stations and ends of cross-sections marked with iron pegs for future retrieval (Harrelson *et al.*, 1994; Gordon *et al.*, 2004). X, y and z co-ordinates were also recorded. To minimize error, a single operator (L. Smith-Adao, June 2010) with a geomorphological background was on the target end selecting points and features. Cross-sections were aligned perpendicular to the main channel or direction of streamflow. They spanned the entire valley floor width, from the left to the right valley margin. This study also made use of three cross-sections previously surveyed in 2009 at site 10, Zandvlakte, with a dumpy level (Johnson-Marshall, 2009).

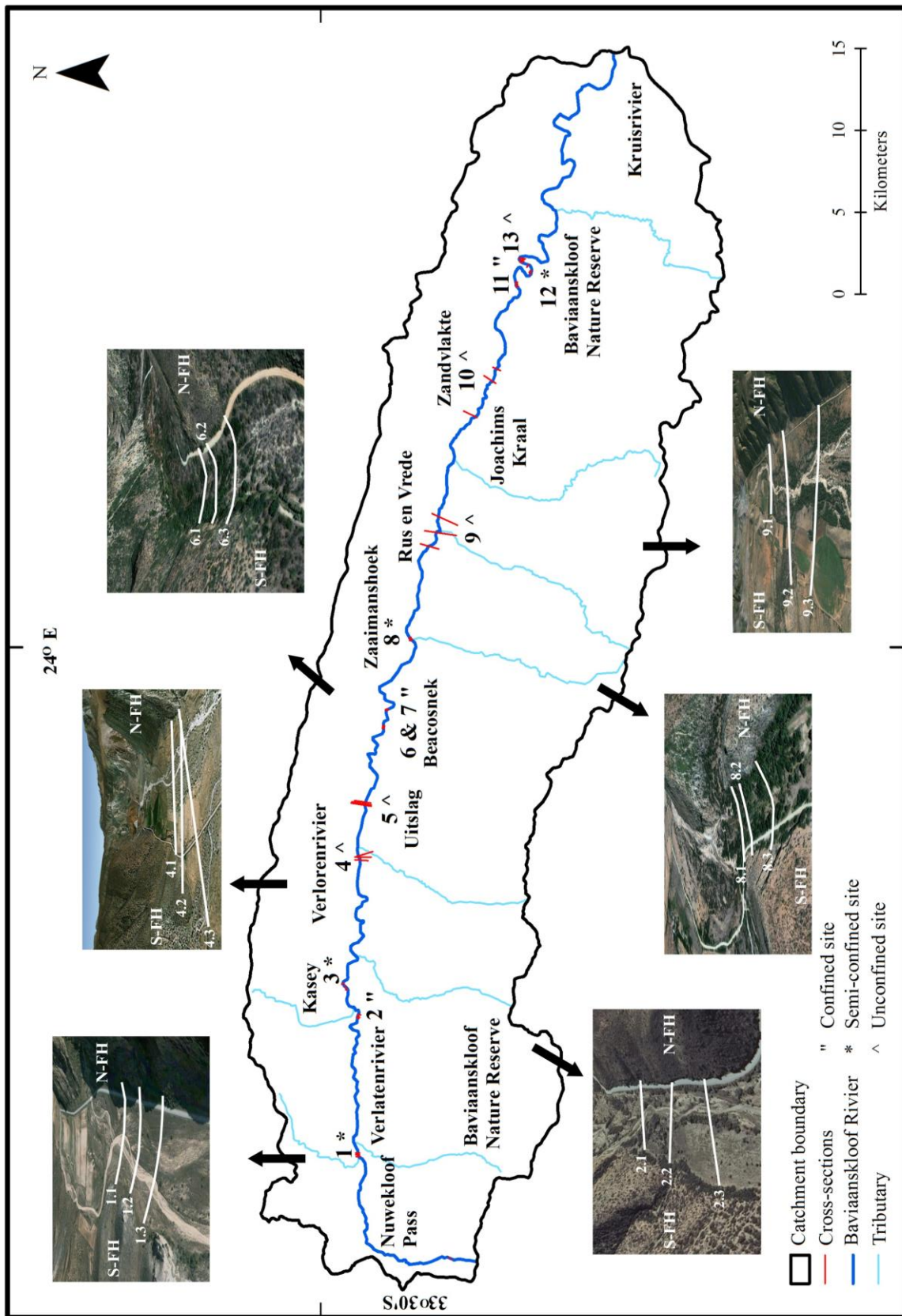


Figure 5.1: Surveyed cross-valley profile locations in the Baviaanskloof with an aerial view of six sites from Google Earth. Profile codes e.g. 1.2 indicates the study site number (1) and the cross-section number (2). S-FH and N-FH represent the south- and north-facing hillslopes.

In most cases, cross-sections (totalling 39) were spaced at least 50 m, 100 m and 600 m apart at confined, semi-confined and unconfined sites respectively. These minimum intervals were considered to be at sufficient resolution to capture the variability within the study reaches. Notable exceptions concerning these intervals involved cross-sections at sites 5, 8 and 13. These intervals were influenced by study reach length which in turn depended mostly on human activity avoidance (e.g. agriculture or settlement). These cross-sections were placed closer to each other. Field routine at each cross-valley profile included geometry and morphology (i.e. morphometry) measurement and differentiation and identification of geomorphic surfaces (Simon and Castro, 2003). Hence, the north-south cross-sectional profiles provided detailed data on slope breaks (e.g. bank or terrace); channel width and depth; and the lateral variability of geomorphic landforms or features (Table 5.1).

Landforms were identified using a combination of published definitions or descriptions (Section 1.2) and knowledge of flow duration, flood frequencies and its elevation relative to the surrounding landforms. To minimize bias, this process was also performed by a single operator (L. Smith-Adao). In no instance were plants used to identify landforms. The identification of landforms in arid areas is especially problematic (e.g. landforms can be obscured) because these landforms tend to be subject to frequent and rapid changes (Bendix and Hupp, 2000; Sandercock *et al.*, 2007). These geomorphic surfaces (Table 5.1) were then represented by sample plots or quadrats (Appendix 5.1) which were selected along the cross-sections. No distinction was made between multiple terraces (e.g. sites 9 and 10) during the survey. The quadrat also represented a basis for comparing biophysical data (Küchler and Zonneveld, 1988; Kent and Coker, 1992). Sediment (Section 5.2.4) and vegetation (Chapter 6) sampling was done at the quadrat scale.

Quadrat locations were representative of the observed geomorphic surfaces rather than being selected randomly or at prescribed increments. Locations were recorded using a Garmin Nüvi 205 GPS unit. Quadrat sizes were influenced by the width of geomorphic surfaces and the species richness or the number of species and growth forms (e.g. trees or herbs) present at a specific study site (Chapter 6). Typically, sizes vary from one vegetation type to another (Küchler and Zonneveld, 1988; Kent and Coker, 1992). A standard length of 8 m (long axis parallel to the landform) was applied to all plot sizes because this was judged suitable for the types of vegetation found at the study sites. Plot dimensions varied for example from 1 x 8 m (8 m²) on the channel bed to 8 x 8 m (64 m²) on the floodplain (Appendix 5.1). Two hundred and ninety eight quadrats were established by setting out stones at each corner and demarcating the area with danger or barricade tape (Figure 5.2).

Table 5.1: Geomorphic landform or feature type, Bavianskloof.

Descriptions as per Table 4.3.

Landform or feature type	Code
Alluvial fan	AF
Artificial embankment	AE
Backwater area	BA
Flood bench	FB
Floodplain	F
Island	I
Lateral bar	LB
Main channel bed	MCB
Main channel left bank	MCLB
Main channel right bank	MCRB
Mid-channel bar	M-CB
Point bar	PB
Scroll bar	SB
Secondary channel bed	SCB
Secondary channel left bank	SCLB
Secondary channel right bank	SCRB
Terrace	T
Tributary channel bed	TCRB
Tributary channel left bank	TCLB
Tributary channel right bank	TCB

**Figure 5.2: A rectangular quadrat, site 6.**

The dimensions of the quadrat located on the channel bed were 3 by 8 m (24 m²).

Site maps were drawn in the field, and scaled to show the entire reach surveyed and the main features of the site. These were also accompanied by a photographic record and detailed field notes. Channel pattern (e.g. straight, meandering or braided) and instream hydraulic biotopes (riffles, runs or pools) were also described for reaches. Any evidence of inundation (e.g. woody debris around trees, scour and sediment deposits) on landforms was noted and

measured where possible (Simon and Castro, 2003). This included erosional features such as incised secondary channels created by flow events (e.g. site 5).

Data processing and handling

The surveyor (R. Vonk) processed the point data acquired in the field using AutoCAD 2013, Computer Aided Drafting (CAD) software. The resultant topographic cross-valley profiles were then imported and redrawn in CorelDraw V13 by L. Smith-Adao. Geomorphic landforms or features with their associated quadrats as well as water levels (where available) were indicated on the cross-valley profile figures. Finally, for each quadrat the elevation above and distance away from the active channel thalweg were calculated. This data set was then used in the vegetation analysis (Chapter 6).

5.2.2 Groundwater table depth: Electrical resistivity survey

A geophysical approach was employed to investigate interactions between vegetation and groundwater in the Baviaanskloof. An indirect geoelectrical method, Electrical Resistivity Tomography (ERT), was used to determine groundwater table depth and depth to bedrock at selected study sites. ERT is a 2D and 3D high-resolution imaging technique used in a wide spectrum of shallow subsurface investigations (Loke and Dahlin, 2002; Maillet *et al.*, 2005; Giocoli *et al.*, 2008; Van Dam, 2012; Loke *et al.*, 2013; Winters *et al.*, 2015).

ERT is relatively inexpensive, environmentally sensitive or non-destructive and generates continuous data that is not spatially limited (Maillet *et al.*, 2005; Martínez *et al.*, 2009). Since direct borehole or piezometer groundwater level data were absent in the Baviaanskloof, this data set could be obtained rapidly with a resistivity survey. The method is an acquisition system that provides a pseudo-section or “picture” of the subsurface in terms of changes in electrical resistivity. Electric currents are injected into the ground through a multi-electrode array and the resulting potential differences are measured between dipoles at the surface. Changes in resistivity are then related to expected changes in the properties of the subsurface (Store *et al.*, 2000; Maillet *et al.*, 2005; Loke *et al.*, 2013). The bulk resistivity of different subsurface units varies mostly because of changes in salinity, porosity or water saturation (Telford *et al.*, 1990).

Data collection

The survey was performed at five study sites across valley floor landforms in the Baviaanskloof (Table 5.2). A hydrogeologist (R. Bagan, August 2010) trained in resistivity data collection techniques aided the study. A reduced selection of sites was necessary because of time constraints and logistical problems linked to site conditions. Measurements were taken with an ABEM Terrameter SAS1000 ground imaging apparatus (resistivity meter), a

switching device, a laptop computer and battery (Figure 5.3a). The measurement sequence was controlled by the ABEM electrode selector ES464. Three resistivity profiles per site were chosen to represent the valley confinement setting and the required depth of investigation, with confined sites having the shortest resistivity profiles. Profile locations or orientations were influenced by site constraints and the number of landforms. The profile locations were representative of the main landforms. The profile length and depth of investigation are presented in Table 5.2.

Table 5.2: Resistivity profile and pit or well localities with water level information.

mbd = meters below datum (i.e. the ground level).

Study site	Profile no.	Lat. and Lon. (start Y, X; end Y, X)	Profile length (m)	Depth (m)	Pit or well position	Lat. and Lon.	Water level (mbd)
Confined 2, Verlatenrivier	1	-33.5219, 23.75592 -33.52218, 23.75647	64	9	Cross-section 2.1	-33.52165, 23.75632	1.95
	2	-33.52133, 23.75636 -33.52161, 23.7569	64	9			
	3	-33.52124, 23.75677 -33.52142, 23.75737	64	9			
Semi-confined 1, Nuwekloof	4	-33.52110, 23.66497 -33.52056, 23.66619	128	17	None		
	5	-33.52163, 23.66488 -33.52159, 23.66626	128	17			
	6	-33.521650, 23.66458 -33.521450, 23.66807	320	70			
12, Baviaanskloof Nature Reserve	7	-33.616694, 24.250639 -33.616278, 24.25017	64	9	Above cross-section 12.1	-33.61194, 24.246583,	4.7
	8	-33.61678, 24.2510278 -33.6172, 24.2514167	64	9			
	9	-33.61776, 24.24909 -33.61542, 24.25099	320	70			
Unconfined 4, Verlorenrivier	10	-33.5228, 23.8598 -33.52175, 23.86015	128	17	Above cross-section 4.1	-33.5224, 23.84575	7.5
	11	-33.5257, 23.86031 -33.52459, 23.86063	128	17			
	12	-33.5985, 24.176194 -33.5974, 24.176361	128	17	Cross-section 10.3	-33.6014167, 24.1820278	3.5
	13	-33.596083, 24.1762 -33.595361, 24.17717	128	17			

Most of the subsurface data (sites 1, 4 and 9) were acquired using two multi-core 64 m cables laid out on the ground end to end in a straight line with 32 electrode take-outs at two (2) meter intervals (Table 5.2). A metal stainless steel electrode (metal rod) was inserted into the ground next to each electrode take-out and these were connected to the cable with a cable jumper (Figure 5.3a). The data were collected using the Wenner array (Loke and Barker, 1996). Data

at all the sites were collected for the electrode spacing multiplication factor (n) = 1 to 9, 11, 13, 15, 17 and 20. At site 2 (Verlatenrivier) one 64 m multi-core cable resulted in an acquisition of n = 1 to 9. The second cable set-up at sites 1 and 12 used four multi-core cables with 16 electrode take-outs every 10 m. The increased depth of investigation (70 m) was intended for interpretation of depth to bedrock at sites 10 and 12. Both 64 m and 320 m investigations followed the same standard protocol as described for the 128 m investigation.

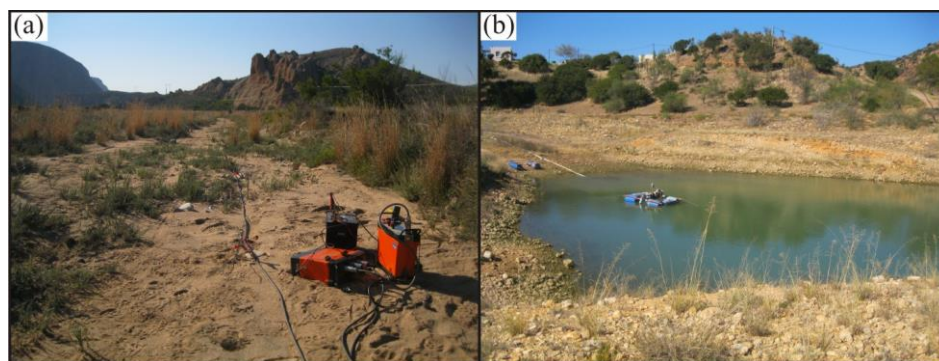


Figure 5.3: An acquisition system with a resistivity profile, site 1 (a) and pit, site 4 (b).

A few surveying problems which were mitigated by, for example, improving contact were also experienced in the field. These included coarse sediments making electrode positioning difficult or resulting in failed electrode tests (site 4) which were also related to faulty cables used, some measurements exhibiting negative resistivity and dry soils preventing contact (site 10). The 320 m long profile at site 9 failed and was therefore aborted.

Data processing and interpretation

The interpretation of the resistivity data was carried out by an experienced geophysicist (L. Soltau). The apparent resistivity data acquired in the field were inverted using RES2DINV software to provide a 2D resistivity model for each profile (Loke and Barker, 1996; Loke, 2001). This basic starting model resembles the distribution of the measured apparent resistivity. Further computational steps removed noise. For example, erratic data points were excluded and 1:50 000 topographic data were added to correct for lateral effects resulting from the changes in elevation along profiles. Through subsequent iterations, minor changes to this starting model were made to define the true resistivity distribution in the subsurface that resulted in the measured resistivity section. The root mean square (RMS) error gives a measure of the difference (Loke and Barker, 1996; Loke, 2001).

The resistivity is generally interpreted over a range. This range is usually site specific (Loke, 2001). For example, the resistivity of sandstone is in the range of 8000 to 4000 ohm (Ω) metre (m). Resistivity values between 3000 and 500 ohm.m in the Baviaanskloof were typical for saturated soil (R. Bagan, CSIR, Stellenbosch, pers.comm., 2015). Groundwater levels (Table

5.2) were measured at pits or wells (Figure 5.3b) and used to validate the obtained geoelectrical model. This, together with distinct breaks in the resistivity was used to interpret the measured profile data. However, the distance between the pits and the resistivity profiles in most cases was a constraining factor on direct correlation.

Data handling

The interpreted outputs were normalised to aid comparison, since the distance and depth along the profiles varied. They were used to qualitatively infer water table depths below the surface. It must be noted that, in the general resistivity literature, the water table or geological layering is usually expressed as a depth (m) and not a height (e.g. Loke and Dahlin, 2002; Martínez *et al.*, 2009). Differing profiles in a specific confinement setting were shown with relative lengths. Shorter lines were shown as shorter, but not the true length relative to the long profiles. This was done to ensure sufficient detail in the outputs which were imported and edited in CorelDraw V13. Likewise, the shape of the resistivity profile is a result of the geoelectrical method. It does not reflect the shape of the underlying sediments. For example, the deeper the measurement, the fewer data points it collects (Loke, 2001).

5.2.3 Land surface-groundwater interactions: Earth observation assessment

Vegetation and surface-groundwater interactions in the Baviaanskloof were further assessed through a desktop analysis of available satellite imagery by M. Lück-Vogel. The goal was to be able to make broad statements regarding vegetative response under general wet and dry conditions in the Baviaanskloof. It was hypothesized that if valley floor vegetation remain green during the dry period (limited or no rains) then there is a groundwater influence. The Normalized Difference Vegetation Index (NDVI) and the Tasseled Cap (TC) transformation from different bands in multispectral Landsat Thematic Mapper (TM) images were calculated for each quadrat and resistivity profile location. The NDVI is used to evaluate changes in vegetation condition and composition (Jones *et al.*, 2008). TC transformation provides a measure of land surface brightness, greenness and wetness (Kauth and Thomas, 1976; Karl and Maurer, 2010).

Image acquisition and pre-processing

Landsat 5 TM images were selected in relation to measured rainfall data in the catchment to represent both wet and dry periods. The images in Level 1G processing were obtained from the U.S. Geological Survey (USGS) via an online search engine, the CSIR Satellite Applications Centre (SAC) currently known as the SANSa (South African National Space Agency) Earth Observation at <http://catalogue.sansa.org.za/>. The study area is covered by the Landsat scene 172-83 (WRS2 path-row), with acquisition dates (yyyy-mm-dd) of 1991-07-10, 1993-09-01 (dry period), 1997-01-15 and 2003-02-12 (wet period). This resulted in a variable

inter-annual interval with two, four and six year time steps. Pixel sizes of the Landsat 5 data were 30 x 30 m (scale 1:100 000).

Image pre-processing involved first matching the projection of the field data by re-projecting the satellite images from the original UTM WGS84 projection to Albers Conical Equal Area. Then, as the spectral information was to be analysed quantitatively, a radiometric correction of the images was conducted using ATCOR-2 software. The software corrects for sensor and atmospheric effects (Richter and Schl pfer, 2012). While a topographic correction (i.e. hill shades and over-illumination) given by the very steep relief would have been desirable, it was not conducted. The reason is that ATCOR requires a very detailed and accurate Digital Elevation Model (DEM) as an input layer. Unfortunately such a DEM was not available for this study, and the use of a less detailed DEM would have caused further spectral artefacts. Subsets covering the extent of the study area were extracted to reduce processing time from the four corrected Landsat scenes.

Normalized Difference Vegetation Index and Tasseled Cap transformation

The NDVI was calculated for each pixel in each of the four subsets as an index for vegetation density and photosynthetic activity. It was selected because it has been shown to be sensitive to the types of low density vegetation found in semi-arid areas and active braided river corridors (Henshaw *et al.*, 2013). Its equation is shown as $NDVI = (NIR - R) / (NIR + R)$ where NIR indicates near infrared light and R indicates visible red light (Yahas and Scuderi, 2009; Henshaw *et al.*, 2013).

Normalize in the context of the red/infrared ratio means to adjust for the effects of the solar zenith angle (https://en.wikipedia.org/wiki/Normalized_Difference_Vegetation_Index, accessed 21 March 2016). This vegetation index has been used to: (1) measure and monitor plant growth, vegetation cover and biomass production; (2) model the abundance of living planet material and (3) identify vegetated areas and their condition (Shahabi *et al.*, 2012). NDVI values range from -1 to +1, with high positive values close to 1 indicating a greener vegetated surface. Water-stressed or dead vegetation have a much lower NDVI value nearing a theoretical value of 0 for bare soil, rocks, or snow. Negative NDVI values usually indicate water bodies (Yahas and Scuderi, 2009; Henshaw *et al.*, 2013). NDVI values were classified into four vegetation density classes: low (0.1-0.2), medium (0.2-0.3), high (0.3-0.4) and very high (> 0.4) based on Sahebjalal and Dashtekian (2013). A very high value represented dense vegetation while a low value represented bare ground or very sparse vegetation.

TC transformation offers a way to optimize data viewing for vegetation studies. It is a fixed linear transformation of spectral information into new orthogonal axes with specific interpretations (Crist and Kauth, 1986; Karl and Maurer, 2010). The first TC band generally corresponds to low vegetation and high reflectors (brightness) and the second to active

vegetation (greenness). Features such as rocks, bare soil and urban areas will have the highest values in the brightness index. The greenness index is indicative of the biomass present. The third TC band, the wetness component, is of particular interest for its sensitivity to plant and soil moisture, canopy structure and shadow (Kauth and Thomas, 1976; Karl and Maurer, 2010). However, it must be mentioned that while greenness may be indicative of soil moisture for some species, this is not the case for others. This might give misleading results. For example, subtropical thicket species such as *Pappea capensis* are evergreen and retain their leaves irrespective of soil moisture. The TC transformation was calculated and the first three resulting bands or components were used for further analysis.

Data processing and handling

The original GPS points for the field data of 282 quadrats and 13 resistivity profiles were converted into point shape files in ArcMap (ESRI, 2012). Using ERDAS imagine software (ERDAS, 2011) the NDVI, TC brightness, TC greenness and TC wetness were extracted for all pixels overlapping with these areas. Values for points in areas which were affected by clouds or shadows or other biases were removed in MS Excel. ERDAS only extracts one value per pixel. Hence, in instances where multiple resistivity or quadrat points occurred within the same Landsat pixel, the respective extracted values were matched to the points closest to it.

The resistivity profile results were plotted according to the valley setting (confined, semi-confined and unconfined). A linear regression analysis was used to establish correlations between the NDVI and the TC bands. Generally, an R-squared value of ≥ 0.8 is indicative of a strong positive correlation. This meant for example that if $R^2 = 0.85$, 85% of the total variation in the y variable can be explained by the linear relationship between the x and y variables as indicated by the regression equation. The other 15% of the total variation in the y variable remains unexplained. The closer the value to one, the better the line fits the data. Typically, an R-squared value of < 0.5 suggests a weak or a low correlation (M. Lück-Vogel, CSIR, Stellenbosch, pers.comm., 2015).

Further analysis was done on the monthly rainfall records from the Baviaanskloof gauge station (number 20237), the NDVI and the TC transformation datasets (resistivity and quadrat extracted points) and the resistivity profile data (groundwater depth levels). Station selection criteria included sufficient record length (the four Landsat acquisition dates were represented) and minimal data gaps (Section 3.2.1, Table 3.1). This analysis involved firstly, examining the rainfall patterns for the 12 months preceding each respective acquisition date and the resistivity survey end date, 12 August 2010. Secondly, the averaged water table depth, NDVI and TC transformation values were plotted for each of the resistivity profiles. Data from the 1991 Landsat image were employed for this purpose because it was the most comparable to the resistivity field conditions in terms of rainfall history.

Thirdly, total rainfall for each image was summarized from the last dry season to the actual image acquisition date. This was done to better characterise the dry and wet periods and to determine relations with the NDVI and TC transformation data. For the dry periods rainfall was considered for two months before the image date and the resistivity survey end date. For the wet periods this included rain until July the previous year (i.e. 12 months). Lastly, the summarized rainfall totals were compared with the averaged NDVI, TC brightness, TC greenness and TC wetness quadrat data (Appendices 5.5 and 5.6) per valley setting. The results were plotted and/or correlated by performing a linear regression analysis.

This was also complemented with an assessment of basic statistics (e.g. maximum and minimum values) (Appendices 5.5 and 5.6). In addition, certain NDVI and TC transformation quadrat results were mapped to visualise the data. Quadrats at sites 1, 2, 4, 6, 8 and 9 (i.e. the selected sites in the historical mapping chapter, Section 4.2.1) were used as examples. These colour composite images represented both dry (1991) and wet (1997) periods (Appendices 5.7 and 5.8).

5.2.4 Grain size distribution and soil chemistry: Sediment sampling

Soil studies provide important information on factors such as biota and their habitats, sediment sources, transport history, depositional conditions and chemistry (Gordon *et al.*, 2004). A variety of methods have been used to sample sediments depending on issues such as study aim, effort and cost and site considerations. All methods involve sediment counting or weighing, and determining a number of size fractions (Pye, 1994; Boggs, 1995; Gordon *et al.*, 2004). The methods used here minimized bias (hence errors) while being efficient enough to be performed by minimally-trained field assistants. Surface sediment analysis in this study involved sampling both coarse and fine sediments in all quadrats (Appendix 5.1) to indicate possible relations between geomorphic landforms, sediment and vegetation.

Coarse sediment analysis

Environmental variables recorded included sediment particle size (i.e. counting of stones) and percent cover of sediments via visual estimations. Particle size was viewed as dependent on site-specific flow energy and therefore constituted a rough guide for the flood history of study sites (Kondolf *et al.*, 2003; Gordon *et al.*, 2004). Coarse-grained material (e.g. gravels or boulders) were sampled using a modified Wolman pebble count procedure (Wolman, 1954). Pebble counts were facilitated by using a sampling grid and particle size analyser or gravelometer. Three to five grid samples 0.5 x 0.5 m (Figure 5.4) were randomly positioned in quadrats (Figure 5.2), where the number of grids was representative of the observed sediment diversity in quadrats. A gravelometer is a metal template consisting of square holes of common sieve sizes (8 to 128 mm) that is used to sort particles in the field by measuring the b-axis sizes of particles (Bunte and Abt, 2001; Kondolf *et al.*, 2003; Gordon *et al.*, 2004). All the sediment sizes were recorded (Table 5.3).



Figure 5.4: A sediment grid, site 6.

This 0.25 m² grid was situated in a quadrat located on the channel bed (Figure 5.2).

Visual estimates or identifications involved estimating percentages (totalling 100%) in four broad size classes by eye (i.e. qualitatively). Grain size classes described in Table 5.3, based on Bunte and Abt (2001) and Kondolf *et al.* (2003), included fine sediment (sand, silt and clay), gravels, cobbles and boulders. The percentage cover of these sediment size classes in each grid was estimated as a proportion on the ground when viewed from above, as seen in Figure 5.4 (Kondolf *et al.*, 2003).

Table 5.3: Sediment size classes.

Adopted from Rowntree and Wadeson (1999), King and Schael (2001) and Fryirs and Brierley (2013).

Class name (Wentworth scale)	Size range, mm (b-axis)	Phi-units (ø)	Guide line
Clay	0.00006 to 0.0039	14 to 9	Mud
Silt	0.0039 to 0.0625	8 to 4	Mud
Sand	0.0625 to 2	4 to -1	Fine to coarse sand
Gravel	2 to 64	-1 to -6	Finger nail to length of small finger
Cobble	64 to 256	-6 to -9	Wrist to halfway along finger; inside elbow to wrist
Boulder	> 256	> -9	Armpit to wrists; ground to waist; > length of tall person

Field description was supplemented by the complete photo coverage of grids. The results were entered into spreadsheets, averaged and cumulative particle size distribution curves and histograms (% cover) were developed for each quadrat, as described in Kondolf *et al.* (2003). Standard grain size parameters (e.g. D_{50} or median, mean, sorting and skewness) were determined using MS Excel and RRSS V4.3 L software (Mecklenburg, 2006). This freeware program can be downloaded from the website: <http://www.dnr.state.oh.us/tabid/24137/Default.aspx>. Lateral and longitudinal variability in grain size was also assessed using the mean and coarsest grain size fractions for each quadrat or geomorphic landform. The resultant data sets were tabulated.

Fine sediment analysis and soil chemistry

Two hundred and eighty eight surface soil samples were collected in grids at a 20 cm depth (Gordon *et al.*, 2004) using a garden trowel. It must be noted that this method is probably limited to characterizing the conditions typical for shallow rooted herbaceous plants or newly established woody seedlings. However, the pilot study in 2009 revealed that the study sites are dominated by herb species, hence this method was deemed suitable. The scoop samples in each quadrat were then combined into one sample per quadrat, bagged and stored until they could be processed in a laboratory. All fine-grained data analyses were done by a local analytical laboratory (BemLab (Pty) LTD, Strand) following standard procedures.

Clay, silt and sand percentages (10, 8, 3, 1 and 0 phi-units) were calculated using the hydrometer and wet-sieve method (van der Watt, 1966). The data were then entered into a spreadsheet and cumulative particle size distribution curves were computed for all the sampling plots (Gordon *et al.*, 2004).

Samples were also analysed for pH (using a pH meter), organic carbon, nitrogen and phosphorus. Organic matter and nitrogen percentages were determined using the Walkley-Black method (Nelson and Sommers, 1982) and a Leco FP528 nitrogen analyser (Horneck and Miller, 1998) respectively. Available phosphorus was measured following the Bray II method by ICP-OES (The Non Affiliated Soil Analysis Work Committee., 1990).

Similar parameters to those of the coarse sediment analysis were produced using Microsoft Excel and GRADISTAT V8 software (Blott and Pye, 2001; Blott, 2010). The software is available from the website: <http://www.kpal.co.uk/gradistat.html>. Both coarse and fine sediment variables were used in the vegetation analysis (Chapter 6).

5.3 Results

The following sections describe the results of the activities that were completed at the confined, semi-confined and unconfined study sites (Sections 5.2.1 to 5.2.4). Although the

analyses were done for all 13 study sites, only the results for sites 1, 2, 4, 6, 8 and 9 are shown here to facilitate presentation and for consistency with the selected study sites in Chapter 4. The remainder of the results are provided in appendices (Appendices 5.1 to 5.28).

5.3.1 Valley floor landforms

Confined study sites

The valley floor at the confined study sites is very narrow with widths ranging from 70-170 m. These sites are characterized by a single thread main channel with restricted lateral displacement and low to moderately high channel banks. The Baviaanskloof River at these sites followed an essentially straight course with the occasional slight bend. Channel widths varied mostly between 1-5 m with depths being deep to shallow. Riffle-run (site 2, Verlatenrivier) and pool-run-riffle (sites 6 and 7, Beacosnek) hydraulic biotopes were present. In addition, in-channel wood jams > 1 m high were observed at Beacosnek. Only site 11 (Baviaanskloof Nature Reserve) had a dry main channel bed. Flood benches (occasionally extensive) and/or poorly developed narrow floodplains were distinguishable at all sites (Figure 5.5, Table 5.4 and Appendix 5.2). Woody debris 0.1-3 m high accumulated on these geomorphic landforms. Flood benches and floodplains were usually located on one side of the active channel. A backwater area was only found at site 7. Although having a wider valley floor, only site 2 lacked narrow secondary channels. Bars occurred at lower elevations adjacent to the main channel. Lateral bars were only present at sites 2 and 11. Point and scroll bars were limited to site 2. Likewise, at this site a wider lower terrace abuts the southern valley margin. High narrow terraces were restricted to sites 2 and 6. Islands or mid-channel bars, tributaries and alluvial fans were absent. A notable exception with regards to fans was at site 2 (Figure 5.5, Table 5.4 and Appendix 5.2). The valley floor surfaces at these sites were generally not flat.

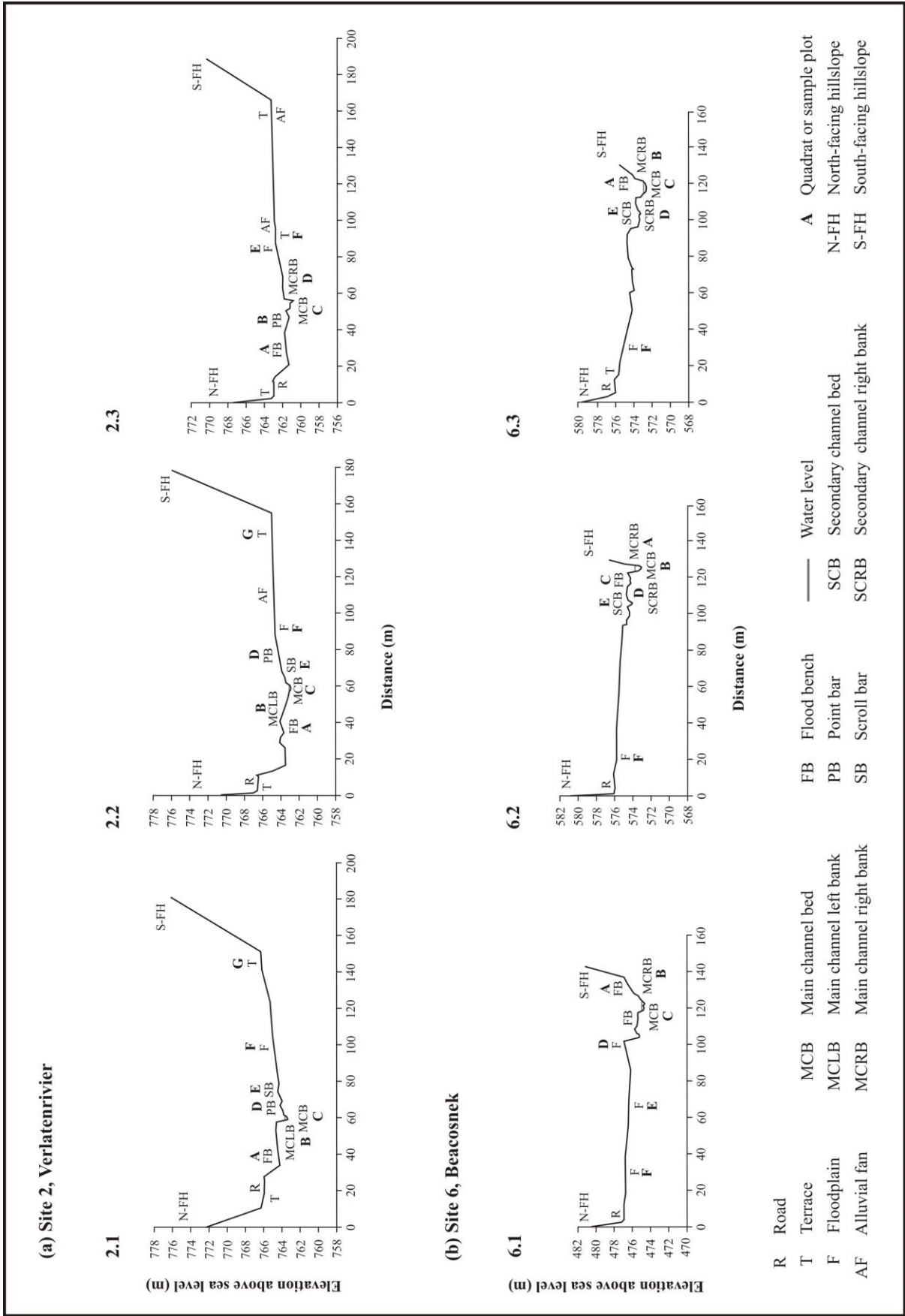


Figure 5.5: Valley floor cross-sections, geomorphic surfaces and quadrats, confined study sites 2 and 6.

Table 5.4: Geomorphic landforms or features recognised within the study sites and their associated number of quadrats.
Landform codes as per Table 5.1. Alluvial fan deposits were located on terraces or floodplains.

Site	T	F	AF	FB	MCB	BA	MCLB	MCRB	AE	PB	LB	M-CB	SB	I	SCB	SCLB	SCRB	TCB	TCLB	TCRB	Total (units)
2*	3	3	1	3	3		2	1	1	1	1		3								20 (9)
6	-	5		3	3			3							2		2				18 (6)
7		1		3	3	1	1	2							1	1					13 (8)
11	6			3	3		1	2			1				1	1					18 (8)
1+	2	6			5		3					1			3		3				23 (7)
3	-	3		2	3		2	1	1	1	1		2								15 (8)
8	-	6		3	3		2	1						1	3	2	1				22 (9)
12	3	5		3	3		2	1													17 (6)
4^	11	5		3	3		1	2				1		2	4	3	1				31 (10)
5	1	9	5		3		1	2	2						1		1	4	2	2	28 (11)
9	8	8	5	2	4		2	2	-		1			2	2	1	1	1	1		35 (11)
10	8	5	3	5	3		2	1			2			2	1	1					30 (10)
13	7			2	3		2	1							2		2				19 (7)
Total	25	75	19	32	42	1	21	19	3	1	6	2	5	7	18	8	10	5	3	3	289 (110)

Semi-confined study sites

The surveyed valley cross-sections revealed that the single thread Baviaanskloof River at the semi-confined sites was less constrained, adjusting laterally across the valley floor. Valley floor widths were between 134 and 272 m. The active channel was wider (4 to > 10 m) with low to very high and steep well-developed banks. Site 3 (Kasey) also contained artificial embankments (Figure 5.6 and Appendix 5.3). Surface flow occurred only at sites 8 (Zaaimanshoek) and 12 (Baviaanskloof Nature Reserve). The reach morphology at these two sites was pool-run-riffle. All the study reaches were slightly more sinuous than at the confined sites. Lateral and scroll bars were only common at site 3. A mid-channel bar and island were observed at sites 1 (Nuwekloof) and 8 respectively (Figure 5.6, Table 5.4 and Appendix 5.3). Other geomorphic landforms along these semi-confined reaches included flood benches (except at site 1), floodplains and terraces. Broader floodplain surfaces were marked with numerous narrow former channels. Woody debris (0.1-3 m high) accumulated instream (site 1) as well as on flood benches and floodplains (all sites). Narrow high terraces were restricted to sites 1 and 8 while site 12 had a wider lower terrace. All the study sites lacked alluvial fans and tributaries (Figure 5.6, Table 5.4 and Appendix 5.3). The valley floor surfaces at sites 1 and 12 were relatively flat and open.

Unconfined study sites

A notable feature of the Baviaanskloof River in the unconfined valley setting was that although the river was adjusting laterally on the extensive continuous floodplain, it was constrained either by alluvial fans (site 4) or both broad terraces and fans (sites 5, 9 and 10) acting as secondary controls. Multiple terraces (i.e. 2-4 levels from low to high elevations) were observed at sites 9 and 10. These confining landforms were absent at site 13 (Baviaanskloof Nature Reserve) where the Baviaanskloof River was actually incised into a bigger macro-channel. Valley floor widths ranged from 205-2050 m. The main channel width was >10 m at all but one site (site 13). Here, the wetted channel width was between 2-10 m while pool and riffle hydraulic biotopes were observed, and channel depth was variable. The Baviaanskloof River at the remainder of the unconfined study sites lacked surface flow. At most sites the main channel banks were generally well developed and high (Figure 5.7 and Appendix 5.4). Higher channel sinuities (i.e. meanders) were also maintained over longer reaches. Furthermore, selected reaches at sites displayed a multi-channel pattern with a large number of islands (sites 4, 9 and 10). A mid-channel bar was restricted to site 4 (Verlorenrivier). Lateral bars were common only at sites 9 (Rus en Vrede) and 10 (Zandvlakte). Flood benches and narrow secondary channels were present at all sites except site 9. Tributaries and artificial embankments were also noted at sites 5 (Uitslag) and 9 (Figure 5.7, Table 5.4 and Appendix 5.4). Flood debris ≤ 2 m high occurred on bars, flood benches and floodplains at all the study sites. The valley floor surfaces at sites 4 and 5 were fairly flat and open.

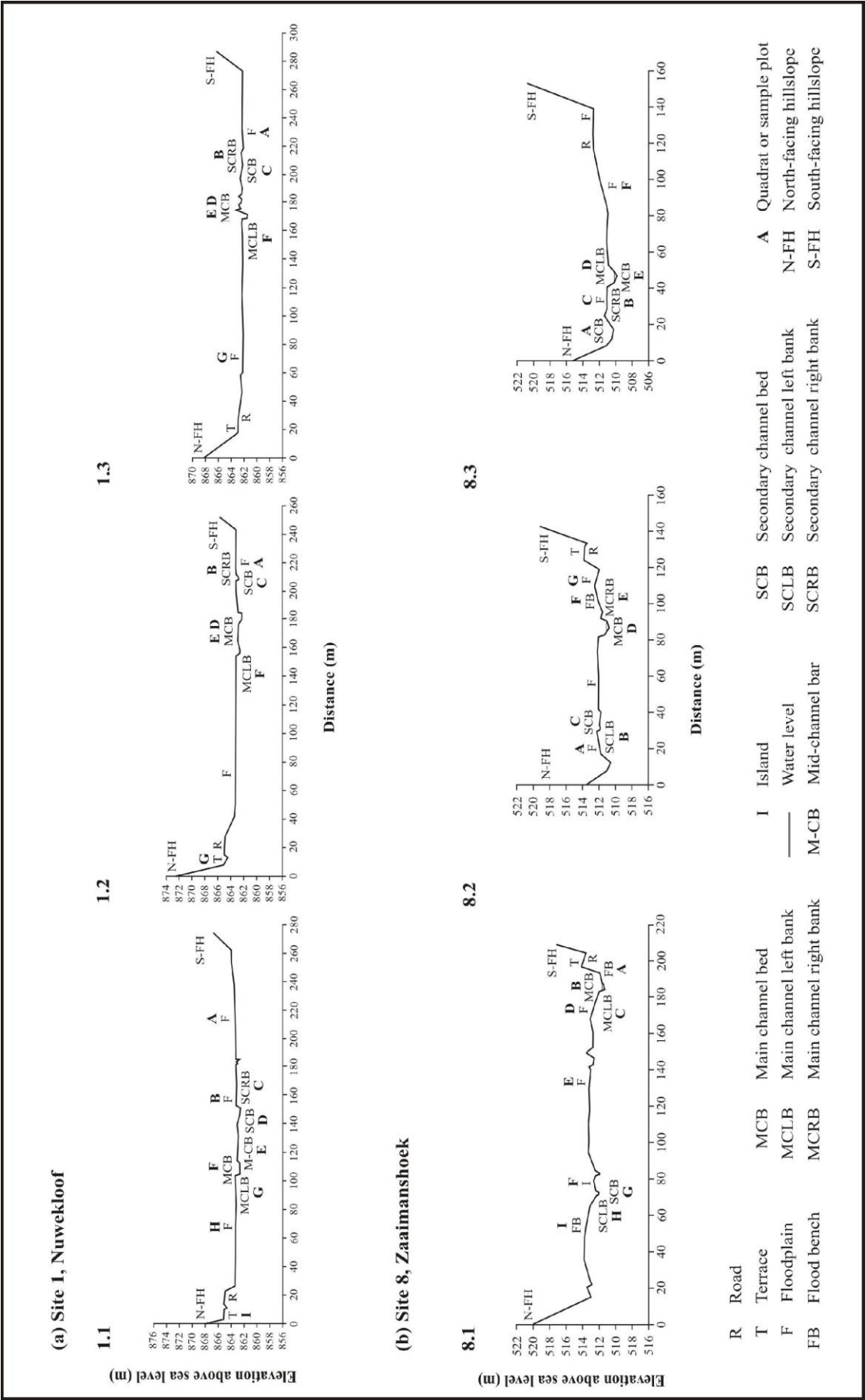


Figure 5.6: Valley floor cross-sections, geomorphic surfaces and quadrats, semi-confined study sites 1 and 8.

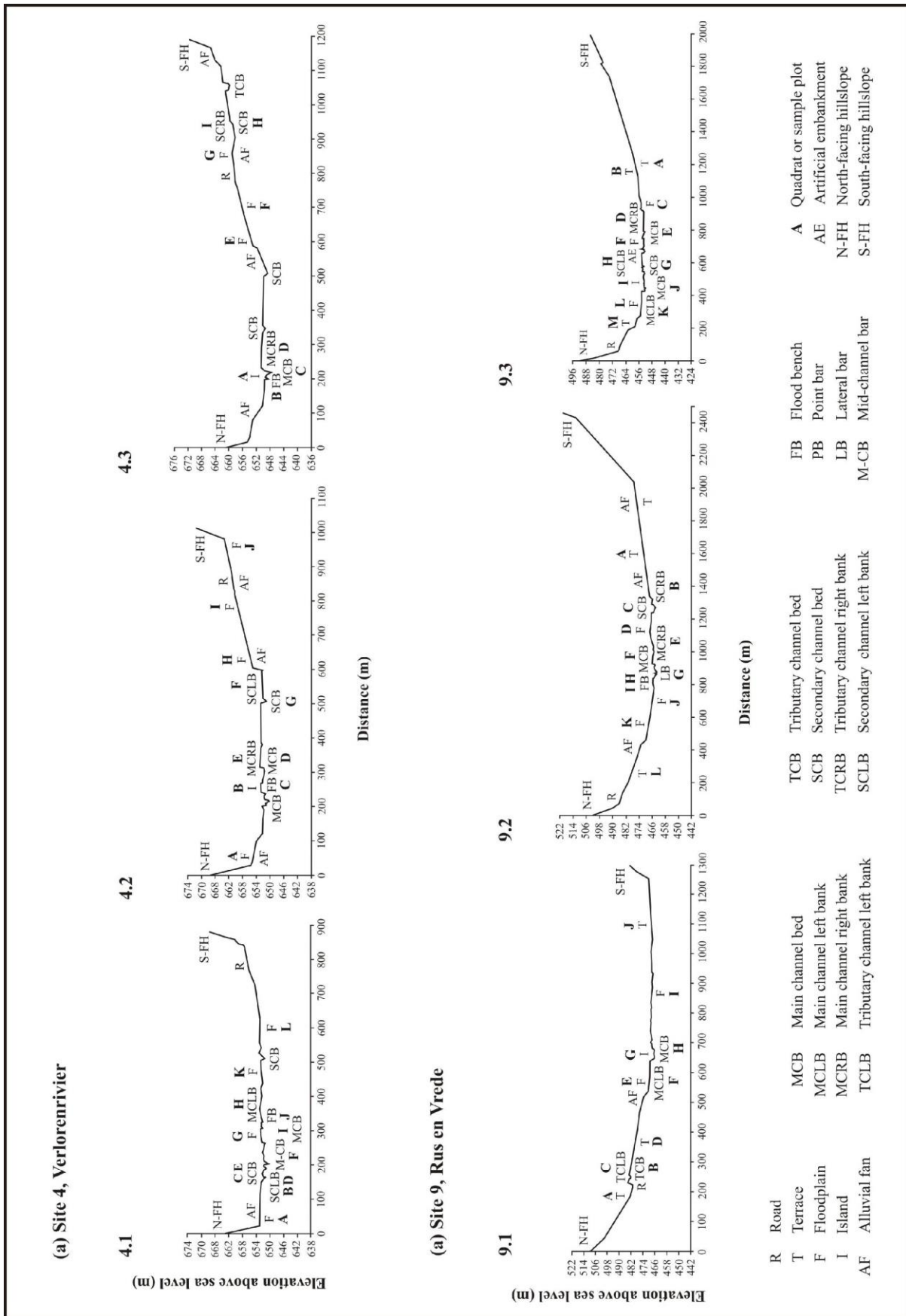


Figure 5.7: Valley floor cross-sections, geomorphic surfaces and quadrats, unconfined study sites 4 and 9..

5.3.2 Surface-groundwater interactions and vegetation relations

Electrical resistivity survey

Confined study site

The three 64 m long inverted resistivity profiles for site 2 (Verlatenrivier) are presented in Figure 5.8. This confined study site with its wetted main channel (Figure 2.16) was located in the upper catchment (Figure 5.2). A well water table depth measurement was available for this site (Table 5.2).

Profile 1 showed a lower resistivity upper layer, underlain by a higher resistivity layer which in turn was underlain by another lower resistivity layer (Figure 5.8). The resistivity section can be interpreted as follows. The lower resistivity upper layer is either a salinized dry soil layer which was a product of past farming activities (i.e. irrigation and fertilisation) at the study site, or the soil layer had a higher water content due to, for example, recent rains. The middle higher resistivity layer was the dry sand while the lower resistivity bottom layer represented the water-saturated sand horizon. A resistivity of 1250 ohm.m indicated a water table depth of between 2.5-5 m below the surface (Table 5.5). This was considered acceptable based on the distance of profile 1 from the well (wind pump) and the Baviaanskloof River (Tables 5.2). Profile 2 displayed a high resistivity upper layer underlain by a lower resistivity layer (Figure 5.8). This would correspond to the dry upper sand and underlying saturated sand. Based on this, the water level is inferred to be around 2-2.5 m below surface as shown by the dotted line on the resistivity profile. This matched very well with the water level of 1.95 mbd measured at the well along cross-section 2.1 (Table 5.2). Profile 2 was located closest to the well, hence this resistivity value (1250 ohm.m) should reflect the actual water table depth at site 2 (Table 5.5). At profile 3 an intermediate resistivity upper layer with a lower resistivity underlying it was shown (Figure 5.8). The intermediate resistivity upper layer was most likely a slightly moist sandy layer. This was possible due to the proximity of the main channel. The interpreted groundwater depth was about 0.5-2 mbd (Table 5.5).

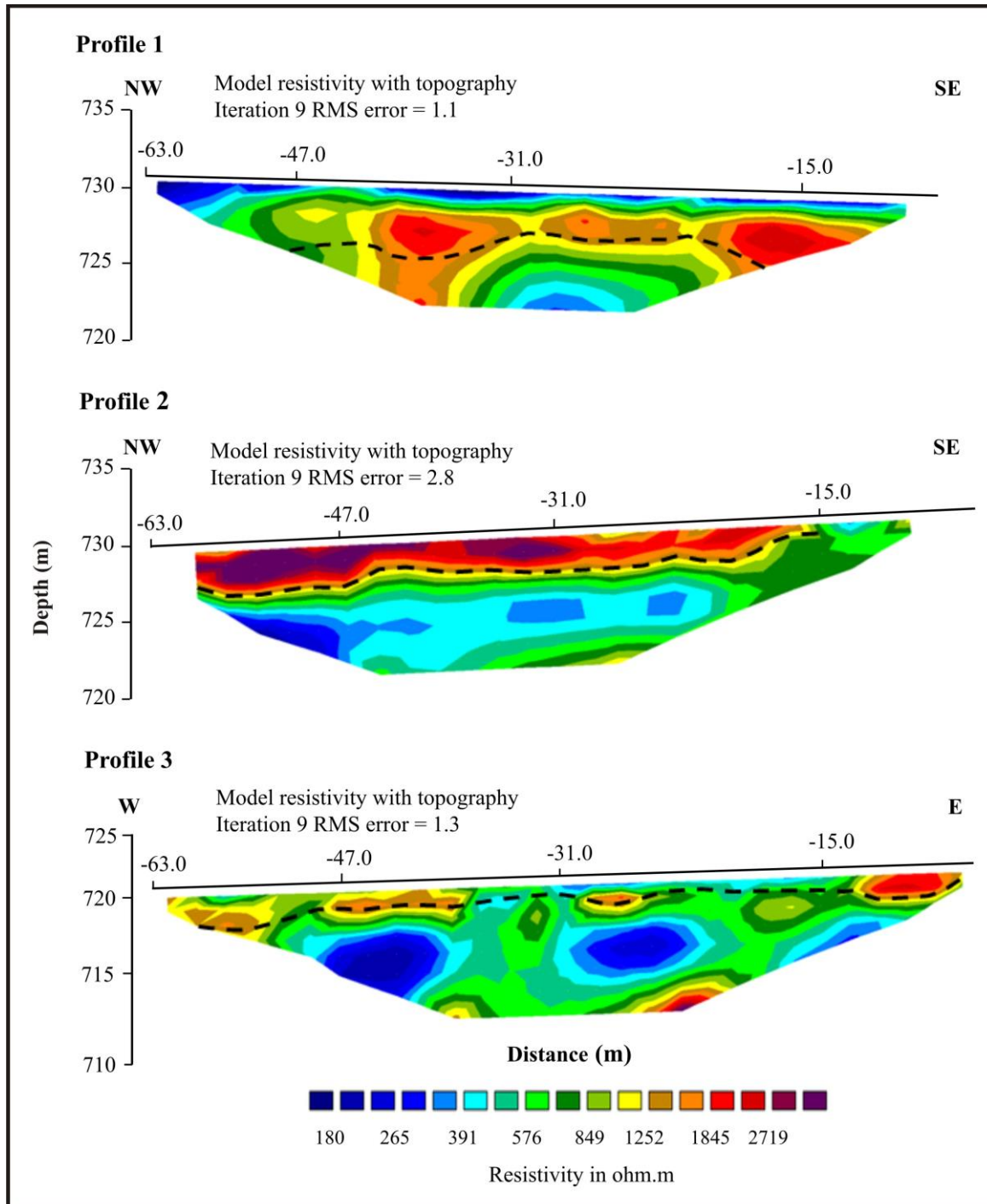


Figure 5.8: Electrical resistivity profiles, confined study site 2. Modified from Soltau *et al.* (2011). Profile locations as per Table 5.2.

The dotted line indicated the inferred water table depth below the surface at a resistivity value of about 1250 ohm.m.

Table 5.5: Groundwater table depth summary statistics. mbd = meters below datum (i.e. the ground level).

Profile and well or pit information as per Table 5.2.

Study site	Profile no.	Measured pit or well water table depth (mbd)	Resistivity water table depth (mbd)	Resistivity (ohm.m)
Confined 2, Verlatenrivier	1	1.95	2.5-5	1250
	2		2-2.5	1250
	3		0.5-2	1250
Semi-confined 1, Nuwekloof	4	None	6-10	2500
	5		6-10	2500
	6		10	2500
12, Baviaanskloof Nature Reserve	7	4.7	2-4	500
	8		2-4	500
	9		5-10	500
Unconfined 4, Verlorenrivier 10, Zandvlakte	10	7.5	15	3000
	11		10-12	3000
	12	3.5	4-6	1200
	13		7-10	1200

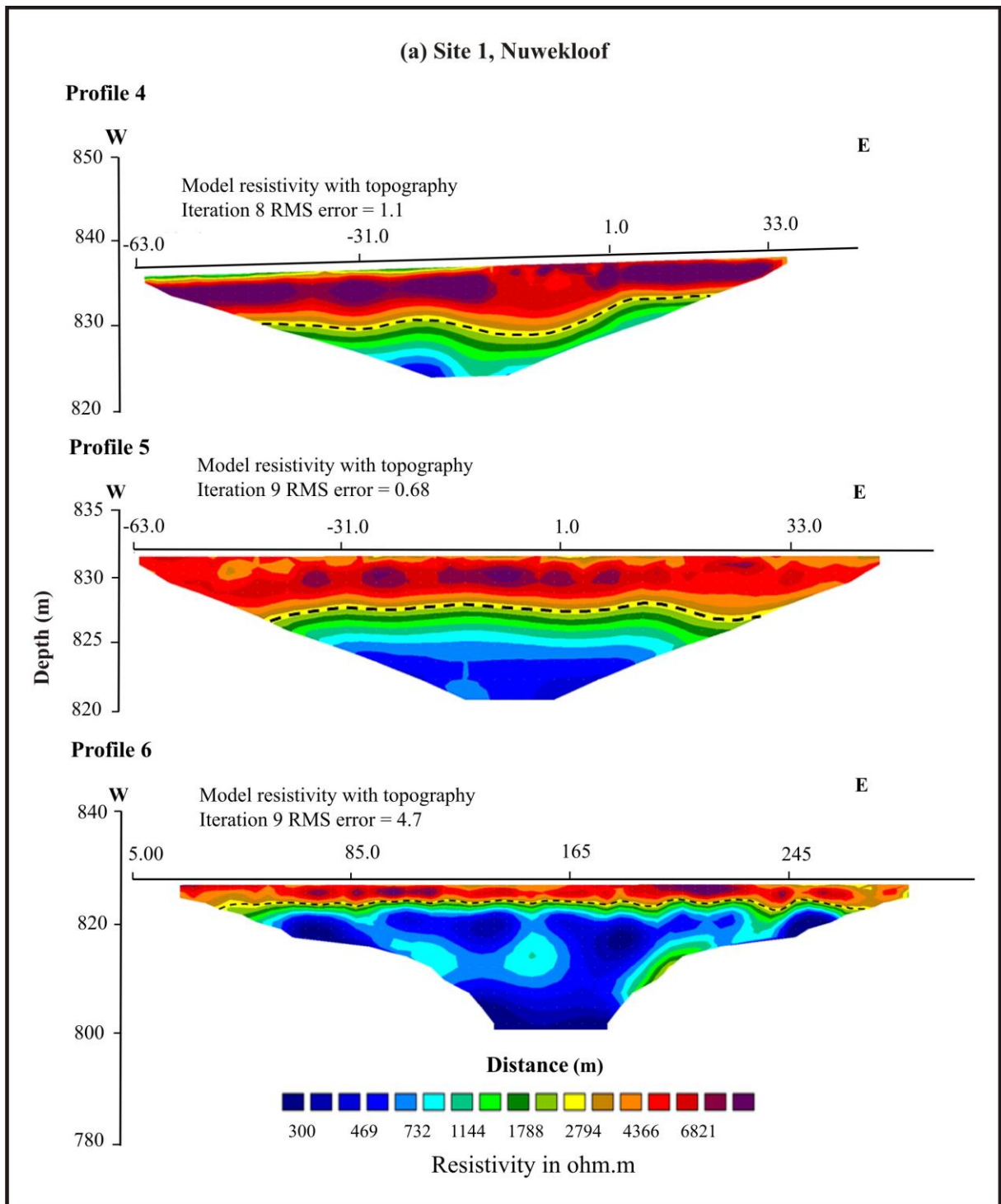
Semi-confined study sites

Figure 5.9 illustrates the inverted resistivity profiles for sites 1 (Nuwekloof) and 12 (Baviaanskloof Nature Reserve). Site 1, with its dry main bed channel (Figure 2.14), occurs in the upper catchment. In contrast, site 12, with its wetted main channel, occurs in the lower catchment (Figure 5.2). Measured water table depth information was only available for site 12 (Table 5.2).

At site 1 profiles 4 and 5 demonstrated a high resistivity layer underlain by a lower resistivity layer. In addition, profile 4 also displayed a shallow lower resistivity layer which seemed typical of similar lower resistivity layers in agricultural areas. The contact between the high and lower resistivity layers was the interpreted water table as indicated by the dotted black line on the profile (Figure 5.8). The water table depth varied between 6-10 mbd along profiles

4 and 5 at a resistivity contact of about 2500 ohm.m (Figure 5.9a and Table 5.5). Although there was no water level information available for this study site, the correlation across the two 128 m long profiles was still good. Profile 6, a longer 320 m resistivity profile, did not show the typical increase in resistivity associated with bedrock. This implied that the bedrock depth was deeper, > 28 m. The contact for the water table as depicted on the profile was around 10 mbd (Figure 5.9a).

At site 12, the inverted resistivity profiles 7 and 8 revealed a high resistivity layer underlain by a lower resistivity layer. The contact between these two layers was the groundwater depth which varied between 2-4 mbd along these profiles at a resistivity of about 500 ohm.m (Figure 5.9b and Table 5.5). This was shallower than the 4.7 mbd water level measured in the pit above cross-section 12.1 (Table 5.2). However, the pit appeared to be at a higher surface elevation than the two 64 m long resistivity profiles. The purpose of the longer resistivity profile 9 was an attempt to delineate the depth to bedrock. The contact for the water table as shown on the profile was around 5-10 mbd (Figure 5.9b). The resolution was much coarser because of the greater spacing between electrodes. However, this depth estimate was considered accurate. Generally, bedrock is indicated by an increase in resistivity at depth. The depth along the profile at the western corner showed an increase in resistivity with depth. This was in all likelihood the bedrock contact. The contact was estimated at a resistivity of about 1200 ohm.m. However, this can only be confirmed with actual drilling data (groundtruthing). The bedrock contact as delineated by the purple line occurred at a depth of between 20-35 mbd. The eastern corner depth showed a significant decrease in resistivity values. This was most likely a fracture zone, although it could also have been related to an increase in salinity or clay content. It was not related to bedrock (Figure 5.9b).



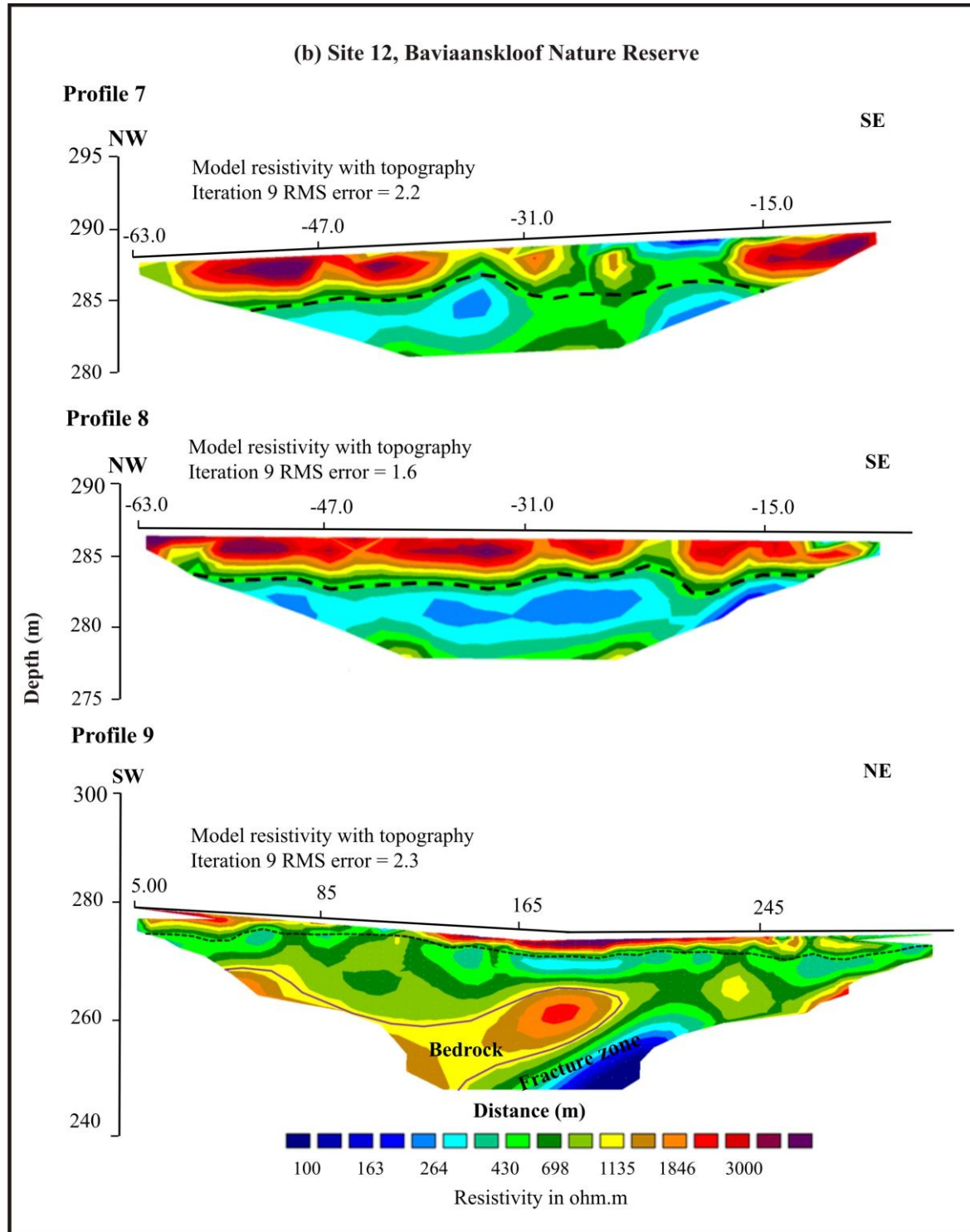


Figure 5.9: Electrical resistivity profiles, semi-confined study sites 1 (a) and 12 (b).

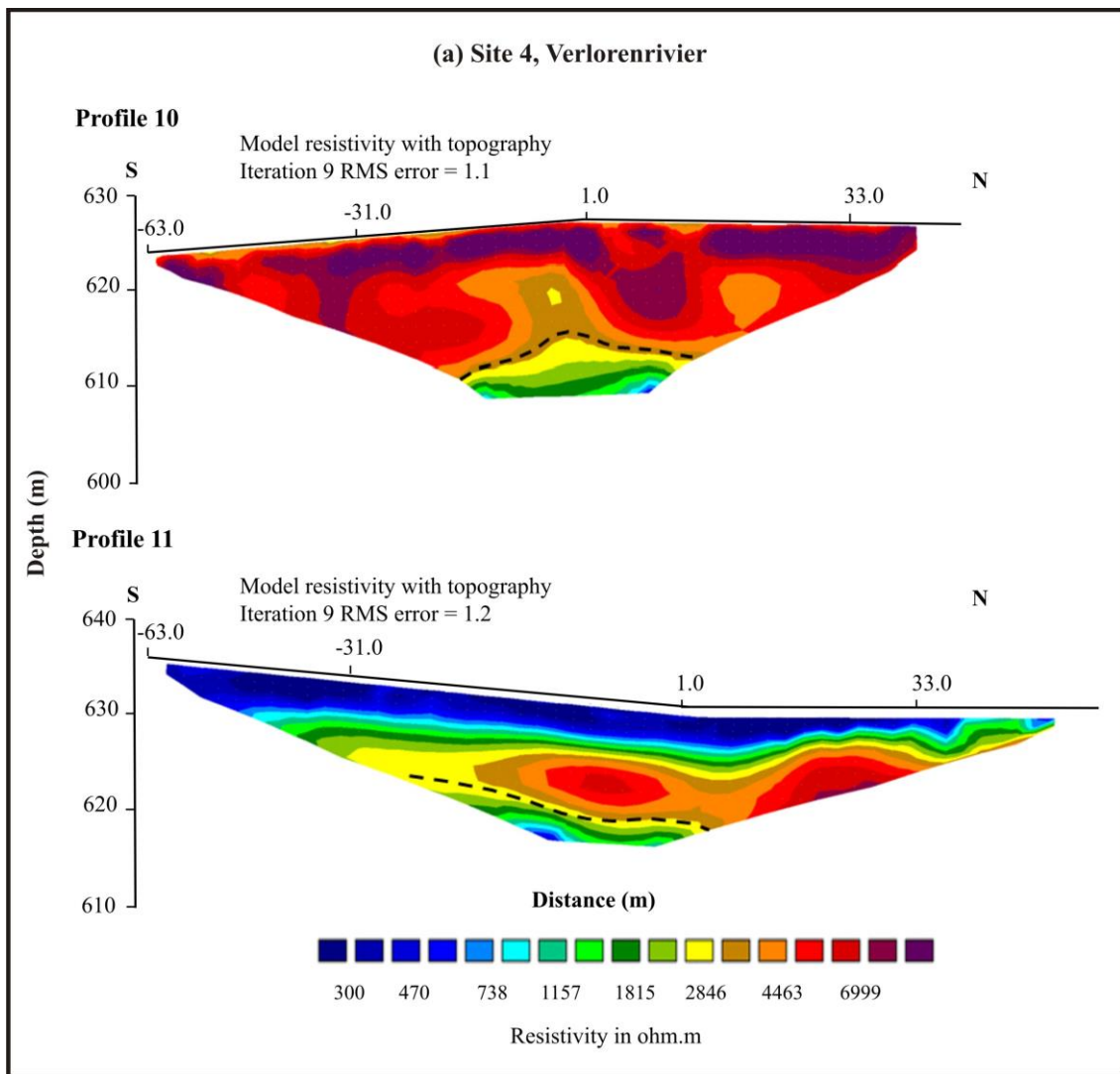
Modified from Soltau *et al.* (2011). Profile locations as per Table 5.2. The dotted line indicated the inferred water table depth below the surface at resistivity values of about 2500 and 500 ohm.m for site 1 and site 12 respectively. The purple line indicated the depth to bedrock.

Unconfined study sites

The inverted resistivity profiles for site 4 (Verlorenrivier) and site 10 (Zandvlakte) are presented in Figure 5.10. Both unconfined study sites lacked surface water at the Baviaanskloof River (Figure 2.16). Site 1 was situated in the upper catchment while site 10 was situated in the lower catchment (Figure 5.2). Measured water table depth information was available for both sites (Table 5.2).

At site 4, profile 10 showed a very high resistivity underlain by a lower resistivity. This very high resistivity was associated with dry gravels and boulders. The lower resistivity layer was associated with a saturated sand-gravel layer. The contact between these layers was the water table as indicated by the dotted line on the profile. The water table was deeper than at confined and semi-confined sites, up to 15 mbd (Figure 5.10a). This is significantly deeper than the measured water level (7.5 mbd) in the pit above cross-section 4.1 at site 4 (Table 5.2). The resistivity contact was approximately 3000 ohm.m. This is quite high, but can be linked to the coarse nature of the sediments at the study site (very high porosity). Profile 11 indicated a low resistivity underlain by a higher resistivity which in turn was underlain by an intermediate resistivity. The low resistivity at shallow depth can be related with either salinization of the soil profile due to fertilisation or more moisture in the soil due to recent irrigation. This was underlain by dry sand-gravel sediments and then a saturated sand-gravel layer. The interpreted depth to the water table was about 10-12 mbd. There was a good correlation between the water table depth values along the two 128 m long resistivity profiles at site 4 (Figure 5.10a and Table 5.5).

At site 10 profile 12 displayed a very high resistivity underlain by a lower resistivity. Similar to profile 10, the very high resistivity was typically associated with a dry gravel-boulder unit while the lower resistivity layer was saturated sand-gravel. The contact between these was the water table. The water table depth varied between 4-6 mbd along this profile at a resistivity contact of roughly 1200 ohm.m (Figure 5.10b and Table 5.5). This correlated very well with the water level of 3.5 mbd measured in the pit at cross-section 9.3 at site 10 (Table 5.2). Profile 13 showed a lower resistivity layer underlain by a higher resistivity layer which in turn was underlain by a lower resistivity. Similar to profile 11, the lower resistivity at shallow depth can be linked to either salinization of the soil profile due to farming practices or higher soil moisture due to recent irrigation. This was underlain by dry sand and gravels which in turn were underlain by a saturated sand-gravel layer. The interpreted groundwater level was about 7-10 mbd. This was considerably deeper than along profile 12. This result was, however, acceptable because there was a substantial change in elevation between the two 128 m long profiles (Figure 5.10b and Table 5.5).



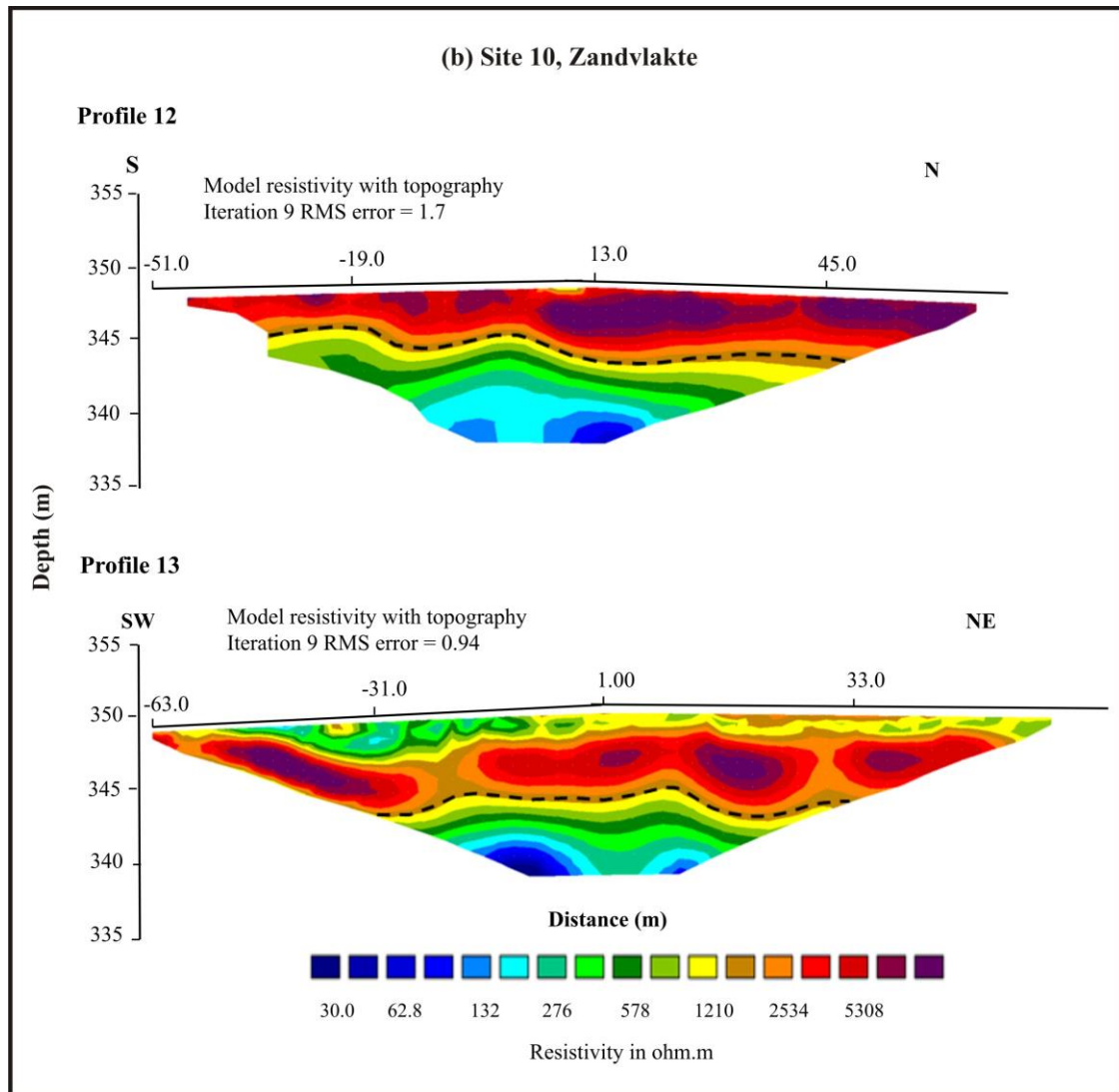


Figure 5.10: Electrical resistivity profiles, unconfined study sites 4 (a) and 10 (b).

Modified from Soltau *et al.* (2011). Profile locations as per Table 5.2. The dotted line indicated the inferred water table depth below the surface at resistivity values of about 3000 and 1200 ohm.m for site 4 and site 10 respectively.

Earth observation assessment

Resistivity profiles

In July 1991, high to very high NDVI values linked to dense vegetation, were only associated with semi-confined site 12 (Baviaanskloof Nature Reserve) profiles (Figure 5.11a). This was also accompanied by high greenness and low brightness values. Surface flow occurs at this semi-confined study site. The remainder of the study sites had mostly low NDVI, low greenness and high brightness values during the dry season. This indicated bare soil and sparse vegetation. These included semi-confined site 1 (Nuwekloof), confined site 2

(Verlatenrivier) and, unconfined sites 4 (Verlorenrivier) and 10 (Zandvlakte). It must be noted that site 1 had limited NDVI and TC point data. Information was only available for resistivity profile 3. Negative wetness index values were shown for all the study sites (Figure 5.11a). This represented low soil and plant moisture. The NDVI and TC transformation results were strongly correlated for the year 1991 as shown by the high R^2 values (Figure 5.12a).

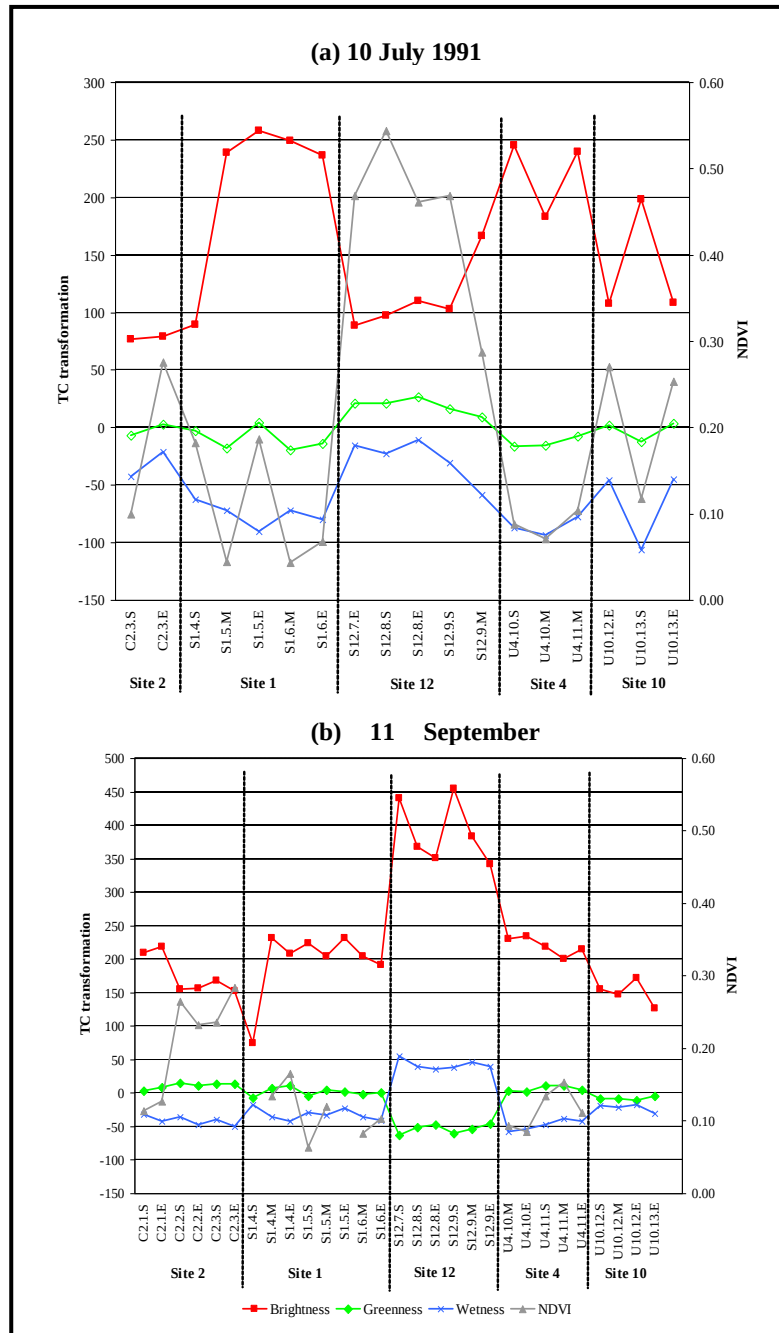


Figure 5.11: NDVI and TC transformation resistivity profile data during the dry periods.

Profile codes e.g. C2.1.S shows the confinement setting and site number plus the profile number and position. C = confined, S = semi-confined and U = unconfined. Profile positions: S = start, M = middle and E = end.

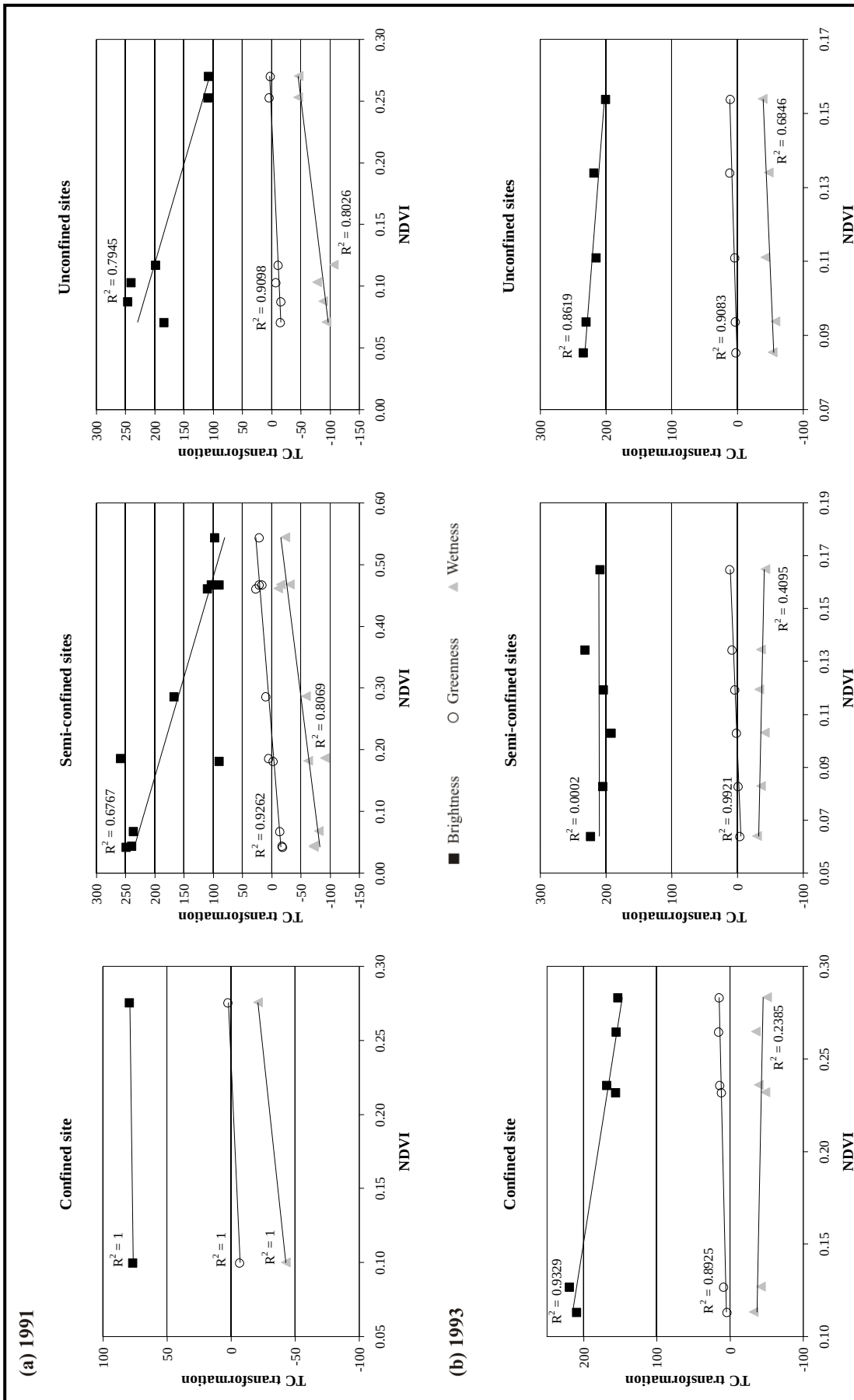


Figure 5.12: NDVI and TC transformation correlations per resistivity profile condition during the dry periods, Bavianskloof.

There were dry conditions weeks before the 1991 image acquisition date (Figure 5.13) with the cumulative rainfall being < 10 mm between March and July. This confirms the results of the SPI analysis in Section 3.3.1 (Table 3.9) which indicated that 1991 was a significant drought year. Similarly, there was no exceptional rainfall before the 2010 resistivity survey (Figure 5.13). This means the 1991 image displayed comparable conditions to the 2010 field campaign year.

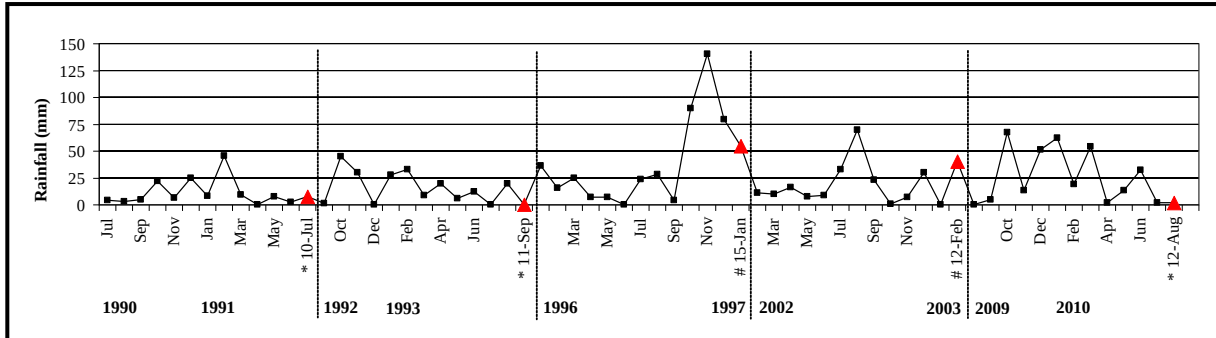


Figure 5.13: Monthly rainfall for the 12 months preceding the respective Landsat acquisition dates and resistivity survey.

* = Dry period image or survey and # = wet period image.

In general, the lower or deeper the water table, the sparser the vegetation. This indicates the ground water-dependency of the vegetation at these sites during the dry period. However, a comparison made between the 1991 water table depth, NDVI and TC transformation data showed a weak correlation between water table depth and the NDVI (Figure 5.14). The weak correlation of 0.46 demonstrates that some sites depend more on ground water availability than others. The shallower the water table depth, the wetter the soil, and the lower the brightness of the soil, the higher the greenness and the higher the wetness (Figure 5.14). From this comparative analysis it can be concluded that NDVI and TC transformation data can be used to determine vegetation and surface-groundwater relationships, with the wetness having the strongest correlation with an R^2 of 0.79.

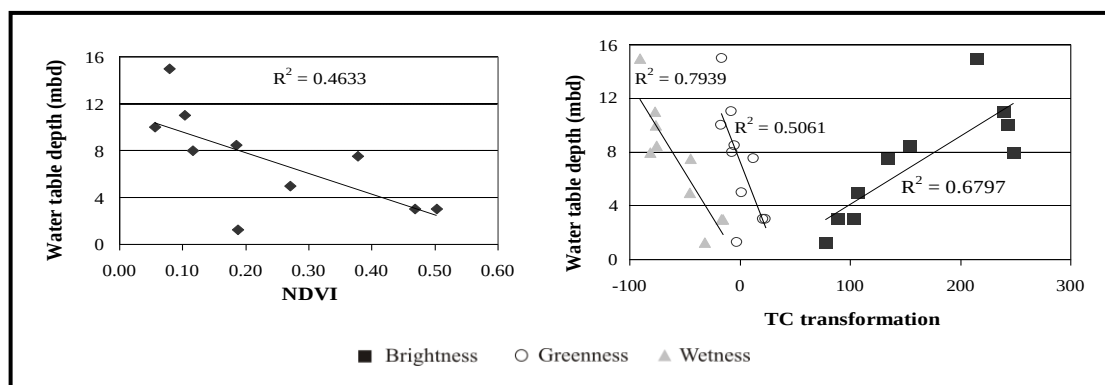


Figure 5.14: Relations between water table depth, NDVI and TC transformation data.

The data were obtained from the 2010 resistivity survey points and the corresponding 1991 Landsat pixels. mbd = meters below datum (i.e. the ground level).

The plots for the dry September 1993 TM scene revealed low NDVI values for the semi-confined and unconfined study sites (Figures 5.11b and 5.12b). This indicates areas covered by sparse vegetation. NDVI values for sites 10 and 12 were lacking, however, due to cloud presence on the satellite image date. Moderate NDVI values indicate some vegetative growth at site 2. Low greenness and wetness values were computed for all the sites, except for site 12. In contrast to 1991, site 12 profiles exhibited very low greenness and very high brightness values indicating barren areas and poor vegetative health. Brightness values were much lower for the remainder of the study sites. Positive wetness index values representing higher surface wetness were also associated with site 12 (Figure 5.11b).

The linear relations between NDVI and TC for sites 1, 2 and 4 are demonstrated in Figure 5.12b. As expected, very strong correlations were observed between the NDVI and the TC greenness index (all confinement setting profiles). Strong correlations between the NDVI and the TC brightness index were also revealed for confined (site 1) and unconfined (site 4) profiles. A strong correlation between the NDVI and the TC wetness index was only found at the unconfined (site 4) profiles. It is shown from Figure 5.13 that there was no exceptional rainfall before the 1993 dry period image. The rainfall was < 20 mm from March 1993.

Concerning the wet periods, high to very high NDVI values linked to lush, verdant vegetation were obtained for profiles at sites 2 (confined), 10 (unconfined) and 12 (semi-confined) in January 1997 (Figure 5.15a). This was also associated with high greenness and low brightness values. Sites 1 and 4 had mostly low to moderate NDVI and greenness values as well as high brightness values. This indicated a low vegetation signal and bare areas. The scatter diagrams in Figure 5.15a also showed negative wetness index values suggesting low soil and plant moisture for all the profile points.

Figure 5.16a displayed very strong correlations between the NDVI and the TC greenness index for all the study sites. The NDVI, the TC brightness index and the TC wetness index were also highly correlated for the unconfined sites. These indices had low correlations for the confined site. For the semi-confined sites they exhibited low to moderate correlations (Figure 5.16a). Figure 5.13 showed wet conditions weeks before the 1997 image acquisition date. Good rains were received from October 1996. The rainfall was > 70 mm per month. The SPI (Section 3.3.1, Figure 3.9) and historical (Section 3.3.4, Table 3.13) analyses also indicated extreme flooding in 1996. This contradicts some of the NDVI and TC transformation results (e.g. the negative wetness index values) shown in Figure 5.16a. Other explanatory variables were also clearly at play.

In February 2003 high to very high NDVI values related to healthy, dense vegetation was only found at site 12 (semi-confined) (Figure 5.15b). Moderate to high NDVI values were also linked to site 2 (confined). At both sites this was accompanied by high greenness and low brightness values. The rest of the study sites had mostly low NDVI, low greenness and high

brightness values. This indicated poorly vegetated areas. The scatter diagrams also showed negative wetness index values indicating low surface moisture for all the study sites (Figure 5.15b). These values were even lower than the 1991 and 1993 dry season values.

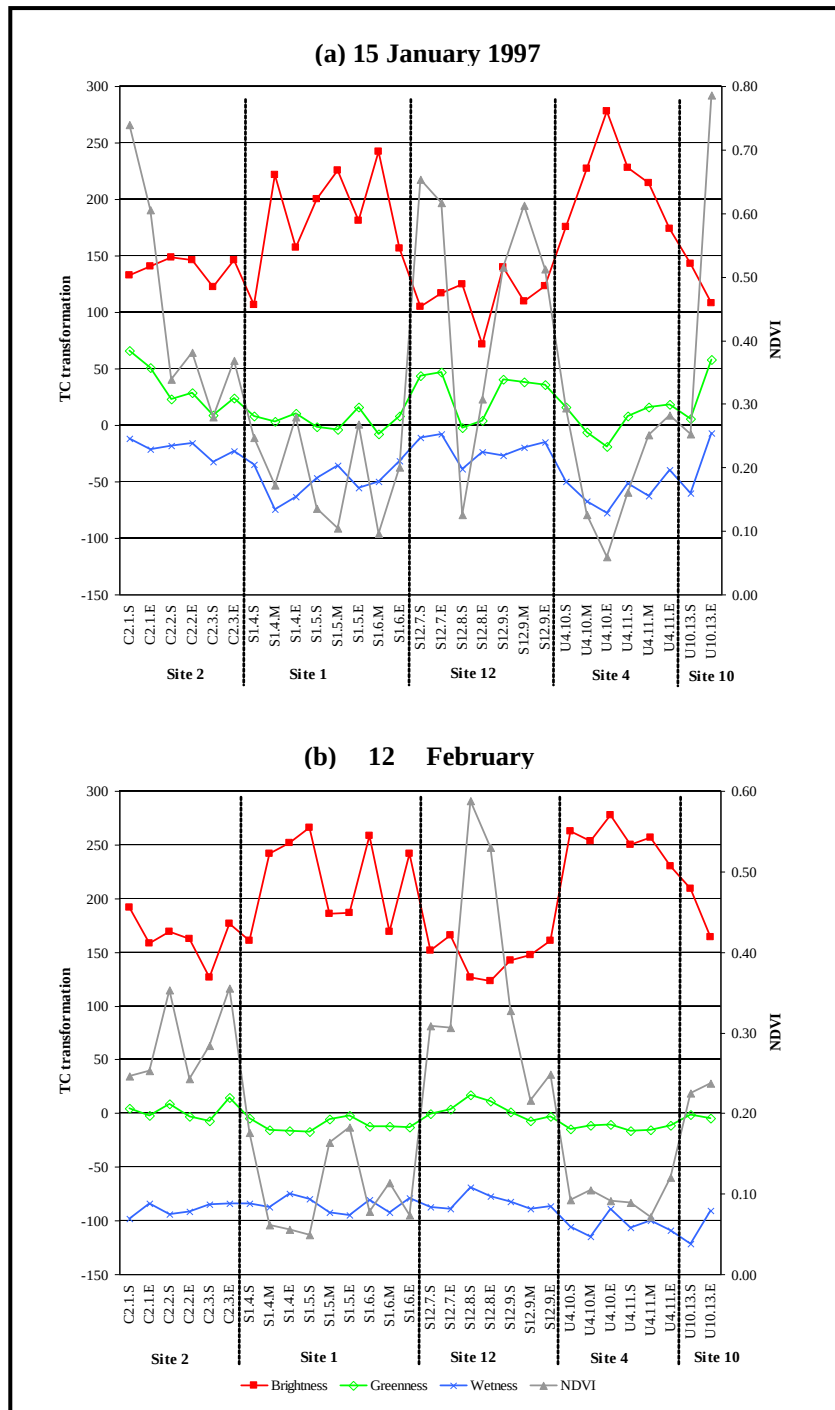


Figure 5.15: NDVI and TC transformation resistivity profile data during the wet periods.

Profile codes e.g. C2.1.S shows the confinement setting and site number plus the profile number and position. C = confined, S = semi-confined and U = unconfined. Profile positions: S = start, M = middle and E = end.

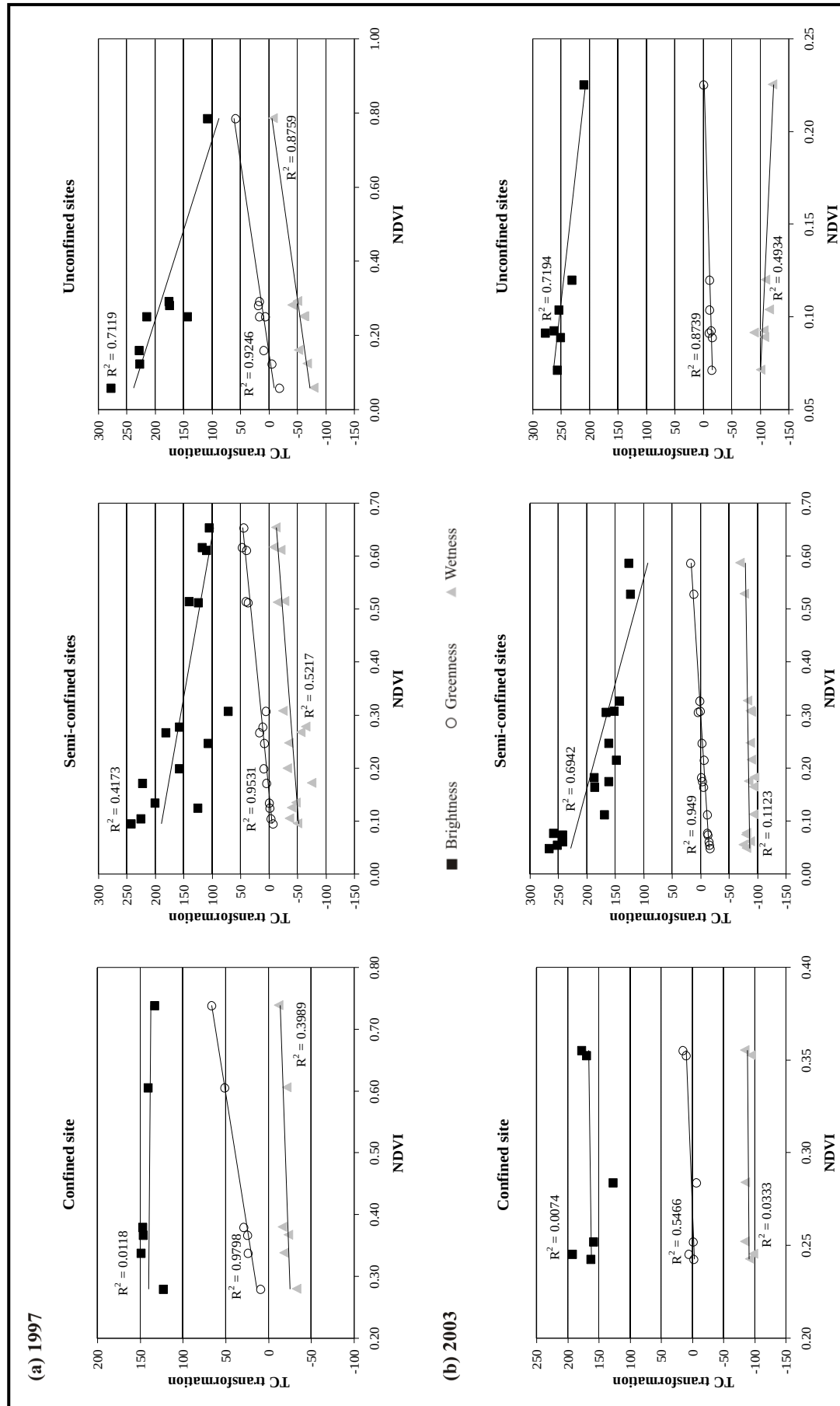


Figure 5.16: NDVI and TC transformation resistivity correlations per profile during the wet periods, Baviaansloof.

Similarly, the linear trend results demonstrated weak correlations between the NDVI and the TC wetness index (all sites) (Figure 5.16b). Moderate correlations were found between the NDVI and the TC brightness index at the semi-confined and unconfined sites. There was no linear correlation for the confined site. As expected, the TC greenness index correlated the strongest with the NDVI for all the study sites. Figure 5.13 illustrates that, except for August 2002, not much rain fell before the 2003 image acquisition date. This implies that the 2003 image actually represents dry season conditions.

Quadrats

Figure 5.17 shows that the 1991 and 1993 Landsat images and the 2010 resistivity survey (i.e. dry periods) did represent dry season conditions. Moreover, the 2003 image, which was selected to represent the wet season, also represented dry season conditions because of reduced rainfall (Figures 5.13 and 5.17). This contrasted with the 1997 Landsat image (a wet period), which actually did represent wet season conditions (Figure 5.17).

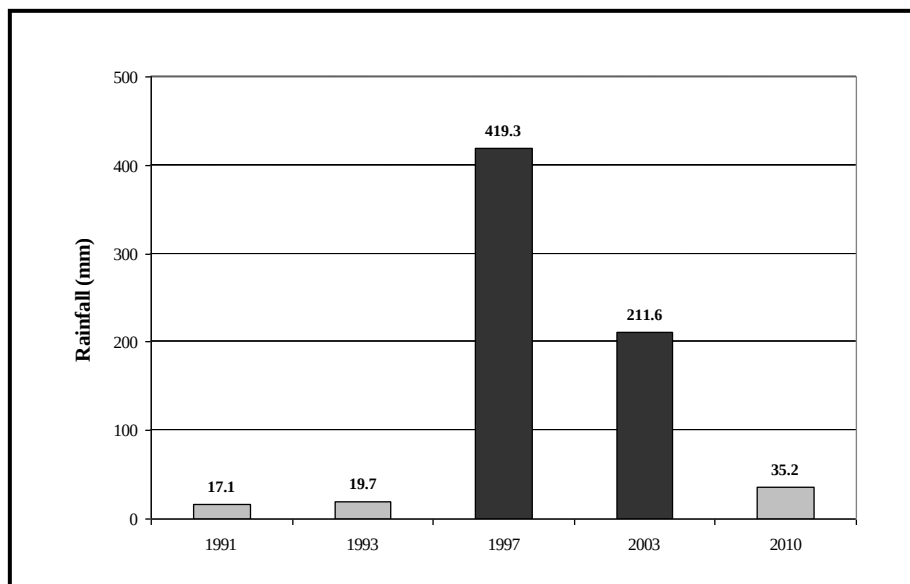


Figure 5.17: Rainfall totals summed since the last dry season.

The years 1991, 1993 and 1997 represent the respective Landsat image acquisition dates while the year 2010 represents the resistivity survey date. Grey bar = a dry period and black bar = a wet period.

When comparing the rainfall, the NDVI and TC transformation datasets separately for confined, semi- and unconfined sites in Figures 5.18 to 5.20 respectively, the following main trends are depicted. At the confined valley setting only site 6 quadrats featured very high NDVI values associated with dense vegetation for both dry and wet periods (Figure 5.18 and Appendices 5.7d and 5.8d). This was also accompanied by high greenness and low brightness

values for both periods. These TC bands were highly correlated with the rainfall dataset. A weak correlation existed between the NDVI and rainfall. This indicated that vegetation growth at site 6 with its permanent surface water (shallow water table) is independent from the rainfall. Similar NDVI and TC transformation results were also obtained for site 11 during the wet period (1997 and 2003). During this period moderate-high NDVI values indicating photosynthetically active vegetation were also observed at sites 2 and 7. This was associated with moderate-high greenness and low-moderate brightness values (Figure 5.18 and Appendix 5.5).

Sites 7 and 11 quadrats had low NDVI and greenness values demonstrating poor vegetation during the dry period (1991 and 1993). At site 7 a negative NDVI value in 1991 was related to an instream backwater area (Figure 5.18 Appendix 5.6). Brightness values were also low for site 7 but high for site 11. The latter indicate bare areas or rocks. Moreover, moderate NDVI, low-moderate greenness and moderate-high brightness values were computed for site 2. This site had both vegetated and bare areas. Positive wetness values implying areas with higher soil or plant moisture were only obtained for sites 7 (1991) and 11 (1993) (Figure 5.18 and Appendix 5.6). The linear trend analysis showed moderate correlations between the NDVI and rainfall for sites 7 and 11 and a strong correlation for site 2 (Figure 5.18). These correlations suggest that the vegetation growth at sites 7 and 11 is sometimes rainfall dependent while at site 2 it is mostly rainfall dependent. Conversely, at sites 2 and 7 the TC greenness index and rainfall correlated poorly while at site 11 this correlation was moderate. These correlations again suggest opposite rainfall dependency trends. In addition, very weak correlations were calculated between the TC brightness index and rainfall for sites 2, 7 and 11. The TC wetness index and rainfall correlation values were very weak for all the confined study sites (Figure 5.18), suggesting that the wetness had another source (other than rainfall), namely the groundwater.

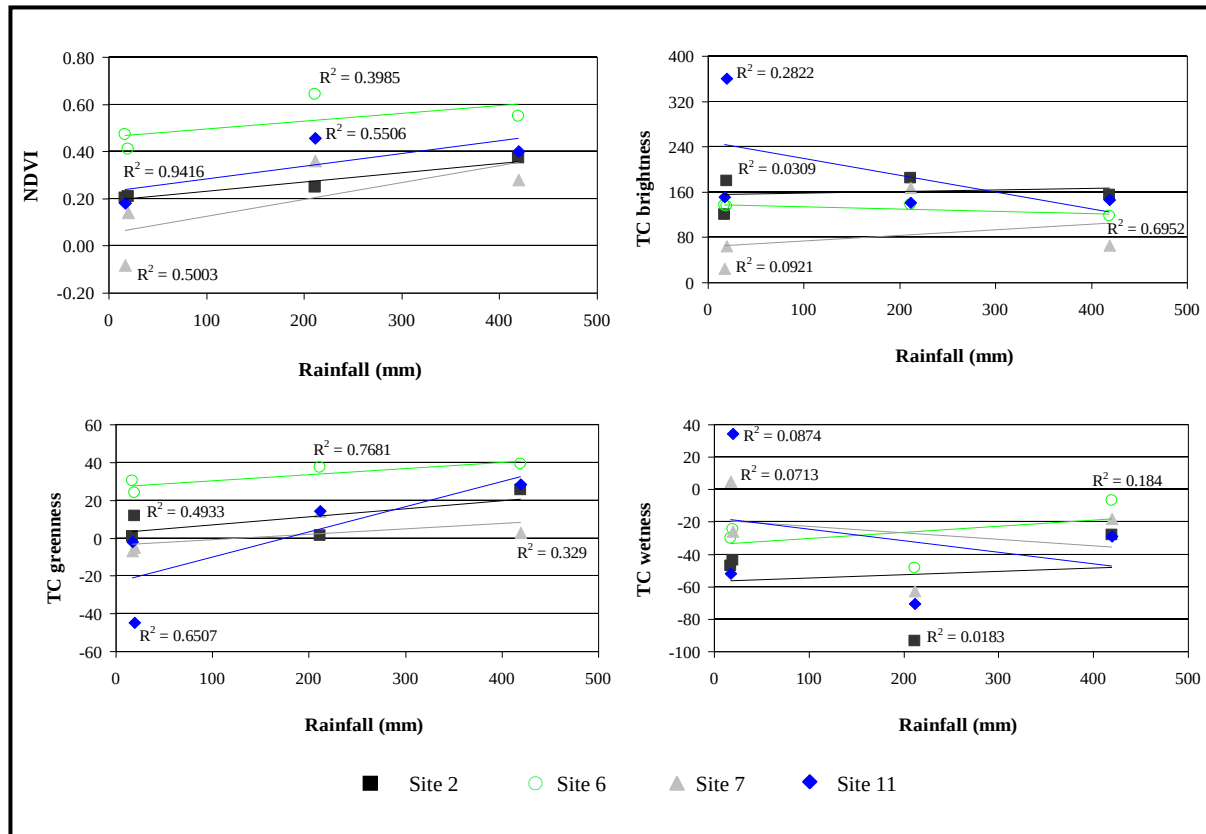


Figure 5.18: Relations between rainfall, the NDVI and TC transformation quadrat data at the confined study sites.

The figure illustrates NDVI and TC index values averaged from Appendices 5.5 and 5.6, and summarized rainfall values as per Figure 5.17.

At the semi-confined valley setting quadrats (Figure 5.19 and Appendices 5.5 and 5.6), high to very high NDVI values were obtained for all the years (site 8) and for the years 1991, 1997 and 2003 (site 12). This indicated vigorous plant growth. Unfortunately, excessive cloud coverage resulted in missing NDVI data in September 1993 for all the reserve study sites, including site 12. In addition, high greenness and low brightness values were obtained for sites 8 (all the years, Appendices 5.7f and 5.8f) and 12 (all the years except for 1993). Strangely, in 1993 very low greenness and very high brightness values were calculated for site 12 with its near-surface water table. These values usually indicate bare soils and poor vegetation growth which suggests that other factors (e.g. disturbance) were also involved. The NDVI and rainfall were very weakly correlated at sites 8 and 12 (Figure 5.19). Similar to the confined site 6, vegetation growth at these sites does not depend on rainfall in both dry and wet periods because of a shallow groundwater table linked to for example a sustained baseflow (i.e. a wetted main channel). Weak relations were calculated between the TC brightness index and rainfall for both sites. The TC greenness index and rainfall also correlated moderately at site 8 and poorly at site 12 (Figure 5.19). These correlations suggest that the vegetation growth at site 8 at times can be reliant on rainfall while at site 12 it is independent from the rainfall.

At sites 1 (Appendix 5.8g) and 3 quadrats, moderate NDVI values were only recorded in the year 1997, a wet period (Figure 5.19 and Appendices 5.6). This signalled partially vegetated areas. This was also accompanied by moderate greenness and brightness values. For the other years, low NDVI values suggested a lack of dense vegetation. The low greenness and high brightness values recorded for these years indicated open areas, too. The NDVI and rainfall were also highly correlated at both sites. This showed that sites 1 and 3, which both lacked permanent surface flow (i.e. a deeper groundwater table), were very reliant on rainfall. The TC brightness index and rainfall correlations were weak at site 1 and strong at site 3, respectively. The TC greenness index and rainfall on the other hand correlated poorly at both sites. A positive wetness value indicative of increased moisture was only recorded at site 12 (1993). The TC wetness index and rainfall correlation values were very weak for all the semi-confined study sites (Figure 5.19), suggesting low rainfall dependency. However, this only applies to study sites 8 and 12.

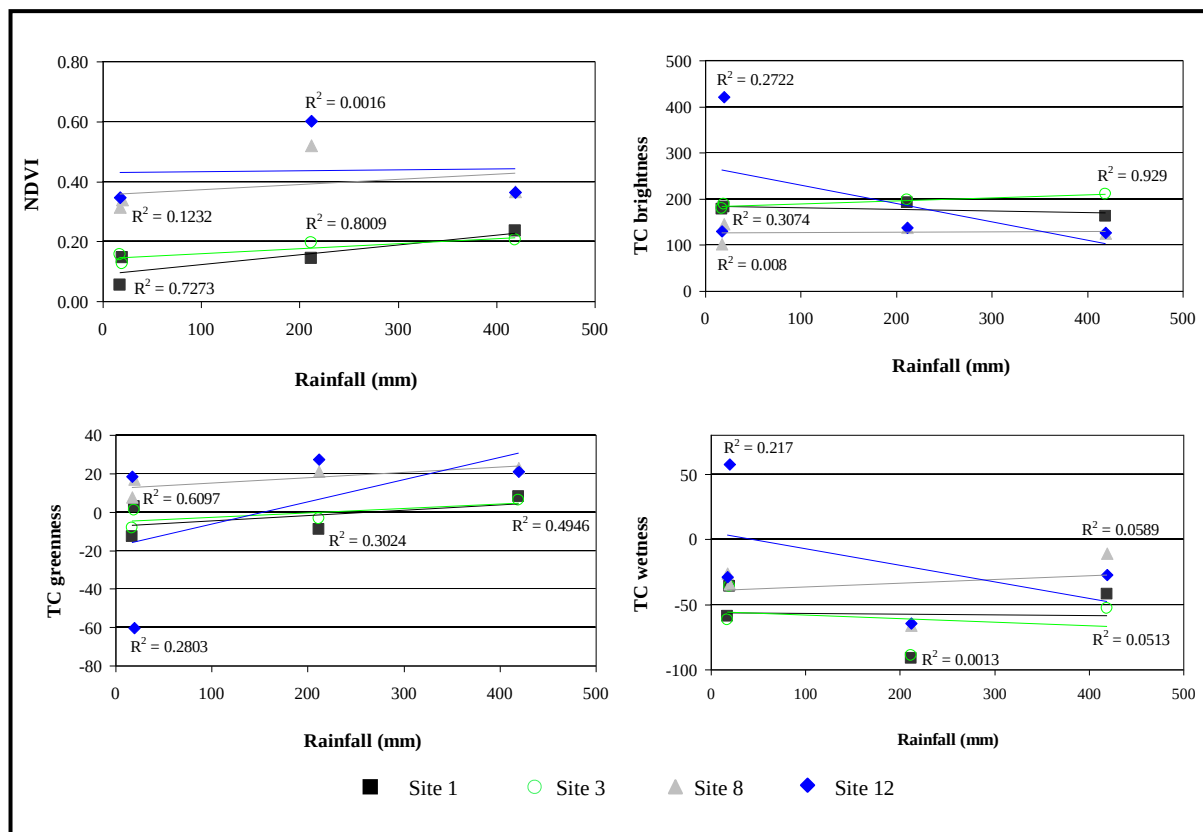


Figure 5.19: Relations between rainfall, the NDVI and TC transformation quadrat data at the semi-confined study sites.

The figure illustrates NDVI and TC index values averaged from Appendices 5.5 and 5.6, and summarized rainfall values as per Figure 5.17.

For the dry 1991 period and both wet periods the unconfined valley setting scatter diagrams displayed high to very high NDVI values associated with dense vegetation only at site 13

quadrats (Figure 5.20 and Appendices 5.5 and 5.6). This site actually had surface flow at the Baviaanskloof River, thus implying a groundwater influence. Similar results were also obtained for quadrats at sites 9 (Appendix 5.8l) and 10 in 1997. Moderate NDVI values were computed for the years 1991 (site 10), 1997 (sites 4 and 5) and 2003 (sites 9 and 10). Low NDVI values indicative of sparse vegetation were limited to the dry period (sites 4, 5, 9 and 10). Low (1993), moderate (1991 and 2003) and high (1997) greenness values were recorded at site 13. Very high brightness values demonstrating barren areas were also computed in 1993 for this site. The remaining years for site 13 all had low brightness values. Moderate (sites 4 and 5) and high (sites 9 and 10) greenness values were obtained in 1997. The rest of the years all had low greenness values for sites 4, 5, 9 and 10. This indicated poorly vegetated areas (Figure 5.20).

Figure 5.20 displayed moderate (1997) and high (1991, 1993 and 2003) brightness values for sites 4 and 5. It also showed low to moderate brightness values for sites 9 and 10. A positive wetness value representing high vegetation or soil moisture was only obtained for site 13 (1993). The linear trend analysis showed strong correlations between the NDVI and rainfall for all the study sites. These high values indicate that these sites are rainfall dependent. This was expected. However, the analysis also showed very weak correlations between the TC brightness and wetness indices and rainfall for all the study sites. This again suggests that these indices operate independently from rainfall at these sites. Low (sites 4 and 5), moderate (site 13) and high (sites 9 and 10) correlations were associated with the TC greenness index and rainfall. The TC results mostly contradict the NDVI results (Figure 5.20) indicating that other variables also influenced the outputs.

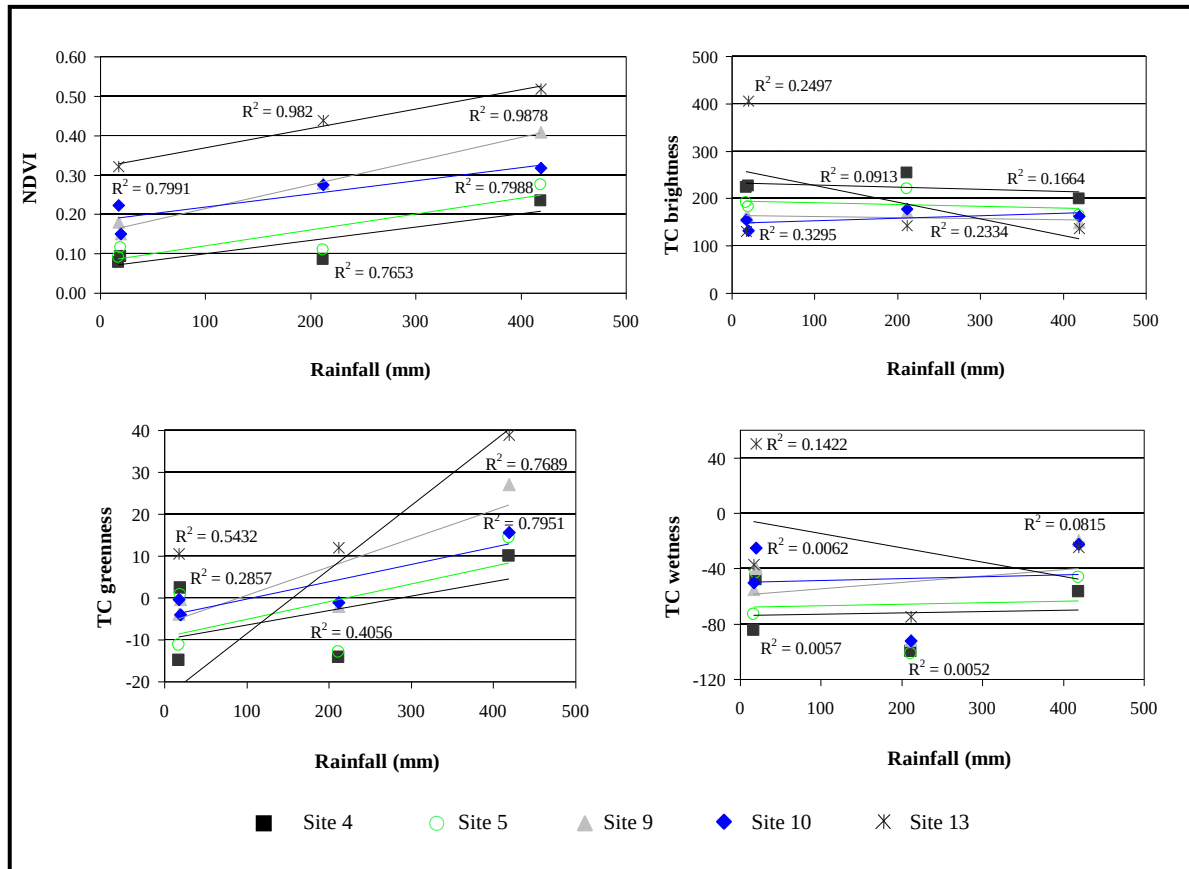


Figure 5.20: Relations between rainfall, the NDVI and TC transformation quadrat data at the unconfined study sites.

The figure illustrates NDVI and TC index values averaged from Appendices 5.5 and 5.6, and summarized rainfall values as per Figure 5.17.

5.3.3 Grain size distribution and soil chemistry

Confined study sites

The pebble count percentage data demonstrated that the dominant grain size across the differing geomorphic landforms (69 quadrats) at the four sites was gravel (Figure 5.21 and Appendix 5.9). Gravel sized material (largely fine-medium) accounted for > 50% of deposits in 54 quadrats (78%). Only six quadrats (9%) contained > 50% of cobble (largely small) or boulder grain size fractions. These coarser-grained sediments formed part of the active (sites 2 and 6) or secondary channel (site 2) banks, a flood bench (site 2) and floodplains (sites 2 and 11). Quadrat 7.3.D, representing a floodplain, held equal amounts of gravels, cobbles and boulders (Appendix 5.9). The above mentioned results were reflected in the grain size percentile and mean values in Appendix 5.11.

The geomorphic unit sorting values for the most part ranged from 1.64 to 3.68, indicating moderately to poorly-sorted material. The skewness values ranged predominately from -0.09

to 0.27, signifying grain sizes that are nearly symmetrical to skewed towards coarse sediments (Appendix 5.11). Table 5.6 showed that the mean grain sizes for most of the landforms were in the medium to very coarse gravel size category with no significant variation in particle distribution. Downstream fining and coarsening trends were, however, observed for the floodplains (all sites), main channel left banks (sites 2 and 11) and benches (sites 7 and 11). The mean grain size changed from cobbles at the upstream extent of the reach to gravel at the downstream extent and vice versa (Table 5.6). Table 5.7a shows similar results to those of Table 5.6, with most landforms having very similar size distributions, except for the declining and increasing downstream grain size trends experienced for the three afore-mentioned landforms.

The visual estimation analysis indicated the elevation and position relative to the thalweg of differing geomorphic surfaces (Figure 5.22 and Appendix 5.12). It demonstrated that the instream or stream side deposits were significantly coarser. The main or secondary bed and banks and bars were characterised by gravels, fines, cobbles and boulders. Flood benches, floodplains and terraces were all mostly finer grained (mixed fines and gravels) with occasional cobbles and boulders occurring. Fines (size < 2 mm) accounted for > 50% of deposits in 50 quadrats (74%) with the gravel size category in just six quadrats (9%). Eight quadrats (12%) consisted only of fine material. These represented a main channel bank (site 7), flood benches (sites 2, 6 and 7) and floodplain surfaces (sites 6, 7 and 11) (Figure 5.22 and Appendix 5.12).

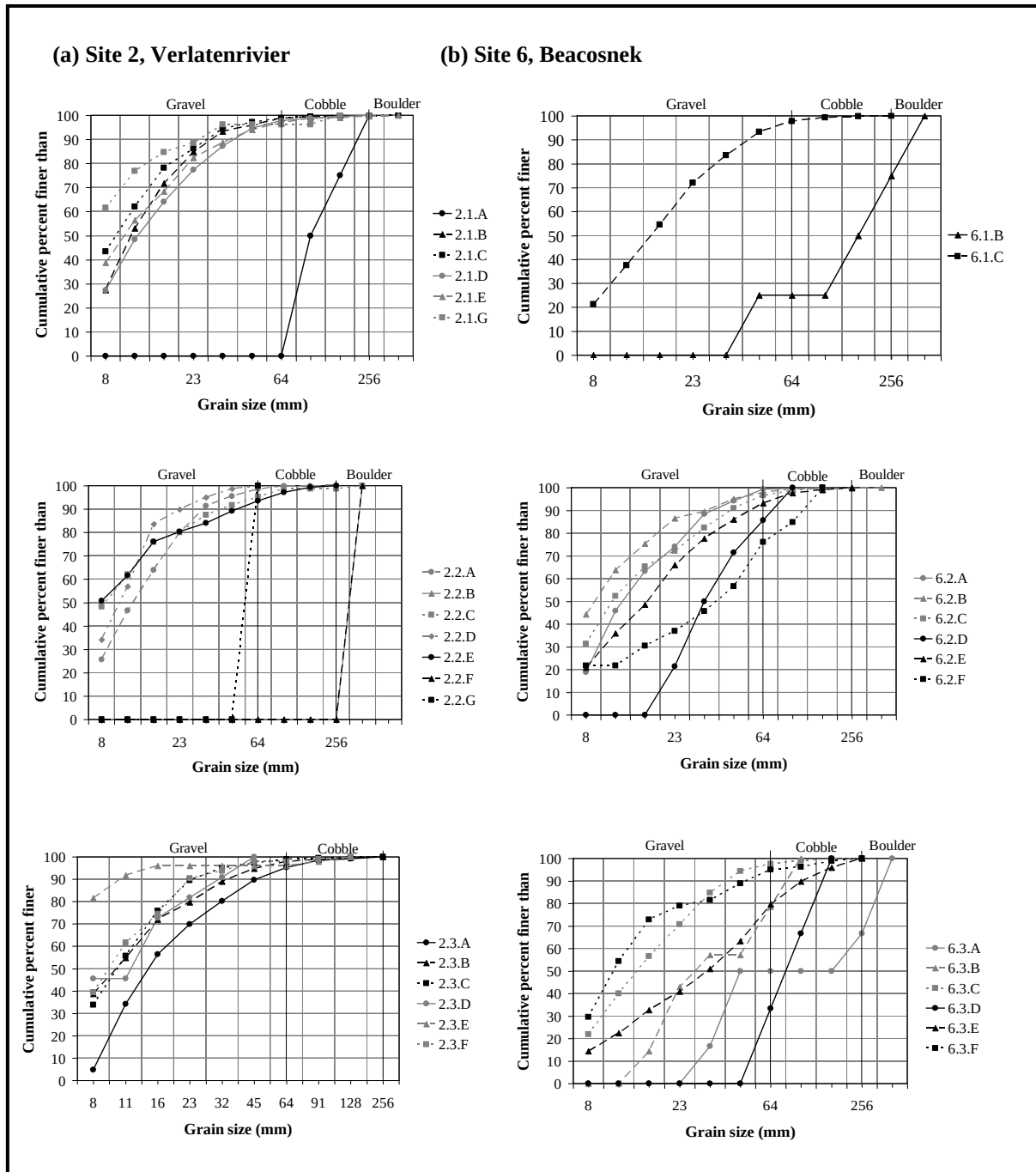


Figure 5.21: Grain size cumulative curves for coarse sediments, confined sites 2 and 6: Quadrat codes and features as per Appendix 5.1.

Table 5.4: Downstream variation of geomorphic landform or feature mean grain size within the Baviaanskloof.

Mean grain size (mm) averaged values with range (upstream-downstream) and site distance downstream (km) in brackets. Landform codes as per Table 5.1. Alluvial fan deposits were located on terraces or floodplains.

Landform or feature	T	F	FB	MCB	BA	MCLB	MCRB	AE	PB	LB	M-CB	SB	I	SCB	SCLB	SCRB	TCB	TCLB	TCRB
Confined sites																			
2 (20) & 6 (41.8)	25.1, Site 2	87.9 (155.2 - 20.6)	53.9 (50.3 - 57.5)	13.1 (12.1 - 14.1)		157.7, Site 2	32.3 (12.6 - 52.0)		14.1, Site 2	10.5, Site 2		13.5, Site 2		21.5, Site 6		55.6, Site 6			
7 (44) & 11 (74.3)		87.1 (128.2 - 45.9)	40.7 (13.1 - 68.2)	20.3 (13.0 - 27.6)	12.5, Site 7	19.9, Site 11	13.8 (12.4 - 15.2)			15.2, Site 11				15.0 (13.8 - 16.2)	17.7 (16.4 - 18.9)				
Semi-confined sites																			
1 (11) & 8 (49.5)	12.8, Site 1	19.7 (11.1 - 28.3)	47.3, Site 8	12.9 (12.5 - 13.2)		59.9 (13 - 106.8)					49.7, Site 1		9.7, Site 8	14.0 (13.1 - 14.9)		68.0 (12.7 - 123.2)			
3 (23) and 12 (77.2)	29.6, Site 12	25.1 (11.6 - 38.5)	61.8 (11.8 - 111.8)	12.8 (11.9 - 13.7)		13.3 (13.1 - 13.5)		13.1, Site 3		12.4, Site 3		13.1, Site 3							
Unconfined sites																			
4 (32) & 9 (54.1)	29, Site 9	54.6 (25.5 - 83.7)	15.2 (16.4 - 13.9)	14.9 (14.2 - 15.5)		14.3 (14.6 - 14)	14.0 (13.6 - 14.3)			12.4, Site 9	14.6, Site 4		25.3 (32 - 18.6)	12.6, Site 4	12.4, Site 4	14.8, Site 4	48.1, Site 9	11.2, Site 9	
5 (36), 10 (71) & 13 (82)	17.4 (13.7 - 16.8, Site 10)	47.0 (11.8 - 10 & 15.5, Site 10 & 15.1, Site 13)	13.9, Site 10	14.8 (13.3 - 15.5, Site 10 & 15.7, Site 13)		18.5 (11.6 - 14.2, Site 10 & 29.8, Site 13)	15.7 (12.7 - 19.4, Site 10 & 15.1, Site 13)	10.8, Site 5		56.2, Site 10			14.5, Site 10	13.4 (11.1 - 14.6, Site 10 & 14.4)	14.6, Site 10	12.3 (11.8 - 12.8, Site 13)	14.4, Site 5	11.4, Site 5	11.9, Site 5

Table 5.5: Downstream variation in geomorphic landform or feature coarse grain size within the Baviaanskloof.

The table illustrates averaged values for the median grain size or 50th percentile, the 84th percentile and the 95th percentile pertaining to the: (a) confined sites, (b) semi-confined sites and (c) unconfined sites. Landform codes as per Table 5.1. Alluvial fan deposits were located on terraces or floodplains.

(a)

Site (distance downstream, km)	Percentile (mm)	T	F	FB	MCB	BA	MCLB	MCRB	PB	LB	SB	SCB	SCLB	SCRB
2 (20)	D ₅₀	23.63	153.60	38.67	9.07		155.50	12	11	10	9.27			
	D ₈₄	31.67	174.30	87.33	22		181	24	28	16	27.33			
	D ₉₅	43	187.50	115.33	43.33		200	37	47	32	57			
6 (41.8)	D ₅₀	23.50	28	12.27			56.33					23.50		54
	D ₈₄	61.50	172	28			129.67					58		85.50
	D ₉₅	87	199	48			157					97		100
7 (44)	D ₅₀	110	11.25	11	11		9.55					11	13	
	D ₈₄	310	25	24	22		22.50					26	37	
	D ₉₅	340	39.50	49.67	38		38.50					57	67	
11 (74.3)	D ₅₀	42.85	41.50	23.97			16	12		12		10	15	
	D ₈₄	60.28	191	64.33			53	32		32		37	49	
	D ₉₅	93.15	212	127.33			100	58		55		80	86	

(b)

Site (distance downstream, km)	Percentile (mm)	T	F	FB	MCB	I	MCLB	AE	LB	M-CB	SB	TCB	SCB	TCR
1 (11)	D ₅₀	10.25	8.80		9.10		10.33			70		12.10		9.77
	D ₈₄	21.50	18.83		23.80		24.33			190		27.67		24
	D ₉₅	28.50	38		48.80		48			230		37.33		50
8 (49.5)	D ₅₀		36.33	46.50	9.23	8.40						14.33		83
	D ₈₄		55	64	26	14						31		220
	D ₉₅		61	80	50	26						50.33		240
3 (23)	D ₅₀		9.07	9.65	9.90		11.67	11	10		8.85			
	D ₈₄		20	20	21		24	24	22		26			
	D ₉₅		52.67	48	45.67		49.67	42	39		65.50			
12 (77.2)	D ₅₀	28.63	55.68	57	11.47		12							
	D ₈₄	49.67	119.50	316	27.33		26							
	D ₉₅	197.33	159	344.67	54		70							

(c)

Site (distance downstream, km)	Percentile (mm)	T	F	FB	MCB	MCLB	MCRB	AE	LB	M-CB	I	SCB	SCLB	SCRB	TCB	TCLB	TCR
4 (32)	D ₅₀		30.64	14	12.10	12	8.85			13	28.90	9.20	9.93	11			
	D ₈₄		58.30	39	28	30	27.50			29	84.50	25	22.33	31			
	D ₉₅		108.20	82.33	45.67	73	48.50			47	151.5	54	44	55			
9 (54.1)	D ₅₀	24.95	82	10.45	13.25	12.60	12.30		9.20		15.50				47.67	9.15	
	D ₈₄	48.67	97	28	33.25	29.50	28.50		23		50				101	19.50	
	D ₉₅	85.17	105.25	49	57	51.50	48		57		116				126.67	45	
5 (36)	D ₅₀	12	8.90		10.07	9	10.50	8.75				9.50		10	9.40	9.25	9.40
	D ₈₄	27	21.89		26	20	23	17.50				18		20	33.75	19	21
	D ₉₅	52	42.89		64.33	42	45.50	40.50				37		39	83.50	34.50	52
10 (71)	D ₅₀	21.11	13.42	12.52	13.67	12	19.50		45.5		11.50	19	12				
	D ₈₄	36.13	33.20	27.20	32	29	52.50		128		29.50	42	29				
	D ₉₅	59.13	65.40	48.60	51	56	121		174		66	61	42				
13 (82)	D ₅₀		98.16		11.60	48	13					10		9.45			
	D ₈₄		196		34	89	32					29.50		24			
	D ₉₅		232.60		60	390	49					65.50		47.50			

Quadrat codes and features as per Appendix 5.1.

The analysis of the fine sediment size fractions indicated that all the geomorphic landforms at the confined sites are dominated by fine sand (Figure 5.23 and Appendices 5.13 and 5.14). The latter accounted for > 50% of soils in 47 sample plots (68%). Coarse sand only occurred in 5 plots (7%) located on the main channel bed (sites 2 and 6). The highest silt (30%) and clay (22.8%) content occurred at site 11 (11.2.A) in the main channel bed. High silt values were also present on flood benches (sites 6 and 11), the main channel banks (sites 7 and 11) and the backwater area at site 7. Negligible amounts of silt and clay were found at the remaining study sites (Figure 5.23 and Appendices 5.13 and 5.14). The statistical analysis in Appendix 5.15 revealed that the particles size distributions of the 69 samples were predominantly unimodal (78%). The sorting values for the geomorphic surfaces were 0.73-1.99, signifying moderately to poorly sorted material. The majority of the grain sizes were also strongly fine skewed with values ranging from 0.13 to 0.73. Overall, no significant difference was found between the sampling areas which contained fine to coarse sand sized materials (Appendix 5.15).

The soil chemistry results are shown in Table 5.8 and Appendix 5.16. Soil pH for the majority of the sample plots (70%) was between 5.1 and 6, indicating moderately acidic soil. Available phosphorus levels were moderate (50% of sample plots) to low (largely limited to site 2). Organic matter levels in the soil were also mostly moderate to low, ranging between 4.85-0.11% (Appendix 5.16). Excessively high values (> 100) were recorded for two flood benches (sites 6 and 11) and a terrace (site 2). High soil carbon values were recorded at a flood bench (site 6) and the main channel banks (sites 7 and 11). Nitrogen levels were predominately low with higher levels (> 0.6%) limited largely to sites 7 (main channel bed and bank) and 11 (flood benches and main channel bank) (Table 5.8).

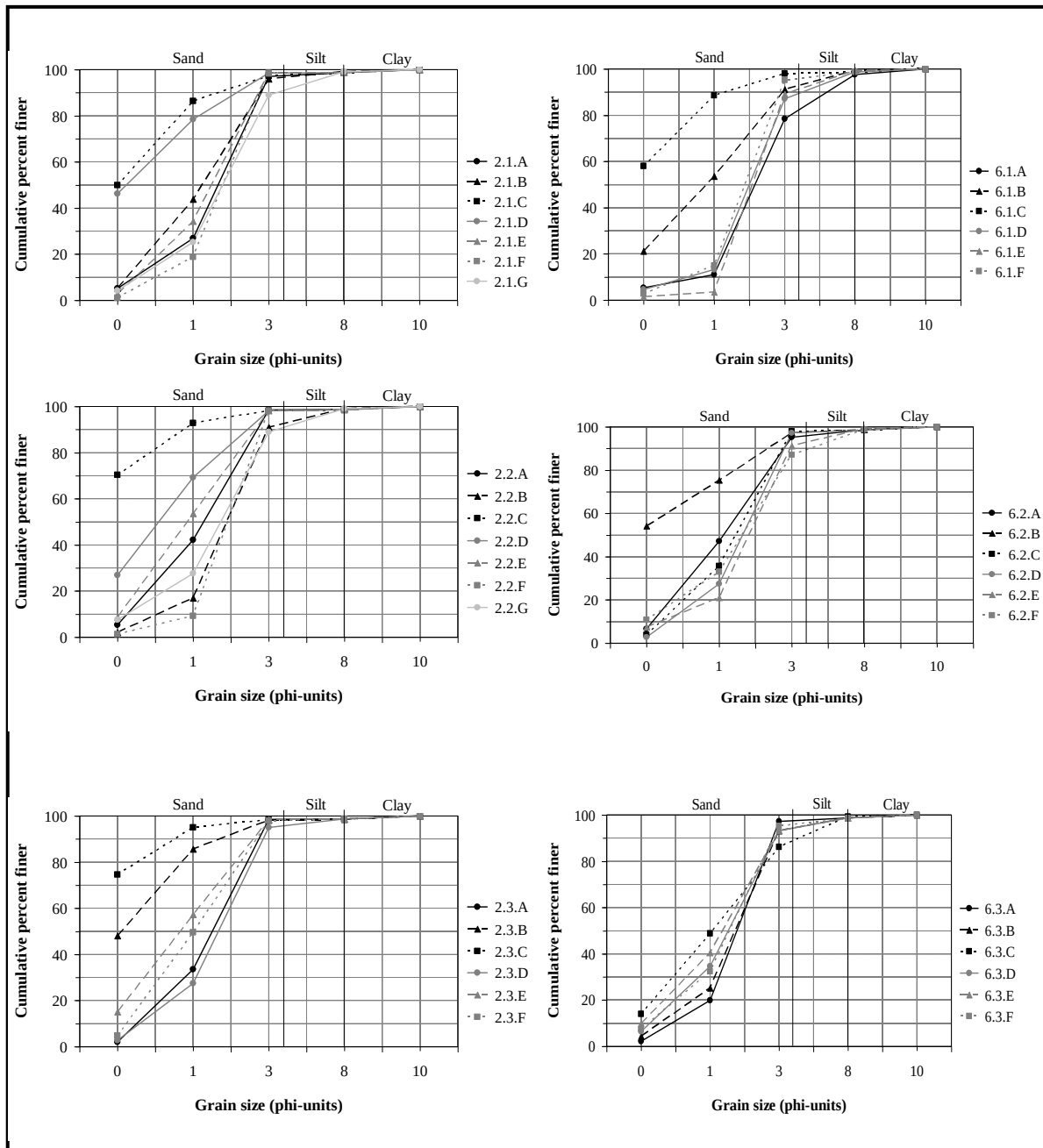


Figure 5.23: Grain size cumulative curves for fine sediments, confined sites 2 and 6. Quadrat codes and features as per Appendix 5.1.

Table 5.8: High soil nitrogen, phosphorus, organic carbon and pH per confinement setting, Baviaanskloof.

High or excessively high or values are indicated in bold. Quadrat codes and geomorphic landforms as per Appendix 5.1.

Confined valley setting					Semi-confined valley setting					Unconfined valley setting				
Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCI)	Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCI)	Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCI)
2.2.G	0.40	110.3	4.74	6.50	1.2.G	0.39	110.8	3.69	6.50	5.3.G	0.39	181.4	2.73	6.10
6.1.A	0.72	68.70	9.13	5.20	8.2.F	0.52	75.34	5.06	5.50	9.1.E	0.43	282.1	3.94	7.40
6.3.A	0.23	124.4	1.46	5.80	8.3.C	0.47	85.68	5.13	5.50	9.1.J	0.87	49.61	6.88	6.20
7.2.B	0.64	37.88	4.46	5.80	12.2.B	0.74	78.18	6.08	5.30	9.2.A	1.11	87.71	4.75	5.70
7.3.A	0.67	14.41	5.14	4.90	12.3.B	0.70	32.20	6.65	4.50	9.3.A	0.41	177.7	3.84	5.70
11.1.F	0.64	63.88	4.81	5.00						9.3.B	1.12	74.40	7.01	5.70
11.2.B	0.70	109.6	4.85	5.50						10.1.A	0.23	118.5	2.51	6.60
11.2.C	0.61	93.53	5.07	5.50						10.3.D	0.45	115.4	3.73	5.60
11.3.B	0.68	75.66	0.68	5.10						13.1.F	0.68	73.75	5.04	7.10
										13.3.A	1.02	42.67	7.95	5.20
										13.3.B	0.78	56.95	6.72	5.00

Semi-confined study sites

The coarse sediment analysis indicated that the dominant grain size across geomorphic landforms at the semi-confined valley setting was fine to medium gravels (Figure 5.24 and Appendix 5.17). This grain size category made up > 50% of soils in 58 quadrats (75%) with mostly small cobbles in eight quadrats (10%). Cobbles were mainly on flood benches, floodplains (sites 8 and 12) and main channel bed and banks (site 8). There were 12 quadrats which were limited to only finer grained deposits on the same landforms mentioned above (Appendix 5.18).

The summary statistics mirrored the grain size percentage results. The sorting values for the majority of the differing geomorphic surfaces reflected moderately sorted sediments. The values largely ranged from 1.42 to 1.99. The skewness was predominantly coarsely skewed with values mostly ranging from 0.11 to 0.47 (Appendix 5.19). The geomorphic unit downstream variation of the mean grain size was mostly in the medium to very coarse gravel size fraction with no significant downstream trends. An exception was the coarsening, gravels to medium cobbles, with distance downstream of the flood benches at sites 3 and 12 and the main channel banks at sites 1 and 8 (Table 5.6). The above mentioned results were reflected in the geomorphic unit coarse grain size fraction analysis (Table 5.7b).

The visual estimates indicated different particle size distributions for the various geomorphic units. The main and secondary channel bed, and some banks, terraces, most flood benches and scroll bars all contained a lot more gravels and cobbles at all the sites. The deposits on the remainder of the geomorphic surfaces were all finer grained with scattered cobbles and

boulders. Overall, fines contributed to > 50% of soils in 60 quadrats (78%) with gravels were found in only 5 quadrats (6%) (Figure 5.25 and Appendix 5.20).

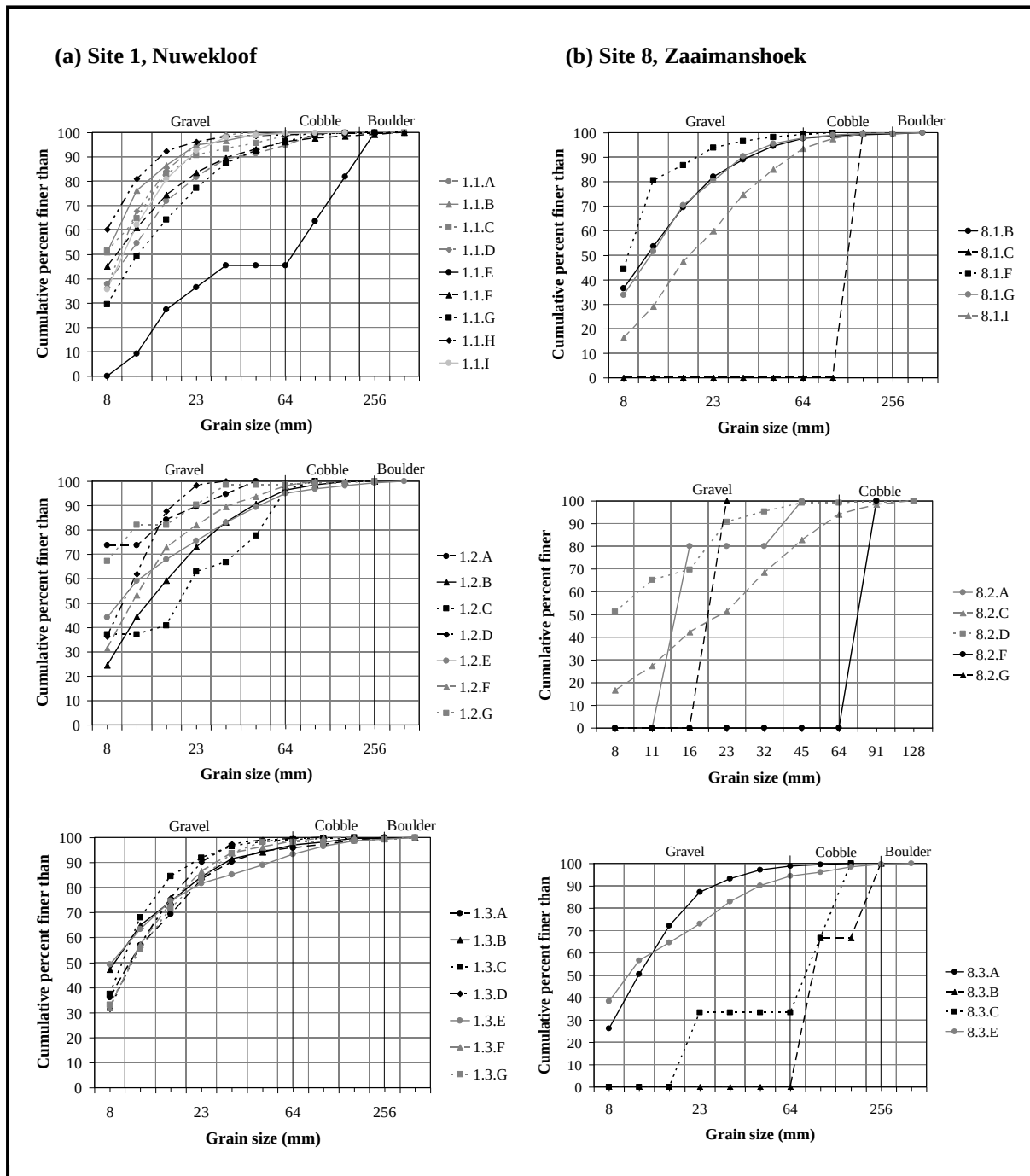


Figure 5.24: Grain size cumulative curves for coarse sediments, semi-confined sites 1 and 8.

Quadrat codes and features as per Appendix 5.1.

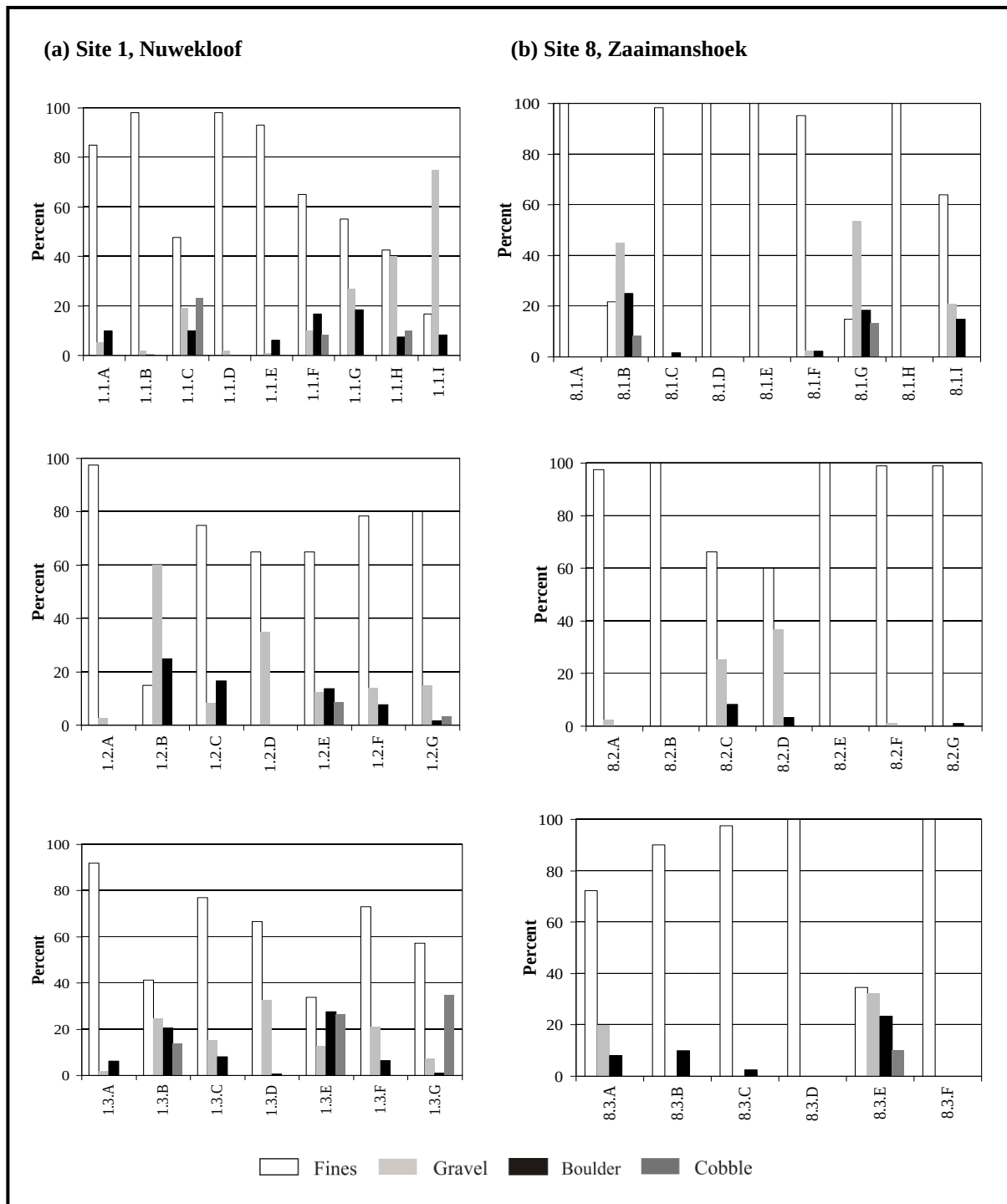


Figure 5.25: Grain size percentage visual estimates for geomorphic landforms, semi-confined sites 1 and 8.

Quadrat codes and features as per Appendix 5.1.

The grain size percentage data for the fine sediments demonstrated that the fluvial landforms at the semi-confined valley setting are characterised mostly by fine to medium sand (Figure 5.26 and Appendix 5.21). These grain size fractions occurred for > 50% of deposits in 40 (52%) and 6 (8%) sample plots respectively. The latter was found at sites 1 (main channel

bed and floodplain) and 3 (flood bench and main channel right bank). Very low silt and clay percentages were recorded for all the sites. The highest silt (32%) and clay (7%) values occurred at sites 1 (main channel left bank) and 12 (flood bench) respectively (Figure 5.26 and Appendix 5.21). The statistical analysis indicated that the sediment samples were largely unimodal. They contained primarily poorly sorted materials that were fine to very finely skewed. The sorting values were mainly between 1.01 and 1.95. The skewness values for the most part ranged from 0.11 to 0.82 (Appendix 5.22).

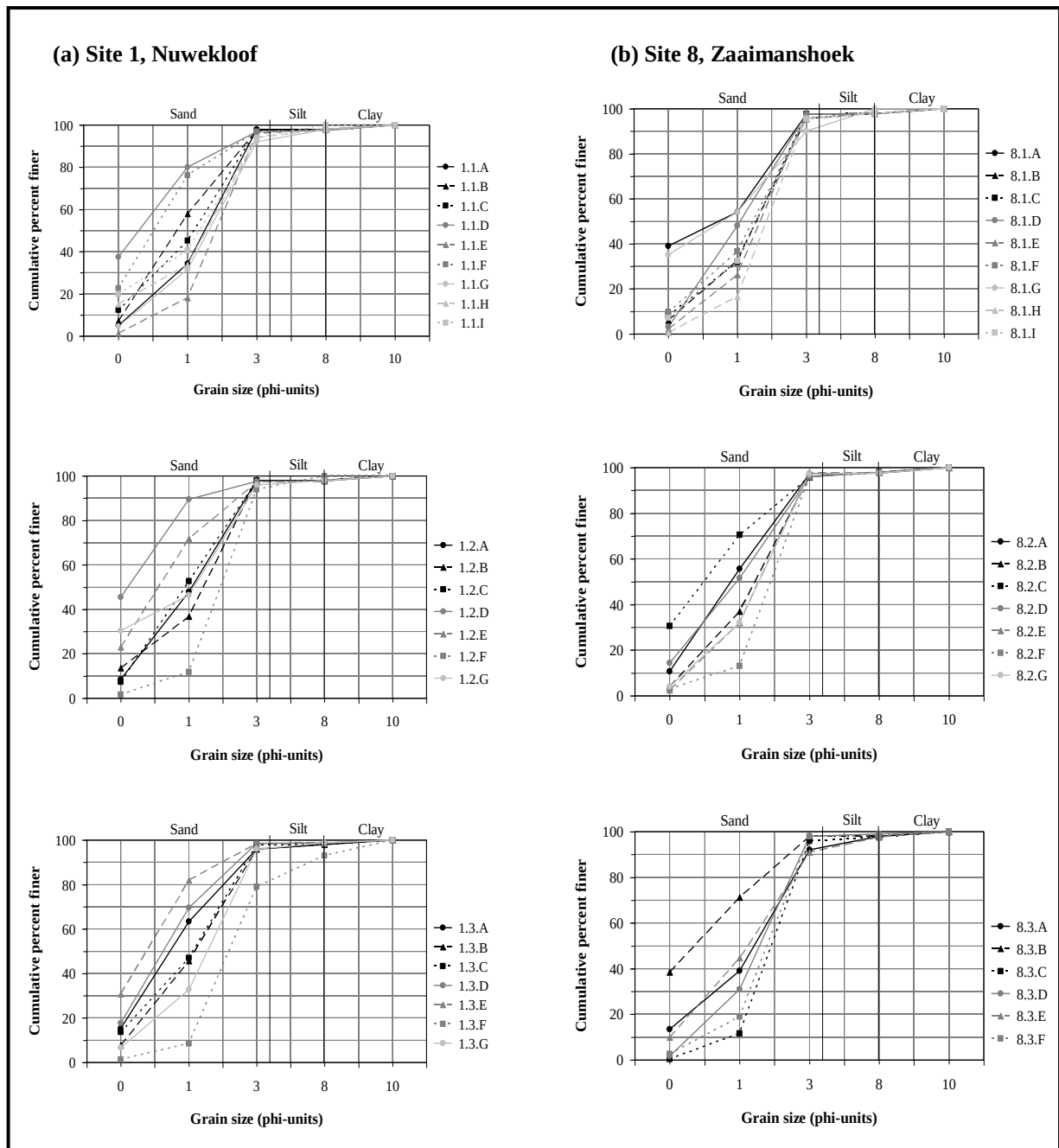


Figure 5.26: Grain size cumulative curves for fine sediments, semi-confined sites 1 and 8.

Quadrat codes and features as per Appendix 5.1.

The data in Appendix 5.16 show that the majority of the semi-confined sites had moderately acidic soils with neutral soils largely found at site 8 (floodplain and main channel plots). Values for the available phosphorus were mostly high to moderate. Only site 1 (a terrace plot) had an excessively high value (110.82 mg/kg) (Table 5.8). Organic matter content was moderate to low with high (> 5%) content recorded at sites 8 (floodplain and flood bench plots) and 12 (a flood bench and main channel bank). The nitrogen levels in the soil were mostly low with high levels (> 0.7%) recorded at site 12 (a flood bench and main channel bank) (Table 5.8 and Appendix 5.16).

Unconfined study sites

The pebble count results indicated that the geomorphic landforms at the unconfined sites consisted mainly of medium to fine gravels (Figure 5.27 and Appendices 5.23 and 5.24). These sediments accounted for > 50% of deposits in 124 quadrats (88%). Only 6 quadrats (4%) contained > 50% of cobble (mostly small) grain size fractions. They were present on a lateral bar (site 10), floodplains (sites 9 and 13) and tributary bed and terrace plots (site 9). Very little material exceeded > 256 mm in diameter. Surfaces lacking coarse grained material were limited to 13 quadrats (9%). These geomorphic surfaces included floodplains, terraces and flood benches (sites 9 and 13) (Figure 5.27 and Appendices 5.23 and 5.24).

The summary statistics data in Appendix 5.25 mirrored the above mentioned results. Sorting values (1.63 to 3.33) for the most part reflected moderately to poorly sorted material. Skewness values (-0.01 to 0.3) indicated particle sizes that are symmetrical to skewed towards the coarse side (Appendix 5.25). The mean grain sizes for most of the geomorphic surfaces were in the medium to coarse gravel grain size fraction with no clear downstream trend. Negligible downstream coarsening (gravel to cobble) was, however, observed for the floodplain (Table 5.6). The results for the downstream variation in fluvial landform coarse grain size fractions mirrored that of the mean grain size analysis (Table 5.7c).

The visual estimation results illustrated that soil texture was affected by elevation above and distance away from the active channel thalweg. Fines accounted for > 50% of deposits in 90 quadrats (63%) with the gravel size category in 20 (14%). Floodplains and terraces were all mostly finer grained with scattered cobbles and boulders present. Islands, flood benches, channel beds and banks and artificial embankments all contained mixed grain size fractions (Figure 5.28 and Appendix 5.26).

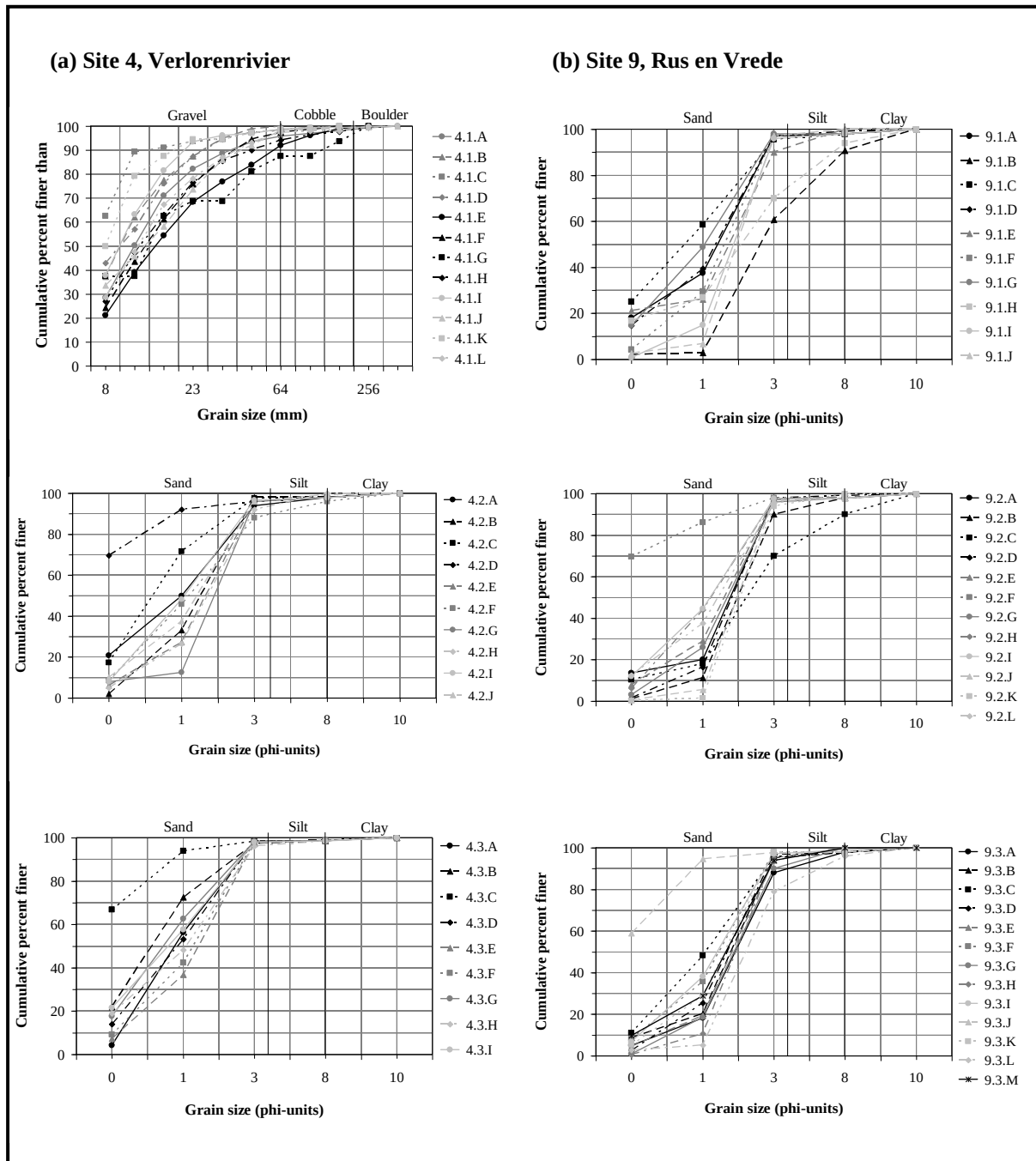


Figure 5.27: Grain size cumulative curves for coarse sediments, unconfined sites 4 and 9.

Quadrat codes and features as per Appendix 5.1.

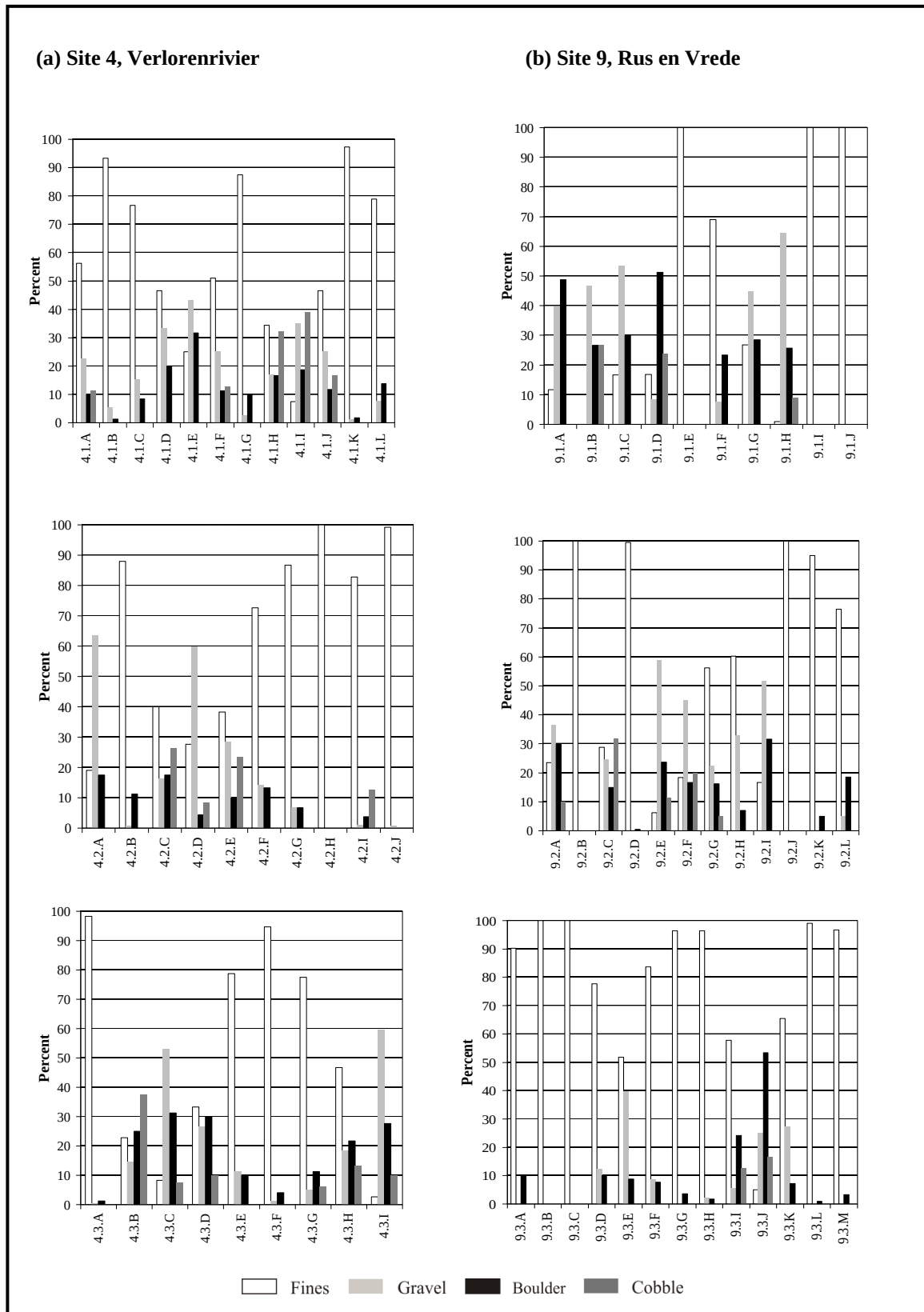


Figure 5.28: Grain size percentage visual estimates for geomorphic landforms, unconfined sites 4 and 9.

Quadrat codes and features as per Appendix 5.1.

The fine sediment calibre results showed that the geomorphic surfaces were largely covered by fine sand (Figure 5.29 and Appendix 5.27). The latter formed part of > 50% of deposits in 95 sample plots (70%) with medium sand in 10 plots (7%) and coarse sand in 7 plots (5%). These coarser-grained sediments were present in the main channel bed (sites 4 and 5) and bank (site 9), islands (sites 9 and 10) and a lateral bar (site 10). Although some silts were present in the sediment deposits, even fewer clays were found. The highest silt (24%) and clay (10%) values occurred at site 9, forming part of an island and tributary channel bank respectively (Figure 5.29 and Appendix 5.27). The summary statistics results showed that the sediment samples were mostly unimodal with primarily poorly sorted materials. Sorting values mainly ranged from 1.01 to 1.89. Particle sizes were also symmetrical to very finely skewed with skewness values mostly ranging from 0.01 to 0.71 (Appendix 5.28).

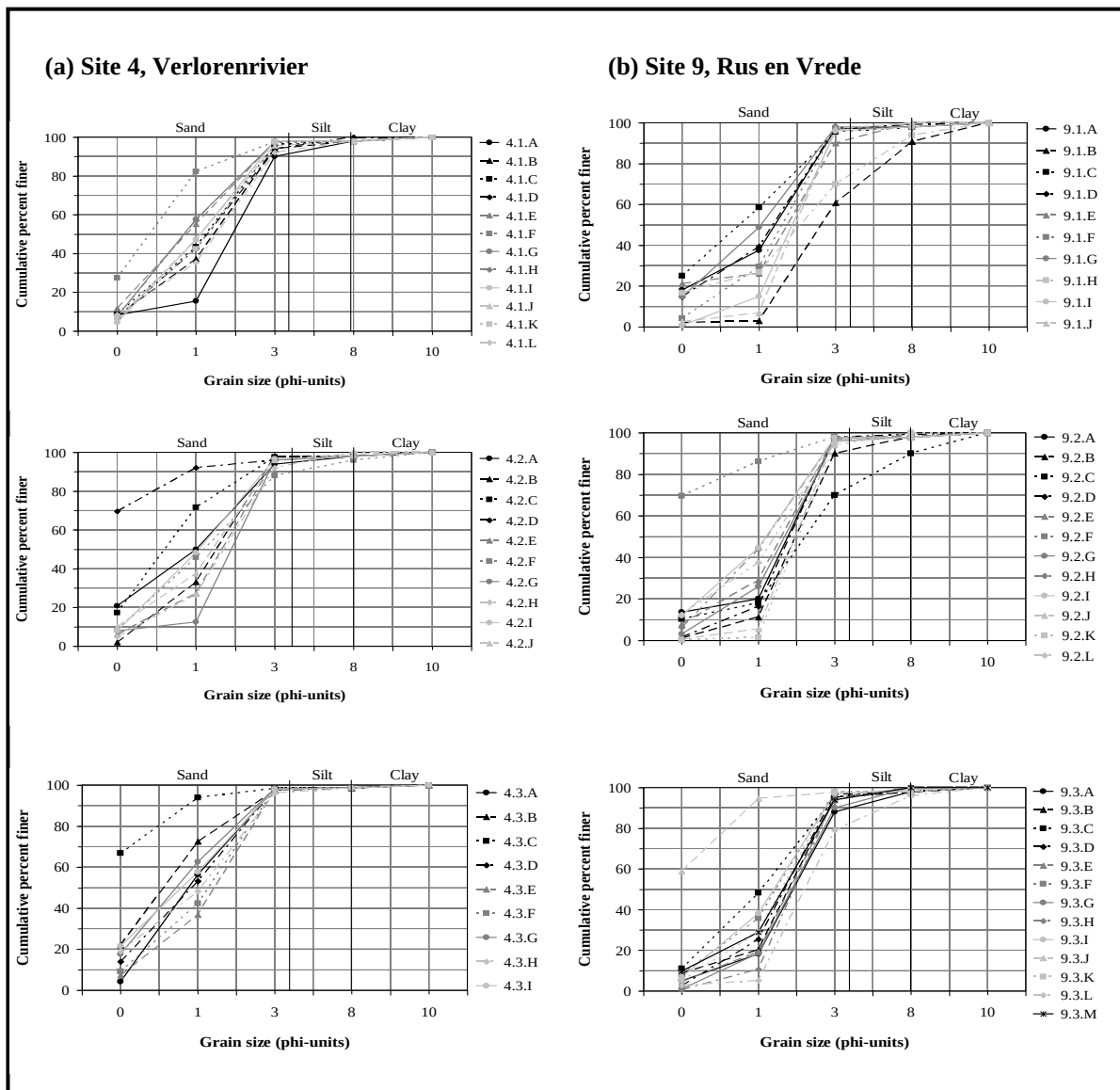


Figure 5.29: Grain size cumulative curves for fine sediments, unconfined sites 4 and 9.

Quadrat codes and features as per Appendix 5.1.

The soils sampled at the unconfined sites were characterised predominantly by strong to moderate acidic soils. Neutral soils were also present at some terraces (sites 9 and 10) and floodplains (sites 9 and 13) (Appendix 5.16). Available phosphorus levels were high to moderate for most of the sites. Excessively high values were also recorded for floodplains (sites 5 and 9), a lateral bar (site 10) and terraces (sites 9 and 10) (Table 5.8). Soil carbon was moderate to low across differing geomorphic units. However values of $> 5\%$ were recorded on a main channel bank (site 13), some floodplains (sites 9, 10 and 13) and a terrace (site 9). Soil nitrogen levels were mostly low across landforms but high levels (0.7-1.1%) were present on floodplains (sites 9 and 13), a terrace (site 9) and a main channel bank (site 13) (Table 5.8 and Appendix 5.16).

5.4 Summary

This chapter aimed to partially meet objective 3 of the study by examining the physical river valley dynamics at alternating valley confinement settings in the foothills of the Baviaanskloof. This was achieved through surveying (i.e. valley cross-sections and resistivity profiles), an earth observation assessment (i.e. NDVI and TC transformation) and sediment sampling (i.e. grain size distribution and soil chemistry). The results obtained are used in Chapter 7 to interpret process-form and vegetation relationships on the valley floor system.

The cross-valley profile reach scale analysis showed that valley confinement (i.e. differences in valley width) influence river form and process. Specifically, it affects flow and sediment processes and the resulting landforms. The confined valley setting tended to have narrow valley floor widths associated with an essentially straight main channel and limited geomorphic landforms. Wider valley floors were observed at the semi-confined study sites which resulted in the Baviaanskloof River being less constrained, wider and more sinuous. However, landforms were still limited. Broad valley floors characterized the unconfined valley setting. The Baviaanskloof River in the unconfined setting adjusted laterally across extensive continuous floodplain surfaces. It was both single and multi-channelled and had higher channel sinuosities. However, it was constrained by alluvial fans and broad terraces acting as secondary controls. More geomorphic landforms were observed at the unconfined study sites.

The resistivity, NDVI and Tasseled Cap analyses showed that surface-subsurface exchange of water influences landscape connectivity and vegetation patterns. Specifically, the resistivity analysis indicated that the water table at the confined valley setting (e.g. site 2) is very shallow or near the surface while at the unconfined valley setting (e.g. site 4) it is very deep. This contrasted with the variable (shallow and deeper) water table levels at the semi-confined valley setting (sites 1 and 12) which was mostly related to flow permanence. For example, a lack of mainstem surface flow was associated with a deeper groundwater table. The confined reaches had strong within-channel vertical connectivity imposed by the local geology and

sustained baseflow. This in turn, was related to high longitudinal connectivity. Conversely, the unconfined reaches were associated with irregular instream vertical exchanges which were typically related to limited longitudinal connectivity.

The earth observation analyses then demonstrated that NDVI and TC transformation data can be used to determine vegetation and surface-groundwater relationships. The dry and wet period NDVI and TC profile results for the most part supported the assumption that vegetation and surface-groundwater interact in the Baviaanskloof, i.e. that vegetation growth depends on surface-groundwater availability. The dry and wet period NDVI and TC quadrat results also revealed the importance of water availability for plant growth in the study area. It reinforced the assumption of a groundwater influence in the catchment. This was reflected in the vegetation patterns with confined (e.g. site 6) and semi-confined (e.g. sites 8 and 12) quadrat vegetation mostly remaining in good health in the dry months. It also indicated the significance of precipitation events during the wet period with the vegetation at some unconfined sites (e.g. sites 9 and 10) displaying denser foliage.

The sediment analyses (fine and coarse) at the three valley confinement settings indicated that grain size variability is reflected in distinct landforms occurring at differing positions and elevations in a cross-section. Coarser grained materials (e.g. cobbles and boulders) were associated with instream or stream side geomorphic landforms (e.g. channel banks and bars). Floodplain or terrace surfaces on the other hand consisted of finer grained materials. However, these surfaces were sometimes accompanied by coarse sediment additions from for example alluvial fans or tributaries (unconfined sites). These lateral sediment inputs disrupted the usual associated grain size organisation. Within the study the dominant coarse grain size fraction across landforms (i.e. lateral gradient) were gravels, i.e. either fine to medium (confined and unconfined sites) or medium to coarse (semi-confined sites).

These results were also reflected in the downstream geomorphic unit analyses with the difference that the mean and coarse grain sizes were largely in the medium to very coarse gravel size fraction with mostly no significant longitudinal trends. Exceptions included the downstream fining (e.g. floodplains) and coarsening (e.g. flood benches) at the confined valley setting. Downstream coarsening (gravel to cobble) also occurred at benches and river banks at the semi-confined valley setting as well as at floodplains (e.g. sites 4 and 9) at the unconfined valley setting. Fine sand also dominated at the confined and unconfined sites while by fine to medium sand dominated at the semi-confined sites. Low silt and clay percentages were recorded at all the sites. The soil chemistry analysis showed that high nitrogen and very high available phosphorus levels were obtained, for example, on floodplain and terrace surfaces at the unconfined valley setting. Organic matter values were mostly moderate to low (all sites). Soil pH varied mainly between moderate acidic soils (confined and semi-confined sites) and strong to moderate acidic soils (unconfined sites).

Chapter 6: River valley vegetation patterns

6.1 Introduction

There has been a longstanding realization that vegetation controls fluvial geomorphic form and process, through factors such as (1) roughness or flow resistance; (2) sediment/bank reinforcement; (3) channel morphodynamics (e.g. channel incision), (4) the development of particular landforms (e.g. bars) and (5) woody debris or jam formation (Hickin, 1984; Gregory, 1992; Francis, 2006; Corenblit *et al.*, 2007; Osterkamp and Hupp, 2010; Bendix and Stella, 2013; Gurnell, 2014). Flow obstruction by plant species increases channel resistance and hydraulic roughness which reduce flow velocities. This in turn results in decreased erosion, enhanced sediment deposition, floodplain inundation and increased groundwater recharge (i.e. raised groundwater levels) (Friedman and Auble, 2000; Sandercock *et al.*, 2007; Osterkamp and Hupp, 2010; Merritt, 2013; Gurnell, 2014). In general, tall rigid and closely packed stems bring about greater channel resistance (Friedman and Auble, 2000). However, resistance will decline as soon as vegetation is flattened (Green, 2005).

Riparian vegetation has a direct impact on streambank stability through reduced near-bank flow velocities and mechanical root-reinforcement (Thorne, 1990; Francis, 2006; Pollen-Bankhead *et al.*, 2013; Gurnell, 2014). Well-vegetated banks are generally associated with lower ratios of channel width-to-depth and increased channel stability (Hickin, 1984; Abernethy and Rutherford, 2000; Allmendinger *et al.*, 2005; Labbe *et al.*, 2011). The strength and stability of channel banks are important in determining channel form, which in turn can influence channel planform (Beechie *et al.*, 2006; Jansen and Nanson, 2010; Tal and Paola, 2010; Labbe *et al.*, 2011; Merritt, 2013). Murray *et al.* (2008) for example suggested that substantial bank stabilization could result in a single channel pattern where a braided pattern would otherwise have existed. Studies have also reported that channels with grassy banks are wider and shallower than tree-lined channels (Knighton, 1987; Rowntree, 1991; Rowntree and Dollar, 1996; Allmendinger *et al.*, 2005). Grasses have a low biomass, a dense near-surface root mat, with shallow rooting and good surface cover that is effective against scour and shallow slips. Deep-rooted trees increase the cohesion of bank sediments, reducing the prospective for mass failure (Abernethy and Rutherford, 2001; Van De Wiel and Darby, 2007). However, vegetation also has destabilizing effects such as increased local pore-water pressures around plant stems (Pollen-Bankhead and Simon, 2010), surcharge due to the weight of overhanging trees (Thorne, 1990; Simon *et al.*, 2004a) and increased infiltration capacity (Simon *et al.*, 2004a; Pollen-Bankhead and Simon, 2010).

Interactions between disturbances, sediment transport and vegetation growth often lead to development of distinct fluvial landforms of different ages occupied by specific plant communities (Hupp and Osterkamp, 1985; Gurnell, 1995; Friedman and Auble, 2000; Osterkamp and Hupp, 2010; Chalmers *et al.*, 2012; Gurnell *et al.*, 2012; Gurnell, 2014). Site

suitability and environmental conditions determine the likelihood of a given species growing on a particular geomorphic landform (Hupp and Osterkamp, 1996; Bendix and Hupp, 2000). In addition, once established certain plants species also act as “ecosystem engineers” by trapping and stabilizing sediments, organic matter and plant propagules. This drives landform development (e.g. islands and floodplains) associated with habitat provision linked to further plant establishment which in turn reinforces the development of landforms (Gurnell and Petts, 2006; Corenblit *et al.*, 2010; Gurnell *et al.*, 2012; Gurnell, 2014). According to Jones *et al.* (1994), ecosystem engineers are organisms that directly or indirectly regulate the availability of resources to other species by modifying their physical environment. Hence, organisms not only respond and adjust to the physical environment but also create it in certain cases (Corenblit *et al.*, 2011).

The ecological and geomorphological significance of woody debris across a range of spatial and temporal scales has been well established in recent decades (Gurnell *et al.*, 2002; Montgomery and Piégay, 2003; Francis *et al.*, 2008a; Bendix and Stella, 2013). Several of the geomorphic effects of woody debris arise from the fact that the wood acts as an obstruction to local flow hydraulics and sediment processes and collects additional material which further reinforce obstruction (Montgomery and Piégay, 2003; Dollar, 2004; Naiman *et al.*, 2008; Stoffel and Wilford, 2012). Studies have shown that woody debris add roughness elements to the channel and floodplain, in the case of overbank flows from channel blocking, thereby influencing discharge and organic matter and sediment transport and storage (Piégay and Gurnell, 1997; Gurnell and Petts, 2006; Sear *et al.*, 2010). These influences affect channel processes and morphology, including inducing in-channel pool, riffle or step formations (Montgomery and Buffington, 1997; Gurnell *et al.*, 2002; Curran, 2010) and local erosion (Tabacchi *et al.*, 2000; Allmendinger *et al.*, 2005). Large wood can cause channel changes, particularly involving the development of cut-offs, multiple channel patterns and channel avulsion in low gradient rivers (Gregory, 1992; Sear *et al.*, 2010). Furthermore, wood accumulations assist in the formation of valley bottom landforms (Montgomery and Wohl, 2003), such as bars, islands and floodplains, enhancing aquatic ecosystems by providing diverse habitats supporting varied vegetation and ecology (Gurnell and Petts, 2006; Francis *et al.*, 2008a; Sear *et al.*, 2010).

This chapter examines plant community distribution patterns in the semi-arid Baviaanskloof River valley. It intends to partially meet objective 3 of the study (Figure 1.2) by investigating patterns at site and geomorphic landform scales. Objective three examines the two-way links between hydrogeomorphic processes and landforms, including surface-groundwater interactions, and vegetation distribution patterns on the valley floor. The above information will then be used in Chapter 7 to interpret hydrogeomorphic form and process and vegetation relationships on the valley floor.

The chapter is structured into three main sections: methods, results and an overall summary. The methods section (Section 6.2) deals with data collection, analysis and presentation. Under the results section (Section 6.3), the analysis related to general vegetation characteristics in the study area will be presented first. This will then be followed by an analysis comparing all the study sites together. The analyses comparing site groups are presented third. The summary section (Section 6.4) highlights key chapter findings, which will be used together with findings from Chapter 5 to inform Chapter 7.

6.2 Methods: Data collection, analysis and presentation

6.2.1 Plant community distribution patterns: Vegetation sampling

Species data collection

An area-based vegetation sampling method was used to survey valley floor vegetation from a series of variable-sized rectangular and square sample quadrats or relevés (Section 5.2.1). A total of 289 plots were sampled during the survey. The number of plots varied among the sites, ranging from 13 at confined sites to 35 at unconfined sites (Appendix 5.1). This mainly depended on the number of landforms and plant species richness at each site. Multiple high resolution digital photographs were also taken of each plot (e.g. Figure 5.2). The species data recorded at every quadrat in the vicinity of each cross-valley profile included: species names and presence/absence, cover abundance, frequency of occurrence, condition, age and height estimates (m). This information was used in the description of the different vegetation groups. All plant species present were documented. The percentage cover of each species was visually estimated as the proportion of the ground occupied by the above-ground parts of the species when viewed from above (Kent and Coker, 1992; McCune *et al.*, 2002). This method allowed for comparisons among variable-sized quadrats (Bornette *et al.*, 2001). This was also accompanied by visual estimates of substrate (e.g. 20% bare ground) and leaf litter where present (Gordon *et al.*, 2004). Multiple layers of vegetation resulting in total cover values of over 100% were also recorded at several quadrats (McCune *et al.*, 2002). Six classes were distinguished (Table 6.1) for the frequency of occurrence of taxa (Küchler and Zonneveld, 1988).

The condition of plants was also documented as healthy (alive) or unhealthy (dead). Moreover, events such as frost or herbivory were indicated where encountered. Evidence of disturbance was also noted. Plant age was visually estimated for trees, shrubs and herbs (Table 6.2). Because different species age in different ways, the categories used are only a general guideline. Since all estimates were done by eye, there is certain to have been a degree of error (i.e. overestimates or underestimates). However, the subjectivity of the above mentioned visual estimates was reduced by using an experienced botanist (J. Raath, July 2010) to record all the species data in the study. Lastly, photographs of some of the typical and differentiating species were taken in the field.

Table 6.1: Frequency of occurrence of plant species, Baviaanskloof.
After Küchler and Zonneveld (1988) and J. Raath, July 2010.

Class	Number and or type of plant species
1	1 individual
2	2 to 5 individuals
3	5 to many individuals
4	Many to numerous individuals
5	Tree/shrub dominant and 30% of the cover smaller plant types
6	Tree/shrub dominant and 50% of the cover smaller plant types

Table 6.2: Plant age categories for trees, shrubs and herbs.
After J. Raath, July 2010.

Age	Trees and shrubs	Perennial/biennial herbs	Annual herbs
Seedling	1 year	1 to 4 months	1 month
Young	1 to 2 years	2 to 6 months	1 to 2 months
Immature	2 to 7 years	N/A	N/A
Mature	7 to 50 years	Flowers	Flowers
Old	> 50 years	Dying	Dying

Species which could not be positively identified in the field were collected, pressed and labelled with a unique specimen number. Identifications were then made by E. Brink at the Selmar Schonland Herbarium in Grahamstown which is affiliated to Rhodes University and the Albany Museum. Determinations were verified by the curator, T. Dold. Plants were identified to species when possible, otherwise only the genus was recorded. A small number of species were also only identified to family level. This resulted because in several instances identification is only certain when individuals have flowers, seeds or fruit. Insufficient plant material also hampered identifications.

Descriptions of plant species were obtained from published floras which incorporated appropriate revisions of work. These included Shearing and van Heerden (1994), Goldblatt and Manning (2000), Henderson (2001), Mucina and Rutherford (2006), Raimondo *et al.* (2009), Bromilow (2010), Vlok and Schutte-Vlok (2010), Manning and Goldblatt (2012), Snijman (2013) and DEA (2014). Information was also supplied by the South African National Biodiversity Institute (SANBI) from digitized collections accessible at the website: <http://www.sanbi.org/information>, accessed 19 February to 6 March 2014. Species were assigned to one of 11 growth form categories (Table 6.3).

Table 6.3: Growth form definitions.

Adapted from Goldblatt and Manning (2000); Mucina *et al.* (2006); and Bromilow (2010). Information was also obtained from the SANBI website: http://posa.sanbi.org/intro_posa.php, accessed 17 November 2014.

Growth form category	Definition
Climber	A weak-stemmed plant that derives its support from climbing, twining or creeping along a surface.
Geophyte	An herbaceous plant that survives an unfavourable season with underground storage structures such as rhizomes, bulbs, tubers and corms.
Grass (Graminoid)	An herbaceous plant in the family Poaceae.
Helophyte	An herbaceous plant found in marshy ground.
Herb	A plant that is not woody but soft and leafy (a few centimetres to > 1 m). It can be annual, biennial or perennial. This includes the family Cyperaceae.
Hydrophyte	An herbaceous plant with morphological adaptations to spend at least part of its life cycle submerged under water.
Parasite	A plant that lacks a fully functional photosynthetic apparatus, i.e. fully parasitizes other plants.
Scrambler	An herbaceous plant that produces long weak shoots by which it grows over other plants.
Shrub	A woody perennial plant often with multiple stems (<1 to 2 m or more).
Succulent	A plant with fleshy and juicy stems and leaves that contain reserves of moisture.
Tree	A woody perennial plant usually with main trunk and multiple stems or branches (2 to > 10 m). If taller than 10 m, a distinct elevated crown is present.

Species composition

Indirect ordination or gradient analysis was used to identify sampling plots similar in species composition. This approach involved two steps. First, % vegetation cover was analysed independent of environmental variables therefore, without assuming cause and effect (Kent and Coker, 1992; McCune *et al.*, 2002). Second, the community group/plot data were then compared with the available environmental data, thus relating variation in the species composition to variation in the physical environment (Clarke and Warwick, 2001; Clarke and Gorley, 2006). A disadvantage of using direct ordination or gradient analysis is that important environmental variables must be prejudged, often creating bias toward easily measured variables (McCune *et al.*, 2002).

Multivariate techniques in PRIMER V6 (Clarke and Gorley, 2006) were used to investigate species distribution patterns at site (between valley settings) and geomorphic landform (within sites) scales. Cover abundance data at the site scale was calculated by adding the % cover for each plant species. The data were then standardised to deal with the variable-sized

plots, and 4th root transformed to boost the presence of smaller species at lower covers. All other default settings in the program were used. Techniques included ANOSIM (analysis of similarities) tests (global and pair-wise), hierarchical agglomerative clustering of plots into groups and non-metric multi-dimensional scaling (MDS) (Clarke and Warwick, 2001; Clarke and Gorley, 2006). These methods, also employed by for example Davies *et al.* (2005), Corenblit *et al.* (2009), Corenblit *et al.* (2014) and Reinecke *et al.* (2015), were selected because they generally produce clear species patterns (McCune *et al.*, 2002).

ANOSIM, a non-parametric permutation procedure analogous to ANOVA, was first used to determine significance of separation between groups. This procedure requires prior identification of the sample plots into groups using factors (duplicates are needed per group). Factors are used to define a group structure for multivariate hypothesis testing. This group structure is vital in the interpretation of which variables (e.g. species) are largely responsible for distinguishing specific groups (Clarke and Gorley, 2006). Factors at the site scale included the confinement setting (confined, semi-confined and unconfined) and water availability. The latter was related to a wet or dry main channel bed at each of the study sites. Factors at the sample plot scale included the site (numbers 1-13), cross-section (numbers 1-39) and landform (numbers 1-18). One-way (e.g. landform as a factor) and two-way nested (e.g. cross-section and site factors) ANOSIM analyses were conducted. An output of the degree of difference between groups is provided through the global R^2 values. R^2 values > 0.6 indicate strong or significant differences, 0.3 to 0.6 values indicate intermediate or moderate differences and values < 0.3 indicate weak or no distinguishable differences (Clarke and Gorley, 2006). Only data with high to moderate global R^2 results were analysed further.

A cluster analysis was then performed using the Bray-Curtis similarity index by means of a resemblance matrix. Bray-Curtis similarity coefficients were calculated between groups. MDS ordination utilizes the resemblance matrix and represents samples in two or three dimensions. Sample plots that are close together (i.e. clustered plots) have very similar community composition while those further apart reflect dissimilarity in community composition. Clustering and MDS ordination works well if the samples are strongly grouped (Clarke and Warwick, 2001; Clarke and Gorley, 2006). In ordination, a stress value of < 0.05 gives excellent representation with no prospect of misleading interpretation. In contrast, a stress value of > 0.3 should be treated with caution since it indicates that the points are close to being arbitrarily placed in the ordination. Stress is the distance in the MDS plot predicted from the fitted regression line corresponding to dissimilarity. Large scatter leads to large stress (Clarke and Warwick, 2001). The resultant dendrogram and 2-dimensional MDS plot were imported into CorelDraw V13 where the different community groups and subgroups were manually demarcated. Subgroups were delimited using a cut-off of $\geq 40\%$ information remaining (Reinecke and Brown, 2013).

Typical and differentiating species

The SIMPER (similarity percentages) routine was then used to discern typical or dominant and differentiating species between the vegetation groups at the sampling plot or geomorphic landform scale. Typical species were limited to the five highest similarity coefficient/standard deviation (Sim/SD) values. However, where Sim/SD values were absent (< 2 sample plots), the species with the five highest percentage cover were selected. The results, arranged from highest to lowest, were tabulated. Differentiating species were limited to the three highest dissimilarity coefficient/standard deviation (Diss/SD) values and also arranged from highest to lowest in table format. In both cases a cut-off value of ≥ 1.5 was used which indicated statistically valid differences (M.K. Reinecke, Southern Waters Ecological Research and Consulting cc, Cape Town, pers. comm., 2015). However, at a few geomorphic landforms typical species with slightly lower values were also included.

Comparison between species data and environmental variables

The BIO-ENV and BVSTEP procedures in PRIMER V6 were then applied to determine which of the measured environmental variables best explained the variation in species composition at the plots or landforms. These procedures both search for high rank correlations in the data through primary (abiotic) and secondary (biotic) matrices. They explore the relationships between all the variables. Subsets of abiotic variables (usually < 17) are matched to assemblage patterns. BIO-ENV carries out a full search for all possible combinations whereas BVSTEP uses a forward-stepping and backward-elimination stepwise process to arrive at a possible optimal set. Available environmental variables incorporated in the analysis included: elevation above and distance away from the active channel thalweg (Section 5.2.1), particle sizes, soil pH, organic carbon, nitrogen and phosphate (Section 5.2.4). The data set was first log transformed and then normalised to deal with data differences (e.g. diverse units) between the environmental variables (Clarke and Gorley, 2006). Strong correlations between specific variables and groups were indicated by the highest correlation values (Clarke and Warwick, 2001).

6.3 Results

6.3.1 Plant community distribution patterns

General vegetation characteristics of the Baviaanskloof

Three hundred and thirty seven vascular plant species belonging to 76 families were recorded in 289 quadrats at the 13 study sites (Appendices 6.1 and 6.2). Overall, herbaceous species were the most commonly recorded growth form, followed by shrubs and then trees (Figure 6.1a). The family Asteraceae comprised the most plant species (50), mostly annual herbaceous plants. The herb category contained largely grasses and other herbs. Small

numbers of climbers, helophytes, hydrophytes and scramblers also occurred. Woody and succulent shrubs dominated the shrub species. In addition, an insignificant number of parasitic and climbing shrubs were present (Table 6.4). The majority of the plant species (229) were perennial (mostly shrubs and herbs) (Figure 6.1b) and indigenous, 280 (Figure 6.1c). Only 45 exotics were recorded. Of these 12 were weeds. Invaders (*Eucalyptus* sp. and *Jacaranda mimosifolia*) and proposed invaders (*Agave Americana* and *Rumex crispus*) were also noted (Table 6.4). Most of the weeds (eight species) occurred at semi-confined study site 8. This was then followed by study sites 7 (six species) and 12 (five species) which were confined and semi-confined respectively (Appendices 6.1 and 6.2).

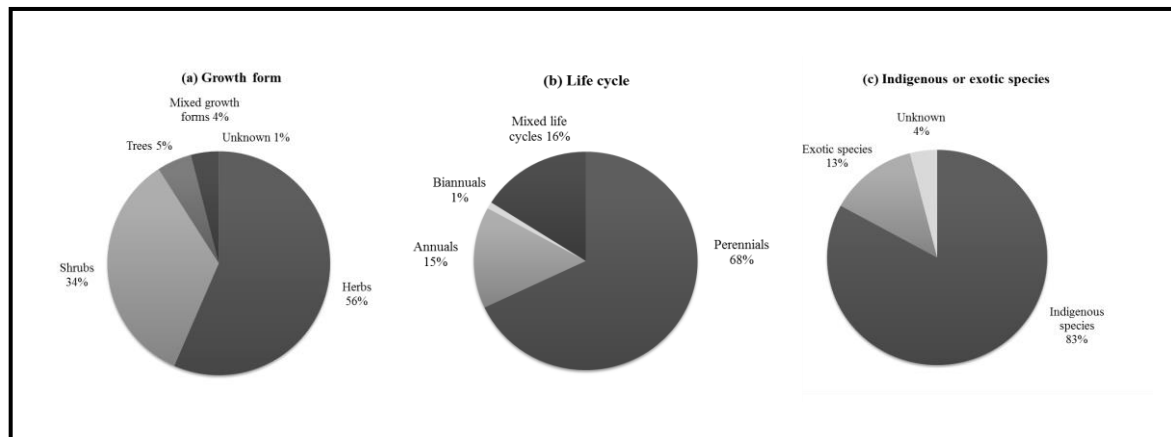


Figure 6.1: Vegetation characteristics in the study area.

The confined valley setting site 2 (Verlatenrivier) was the most species rich, while site 11 (Baviaanskloof Nature Reserve) was the poorest. Overall, sites 7 and site 2 were the richest in herbs and shrubs respectively (Table 6.5). Similarly, sites 2 and 11 were typified by the most grass species. These two sites were also more disturbed or degraded (pers. obs.). Although succulents were encountered at all the sites, the greatest cover was at site 11. The majority of the trees and geophytes were found at sites 6 and 2 respectively. Helophytes were only common to sites 6 and 7 (Beacosnek). During the sampling period site 6 was the most intact (i.e. in the best condition) of all 13 study sites. This heterogeneous, more natural site had very good structural diversity and maturity of vegetation. The channel banks were well vegetated (i.e. increased channel stability). Site 7 was also in a fairly good condition and similar to site 6 with low disturbance (pers. obs.). Small numbers of hydrophytes and mixed vegetation growth forms were recorded at all the sites, whilst only site 2 lacked climbers. Site 6 supported the most climbers. Parasites and scramblers were absent at all the confined study reaches (Table 6.5).

When examining the geomorphic surfaces (Appendix 5.1), floodplains or flood benches (64 m² plot sizes) generally supported the most species. Site 7 was the only site where the backwater area (a 48 m² plot with 36 species) and secondary channel left bank (a 20 m² plot

with 29 species) were richer in species. As expected, the channel bed was, with a few exceptions, mostly the poorest in species richness.

Table 6.4: Comparison of herb, shrub and exotic vegetation categories, Baviaanskloof.
Growth form definitions as per Table 6.3. Exotic categories after DEA (2014).

Vegetation categories	Number of species (%)
Herbs	
Scramblers	2 (1)
Helophytes	6 (3)
Climbers	6 (3)
Hydrophytes	7 (4)
Succulents	14 (7)
Geophytes	14 (7)
Grasses	32 (17)
Other herbs	111 (58)
Shrubs	
Climbers	3 (3)
Parasites	4 (4)
Succulents	19 (17)
Other woody shrubs	87 (76)
Exotics	
Proposed invaders	2 (4)
Invaders	2 (4)
Weeds	12 (27)
Other exotics	29 (64)

Table 6.5: Species richness (i.e. plant numbers) per study site, Baviaanskloof.

Growth form definitions and plant species as per Table 6.3 and Appendices 6.1 and 6.2 respectively.

Vegetation growth form categories	Confined study sites				Semi-confined study sites				Unconfined study sites				
	2	6	7	11	1	3	8	12	4	5	9	10	13
Climbers	0	4	2	2	2	1	5	3	2	2	3	5	1
Geophytes	6	2	2	1	5	3	3	2	4	7	8	6	1
Grasses	14	11	10	14	16	11	11	10	11	11	10	16	13
Helophytes	0	3	4	0	0	0	2	4	1	0	0	0	3
Herbs	35	30	38	27	42	20	51	33	37	32	37	28	33
Hydrophytes	2	2	2	1	0	0	1	3	1	0	1	1	0
Mixed growth forms	3	3	1	2	6	3	5	1	1	2	2	3	1
Parasites	0	0	0	0	0	1	3	0	2	1	3	1	1
Scramblers	0	0	0	0	0	1	1	0	1	1	1	0	1
Shrubs	29	22	22	22	33	24	30	20	39	39	45	38	18
Succulents	8	8	8	9	14	7	12	4	9	10	15	16	8
Trees	3	5	2	4	2	3	9	3	2	4	5	4	3
Total number of species	100	90	91	82	120	74	133	83	110	109	130	118	83

At the semi-confined valley setting sites 8 (Zaaimanshoek) and 3 (Kasey) had the highest and lowest number of species respectively in the entire study area (Table 6.5). The following overall trends are evident when comparing the four semi-confined sites. Site 1 (Nuwekloof) and site 8 were the richest in herbs, shrubs and succulents. This site also supported the most grasses and geophytes, while site 8 supported the most climbers and parasites. Species typical of wet or moist habitats such as hydrophytes and helophytes were only common to sites 8 and 12 (Baviaanskloof Nature Reserve). The highest species numbers pertaining to these two growth forms were recorded in the reserve (Table 6.5). At sites 1 and 12, floodplain surfaces were richest in species with 30 and 24 species respectively. Main channel banks at site 3 were richest in species with, for example, 30 species encountered at quadrat 3.1.B (a 32 m² plot). At site 8 the flood bench (a 48 m² plot) and secondary channel left bank (a 16 m² plot) supported the most plant species, 38 and 37 respectively. Although the species varied, a repeating pattern was displayed at the semi-confined reaches with main or secondary channel beds generally having the lowest plant species numbers.

Site 8 was a very complex and dynamic site. It was however contradictory in that it had good vegetation structure and diversity but it was also very impacted by human activities. Disturbance at this site was linked to overgrazing, numerous paths and wood cutting (pers. obs.). This in turn was accompanied by plant invasion. In the entire study area, the most trees and exotics (32 species) occurred here. Exotic species included for example the tree *Tecoma stans*, the shrub *Solanum mauritianum* and the herb *Datura stramonium* (Appendices 6.1 and 6.2). Site 3 with its modified main channel banks (Appendix 5.3) was probably one of the most degraded sites in the whole study area. This site was in a very poor condition and dominated by pioneer species (pers. obs.). However, it only contained five exotics. Two of these exotic species were weedy grass species, *Pennisetum clandestinum* and *Pennisetum setaceum* (Appendices 6.1 and 6.2). Similarly, even though site 1 was less impacted it was somewhat homogenous in species composition and dominated by grasses. Site 12 had experienced a fire but overall it was still in a good condition (pers. obs.).

At the unconfined valley setting the most plant species were present at site 9 (Rus en Vrede) and the least at site 13 (Baviaanskloof Nature Reserve) (Table 6.5). Most of the shrub and tree species also occurred at site 9. Site 4 (Verlorenrivier) and site 9 supported the highest number of herb species. Site 10 (Zandvlakte) and site 13 were the richest in grass species. The most succulents were found at sites 9 and 10. Helophytes were limited to site 13. Only one annual hydrophytic herb species (*Salvia stenophylla*) were identified at sites 4, 9 and 10. Scramblers were common to all the sites except for site 10. Site 10 was, however, the richest in climbers. Parasitic shrubs were present at all the unconfined sites with site 9 supporting the most. Sites 9 and 5 (Uitslag) had the greatest cover of geophytes (Table 6.5). When looking at the geomorphic surfaces specifically, the main channel bank (a 32 m² plot) and flood bench (a 64 m² plot) at site 10 supported the most species, 31 and 25 respectively. With a few exceptions, channel beds were the poorest in species at sites 4, 5 and 9. This contrasted with sites 10 and 13 where the lowest species diversity was associated with, for example, the active

and secondary channel banks, a flood bench and a lateral bar. Concerning declared exotics, the most species were recorded at sites 9 and 13. Five of the 15 exotic species at site 9 were weeds. Similarly, three of the 13 exotic species in the reserve were weeds (Appendices 6.1 and 6.2).

In general, site 4 was homogenous in species composition and very grassy. Site 5 had a lot in common with site 4 but was more degraded and impacted. This site was in a very poor condition with predominance of pioneer species. Furthermore, fence line boundaries created mosaic effects and different age cohorts. Site 9 was the largest site in the entire study area and very variable. It exhibited dense vegetation growth across a relatively broad valley floor. Also, fence line boundaries resulted in different community structures adjacent to each other. At sites 4, 5 and 9 agricultural pressure was intense. Site 10 was very similar to site 9 both in structure and species assemblages. The main difference was, however, that site 10 was no longer being actively farmed; it was in a process of recovery. Overall, site 13 had good structure and development of the vegetation. This site was very similar to the semi-confined study site 12 (pers. obs.).

The highest grass cover was at the confined sites at a backwater area, point bar and secondary channel left banks (Figure 6.2). The highest herb cover was at the semi-confined sites at an island, a point bar and secondary channel right banks. The highest shrub cover also occurred here on scroll and mid-channel bars and secondary channel right banks. In addition, the confined (e.g. at the floodplain) and semi-confined (e.g. at the main channel right banks) sites had the highest tree coverage. The highest succulent and climber coverages were at the unconfined sites. Succulents dominated on islands and lateral bars while climbers dominated on the secondary channel and tributary channel right banks. The highest coverages of helophytes and hydrophytes were mainly restricted to the main channel bed (all sites), backwater area (confined sites) and terrace (unconfined sites).

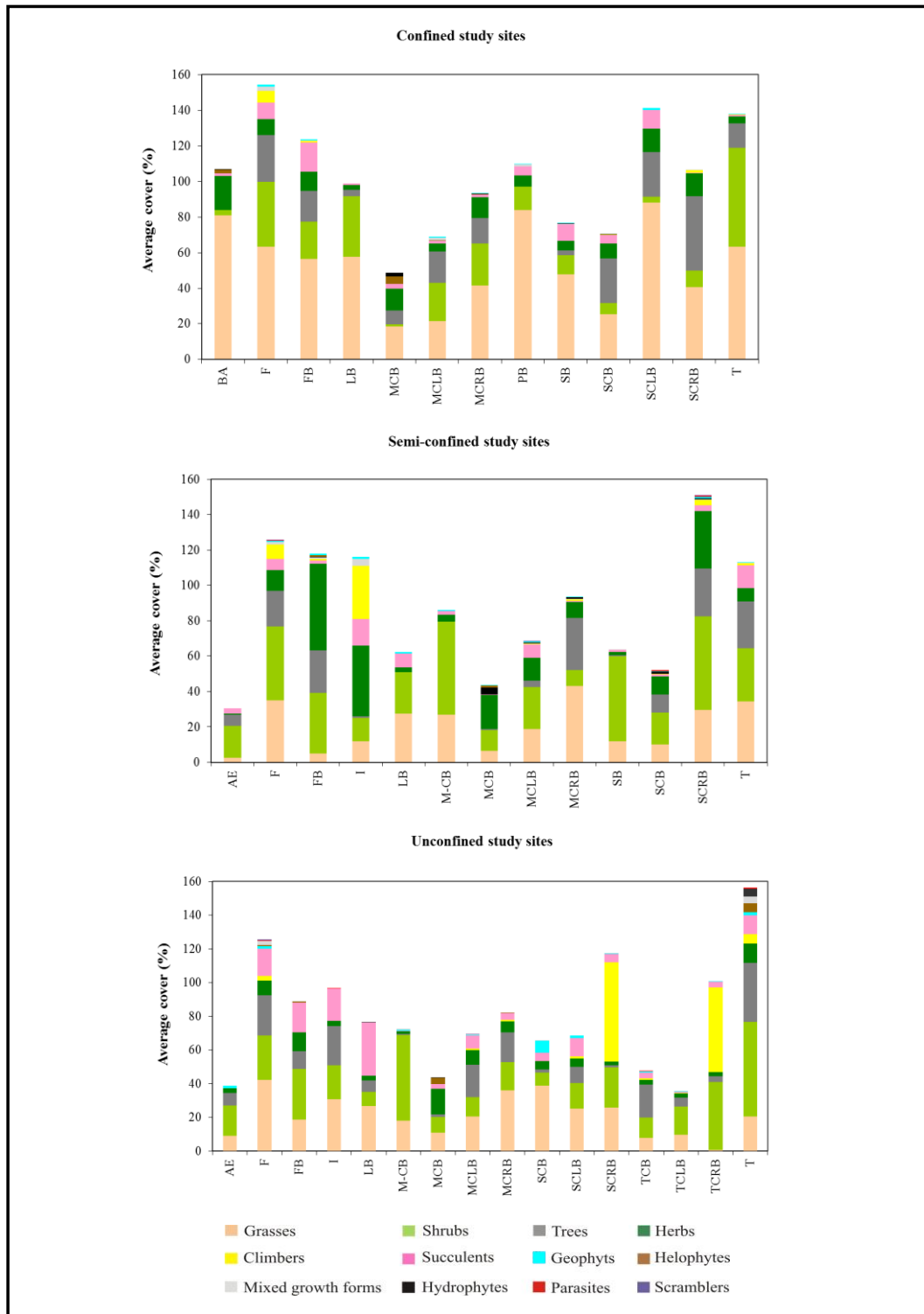


Figure 6.2: Vegetation growth forms associated with geomorphic landforms.

Growth form definitions and geomorphic landform codes as per Tables 6.3 and 5.1 respectively.

Comparison between all the sites

The global ANOSIM test of species abundances between the 13 sites revealed a very weak link between plant distribution patterns and the three valley confinement settings ($R^2 = 0.122$). Interpretations of patterns between valley confinement settings were therefore not considered any further. However, the pair-wise tests did indicate moderate vegetation differences between confined and unconfined valley settings ($R^2 = 0.356$). Thus, variation in confinement (valley width) and its effect on stream power did have some influence on the vegetation patterns. The higher stream power at confined reaches means that the plants in these reaches are more likely to suffer flood damage.

In contrast, the global R^2 test based upon species abundances between sites with water availability as a factor indicated significant differences between vegetation groups ($R^2 = 0.704$). Cluster and MDS analyses confirmed a strong link between plant distribution patterns and water availability. The cluster dendrogram and MDS ordination plot were in agreement, both showing two groups (Figure 6.3). Moreover, the MDS ordination plot had a stress value of 0.1 which also indicated robust vegetation groups. The two groups of sites were closely related to flow permanence, i.e. the absence or presence of surface flow at the Baviaanskloof River. Sites of the left hand division (Group 1) had a wetted channel or a near-surface groundwater table. The sites of the right hand division (Group 2) were primarily associated with a dry bed channel (i.e. indicating a deeper groundwater table) (Figures 6.3 and 2.9). Therefore, longitudinal and vertical changes in water supply (i.e. permanent versus intermittent flow related to surface-groundwater interactions) are reflected in the spatial distribution of the vegetation.

Group 1 consisted mostly of confined (6, 7 and 11) and semi-confined (8 and 12) sites. One surprising result was the presence of the unconfined site 13 in Group 1 (Figure 6.3) since support was found for the hypothesis that the water table at the unconfined sites is usually deeper (Section 5.3.2). However, the historical rainfall analysis (Section 3.3.4) indicated localized flash floods in the Baviaanskloof Nature Reserve in 2009. In addition, it showed that these unconfined reaches often flow after intense rainfall of > 50 mm (Section 3.3.1). In contrast, Group 2 consisted mostly of unconfined (4, 5, 9 and 10) and semi-confined (1 and 3) sites. Again, an unexpected result was the presence of the confined site 2 in Group 2 (Figure 6.3). Results presented later in the chapter show that aquatic and semi-aquatic plants are grouped with dry bed channel sites. The historical mapping results (Section 4.3.3) did reveal that this site was farmed in the past. In addition, just like the remainder of the Group 2 sites, it was also more disturbed or degraded during 2010 (pers. obs.).

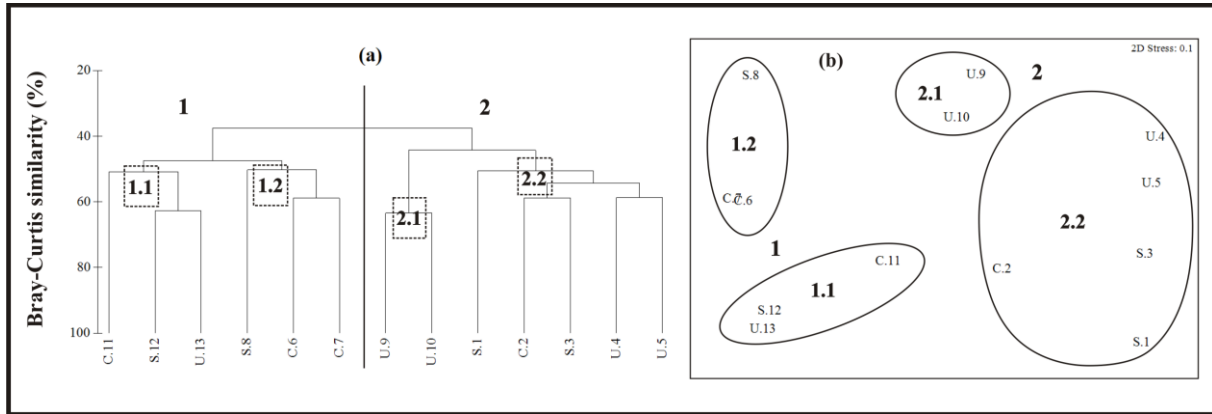


Figure 6.3: Cluster dendrogram (a) and MDS ordination (b) of Bray-Curtis similarity between species composition at all the sites.

Site codes e.g. C.11 indicates the confinement setting and site number. C = confined, S = semi-confined and U = unconfined. The solid and dotted lines represent the split between the different groups and subgroups.

Within Group 1, two subgroups formed at 46% similarity, with sites from Subgroups 1.1 and 1.2 being 50% similar. Study sites 6 to 8 separated from study sites 11 to 13 which were all located in the Baviaanskloof Nature Reserve. Semi-confined site plant species commonly grouped closely with the plant species from the confined study sites. Group 2 further divided into Subgroups 2.1 and 2.2 (Figure 6.3). The plant species which occupied the sites in Subgroup 2.1 were 62% similar, whereas those found in Group 2.2 were 51% similar. The vegetation at Subgroup 2.1 was limited to the unconfined study sites 9 and 10. On the other hand, Subgroup 2.2 vegetation was associated with sites 2 (confined), 1 and 3 (semi-confined) and 4 and 5 (unconfined). A third level of division clearly showed that the vegetation at sites 2 and 3 grouped closer while the vegetation at sites 4 and 5 were again more similar. Also, the vegetation at sites 6 and 7 grouped strongly whereas the plants at sites 12 and 13 were more similar (Figure 6.3). From the aforementioned results it is clear that there are statistically valid differences between the species composition at Groups 1 and 2. Thus, interpretation of patterns within the data was further focussed on each of the groups.

Comparison between Group 1 sites

The two-way nested ANOSIM analysis did not reveal significant plant species differences within the study sites. The global R^2 value was 0.077. This implies that the three cross-sections at each of the six sites were, in fact, replicates and not independent observations. Interpretations of patterns within site cross-sections were therefore not considered further. In contrast, the same analysis disclosed that the plant species at cross-sections differed between the six sites. Overall, the global R^2 value was 0.71, so vegetation of these study sites differed from one another. This result was also confirmed by the pair-wise comparisons which mainly exhibited R^2 values > 0.6 . Exceptions included sites 6 and 7 ($R^2 = 0.37$) and sites 12 and 13

($R^2 = 0.296$) which were more similar to each other. When considering species distribution patterns across sites at the geomorphic landform scale, the global R^2 test showed that the plants, in general, did not differ much between the 12 landforms ($R^2 = 0.278$). However, the pair-wise tests (14 comparisons in total) did indicate landform specific plants (Table 6.6). This result affirm a link between landforms and species composition. The strongest vegetation differences (pair-wise R^2 values > 0.6) were at a backwater area (site 7), floodplain surfaces (all sites), an island (site 8), the main channel bed (all sites), a lateral bar (site 11) and the terrace (site 12) (Tables 6.6 and 6.7).

Table 6.6: R^2 values for pair-wise tests of differences between factor groups or geomorphic landforms at Group 1.

A significant level of $\leq 5\%$ (*) is also indicated. Landform codes and study sites at Group 1 as per Table 5.1 and Figure 6.3 respectively.

Factor group, landform	3, F	4, I	5, LB	7, MCLB	10, SCLB	11, SCRB	12, T
1, BA	0.662						1.00
3, F				0.448*	0.349*		
4, I							1.00
5, LB							0.556
6, MCB	0.666*	0.365	0.625			0.434*	0.444*
7, MCLB			0.500				
8, MCRB	0.386*						
10, SCLB							0.463

Across sites, the plant species on 10 geomorphic surfaces were identified as being different. The geomorphic surfaces with the most number of plots included the floodplain, main channel bed and main channel right bank. The backwater area, island and lateral bar were only represented by one sample plot (Table 6.7). Table 6.7 also demonstrates that geomorphic surfaces at site 13 are similar to five geomorphic surfaces (i.e. sample plots grouped closely) at Group 1. This implies similar plant distribution patterns.

Table 6.7: Geomorphic landforms of Table 6.6 and their associated site information

Study sites at Group 1 as per Figure 6.3.

Landform	Site	Number of sites	Number of plots
Backwater area	7	1	1
Floodplain	6, 7, 8, 11, 12, 13	6	31
Island	8	1	1
Lateral bar	11	1	1
Main channel bed	6, 7, 8, 11, 12, 13	6	18
Main channel left bank	7, 8, 11, 12, 13	5	8
Main channel right bank	6, 7, 8, 11, 12, 13	6	10
Secondary channel left bank	7, 8, 11	3	4
Secondary channel right bank	6, 8, 13	3	5
Terrace	12	1	3

The most common plant species on each of the geomorphic landforms are presented in Table 6.8. Photographs of some of these typical species are also displayed in Figure 6.4. Additional information on these species is available at the following websites: <http://redlist.sanbi.org/> and <http://www.ispotnature.org/communities/southern-africa>. The SIMPER analysis showed that these plant species consisted mainly of herbs and shrubs that were predominantly perennial and indigenous. High cover exotics were found only in a backwater area, an island and the main channel bed and banks. Examples included the grasses *Pennisetum clandestinum* and *Pennisetum setaceum* (both weeds) and the herbs *Datura stramonium* and *Rumex crispus* (a proposed invader) (Table 6.8 and Appendix 6.2).

The analysis further demonstrated that instream, bar and wet bank vegetation assemblages were associated primarily with free floating and rooted herbaceous species (e.g. hydrophytes and grasses). However, high cover riparian tree species, such as *Salix mucronata*, are also present on the wet bank. These communities must survive the stresses of high flow velocities and changing substrata generally associated with these erosion and deposition dominated landforms. They are mainly pioneer or early successional communities. They consisted of the sedge *Cyperus textilis* and the hydrophytes *Persicaria attenuata* and *Persicaria decipiens* (Table 6.8 and Appendix 6.2). Other typical high cover herb species also included *Cheilanthes hirta*, *Mentha longifolia* and the grass *Panicum deustum* (Table 6.8, Figure 6.4 and Appendix 6.2).

Dry bank and upland vegetation assemblages usually contained a mix of rooted herbs (particularly grasses), shrubs and trees (Table 6.8). These communities generally occurred on deposition dominated landforms such as the floodplain and terrace (Table 6.7). The shrub component was dominated by *Chrysocoma ciliata* (secondary channel right bank), *Leonotis ocymifolia* (secondary channel left bank), *Lycium cinereum* (floodplain) and *Sutera halmifolia*, lateral bar (Table 6.8, Figure 6.4 and Appendix 6.2). The tree component was completely dominated by *Vachellia karroo* (previously known as *Acacia karroo*) (Figure 6.4). The degree of similarity between the species abundances on the differing landforms ranged from 17-42 % reflecting some variance in the distribution of plants between landforms. Characteristics of selected species are shown in Table 6.9.

Table 6.8: Typical species on each geomorphic landform, Group 1, as identified by PRIMER.

Species characteristics as per Appendix 6.2 and listed in decreasing order of importance. Av. sim = Average similarity coefficient, * = No value, less than 2 sample plots. Study sites at Group 1 as per Figure 6.3.

Landform	Av. sim (%)	Species
Backwater area	*	<i>Pennisetum clandestinum</i> , <i>Pennisetum setaceum</i> , <i>Mentha longifolia</i> , <i>Salix mucronata</i> , <i>Cotula australis</i> .
Floodplain	28.37	<i>Panicum deustum</i> , <i>Vachellia karroo</i> , <i>Lycium cinereum</i> , <i>Oxalis</i> sp.2, <i>Cotula australis</i> .
Island	*	<i>Cliffortia strobilifera</i> , <i>Datura stramonium</i> , <i>Cynodon incompletus</i> , <i>Salix mucronata</i> , <i>Zygophyllum foetidum</i> .
Lateral bar	*	<i>Sutera halmifolia</i> , <i>Cheilanthes hirta</i> , <i>Senecio glutinosus</i> , <i>Senecio leptophyllus</i> , <i>Hermannia althaeoides</i> .
Main channel bed	19.95	<i>Paspalum paspaloides</i> , <i>Salix mucronata</i> , <i>Cyperus denudatus</i> , <i>Persicaria attenuata</i> , <i>Persicaria decipiens</i> .
Main channel left bank	17.64	<i>Mentha longifolia</i> , <i>Oxalis</i> sp.2, <i>Panicum deustum</i> , <i>Rumex crispus</i> , <i>Searsia pyroides</i> .
Main channel right bank	18.15	<i>Vachellia karroo</i> , <i>Panicum deustum</i> , <i>Rumex crispus</i> , <i>Mentha longifolia</i> , <i>Pennisetum clandestinum</i> .
Secondary channel left bank	20.41	<i>Panicum deustum</i> , <i>Troglophyton capillaceum</i> , <i>Leonotis ocymifolia</i> , <i>Sisymbrium capense</i> , <i>Lepidium africanum</i> .
Secondary channel right bank	17.27	<i>Panicum deustum</i> , <i>Chrysocoma ciliata</i> , <i>Lepidium africanum</i> , <i>Sisymbrium capense</i> , <i>Cynodon incompletus</i> .
Terrace	42.15	<i>Cotula australis</i> , <i>Panicum deustum</i> , <i>Vachellia karroo</i> , <i>Cynodon incompletus</i> , <i>Lycium cinereum</i> .

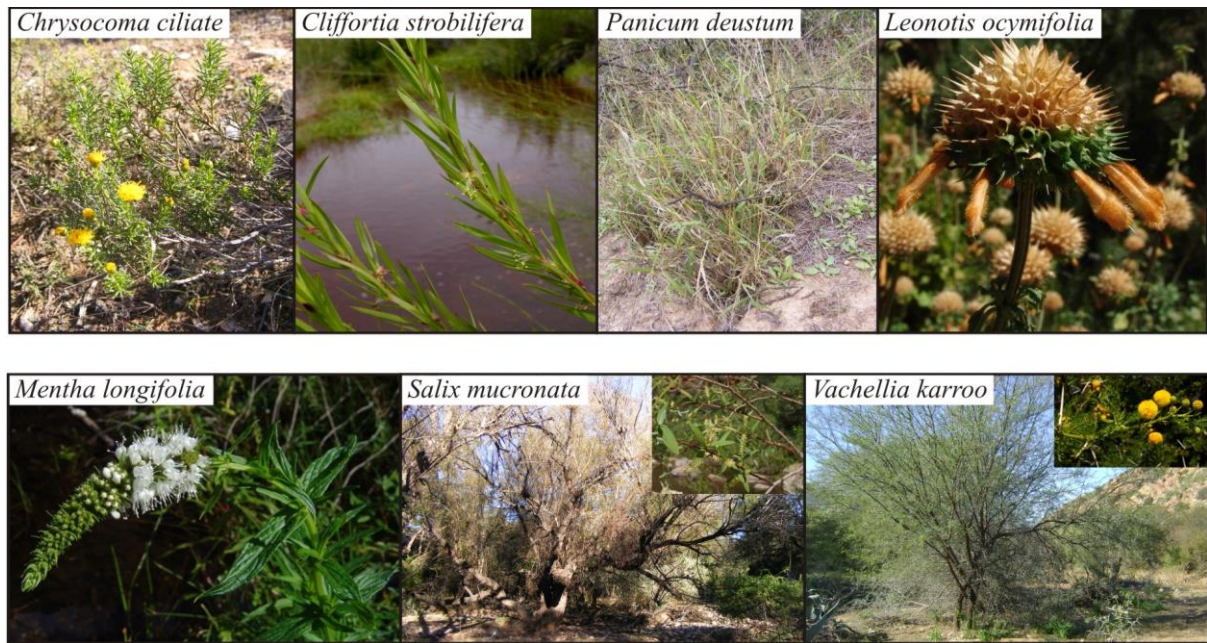


Figure 6.4: Photographs of typical species occurring on differing geomorphic landforms, Group 1.

Group 1 and species characteristics as per Figure 6.3 and Appendix 6.2 respectively. Geomorphic landforms are indicated in Table 6.8. Photographs by J. Raath, L. Smith-Adao and Vlok and Schutte-Vlok (2010).

Table 6.9: Characteristics of selected species from Groups 1 and 2 occurring on differing geomorphic landforms.

Species as per Figures 6.4 and 6.5 and Tables 6.8 and 6.13. View also Appendix 6.2. Growth forms as indicated in Table 6.3. After Gibbs Russell *et al.* (1990); le Roux *et al.* (1994); Shearing and van Heerden (1994); van Wyk and Gericke (2000); Brown and Brooks (2002); Coates Palgrave and Coates Palgrave (2002); Hartmann (2002); Vlok and Schutte-Vlok (2010) and Manning and Goldblatt (2012). Information was also sourced from Google (accessed 6-10 July 2015) using for example the SANBI website: <http://www.plantzafrica.com/>, R. Blanchard (CSIR, Stellenbosch, pers.comm., 2015), D. Euston-Brown (Scarborough, pers.comm., 2015), D. Le Maitre (CSIR, Stellenbosch, pers.comm., 2015) and C. Whitehouse (Phillipskop Mountain Reserve, Stanford, pers.comm., 2015).

Scientific name	Common name	Growth form	Life history	Height (m)	Reproductive strategy	Resprouter	Root system	Habitat preference
<i>Aristida congesta</i>	Tassel three-awn grass	Grass	Perennial	Up to 0.9	Seeds	Yes	Stoloniferous & rhizomatous	Rocky slopes, disturbed areas (e.g. old fields) & open eroded places.
<i>Chrysocoma ciliata</i>	Bitter bush	Shrub	Perennial	0.1-0.6	Seeds	No	Adventitious or fibrous	Rocky slopes, flats & disturbed & overgrazed areas.
<i>Cliffortia strobilifera</i>	Cone rice-bush	Shrub	Perennial	Up to 4 but mostly 3 or less	Seeds & vegetative multiplication	Yes	Adventitious or fibrous	Riverine (e.g. along river banks). Close to flowing or open water.
<i>Cyperus denudatus</i>	Winged sedge	Herb	Perennial	Up to 0.6	Seeds & vegetative multiplication	Yes	Adventitious or fibrous & rhizomatous	Riverine (e.g. along river banks), marshy & wetland areas.
<i>Cynodon incompletus</i>	Karoo quick grass	Grass	Perennial	0.05-0.3	Seeds & vegetative	Yes	Stoloniferous & adventitious or fibrous	Sandy flats, along roadsides, pastures & dry rocky areas.
<i>Diospyros lycioides</i>	Bluebush	Shrub	Perennial	2-3 but if small tree up to 7	Seeds	Yes	Adventitious or fibrous	Rocky slopes, riverine & flats.

Table 6.9: Continued from previous page.

Scientific name	Common name	Growth form	Life history	Height (m)	Reproductive strategy	Resprouter	Root system	Habitat preference
<i>Drosera peltata</i>	Drosera peltata	Succulent shrub	Perennial	Up to 1	Seeds	No	Adventitious or fibrous	Disturbed clayey or loamy soils on flats.
<i>Eragrostis curvula</i>	Weeping love grass	Grass	Perennial	0.3-1.2	Seeds	No	Adventitious or fibrous	Disturbed areas (e.g. old fields, roadsides) & pastures.
<i>Eragrostis lehmanniana</i>	Lehmann's love grass	Grass	Perennial	0.2-0.6	Seeds	No	Adventitious or fibrous	Disturbed areas (e.g. old fields) & sandy flats.
<i>Galenia procumbens</i>	Kraalbos	Shrub	Perennial	0.5-1	Seeds	No	Deep taproot with lateral roots	Disturbed areas (e.g. trampled soil) & stoney flats.
<i>Helichrysum rosom</i>	Bergankerkaroo	Shrub	Perennial	Up to 0.5	Seeds & vegetative multiplication	No	Adventitious or fibrous	Stoney slopes, ridges, kloof areas & flats.
<i>Leonotis ocymifolia</i>	Lion ear or wild dagga	Shrub	Perennial	1-3	Seeds & vegetative multiplication	Yes	Rhizomatous	Rocky slopes & sometimes in dry river beds.
<i>Mentha longifolia</i>	Wild mint	Herb	Perennial	Up to 1.5 but mostly 0.5-1	Seeds & vegetative multiplication	Yes	Rhizomatous	Riverine, marshy areas & seeps.
<i>Panicum deustum</i>	Reed or broad-leaved panicum	Grass	Perennial	Up to 2.5	Seeds	Yes	Rhizomatous	Rocky slopes & moist shady areas (e.g. along river banks).
<i>Salix mucronata</i>	Cape silver willow	Tree	Perennial	Up to 12 but can be < 5	Seeds & vegetative multiplication	Yes	Adventitious or fibrous	Riverine (e.g. along river banks).
<i>Vachellia (Acacia) karroo</i>	Sweet thorn	Tree	Perennial	Up to 15 but mostly 3-5	Seeds	Yes	Deep taproot with lateral roots	Very diverse, from riverine to coastal, low land, disturbed or upland areas.

The SIMPER analysis showed that the degree of dissimilarity between the species abundances at the differing landforms in the Group 1 study sites (Table 6.10) ranged from 68-91% reflecting great dissimilarity with some plants only occurring on particular landforms. Therefore, these plants were good differentiators for the various geomorphic surfaces. For example the shrub *Leysera gnaphaloides* and grass *Eragrostis curvula* were good differentiators for the lateral bar, main channel left bank and terrace. Similarly, the tree *Searsia pallens* and the herb *Chenopodium mucronatum* were good differentiating species for the main channel bed and lateral bar. In some cases a plant species, for example the grass *Pennisetum setaceum*, was a good differentiating species for two or more different landforms (e.g. the backwater area, floodplain and terrace) (Table 6.10).

Table 6.10: Differentiating species between geomorphic landforms, Group 1.

Group 1 as per Figure 6.3. Reported differentiating species are limited to Diss/SD values of ≤ 1.5 arranged from highest to lowest. Av. diss = average dissimilarity coefficient, Diss/SD = dissimilarity coefficient/standard deviation. Species characteristics as indicated in Appendix 6.2.

Landform	Av. diss (%)	Species	Diss/SD
Backwater area & floodplain	86.67	<i>Pennisetum setaceum</i>	11.90
		<i>Cyperus textilis</i>	11.90
		<i>Paspalum paspaloides</i>	11.90
Backwater area & terrace	90.76	<i>Pennisetum clandestinum</i>	27.57
		<i>Pennisetum setaceum</i>	27.57
		<i>Mentha longifoliam</i>	27.57
Island & terrace	76.93	<i>Cliffortia strobilifera</i>	29.45
		<i>Datura stramonium</i>	29.45
		<i>Salix mucronata</i>	29.45
Lateral bar & terrace	68.38	<i>Leysera gnaphaloides</i>	19.48
		<i>Eragrostis curvula</i>	19.48
		<i>Searsia pallens</i>	19.48
Main channel bed & floodplain	91.07	<i>Panicum deustum</i>	1.50
Main channel bed & island	88.97	<i>Datura stramonium</i>	8.51
		<i>Zygophyllum foetidum</i>	8.51
		<i>Agave Americana</i>	8.51
Main channel bed & lateral bar	93.80	<i>Searsia pallens</i>	5.44
		<i>Chenopodium mucronatum</i>	5.44
		<i>Pellaea calomelanos</i>	5.44
Main channel bed & terrace	90.49	<i>Lycium cinereum</i>	2.45
		<i>Vachellia karroo</i>	2.39
		<i>Panicum deustum</i>	1.77
Main channel left bank & lateral bar	90.96	<i>Metalasia sp.2</i>	7.83
		<i>Leysera gnaphaloides</i>	7.83
		<i>Eragrostis curvula</i>	7.83
Main channel right bank & floodplain	82.57	<i>Panicum deustum</i>	1.50
Secondary channel left bank & terrace	82.24	<i>Cynodon incompletus</i>	2.59
		<i>Lycium cinereum</i>	2.35
		<i>Troglophyton capillaceum</i>	1.60

The BIO-ENV and BVSTEP analyses revealed that the measured abiotic variables which best explained the variation in vegetation at the differing geomorphic landforms were: elevation above and distance away from the active channel thalweg, and fine sand (correlation value = 0.36). This output concurs with the aforementioned ANOSIM and SIMPER results (Tables 6.6 and 6.8). Plants on floodplain and main channel bed geomorphic surfaces, for example, differed because of their different habitat preferences associated with varied environmental conditions. The valley cross-section (Section 5.3.1) and sediment (grain size and soil chemistry, Section 5.3.3) analyses did show significant differences between these two geomorphic surfaces. However, this moderate or average correlation value for the best variable combination indicated that other factors such as water availability (as shown by the site scale analyses in this chapter) are also crucial in explaining the resultant species distribution patterns at Group 1.

Comparison between Group 2 sites

Similar to Group 1, the two-way nested ANOSIM analysis did not show significant plant species differences within Group 2 study sites. The global R^2 value was 0.025. This means that the three cross-sections at each of the seven sites were very similar (i.e. replicates). Interpretations of patterns within site cross-sections were thus not considered any further. The same analysis also revealed that the plants at cross-sections between the seven sites were very different. The global R^2 value was 0.838. Therefore, from a vegetation perspective the sites at Group 2 differed from one another. This finding concurred with the pair-wise comparisons which mainly displayed R^2 values of 1.0, which indicates strong relationships. When examining species distribution patterns across sites at the geomorphic landform scale, the global R^2 test overall showed that the plant species mostly did not differentiate between the 18 landforms ($R^2 = 0.163$).

However, the pair-wise tests (46 comparisons in total) indicated that some plants do prefer particular landforms (Table 6.11), thereby, confirming a relationship between geomorphic surfaces and species composition. The strongest plant species differences (pair-wise R^2 values > 0.6) were for example related to flood benches (five sites), tributary channel right banks (sites 5 and 9), scroll bars (sites 2 and 3), a point bar (site 2), secondary channel right banks (sites 1, 4 and 5) and terraces (five sites) (Tables 6.11 and 6.12). Across sites, the plants at 18 geomorphic surfaces were identified as being different. The geomorphic surfaces with the most number of plots included the floodplain, main channel bed and terrace. The least amount of sample plots were at point (one) and mid-channel (two) bars, artificial embankments (three) and tributary channel right banks (three) (Table 6.12).

Table 6.11: R^2 values for pairwise tests of differences between factor groups or geomorphic landforms at Group 2
A significant level of $\leq 5\%$ (*) is also indicated. Landform codes and study sites at Group 2 as per Table 5.1 and Figure 6.3 respectively.

Factor group, landform	2, FB	4, I	6, MCB	8, MCRB	9, M-CB	10, PB	11, SB	12, SCB	13, SCLB	14, SCRB	16, TCB	17, TCLB	18, TCRB
1, AE	0.314	0.333								0.323			
2, FB						0.643			0.306*		0.560*	0.361*	0.853*
3, F					0.334*	0.540*					0.354*		0.438*
4, I													0.667*
5, LB													0.446
6, MCB													0.399*
7, MCLB											0.306*		0.562*
8, MCRB													0.528*
9, M-CB												0.357	0.375
10, PB		0.49*		0.609*		1			0.333		0.388	0.750	
11, SB		0.800		0.622					0.406*			0.388*	0.703*
12, SCB		0.429*		0.300*									0.519*
14, SCRB						0.383							0.631*
15, T	0.347*				0.561*	0.760	0.357*	0.410*		0.412*		0.319	
			0.377*			0.675							

Table 6.12: Geomorphic landforms of Table 6.11 and their associated site information.

The plants on these landforms were identified as being different. Study sites at Group 2 as per Figure 6.3.

Landform	Site	Number of sites	Number of plots
Artificial embankment	3, 5	2	3
Flood bench	2, 3, 4, 9, 10	5	14
Floodplain	1, 2, 3, 4, 5, 9, 10	7	45
Island	4, 9, 10	3	6
Lateral bar	2, 3, 9, 10	4	5
Main channel bed	1, 2, 3, 4, 5, 9, 10	7	24
Main channel left bank	1, 2, 3, 4, 5, 9, 10	7	12
Main channel right bank	2, 3, 4, 5, 9, 10	6	10
Mid-channel bar	1, 4	2	2
Point bar	2	1	1
Scroll bar	2, 3	2	5
Secondary channel bed	1, 4, 5, 10	4	9
Secondary channel left bank	4, 10	2	4
Secondary channel right bank	1, 4, 5	3	5
Terrace	1, 2, 5, 9, 10	5	22
Tributary channel bed	5, 9	2	7
Tributary channel left bank	5, 9	2	4
Tributary channel right bank	5, 9	2	3

Typical plant species on each of the geomorphic landforms are summarized in Table 6.13. Photographs of some of these common species are also shown in Figure 6.5. Supplementary information on these species is available at the following websites: <http://redlist.sanbi.org/> and <http://www.ispotnature.org/communities/southern-africa>. The SIMPER analysis indicated that these plant species were indigenous perennial shrub (mainly) and herb species. Trees occurred infrequently and were unevenly distributed. Exotic species were not abundant on the landforms at the Group 2 study sites. Examples however, included the herbs *Argemone ochroleuca* (a weed) and *Rumex crispus* (a proposed invader) as well as the grass *Pennisetum clandestinum* (a weed) (Table 6.13 and Appendix 6.2). High cover aquatic or semi-aquatic vegetation was absent. This result was unanticipated since some hydrophytes or helophytes were expected to occur at site 2 with its wetted channel. However, this finding helps to explain why site 2 forms part of Group 2 with its primarily dry bed channel sites (Table 6.2). Site 2 landforms are similar to seven Group 2 landforms (i.e. sample plots grouped closely). This implies that this site has indeed similar plant distribution patterns (Table 6.3).

The most abundant species included the grasses *Aristida congesta*, *Cynodon incompletus* (at most landforms), *Eragrostis curvula* and *Eragrostis lehmanniana*. Other herbaceous plants were *Lepidium africanum* and *Chenopodium mucronatum*. The shrub component was represented by for example *Chrysocoma ciliata*, *Drosanthemum ligue* (a succulent),

Diospyros lycioides, *Galenia procumbens*, *Helichrysum rosum*, *Lycium cinereum*, *Metalasia* sp.2 and *Selago saxatilis* (Table 6.13, Figure 6.5 and Appendix 6.2). *Vachellia karroo* (previously known as *Acacia karroo*) was the most abundant tree species (Table 6.12 and Figure 6.4). In general, dominant species included those species with affinities for specific geomorphic landforms and those species which occurred anywhere. In-channel, dry and wet bank, and upland vegetation assemblages also typically comprised a mix of rooted herbs (mostly grasses), shrubs and a few trees. The degree of similarity between the species abundance at the different landforms ranged from 13-37.5% reflecting some variance in the abundances of plants between landforms (Table 6.13).

Table 6.13: Typical species on each geomorphic landform, Group 2.

Species characteristics as per Appendix 6.2 and listed in decreasing order of importance. Av. sim = Average similarity coefficient, * = No value, less than 2 sample plots. Study sites at Group 2 as per Figure 6.3.

Landform	Av. sim (%)	Species
Artificial embankment	21.06	<i>Cynodon incompletus</i> , <i>Vachellia karroo</i> , <i>Galenia procumbens</i> , <i>Selago saxatilis</i> , <i>Arctotheca calendula</i> .
Flood bench	36.35	<i>Selago saxatilis</i> , <i>Eragrostis lehmanianna</i> , <i>Cynodon incompletus</i> , <i>Helichrysum rosum</i> , <i>Chrysocoma ciliata</i> .
Floodplain	25.53	<i>Cynodon incompletus</i> , <i>Eragrostis lehmanianna</i> , <i>Lepidium africanum</i> , <i>Lycium cinereum</i> , <i>Galenia procumbens</i> .
Island	39.24	<i>Lepidium africanum</i> , <i>Chrysocoma ciliata</i> , <i>Eragrostis curvula</i> , <i>Drosanthemum lique</i> , <i>Eragrostis lehmanianna</i> .
Lateral bar	31.27	<i>Chrysocoma ciliata</i> , <i>Lepidium africanum</i> , <i>Eragrostis lehmanianna</i> , <i>Drosanthemum lique</i> , <i>Cynodon incompletus</i> .
Main channel bed	17.14	<i>Cynodon incompletus</i> , <i>Metalasia</i> sp.2, <i>Eragrostis curvula</i> , <i>Lepidium africanum</i> , <i>Argemone ochroleuca</i> .
Main channel left bank	27.05	<i>Chrysocoma ciliata</i> , <i>Lepidium africanum</i> , <i>Eragrostis curvula</i> , <i>Eragrostis lehmanianna</i> , <i>Selago saxatilis</i> .
Main channel right bank	28.11	<i>Cynodon incompletus</i> , <i>Eragrostis lehmanianna</i> , <i>Lycium cinereum</i> , <i>Lepidium africanum</i> , <i>Vachellia karroo</i> .
Mid-channel bar	36.61	<i>Metalasia</i> sp.2, <i>Eragrostis curvula</i> , <i>Pelargonium glutinosum</i> , <i>Chrysocoma ciliata</i> , <i>Drosanthemum lique</i> .
Point bar	*	<i>Pennisetum clandestinum</i> , <i>Eragrostis curvula</i> , <i>Stoebe plumose</i> , <i>Rumex crispus</i> , <i>Arctotheca calendula</i> .
Scroll bar	37.45	<i>Eragrostis curvula</i> , <i>Cynodon incompletus</i> , <i>Helichrysum rosum</i> , <i>Lepidium africanum</i> , <i>Elytropappus rhinocerotis</i> .
Secondary channel bed	28.55	<i>Drosanthemum lique</i> , <i>Selago saxatilis</i> , <i>Eragrostis curvula</i> , <i>Metalasia</i> sp.2, <i>Eragrostis lehmanianna</i> .
Secondary channel left bank	25.47	<i>Cynodon incompletus</i> , Sp.8, <i>Eragrostis curvula</i> , <i>Eragrostis lehmanianna</i> , <i>Lycium cinereum</i> .

Landform	Av. sim (%)	Species
Secondary channel right bank	34.94	<i>Aristida congesta</i> , <i>Selago saxatilis</i> , <i>Drosanthemum lique</i> , <i>Limeum aethiopicum</i> , <i>Eragrostis lehmanianna</i> .
Terrace	21.48	<i>Lycium cinereum</i> , <i>Cynodon incompletus</i> , <i>Panicum deustum</i> , <i>Chenopodium mucronatum</i> , <i>Lepidium africanum</i> .
Tributary channel bed	13.93	<i>Vachellia karroo</i> , <i>Lepidium africanum</i> , <i>Oxalis</i> sp.2, <i>Leonotis ocymifolia</i> , <i>Eragrostis lehmanianna</i> .
Tributary channel left bank	21.33	<i>Lepidium africanum</i> , <i>Vachellia karroo</i> , <i>Cynodon incompletus</i> , <i>Selago saxatilis</i> , <i>Chrysocoma ciliata</i> .
Tributary channel right bank	13.12	<i>Clutia daphnoides</i> , <i>Diospyros lycioides</i> , <i>Lycium cinereum</i> , <i>Oedera genistaefolia</i> .

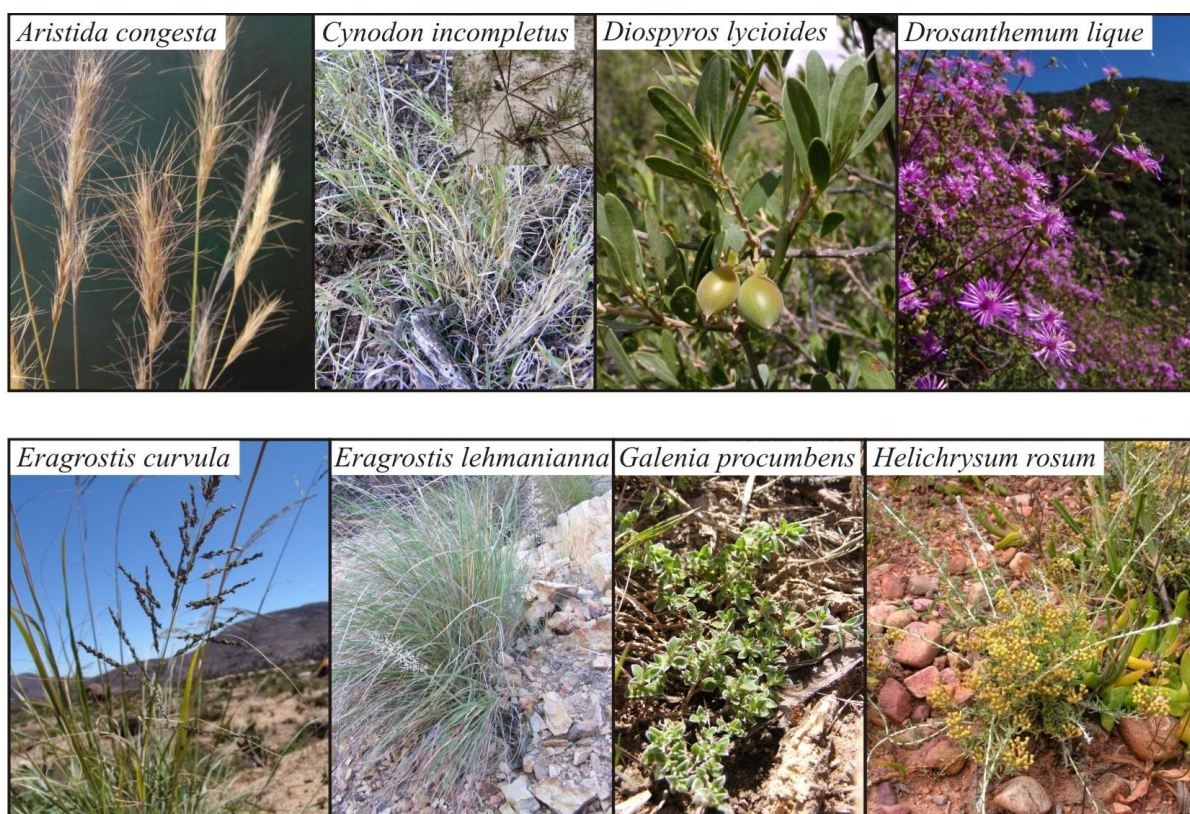


Figure 6.5: Photographs of typical species occurring on differing geomorphic landforms, Group 2.

Group 2 and species characteristics as per Figure 6.3 and Appendix 6.2 respectively. Geomorphic landforms are indicated in Table 6.12. Characteristics as per Table 6.9. Photographs by J. Raath and Vlok and Schutte-Vlok (2010).

The SIMPER analysis revealed that the degree of dissimilarity between the species abundance at the different landforms ranged from 71-92.7% implying great dissimilarity with some plant species only present on certain landforms (Table 6.14).

Table 6.14: Differentiating species between geomorphic landforms, Group 2.

Group 2 as per Figure 6.3. Reported differentiating species are limited to Diss/SD values of ≤ 1.5 arranged from highest to lowest. Av. diss = average dissimilarity coefficient, Diss/SD = dissimilarity coefficient/standard deviation. Species characteristics as indicated in Appendix 6.2.

Landform	Av. diss (%)	Species	Diss/SD
Artificial embankment & flood bench	73.27	<i>Eragrostis lehmanianna</i>	1.61
Artificial embankment & island	71.98	<i>Galenia procumbens</i>	1.76
		<i>Drosanthemum lique</i>	1.68
		<i>Cynodon incompletus</i>	1.53
Artificial embankment & secondary channel right bank	77.25	<i>Cynodon incompletus</i>	2.64
		<i>Aristida congesta</i>	2.19
		<i>Drosanthemum lique</i>	1.87
Flood bench & point bar	80.59	<i>Ruschia rigens</i>	6.31
		<i>Pennisetum setaceum</i>	6.31
		<i>Mentha longifolia</i>	6.31
Flood bench & secondary channel left bank	73.76	Sp.8	1.56
Flood bench & tributary channel bed	82.77	<i>Selago saxatilis</i>	1.50
		<i>Chrysocoma ciliata</i>	1.50
Flood bench & tributary channel right bank	88.27	<i>Eragrostis lehmanianna</i>	1.71
		<i>Chrysocoma ciliata</i>	1.63
		<i>Helichrysum rosum</i>	1.53
Floodplain & mid-channel bar	82.12	<i>Metalasia</i> sp.2	4.39
		<i>Pelargonium glutinosum</i>	3.52
		<i>Ifloga glomerata</i>	2.69
Floodplain & point bar	86.06	<i>Stoebe plumosa</i>	8.63
		<i>Pennisetum setaceum</i>	8.63
		<i>Mentha longifolia</i>	8.63
Island & tributary channel right bank	83.52	<i>Chrysocoma ciliata</i>	1.80
		<i>Drosanthemum lique</i>	1.66
Lateral bar & tributary channel right bank	85.34	<i>Chrysocoma ciliata</i>	6.13
		<i>Cynodon incompletus</i>	1.55
Main channel left bank & tributary channel bed	82.19	<i>Chrysocoma ciliata</i>	1.52
Main channel left bank & tributary channel right bank	86.07	<i>Chrysocoma ciliata</i>	2.21
Main channel right bank & tributary channel right bank	84.44	<i>Cynodon incompletus</i>	1.69
		<i>Eragrostis lehmanianna</i>	1.61
Mid-channel bar & island	71.24	<i>Pelargonium glutinosum</i>	4.58
		<i>Metalasia</i> sp.2	3.54
		<i>Ifloga glomerata</i>	2.31
Mid-channel bar & main channel right bank	83.97	<i>Ifloga glomerata</i>	8.82
		<i>Metalasia</i> sp.2	4.86
		<i>Pelargonium glutinosum</i>	4.49
Mid-channel bar & point bar	73.93	<i>Metalasia</i> sp.2	27.95
		<i>Drosanthemum lique</i>	23.64
		<i>Pennisetum clandestinum</i>	20.00
Mid-channel bar & tributary channel left bank	83.88	<i>Ifloga glomerata</i>	5.29
		<i>Pelargonium glutinosum</i>	3.59
		<i>Eragrostis curvula</i>	3.38
Mid-channel bar & tributary channel right bank	92.71	<i>Drosanthemum lique</i>	9.99
		<i>Metalasia</i> sp.2	9.78
		<i>Ifloga glomerata</i>	8.45

Consequently, these plant species were good differentiators for the different geomorphic surfaces. For example the herbs *Ruschia rigens* (a succulent) and *Mentha longifolia* as well as the grass *Pennisetum setaceum* (an exotic weed) were good differentiators for flood benches, floodplains and a point bar (Table 6.14 and Figure 6.4). Similarly, the shrubs *Metalasia* sp.2 and *Drosanthemum lique* were good differentiating species for the mid-channel bar and point bar. The shrub *Chrysocoma ciliata* was a good differentiating species for two or more different landforms (e.g. main channel left banks and tributary channel bed and banks) (Table 6.13 and Figure 6.4).

The BIO-ENV and BVSTEP analyses indicated that the measured environmental variables which best explained the variation in vegetation at the differing geomorphic landforms were: elevation and distance, fine and coarse sand, and available phosphorus (correlation value = 0.45). This output agrees with the aforementioned ANOSIM and SIMPER results (Tables 6.11 and 6.13). The valley cross-section (Section 5.3.1) and sediment (grain size and soil chemistry, Section 5.3.3) analyses also showed differences between the geomorphic landforms. For example, instream or stream side deposits were typically coarser than floodplain and terrace deposits. An exception was at some sites where coarse alluvial fan deposits are present on these geomorphic surfaces (e.g. site 9). Similarly, excessively high values for available phosphorus were recorded for floodplains (sites 5, 9 and 10) and terraces (sites 9 and 10). However, this average correlation value for the best variable combination demonstrated that other issues such as water availability (as presented by the site scale analyses) are also vital in explaining the resultant species distribution patterns at the Group 2 study sites.

6.4 Summary

This chapter intended to partially meet objective 3 of the study by using a vegetation survey and multivariate techniques in PRIMER V6 (Clarke and Gorley, 2006) to investigate plant community distribution patterns at site and geomorphic landform scales in the Baviaanskloof River valley. The results will be employed in Chapter 7 to interpret hydrogeomorphic process, landform and vegetation relationships on the valley floor. Key findings from this chapter and their implications for understanding these relationships are presented below.

General vegetation characteristics in the study area showed that herbs were the most commonly recorded growth form (56%, mainly grasses and other herbs), followed by shrubs (34%, succulents and other shrubs) and then trees (5%). The remainder of the growth forms were limited. Most of the plants were perennial (68%), thus having a longer lasting impact and indigenous (83%). Only 45 exotics (13%) were recorded of which 12 were weeds. In this study, exotic species therefore do not play a major role in valley floor changes. Concerning species richness, semi-confined sites had the highest and lowest number of species respectively. At most sites the channel bed had lower species diversity while floodplains or

flood benches had higher species diversity. However, it is clear from the results that there are both plant species adapted to high stream power surfaces and opportunistic species (e.g. upland species) colonizing these surfaces. For example at site 7 (Beacosnek) the backwater area and secondary channel left bank were richest in species.

Site 8 had good vegetation structure and diversity but it was also very impacted by human activities. In the entire study area, the most trees and exotics (32 species) occurred here. Site 3 was probably the most degraded site. This site was in a very poor condition and dominated by pioneer species. Degraded or disturbed sites are usually linked to landform instability. Confined study site 6 (Beacosnek) was the most intact (i.e. in the best condition). This site had very good structural diversity and maturity of vegetation.

Hydrophytes and helophytes were typical of wet or moist habitats. The most helophytes occurred at sites 6 (Beacosnek), 7, 12 and 13 (Baviaanskloof Nature Reserve). The most hydrophytes were present at sites 2, 6, 7 and 12. The highest succulent numbers were recorded at sites 9 (Rus en Vrede) and 10 (Zandvlakte). The highest geophyte numbers were recorded at sites 5 (Uitslag) and 9. Both succulents and geophytes are typically associated with dry or unfavourable conditions.

A comparison between all the study sites in PRIMER showed a very weak correlation between plant distribution patterns and the three valley confinement settings. The plants did not distinguish well between the three settings. However, moderate vegetation differences were shown between confined and unconfined valley settings. Confined reaches tend to have higher stream power which means that the vegetation in these reaches is more likely to suffer flood damage than in unconfined reaches. In contrast, a strong relationship was found to exist between plant distribution patterns and water availability. There were significant differences between two groups of sites. These differences related to the discontinuities brought on by shifts between permanent and intermittent surface water in the Baviaanskloof River linked to surface-groundwater interactions. Wetted channel sites, or sites with a near-surface groundwater table, grouped closely (Group 1, sites 6-8 and 11-13). This included wetted channel semi-confined sites, which grouped with confined sites. Likewise, dry bed channel sites, or sites with a deeper groundwater table, grouped closely (Group 2, sites 1, 3 4, 5, 9 and 10). This included dry bed channel semi-confined sites, which grouped with unconfined sites. The presence of site 2 (i.e. a wetted channel) in Group 2 was unexpected but explained by its impacted state.

A comparison between Group 1 sites in PRIMER (i.e. sites with higher water availability) revealed that there were no significant plant species differences within the study sites. The three cross-sections at each of the sites were replicates. In contrast, the plant species at cross-sections between the sites were different. Therefore, from a vegetation perspective the study sites differed from one another.

The geomorphic landform scale analysis also indicated that some plants prefer particular landforms (i.e. they were landform specific), thus confirming a relationship between geomorphic landforms and species composition. For Group 1, across sites the plants on 10 geomorphic surfaces were identified as being different. The strongest vegetation differences were at a backwater area (site 7), floodplain surfaces (all sites), an island (site 8), the main channel bed (all sites), a lateral bar (site 11) and the terrace (site 12). Similar results were shown for Group 2 sites. For Group 2, across sites the plants at 18 geomorphic surfaces were identified as being different. The strongest plant species differences were at flood benches (five sites), tributary channel right banks (sites 5 and 9), scroll bars (sites 2 and 3), a point bar (site 2), secondary channel right banks (sites 1, 4 and 5) and terraces (five sites).

The PRIMER analysis also showed that typical plant species at Group 1 and 2 sites consisted mainly of herbs and shrubs that were predominantly perennial and indigenous. Exotic species were not abundant on landforms. At Group 1 sites (wetter), instream and marginal vegetation assemblages were mostly associated with herbs (e.g. hydrophytes and grasses). However, tree species such as *Salix mucronata* was also present on the wet bank. These species are mainly pioneer or early successional species which are adapted to the regularity of flows that inundate these erosion and deposition dominated geomorphic landforms. They included the sedge *Cyperus textilis* and the hydrophyte *Persicaria attenuata*. Other typical high cover herb species also included *Mentha longifolia* and the grass *Panicum deustum*. Dry bank and upland vegetation assemblages usually contained a mix of herbs (mainly grasses), shrubs and trees. These species occurred on deposition dominated landforms such as the floodplain and terrace where flow events are less frequent. They are adapted to the dry conditions. The shrub component was dominated by for example *Chrysocoma ciliata* and *Sutera halmifolia*. The tree component was dominated by *Vachellia (Acacia) karroo*.

At Group 2 sites (drier), abundant tree species were limited while high cover aquatic vegetation was completely absent. The most abundant species included the grasses *Aristida congesta*, *Cynodon incompletus* (at most landforms) and *Eragrostis curvula*. Other herbs were *Lepidium africanum* and *Chenopodium mucronatum*. The shrub component was represented by for example *Drosanthemum lique* (a succulent), *Lycium cinereum*, and *Selago saxatilis*. *Vachellia karroo* was the most abundant tree species. Dominant species included those species with affinities for specific geomorphic landforms and those species which occurred anywhere. Instream, dry and wet bank and upland vegetation assemblages were comprised of a mix of herbs (mostly grasses), shrubs and a few trees.

The results demonstrated that geomorphic landforms and vegetation assemblages are linked along a lateral gradient according to the structural adaptations of the plants to disturbance regimes. This lateral gradient in plant distribution can also be explained by life history traits that affect a plant's adaptation to disturbance regimes. Life history traits (e.g. efficient seed dispersal) of plants are closely related to the natural dynamics of their environment. Plant

distribution patterns of adjacent landforms are similar but decrease in similarity with landforms further away. This lateral pattern is stronger at Group 1 sites (confined and semi-confined sites). Landforms experiencing less flooding have more mature to old vegetation assemblages (i.e. trees and shrubs) since floods generally do not reach these landforms unless in an extreme event. For example, trees occurred on floodplain and terrace geomorphic surfaces at Group 1 sites.

The results also reflected great dissimilarity, with some plants only occurring on certain landforms. Common differentiating species distinguishing geomorphic landforms at Group 1 included the shrub *Leysera gnaphaloides* and grass *Eragrostis curvula*. These species were good differentiators for the lateral bar, main channel left bank and terrace. In some cases a plant species, for example the grass *Pennisetum setaceum*, was a good differentiating species for two or more different landforms (e.g. the backwater area, floodplain and terrace). Common differentiating species distinguishing geomorphic landforms at Group 2 included the herb *Ruschia rigens* (a succulent) and the grass *Pennisetum setaceum* (an exotic weed). These species were good differentiators for flood benches, floodplains and a point bar. The shrub *Chrysocoma ciliata*, was a good differentiating species for main channel left banks and tributary channel bed and banks.

The measured abiotic variables which best explained the variation in vegetation for Group 1 landforms were elevation and distance, and fine sand. For Group 2 landforms the distinguishing abiotic variables were elevation and distance, fine and coarse sand, and available phosphorus. Plants at floodplain and main channel bed geomorphic surfaces at Group 1 for example differed because of their different habitat preferences associated with varied environmental conditions.

Chapter 7: River valley inter-relationships discussion

7.1 Introduction

The preceding two chapters outlined the results of the 2010 field surveys and earth observation assessment. Chapter 5 dealt with physical river valley dynamics while Chapter 6 dealt with river valley vegetation patterns. The aim of this chapter is to interpret these results collectively by examining hydrogeomorphic process-form and vegetation relationships on the valley floor in light of study objective three (Section 1.4, Chapter 1). Objective three investigates the two-way links between hydrogeomorphic processes and landforms, including surface-groundwater interactions, and vegetation distribution patterns on the valley floor. This chapter will focus on possible explanations of why the observed valley floor characteristics differed between the three valley confinement settings. Biophysical and anthropogenic information from Chapter 2, from historical data obtained from Chapters 3 (rainfall, streamflow and climate chronology) and 4 (geomorphic and land cover change) also provided significant input into this chapter (Figure 1.2). The information in this chapter will then inform restoration efforts in the Baviaanskloof River valley (Chapter 8).

This interdisciplinary investigation clearly demonstrates a strong link between valley confinement setting, surface-groundwater interaction, cross-valley landforms, human activities and vegetation in the Baviaanskloof (Figure 7.1). Specifically, there are bi-directional relationships between vegetation and fluvial geomorphic process and form. Vegetation both affects and responds to hydrogeomorphic processes and their resulting landforms.

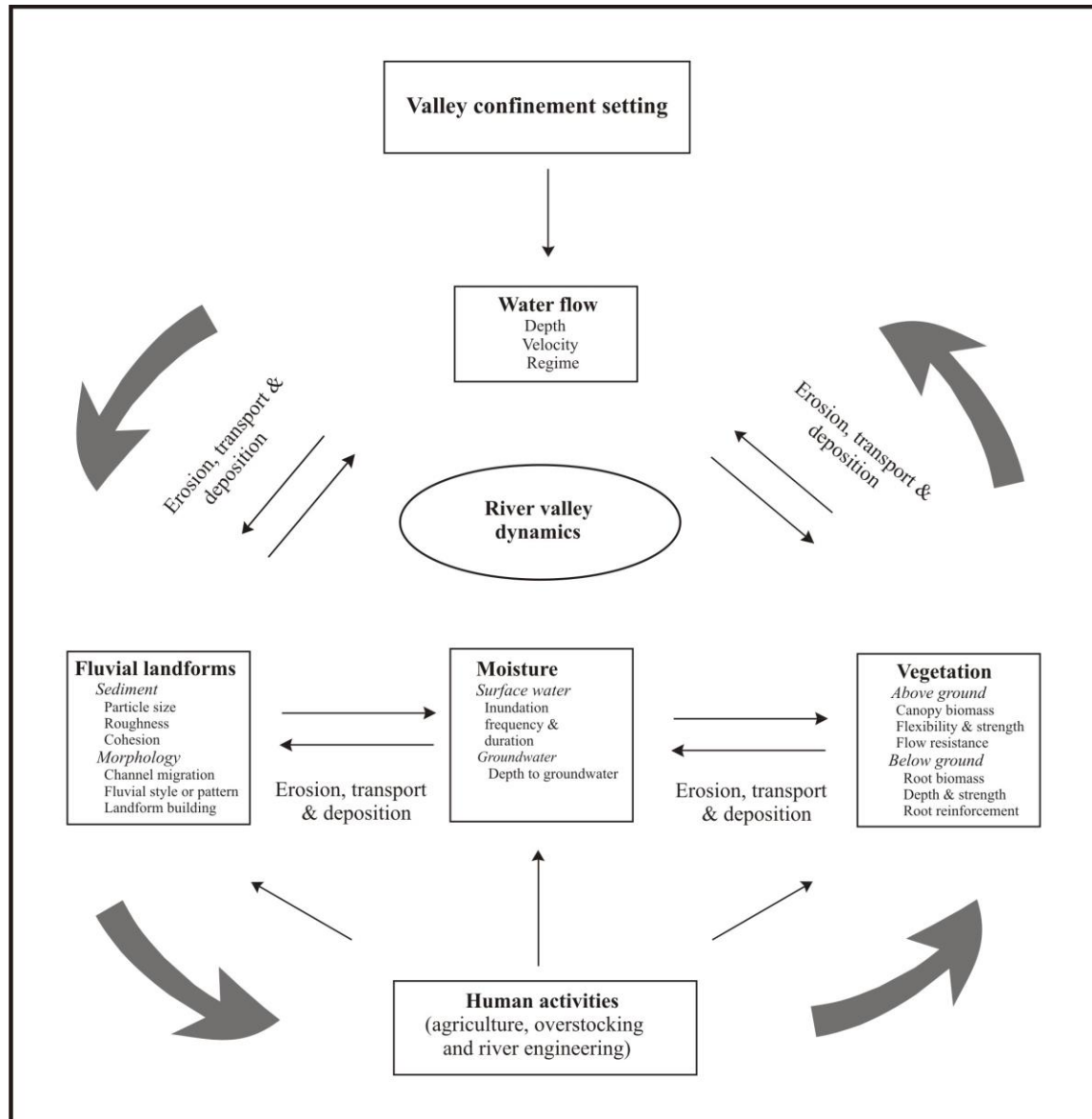


Figure 7.1: Links between valley confinement, surface-groundwater interactions, hydrogeomorphic processes and landforms, human activities and vegetation.

The discussion below is structured into two main sections: (1) physical controls on valley floor vegetation patterns, and (2) vegetation controls on valley floor process-form dynamics.

7.2 Physical controls on valley floor vegetation patterns

This study revealed that several key variables influence the composition and distribution of vegetation on the Baviaanskloof valley floor. These include surface-groundwater availability, landform characteristics and anthropogenic influences, which are each discussed below.

7.2.1 Surface-groundwater and valley form influences

This research demonstrated that water availability is the primary control on vegetative response in this semi-arid environment. This subject has received increasing interest in the scientific literature over the past decade in other arid and semi-arid areas (e.g. Lite *et al.*, 2005; Newman *et al.*, 2006; Richardson *et al.*, 2007; McLendon *et al.*, 2008; Stromberg *et al.*, 2010a; Chalmers *et al.*, 2012).

PRIMER analyses showed a strong link between water availability and vegetation distribution patterns ($R^2 = 0.704$), distinguishing two site groupings (Figure 6.3) that were closely related to flow permanence such that study sites with surface flow grouped closely, while those without surface flow grouped together. The wetted channel reaches were mostly associated with confined and semi-confined valley settings. In contrast, the dry bed channel reaches were mainly situated in the unconfined valley setting (Table 2.3). The electrical resistivity and earth observation (Normalized Difference Vegetation Index, NDVI and Tasseled Cap transformation, TC) analyses also revealed the importance of surface-groundwater interactions at the three valley confinement settings, showing clear relationships between rainfall variability, groundwater table depth, flow permanence and vegetation density.

The positive correlation between the water level data from the pits or wells and the 13 resistivity profiles showed that the Electrical Resistivity Tomography technique is a suitable tool for groundwater depth analyses. This technique was used with success in the study area to define water table levels across valley floor landforms at five selected sites (Figures 5.8 to 5.10 and Table 5.5). Water table depth usually affects soil moisture availability. Shallower water tables are associated with a more reliable water supply which supports plant germination and growth (Lite *et al.*, 2005; Chalmers *et al.*, 2012; Gurnell *et al.*, 2012). Dense riparian vegetation promotes bank strength. This substantially improves resistance to fluvial erosion and contributes to channel stability (Hickin, 1984; Thorne, 1990; Francis, 2006; Labbe *et al.*, 2011).

As predicted, the groundwater table at the confined valley setting (site 2, Verlatenrivier) was close to the surface, 0.5-2.5 mbd. At the semi-confined valley setting water table levels fluctuated between shallow (site 12) and deep (site 1, Nuwekloof). However, the groundwater table was the deepest at the unconfined valley setting. Water table levels ranged for instance between 10-15 mbd at site 4 (Verlorenrivier). Therefore, support was found for the hypothesis that the water table at the confined sites is very shallow while at the unconfined sites it is found much further below the ground surface.

At the narrow confined reaches baseflow is the dominating contribution to streamflow during the dry periods. Here, the groundwater flow is forced to the surface resulting in more sustained surface flow (Rowntree, 2012). These reaches are therefore groundwater driven. The resulting permanent or intermittent surface water (Table 1.2) at the confined sites

promotes vigorous riparian vegetation growth (Figure 2.10h). This is in agreement with Lite *et al.* (2005) and Lite and Stromberg (2005). They found that streamflow permanence (i.e. surface water availability) is a suitable indicator of groundwater depth fluctuations and vegetation cover is higher with greater flow permanence.

Variable groundwater tables (shallow and deeper) were present at the semi-confined study sites, which are essentially transitional zones. These water tables are typically associated with both temporary and permanent streamflows and explain why sites can have both low (site 1) and high (site 12) density vegetation in the riparian zone (Figure 2.16). The evidence suggests that the movement of groundwater in the Baviaanskloof is strongly governed by the local geology (i.e. structural and lithological characteristics) and geomorphology (Section 2.2). This is consistent with work by Meyer (1998) and Langhoff *et al.* (2006).

The results show that the alluvial aquifer at the broad unconfined study sites under normal conditions does not intersect the main channel surface (i.e. it is well above the water table). Except for extremely wet periods, streamflow is only present during or immediately after flooding events (Ellery and Rowntree, 2011). Hence, unconfined sites are flood driven and flood variables and water table depth are highly correlated in these settings. Other researchers have demonstrated similar interactions (e.g. Stromberg *et al.*, 2007; Stromberg *et al.*, 2010a). The intermittent or ephemeral channel reaches at unconfined study sites are associated with sparse vegetation (e.g. site 4, Figure 2.14). This compromises bank strength which in turn affects channel form (Hickin, 1984; Francis, 2006; Jansen and Nanson, 2010) demonstrating strong two-way controls between vegetation and geomorphic processes and landforms (Figure 7.1). These channels are less stable during floods and more vulnerable, for example, to agricultural land use impacts such as increased peak discharges (Wohl, 2000a; Knox, 2001; Brierley and Fryirs, 2005).

Water availability in the semi-confined and unconfined valley settings is profoundly influenced by human activities. The numerous pits in the valley which are associated with groundwater extraction for human use most likely contributed to the lowered water tables at these valley settings. Similar drawdown relationships have been shown by various studies (Stromberg *et al.*, 1996; Le Maitre *et al.*, 1999; Stromberg *et al.*, 2007). At the unconfined site 10 (Rus en Vrede), for example (Figure 2.9c), where groundwater pumping from pits was observed during 2010, the groundwater table was intermediate to deep.

The resistivity profile NDVI and TC analyses generally substantiated the above mentioned findings from the resistivity survey. The dry period NDVI results (Figures 5.11 and 5.12) show that the resistivity profiles at the confined and semi-confined sites were associated with medium to high density vegetation. Permanent streamflows indicating a near-surface groundwater table were observed at these sites during the study period, indicating that the plant species at these sites had access to groundwater. These plants both exploit the available

subsurface sources and also are likely to maintain high infiltration rates. This infiltration allows water to slowly move through the soil profile, further sustaining flows during dry periods (Le Maitre *et al.*, 1999). In contrast, the dry period NDVI and TC results (Figures 5.11 and 5.12) show that the resistivity profiles at semi-confined and unconfined sites with ephemeral or intermittent flow (indicating a deeper water table, Figure 2.16), were mainly associated with scattered vegetation. The plant species at these sites experienced slower growth linked to water stress (Horton *et al.*, 2001; Lite *et al.*, 2005). This was probably also associated with lower infiltration rates and higher surface run-off rates (Stromberg *et al.*, 2007).

At all the sites the NDVI and TC transformation data (greenness, brightness and wetness) for very dry years (July 1991 and September 1993) were strongly correlated (Figure 5.12a). In the same year, correlations varied for the brightness and wetness Tasseled Cap indices (Figure 5.12b). A comparison made between the 2010 groundwater levels and the 1991 NDVI and Tasseled Cap data revealed that the deeper the water table, the sparser the vegetation. Similar findings have been reported in other vegetation and groundwater comparison investigations (e.g. Stromberg *et al.*, 1996; Lite *et al.*, 2005; Chalmers *et al.*, 2012).

Exceptions to these overall findings could be explained by floods and droughts (Chapter 3) or human impacts (Chapter 4). In addition, field observations indicated senescence (i.e. a process of growing older and showing the effects of ageing) in sweet thorn (*Vachellia (Acacia) karroo*) (Figure 6.4) that could be associated with a shift in tree vigour over the years (D. Le Maitre, Council for Scientific and Industrial Research, Stellenbosch, pers.comm., 2015). These trees dominated the valley floor (e.g. Table 6.8).

Along the resistivity profiles the NDVI and TC data showed lush verdant vegetation in wet years (Figures 5.15 and 5.16) at sites 2 (1997 and 2003), 10 (1997) and 12 (1997 and 2003). In contrast, sites 1 (semi-confined) and 4 (unconfined) had partial vegetative health in January 1997. In February 2003 sites 1, 4 and 10 all had very poor vegetative health. At all the sites (both years) only the NDVI and TC greenness index were very strongly correlated. High precipitation in 1996 (Table 3.12) resulted in a major flood shortly before the 1997 image acquisition date (Figures 3.7 and 5.13 and Table 3.5), the water table rising (i.e. higher groundwater flow) and wetter soils. This caused better growth performance at sites 2 (confined), 10 (unconfined) and 12 (semi-confined).

Similar observations were made by Chalmers *et al.* (2012) and Singer *et al.* (2013). However, floodwaters also removed or physically damaged plants at sites 1 and 4 as has been observed elsewhere (e.g. Bendix and Hupp, 2000; Friedman and Auble, 2000; Francis, 2006). As discussed above, channels at these sites are unstable and normally also associated with sparse vegetation. Furthermore, these two sites were exposed to agricultural impacts (Figures 4.11 and 4.13). Dry conditions prevailed 16 weeks before the 2003 image acquisition date

(Figure 5.13). This almost certainly contributed to the lack of dense vegetation at sites 1, 4 and 10 profiles in 2003 as was also found by Stromberg *et al.* (2007) and Singer *et al.* (2013). Surprisingly, negative wetness index values related to low surface moisture were extracted at all the resistivity sites (Figures 5.15 and 5.16). General change detection errors, linked for example to the limited spatial resolution (Dymond *et al.*, 2002; Henshaw *et al.*, 2013) or resistivity points, could possibly explain why no relationship was found between the NDVI data and the TC wetness index data.

Examining the NDVI and TC in relation to the vegetation quadrats at the three valley settings (Figures 5.18 to 5.20 and Appendices 5.5 to 5.8) also revealed a direct relationship between surface-groundwater availability and vegetation response. Valley floor vegetation remained green during the dry period, indicating a groundwater influence. Many studies have noted this association (e.g. Horton *et al.*, 2001; Cooper *et al.*, 2006; Stromberg *et al.*, 2007; Chalmers *et al.*, 2012; Singer *et al.*, 2013). Shallow groundwater, related to the perennial flow of surface water at sites 6 (Beacosnek, confined), 8 (Zaaimanshoek), 12 (semi-confined) and 13 (unconfined), accounted for vigorous plant growth during the dry period. A weak correlation between the NDVI and rainfall datasets further suggested that the plants at these sites had access to groundwater and were less reliant on rainfall. Shallow groundwater, related to the perennial flow of surface water at sites 6 (Beacosnek, confined), 8 (Zaaimanshoek), 12 (semi-confined) and 13 (unconfined), accounted for vigorous plant growth during this time. Exceptions could be explained by grazing and browsing impacts, past farming activities (Chapter 4) and general change detection errors linked to the limited spatial resolution (Dymond *et al.*, 2002; Henshaw *et al.*, 2013).

7.2.2 Hydrogeomorphological influences: Processes and landforms

Valley confinement and fluvial landform characteristics (both substrate and hydrologic conditions) act as secondary controls on the vegetation at the 13 study sites assessed. This speaks to the vegetation response to landform characteristics associated with each valley confinement setting. The sites were comprised mostly of perennial (herbs and shrubs) and indigenous plant species (Figure 6.1 and Appendix 6.2). Pair-wise tests in PRIMER ($R^2 = 0.356$) showed moderate vegetation differences between confined and unconfined valley settings. Specifically, valley confinement exerted a significant influence on valley floor process-form dynamics, and vegetation associations, through its effect on flow and sediment regimes (Tooth *et al.*, 2004; Brierley and Fryirs, 2005; Cowie and Brierley, 2008; Fotherby, 2009; Kuo and Brierley, 2013; Yu *et al.*, 2013).

Low global R^2 test values (0.163 and 0.278) also indicated that vegetation distribution patterns in the study area were in general highly dynamic and spatially very variable. Vegetation distribution was often widespread, not indicative of particular hydrogeomorphic conditions, and linked to disturbed areas. This is in agreement with Malanson (1993) and Hupp and Rinaldi (2007). Sandercock *et al.* (2007) noted that vegetation zonation and

landform studies in humid and temperate settings differ markedly from those of dryland environments. Hence, cross-valley vegetation composition and patterning (i.e. lateral zonation) were associated with a degree of unpredictability (e.g. not always along the transverse flood disturbance gradient), reflecting the frequent and rapid changes (i.e. variability) of the observable geomorphic landforms (Tables 4.8 to 4.11) and their hydrogeomorphic processes at the three alternating valley confinement settings. The latter finding, in turn, emphasises the importance of the inter-annual variability of the rainfall (Figure 3.7).

Despite the high variability in vegetation distribution within valley settings, pair-wise tests (Tables 6.6 and 6.11) revealed that, across valley confinement settings, certain plant species colonized particular geomorphic landforms (Tables 6.8 and 6.13). Hence, these species had specialized physical habitats. Their patterning can possibly be useful in the identification of areas with specific environmental conditions. In addition, BIO-ENV and BVSTEP analyses demonstrated that landform elevation and distance (position) and sediment size (fine and coarse sand) are relatively good correlates of vegetation distribution patterns (correlation values were up to 0.45) across valley settings. This finding is documented by many riparian vegetation investigations (e.g. Harris, 1987; Bendix and Hupp, 2000; van Coller *et al.*, 2000; Gilvear and Willby, 2006; Sieben *et al.*, 2009; Osterkamp and Hupp, 2010; Merritt, 2013). Typically, flood magnitude-frequency relations of formation and reworking (i.e. depositional and erosional forces) can be inferred from these factors. They are also directly related to the amount of water available for plant development (establishment followed by growth and continued survival until reproductive age).

The valley cross-section analysis indicated that the valley floor width in confined settings did not exceed 170 m (Figure 5.5 and Appendix 5.2). These are associated with resistant sandstone valley margin cliffs (Mills and Cowling, 2010) which constrain accommodation space on the valley floor. This constricted valley configuration then imposed major constraints on channel adjustment (e.g. lateral migration) and planform as well as sediment storage or reworking (i.e. few fluvial landforms). Similar results were presented by Schumm (1977), Montgomery and Buffington (1997) and Brierley and Fryirs (2005). The confined valley setting had a laterally constrained single thread main channel with a distinct stepped form, a narrow (widths ≤ 5 m) low-flow inset channel within a wider flood channel or macro-channel. An example included site 7 (Beacosnek) where out-of-channel woody debris gave an indication of the flood channel (Figure 2.16). The narrow, deep to shallow channel was mainly straight (i.e. low sinuosity). In general, confined rivers are associated with high stream power (i.e. increased discharges) and high bedload transport rates. The former usually promotes bed incision while the latter is associated with reduced sediment deposition and trapping (Wohl, 2000b; Brierley and Fryirs, 2005; Fryirs and Brierley, 2013). The vegetation found in these reaches is ordinarily more prone to flood damage (Sandercock *et al.*, 2007). In-channel wood jams were observed at, for example, study site 6, Beacosnek (pers. obs.). In the

confined valley settings, water exchanges are also restricted because depositional overbank events are limited, and usually occur in the reach cross-section where there is a high potential for recharge and surface-groundwater interaction (Newman *et al.*, 2006). According to Fisher *et al.* (2007) alluvial aquifers normally supply baseflow within confined reaches. The findings in Sections 2.5.1 and 7.2.1 support this, showing that confined reaches of the Baviaanskloof River are groundwater driven and contain semi-permanent baseflow that supports dense riparian vegetation (Figure 2.10h).

The confined valley setting resulted in domination by narrow flood benches and poorly developed floodplains (Table 5.4). In common with studies by Montgomery (1999) and Polvi *et al.* (2011) and Yu *et al.* (2013), these features had narrow riparian and terrestrial vegetation associations. The mapping analysis (Section 4.3.1) showed that past high stream power, related to flooding disturbance, reworked sediments reducing bars (habitat destruction) while increasing bench and floodplain surfaces (habitat creation). Similar landform changes in narrow valleys were discussed by for example Tooth *et al.* (2004), Keen-Zebert *et al.* (2013) and Kuo and Brierley (2014). Bench and floodplain surfaces were also associated with increased vegetation cover (Figure 4.9 and Table 4.12). Moreover, the higher flood channel can be bounded by benches or floodplains or extend across the valley floor. In the confined valley, bars and high terraces were restricted while islands, tributaries and alluvial fans (i.e. except at site 2, Verlatenrivier) were absent (Table 5.4). This rather homogenous out-of-channel geomorphic unit arrangement (Figure 5.5 and Appendix 5.2) contrasted with the greater in-channel habitat diversity (e.g. wood jams, backwater areas, pools, runs and riffles) that were linked to a more permanent water source (Table 2.3) Gregory *et al.* (1991).

In the semi-confined valley setting wider valley floors (134-272 m) were observed (Figure 5.6 and Appendix 5.3). The increased accommodation space resulted in the single thread active channel with its distinct stepped form being less constrained. Hence, it adjusted more laterally across the valley floor. Fryirs and Brierley (2010) described related results. The channel was also less deep and wider (4 to < 10 m), with low to very high well-developed banks and more sinuous (Table 2.3). This transitional valley setting was associated with variable surface-groundwater interaction (i.e. the water table was shallow and deeper, Table 5.5) and vegetation cover. For instance, surface flow was restricted to sites 8 (Zaaimanshoek) and 12 (Baviaanskloof Nature Reserve) which had vigorous vegetation growth (Figure 2.16). Here, sediment storage was also increased and consequently promoted greater habitat diversity. However, valley morphometry continued to control stream power (i.e. flow stages), thereby also sediment aggradation and reworking (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013). For example, bars (e.g. site 3, Kasey) and islands (site 8) were still restricted while alluvial fans and tributaries remained absent. Dominant landforms included terraces and wider flood benches and floodplains (Table 5.4). Related work has been carried out by Brierley *et al.* (2002), Fryirs and Brierley (2010) and Yu *et al.* (2013). Terraces (mostly narrow and high) only lined one channel bank. They indicate that rapid incision and local base-level lowering

has occurred (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013). Conversely, broader floodplain surfaces usually occurred along both main channel banks. Flood benches and floodplains resulted from large magnitude floods in the past (e.g. 1981 and 1996, Table 3.12) which reworked bars and transformed the active channel from braided to single thread (Figure 4.4 and Table 4.6).

The unconfined valley setting was characterized by broad valley floors (up to 2050 m wide) (Figure 5.7 and Appendix 5.4). Here, the Baviaanskloof River channel adjusted laterally across extensive continuous floodplain surfaces. However, it was constrained by alluvial fans and broad terraces (Table 5.4) which acted as critical additional controls as found by Fryirs *et al.* (2007b) and Benda *et al.* (2011). These landforms (found along both channel banks) reduced the available accommodation space. They also promote the formation of alternating confined and unconfined river segments (Benda *et al.*, 2011). Artificial embankments (e.g. site 5, Uitslag, Table 5.4) likewise prevented overbank flooding and sediment reworking on floodplains. At this valley setting the main channel was mostly very wide (> 10 m) with both high, well-developed and low, deformable banks. In addition, it was single and multi-channelled and had higher channel sinuosity (i.e. meanders) (Table 2.3). Channel depth was also varied. It was both shallower, at for example site 4 (Verlorenrivier), and deeper, at site 9 (Rus en Vrede). Surface flow was limited to site 13 (Baviaanskloof Nature Reserve) indicating a much deeper groundwater table (Table 5.5). Shallow groundwater for the most part provides a more permanent water source than does periodic overbank flooding (Stromberg *et al.*, 1996). Also, at this valley setting inefficient sediment transfer was related to a lack of mainstem permanent surface flow. With a few exceptions, this resulted in sparsely vegetated geomorphic surfaces (e.g. site 4, Figure 2.16).

In general, unconfined rivers are related to a reduction in stream power which is ultimately linked to significant sediment deposition and storage. The associated morphology and sedimentology of unconfined valleys create spatial heterogeneity and a mosaic of habitats or landforms (Montgomery and Buffington, 1998; Fryirs and Brierley, 2013). In the study area, a variety of landforms were detected in the unconfined valley setting. These included various bars, islands, narrow flood benches, floodplains and secondary channels (Table 5.4). Similarly, unconfined rivers are highly dynamic systems. For example, channel switching and avulsion are common (Brierley and Fryirs, 2005; Beechie *et al.*, 2006; Yu *et al.*, 2013). This diverse habitat mosaic can give rise to broad complex plant groupings of various stand ages (Gregory *et al.*, 1991). In the Baviaanskloof past flood events (Table 3.12) at the unconfined valley caused, for instance, floodplain and main channel width expansion and contraction as well as planform changes (e.g. Figures 4.6 and 4.8). These changes were mostly associated with sparse vegetation covering; however, over time, denser canopy cover also resulted (Table 4.14). River channel changes to a lesser degree also influence established plant communities (Figures 4.8 and 4.15).

The sediment analyses (Section 5.3.3) at the three valley confinement settings showed that grain size variability resulted in distinct landforms occurring at differing positions cross-valley. Generally, this variability is mainly related to lithological and hydrological controls, sediment supply rates and sediment transport and deposition history (Gordon *et al.*, 2004; Cowie and Brierley, 2008; Heitmuller and Hudson, 2009). Increasing landform elevation and distance from the channel (i.e. the thalweg to the valley edge) are also associated with a number of interconnected abiotic factors that account for vegetation differences. These include decreasing flood duration, inundation frequency and intensity (i.e. scour); decreasing soil texture and moisture; decreasing anoxia; increasing depth to groundwater or saturated soil and increasing landform age (Hupp and Osterkamp, 1985; Malanson, 1993; Ward *et al.*, 2001; Hupp and Rinaldi, 2007; Merritt, 2013).

In the Baviaanskloof the dominant grain size fractions across landforms (i.e. lateral gradient) were gravels (e.g. Figures 5.21, 5.24 and 5.27) and sands (e.g. Figures 5.23, 5.26 and 5.29). Low silt and clay values were mostly recorded at all the valley confinement settings. Gravels were either fine to medium (confined and unconfined sites) or medium to coarse (semi-confined sites). Sands were either fine (confined and unconfined sites) or fine to medium (semi-confined sites). These trends attest to the influence of valley confinement, the position of differing geomorphic landforms relative to the thalweg, and the use of energy by the active channel (i.e. sediment entrainment, transport, reworking and sorting). They may also help to explain why the plant species in the study area were also not landform specific. Finer sediment sizes interact with water availability (e.g. via infiltration and water-holding capacity) to influence species germination and survival (Hupp and Osterkamp, 1985; Gilvear and Willby, 2006).

The above mentioned sediment results were also reflected in the downstream geomorphic unit analyses (Tables 5.6 and 5.7), with the difference that the mean and coarse grain sizes were largely in the medium to very coarse gravel size fraction class with mostly no significant longitudinal trends. Hassan (2005) noted that arid and semi-arid river systems with their highly variable flow regimes might not display marked downstream trends in sediment size since the probability of equal mobility is high when the bulk of flows surpass the threshold of entrainment for all channel bed sediment sizes. In this river valley exceptions included the downstream fining (floodplains and main channel banks) and coarsening (flood benches) at the confined valley setting. Downstream coarsening (gravel to cobble) also occurred at benches (sites 3 and 12, Baviaanskloof Nature Reserve) and river banks (sites 1 and 8) at the semi-confined valley setting as well as at floodplains (e.g. sites 4 and 9) at the unconfined valley setting (Tables 5.6 and 5.7). Downstream fining in gravel bed rivers results mainly from abrasion of sediment and selective transport processes and sorting (Bluck, 1987; Cowie and Brierley, 2008; Heitmuller and Hudson, 2009; Kleinhans, 2010).

Moreover, sorting by size during transport also brings forth other distinct depositional structures such as lateral fining or vertical armouring (Cowie and Brierley, 2008). Rowntree and Dollar (1999) defined armouring as the upper layer of the movable bed that is coarser than the material beneath it. This happens normally during periods when no bed load transport occurs in gravel bed rivers (Knighton, 1998; Hicks and Basil, 2003). This downstream fining pattern can however be repeatedly disrupted, negated or reversed by localised mechanisms or sources (Heitmuller and Hudson, 2009). Examples include coarse sediment additions from tributary junctions (Ferguson *et al.*, 2006) and non-point sources such as alluvial fans (Cowie and Brierley, 2008); overbank deposition; distributary bifurcations and entrainment at local bedrock outcrops (Frings, 2008). Different sedimentary event related gravels in the channel bank can also contribute to the sediment load, while grain size changes are associated with rivers entering gorge areas (Bluck, 1987).

In the study area the coarsest grained materials (e.g. cobbles and boulders) were mostly associated with in-channel and channel margin geomorphic features such as channel banks (dry and wet), bars and flood benches (e.g. Figure 5.22 and Appendix 5.1). These erosion and deposition dominated low-lying features are often unstable due to high flood disturbance linked to frequent inundation and long flow duration. This in turn influences vegetation composition and patterning (Osterkamp and Hupp, 1984; Hupp and Osterkamp, 1985). Here, floodwaters can reset physical habitats and uproot, remove, trap, smother, damage or kill plants. Floods, however, can also bring about species establishment by dispersing diaspores (e.g. seeds, spores, fruit and vegetative propagules) and providing new moist nutrient rich habitats (Bendix and Hupp, 2000; Friedman and Auble, 2000; Francis, 2006; Gurnell, 2014). Contrary to temperate and humid regions, drylands are characterized by scarce and erratic rainfall coupled with severe droughts, extreme flow variability and infrequent high-magnitude localized floods of short duration (Bull and Kirkby, 2002; Nanson *et al.*, 2002; Young and Kingsford, 2006). This harsh environment, where floods are sudden and violent, can act as a limiting factor on vegetation, constraining vegetation growth (Tooth and Nanson, 2000; Gurnell, 2014). The climate analyses showed that Baviaanskloof is an area prone to frequently alternating floods and droughts (Chapter 3). Average floods had flood frequencies of 1-3 years while major floods had frequencies of 9-21 years (Table 3.13). These major floods were associated with heavy rainfall events (50 to > 100 mm) (Table 3.5) with return periods of > 3 years but < 40 years (Table 3.4).

Unfortunately, the flood chronology lacked detailed information on droughts and intra-annual floods (Table 3.13). However, droughts were confirmed in 1942, 1983, 1989 and 1995. During and after these years the vegetation at especially the unconfined valley setting was under severe water stress with little vegetation covering (e.g. site 4, Figure 4.13). According to Boucher (2002), in South Africa the channel bed and wet bank are inundated intra-annually while the dry bank is inundated inter-annually. The dry bank has flood return periods of 1:2 to 1:20 years. The back dynamic zone (a transition zone with a mixture of plants) is maintained

by large floods recurring every 10-100 years. Reinecke *et al.* (2015) also investigated links between river flow and lateral vegetation zones and noted that marginal and lower dynamic zones (i.e. the wet bank) were related to floods with return periods of < 2 years. In contrast, the lower zone and the lower limit of the upper zone (i.e. the dry bank) were inundated every 2.4 years. These authors selected perennial rivers with different flow hydrographs in several climates. Reinecke *et al.* (2015) for example studied rivers in Mpumalanga with its subtropical climate (summer peak flow); the Southern Cape with a variable climate (temperate, subtropical and humid) (aseasonal or early spring peak flow); and the Western Cape with a Mediterranean climate (winter peak flow) (Reinecke *et al.*, 2015).

Tooth (2000b) also notes that the infrequent high-magnitude floods in drylands homogenize the lateral flood disturbance gradient (i.e. submersion frequency and duration), while transmission losses and sediment loads are high. This promotes substrate accumulation which can lead to the encroachment or terrestrialisation of instream and stream side landforms and the replacement of herbaceous flood tolerant species (e.g. macrophytes) with opportunistic upland woody plant species (Sandercock *et al.*, 2007; Stromberg *et al.*, 2010a; Bornette and Puijalon, 2011). The quadrat scale analysis (Section 4.3.2) demonstrated that geomorphic surfaces in the study area are highly dynamic. For example, channel beds transformed into bars which became densely vegetated (i.e. stable islands) while bars were reworked into flood benches and floodplain surfaces (Tables 4.8 and 4.10). Species compositional shifts resulted in trees such as *Vachellia (Acacia) karroo* being common to the channel bed (Figures 3.2b and 6.4 and Table 6.12) and directly contributing to the creation of depositional features such as islands or benches (discussed further in Section 7.3.1). More typically channel beds are devoid of woody vegetation (Bornette and Puijalon, 2011). This aggressive colonizer is one of southern Africa's most abundant and widespread trees. It invades for example rangelands, grasslands, dryland environments, river courses and disturbed areas (O'Connor, 1995; Barnes *et al.*, 1996; O'Connor *et al.*, 2014). Instream, bar and wet bank species that were associated with Group 1 (i.e. wetted channel sites across confinement settings, Figure 6.3 and Table 6.7), for example, consisted mainly of free floating and rooted herbs of young age that were pioneer, ruderal or early successional. They included the sedge *Cyperus denudatus*, the hydrophyte *Persicaria decipiens*, the herb *Mentha longifolia* and the grass *Panicum deustum*. High cover riparian tree species such as *Salix mucronata* (wet bank) and exotics also occurred, e.g. site 8 (Tables 6.8 and 6.14, Figure 6.4 and Appendix 6.2).

These species usually have many morphological (e.g. adventitious roots and stem flexibility), physiological (e.g. aerated tissue development for rhizosphere oxygenation) and reproductive phenological (e.g. dormancy timing) life history strategies or adaptations to deal with the fluvial environment (Blom *et al.*, 1990; Lenssen *et al.*, 2000; Grime, 2002; Naiman *et al.*, 2005; Brock *et al.*, 2006; Gurnell, 2014). Sedges in the genus *Cyperus*, for example, survive physical flood disturbance because of their thin flexible leaves and placement of growth close to the ground. They also tolerate anoxia because they have hollow stems for oxygen transport

to the roots and chemical pathways for detoxification of the products of anaerobic respiration (Gill, 1970). In contrast, the ruderal strategy involves an annual life-span with high reproductive effort (i.e. large populations) and rapid growth close to the ground (shallow rooted, e.g. rhizomatous) linked to abundant nutrients. Fast rates of root and shoot growth allow these plants to gain rapid anchorage and strong uprooting resistance (Tabacchi *et al.*, 1996; Friedman and Auble, 2000; Grime, 2002). Reinecke (2013) also reported that seed dispersal (i.e. lasting two to three months) of the riparian pioneer *Salix mucronata* coincides with dry-season flows, thereby promoting germination and minimising seedling mortality. Seedlings, although subject to scour, also occupy the river fringes because they are reliant on moist conditions (Reinecke, 2013). Dry banks and flood benches contained mostly a mix of rooted herbs (particularly grasses) and shrubs with canopy-forming trees to a lesser extent (Table 6.8). Dry banks for example supported species such as the herb *Mentha longifolia*, the grass *Pennisetum clandestinum* (an exotic weed) and the shrub *Chrysocoma ciliata* (Table 6.8 and Figure 6.4). The most tree species were located at the confined and semi-confined valley settings (Figure 6.2).

The plant species closest to the active channel was linked to Group 2 (i.e. except site 2, dry bed channel sites in semi-confined and unconfined valleys, Figure 6.3 and Table 6.13). They consisted mainly of indigenous perennial shrub (mainly) and herb species that included upland (floodplains or terraces) species that were more tolerant to drier conditions, e.g. succulents and geophytes (Tables 6.13 and 6.9, Figure 6.5 and Appendix 6.2). These species have adaptations such as the use of refugia and life-history scheduling to survive dry conditions (Lake, 2003; Stromberg *et al.*, 2007; Bornette and Puijalon, 2011). Some plants, for instance, produce long-lived soil-stored seed banks that are resistant to desiccation (Humphries and Baldwin, 2003). Likewise, succulents have fleshy stems and leaves that contain reserves of moisture, while geophytes have underground storage structures such as rhizomes, bulbs and tubers (Goldblatt and Manning, 2000; Mucina and Rutherford, 2006). However, these adaptations may not fully protect species from the stresses caused by a lack or scarcity of water and high mortality rates still occur (Humphries and Baldwin, 2003). Drought tolerant species are often shade intolerant, slow growing and have deeper roots (Gilvear and Willby, 2006). At in-channel and channel margin landforms at Group 2 sites high cover aquatic or semi-aquatic vascular plants were absent while trees were few and scattered. Exotic species were also limited. Plant species here included the grasses *Aristida congesta*, *Cynodon incompletus* (at most landforms), *Eragrostis curvula* and *Eragrostis lehmanniana*. Other herbs were *Lepidium africanum* and *Chenopodium mucronatum*. Shrubs included *Chrysocoma ciliata*, *Drosanthemum ligue* (a succulent), *Diospyros lycioides*, *Galenia procumbens* and *Helichrysum rosum*. *Vachellia* (*Acacia*) *karroo* was the most abundant tree species. Examples of exotic species included the herbs *Argemone ochroleuca* (a weed) and *Rumex crispus* (a proposed invader) (Tables 6.13 and 6.9, Figure 6.5 and Appendix 6.2).

As found by many studies (e.g. Osterkamp and Hupp, 1984; Hupp and Osterkamp, 1985), across valley settings, older surfaces (floodplains and terraces) consisted largely of finer grained materials (e.g. Figure 5.28 and Appendix 5.1). However, on occasion they (e.g. unconfined sites) had coarse sediment additions from, for example, alluvial fans and tributary confluences. These lateral sediment inputs disrupted the usual grain size organisation (Cowie and Brierley, 2008; Heitmuller and Hudson, 2009). In general, these geomorphic surfaces are drier and more stable, with terraces the least inundated feature. Hupp and Osterkamp (1996) and Bendix and Hupp (2000) reported that floodplains in northern Virginia flooded on average once every 1-3 years and terraces on average once every ≥ 3 years. Floodplains and terraces highlight the importance of the transition to an environment dominated by gap formation and competition for resources rather than floods (Latterell *et al.*, 2006). Plant communities on floodplains are often transitional between those of river banks and upland terrestrial areas (Brock *et al.*, 2006). Terraces also support upland plant species exclusively or in association with floodplain plant species (Hupp and Rinaldi, 2007). At both site groupings (Figure 6.3) these low flood-frequency landforms were dominated by species that were adapted to the dryness at higher elevations. They included the grasses *Panicum deustum* and *Cynodon incompletes*; the herb *Cotula australis*; the shrub *Lycium cinereum* and the tree *Vachellia (Acacia) karroo* (Tables 6.8 and 6.13 and Appendix 6.2). Here, vegetation of different age and density occurred which included mature woody stands. Terraces had the oldest communities (pers. obs.). These surfaces also supported species found on lower elevation landforms such as *Lepidium africanum* (e.g. tributary channel bed) and *Eragrostis lehmanianna* (e.g. benches, bars and main channel banks).

Across all valley settings floodplains and flood benches in most cases had the highest plant species richness despite their contrasting hydrogeomorphic characteristics, a finding similar to the predictions of the intermediate disturbance hypothesis (Connell, 1978; Bornette *et al.*, 1998). The results showed that in the Baviaanskloof benches with their coarse sediments were successfully colonized by woody vegetation (Figure 6.2) through channel narrowing (Figure 4.2) which reduced discharge and increased fine sediment accretion (e.g. Figure 5.22 and Appendix 5.1). As expected, species richness was the lowest at the channel bed (Figure 6.2). Robertson (2006) indicated that plant diversity is usually low on bars (frequent floods), increases on flood benches (lower flood frequencies) then decreases again on floodplains (infrequent floods) and further diminishes on terraces. So, according to this researcher both extremely disturbed and undisturbed fluvial landforms have a tendency to support low plant species numbers. In contrast, Hupp and Rinaldi (2007) found that species richness increased from the channel bed to the terrace with intermediate species richness at almost the same for bars and benches.

Also, several geomorphic features in the study area supported species that were not found on other landforms (Tables 6.3 and 6.14 and Appendix 6.2). These species were landform specific, i.e. had clear surface preferences linked to variable environmental conditions. At

Group 1 sites they included for example the shrub *Leysera gnaphaloides* (lateral bar) and the exotic succulent shrub *Agave Americana* (island). Species at Group 2 sites included the herb *Ifloga glomerata* (mid-channel bar) and the succulent herb *Ruschia rigens* (flood bench). However, adjacent landforms at all three valley confinement settings at times also shared similar plants. There was generally a decrease in similarity with landforms further away. This trend was stronger at Group 1 sites (confined and semi-confined sites) and mostly likely related to water availability (Figure 2.16 and Table 5.5). These findings are corroborated by several interrelated investigations (e.g. Hupp and Osterkamp, 1985; Bendix and Hupp, 2000; Hupp and Rinaldi, 2007; Osterkamp and Hupp, 2010).

7.2.3 Anthropogenic influences

The next most important explanatory variables for the vegetation changes on the valley floor were related to human impacts (Figure 7.1). BIO-ENV and BVSTEP results confirmed a link between available phosphorus and vegetation variance at Group 2 sites. These encompassed the dry bed channel sites at the semi-confined and unconfined valley settings (Figure 6.3 and Table 6.12). This finding concurred with the high to very high values for available nitrogen and phosphorus that were recorded at the unconfined valley setting for floodplains (sites 5, 9 and 10) and terraces (sites 9 and 10) (Table 5.8 and Appendix 5.1). These nutrients are often a response to anthropogenic disturbance linked to intensive agricultural land use at higher elevation floodplain and terrace surfaces (Downs and Gregory, 2004; Brierley and Fryirs, 2005; Noe and Hupp, 2005; Lamers *et al.*, 2006). Agricultural land use involves the conversion of natural vegetation to crop production and pastures for livestock grazing (Knox, 1977; FISRWG., 1998). In arid and semi-arid environments it is frequently identified as a major cause of land degradation and desertification (Darkoh, 1998; Allsopp, 1999; Ravi *et al.*, 2010). Nutrients from, for example, high fertiliser and manure applications are either dissolved (e.g. nitrogen) or bound (e.g. phosphorus) to fine soil particles (FISRWG., 1998; Naiman *et al.*, 2010). Floodplains can either be their sources (i.e. inputs or release during flooding) or sinks (i.e. accumulation), i.e. from overbank flooding (Noe and Hupp, 2005; Knox, 2006; Noe, 2013).

The historic mapping analysis showed how agricultural fields extended into the vast floodplain and terrace areas of the unconfined valley setting. Highly transformed agricultural areas however, also occurred along the main channel (Figure 4.13 and 4.15). Over the years these areas were both reduced (site 5) and increased (site 9) (Figure 4.14). Better performance of grass species at former agricultural areas leads to a higher degree of dominance in the vegetation (pers. obs.). Poorly managed crop and grazing systems can result in significant changes in surface runoff, soil properties, erosion rates and sediment production (Knox, 1977; 2001; Strauch *et al.*, 2009; Rebelo *et al.*, 2013). For example, irrigation or heavy herbicide applications can increase soil salinity, thus altering soil structure, supporting waterlogging, causing salt toxicity in plants and reducing the ability of plants to take up water (FISRWG., 1998; Holmes *et al.*, 2005). This is increasingly becoming a problem in semi-arid agricultural

areas in South Africa (Davies and Day, 1998). Furthermore, Figure 2.12 indicated that floodplain and terrace surfaces were grazed by various livestock (e.g. sheep, goats, ostriches and cattle). In rural African communities living in dry areas, livestock are vital components of economic and social systems (Strauch *et al.*, 2009). Overstocking of domestic animals or wildlife species lead to overgrazing (Esler *et al.*, 2006) which is the result of prolonged grazing without adequate recovery of the vegetation. Grazing reduces habitat diversity while vegetation removal and physical damage can impact negatively on species composition and biomass production. Upland species typically also invade former riparian habitats (Kauffman and Krueger, 1984; Toledo and Kauffman, 2001; Sarr, 2002; Allsopp *et al.*, 2007).

As many land use activities often occur concurrently (Wohl, 2006), agriculture in the valley was also accompanied by river-floodplain engineering. This included channel straightening (i.e. realignment) and the construction of levees or artificial embankments to protect fields and infrastructure from flooding (Table 2.2). Channel straightening involves shortening of sinuous channels (Wohl, 2000a) or confining braided reaches to a single channel (King *et al.*, 2003). It leads to an increase in bed gradient, flow velocity and the sediment transport capacity of the river (Brooker, 1985; Downs and Gregory, 2004; Brierley and Fryirs, 2005). In the study area, main channel incision at the unconfined valley setting triggered groundwater table lowering (Figure 2.13). Channel incision also resulted in the loss of wetlands and their associated vegetation in this valley setting (Rowntree, 2012). Levees are linear earthen mounds erected along channel banks to restrict flood flows to the main channel (Watson and Biedenharn, 2000). Both these engineering activities disconnect floodplains from rivers thereby minimizing the frequency and duration of floods on these surfaces and, among other things, reducing sediment and nutrient loading to floodplains (Brierley and Fryirs, 2005; Noe and Hupp, 2005; Antheunisse *et al.*, 2006). This, in turn, affects hydrodynamic and biogeochemical (e.g. nutrient and water cycling and organic matter production and decomposition) gradients (Hohensinner *et al.*, 2004; Lamers *et al.*, 2006). Allsopp (1999) and Sarr (2002) concluded that nutrient- and moisture poor soils can be inhospitable for many plant species. In general, disconnection may result in habitat simplification or reduction and the loss of plant species richness (Pedroli *et al.*, 2002; Van Looy *et al.*, 2003; Hohensinner *et al.*, 2004; Leyer, 2005). In the Baviaanskloof the combination of all the above mentioned anthropogenic impacts contributed to the decline in the native vegetative cover at the unconfined valley setting. This was also accompanied by fragmented or patchy plant communities of medium to high densities cross-valley (Figures 4.13, 4.15 and 5.2). This response was mirrored in the field distributions in 2010 (pers. obs.).

7.3 Vegetation controls on valley floor process-form dynamics

Whilst vegetation composition and patterning are strongly influenced by hydrogeomorphic process and form, plant species may significantly influence hydrogeomorphic processes and

landforms in return (Corenblit *et al.*, 2007; Osterkamp and Hupp, 2010; Gurnell *et al.*, 2012; Merritt, 2013; Gurnell, 2014).

7.3.1 Vegetation and landform formation

The cross-profile (Figures 5.5-5.7 and Appendices 5.2-5.4) and particle size (Figures 5.21-5.29 and Appendices 5.9-5.28) analyses at the three valley confinement settings demonstrated that sediment variability is reflected in distinct fluvial landforms occurring at differing positions across the valley floor. Sediment (erosion, transport and deposition) is a vital component of landform dynamics and habitats. A substantive body of evidence exists on vegetation encouraging sediment deposition and retention and thereby contributing to landform formation and development. Generally the hydraulic resistance of obstructing vegetation (living and dead) reduces flow velocities, which results in a reduction of the carrying capacity of the flow and, thus, the deposition of dispersed diaspores (e.g. seeds or propagules) and fine sediments on coarse substrates. These sediments often have higher moisture and nutrient levels. This leads to further plant establishment and growth, aggradation and landform building, i.e. the spatial extension of vegetated patches (Hickin, 1984; Hupp and Osterkamp, 1985; 1996; Francis, 2006; Sandercock *et al.*, 2007; Corenblit *et al.*, 2009; Sandercock and Hooke, 2010; Gurnell, 2014). In addition to this, field studies have revealed that a few plants (e.g. pioneer herbs or trees) are especially well equipped to colonize bare or inundated alluvial sediment and create, maintain or modify geomorphic landforms. They trap and stabilize sediment to build pioneer landforms and facilitate rapid colonization by post-pioneer plants which, in turn, reinforce landform development. These engineering plant species strongly influence river flow, vegetation and sediment feedbacks therefore, fluvial morphodynamics in river systems. Many factors (biotic and abiotic) interact to allow specific plants to act as physical ecosystem engineers (Jones *et al.*, 1997; Corenblit *et al.*, 2007; Corenblit *et al.*, 2011; Gurnell *et al.*, 2012; Gurnell, 2014).

In the study area confined, semi-confined and unconfined valley settings were characterized by cross-valley landform formation and modification (Tables 4.8 to 4.11) driven by the interplay of flood disturbance (moderate and extreme, Table 3.13), sediment (Table 5.6), soil moisture availability (e.g. depth to groundwater, Table 5.5) and vegetation (Table 6.2 and Figures 7.1 and 7.2). Additionally, areal (lateral and longitudinal) and elevational (vertical) growth of landforms along the Baviaanskloof River were most likely also engineered by certain aquatic, riparian and terrestrial vegetation in what Gurnell (2014) described as a “hotspot”. This refers to the interface between areas dominated by fluvial disturbance and competition with other species. For example, at high energy river reaches within the confined and semi-confined valley settings the main channel bed and bars (e.g. point and lateral) aggraded into flood benches which were gradually incorporated into floodplain surfaces (Tables 4.8 and 4.9).



Figure 7.2: Structure, growth and landform building at the confined valley setting, 2010 field study.

Full shoot development and root architecture (i.e. adventitious and rhizomatous) of *Cyprus denudatus* (a). Flood bench development resulting from sediment trapping by strips of *Cyprus denudatus* seedlings along the Baviaanskloof River (b). A close up view of sediment trapping by *Cyprus denudatus* showing heavy deposition of fine sediment (c). *Salix mucronata* stem snap (d). Channel margin wood accumulation (background) associated with sprouting, sediment aggradation and bank strengthening (e). Photographs by L. Smith-Adao. and J. Raath.

PRIMER results indicated that these in-channel and channel margin geomorphic features were dominated by for example the winged sedge (*Cyprus denudatus*), wild mint (*Mentha longifolia*) and Cape willow (*Salix mucronata*) (Table 6.10 and Figure 6.4). These species all share traits associated with regular flooding such as sexual and vegetative reproduction, being able to resprout and anchoring via dense adventitious root networks (Table 6.9 and Figure 7.2a-b). The Cape willow is also inundated but not overtopped by intra-annual floods (Reinecke, 2013) and is able to root on larger calibre substrates such as gravel bars (van Collier *et al.*, 1997). Moreover, studies have shown that willow species of the Salicaceae family, like *Salix mucronata* (Appendix 6.2), develop above- and below-ground biomass rapidly (Gurnell, 2014) and are strongly influenced by groundwater changes. Young plants display prompt root development that tracks the falling water table (e.g. Mahoney and Rood,

1998; Imada *et al.*, 2008). The robust roots then reinforce sediment that is retained within plant stands (Gurnell, 2014).

Reinecke (2013) also noted that although *Salix mucronata* is mostly dependent on seed-driven recruitment, stem snap (breaking of branches) occurred regularly because the stems of the plant are not very flexible (Figure 7.2d). These branch fragments are typically released during high flow and then take root if buried at suitable sites (Nilsson and Svedmark, 2002). Usually a mix of reproduction strategies results in the successful recruitment of a plant species at different sites during the same time period (Asaeda *et al.*, 2011). Tree parts trapped in large wood accumulations or woody debris can also sprout, while seeds deposited amongst the wood jam or buried under its surrounding sediments may regenerate and trap sediment, forming for example pioneer bars or islands (Gurnell *et al.*, 2002; Francis *et al.*, 2008a; Sear *et al.*, 2010; Bertoldi *et al.*, 2013; Gurnell, 2014). Wood accumulation was found to be associated with landform building and stabilization along the Baviaanskloof River during the 2010 field study (Figure 7.2e). At the unconfined valley setting, reduced stream power linked to limited flow depths resulted in the main channel bed transforming into mid-channel bars, islands and floodplains (Tables 4.10 and 4.11). PRIMER analyses showed that these landforms were occupied for example by karoo quick grass (*Cynodon incompletus*), Lehmann's love grass (*Eragrostis lehmanianna*), bitter bush (*Chrysocoma ciliata*) and sweet thorn (*Vachellia (Acacia) karroo*) (Tables 6.13 and 6.9 and Figure 6.5).

In particular, sweet thorn was dominant in many sites. In the Baviaanskloof this perennial tree can be considered a landform-constructing pioneer plant species which has an opportunistic growth pattern. I propose that there are no strong competitors for the niches that this species is exploiting with such success, which would explain its aggressive coverage of large areas of the valley floor. It regenerates rapidly from seed forming dense thorny thickets that can exclude other trees. This adaptable tree stabilizes landforms, especially in disturbed or degraded areas (e.g. site 8, Figure 2.16) and tolerates drought, fire, frost and high salinities. Sweet thorn is also independent of surface moisture where groundwater is available. It has access to water throughout the growing season (Barnes *et al.*, 1996). The plant's long taproot, with extensive lateral roots, enables it to access water and nutrients from deep underground (Table 6.9 and Figure 7.3b). Resprouting (i.e. regeneration) is also common after fire. Likewise, its ability to fix nitrogen often leads to it having an understorey of grasses and shrubs (Barnes *et al.*, 1996). The latter trend was observed cross-valley at all the valley confinement settings with grass species dominating (Figure 2.16 and Tables 6.7 and 6.12). Figure 7.3c shows an array of understorey grass species associated with sweet thorn. Moreover, these species also dominated at former agricultural fields (Figure 7.2d).

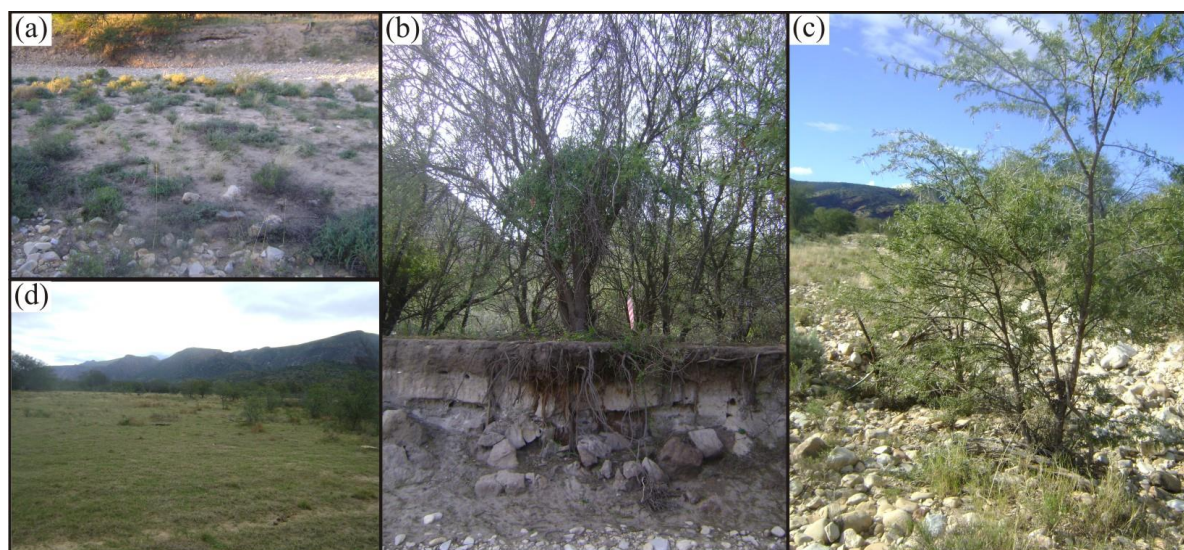


Figure 7.3: Vegetation and landform formation at the unconfined valley setting, 2010 field observations.

Vegetated patches accompanied by high sediment retention and reinforcement within an aggraded and stabilized flood bench (a). Extensive root system of sweet thorn exposed on an eroding river bank of the Baviaanskloof River. Note the dense surface roots (b). Sweet thorn with an understory of grassy vegetation (c). Grasses dominating at an abandoned agricultural field, regrowth also included small shrubs and trees such as sweet thorn, background (d).

7.3.2 Vegetation and landform morphodynamics

In this study, geomorphic mapping revealed strong linkages between patterns of sediment erosion (e.g. bank retreat), deposition (Figures 4.2-4.8) and vegetation (Figures 4.9-4.15) over a 63 year period. This was reflected at the cross-sectional scale where, for example, narrow, stable and wide, less stable main channels alternated at the three valley confinement settings (Figures 5.5-5.7 and 7.4a-b and Appendices 5.2-5.4), as discussed in Section 7.2.2. Usually morphological change in rivers consists of adjustments to channel width-to-depth ratios (i.e. size and shape) and pattern or planform which mainly depends on available stream power (Brierley and Fryirs, 2005; Fryirs and Brierley, 2013). However, there is wide agreement that plants (i.e. type and density) and channel boundary conditions (e.g. erodibility of bank materials) amongst other controls, also influence river morphology (Thorne, 1990; Allmendinger *et al.*, 2005; Labbe *et al.*, 2011; Gurnell *et al.*, 2012; Merritt, 2013). All these factors do this by reinforcing river banks and resistance to fluvial action (Hickin, 1984; Thorne, 1990; Abernethy and Rutherford, 2000; Francis, 2006; Pollen-Bankhead and Simon, 2010). In the Baviaanskloof narrowing of the main channel at the confined (sites 2 and 6), and semi-confined (site 8) reaches (Figures 4.2 and 4.4) was associated with densely vegetated lateral accretion deposits and landform stability (Figures 4.9 and 4.11). These findings concurred, for example, with studies by Hession *et al.* (2003) and Cadol *et al.* (2011). Moreover, often grassy and herbaceous vegetation (e.g. Figures 7.3a) were related to a

persistent water table (Table 5.5), more permanent surface flow and inhabited banks (i.e. increased channel stability). Similar results have been reported by several studies (Thorne, 1990; Allmendinger *et al.*, 2005; Francis, 2006). The results also showed that the highest grass cover occurred at the confined valley setting (Figure 6.2).

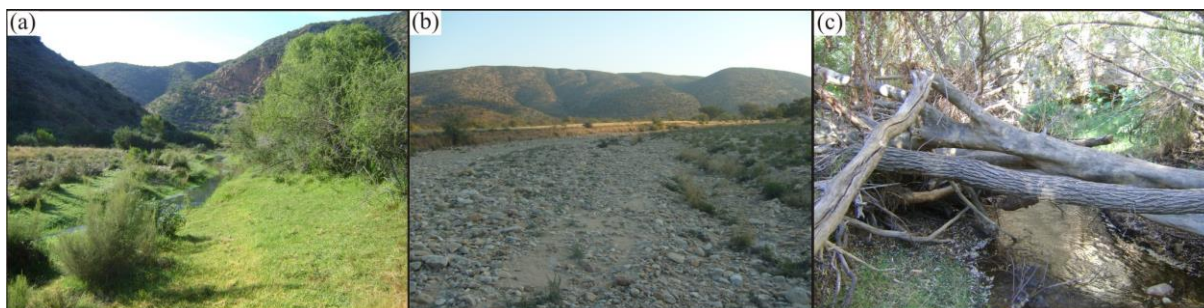


Figure 7.4: Vegetation and channel form dynamics in the Baviaanskloof, 2010 field campaign.

Grass and herb dominated banks linked to groundwater just below the channel bed resulting in a stable narrow main channel, confined valley setting (a). Sparse bank lined vegetation associated with a deeper groundwater table and a more unstable wider main channel at a typical unconfined study reach (b). Instream woody debris (i.e. tree deposition) and bank erosion at a confined study reach (c).

Vegetation has a direct impact on bank stability through: reduced near-bank flow velocities due to an increase in flow resistance and disruption; improved bank soil drainage and increased tensile strength of bank sediments due to roots (Thorne, 1990; Simon *et al.*, 2004b). Canopy interception of runoff and evapotranspiration also result in the lowering of the water table (Langendoen *et al.*, 2009) and drier banks with reduced bulk unit weight and lower positive pore-water pressure which encourage matric suction (Simon *et al.*, 2004b; Pollen-Bankhead and Simon, 2010). However, it is important to point out that reinforcement extends only down to the rooting depth of the vegetation, which is a proportion of the bank height (Pizzuto, 1984; Thorne, 1990; Allmendinger *et al.*, 2005). For trees it is a more or less a metre, for shrubs tens of centimetres and for grasses just a few centimetres (Thorne, 1990). In the study area this is clearly illustrated in Figures 7.3e and 7.4c where floodwaters uprooted or removed channel margin woody and grassy vegetation. Thorne (1990) also reported that cohesive vegetated soils decrease channel width and increase the thresholds for bank erosion. As discussed in Section 7.2.2, finer textured sediments (gravels and sand) dominated cross-valley at the 13 study sites. In addition, the grain size analysis indicated higher silt percentages at main channel banks (e.g. sites 1 and 7, Figure 5.26 and Appendices 5.13 and 5.14), islands (Figure 5.29 and Appendix 5.28) and flood benches (e.g. sites 6 and 12, Figure 5.23 and Appendices 5.14 and 5.21). This reflected the cohesiveness of these geomorphic features. Generally silt-clay layers are underlain with gravel and sand layers (Thorne, 1990) resulting in increased fluvial erosion resistance and landform stability (Labbe *et al.*, 2011; Veihe *et al.*, 2011; Merritt, 2013).

At the unconfined valley setting main channel widening over the decades (e.g. site 4, Figures 4.7 and 4.13) was primarily related to sparse bank lined vegetation associated with intermittent or ephemeral flow (i.e. a deeper groundwater table, Table 5.5) which resulted in bank instability and failure, but also landform formation (Table 4.10). The 2010 field study confirmed this finding (Table 5.5 and Figures 7.3b and 7.4b). Vegetation is therefore sometimes not a stabilizing agent. Common destabilizing effects of plants include increased local pore-water pressures around plant stems (Pollen-Bankhead and Simon, 2010), surcharge due to the weight of overhanging trees (Thorne, 1990; Simon *et al.*, 2004a) and increased infiltration capacity leading to water logging (Simon *et al.*, 2004a; Pollen-Bankhead and Simon, 2010). Main channel width increases also triggered planform changes at study site 9. Single thread meandering reaches transformed into unstable multi-thread braided reaches with bars (Figure 4.15). Here, species such as *Vachellia (Acacia) karroo*, which often colonized the channel bed (Figure 3.2) during periods of low peak flow, probably also contributed to channel pattern change, a trend noted by for example Tooth and Nanson (2000) and Tooth (2013). Bank retreat or erosion is a natural process of geomorphic significance. It is important in channel width and planform adjustments, catchment sediment processes, lateral channel migration, meander formation, floodplain alterations, landform development and vegetation settlement (Wohl, 2000b; Couper and Maddock, 2001; Couper, 2004; Kingsford *et al.*, 2006; Kleinhans, 2010). Bank shape (e.g. stepped, concave, convex and vertical) reflects fluvial process operations and flow depth and width discharge related adjustments. For example vertical banks (as seen in Figures 2.14 and 7.3b) generally signify active basal erosion associated with increased discharge (Rowntree and Wadeson, 1999). Indicators of enlarging river channels with eroding banks include tree root exposure as displayed in Figure 7.2b, bent trunks, undercut banks and in-channel trees (e.g. Figure 7.4c) (Gregory, 1992). Large wood in rivers can greatly increase channel roughness but, once mobilized downstream, it can induce local scour as well as channel pattern changes linked to channel avulsion and flow diversion (Hickin, 1984; Rowntree and Dollar, 1999; Wohl, 2000c; Francis *et al.*, 2008b; Naiman *et al.*, 2010).

Although low levels of invasion occurred across valley settings (Figure 6.1 and Table 6.4), morphological change (e.g. channel contraction linked to aggradation) in the Baviaanskloof at confined and semi-confined valley settings could possibly also be related to the presence of exotic species. PRIMER results (Table 6.8 and Appendix 6.2) showed that species such as the grasses *Pennisetum clandestinum* and *Pennisetum setaceum* (both weeds) and the herbs *Datura stramonium* and *Rumex crispus* (a proposed invader) dominated at a few habitat types. These were main channel banks, a backwater area and an island. Usually invasive plant characteristics include high seed or propagule production, efficient dispersal mechanisms, rapid growth, aggressive competition for resources, and wide tolerance for unfavourable conditions (Tickner *et al.*, 2001; Bromilow, 2010; Rebelo *et al.*, 2013). Worldwide riparian zones are considered to be especially prone to invasion by exotic species (Tickner *et al.*, 2001; Galatowitsch and Richardson, 2005; Holmes *et al.*, 2005; Richardson *et al.*, 2007). This is

mainly because the same factors (e.g. available landforms, nutrient replenishment, flowing water, etc.) supporting high species richness and diversity in zones, may also increase susceptibility to invasion (Hood and Naiman, 2000; Galatowitsch and Richardson, 2005; Corenblit *et al.*, 2014).

Consequences of invasions can include: habitat loss and fragmentation; replacing native vegetation with dense monocultures which cause a decline in species diversity (Brock and Green, 2003; Richardson *et al.*, 2007; Meek *et al.*, 2010); increased flooding risk (Bromilow, 2010); reduction in water table levels and increasing salinity (Tickner *et al.*, 2001), increased transpiration causing reduced stream flow (Holmes *et al.*, 2005; Richardson *et al.*, 2007; Meek *et al.*, 2010) and river channel changes (Rowntree, 1991; Tickner *et al.*, 2001; Birken and Cooper, 2006; Richardson *et al.*, 2007; Smith-Adao and Scheepers, 2007). Specifically, impacts of exotic vegetation on river morphology are related to the fact that these species may alter bank resistance and stability; overbank hydraulic roughness and sedimentation (Rowntree and Dollar, 1996; Rowntree and Dollar, 1999; Wohl, 2000a) as well as channel width and planform (Wohl, 2000a). Researchers for instance have described severe bank erosion and collapse by species such as *Acacia mearnsii* or *Salix babylonica* (Rowntree, 1991; Smith-Adao and Scheepers, 2007; Rebelo *et al.*, 2013) and sediment deposition linked to channel narrowing by *Tamarix* species (Tickner *et al.*, 2001).

7.4 Concluding remarks

This interdisciplinary investigation clearly demonstrates a strong link between valley confinement, surface-groundwater interactions, cross-valley landforms and vegetation in the Baviaanskloof (Figure 7.1). Specially, there are mutual implications of vegetation and hydrogeomorphic process and form on each other. However, from the discussion above it is evident that the interactions between these two variables are manifold and complex. This is presumably a result of the extreme variability (i.e. an unpredictable nature) of this semi-arid environment. Knowledge of valley morphology should feed into restoration designs. This could provide greater control of processes such as erosion and deposition in restored areas.

Chapter 8: General conclusions and recommendations

8.1 Key research findings

The overall aim of this thesis was to examine the relationship between valley confinement, fluvial style, valley floor morphology and vegetation in the semi-arid environment of the Baviaanskloof river catchment, South Africa. This aim was approached in a stepwise manner, with results from each data chapter informing the subsequent data collection and analysis of later chapters (Figure 1.2). Its intension was to provide a theoretical and applied understanding of dryland river system dynamics by exploring biophysical pattern and process interactions. This was done to contribute to an evolving body of interdisciplinary river science and to inform river restoration efforts in the Baviaanskloof.

This section summarizes the key findings or conclusions of the core chapters (Chapters 3-7) in light of the research objectives and knowledge gaps posed in the introduction to this thesis (Chapter 1).

8.1.1 Objective 1: To examine historic rainfall patterns and climate extremes (Chapter 3)

Chapter 3 presented a historical analysis based on available secondary data sources for the ungauged Baviaanskloof River catchment. Its primary goal was to obtain information on rainfall patterns and extreme event occurrence (modelled river flows, floods and droughts) in order to explain past (Chapter 4) and present (Chapters 5-7) hydrogeomorphic process-form and vegetation relations in the catchment using a mixed method approach. There was a specific focus on the magnitude, frequency and seasonality of moderate to extreme rainfall events. The following broad conclusions can be drawn from this research.

Firstly, the mixed method approach employed in this study was found to be vital to improving the spatial and temporal consistency of data and thus robustness of the resulting findings. The combination of available methodologies related to rainfall, modelled streamflow and historical accounts (documentary evidence and interviews) extended the climatic record and partially filled the streamflow gap in the study area (Chapter 2). According to Juracek and Fitzpatrick (2009) and Benito *et al.* (2010) continuous long-term streamflow data used in fluvial geomorphic investigations are generally lacking in dryland environments, and this approach offers a good method for improving data in similar data poor semi-arid areas in other parts of the world.

Secondly, the rainfall (daily, monthly and yearly) results indicated a typical semi-arid situation (for example see Tooth, 2000b; Bull and Kirkby, 2002; Young and Kingsford, 2006). The area was characterized by low and highly variable rainfall. The number of rain

days was less than 12% for the total rainfall record. Hence, the dry days far exceeded that of the number of rain days. However, over time there was both a reduction in the number of consecutive dry days and the maximum number of consecutive wet days. Furthermore, the moderate rainfall events (10-25 mm) contributed more than 80% of all events across rain gauge stations. These events accounted for most of the total number of rainfall events but the good to extreme rainfall events (40-100 mm) contributed most of the actual rainfall amount. There was also far less extreme rainfall than heavy (50-70 mm) rainfall. Although rain fell all year, the most intense storm events occurred in the summer and autumn months. March had the highest frequency of 12 heavy rainfall events. The driest season was winter.

Across time periods, the 1970s experienced the most intense storm events (1971, 1974 and 1979). In contrast, the most extreme dry periods occurred in the 1920s (1926/27) and 1980s (1983/84). A significant finding of this study was that there is considerable inter-annual variability in the rainfall. The yearly rainfall analysis revealed that across stations the most wet years were found in the 1970s and 1980s while the most dry years were found in the 1940s. Extreme conditions occurred in the years 1974 (extreme wetness) and 1984 (extreme dryness). The chance of extreme floods and droughts occurring in these years were very high.

Thirdly, the streamflow model was useful in extreme events (i.e. reasonable accuracy) which drive the system in the Baviaanskloof. The river flow analysis demonstrated that the study area was characterized by extreme flow variability which was linked to very low flows to flood flows. These flows were highly episodic and flashy. Importantly, the unconfined reaches of the Baviaanskloof River flowed for longer periods after intense rainfall events of > 50 mm. This was mainly related to above average seasonal rainfall. This finding is significant because it is directly related to improved surface-groundwater interactions which, in turn, results in increased vegetation and channel stability at the unconfined valley setting. Longitudinal connectivity is also increased. The combination of low to average flows and high transmission losses resulted in disconnected reaches, at especially the unconfined valley setting. Most of the very low river flows (< 15 Mcm/a) occurred in the 1940s (e.g. 1948, 7.73 Mcm/a). Extreme river flows (> 100 Mcm/a) which are typically associated with damaging flood events, were predicted six times in 84 years (e.g. 1996, 129.31 Mcm/a).

Fourthly, the flood and drought chronology indicated that at least 34 floods occurred in the Baviaanskloof. The majority of the floods were observed in the 1970s and 1980s. In general, major floods tend to occur at least once in each decade with moderate flooding occurring every 1-3 years. The chronology also revealed an under-reporting of drought events. The oldest written reference to a drought in the study area was in 1915. Since that time droughts were only noted in 1933, 1966 and 1987 (i.e. an extreme event).

Lastly, an important conclusion of this synthesis was data on rainfall, modelled streamflow and major floods and droughts were cross-checked, there was a general correlation. However,

there was generally disagreement between major floods and rainfall events of high return periods. For example, the flood event of 31 December 1931 did not correspond to rainfall with a 10.4 year return period. Regardless of the limitations of the mixed method approach, it is felt that it resulted in a combined data set that is more robust. It is recommended that the flood and drought chronology should be used as a foundation for future studies in the Baviaanskloof.

8.1.2 Objective 2: To investigate historic geomorphological (i.e. fluvial morphology), land cover and vegetation changes (Chapter 4 with inputs from Chapters 2 and 3).

Chapter 4 investigated historical valley floor changes at selected study sites (Figure 4.1) in the Baviaanskloof River catchment. Time-tested methods (e.g. aerial photo interpretation) were employed. Valley floor changes observed today (Chapters 5-7) reflect an integrated history of former events and impacts (Chapters 3 and 4). Winterbottom (2000) and Dollar (2004) noted that only by understanding the past can we begin to disentangle the complex factors which affect current river systems. This chapter revealed that at a catchment scale valley confinement is a primary control influencing hydrogeomorphic processes and landforms in the study area. Furthermore, secondary confining features such as alluvial fans and terraces acted as additional controls at 50% of the study sites at especially the unconfined valley setting. Within confinement settings landforms are highly variable, reflecting rainfall and bi-directional biophysical feedbacks between vegetation and landforms related to fluvial processes of sediment. Distinct characteristics in geomorphology, and vegetation across confined, semi-confined and unconfined valley settings are revealed.

Confined valley settings had narrow valley floors associated with limited accommodation space which restricted channel adjustments (e.g. limited lateral channel migration) and sediment storage or reworking (i.e. landform formation). Terraces and alluvial fans situated along valley margins are limited in confined settings but when present, further constrained morphology. Single thread channel reaches narrowed while bars were reduced and transformed into narrow flood benches and poorly developed floodplains. These landforms had constricted riparian and terrestrial vegetation associations that were of medium to high density.

Semi-confined valley settings had wider valley floors linked to increased accommodation space which resulted in the river reaches being less constrained. However, shifts in channel position from one valley side to another varied while sediment stores remained to some extent restricted. The Baviaanskloof River experienced a planform change (braided to sinuous single thread) which was accompanied by channel narrowing. There was also a general reduction in mid-channel and point bars that were later reworked into larger floodplain surfaces. High

narrow terraces lined one valley margin while alluvial fans were limited. The vegetation density either remained low or increased substantially which was later shown to be related to water availability (Chapter 5).

Unconfined valley settings had increased accommodation space associated with broad valley floors. However, secondary controls by terrace and fan sediments resulted in the main channel only adjusting laterally across floodplains at certain places. These extensive secondary confining features lined both valley margins. Moreover, main channel reaches changed from single thread to multi-thread (i.e. a braided morphology). They had higher sinuosity and highly variable widths (i.e. widening and narrowing). Sediment storage and reworking at unconfined valley settings caused an increase in the number of landforms as well as landform expansion and contraction (e.g. floodplains). In addition, the valley floor was mostly covered by low density vegetation which decreased over the years, only becoming denser after, for example, flood events.

Valley floor changes at the three valley confinement settings were also influenced by other variables such as floods, droughts and human impacts. For example, river pattern and sediment storage changes were probably a consequence of channel narrowing linked to the periods and droughts on record (Chapter 3). Likewise, flow permanence (from the shallow groundwater table) at the confined and semi-confined valley settings caused vegetation growth which stabilized the channel banks and contributed to channel narrowing. Vegetation increase can also be linked to the total absence or abandonment of agricultural activities over the decades (Chapter 2).

The findings further suggested that main channel expansion at the unconfined valley setting was associated with high river flows which promoted channel bed and bank erosion. Increased river discharges resulted from the extremely wet periods and major floods (e.g. 1981 and 1996) on record (Chapter 3). The channel widening at this valley setting correlated well with the identified large floods and supplied the sediments needed to form new landforms (e.g. bars). However, sediment stores could have been related to the lateral shifts in main channel position or historic overstocking and subsequent soil erosion due to overgrazing (Chapter 2). In addition, past management interventions such as levee construction or river channelization most likely also contributed to channel widening. Channel widening, in turn, resulted in shifting inherently unstable multi-thread braided reaches with bars.

The intermittent or ephemeral flow (i.e. indicating a deeper groundwater table) at the semi-confined and unconfined valley settings supported largely sparse vegetation which was associated with landform instability. However, here vegetation changes were also related to agriculture (abandonment, increases and decreases). The valley floor at the unconfined sites has been especially heavily impacted as natural vegetation was converted to crops production

and pastures (Chapter 2). There was a tendency for former agricultural areas to be mostly covered by grass species.

Aerial photograph interpretation within valley settings at the quadrat scale yielded new insights into the morpho-dynamics of geomorphic landforms on the valley floor. There was strong evidence that the landforms at the three valley confinement settings were associated with frequent and rapid change and were therefore very unpredictable. Over the last 63 years fluvial action and vegetation relations resulted in both positive and negative biophysical feedbacks. For example, existing features were abandoned (e.g. old channels), evolved into new landforms (e.g. benches) and became densely vegetated (e.g. stable islands). Positive feedbacks were related to sediment accumulation and vegetation establishment. Ultimately landform heterogeneity was the result, with features at times also reverting back to previous ones.

8.1.3 Objective 3: To determine the two-way links between hydrogeomorphic processes and landforms, including surface-groundwater interactions, and vegetation distribution patterns on the valley floor (Chapters 5-7 with inputs from Chapters 2-4)

The overall goal of Chapters 5-7 was to explore hydrogeomorphic process-form and vegetation relationships on the valley floor. This goal was achieved in a stepwise manner, with results from the core data from Chapters 5 (physical dynamics) and 6 (vegetation patterns) synthesized collectively in the subsequent chapter, Chapter 7. A mix of methods which included some unconventional approaches (e.g. multivariate analyses) was used in this interdisciplinary investigation. This approach significantly improved data quality. Several key variables influenced the biophysical patterns and processes in the study area. Study findings highlighted the fact that very strong links exist between valley confinement settings, surface-groundwater interactions, vegetation composition and patterning, fluvial geomorphic forms and processes and human activities (Figure 7.1).

8.1 Physical controls on valley floor vegetation patterns

An important conclusion of this synthesis was that water availability mainly controlled (i.e. exerted the greatest influence) vegetative response in the Baviaanskloof. Two groupings were closely related to flow permanence (i.e. the absence or presence of surface flow at the Baviaanskloof River). The channel reaches with surface flow grouped closely and were mostly associated with confined and semi-confined valley settings. In contrast, the dry bed channel reaches were more similar again and primarily situated in the unconfined valley setting (Chapter 6). Furthermore, this research revealed high surface-groundwater interactions across valley settings. More specifically, links were found between rainfall variability,

groundwater table depth, flow permanence and vegetation density (Chapter 7). The Electrical Resistivity Tomography technique was used with success in the study area to define water table levels across valley floor landforms at five selected sites.

As hypothesised, the groundwater table at the confined valley setting was close to the surface (0.5-2.5 mbd). Baseflow is the dominating contribution to streamflow during the dry periods (i.e. reaches are groundwater driven). The resulting permanent or intermittent surface water at the confined valley setting promoted dense riparian vegetation which contributed to channel stability. At the semi-confined valley setting water table levels were variable (shallow and deep). They were associated with both temporary and permanent streamflows. This explained the low and high density vegetation in the riparian zone at this valley setting. The groundwater table was the deepest at the unconfined valley setting (e.g. 10-15 mbd) (Chapter 5). Here, except for extremely wet periods, streamflow is only present during or immediately after flooding events (i.e. reaches are flood driven). The intermittent or ephemeral channel reaches at this valley setting were associated with sparse vegetation and channel instability. The resistivity profile NDVI and Tasseled Cap analysis generally substantiated the above mentioned findings from the resistivity survey. Support was also found for the hypothesis that if valley floor vegetation remains green during the dry period, then there is a groundwater influence. Hence, the rainfall, NDVI and Tasseled Cap quadrat analysis also indicated a direct relationship between surface-groundwater availability and vegetation response (Chapter 7).

This research demonstrated that vegetative response was also the product of valley confinement differences (e.g. narrow versus broad valley floors) and fluvial landform characteristics (substrate and hydrologic conditions) (Chapter 5). These features acted as secondary controls on the vegetation which had mostly perennial (mainly herbs and shrubs) and indigenous plant species. Pair-wise tests showed moderate vegetation differences between confined and unconfined valley settings. Low global R^2 test values also indicated that the vegetation distribution patterns in Baviaanskloof were highly dynamic and spatially very variable (e.g. often widespread) (Chapter 6). However, pair-wise tests did reveal that across valley confinement settings certain plant species were landform specific. In addition, BIO-ENV and BVSTEP analyses showed that landform elevation and distance (position) and sediment size (fine and coarse sand) are relatively good correlates of vegetation distribution patterns.

The sediment analyses at the three valley confinement settings showed that grain size variability resulted in distinct landforms occurring at differing positions cross-valley. Increasing landform elevation and distance from the channel (i.e. the thalweg to the valley edge) are also associated with a number of interconnected abiotic factors that account for vegetation differences. In the study area the dominant grain size fractions across landforms were gravels and sands (Chapter 5). Gravels were either fine to medium (e.g. confined sites) or medium to coarse (semi-confined sites). Sands were either fine (e.g. unconfined sites) or

fine to medium (semi-confined sites). Low silt and clay values were mostly recorded at all the valley confinement settings. The downstream geomorphic unit analyses related to the mean (i.e. average) and coarse grain sizes were largely in the medium to very coarse gravel size fraction class with mostly no significant longitudinal trends. Exceptions included for example the downstream fining (floodplains and main channel banks) and coarsening (flood benches) at the confined valley setting.

The coarsest grained materials (e.g. cobbles and boulders) were mostly associated with in-channel and channel margin landforms such as bars and flood benches. These erosion and deposition dominated low-lying features were often unstable due to high flood disturbance. This, in turn, influenced vegetation composition and patterning. Species compositional shifts resulted in trees such as *Vachellia (Acacia) karroo* being common to the channel bed and directly contributing to the creation of depositional features such as islands (Chapter 6). Instream, bar and wet bank species (e.g. the sedge *Cyperus denudatus*) that were associated with Group 1 (i.e. wetted channel sites across confinement settings), for example, consisted mainly of free floating and rooted herbs of young age that were pioneer, ruderal or early successional. High cover riparian tree species such as *Salix mucronata* (wet bank) and exotics also occurred. These species usually have many life history strategies or adaptations to deal with the fluvial environment. Dry banks and flood benches contained mostly a mix of rooted herbs (particularly grasses) and shrubs with canopy-forming trees to a lesser extent. The most tree species were located at the confined and semi-confined valley settings.

The plants closest to the active channel were linked to Group 2 (i.e. except site 2, dry bed channel sites in semi-confined and unconfined valleys). They consisted mainly of indigenous perennial shrub (mostly) and herb species that included upland (floodplains or terraces) species that were more tolerant to drier conditions, e.g. succulents and geophytes. These species have adaptations such as the use of refugia to survive dry conditions. At in-channel and channel margin landforms at Group 2 sites, high cover aquatic or semi-aquatic vascular plants were absent while trees were few and scattered. Exotic species were also limited. Plant species here included the grass *Aristida congesta* and the shrub *Chrysocoma ciliate*. *Vachellia (Acacia) karroo* was the most abundant tree species. In agreement with many studies, across valley settings older surfaces (e.g. terraces) consisted largely of finer grained materials. However, on occasion they (e.g. unconfined sites) had coarse sediment additions from, for example, alluvial fans and tributary confluences. In general, these landforms were drier and more stable, with terraces the least inundated feature. At both site groupings these low flood-frequency landforms were dominated by species that were adapted to the dryness at higher elevations (Chapter 6). They included the grass *Panicum deustum* and the shrub *Lycium cinereum*.

Across all valley settings, the floodplains and flood benches predominantly had the highest plant species richness despite their contrasting hydrogeomorphic characteristics. As expected,

species richness was also the lowest at the channel bed. An important finding of this study was that several geomorphic features in the study area supported species that were not found on other landforms. At Group 1 sites they included for example the shrub *Leysera gnaphaloides* (lateral bar) and the exotic succulent shrub *Agave Americana* (island) (Chapter 6). Species at Group 2 sites included the herb *Ifloga glomerata* (mid-channel bar) and the succulent herb *Ruschia rigens* (flood bench). However, adjacent landforms at all three valley confinement settings at times also shared similar plants. There was generally a decrease in similarity with landforms further away from the active channel. This trend was stronger at Group 1 sites (confined and semi-confined sites) and mostly likely related to water availability.

The next most important explanatory variables for the vegetation changes on the valley floor were related to human impacts. BIO-ENV and BVSTEP results confirmed a link between available phosphorus and vegetation variance at Group 2 sites. These encompassed the dry bed channel sites at the semi-confined and unconfined valley. This finding concurred with the high to very high values for available nitrogen and phosphorus that were recorded at the unconfined valley setting for floodplains. These nutrients are often a response to anthropogenic disturbance linked to intensive agricultural land use at higher elevation floodplain and terrace surfaces (Noe and Hupp, 2005; Lamers *et al.*, 2006). The historic mapping analysis showed how agricultural fields extended into the vast floodplain and terrace areas of the unconfined valley setting (Chapter 4). Furthermore, these surfaces were grazed by various livestock (e.g. sheep, goats, ostriches and cattle). Agriculture in the valley was also accompanied by river-floodplain engineering. This included channel straightening and the construction of levees to protect fields and infrastructure from flooding (Chapter 2). In the Baviaanskloof the combination of all the above mentioned anthropogenic impacts contributed to the decline in the native vegetative cover at the unconfined valley setting. This was also accompanied by fragmented or patchy plant communities of medium to high densities cross-valley (Chapter 4).

8.2 Vegetation controls on valley floor process-form dynamics

In the study area confined, semi-confined and unconfined valley settings were characterized by cross-valley landform formation and modification driven by the interplay of flood disturbance (moderate and extreme), sediment, soil moisture availability (e.g. depth to groundwater) and vegetation. In addition, landforms along the Baviaanskloof River were probably also engineered by certain aquatic, riparian and terrestrial vegetation. The results indicated that in-channel and channel margin geomorphic features were dominated by for example the winged sedge (*Cyprus denudatus*) and Cape willow (*Salix mucronata*). These species all share traits associated with regular flooding such as sexual and vegetative reproduction, being able to resprout and anchoring via dense adventitious root networks (Chapter 6). They are especially well equipped to colonize bare or inundated alluvial sediment

and create, maintain or modify geomorphic landforms. They trap and stabilize sediment to build pioneer landforms and facilitate rapid colonization by post-pioneer plants which, in turn, reinforce landform development (Corenblit *et al.*, 2011; Gurnell, 2014).

Wood accumulation was also found to be associated with landform building and stabilization in the study area. At the unconfined valley setting, reduced stream power linked to limited flow depths resulted in the main channel bed transforming into bars, islands and floodplains. These landforms were occupied for example by karoo quick grass (*Cynodon incompletus*) and sweet thorn which dominated. In the Baviaanskloof this perennial tree can be considered a landform-constructing pioneer plant species which has an opportunistic growth pattern. Currently, there are no strong competitors for the niches that this species is exploiting with such success, which would explain its aggressive coverage of large areas of the valley floor. Likewise, its ability to fix nitrogen often resulted in it having an understorey of grasses and shrubs (Barnes *et al.*, 1996). The latter trend was observed cross-valley at all the valley confinement settings with grass species dominating.

This research highlighted strong linkages between patterns of sediment erosion (e.g. bank retreat), deposition and vegetation (Chapter 4). This was reflected at the cross-sectional scale where, for example, narrow, stable and wide, less stable main channels alternated at the three valley confinement settings. In the Baviaanskloof narrowing of the main channel at the confined and semi-confined reaches was associated with densely vegetated lateral accretion deposits and landform stability. Often grassy and herbaceous vegetation were related to a persistent water table, more permanent surface flow and increased bank strength. The highest grass cover occurred at the confined valley setting. However, at times floodwaters uprooted or removed channel margin woody and grassy vegetation. Higher silt percentages at main channel banks, islands and flood benches also reflected the cohesiveness of these geomorphic features (i.e. increased fluvial erosion resistance) (Thorne, 1990).

At the unconfined valley setting main channel widening over the decades was primarily related to sparse bank lined vegetation associated with intermittent or ephemeral flow (i.e. a deeper groundwater table) which resulted in bank instability and failure, but also landform formation. Main channel width increases also triggered planform changes (e.g. site 9). Single thread meandering reaches transformed into unstable multi-thread braided reaches with bars. Here, species such as *Vachellia karroo*, which often colonized the channel bed during periods of low peak flow (Chapter 3), probably also contributed to channel pattern change. In the Baviaanskloof indicators of enlarging river channels with eroding banks included tree root exposure, bent trunks, undercut banks and in-channel trees (Chapter 7). Large wood in rivers can greatly increase channel roughness but, once mobilized downstream, it can induce local scour as well as channel pattern changes linked to channel avulsion and flow diversion (Wohl, 2000c; Naiman *et al.*, 2010).

Even though low levels of invasion occurred across valley settings (Chapter 6), morphological change (e.g. channel contraction linked to aggradation) in the valley at confined and semi-confined valley settings could possibly also be related to the presence of exotic species. PRIMER results showed that species such as the grasses *Pennisetum clandestinum* and *Pennisetum setaceum* (both weeds) and the herb *Rumex crispus* (a proposed invader) dominated at a few habitat types. These were main channel banks, a backwater area and an island. Impacts of exotic vegetation on river morphology are related to the fact that these species may alter bank resistance and stability, overbank hydraulic roughness and sedimentation as well as channel width and planform (Wohl, 2000a).

In summary, reflecting on the research conducted in this interdisciplinary investigation the following key findings are presented:

- In this semi-arid area, the soil water regime, either through streamflow conditions or groundwater availability at the three valley confinement settings, was the primary control on valley floor vegetation composition and patterning. One group of species was associated with the wetted channel reaches at confined and semi-confined valley settings while the other with dry bed channel reaches at the unconfined valley setting.
- Secondary controls on vegetation included valley confinement differences, fluvial landform characteristics (substrate and hydrological conditions) and human disturbance. The vegetation data thus revealed distinct associations of plants to fluvial landforms and processes of adjustment (channel narrowing and widening). This can also be explained by the life history traits that affect a plant's adaption to the disturbance regime. Landforms close to the channel supported pioneer plants that were adapted to high flood disturbance (e.g. hydrophytes) whereas plants further away were adapted to drier conditions (e.g. succulents). These upland landforms experienced less flooding and supported more mature plant communities. Floods do not reach these landforms unless in an extreme event (Chapter 3).
- However, some species showed no landform preference and occurred across landforms up the lateral and hydraulic gradient on the valley floor. There was the tendency at times for adjacent landforms across valley confinement settings to share similar plants. There was also a decrease in similarity with landforms further away at confined and semi-confined valley settings. This trend was probably related to water availability. Although species richness increased from the channel bed to the terrace surface, across all valley confinement settings, species richness was the greatest on floodplains and flood benches.
- Valley confinement, which is a direct influence of geology, is the most important factor shaping hydrogeomorphic processes and landforms at the three valley confinement settings. Alluvial fans and terraces acted as critical additional controls at the unconfined valley setting. These controls imposed constraints on channel adjustment (e.g. lateral migration) and planform as well as sediment storage or reworking and surface-groundwater interaction.

- Grain size variability resulted in distinct landforms occurring at differing positions cross-valley (lateral gradient). Across landforms gravel and sand grain size fractions dominated. The coarsest grained materials (e.g. cobbles and boulders) were mostly associated with near channel landforms (e.g. banks and bars). They were erosion and deposition dominated low-lying features that were generally less stable. Floodplain and terrace surfaces were more stable and characterized mostly by finer grained materials. These sediment trends attest to the influence of valley confinement, the position of differing geomorphic landforms relative to the thalweg, and the use of energy by the active channel. The downstream geomorphic unit analyses mostly indicated no significant longitudinal trends.
- Certain aquatic, riparian and upland plants also strongly affected sediment erosion and deposition and were integral in the development and overall stability of valley floor fluvial landforms at the three confinement settings. This was mainly linked to root reinforcement (i.e. improved soil drainage and tensile strength) and an increase in flow resistance (i.e. reduced near-bank flow velocities). These plants acted as river system engineers. In addition, morphological change (e.g. channel narrowing and widening) was associated with these engineering plants, low and flood flows and human alteration. This could also be related to the presence of exotic species at the confined and semi-confined valley settings.

8.2 Implications for river restoration efforts in the Baviaanskloof

Knowledge gained on historical valley floor changes and morphodynamics in this study should feed into the alluvial fan, tributary and floodplain restoration works which began in 2011 (Van den Broek *et al.*, 2012). Results from this study indicate that old agricultural fields in unconfined valley setting will not recover without active revegetation on the floodplains (Chapter 4). The deeper groundwater table and thus, lower surface-groundwater interaction (Chapter 5) preclude natural recolonization of these areas. These abandoned fields at present are mostly covered by grass species, which contribute to instability at unconfined valley sections. The landform-constructing, pioneer tree species, sweet thorn (*Vachellia karroo*) (Chapter 7) should be considered in revegetation of these areas. This engineering plant stabilizes landforms and facilitates rapid colonization by post-pioneer plants which, in turn reinforces landform development. Its ability to fix nitrogen often results in it having an understorey of mixed vegetation. However, this is dependent on it not growing too densely. Some grazing at low carrying capacity is beneficial for keeping sweet thorn at a good density that promotes species diversity and vegetation recovery (Barnes *et al.*, 1996).

Restoration works in the Baviaanskloof also consist of the removal of levees along the main and fan channels on the floodplain (Figure 2.15c-d) and newly constructed blocking structures in tributaries and on alluvial fans to redirect the water and the removal or closure of man-made channels to the main channel primarily at the unconfined valley setting (Living Lands,

2011; de Jong, 2013). These interventions all aim to force the water back onto fan and floodplain surfaces (i.e. retain water in the landscape) and restore the buffering capacity of the alluvial fans. Fans thus, reinstating the natural water pathways and slowing down flood water while promoting groundwater storage and sedimentation on the valley floor. Moreover, they bring about increased lateral connectivity but variable longitudinal connectivity. For instance tributary-trunk linkages are increased but upstream-downstream linkages are reduced. Levee removal should not be such a problem since active agriculture mostly decreased over the years (Chapter 4). The substrates (e.g. cobbles and boulders) can then be returned to the incised mainstem reaches to aggrade the channel bed. Provided that longitudinal connectivity is high, floods should redistribute the coarse sediments restoring the natural functioning of these reaches.

Trade-offs will have to be made by farmers with reduced surface water availability in the short term owing to increased soil infiltration and groundwater recharge. The regulation of groundwater abstraction and limited floodplain use (grazing at low carrying capacity only) will also be crucial. This is especially important for the vegetation. Results from this research indicated that water availability mainly controlled vegetative response in the Baviaanskloof (Chapter 6). However, there are also complications with attempts to restore the floodplains using artificial embankments. These structures that redirect tributary channels onto the floodplain surfaces is not likely to succeed because of the variability of the landforms. Findings from this study showed that the geomorphic landforms are highly dynamic and unpredictable and, therefore subject to rapid changes (Chapter 4). Hence, blocking alluvial fan channels at one point may simply result in another channel developing elsewhere. Furthermore, incised fan channels are often the result of main river channel toe trimming. Restoration would be working against a natural process and would therefore be counterproductive (Rowntree *et al.*, 2011)

Restoration measures also involve the construction of gabion weirs across the Baviaanskloof River and adjacent flood benches in the unconfined valley setting (Figure 2.15e-f). Specifically, this restoration action focuses on increasing the frequency of floodplain inundation (i.e. overbank flooding), recharge of valley floor groundwater (i.e. raised groundwater table depth levels) and duration of baseflow in the main channel. It is linked to lower longitudinal connectivity but stronger lateral and vertical connectivity. Likewise, the water retained behind the gabion weirs ought to restore the wetlands (i.e. via habitat creation). The colonization of channel margin geomorphic features typically accelerate sediment retention and cross-profile recovery of engineered channels (Gurnell, 2014).

However, this restoration action may not be so effective in meeting its intended objectives. The construction of these artificial structures could also result in downstream channel incision and channel switching. Geomorphic mapping results from this study showed how high-energy conditions promoted lateral shifting of the inherently unstable multi-thread braided reaches of

the Baviaanskloof River at broad valley floors (Chapter 4). Channel incision can be the consequence of a reduction in sediment transport and may undercut structures (i.e. cost implications), while channel switching in itself is not undesirable, it would leave the structures in abandoned channels since braided channels are naturally prone to channel switching during floods.

Lastly, many studies have highlighted the fact that continued monitoring is essential to the success of restoration projects as adjustments to the restoration plan may be required (Palmer *et al.*, 2005; Brierley *et al.*, 2010; Mika *et al.*, 2010). Findings from this study indicate that, for a variable system such as that of the Baviaanskloof landscape, there is a need for monitoring sites (e.g. groundwater or reserve determination sites) to be representative and therefore actually placed in different valley confinement settings in order to get the full picture. To this end, the surveyed north-south cross-sectional profiles which were the basis for landform change, sediment and vegetation analyses (Chapter 5) should be considered in future monitoring plans.

8.3 Future research

Given the research findings and the limitations of this study, the following areas offer unique opportunities for future research.

- Since long-term streamflow and groundwater level data are not available for the study area, the next logical step would be the collection and collation of these datasets. Data on streamflows are central to understanding river structure and function. As mentioned in Chapter 2, this process was started by PhD student, R. Powell and Glenday (2015).
- Further investigation is needed into the biophysical controls (e.g. vegetation, hydrology, geomorphology and human activities) on connectivity (vertically, laterally longitudinally and temporally) of both water and sediment at the three valley confinement settings.
- Further research on bio-physical feedbacks on the valley floor related to hydrogeomorphic process-form and vegetation bi-directional relations over longer time periods is also needed. As fieldwork in this research was limited, a comparative study over an extended period (e.g. 3 to 5 years), in different seasons and in other regions of South Africa is recommended.
- More work is also needed on valley floor vegetation composition and distribution patterns. There should be a specific focus on the vegetation types that are under sampled. These should have preference to be surveyed. In addition, the identification of engineering species that modify or create landforms and respond to changes must be prioritized.

In conclusion, biophysical patterns and processes are closely integrated environmental phenomena within the study area. In broader terms, the findings from this study contributed to

a better understanding of dryland river structure and function by addressing the knowledge gaps outlined in Chapter 1, Section 1.3. Specifically, information was provided on the little-studied relations between valley confinement, hydrogeomorphic process and form, surface-groundwater interaction and vegetation in a semi-arid valley floor environment (Figure 7.1).

REFERENCES

- ABERNETHY, B. & RUTHERFURD, I. D. 2000. The effect of riparian tree roots on the mass-stability of riverbanks. *Earth Surface Processes and Landforms*, 25(9): 921-937.
- ABERNETHY, B. & RUTHERFURD, I. D. 2001. The distribution and strength of riparian tree roots in relation to riverbank reinforcement. *Hydrological Processes*, 15(1): 63-79.
- ACOCKS, J. P. H. 1953. Veld types of South Africa. *Memoirs of the Botanical Survey of South Africa*, 28: 1- 192.
- ACOCKS, J. P. H. 1988. Veld types of South Africa. 3rd Edition. *Memoirs of the Botanical Survey of South Africa*, 57: 1-146.
- ALLMENDINGER, N. E., PIZZUTO, J. E., POTTER, N., JR., JOHNSON, T. E. & HESSION, W. C. 2005. The influence of riparian vegetation on stream width, eastern Pennsylvania, USA. *Geological Society of America Bulletin*, 117(1-2): 229-243.
- ALLSOPP, N. 1999. Effects of Grazing and Cultivation on Soil Patterns and Processes in the Paulshoek Area of Namaqualand. *Plant Ecology*, 142(1/2): 179-187.
- ALLSOPP, N., GAIKA, L., KNIGHT, R., MONAKISI, C. & HOFFMAN, M. T. 2007. The impact of heavy grazing on an ephemeral river system in the succulent karoo, South Africa. *Journal of Arid Environments*, 71(1): 82-96.
- AMLIN, N. & ROOD, S. 2002. Comparative tolerances of riparian willows and cottonwoods to water-table decline. *Wetlands*, 22(2): 338-346.
- AMLIN, N. M. & ROOD, S. B. 2003. Drought stress and recovery of riparian cottonwoods due to water table alteration along Willow Creek, Alberta. *Trees* 17: 351–358.
- AMOROS, C. & BORNETTE, G. 2002. Connectivity and biocomplexity in waterbodies of riverine floodplains. *Freshwater Biology*, 47(4): 761-776.
- ANTHEUNISSE, A. M., LOEB, R., LAMERS, L. P. M. & VERHOEVEN, J. T. A. 2006. Regional differences in nutrient limitation in floodplains of selected European rivers: implications for rehabilitation of characteristic floodplain vegetation. *River Research and Applications*, 22(9): 1039-1055.
- ARNAUD, F., PIÉGAY, H., SCHMITT, L., ROLLET, A. J., FERRIER, V. & BÉAL, D. 2015. Historical geomorphic analysis (1932–2011) of a by-passed river reach in process-based restoration perspectives: The Old Rhine downstream of the Kembs diversion dam (France, Germany). *Geomorphology*, 236(0): 163-177.
- ASAEDA, T., GOMES, P. I. A., SAKAMOTO, K. & RASHID, M. H. 2011. Tree colonization trends on a sediment bar after a major flood. *River Research and Applications*, 27(8): 976-984.
- ASHWELL, A., SANDWITH, T., BARNETT, M., PARKER, A. & WISANI, F. 2006. Fynbos fynmense: People making biodiversity work. SANBI biodiversity Series 4. Pretoria, South Africa.
- BARNES, R. D., FILER, D. L. & MILTON, S. J. 1996. *Acacia karroo: Monograph and annotated bibliography*. Tropical Forestry Papers No. 32 Oxford: Oxford Forestry Institute.
- BEECHIE, T. J., LIERMANN, M., POLLOCK, M. M., BAKER, S. & DAVIES, J. 2006. Channel pattern and river-floodplain dynamics in forested mountain river systems. *Geomorphology*, 78(1-2): 124-141.
- BENDA, L., MILLER, D. & BARQUÍN, J. 2011. Creating a catchment perspective for river restoration. *Hydrology and Earth System Sciences Discussions*, 8(2): 2929-2973.

- BENDIX, J. & COWELL, C. M. 2010. Fire, floods and woody debris: Interactions between biotic and geomorphic processes. *Geomorphology*, 116(3-4): 297-304.
- BENDIX, J. & HUPP, C. R. 2000. Hydrological and geomorphological impacts on riparian plant communities. *Hydrological Processes*, 14(16-17): 2977-2990.
- BENDIX, J. & STELLA, J. C. 2013. 12.5 Riparian vegetation and the fluvial environment: A biogeographic perspective. In: SHRODER, J. F. (ed.) *Treatise on Geomorphology*. San Diego, USA: Academic Press, pp. 53-74.
- BENITO, G., BOTERO, B. A., THORNDYCRAFT, V. R., RICO, M., SÁNCHEZ-MOYA, Y., SOPEÑA, A., MACHADO, M. J. & DAHAN, O. 2010. Rainfall-runoff modelling and palaeoflood hydrology applied to reconstruct centennial scale records of flooding and aquifer recharge in ungauged ephemeral rivers. *Hydrology and Earth System Sciences Discussions*, 7: 9631-9660.
- BENITO, G., THORNDYCRAFT, V. R., RICO, M. T., SÁNCHEZ-MOYA, Y., SOPEÑA, A., BOTERO, B. A., MACHADO, M. J., DAVIS, M. & PÉREZ-GONZÁLEZ, A. 2011. Hydrological response of a dryland ephemeral river to southern African climatic variability during the last millennium. *Quaternary Research*, 75(3): 471-482.
- BERTOLDI, W., DRAKE, N. A. & GURNELL, A. M. 2011. Interactions between river flows and colonizing vegetation on a braided river: exploring spatial and temporal dynamics in riparian vegetation cover using satellite data. *Earth Surface Processes and Landforms*, 36(11): 1474-1486.
- BERTOLDI, W., GURNELL, A. M. & WELBER, M. 2013. Wood recruitment and retention: The fate of eroded trees on a braided river explored using a combination of field and remotely-sensed data sources. *Geomorphology*, 180-181(0): 146-155.
- BINNEMAN, J. 1989. Towards a management strategy for the cultural resources in the Baviaanskloof In: KERLEY, G. I. H. & ELS, L. M. (eds.) *The Kouga-Baviaanskloof Complex: Conservation status and management problems. Proceedings of a workshop held at the University of Port Elizabeth*. Port Elizabeth, South Africa Chief Directorate: Nature and Environmental Conservation and University of Port Elizabeth pp. 8-13.
- BINNEMAN, J. 2000. Results from two test excavations in the Baviaanskloof Mountains, Eastern Cape. *Southern African Field Archaeology* 9: 83-96.
- BIRKEN, A. S. & COOPER, D. J. 2006. Processes of Tamarix invasion and floodplain development along the lower Green River, Utah. *Ecological Applications*, 16(3): 1103-1120.
- BISHOP, M. P., JAMES, L. A., SHRODER, J. F. & WALSH, S. J. 2012. Geospatial technologies and digital geomorphological mapping: Concepts, issues and research. *Geomorphology*, 137(1): 5-26.
- BLANTON, P. & MARCUS, W. A. 2009. Railroads, roads and lateral disconnection in the river landscapes of the continental United States. *Geomorphology*, 112(3-4): 212-227.
- BLAZKOVA, S. & BEVEN, K. 1997. Flood frequency prediction for data limited catchments in the Czech Republic using a stochastic rainfall model and TOPMODEL. *Journal of Hydrology*, 195(1-4): 256-278.
- BLOM, C. W. P. M., BÖGEMANN, G. M., LAAN, P., VAN DER SMAN, A. J. M., VAN DE STEEG, H. M. & VOESENEK, L. A. C. J. 1990. Adaptation of plants to flooding adaptations to flooding in plants from river areas. *Aquatic Botany*, 38(1): 29-47.
- BLOTT, S. 2010. GRADISTAT version 8.0: A grain size distribution and statistics package for the analysis of unconsolidated sediments by sieving or laser granulometer. Berkshire, UK Kenneth Pye Associates Ltd., Crowthorne Enterprise Centre.

- BLOTT, S. & PYE, K. 2001. GRADISTAT: A grain size distribution and statistics package for the analysis of unconsolidated sediments. *Earth Surface Processes and Landforms*, 16: 1237–1248.
- BLUCK, B. J. 1987. Bed forms and clast size changes in gravel-bed rivers. In: RICHARDS, K. S. (ed.) *River channels: Environment and Process*. Oxford, UK: Basil Blackwell Ltd, pp. 159-178.
- BOBBINS, K. 2011. *Developing a form-process framework to describe the functioning of semi-arid alluvial fans in the Baviaanskloof valley*. Unpublished MSc dissertation, Rhodes University, Grahamstown, South Africa, 174 pp.
- BOGGS, S. 1995. *Principles of sedimentology and stratigraphy* New Jersey: Prentice-Hall, Inc., pp.
- BOIX-FAYOS, C., BARBERÁ, G. G., LÓPEZ-BERMÚDEZ, F. & CASTILLO, V. M. 2007. Effects of check dams, reforestation and land-use changes on river channel morphology: Case study of the Rogativa catchment (Murcia, Spain). *Geomorphology*, 91(1-2): 103-123.
- BORNETTE, G., AMOROS, C. & LAMOUROUX, N. 1998. Aquatic plant diversity in riverine wetlands: the role of connectivity. *Freshwater Biology*, 39(2): 267-283.
- BORNETTE, G., PIÉGAY, H., CITTERIO, A., AMOROS, C. & GODREAU, V. 2001. Aquatic plant diversity in four river floodplains: a comparison at two hierarchical levels. *Biodiversity and Conservation*, 10(10): 1683-1701.
- BORNETTE, G. & PUIJALON, S. 2011. Response of aquatic plants to abiotic factors: a review. *Aquatic Sciences - Research Across Boundaries*, 73(1): 1-14.
- BOSHOF, A. 2005. The Baviaanskloof Mega-reserve: An environmentally, socially and economically sustainable conservation and development initiative. *Terrestrial Ecology Research Unit Report No. 52*. Port Elizabeth, South Africa.
- BOSHOF, A. 2008. The Baviaanskloof Mega Reserve: From concept to implementation *ACE Report No. 58*. Port Elizabeth, South Africa.
- BOSHOF, A., COWLING, R. & KERLEY, G. 2000. The Baviaanskloof conservation area: A conservation and tourism development priority *Report No. 27*. Port Elizabeth, South Africa.
- BOUCHER, C. 2002. Flows as determinants of riparian vegetation zonation patterns in selected Southern African rivers. *Enviro Flows 2002 4th Ecohydraulics Conference*. Cape Town, South Africa.
- BOULTON, A. J. 2003. Parallels and contrasts in the effects of drought on stream macroinvertebrate assemblages. *Freshwater Biology*, 48(7): 1173-1185.
- BRACKEN, L. J. & CROKE, J. 2007. The concept of hydrological connectivity and its contribution to understanding runoff-dominated geomorphic systems. *Hydrological Processes*, 21(13): 1749-1763.
- BRACKEN, L. J., TURNBULL, L., WAINWRIGHT, J. & BOGAART, P. 2015. Sediment connectivity: a framework for understanding sediment transfer at multiple scales. *Earth Surface Processes and Landforms*, 40(2): 177-188.
- BRACKEN, L. J., WAINWRIGHT, J., ALI, G. A., TETZLAFF, D., SMITH, M. W., REANEY, S. M. & ROY, A. G. 2013. Concepts of hydrological connectivity: Research approaches, pathways and future agendas. *Earth-Science Reviews*, 119: 17-34.
- BRIERLEY, G. & FRYIRS, K. 2009. Don't fight the site: Three geomorphic considerations in catchment-scale river rehabilitation planning. *Environmental Management*, 43(6): 1201-1218.

- BRIERLEY, G., FRYIRS, K., CULLUM, C., TADAKI, M., HUANG, H. Q. & BLUE, B. 2013. Reading the landscape: Integrating the theory and practice of geomorphology to develop place-based understandings of river systems. *Progress in Physical Geography*.
- BRIERLEY, G., FRYIRS, K. & JAIN, V. 2006. Landscape connectivity: The geographic basis of geomorphic applications. *Area*, 38(2): 165-174.
- BRIERLEY, G., FRYIRS, K., OUTHET, D. & MASSEY, C. 2002. Application of the River Styles framework as a basis for river management in New South Wales, Australia. *Applied Geography*, 22(1): 91-122.
- BRIERLEY, G., REID, H., FRYIRS, K. & TRAHAN, N. 2010. What are we monitoring and why? Using geomorphic principles to frame eco-hydrological assessments of river condition. *Science of The Total Environment*, 408(9): 2025-2033.
- BRIERLEY, G. J. & FRYIRS, K. A. 2005. *Geomorphology and river management: Applications of the river styles framework*, Oxford, UK: Blackwell Publishing, 398 pp.
- BROCK, J. H. & GREEN, D. M. 2003. Impacts of livestock grazing, mining, recreation, roads, and other land uses on watershed resources. *Journal of the Arizona-Nevada Academy of Science*, 35(1): 11-22.
- BROCK, M. A., CAPON, S. J. & PORTER, J. L. 2006. Disturbance of plant communities dependent on desert rivers. In: KINGSFORD, R. T. (ed.) *Ecology of desert rivers*. Cambridge: Cambridge University Press, pp. 100-132.
- BROMILOW, C. 2010. *Problem plants and alien weeds of South Africa*, Arcadia, Pretoria: Briza Publications, 424 pp.
- BROOKER, M. P. 1985. The ecological effects of channelization. *The Geographical Journal*, 151(1): 63-69.
- BROWN, K. & BROOKS, K. 2002. *Bushland weeds: A practical guide to their management*, Greenwood, Australia: Environmental Weeds Action Network (Inc), 108 pp.
- BROWNING, D. M., ARCHER, S. R. & BYRNE, A. T. 2009. Field validation of 1930s aerial photography: What are we missing? *Journal of Arid Environments*, 73(9): 844-853.
- BULL, L. J. & KIRKBY, M. J. 2002. Dryland river characteristics and concepts. In: BULL, L. J. & KIRKBY, M. J. (eds.) *Dryland Rivers: Hydrology and geomorphology of semi-arid channels*. Chichester: John Wiley & Sons, Ltd, pp. 3-15.
- BUNTE, K. & ABT, S. R. 2001. *Sampling surface and subsurface particle-size distributions in wadable gravel- and cobble-bed streams for analysis in sediment transport, hydraulics and streambed monitoring*. General Technical Report No RMRS-GTR-74, Colorado, USA: Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, 428 pp.
- BURGE, L. M. 2004. Testing links between river patterns and in-channel characteristics using MRPP and ANOVA. *Geomorphology*, 63(3-4): 115-130.
- CADOL, D., RATHBURN, S. L. & COOPER, D. J. 2011. Aerial photographic analysis of channel narrowing and vegetation expansion in Canyon De Chelly National Monument, Arizona, USA, 1935–2004. *River Research and Applications*, 27(7): 841-856.
- CALLOW, J. N. & SMETTEM, K. R. J. 2007. Channel response to a new hydrological regime in southwestern Australia. *Geomorphology* 84(3-4): 254-276.
- CEBALLOS, A., MARTÍNEZ-FERNÁNDEZ, J. & LUENGO-UGIDOS, M. Á. 2004. Analysis of rainfall trends and dry periods on a pluviometric gradient representative of Mediterranean climate in the Duero Basin, Spain. *Journal of Arid Environments*, 58(2): 215-233.

- CENTRE NATIONAL D' ETUDES SPATIALES 2012. SPOT-5 satellite imagery. France: Distribution Astrium Services/Spot Image S.A.
- CHALMERS, A. C., ERSKINE, W. D., KEENE, A. F. & BUSH, R. T. 2012. Relationship between vegetation, hydrology and fluvial landforms on an unregulated sand-bed stream in the Hunter Valley, Australia. *Austral Ecology*, 37(2): 193-203.
- CHEN, Y. N., ZILLIACUS, H., LI, W. H., ZHANG, H. F. & CHEN, Y. P. 2006. Ground-water level affects plant species diversity along the lower reaches of the Tarim river, Western China. *Journal of Arid Environments*, 66(2): 231-246.
- CHIEW, F. & SIRIWARDENA, L. 2005. *User guide for TREND version 1.0.2*, Australia: CRC for Catchment Hydrology, 23 pp.
- CHORLEY, R. J. & KENNEDY, B. A. 1971. *Physical geography: A systems approach*, London: Prentice-Hall International, 370 pp.
- CHURCH, M. 2002. Geomorphic thresholds in riverine landscapes. *Freshwater Biology*, 47(4): 541-557.
- CLARKE, K. R. & GORLEY, R. N. 2006. *PRIMER v6: User manual/tutorial* Plymouth, United Kingdom: PRIMER-E Ltd, 190 pp.
- CLARKE, K. R. & WARWICK, R. M. 2001. *Change in marine communities: An approach to statistical analysis and interpretation, 2nd Edition*, Plymouth, United Kingdom: PRIMER-E Ltd, 91 pp.
- CLARKE, S. J., BRUCE-BURGESS, L. & WHARTON, G. 2003. Linking form and function: towards an eco-hydromorphic approach to sustainable river restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 13(5): 439-450.
- COATES PALGRAVE, K. & COATES PALGRAVE, M. 2002. *Trees of southern Africa. 3rd Edition* Cape Town, South Africa: Struik publishers, 1212 pp.
- CONNELL, J. H. 1978. Diversity in tropical forests and coral reefs. *Science*, 199: 1302-1310.
- COOPER, D. J., SANDERSON, J. S., STANNARD, D. I. & GROENEVELD, D. P. 2006. Effects of long-term water table drawdown on evapotranspiration and vegetation in an arid region phreatophyte community. *Journal of Hydrology* 325: 21-34.
- CORENBLIT, D., BAAS, A. C. W., BORNETTE, G., DARROZES, J., DELMOTTE, S., FRANCIS, R. A., GURNELL, A. M., JULIEN, F., NAIMAN, R. J. & STEIGER, J. 2011. Feedbacks between geomorphology and biota controlling Earth surface processes and landforms: A review of foundation concepts and current understandings. *Earth-Science Reviews*, 106(3-4): 307-331.
- CORENBLIT, D., STEIGER, J., GURNELL, A. M., TABACCHI, E. & ROQUES, L. 2009. Control of sediment dynamics by vegetation as a key function driving biogeomorphic succession within fluvial corridors. *Earth Surface Processes and Landforms*, 34(13): 1790-1810.
- CORENBLIT, D., STEIGER, J. & TABACCHI, E. 2010. Biogeomorphologic succession dynamics in a Mediterranean river system. *Ecography*, 33(6): 1136-1148.
- CORENBLIT, D., STEIGER, J., TABACCHI, E., GONZÁLEZ, E. & PLANTY-TABACCHI, A. M. 2014. Ecosystem engineers modulate exotic invasions in riparian plant communities by modifying hydrogeomorphic connectivity. *River Research and Applications*, 30(1): 45-59.
- CORENBLIT, D., TABACCHI, E., STEIGER, J. & GURNELL, A. M. 2007. Reciprocal interactions and adjustments between fluvial landforms and vegetation dynamics in river corridors: A review of complementary approaches. *Earth-Science Reviews*, 84(1-2): 56-86.

- COSTA, A. C. & SOARES, A. 2009. Trends in extreme precipitation indices derived from a daily rainfall database for the South of Portugal. *International Journal of Climatology*, 29(13): 1956-1975.
- COUNCIL FOR GEOSCIENCE 1979 and 1991. Geology shapefile (1:250 000): 3322 Oudthsoon and 3324 Port Elizabeth Pretoria, South Africa: Spatial Data Management Unit, Council for Geoscience
- COUPER, P. R. 2004. Space and time in river bank erosion research: A review. *Area*, 36(4): 387-403.
- COUPER, P. R. & MADDOCK, I. P. 2001. Subaerial river bank erosion processes and their interaction with other bank erosion mechanisms on the River Arrow, Warwickshire, UK. *Earth Surface Processes and Landforms*, 26(6): 631-646.
- COWIE, M. & BRIERLEY, G. 2008. The influence of lateral confinement upon the downstream gradation in grain size of the lower Ngaruroro River, New Zealand. *The Open Geological Journal*, 2: 46-63.
- COWLING, S., REICHERT, K., BINNEMAN, J., HENDERSON, Z., VAN RYNEVELD, K., MOODLEY, S., COWLING, R., WOLF, D., LOGIE, B. & JOUBERT, P. 2007. The Baviaanskloof heritage route guide. *Report No. 27*. Port Elizabeth, South Africa.
- CRANE, W. 2006. Biodiversity conservation and land rights in South Africa: Whither the farm dwellers? *Geoforum*, 37(6): 1035-1045.
- CRIST, E. P. & KAUTH, R. J. 1986. The Tasseled Cap de-mystified. *Photogrammetric and Remote Sensing*, 52(1): 81-86.
- CURRAN, J. C. 2010. Mobility of large woody debris (LWD) jams in a low gradient channel. *Geomorphology*, 116(3-4): 320-329.
- DANIELS, J. M. 2003. Floodplain aggradation and pedogenesis in a semiarid environment. *Geomorphology*, 56(3-4): 225-242.
- DARKOH, M. B. K. 1998. The nature, causes and consequences of desertification in the drylands of Africa. *Land Degradation & Development*, 9(1): 1-20.
- DAVIES, B. & DAY, J. 1998. *Vanishing waters*, Cape Town, South Africa: UCT Press, 487 pp.
- DAVIES, B. R., THOMS, M. C., WALKER, K. F., O'KEEFFE, J. H. & GORE, J. A. 1994. Dryland rivers: Their ecology, conservation and management. In: CALOW, P. & PETTS, G. E. (eds.) *The rivers handbook: Hydrological and ecological principles. Volume two*. Oxford: Blackwell Science Ltd., pp. 484-523.
- DAVIES, P. E., MCINTOSH, P. D., WAPSTRA, M., BUNCE, S. E. H., COOK, L. S. J., FRENCH, B. & MUNKS, S. A. 2005. Changes to headwater stream morphology, habitats and riparian vegetation recorded 15 years after pre-Forest Practices Code forest clearfelling in upland granite terrain, Tasmania, Australia. *Forest Ecology and Management*, 217(2-3): 331-350.
- DE JONG, J. S. 2013. *Living landscape restoration: The common vision for the Hartland in the Baviaanskloof*. Unpublished MSc thesis, Wageningen University, Wageningen, The Netherlands, 187 pp.
- DE LA FLOR TEJERO, I. 2008. *Valuation of the goods and services provided by the thicket ecosystem in the western Baviaanskloof, South Africa*. Unpublished MSc dissertation, Wageningen University, Wageningen, The Netherlands, 144 pp.
- DE PAOLI, G. 2008. *River system restoration for a sustainable land and water management in the Baviaanskloof Mega-Reserve, South Africa. Preliminary assessment of the opportunities and challenges to the creation of a payment for watershed services scheme*. Unpublished MSc dissertation, Wageningen University, Wageningen, The Netherlands, pp.

- DE VILLIERS, J. 1941. The geology of the Baviaans Kloof. *Transactions of the Geological Society of South Africa*, 44: 151-159.
- DEA 2014. *National Environmental Management: Biodiversity Act (No. 10 of 2004), Draft alien and invasive species lists*, Government gazette, Vol. 584 (37320), 12 February, Government notice No. 78, Pretoria, South Africa: Government Printer, 96 pp.
- DEAN, D. J. & SCHMIDT, J. C. 2011. The role of feedback mechanisms in historic channel changes of the lower Rio Grande in the Big Bend region. *Geomorphology*, 126: 333-349.
- DÉCAMPS, H., PINAY, G., NAIMAN, R. J., PETTS, G. E., MCCLAIN, M. E., HILLBRICHT-ILKOWSKA, A., HANLEY, T. A., HOLMES, R. M., QUINN, J., GIBERT, J., PLANTY TABACCHI, A.-M., SCHIEMER, F., TABACCHI, E. & ZALEWSKI, M. 2004. Riparian zones: Where biogeochemistry meets biodiversity in management practice *Polish Journal of Ecology* 52(1): 3-18.
- DLA-CDSM 1967, 1985, 1986, 2000. Topographical maps (1:50 000). Pretoria, South Africa: Department of Land Affairs, Chief Directorate: Surveys and Mapping (DLA-CDSM)
- DLA-CDSM 1985, 2000. Topographical maps (1:50 000). Pretoria, South Africa: Department of Land Affairs, Chief Directorate: Surveys and Mapping (DLA-CDSM)
- DLA-CDSM 2005. Dam polygons extracted from the waterbodies shapefile. Pretoria, South Africa: Department of Land Affairs, Chief Directorate: Surveys and Mapping (DLA-CDSM)
- DLA-CDSM 2006. Relief lines Pretoria, South Africa: Department of Land Affairs, Chief Directorate: Surveys and Mapping (DLA-CDSM)
- DOLLAR, E. S. J. 2000. Fluvial geomorphology. *Progress in Physical Geography*, 24(3): 385-407.
- DOLLAR, E. S. J. 2002. Fluvial geomorphology. *Progress in Physical Geography*, 26(1): 123-143.
- DOLLAR, E. S. J. 2004. Fluvial geomorphology. *Progress in Physical Geography*, 28(3): 405-450.
- DOLLAR, E. S. J., JAMES, C. S., ROGERS, K. H. & THOMS, M. C. 2007. A framework for interdisciplinary understanding of rivers as ecosystems. *Geomorphology*, 89(1-2): 147-162.
- DOWNS, P. W. & GREGORY, K. J. 2004. *River channel management: Towards sustainable catchment hydrosystems*, London: Arnold, A member of the Hodder Headline Group 385 pp.
- DRAAIJER, A. G. 2010. *Erosion risk mapping in the Baviaanskloof watershed, South Africa*. Unpublished MSc thesis, Wageningen University, Wageningen, The Netherlands, 45 pp.
- DRIVER, A., DESMET, P., ROUGET, M., COWLING, R. & MAZE, K. 2003. Succulent Karoo Ecosystem Plan: Biodiversity component, technical report. *Cape Conservation Unit, Report No. CCU 1/03*. South Africa.
- DUKER, R., COWLING, R. M., DU PREEZ, D. R., VAN DER VYVER, M. L., WEATHERALL-THOMAS, C. R. & POTTS, A. J. 2015. Community-level assessment of freezing tolerance: Frost dictates the biome boundary between Albany subtropical thicket and Nama-Karoo in South Africa. *Journal of Biogeography*, 42(1): 167-178.
- DWAF 2004a. Fish to Tsitsikamma Water Management Area: Tsitsikamma to Coega internal strategic perspective. Prepared by Ninham Shand in association with Umvoto Africa, on behalf of the Directorate National Water Resources Planning. *Report No. PWMA 15/000/00/0304*. Pretoria, South Africa.

- DWAF 2004b. South African 1: 50 000 river coverage. Pretoria, South Africa: Resource Quality Services Directorate, Department of Water Affairs and Forestry (DWAF)
- DWAF 2006. South African 1: 500 000 river coverage. Pretoria, South Africa: Resource Quality Services Directorate, Department of Water Affairs and Forestry (DWAF)
- DYMOND, C. C., MLADENOFF, D. J. & RADELOFF, V. C. 2002. Phenological differences in Tasseled Cap indices improve deciduous forest classification. *Remote Sensing of Environment*, 80(3): 460-472.
- DYSON, L. L. 2009. Heavy daily-rainfall characteristics over the Gauteng Province. *Water SA*, 35(5): 627-637.
- EATON, B. C., MILLAR, R. G. & DAVIDSON, S. 2010. Channel patterns: Braided, anabranching, and single-thread. *Geomorphology*, 120(3-4): 353-364.
- ECPB 2007. Integrated reserve management plan. Strategic management plan: Baviaanskloof cluster draft 1.0. Eastern Cape, South Africa.
- EDWARDS, D. C. & MCKEE, T. B. 1997. Characteristics of 20th century drought in the United States at multiple time scales Fort Collins, CO Department of Atmospheric Science, Colorado State University
- ELLERY, F. & ROWNTREE, K. 2011. The landscape. In: HATTINGH, L. (ed.) *Baviaanskloof: A world apart*. Willowmore, South Africa: Baviaanskloof Tourism Association, pp. 30-48.
- ENGELBRECHT, C. J. & LANDMAN, W. A. 2015. Interannual variability of seasonal rainfall over the Cape south coast of South Africa and synoptic type association. *Climate Dynamics*: 1-19.
- ERDAS 2011. *ERDAS IMAGINE Desktop* Georgia, USA: Earth Resources Data Analysis System (ERDAS), Inc., 344 pp.
- ESLER, K. J., MILTON, S. J. & DEAN, W. R. 2006. *Karoo veld*, Pretoria, South Africa: Briza Publications, 214 pp.
- ESRI 2012. *ArcGIS Desktop*, Redlands, CA, USA: Environmental Systems Research Institute (ESRI), pp.
- EUSTON-BROWN, D. 1995. *Environmental and dynamic determinants of vegetation distribution in the Kouga and Baviaanskloof Mountains, Eastern Cape*. Unpublished MSc thesis, University of Cape Town, Cape Town, South Africa, 132 pp.
- EUSTON-BROWN, D. 2006. Baviaanskloof Mega-Reserve project: Vegetation mapping contract: Report on methodology, vegetation classification and short descriptions of habitat units. Scarborough, Cape Town.
- EUSTON-BROWN, D. 2010. Riparian vegetation component of the Baviaanskloof Mega Reserve environmental water requirement determination. Sunninghill, South Africa.
- FERGUSON, R. I., CUDDEN, J. R., HOEY, T. B. & RICE, S. P. 2006. River system discontinuities due to lateral inputs: generic styles and controls. *Earth Surface Processes and Landforms*, 31(9): 1149-1166.
- FISHER, S. G., HEFFERNAN, J. B., SPONSELLER, R. A. & WELTER, J. R. 2007. Functional ecomorphology: Feedbacks between form and function in fluvial landscape ecosystems. *Geomorphology*, 89(1): 84-96.
- FISRWG. 1998. *Stream corridor restoration: Principles, processes, and practices. Revised 2001*, USA: USDA-Natural Resources Conservation Service, pp.
- FOTHERBY, L. M. 2009. Valley confinement as a factor of braided river pattern for the Platte River. *Geomorphology*, 103(4): 562-576.
- FRANCIS, R., TIBALDESCHI, P. & MCDOUGALL, L. 2008a. Fluvially-deposited large wood and riparian plant diversity. *Wetlands Ecology and Management*, 16(5): 371-382.

- FRANCIS, R. A. 2006. Allogenic and autogenic influences upon riparian vegetation dynamics. *Area*, 38(4): 453-464.
- FRANCIS, R. A., PETTS, G. E. & GURNELL, A. M. 2008b. Wood as a driver of past landscape change along river corridors. *Earth Surface Processes and Landforms*, 33(10): 1622-1626.
- FREEMAN, M. C., PRINGLE, C. M. & JACKSON, C. R. 2007. Hydrologic connectivity and the contribution of stream headwaters to ecological integrity at regional scales. *Journal of the American Water Resources Association*, 43(1): 5-14.
- FREEMAN, N. M. & ROWNTREE, K. 2005. Our changing rivers: An introduction to the science and practice of fluvial geomorphology WRC Report No. TT238/05. Pretoria, South Africa: Water Research Commission.
- FRIEDMAN, J. M. & AUBLE, G. T. 2000. Floods, flood control and bottomland vegetation. In: WOHL, E. E. (ed.) *Inland flood hazards: Human, riparian and aquatic communities*. Cambridge: Cambridge University Press, pp. 219-237
- FRIEDMAN, J. M. & LEE, V. J. 2002. Extreme floods, channel change, and riparian forests along ephemeral streams. *Ecological Monographs*, 72(3): 409-425.
- FRIEDMAN, J. M., OSTERKAMP, W. R. & LEWIS, W. M. 1996. The role of vegetation and bed-level fluctuations in the process of channel narrowing. *Geomorphology*, 14: 341-351.
- FRINGS, R. M. 2008. Downstream fining in large sand-bed rivers. *Earth-Science Reviews*, 87(1-2): 39-60.
- FRISSEL, C. A., LISS, W. J., WARREN, C. E. & HURLEY, M. D. 1986. A hierarchical framework for stream classification viewing streams in a watershed context. *Environmental Management* 10: 199-214.
- FRYIRS, K. 2002. Antecedent landscape controls on river character, behaviour and evolution at the base of the escarpment in Bega catchment, South Coast, New South Wales, Australia. *Zeitschrift für Geomorphologie*, 46(4): 475-504.
- FRYIRS, K. 2013. (Dis)Connectivity in catchment sediment cascades: A fresh look at the sediment delivery problem. *Earth Surface Processes and Landforms*, 38(1): 30-46.
- FRYIRS, K. & BRIERLEY, G. J. 2010. Antecedent controls on river character and behaviour in partly confined valley settings: Upper Hunter catchment, NSW, Australia. *Geomorphology*, 117(1-2): 106-120.
- FRYIRS, K., CHESSMAN, B. & RUTHERFURD, I. 2013. Progress, problems and prospects in Australian river repair. *Marine and Freshwater Research*, 64(7): 642-654.
- FRYIRS, K., SPINK, A. & BRIERLEY, G. 2009. Post-European settlement response gradients of river sensitivity and recovery across the upper Hunter catchment, Australia. *Earth Surface Processes and Landforms*, 34(7): 897-918.
- FRYIRS, K. A. & BRIERLEY, G. J. 2013. *Geomorphic analysis of river systems: An approach to reading the landscape*, Chichester, UK: Wiley-Blackwell, 345 pp.
- FRYIRS, K. A., BRIERLEY, G. J., PRESTON, N. J. & KASAI, M. 2007a. Buffers, barriers and blankets: The (dis)connectivity of catchment-scale sediment cascades. *CATENA*, 70(1): 49-67.
- FRYIRS, K. A., BRIERLEY, G. J., PRESTON, N. J. & SPENCER, J. 2007b. Catchment-scale (dis)connectivity in sediment flux in the upper Hunter catchment, New South Wales, Australia. *Geomorphology*, 84(3-4): 297-316.
- GALATOWITSCH, S. & RICHARDSON, D. M. 2005. Riparian scrub recovery after clearing of invasive alien trees in headwater streams of the Western Cape, South Africa. *Biological Conservation*, 122(4): 509-521.

- GASITH, A. & RESH, V. H. 1999. Streams in Mediterranean Climate Regions: Abiotic Influences and Biotic Responses to Predictable Seasonal Events. *Annual Review of Ecology and Systematics*, 30: 51-81.
- GERICKE, O. J. & DU PLESSIS, J. A. 2013. Development of a customised design flood estimation tool to estimate floods in gauged and ungauged catchments. *Water SA*, 39(1): 67-94.
- GIBBS RUSSELL, G. E., WATSON, L., KOEKEMOER, M., SMOOK, L. M., BARKER, N. P., ANDERSON, H. M. & DALLWITZ, M. J. 1990. *Grasses of Southern Africa. Memoirs of the Botanical Survey of South Africa No. 58*, South Africa: National Botanical Gardens, 437 pp.
- GILL, C. J. 1970. The flooding tolerance of woody species-a review. *Forest Abstracts*, 31: 761-688.
- GILVEAR, D. & WILLBY, N. 2006. Channel dynamics and geomorphic variability as controls on gravel bar vegetation; River Tummel, Scotland. *River Research and Applications*, 22(4): 457-474.
- GILVEAR, D. J. 1999. Fluvial geomorphology and river engineering: future roles utilizing a fluvial hydrosystems framework. *Geomorphology*, 31(1-4): 229-245.
- GIOLCOLI, A., MAGRÌ, C., VANNOLI, P., PISCITELLI, S., RIZZO, E., SINISCALCHI, A., BURRATO, P., BASSO, C. & DI NOCERA, S. 2008. Electrical resistivity tomography investigations in the Ufita Valley (southern Italy). *Annals of Geophysics*, 51(1).
- GLENDAY, J. A. 2015. *Modeling the hydrologic impacts of vegetation and channel network change for a semi-arid, mountainous, meso-scale catchment: The Baviaanskloof, South Africa*. Unpublished PhD thesis, University of California, Santa Barbara, 435 pp.
- GOEDHART, M. L. & BOOTH, P. W. K. 2009. Early Holocene extensional tectonics in the South-Eastern Cape Fold Belt, South Africa. *11 th SAGA Biennial Technical Meeting and Exhibition Swaziland, 16-18 September 2009*.
- GOLDBLATT, P. & MANNING, J. C. 2000. *Cape Plants: A conspectus of the Cape Flora of South Africa, Strelitzia 9* Pretoria, South Africa: National Botanical Institute of South Africa, 743 pp.
- GONG, D., SHI, P. & WANG, J. 2004. Daily precipitation changes in the semi-arid region over northern China. *Journal of Arid Environments*, 59: 771-784.
- GORDON, N. D., MCMAHON, T. A., FINLAYSON, B. L., GIPPEL, C. J. & NATHAN, R. J. 2004. *Stream hydrology: An introduction for ecologists*, Chichester: John Wiley & Sons, Ltd, 429 pp.
- GOUDIE, A. S. 2006. Global warming and fluvial geomorphology. *Geomorphology*, 79(3-4): 384-394.
- GRABOWSKI, R. C., SURIAN, N. & GURNELL, A. M. 2014. Characterizing geomorphological change to support sustainable river restoration and management. *Wiley Interdisciplinary Reviews: Water*, 1(5): 483-512.
- GRECO, S. E., FREMIER, A. K., LARSEN, E. W. & PLANT, R. E. 2007. A tool for tracking floodplain age land surface patterns on a large meandering river with applications for ecological planning and restoration design. *Landscape and Urban Planning*, 81(4): 354-373.
- GREEN, J. C. 2005. Modelling flow resistance in vegetated streams: review and development of new theory. *Hydrological Processes*, 19(6): 1245-1259.

- GREGORY, K. J. 1992. Vegetation and river channel process interactions. In: BOON, P. J., CALOW, P. & PETTS, G. E. (eds.) *River conservation and management*. Chichester, England: John Wiley & Sons, Ltd., pp. 255-269.
- GREGORY, S. V., SWANSON, F. J., MCKEE, W. A. & CUMMINS, K. W. 1991. An ecosystem perspective of riparian zones. *Bioscience*, 41(8): 540-551.
- GRENFELL, S. E., ELLERY, W. N. & GRENFELL, M. C. 2009. Geomorphology and dynamics of the Mfolozi River floodplain, KwaZulu-Natal, South Africa. *Geomorphology*, 107(3-4): 226-240.
- GRENFELL, S. E., GRENFELL, M. C., ROWNTREE, K. M. & ELLERY, W. N. 2014. Fluvial connectivity and climate: A comparison of channel pattern and process in two climatically contrasting fluvial sedimentary systems in South Africa. *Geomorphology*, 205: 142-154.
- GRIME, J. P. 2002. *Plant strategies, vegetation processes and ecosystem properties*, Chichester: John Wiley & Sons Ltd., 456 pp.
- GURNELL, A. 2014. Plants as river system engineers. *Earth Surface Processes and Landforms*, 39(1): 4-25.
- GURNELL, A. & PETTS, G. 2006. Trees as riparian engineers: The Tagliamento river, Italy. *Earth Surface Processes and Landforms*, 31(12): 1558-1574.
- GURNELL, A. M. 1995. Vegetation along river corridors: Hydrogeomorphological interactions. In: GURNELL, A. M. & PETTS, G. E. (eds.) *Changing river channels*. Chichester, England: John Wiley and Sons Ltd., pp. 369-388.
- GURNELL, A. M., BERTOLDI, W. & CORENBLIT, D. 2012. Changing river channels: The roles of hydrological processes, plants and pioneer fluvial landforms in humid temperate, mixed load, gravel bed rivers. *Earth-Science Reviews*, 111(1-2): 129-141.
- GURNELL, A. M., PEIRY, J.-L. & G.E., P. 2003. Using historical data in fluvial geomorphology. In: KONDOLF, G. M. & PIÉGAY, H. (eds.) *Tools in fluvial geomorphology*. Chichester, England: John Wiley & Sons, Ltd, pp. 77-101.
- GURNELL, A. M., PIÉGAY, H., SWANSON, F. J. & GREGORY, S. V. 2002. Large wood and fluvial processes. *Freshwater Biology*, 47(4): 601-619.
- GUTTMAN, N. B. 1999. Accepting the standardized precipitation index: A calculation algorithm. *Journal of the American Water Resources Association*, 35(2): 311-322.
- HAO, X.-M., CHEN, Y.-N. & LI, W.-H. 2009. Indicating appropriate groundwater tables for desert river-bank forest at the Tarim River, Xinjiang, China. *Environmental Monitoring and Assessment*, 152(1): 167-177.
- HARPER, D. M., EBRAHIMNEZHAD, M., TAYLOR, E., DICKINSON, S., DECAMP, O., VERNIERS, G. & BALBI, T. 1999. A catchment-scale approach to the physical restoration of lowland UK rivers. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 9(1): 141-157.
- HARRELSON, C. C., RAWLINS, C. L. & POTYONDY, J. P. 1994. *Stream channel reference sites: An illustrated guide to field technique*. Technical Report RM-245, Colorado, USA: Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station, 61 pp.
- HARRIS, R. R. 1987. Occurrence of Vegetation on Geomorphic Surfaces in the Active Floodplain of a California Alluvial Stream. *American Midland Naturalist*, 118(2): 393-405.
- HARTMANN, H. E. K. 2002. *Illustrated handbook of succulent plants: Aizoaceae a-e, Vol 1*, Berlin, Heidelberg: Springer-Verlag, 268 pp.

- HARVEY, A. M. 1996. The role of alluvial fans in the mountain fluvial systems of Southeast Spain: Implications of climatic change. *Earth Surface Processes and Landforms*, 21(6): 543-553.
- HARVEY, A. M. 2001. Coupling between hillslopes and channels in upland fluvial systems: implications for landscape sensitivity, illustrated from the Howgill Fells, northwest England. *CATENA*, 42(2-4): 225-250.
- HARVEY, A. M. 2002a. Effective timescales of coupling within fluvial systems. *Geomorphology*, 44(3-4): 175-201.
- HARVEY, A. M. 2002b. The role of base-level change in the dissection of alluvial fans: case studies from southeast Spain and Nevada. *Geomorphology*, 45(1-2): 67-87.
- HARVEY, A. M. 2012. The coupling status of alluvial fans and debris cones: a review and synthesis. *Earth Surface Processes and Landforms*, 37(1): 64-76.
- HASSAN, M. A. 2005. Characteristics of gravel bars in ephemeral streams. *Journal of Sedimentary Research* 75: 29-42.
- HATTINGH, J. 2008. Fluvial systems and landscape evolution. In: LEWIS, C. A. (ed.) *Geomorphology of the Eastern Cape of South Africa*. Grahamstown, South Africa: NISC, pp. 21-42.
- HATTINGH, L. 2011. *Baviaanskloof: A world apart*, Willowmore, South Africa: Baviaanskloof Tourism Association, 101 pp.
- HAUER, F. R. & LORANG, M. S. 2004. River regulation, decline of ecological resources, and potential for restoration in a semi-arid lands river in the western USA. *Aquatic Sciences - Research Across Boundaries*, 66(4): 388-401.
- HAYES, M., SVOBODA, M. & WILHITE, D. A. 2000. Monitoring drought using the Standardized Precipitation Index. In: WILHITE, D. A. (ed.) *Drought volume 1: A global assessment*. London: Routledge Hazard and Disaster Series, pp. 169-180.
- HEITMULLER, F. T. & HUDSON, P. F. 2009. Downstream trends in sediment size and composition of channel-bed, bar, and bank deposits related to hydrologic and lithologic controls in the Llano River watershed, central Texas, USA. *Geomorphology*, 112(3-4): 246-260.
- HENDERSON, L. 2001. *Alien weeds and invasive plants: A complete guide to declared weeds and invaders in South Africa*. PPRI handbook no. 12, Stellenbosch: ARC-PPRI, 300 pp.
- HENSHAW, A. J., GURNELL, A. M., BERTOLDI, W. & DRAKE, N. A. 2013. An assessment of the degree to which Landsat TM data can support the assessment of fluvial dynamics, as revealed by changes in vegetation extent and channel position, along a large river. *Geomorphology*, 202(0): 74-85.
- HESSION, W., PIZZUTO, J. E., JOHNSON, T. E. & HORWITZ, R. J. 2003. Influence of bank vegetation on channel morphology in rural and urban watersheds. *Geology*, 31(2): 147-150.
- HICKIN, E. J. 1984. Vegetation and channel dynamics. *Canadian Geographer*, 28(2): 111-126.
- HICKS, D. M. & BASIL, G. 2003. Sediment transport. In: KONDOLF, G. M. & PIÉGAY, H. (eds.) *Tools in Fluvial Geomorphology*. Chichester, England: John Wiley & Sons, Ltd, pp. 425-461.
- HOFFMAN, M. & ROHDE, R. 2011. Rivers through time: Historical changes in the riparian vegetation of the semi-arid, winter rainfall region of South Africa in response to climate and land Use. *Journal of the History of Biology*, 44(1): 59-80.

- HOFFMAN, M. T. & ROHDE, R. F. 2007. From pastoralism to tourism: The historical impact of changing land use practices in Namaqualand. *Journal of Arid Environments*, 70(4): 641-658.
- HOHENSINNER, S., HABERSACK, H., JUNGWIRTH, M. & ZAUNER, G. 2004. Reconstruction of the characteristics of a natural alluvial river-floodplain system and hydromorphological changes following human modifications: The Danube River (1812-1991). *River Research and Applications*, 20(1): 25-41.
- HOLMES, P. M., RICHARDSON, D. M., ESLER, K. J., WITKOWSKI, E. T. F. & FOURIE, S. 2005. A decision-making framework for restoring riparian zones degraded by invasive alien plants in South Africa. *South African Journal of Science*, 101: 553-564.
- HOOD, W. G. & NAIMAN, R. J. 2000. Vulnerability of riparian zones to invasion by exotic vascular plants. *Plant Ecology*, 148(1): 105-114.
- HOOKE, J. M. 2003. Coarse sediment connectivity in river channel systems: a conceptual framework and methodology. *Geomorphology*, 56: 79-94.
- HOOKE, J. M. 2007. Monitoring morphological and vegetation changes and flow events in dryland river channels. *Environmental Monitoring and Assessment*, 127(1-3): 445-457.
- HORNECK, D. A. & MILLER, R. O. 1998. Determination total nitrogen in plant tissue. In: KALRA, Y. P. (ed.) *Handbook of reference methods for plant analysis*. Boca Raton: Soil and Plant Analysis Council Inc., CRC Press pp. 75-83.
- HORTON, J. L., KOLB, T. E. & HART, S. C. 2001. Responses of riparian trees to interannual variation in ground water depth in a semi-arid river basin. *Plant, Cell & Environment*, 24(3): 293-304.
- HOUGH, J. A. & PROZESKY, H. E. 2010. 'But we don't spoil it, we protect it': Coleske residents' conceptualisations of the Baviaanskloof Nature Reserve and its protection. *South African Geographical Journal*, 92(2): 160-172.
- HOUSTON, J. 2002. Groundwater recharge through an alluvial fan in the Atacama Desert, northern Chile: Mechanisms, magnitudes and causes. *Hydrological Processes* 16 3019-3035.
- HUGHES, M. L., MCDOWELL, P. F. & MARCUS, W. A. 2006. Accuracy assessment of georectified aerial photographs: Implications for measuring lateral channel movement in a GIS. *Geomorphology*, 74(1-4): 1-16.
- HUMPHRIES, P. & BALDWIN, D. S. 2003. Drought and aquatic ecosystems: an introduction. *Freshwater Biology*, 48(7): 1141-1146.
- HUPP, C. R. 1990. Vegetation patterns in relation to basin hydrogeomorphology. In: THORNES, J. B. (ed.) *Vegetation and erosion*. Chichester, England: John Wiley & Sons Ltd, pp. 217-237.
- HUPP, C. R. 2000. Hydrology, geomorphology and vegetation of coastal plain rivers in the south-eastern USA. *Hydrological Processes*, 14: 2991-3010.
- HUPP, C. R., NOE, G. B., SCHENK, E. R. & BENTHEM, A. J. 2013. Recent and historic sediment dynamics along Difficult Run, a suburban Virginia Piedmont stream. *Geomorphology*, 180-181(0): 156-169.
- HUPP, C. R. & OSTERKAMP, W. R. 1985. Bottomland vegetation distribution along Passage Creek, Virginia, in relation to fluvial landforms. *Ecology*, 66(3): 670-681.
- HUPP, C. R. & OSTERKAMP, W. R. 1996. Riparian vegetation and fluvial geomorphic processes. *Geomorphology*, 14(4): 277-295.
- HUPP, C. R. & RINALDI, M. 2007. Riparian vegetation patterns in relation to fluvial landforms and channel evolution along selected rivers of Tuscany (central Italy). *Annals of the Association of American Geographers*, 97(1): 12-30.

- ILLGNER, P. M. & HAIGH, E. H. 2003. Identification, mapping and present state assessment of the wetlands in the Baviaanskloof River Catchment. Report for Working for Wetlands. Eastern Cape IWR Wetland Group. Grahamstown, South Africa.
- IMADA, S., YAMANAKA, N. & TAMAI, S. 2008. Water table depth affects *Populus alba* fine root growth and whole plant biomass. *Functional Ecology*, 22(6): 1018-1026.
- JAIN, V. & TANDON, S. K. 2010. Conceptual assessment of (dis)connectivity and its application to the Ganga River dispersal system. *Geomorphology*, 118(3-4): 349-358.
- JANSEN, H. 2008. Water for food and ecosystems in the Baviaanskloof Mega Reserve: Land and water resources assessment in the Baviaanskloof, Eastern Cape Province, South Africa Alterra, Wageningen: Wageningen University.
- JANSEN, J. D. & NANSON, G. C. 2010. Functional relationships between vegetation, channel morphology, and flow efficiency in an alluvial (anabranching) river. *Journal of Geophysical Research*, 115(F04030): 1-17.
- JANSSEN, K. 2008. *The relevance of socio-cultural values of ecosystem services to restoration planning and implementation in the Baviaanskloof*. Unpublished MSc dissertation, Wageningen University, Wageningen, The Netherlands, 165 pp.
- JOHNSON-MARSHALL, A. J. 2009. *Fluvial pattern and process in mountainous dryland floodplain streams: A case study of Zandvlakte in the Western Baviaanskloof*. Unpublished Honours project, Rhodes University, Grahamstown, South Africa, 34 pp.
- JOHNSON, M. R., ANHAEUSSER, C. R. & THOMAS, R. J. 2006. *The Geology of South Africa* Johannesburg/Pretoria, South Africa: Geological Society of South Africa/Council for Geoscience 691 pp.
- JONES, C. G., LAWTON, J. H. & SHACHAK, M. 1994. Organisms as Ecosystem Engineers. *Oikos*, 69(3): 373-386.
- JONES, C. G., LAWTON, J. H. & SHACHAK, M. 1997. Positive and negative effects of organisms as physical ecosystem engineers. *Ecology* 78(7): 1946-1957.
- JONES, K. B., EDMONDS, C. E., SLONECKER, E. T., WICKHAM, J. D., NEALE, A. C., WADE, T. G., RIITTERS, K. H. & KEPNER, W. G. 2008. Detecting changes in riparian habitat conditions based on patterns of greenness change: A case study from the Upper San Pedro River Basin, USA. *Ecological Indicators*, 8(1): 89-99.
- JORDAAN, P. 2010. Baviaanskloof Mega Reserve: Ecotatus level III ecological reserve assessment Sunninghill, South Africa.
- JORDAAN, P. & BRAND, M. 2010. Baviaanskloof Mega Reserve study: State-of-rivers report. Sunninghill, South Africa.
- JURACEK, K. E. & FITZPATRICK, F. A. 2009. Geomorphic applications of stream-gage information. *River Research and Applications*, 25(3): 329-347.
- KARAVITIS, C. A., ALEXANDRIS, S., TSESMELIS, D. E. & ATHANASOPOULOS, G. 2011. Application of the Standardized Precipitation Index (SPI) in Greece. *Water* 3: 787-805.
- KARIMI-GOOGHARI, S. 2011. Analysis of precipitation climate and evapotranspiration in Kerman of Iran. *International Journal of Agricultural Science, Research and Technology*, 1(3): 105-108.
- KARL, J. W. & MAURER, B. A. 2010. Multivariate correlations between imagery and field measurements across scales: comparing pixel aggregation and image segmentation. *Landscape Ecology*, 25: 591-605.
- KAUFFMAN, J. B. & KRUEGER, W. C. 1984. Livestock impacts on riparian ecosystems and streamside management implications. *Journal of Rangeland Management*, 37(5): 430-438.

- KAUTH, R. J. & THOMAS, G. S. 1976. *The Tasseled Cap: A graphic description of the spectral-temporal development of agricultural crops as seen by LANDSAT. Proceedings of the symposium on machine processing of remotely sensed data* Indiana: Purdue University of West Lafayette, 4B-41 to 4B-51 pp.
- KEEN-ZEBERT, A., TOOTH, S., RODNIGHT, H., DULLER, G. A. T., ROBERTS, H. M. & GRENFELL, M. 2013. Late Quaternary floodplain reworking and the preservation of alluvial sedimentary archives in unconfined and confined river valleys in the eastern interior of South Africa. *Geomorphology*, 185(0): 54-66.
- KELSO, C. & VOGEL, C. 2007. The climate of Namaqualand in the nineteenth century. *Climatic Change*, 83(3): 357-380.
- KENDALL, M. G. 1970. *Rank correlation methods, Fourth edition*, London: Griffen, 202 pp.
- KENNEDY, J. B. & NEVILLE, A. M. 1986. *Basic statistical methods for engineers and scientists: 3rd edition*, New York, USA: Harper & Row Publishers, 613 pp.
- KENT, M. & COKER, P. 1992. *Vegetation description and analysis*, Chichester: John Wiley, pp.
- KING, J. M., SCHEEPERS, A. C. T., FISHER, R. C., REINECKE, K. M. & SMITH, L. B. 2003. River rehabilitation: Literature review, case studies and emerging principles. *WRC Report No 1161/1/03*. Pretoria, South Africa: Water Research Commission.
- KINGSFORD, R. T., LEMLY, A. D. & THOMPSON, J. R. 2006. Impacts of dams, river management and diversions on desert rivers. In: KINGSFORD, R. T. (ed.) *Ecology of desert rivers*. Cambridge, UK: Cambridge University Press, pp. 203-247.
- KINGSFORD, R. T. & THOMPSON, J. R. 2006. Desert or dryland rivers of the world: An introduction. In: KINGSFORD, R. T. (ed.) *Ecology of desert rivers*. Cambridge, UK: Cambridge University Press, pp. 3-10.
- KLEINHANS, M. G. 2010. Sorting out river channel patterns. *Progress in Physical Geography*, 34(3): 287-326.
- KNIGHT, F. 2012. Agricultural assessment of the Baviaanskloof. Durbanville, South Africa: Agri Informatics Development Trust.
- KNIGHTON, A. D. 1987. River channel adjustment: The downstream dimension. In: RICHARDS, K. (ed.) *River channels: Environment and process*. Oxford, UK: Basil Blackwell Ltd, pp. 95- 128.
- KNIGHTON, D. 1998. *Fluvial forms and processes: A new perspective*, London: Arnold Publishers, 383 pp.
- KNOX, J. C. 1977. Human impacts on Wisconsin stream channels. *Annals of the Association of American Geographers*, 67(3): 323-342.
- KNOX, J. C. 2001. Agricultural influence on landscape sensitivity in the upper Mississippi River valley. *CATENA*, 42(2-4): 193-224.
- KNOX, J. C. 2006. Floodplain sedimentation in the Upper Mississippi Valley: Natural versus human accelerated. *Geomorphology*, 79(3-4): 286-310.
- KONDOLF, G. M., ANDERSON, S., LAVE, R., PAGANO, L., MERENLENDER, A. & BERNHARDT, E. S. 2007. Two decades of river restoration in California: What can we learn? *Restoration Ecology*, 15(3): 516-523.
- KONDOLF, G. M., BOULTON, A. J., O'DANIEL, S., POOLE, G. C., RAHEL, F. J., STANLEY, E. H., WOHL, E., BANG, A., CARLSTROM, J., CRISTONI, C., HUBER, H., KOLJONEN, S., LOUHI, P. & NAKAMURA, K. 2006. Process-based ecological river restoration: Visualizing three-dimensional connectivity and dynamic vectors to recover lost linkages. *Ecology and Society*, 11(2): 1-17.

- KONDOLF, G. M. & LARSON, M. 1995. Historical channel analysis and its application to riparian and aquatic habitat restoration. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 5(2): 109-126.
- KONDOLF, G. M., LISLE, T. E. & WOLMAN, G. M. 2003. Bed sediment measurement. In: KONDOLF, G. M. & PIÉGAY, H. (eds.) *Tools in fluvial geomorphology*. Chichester, England: John Wiley & Sons, pp. 347-395.
- KRUGER, A. C. 2006. Observed trends in daily precipitation indices in South Africa: 1910–2004. *International Journal of Climatology*, 26(15): 2275-2285.
- KRUGER, A. C. & SHONGWE, S. 2004. Temperature trends in South Africa: 1960–2003. *International Journal of Climatology*, 24(15): 1929-1945.
- KÜCHLER, A. W. & ZONNEVELD, I. S. 1988. Floristic analysis of vegetation. In: KÜCHLER, A. W. & ZONNEVELD, I. S. (eds.) *Vegetation mapping*. Dordrecht, The Netherlands: Kluwer Academic Publishers, pp. 51-80.
- KUMAR, M. N., MURTHY, C. S., SESA, M. V. R. S. & ROY, P. S. 2009. On the use of Standardized Precipitation Index (SPI) for drought intensity assessment. *Meteorological Applications*, 16: 381–389
- KUO, C.-W. & BRIERLEY, G. 2014. The influence of landscape connectivity and landslide dynamics upon channel adjustments and sediment flux in the Liwu Basin, Taiwan. *Earth Surface Processes and Landforms*, 39(15): 2038-2055.
- KUO, C.-W. & BRIERLEY, G. J. 2013. The influence of landscape configuration upon patterns of sediment storage in a highly connected river system. *Geomorphology*, 180–181(0): 255-266.
- LABBE, J. M., HADLEY, K. S., SCHIPPER, A. M., LEUVEN, R. S. E. W. & GARDINER, C. P. 2011. Influence of bank materials, bed sediment, and riparian vegetation on channel form along a gravel-to-sand transition reach of the Upper Tualatin River, Oregon, USA. *Geomorphology*, 125(3): 374-382.
- LAING, M. 1992. Drought monitoring and advisory services in South Africa *Drought Network Newsletter*. Nebraska, USA.
- LAKE, P. S. 2000. Disturbance, patchiness and diversity in streams. *Journal of the North American Benthological Society*, 19(4): 573-592.
- LAKE, P. S. 2003. Ecological effects of perturbation by drought in flowing waters. *Freshwater Biology*, 48(7): 1161-1172.
- LAKE, P. S., BOND, N. & REICH, P. 2007. Linking ecological theory with stream restoration. *Freshwater Biology*, 52: 597-615.
- LAMERS, L. P. M., LOEB, R., ANTHEUNISSE, A. M., MILETTO, M., LUCASSEN, E. C. H. E. T., BOXMAN, A. W., SMOLDERS, A. J. P. & ROELOFS, J. G. M. 2006. Biogeochemical constraints on the ecological rehabilitation of wetland vegetation in river floodplains. *Hydrobiologia*, 565(1): 165-186.
- LANGENDOEN, E. J., RICHARD LOWRANCE, R. & SIMON, A. 2009. Assessing the impact of riparian processes on streambank stability. *Ecohydrology*, 2(3): 360-369.
- LANGHOFF, J. H., RASMUSSEN, K. R. & CHRISTENSEN, S. 2006. Quantification and regionalization of groundwater-surface water interaction along an alluvial stream. *Journal of Hydrology*, 320(3-4): 342-358.
- LATTERELL, J. J., SCOTT BECHTOLD, J., O'KEEFE, T. C., VAN PELT, R. & NAIMAN, R. J. 2006. Dynamic patch mosaics and channel movement in an unconfined river valley of the Olympic Mountains. *Freshwater Biology*, 51(3): 523-544.
- LE MAITRE, D. C., KRUGER, F. J. & FORSYTH, G. G. 2014. Interfacing ecology and policy: Developing an ecological framework and evidence base to support wildfire management in South Africa. *Austral Ecology*, 39(4): 424-436.

- LE MAITRE, D. C., SCOTT, D. F. & COLVIN, C. 1999. Review of information on interactions between vegetation and groundwater. *Water SA*, 25(2): 127-152.
- LE ROUX, P. M., KOTZÉ, C. D., NEL, G. P. & GLEN, H. F. 1994. *Bossieveld: Grazing plant of the Karoo and karoo-like areas*. Bulletin 428, Pretoria, South Africa: Department of Agriculture, 231 pp.
- LECCE, S. A. 1997. Spatial patterns of historical overbank sedimentation and floodplain evolution, Blue river, Wisconsin. *Geomorphology*, 18(3-4): 265-277.
- LECHMERE-OERTEL, R. G., KERLEY, G. I. H. & COWLING, R. M. 2005. Patterns and implications of transformation in semi-arid succulent thicket, South Africa. *Journal of Arid Environments*, 62(3): 459-474.
- LEGLEITER, C. J., LAWRENCE, R. L., FONSTAD, M. A., ANDREW MARCUS, W. & ASPINALL, R. 2003. Fluvial response a decade after wildfire in the northern Yellowstone ecosystem: a spatially explicit analysis. *Geomorphology*, 54(3-4): 119-136.
- LENSSEN, J. P. M., MENTING, F. B. J., VAN DER PUTTEN, W. H. & BLOM, C. W. P. M. 2000. Vegetative reproduction by species with different adaptations to shallow-flooded habitats. *New Phytologist*, 145(1): 61-70.
- LEYER, I. 2005. Predicting plant species' responses to river regulation: The role of water level fluctuations. *Journal of Applied Ecology*, 42(2): 239-250.
- LITE, S. J., BAGSTAD, K. J. & STROMBERG, J. C. 2005. Riparian plant species richness along lateral and longitudinal gradients of water stress and flood disturbance, San Pedro River, Arizona, USA. *Journal of Arid Environments*, 63(4): 785-813.
- LITE, S. J. & STROMBERG, J. C. 2005. Surface water and ground-water thresholds for maintaining Populus Salix forests, San Pedro River, Arizona. *Biological Conservation*, 125(2): 153-167.
- LIVING LANDS 2011. Pilot restoration of alluvial fans, Round II: Intelligent tinkering with the restoration of alluvial fans in the Baviaanskloof Eastern Cape, South Africa: Living Lands
- LLOYD-HUGHES, B. & SAUNDERS, M. 2002. A drought climatology for Europe. *International Journal of Climatology*, 22: 1571-1592.
- LOKE, M. H. 2001. *Rapid 2D resistivity and IP inversion using the least-squares method. RES2DINV version 3.4 manual*, Penang, Malaysia: Geotomo Software, 50 pp.
- LOKE, M. H. & BARKER, R. D. 1996. Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method1. *Geophysical Prospecting*, 44(1): 131-152.
- LOKE, M. H., CHAMBERS, J. E., RUCKER, D. F., KURAS, O. & WILKINSON, P. B. 2013. Recent developments in the direct-current geoelectrical imaging method. *Journal of Applied Geophysics*, 95(0): 135-156.
- LOKE, M. H. & DAHLIN, T. 2002. A comparison of the Gauss–Newton and quasi-Newton methods in resistivity imaging inversion. *Journal of Applied Geophysics*, 49: 149–162.
- LOW, A. B. & REBELO, A. G. 1996. *Vegetation of South Africa, Lesotho and Swaziland*. Pretoria, South Africa.
- LUDWIG, J. A. & TONGWAY, D. J. 1995. Spatial organisation of landscapes and its function in semi-arid woodlands, Australia. *Landscape Ecology*, 10(1): 51-63.
- LYNCH, S. D. 2004. Development of a raster database of annual, monthly and daily rainfall for Southern Africa. *WRC Report No. 1156/1/04*. Pretoria, South Africa: Water Research Commission.

- MAHONEY, J. M. & ROOD, S. B. 1998. Streamflow requirements for cottonwood seedling recruitment: An integrative model. *Wetlands* 18: 634-645.
- MAILLET, G. M., RIZZO, E., REVIL, A. & VELLA, C. 2005. High resolution electrical resistivity tomography (ERT) in a transition zone environment: Application for detailed internal architecture and infilling processes study of a Rhône River paleo-channel. *Marine Geophysical Researches*, 26: 317-328.
- MALANSON, G. P. 1993. *Riparian landscapes*, Cambridge: Cambridge University Press, 296 pp.
- MANDER, M., BLIGNAUT, J., VAN NIEKERK, M., COWLING, R., HORAN, M., KNOESEN, D., MILLS, A., POWELL, M. & SCHULZE, R. 2010. Baviaanskloof-Tsitsikamma payment for ecosystem services: A feasibility assessment. Synthesis Report. Everton, South Africa.
- MANNING, J. & GOLDBLATT, P. 2012. *Plants of the greater Cape Floristic Region, Vol. 1: The core Cape flora. Strelitzia* 29, Pretoria, South Africa: South African National Biodiversity Institute, 853 pp.
- MARTÍNEZ, J., BENAVENTE, J., GARCÍA-ARÓSTEGUI, J. L., HIDALGO, M. C. & REY, J. 2009. Contribution of electrical resistivity tomography to the study of detrital aquifers affected by seawater intrusion-extrusion effects: The river Vélez delta (Vélez-Málaga, southern Spain). *Engineering Geology*, 108(3-4): 161-168.
- MAUD, R. R. 2008. The macro-geomorphology of the Eastern Cape. In: LEWIS, C. A. (ed.) *Geomorphology of the Eastern Cape of South Africa*. Grahamstown, South Africa: NISC, pp. 1-20.
- MCCARTHY, T. S. & RUBIDGE, B. 2005. *The story of Earth and Life: A southern African perspective on a 4.6-billion-year journey* Cape Town, South Africa: Struik Publishers, 333 pp.
- MCCUNE, B., GRACE, J. B. & URBAN, D. L. 2002. *Analysis of ecological communities*, Oregon, U.S.A: MjM Software Design, 300 pp.
- MCKEE, T. B., DOESKEN, N. J. & KLIEST, J. 1993. The relationship of drought frequency and duration to time scales. *Proceedings of the 8th Conference on Applied Climatology, 17-22 January*. Anaheim, California: American Meteorological Society, Boston, Massachusetts.
- MCLENDON, T., HUBBARD, P. J. & MARTIN, D. W. 2008. Partitioning the use of precipitation- and groundwater-derived moisture by vegetation in an arid ecosystem in California. *Journal of Arid Environments*, 72(6): 986-1001.
- MECKLENBURG, D. 2006. *Reference Reach Spreadsheet Survey. A STREAM module: Spreadsheet tools for river evaluation, assessment and monitoring*, Columbus, Ohio: Ohio Department of Natural Resources, pp.
- MEEK, C. S., RICHARDSON, D. M. & MUCINA, L. 2010. A river runs through it: Land-use and the composition of vegetation along a riparian corridor in the Cape Floristic Region, South Africa. *Biological Conservation*, 143(1): 156-164.
- MERRIAM, G. 1984. Connectivity: A fundamental ecological characteristic of landscape pattern. *Proceedings of the International Association for Landscape Ecology* 1: 5-15.
- MERRITT, D. M. 2013. 9.14 Reciprocal relations between riparian vegetation, fluvial landforms and channel processes. In: SHRODER, J. F. (ed.) *Treatise on Geomorphology*. San Diego, USA: Academic Press, pp. 219-243.
- MEYER, P. S. 1998. An explanation of the 1:500 000 general hydrogeological map: Port Elizabeth 3324. Pretoria, South Africa.
- MICHAELIDES, K. & CHAPPELL, A. 2009. Connectivity as a concept for characterising hydrological behaviour. *Hydrological Processes*, 23(3): 517-522.

- MICHELI, E. R. & KIRCHNER, J. W. 2002. Effects of wet meadow riparian vegetation on streambank erosion. 1. Remote sensing measurements of streambank migration and erodibility. *Earth Surface Processes and Landforms*, 27: 627-639.
- MIDDLETON, B. J. & BAILEY, A. K. 2009. Water resources of South Africa, 2005 study (WR2005). Version 1 WRC Report Numbers TT380/08 TT (Executive summary), TT381/08 (User's guide) and TT382/08 (Book of maps) and DVD Pretoria, South Africa.
- MIDGLEY, D. C., PITMAN, W. V. & MIDDLETON, B. J. 1994. Surface water resources of South Africa 1990. Volumes 1 to 6. WRC Report Numbers 298/1/94 (User's guide), 298/2.1-2.6/94 (Appendices), 298/3.1-3.6/94 (Book of maps) and CD-ROM with selected data sets Pretoria, South Africa.
- MIKA, S., HOYLE, J. & KYLE, G. 2010. Inside the 'black box' of river restoration: Using catchment history to identify disturbance and response mechanisms to set targets for process-based restoration. *Ecology and Society*, 15.
- MILLS, A., VYVER, M., GORDON, I., PATWARDHAN, A., MARAIS, C., BLIGNAUT, J., SIGWELA, A. & KGOPE, B. 2015. Prescribing innovation within a large-scale restoration programme in degraded subtropical thicket in South Africa. *Forests*, 6(11): 4328-4348.
- MILLS, A. J. & COWLING, R. M. 2010. Below-ground carbon stocks in intact and transformed subtropical thicket landscapes in semi-arid South Africa. *Journal of Arid Environments*, 74(1): 93-100.
- MILLS, A. J., TURPIE, J., COWLING, R. M., MARAIS, C., KERLEY, G. I. H., LECHMERE-OERTEL, R. G., SIGWELA, A. M. & POWELL, M. 2007. Assessing costs, benefits, and feasibility of restoring natural capital in Subtropical Thicket in South Africa. In: ARONSON, J., MILTON, S. & BLIGNAUT, J. (eds.) *Restoring natural capital: Science, business and practice*. Washington: Society for Ecological Restoration, Island Press, pp. 179-187.
- MONTGOMERY, D. R. 1999. Process domains and the river continuum. *Journal of the American Water Resources Association*, 35(2): 397-410.
- MONTGOMERY, D. R. & BUFFINGTON, J. M. 1997. Channel-reach morphology in mountain drainage basins. *Geological Society of America Bulletin*, 109(5): 596-611.
- MONTGOMERY, D. R. & BUFFINGTON, J. M. 1998. Channel processes, classification and response. In: NAIMAN, R. J. & BILBY, R. E. (eds.) *River ecology and management: Lessons from the Pacific Coastal Ecoregion*. New York: Springer, pp. 13-42.
- MONTGOMERY, D. R. & PIÉGAY, H. 2003. Wood in rivers: Interactions with channel morphology and processes. *Geomorphology*, 51(1-3): 1-5.
- MONTGOMERY, D. R. & WOHL, E. E. 2003. Rivers and riverine landscapes. In: A.R. GILLESPIE, S. C. P. & ATWATER, B. F. (eds.) *Developments in Quaternary Sciences*. Elsevier, pp. 221-246.
- MOODY, J. A., MARTIN, D. A., HAIRE, S. L. & KINNER, D. A. 2008. Linking runoff response to burn severity after a wildfire. *Hydrological Processes*, 22(13): 2063-2074.
- MOOLMAN, J. 2008. River long profiles aid in ecological planning. *PositionIT*, Jan/Feb: 43-45.
- MOON, B. P. 1988. Structural control. In: MOON, B. P. & DARDIS, G. F. (eds.) *The geomorphology of Southern Africa*. Johannesburg, South Africa: Southern Book Publishers (Pty) Ltd, pp. 231-248.
- MOON, B. P. & DARDIS, G. F. 1988. Introduction. In: MOON, B. P. & DARDIS, G. F. (eds.) *The geomorphology of Southern Africa*. Johannesburg, South Africa: Southern Book Publishers (Pty) Ltd, pp. 1-11

- MOON, B. P., NIEKERK, A. W. V., HERITAGE, G. L., ROGERS, K. H. & JAMES, C. S. 1997. A Geomorphological Approach to the Ecological Management of Rivers in the Kruger National Park: The Case of the Sabie River. *Transactions of the Institute of British Geographers*, 22(1): 31-48.
- MOUW, J. E. B., STANFORD, J. A. & ALABACK, P. B. 2009. Influences of flooding and hyporheic exchange on floodplain plant richness and productivity. *River Research and Applications*, 25(8): 929-945.
- MUCINA, L. & RUTHERFORD, M. C. 2006. *The vegetation of South Africa, Lesotho and Swaziland. Strelitzia 19*, Pretoria, South Africa: South African National Biodiversity Institute, 807 pp.
- MUCINA, L., RUTHERFORD, M. C. & POWRIE, L. W. 2006. The logic of the map: Approaches and procedures In: MUCINA, L. & RUTHERFORD, M. C. (eds.) *The Vegetation of South Africa, Lesotho and Swaziland. Strelitzia 19*. Pretoria, South Africa: South African National Biodiversity Institute, pp. 14-29.
- MURRAY, A. B., KNAAPEN, M. A. F., TAL, M. & KIRWAN, M. L. 2008. Biomorphodynamics: Physical-biological feedbacks that shape landscapes. *Water Resoures Research*, 44(W11301): 1-18.
- NAIMAN, R., BECHTOLD, J. S., BEECHIE, T., LATTERELL, J. & VAN PELT, R. 2010. A process-based view of floodplain forest patterns in coastal river valleys of the Pacific Northwest. *Ecosystems*, 13(1): 1-31.
- NAIMAN, R. J., DÉCAMPS, H. & MCCLAIN, M. E. 2005. *Riparia: Ecology, conservation and management of streamside communities*, Burlington, USA: Elsevier Academic Press, 430 pp.
- NAIMAN, R. J., DÉCAMPS, H. & POLLOCK, M. 1993. The Role of Riparian Corridors in Maintaining Regional Biodiversity. *Ecological Applications*, 3(2): 209-212.
- NAIMAN, R. J., LATTERELL, J. J., PETTIT, N. E. & OLDEN, J. D. 2008. Flow variability and the biophysical vitality of river systems. *Comptes Rendus Geosciences*, 340(9-10): 629-643.
- NANSON, G. C., TOOTH, S. & KNIGHTON, A. D. 2002. A global perspective on dryland rivers: Perceptions, misconceptions and distinctions. In: BULL, L. J. & KIRKBY, M. J. (eds.) *Dryland Rivers: Hydrology and geomorphology of Semi-arid channels*. Chichester, England: John Wiley & Sons, Ltd, pp. 17-54.
- NASH, D. & ENDFIELD, G. 2008. 'Splendid rains have fallen': Links between El Niño and rainfall variability in the Kalahari, 1840–1900. *Climatic Change*, 86(3): 257-290.
- NASH, D. J. 1996. On the dry valleys of the Kalahari: Documentary evidence of environmental change in central Southern Africa. *The Geographical Journal*, 162(2): 154-168.
- NELSON, D. W. & SOMMERS, L. E. 1982. Total carbon, organic carbon and organic matter In: PAGE, A. L., MILLER, R. H. & KEENEY, D. R. (eds.) *Methods of Soil Analysis, Part 2. Agron. Monogr. 9* Madison, WI: ASA and SSSA, pp. 539-579.
- NEWMAN, B. D., VIVONI, E. R. & GROFFMAN, A. R. 2006. Surface water–groundwater interactions in semiarid drainages of the American southwest. *Hydrological Processes*, 20(15): 3371-3394.
- NEWMAN, M. D. & LARGE, A. R. G. 2006. Natural rivers, hydromorphological quality and river restoration: A challenging new agenda for applied fluvial geomorphology. *Earth Surface Processes and Landforms*, 31: 1606-1624.

- NEWSON, M. D. 2002. Geomorphological concepts and tools for sustainable river ecosystem management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 12(4): 365-379.
- NEWSON, M. D. & LARGE, A. R. G. 2006. 'Natural' rivers, 'hydromorphological quality' and river restoration: A challenging new agenda for applied fluvial geomorphology. *Earth Surface Processes and Landforms*, 31(13): 1606-1624.
- NILSSON, C. & SVEDMARK, M. 2002. Basic Principles and Ecological Consequences of Changing Water Regimes: Riparian Plant Communities. *Environmental Management*, 30(4): 468-480.
- NOE, G. B. 2013. 12.21 Interactions among Hydrogeomorphology, Vegetation, and Nutrient Biogeochemistry in Floodplain Ecosystems. In: SHRODER, J. F. (ed.) *Treatise on Geomorphology*. San Diego: Academic Press, pp. 307-321.
- NOE, G. B. & HUPP, C. R. 2005. Carbon, nitrogen and phosphorus accumulation in floodplains of Atlantic Coastal Plain rivers, USA. *Ecological Applications*, 15(4): 1178-1190.
- NOIRTIN, E. 2008. *Analysis of Stakeholder Interactions and Involvement in Thicket Restoration, Western Baviaanskloof, South Africa. Who is willing to restore and why?*. Unpublished MSc dissertation, Wageningen University, Wageningen, The Netherlands, 167 pp.
- NORTJE, P. H. 1984. *The wild grape tree*, Cape Town, South Africa Tafelberg Publishers, pp.
- O'CONNOR, T. G. 1995. Acacia karroo invasion of grassland: Environmental and biotic effects influencing seedling emergence and establishment. *Oecologia*, 103(2): 214-223.
- O'CONNOR, T. G. 2001. Effect of small catchment dams on downstream vegetation of a seasonal river in semi-arid African savanna. *Journal of Applied Ecology*, 38(6): 1314-1325.
- O'CONNOR, T. G., PUTTICK, J. R. & HOFFMAN, M. T. 2014. Bush encroachment in southern Africa: Changes and causes. *African Journal of Range & Forage Science*, 31(2): 67-88.
- OLOGUNORISA, E. T. & TERSOO, T. 2006. The changing rainfall pattern and its implication for flood frequency in Makurdi, Northern Nigeria. *J. Appl. Sci. Environ. Mgt.*, 10(3): 97-102.
- OSTERKAMP, W. & HUPP, C. 1984. Geomorphic and vegetative characteristics along three northern Virginia streams. *Geological Society of America Bulletin*, 95 1093-1101.
- OSTERKAMP, W. R. & HUPP, C. R. 2010. Fluvial processes and vegetation: Glimpses of the past, the present and perhaps the future. *Geomorphology*, 116(3-4): 274-285.
- PALMER, M. A., BERNHARDT, E. S., ALLAN, J. D., LAKE, P. S., ALEXANDER, G., BROOKS, S., CARR, J., CLAYTON, S., DAHM, C. N., FOLLSTAD SHAH, J., GALAT, D. L., LOSS, S. G., GOODWIN, P., HART, D. D., HASSETT, B., JENKINSON, R., KONDOLF, G. M., LAVE, R., MEYER, J. L., O'DONNELL, T. K., PAGANO, L. & SUDDUTH, E. 2005. Standards for ecologically successful river restoration. *Journal of Applied Ecology*, 42(2): 208-217.
- PARSONS, A. J., BRACKEN, L., POEPL, R. E., WAINWRIGHT, J. & KEESSTRA, S. D. 2015. Introduction to special issue on connectivity in water and sediment dynamics. *Earth Surface Processes and Landforms*, 40(9): 1275-1277.
- PARSONS, H. & GILVEAR, D. 2002. Valley floor landscape change following almost 100 years of flood embankment abandonment on a wandering gravel-bed river. *River Research and Applications*, 18(5): 461-479.

- PARSONS, M. & THOMS, M. C. 2007. Hierarchical patterns of physical-biological associations in river ecosystems. *Geomorphology*, 89(1-2): 127-146.
- PARTRIDGE, T. C., DOLLAR, E. S. J., MOOLMAN, J. & DOLLAR, L. H. 2010. The geomorphic provinces of South Africa, Lesotho and Swaziland: A physiographic subdivision for earth and environmental scientists. *Transactions of the Royal Society of South Africa*, 65(1): 1 - 47.
- PARTRIDGE, T. C. & MAUD, R. R. 1987. Geomorphic evolution of Southern Africa since the Mesozoic. *South African Journal of Geology*, 90(2): 179-208.
- PEDROLI, B., DE BLUST, G., VAN LOOY, K. & VAN ROOIJ, S. 2002. Setting targets in strategies for river restoration. *Landscape Ecology*, 17(1): 5-18.
- PETERS, D. P. C. & HAVSTAD, K. M. 2006. Nonlinear dynamics in arid and semiarid systems: interactions among drivers and processes across scales. *Journal of Arid Environments*, 65: 196-206.
- PIÉGAY, H. & GURNELL, A. M. 1997. Large woody debris and river geomorphological pattern: examples from S.E. France and S. England. *Geomorphology*, 19(1-2): 99-116.
- PITMAN, W. V., KAKEBEEKE, J. P. & BAILEY, A. K. 2008. WRSM2000 (Enhanced) Water Resources Simulation Model for Windows user's guide. Final draft, Version 7 Compiled by Stewart Scott Consulting Engineers in collaboration with TiSD on behalf of the Directorate: Project Planning Pretoria, South Africa.
- PIZZUTO, J. E. 1984. Bank erodibility of shallow sandbed streams. *Earth Surface Processes and Landforms*, 9(2): 113-124.
- PODGER, G. & ARGENT, R. 2006. *Toolkit data file formats*, Australia: CRC for Catchment Hydrology, 30 pp.
- POFF, N. & WARD, J. 1990. Physical habitat template of lotic systems: Recovery in the context of historical pattern of spatiotemporal heterogeneity. *Environmental management*, 14(5): 629-645.
- POFF, N. L., ALLAN, J. D., BAIN, M. B., KARR, J. R., PRESTEGAARD, K. L., RICHTER, B. D., SPARKS, R. E. & STROMBERG, J. C. 1997. The natural flow regime: a paradigm for river conservation and restoration. *BioScience*, 47: 769-784.
- POLLEN-BANKHEAD, N. & SIMON, A. 2010. Hydrologic and hydraulic effects of riparian root networks on streambank stability: Is mechanical root-reinforcement the whole story? *Geomorphology*, 116(3-4): 353-362.
- POLLEN-BANKHEAD, N., SIMON, A. & THOMAS, R. E. 2013. 12.8 The Reinforcement of Soil by Roots: Recent Advances and Directions for Future Research. In: SHRODER, J. F. (ed.) *Treatise on Geomorphology*. San Diego: Academic Press, pp. 107-124.
- POLVI, L. E., WOHL, E. E. & MERRITT, D. M. 2011. Geomorphic and process domain controls on riparian zones in the Colorado Front Range. *Geomorphology*, 125 (4): 504-516.
- POOLE, G. C. 2002. Fluvial landscape ecology: addressing uniqueness within the river discontinuum. *Freshwater Biology*, 47(4): 641-660.
- POOLE, G. C., STANFORD, J. A., FRISSELL, C. A. & RUNNING, S. W. 2002. Three-dimensional mapping of geomorphic controls on flood-plain hydrology and connectivity from aerial photos. *Geomorphology*, 48(4): 329-347.
- POWELL, M. 2007. Subtropical Thicket Restoration Programme: Progress report. Zandvlakte, 11-14 November, Baviaanskloof Mega-Reserve. Grahamstown, South Africa.
- POWELL, M. & MANDER, M. 2009. Baviaanskloof-Tsitsikamma payment for ecosystem services: Water service suppliers report. Everton, South Africa.

- PRINGLE, C. 2003. What is hydrologic connectivity and why is it ecologically important? . *Hydrological Processes*, 17: 2685-2689.
- PYE, K. 1994. Properties of sediment particles. In: PYE, K. (ed.) *Sediment Transport and Depositional Processes*. Oxford: Blackwell Scientific Publications, pp. 1-24.
- RAIMONDO, D., VON STADEN, L., FODEN, W., VICTOR, J., HELME, N., TURNER, R., KAMUNDI, D. & MANYAMA, P. 2009. *Red list of South African plants 2009. Strelitzia 25: 83* Pretoria: South African National Biodiversity Institute, 668 pp.
- RAVI, S., BRESHEARS, D. D., HUXMAN, T. E. & D'ODORICO, P. 2010. Land degradation in drylands: Interactions among hydrologic-aeolian erosion and vegetation dynamics. *Geomorphology*, 116(3-4): 236-245.
- REBELO, A. G., BOUCHER, C., HELME, N., MUCINA, L. & RUTHERFORD, M. C. 2006. Fynbos Biome. In: MUCINA, L. & RUTHERFORD, M. C. (eds.) *The Vegetation of South Africa, Lesotho and Swaziland. Strelitzia 19*. Pretoria, South Africa: South African National Biodiversity Institute, pp. 53-219.
- REBELO, A. J., LE MAITRE, D. C., ESLER, K. J. & COWLING, R. M. 2013. Are we destroying our insurance policy? The effects of alien invasion and subsequent restoration on wetlands. A case study of the Kromme River system, South Africa. In: FU, B. & JONES, B. (eds.) *Landscape ecology for sustainable environment and culture*. New York: Springer, pp. 335-364.
- REBELO, A. J., LE MAITRE, D. C., ESLER, K. J. & COWLING, R. M. 2015. Hydrological responses of a valley-bottom wetland to land-use/land-cover change in a South African catchment: making a case for wetland restoration. *Restoration Ecology*, 23(6): 829-841.
- REINECKE, K. M. 2013. *Links between lateral riparian vegetation zones and flow*. Unpublished PhD thesis, Stellenbosch University, Stellenbosch, South Africa, 148 pp.
- REINECKE, K. M. & BROWN, K. 2013. Links between riparian vegetation and flow. WRC *Report No K5/1981*. Pretoria, South Africa: Water Research Commission.
- REINECKE, M. K., BROWN, C. A., ESLER, K. J., KING, J. M., KLEYNHANS, M. T. & KIDD, M. 2015. Links between lateral vegetation zones and river flow. *Wetlands*: 1-14.
- RENSCHLER, C. S., DOYLE, M. W. & THOMS, M. 2007. Geomorphology and ecosystems: Challenges and keys for success in bridging disciplines. *Geomorphology*, 89(1-2): 1-8.
- RICHARDSON, D. M., HOLMES, P. M., ESLER, K. J., GALATOWITSCH, S. M., STROMBERG, J. C., KIRKMAN, S. P., PYSEK, P. & HOBBS, R. J. 2007. Riparian vegetation: degradation, alien plant invasions, and restoration prospects. *Diversity and Distributions*, 13(1): 126-139.
- RICHTER, R. & SCHLÄPFER, D. 2012. *Atmospheric / topographic correction for satellite imagery: ATCOR-2/3 user guide, Version 8.2 BETA*, Switzerland: ReSe Applications Schläpfer, 203 pp.
- RIDEFELT, H., BOELHOUWERS, J. & EIKEN, T. 2009. Measurement of solifluction rates using multi-temporal aerial photography. *Earth Surface Processes and Landforms*, 34: 725-737.
- ROBERTSON, K. M. 2006. Distributions of tree species along point bars of 10 rivers in the south-eastern US Coastal Plain. *Journal of Biogeography*, 33(1): 121-132.
- ROSGEN, D. L. 1994. A classification of natural rivers. *CATENA*, 22(3): 169-199.
- ROWNTREE, K. 1991. An assessment of the potential impact of alien invasive vegetation on the geomorphology of the river channels in South Africa. *Southern African Journal of Aquatic Sciences*, 17(1-2): 28-43.

- ROWNTREE, K. 2014. Report on river restoration proposal, Baviaans River. Grahamstown, South Africa: Catchment Research Group, Department of Geography, Rhodes University.
- ROWNTREE, K. M. 2012. Fluvial geomorphology. In: HOLMES, P. & MEADOWS, M. (eds.) *Southern African geomorphology: Recent trends and new directions*. Bloemfontein: SUN PReSS, pp. 95-140.
- ROWNTREE, K. M. & DOLLAR, E. S. J. 1996. Controls on channel form and channel change in the Bell River, Eastern Cape, South Africa. *South African Geographical Journal*, 78(1): 20-28.
- ROWNTREE, K. M. & DOLLAR, E. S. J. 1999. Vegetation controls on channel stability in the Bell River, Eastern Cape, South Africa. *Earth Surface Processes and Landforms*, 24(2): 127-134.
- ROWNTREE, K. M., ELLERY, W., SMITH-ADAO, L., BOBBINS, K. & JOUBERT, R. Landscape connectivity: A hydro-geomorphic framework for landscape restoration in the Baviaans Kloof, South Africa. IAG/AIG Regional conference on geomorphology for human adaptation to changing tropical environments, 2011 Addis Ababa, Ethiopia. 18-22.
- ROWNTREE, K. M. & WADESON, R. A. 1999. A hierarchical geomorphological model for the classification of selected South African rivers. *WRC Report No. 497/1/99*. Pretoria, South Africa: Water Research Commission.
- ROWNTREE, K. M., WADESON, R. A. & O'KEEFFE, J. H. 2000. The development of geomorphological classification system for the longitudinal zonation of South African rivers. *South African Geographical Journal*, 82(3): 163-172.
- RUST, I. C. & ILLENBERGER, W. K. 1989. Geology and geomorphology of the Baviaanskloof In: KERLEY, G. I. H. & ELS, L. M. (eds.) *The Kouga-Baviaanskloof Complex: Conservation status and management problems. Proceedings of a workshop held at the University of Port Elizabeth*. Port Elizabeth, South Africa Chief Directorate: Nature and Environmental Conservation and University of Port Elizabeth pp. 42-45.
- SAHEBJALAL, E. & DASHTEKIAN, K. 2013. Analysis of land use-land covers changes using normalized difference vegetation index (NDVI) differencing and classification methods. *African Journal of Agricultural Research*, 8(37): 4614-4622.
- SANDERCOCK, P. J. & HOOKE, J. M. 2010. Assessment of vegetation effects on hydraulics and of feedbacks on plant survival and zonation in ephemeral channels. *Hydrological Processes*, 24(6): 695-713.
- SANDERCOCK, P. J., HOOKE, J. M. & MANT, J. M. 2007. Vegetation in dryland river channels and its interaction with fluvial processes. *Progress in Physical Geography*, 31(2): 107-129.
- SARR, D. A. 2002. Riparian livestock enclosure research in the western United States: A critique and some recommendations. *Environmental Management*, 30(4): 516-526.
- SCHELTEMA, J. C. 2007. *Baviaanskloof stories*, Willowmore, South Africa: Baviaanskloof Tourism Association, 150 pp.
- SCHMITT, L., MAIRE, G. R., NOBELIS, P. & HUMBERT, J. L. 2007. Quantitative morphodynamic typology of rivers: a methodological study based on the French Upper Rhine basin. *Earth Surface Processes and Landforms*, 32(11): 1726-1746.
- SCHMITZ, D., BLANK, M., AMMONDT, S. & PATTEN, D. T. 2009. Using historic aerial photography and paleohydrologic techniques to assess long-term ecological response to two Montana dam removals. *Journal of Environmental Management*, 90(Supplement 3): S237-S248.

- SCHULZE, R. E. 2007. South African Atlas of Climatology and Agrohydrology. WRC Report 1489/1/06. Pretoria, South Africa: Water Research Commission.
- SCHUMM, S. A. 1977. *The fluvial system*, New York, USA: John Wiley & Sons, Inc, 338 pp.
- SCOTT, M. L., FRIEDMAN, J. M. & AUBLE, G. T. 1996. Fluvial process and the establishment of bottomland trees. *Geomorphology*, 14: 327-339.
- SEAR, D. A., MILLINGTON, C. E., KITTS, D. R. & JEFFRIES, R. 2010. Logjam controls on channel:floodplain interactions in wooded catchments and their role in the formation of multi-channel patterns. *Geomorphology*, 116(3-4): 305-319.
- SEAR, D. A., NEWMAN, M. D. & THORNE, C. R. 2003. Guidebook of applied fluvial geomorphology. *R&D Technical Report FD1914*. London.
- SHAHABI, H., ALLAHVIRDIASL, H. & ZABIHIAN, H. 2012. Monitoring vegetation conditions of catchments using multispectral remote sensing data (case study: Central Zab basin). *International Journal of Engineering Research & Technology*, 1(7): 1-6.
- SHAW, J. R. & COOPER, D. J. 2008. Linkages among watersheds, stream reaches, and riparian vegetation in dryland ephemeral stream networks. *Journal of Hydrology*, 350(1-2): 68-82.
- SHEARING, D. & VAN HEERDEN, K. 1994. *Karoo: South African wild flower guide 6*, Claremont: Botanical Society of South Africa, 192 pp.
- SHONE, R. W. 2006. Onshore post-Karoo Mesozoic deposits. In: JOHNSON, M. R., ANHAEUSSER, C. R. & THOMAS, R. J. (eds.) *The Geology of South Africa* Johannesburg/Pretoria, South Africa: Geological Society of South Africa/Council for Geoscience pp. 541-552.
- SIEBEN, E. J. J., MUCINA, L. & BOUCHER, C. 2009. Scaling hierarchy of factors controlling riparian vegetation patterns of the Fynbos Biome at the Western Cape, South Africa. *Journal of Vegetation Science*, 20(1): 17-26.
- SIMON, A., BENNETT, S. J. & NEARY, V. S. 2004a. Riparian vegetation and fluvial geomorphology: Problems and opportunities. In: BENNETT, S. J. & SIMON, A. (eds.) *Riparian vegetation and fluvial geomorphology. Water Science and Applications 8*. Washington, DC: American Geophysical Union, pp.
- SIMON, A. & CASTRO, J. 2003. Measurement and analysis of alluvial channel form. In: KONDOLF, G. M. & PIÉGAY, H. (eds.) *Tools in fluvial geomorphology*. Chichester, England: John Wiley & Sons, pp. 292-322.
- SIMON, A. & COLLISON, A. J. C. 2002. Quantifying the mechanical and hydrologic effects of riparian vegetation on streambank stability. *Earth Surface Processes and Landforms*, 27(5): 527-546.
- SIMON, A., DICKERSON, W. & HEINS, A. 2004b. Suspended-sediment transport rates at the 1.5-year recurrence interval for ecoregions of the United States: transport conditions at the bankfull and effective discharge? *Geomorphology*, 58(1-4): 243-262.
- SINGER, M. B., STELLA, J. C., DUFOUR, S., PIÉGAY, H., WILSON, R. J. S. & JOHNSTONE, L. 2013. Contrasting water-uptake and growth responses to drought in co-occurring riparian tree species. *Ecohydrology*, 6(3): 402-412.
- SLAYMAKER, O. 2009. The Future of Geomorphology. *Geography Compass*, 3(1): 329-349.
- SMITH-ADAO, L. & SCHEEPERS, A. 2007. An assessment of the channel morphological changes in the Lourens River, Western Cape. *Water SA*, 33(4): 559-570.
- SNIJMAN, D. A. 2013. *Plants of the greater Cape Floristic Region, vol. 2: The core Cape flora. Strelitzia 30*, Pretoria, South Africa: South African National Biodiversity Institute, 544 pp.

- SOLTAU, L., SMITH-ADAO, L. & BUGAN, R. 2011. Baviaanskloof resistivity survey: To define water level and depth to bedrock. Internal project report, 2011: JNEB036. Stellenbosch: CSIR.
- SÖNMEZ, F. K., KÖMÜSCÜ, A. Ü. & TURGU, E. 2005. An analysis of spatial and temporal dimension of drought vulnerability in Turkey using the Standardized Precipitation Index. *Natural Hazards*, 35 (2): 243–264.
- SOUTH AFRICAN WEATHER BUREAU 1996. Climate summary for Southern Africa: November 1996. *Department of Environmental Affairs and Tourism*. Pretoria, South Africa.
- SPINK, A., HILLMAN, M., FRYIRS, K., BRIERLEY, G. & LLOYD, K. 2010. Has river rehabilitation begun? Social perspectives from the Upper Hunter catchment, New South Wales, Australia. *Geoforum*, 41(3): 399-409.
- STANFORD, J. A. & WARD, J. V. 1988. The hyporheic habitat of river ecosystems. *Nature*, 335(6185): 64-66.
- STANLEY, E. H., FISHER, S. G. & GRIMM, N. B. 1997. Ecosystem Expansion and Contraction in Streams. *BioScience*, 47(7): 427-435.
- STEIGER, J., TABACCHI, E., DUFOUR, S., CORENBLIT, D. & PEIRY, J. L. 2005. Hydrogeomorphic processes affecting riparian habitat within alluvial channel–floodplain river systems: a review for the temperate zone. *River Research and Applications*, 21(7): 719-737.
- STOFFEL, M. & WILFORD, D. J. 2012. Hydrogeomorphic processes and vegetation: Disturbance, process histories, dependencies and interactions. *Earth Surface Processes and Landforms*, 37(1): 9-22.
- STORE, H., STORZ, W. & JACOBS, F. 2000. Electrical resistivity tomography to investigate geological structures of earth's upper crust *Geophysical Prospecting* 48: 455–471.
- STRAUCH, A. M., KAPUST, A. R. & JOST, C. C. 2009. Impact of livestock management on water quality and streambank structure in a semi-arid, African ecosystem. *Journal of Arid Environments*, 73(9): 795-803.
- STROMBERG, J. C., BEAUCHAMP, V. B., DIXON, M. D., LITE, S. J. & PARADZICK, C. 2007. Importance of low-flow and high-flow characteristics to restoration of riparian vegetation along rivers in arid south-western United States. *Freshwater Biology*, 52(4): 651-679.
- STROMBERG, J. C., LITE, S. J. & DIXON, M. D. 2010a. Effects of stream flow patterns on riparian vegetation of a semiarid river: Implications for a changing climate. *River Research and Applications*, 26(6): 712-729.
- STROMBERG, J. C., TILLER, R. & RICHTER, B. 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: The San Pedro, Arizona. *Ecological Applications*, 6(1): 113-131.
- STROMBERG, J. C., TLUCZEK, M. G. F., HAZELTON, A. F. & AJAMI, H. 2010b. A century of riparian forest expansion following extreme disturbance: Spatio-temporal change in Populus/Salix/Tamarix forests along the Upper San Pedro River, Arizona, USA. *Forest Ecology and Management*, 259(6): 1181-1189.
- SUPPIAH, R. & HENNESSY, K. J. 1998. Trends in total rainfall, heavy rain events and number of dry days in Australia, 1910–1990. *International Journal of Climatology*, 18(10): 1141-1164.
- SWANSON, F. J., GREGORY, S. V., SEDELL, J. R. & CAMPBELL, A. G. 1982. Land-water interactions: The riparian zone. In: EDMONDS, R. L. (ed.) *Analysis of coniferous forest ecosystems in the western United States*. Stroudsburg, PA: Hutchinson Ross Publishing Co, pp. 267-291.

- ŚWIEŹCHOWICZ, J. 2002. The influence of plant cover and land use on slope–channel decoupling in a foothill catchment: a case study from the Carpathian Foothills, southern Poland. *Earth Surface Processes and Landforms*, 27(5): 463-479.
- TABACCHI, E., CORRELL, D. L., HAUER, R., PINAY, G., PLANTY-TABACCHI, A.-M. & WISSMAR, R. C. 1998. Development, maintenance and role of riparian vegetation in the river landscape. *Freshwater Biology*, 40(3): 497-516.
- TABACCHI, E., LAMBS, L., GUILLOY, H., PLANTY-TABACCHI, A.-M., MULLER, E. & DÉCAMPS, H. 2000. Impacts of riparian vegetation on hydrological processes. *Hydrological Processes*, 14(16-17): 2959-2976.
- TABACCHI, E., PLANTY-TABACCHI, A.-M., SALINAS, M. J. & DÉCAMPS, H. 1996. Landscape structure and diversity in riparian plant communities: A longitudinal comparative study. *Regulated Rivers: Research and Management*, 12(4-5): 367-390.
- TAL, M. & PAOLA, C. 2010. Effects of vegetation on channel morphodynamics: results and insights from laboratory experiments. *Earth Surface Processes and Landforms*, 35(9): 1014-1028.
- TALJAARD, M. S. 1949. *A glimpse of South Africa* Stellenbosh: University Publishers and Booksellers 226 pp.
- TAYLOR, P. D., FAHRIG, L., HENEIN, K. & MERRIAM, G. 1993. Connectivity is a vital element of landscape structure. *Oikos*, 68: 571-573.
- TELFORD, W. M., GELDART, L. P. & SHERIFF, R. E. 1990. *Applied geophysics: Second edition*, United Kingdom: Cambridge University Press, 770 pp.
- THAMM, C. G. A. & JOHNSON, M. R. 2006. The Cape Supergroup. In: JOHNSON, M. R., ANHAEUSSER, C. R. & THOMAS, R. J. (eds.) *The Geology of South Africa* Johannesburg/Pretoria, South Africa: Geological Society of South Africa/Council for Geoscience pp. 443-460.
- THE NON AFFILIATED SOIL ANALYSIS WORK COMMITTEE. 1990. *Extractable phosphorus: Bray-2. Handbook of standard soil testing methods for advisory purposes*, Pretoria, South Africa: Soil Science Society of South Africa, pp.
- THOMS, M. C. & SHELDON, F. 2002. An ecosystem approach for determining environmental water allocations in Australian dryland river systems: the role of geomorphology. *Geomorphology*, 47(2-4): 153-168.
- THOMSON, J. R., TAYLOR, M. P., FRYIRS, K. A. & BRIERLEY, G. J. 2001. A geomorphological framework for river characterization and habitat assessment. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 11(5): 373-389.
- THORNE, C. R. 1990. The effect of vegetation on riverbank erosion and stability. In: THORNES, J. B. (ed.) *Vegetation and erosion*. Chichester: John Wiley & Sons Ltd, pp. 125 –144.
- TICKNER, D. P., ANGOLD, P. G., GURNELL, A. M. & MOUNTFORD, J. O. 2001. Riparian plant invasions: hydrogeomorphological control and ecological impacts. *Progress in Physical Geography*, 25(1): 22-52.
- TOCKNER, K. & STANFORD, J. A. 2002. Riverine flood plains: Present state and future trends. *Environmental Conservation*, 29(3): 308-330.
- TOERIEN, D. K. & HILL, R. S. 1991. The geology of the Port Elizabeth area: Explanation of sheet 3324 (1:250 000) Pretoria, South Africa: Department of Mineral and Energy Affairs, Geological Survey.
- TOLEDO, Z. O. & KAUFFMAN, J. B. 2001. Root biomass in relation to channel morphology of headwater streams. *Journal of the American Water Resources Association*, 37(6): 1653-1663.

- TOOTH, S. 2000a. Downstream changes in dryland river channels: the Northern Plains of arid central Australia. *Geomorphology*, 34(1-2): 33-54.
- TOOTH, S. 2000b. Process, form and change in dryland rivers: a review of recent research. *Earth-Science Reviews*, 51(1-4): 67-107.
- TOOTH, S. 2013. 9.31 Dryland fluvial environments: Assessing distinctiveness and diversity from a global perspective. In: SHRODER, J. F. (ed.) *Treatise on Geomorphology*. San Diego, USA: Academic Press, pp. 612-644.
- TOOTH, S., BRANDT, D., HANCOX, P. J. & MCCARTHY, T. S. 2004. Geological controls on alluvial river behaviour: a comparative study of three rivers on the South African Highveld. *Journal of African Earth Sciences*, 38(1): 79-97.
- TOOTH, S. & NANSON, G. C. 2000. The role of vegetation in the formation of anabranching channels in an ephemeral river, Northern plains, arid central Australia. *Hydrological Processes*, 14(16-17): 3099-3117.
- TOOTH, S. & NANSON, G. C. 2004. Forms and processes of two highly contrasting rivers in arid central Australia, and the implications for channel-pattern discrimination and prediction. *Geological Society of America Bulletin*, 116(7/8): 802-816.
- TURNBULL, L., WAINWRIGHT, J. & BRAZIER, R. E. 2008. A conceptual framework for understanding semi-arid land degradation: ecohydrological interactions across multiple-space and time scales. *Ecohydrology*, 1(1): 23-34.
- TURPIE, J. K., MARAIS, C. & BLIGNAUT, J. N. 2008. The working for water programme: Evolution of a payments for ecosystem services mechanism that addresses both poverty and ecosystem service delivery in South Africa. *Ecological Economics*, 65(4): 788-798.
- TYSON, P. D. & PRESTON-WHITE, R. A. 2000. *The weather and climate of Southern Africa* Cape Town. South Africa.: Oxford University Press, 396 pp.
- UNION OF SOUTH AFRICA 1935. Report for the years 1931-32. *Department of Irrigation, Meteorological Office*. Pretoria, South Africa.
- UNION OF SOUTH AFRICA 1955. Report for the year 1953. *Department of Transport, Weather Bureau*. Pretoria, South Africa.
- URQUHART, C. 1990. Baviaanskloof: A dream not yet come true *African Wildlife*, 44(1): 38-43.
- UYS, M. C. & O' KEEFFE, J. H. 1997. Simple words and fuzzy zones: Early directions for temporary river research in South Africa. *Environmental Management*, 21(4): 517-531.
- VAN COLLER, A., ROGERS, K. & HERITAGE, G. 1997. Linking riparian vegetation types and fluvial geomorphology along the Sabie River within the Kruger National Park, South Africa. *African Journal of Ecology*, 35(3): 194-212.
- VAN COLLER, A. L., ROGERS, K. H. & HERITAGE, G. L. 2000. Riparian vegetation-environment relationships: Complimentarity of gradients versus patch hierarchy approaches. *Journal of Vegetation Science*, 11(3): 337-350.
- VAN DAM, R. L. 2012. Landform characterization using geophysics—Recent advances, applications, and emerging tools. *Geomorphology*, 137(1): 57-73.
- VAN DE WIEL, M. J. & DARBY, S. E. 2007. A new model to analyse the impact of woody riparian vegetation on the geotechnical stability of riverbanks. *Earth Surface Processes and Landforms*, 32(14): 2185-2198.
- VAN DEN BROEK, D., WEEL, S., SELOMANE, O. & ZWINKELS, M. 2012. Living Lands: Four years on the landscape - A review. Eastern Cape, South Africa: Living Lands.

- VAN DER WATT, H. V. H. 1966. Improved tables and a simplified procedure for soil particle size analyses by the hydrometer method. *South African Journal of Agricultural Science*, 9: 911-916.
- VAN JAARSVELD, E. 2011. Natural heritage: Flora. In: HATTINGH, L. (ed.) *Baviaanskloof: A world apart*. Willowmore, South Africa: Baviaanskloof Tourism Association, pp. 54-61.
- VAN LOOY, K., HONNAY, O., BOSSUYT, B. & HERMY, M. 2003. The effects of river embankment and forest fragmentation on the plant species richness and composition of floodplain forests in the Meuse Valley, Belgium. *Belgian Journal of Botany*, 136(2): 97-108.
- VAN LUIJK, G., COWLING, R. M., RIKSEN, M. J. P. M. & GLENDAY, J. 2013. Hydrological implications of desertification: Degradation of South African semi-arid subtropical thicket. *Journal of Arid Environments*, 91(0): 14-21.
- VAN NIEKERK, A. W., HERITAGE, G. L. & MOON, B. P. 1995. River classification for management: The geomorphology of the Sabie River in the Eastern Transvaal. *South African Geographical Journal*, 77(2): 68-76.
- VAN WYK, B. E. & GERICKE, N. 2000. *People's plants: A guide to useful plants of southern Africa*, Pretoria, South Africa: Briza Publications, 351 pp.
- VAUGHAN, I. P., DIAMOND, M., GURNELL, A. M., HALL, K. A., JENKINS, A., MILNER, N. L., NAYLOR, L. A., SEAR, D. A., WOODWARD, G. & ORMEROD, S. J. 2009. Viewpoint: Integrating ecology with hydromorphology: a priority for river science and management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 19: 113-25.
- VEIHE, A., JENSEN, N. H., SCHIØTZ, I. G. & NIELSEN, S. L. 2011. Magnitude and processes of bank erosion at a small stream in Denmark. *Hydrological Processes*, 25(10): 1597-1613.
- VLOK, J. & SCHUTTE-VLOK, A. L. 2010. *Plants of the Klein Karoo*, Hatfield, South Africa: Umdaus Press, 568 pp.
- VLOK, J. H. J. 1989. On the floristics and ecology of the flora of the Kouga-Baviaanskloof complex. In: KERLEY, G. I. H. & ELS, L. M. (eds.) *The Kouga-Baviaanskloof Complex: Conservation status and management problems. Proceedings of a workshop held at the University of Port Elizabeth*. Port Elizabeth, South Africa Chief Directorate: Nature and Environmental Conservation and University of Port Elizabeth pp. 14-25.
- VLOK, J. H. J. & EUSTON-BROWN, D. I. W. 2002. The patterns within, and the ecological processes that sustain, the subtropical thicket vegetation in the planning domain for the Subtropical Thicket Ecosystem Planning (STEP) project. *Report No. 40*. Port Elizabeth, South Africa.
- VOGEL, C. H., LAING, M. & MONNIK, K. 2000. Drought in South Africa, with special reference to the 1980-1994 period. In: WILHITE, D. A. (ed.) *Drought volume 1: A global assessment*. London: Routledge Hazard and Disaster Series, pp. 348-366.
- WADESON, R. A. & ROWNTREE, K. M. 1994. A hierarchical geomorphological model for the classification of South African river systems In: UYS, M. (ed.) *Classification of rivers and environmental health indicators. Proceedings of a joint South African-Australian workshop, Cape Town, 7-14 February*, WRC Report No. TT63/94 Pretoria: Water Research Commission, pp. 49-67.
- WALKER, B. F. 2007. Rainfall data analysis at Newport and the relationship to landsliding in Pittwater. *Australian Geomechanics*, 42(1): 197-207.

- WARD, J. V. 1989. The four-dimensional nature of lotic ecosystems. *Journal of the North American Benthological Society*, 16: 531-544.
- WARD, J. V. 1998. Riverine landscapes: Biodiversity patterns, disturbance regimes, and aquatic conservation. *Biological Conservation*, 83: 269-278.
- WARD, J. V., TOCKNER, K., ARSCOTT, D. B. & CLARET, C. 2002. Riverine landscape diversity. *Freshwater Biology*, 47(4): 517-539.
- WARD, J. V., TOCKNER, K., UEHLINGER, U. & MALARD, F. 2001. Understanding natural patterns and processes in river corridors as the basis for effective river restoration. *Regulated Rivers: Research & Management*, 17(4-5): 311-323.
- WATSON, C. C. & BIEDENHARN, D. S. 2000. Comparison of flood management strategies. In: WOHL, E. E. (ed.) *Inland flood hazards: Human, riparian and aquatic communities*. UK: Cambridge University Press, pp. 381-393.
- WEBLEY, L. 2011a. Cultural heritage. In: HATTINGH, L. (ed.) *Baviaanskloof: A world apart*. Willowmore, South Africa: Baviaanskloof Tourism Association, pp. 83-101.
- WEBLEY, L. 2011b. People. In: HATTINGH, L. (ed.) *Baviaanskloof: A world apart*. Willowmore, South Africa: Baviaanskloof Tourism Association, pp. 8-29.
- WESTERN, A. W., BLÖSCHL, G. & GRAYSON, R. B. 2001. Toward capturing hydrologically significant connectivity in spatial patterns *Water Resources Research*, 37(1): 83-97.
- WILHITE, D. A. 2000. Drought as a natural hazard. In: WILHITE, D. A. (ed.) *Drought volume 1: A global assessment*. London: Routledge Hazard and Disaster Series, pp. 3-18.
- WINTERBOTTOM, S. J. 2000. Medium and short-term channel planform changes on the Rivers Tay and Tummel, Scotland. *Geomorphology*, 34(3-4): 195-208.
- WINTERS, G., RYVKIN, I., RUDKOV, T., MORENO, Z. & FURMAN, A. 2015. Mapping underground layers in the super arid Gidron Wadi using electrical resistivity tomography (ERT). *Journal of Arid Environments*, 121(0): 79-83.
- WMO 2008. Manual on low-flow estimation and prediction In: GUSTARD, A. & DEMUTH, S. (eds.) *WMO-No. 1029, Operational Hydrological Report No. 50*. Geneva, Switzerland.
- WOHL, E. 2005. Compromised rivers: Understanding historical human impacts on rivers in the context of restoration. *Ecology and Society* 10(2): 2.
- WOHL, E. 2006. Human impacts to mountain streams. *Geomorphology*, 79(3-4): 217-248.
- WOHL, E., ANGERMEIER, P. L., BLEDSOE, B., KONDOLF, M. K., MACDONNELL, L., MERRITT, D. M., PALMER, M. A., POFF, N. L. & TARBOTON, D. 2005. River restoration. *Water Resources Research*, 41: W10301.
- WOHL, E. E. 2000a. Anthropogenic impacts on flood hazards. In: WOHL, E. E. (ed.) *Inland flood hazards: Human, riparian and aquatic communities*. UK: Cambridge University Press, pp. 104-141.
- WOHL, E. E. 2000b. Geomorphic effects of floods. In: WOHL, E. E. (ed.) *Inland flood hazards: Human, riparian and aquatic communities*. UK: Cambridge University Press, pp. 167-193.
- WOHL, E. E. 2000c. Inland flood hazards. In: WOHL, E. E. (ed.) *Inland flood hazards: Human, riparian and aquatic communities*. UK: Cambridge University Press, pp. 3-36.
- WOLMAN, M. G. 1954. A method for sampling coarse bed material. *Transactions of the American Geophysical Union*, 35: 951-956.

-
- WU, Y. 2005. *Groundwater recharge estimation in Table Mountain Group aquifer systems with a case study of Kammanassie area*. Unpublished PhD thesis, University of the Western Cape, Bellville, South Africa, pp.
- YOUNG, W. & KINGSFORD, R. T. 2006. Flow variability in large unregulated dry rivers. *In: KINGSFORD, R. T. (ed.) Ecology of desert rivers*. Cambridge: Cambridge University Press, pp. 47-75.
- YU, G.-A., LIU, L., LI, Z., LI, Y., HUANG, H., BRIERLEY, G., BLUE, B., WANG, Z. & PAN, B. 2013. Fluvial diversity in relation to valley setting in the source region of the Yangtze and Yellow Rivers. *Journal of Geographical Sciences*, 23(5): 817-832.
- YUHAS, A. N. & SCUDERI, L. A. 2009. MODIS-derived NDVI characterisation of drought-induced evergreen dieoff in western North America. *Geographical Research*, 47(1): 34-45.
- ZHANG, X. & YANG, F. 2004. RCLimDex (1.0): User manual. Ontario, Canada: Climate Research Branch of Meteorological Service.

APPENDICES

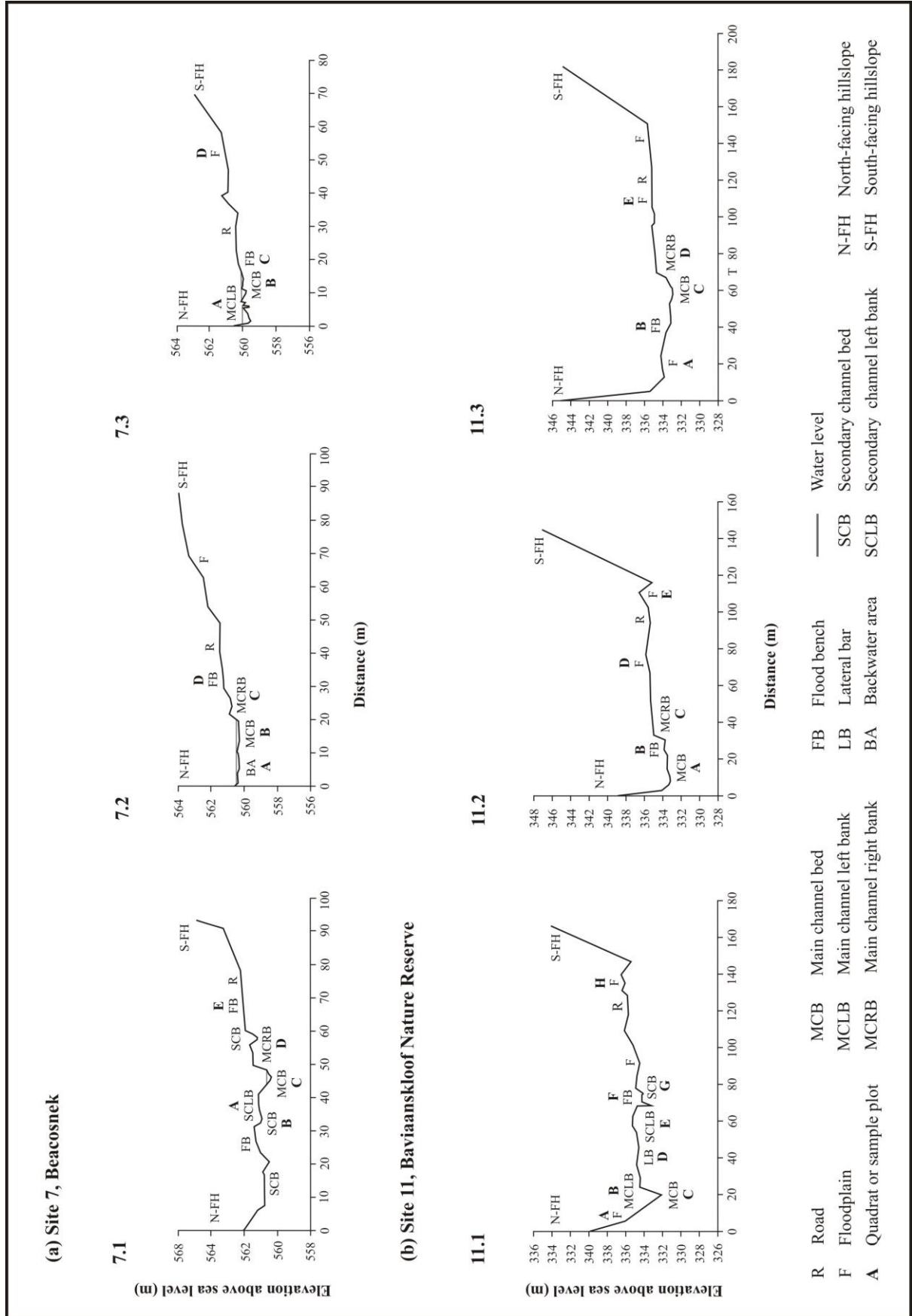
Appendix 5.1: Quadrats and their geomorphic landforms or features per valley confinement setting.

Quadrat codes e.g. 1.1.A indicates the study site number (1) followed by the cross-section number (1) and then the quadrat or sample plot (A).

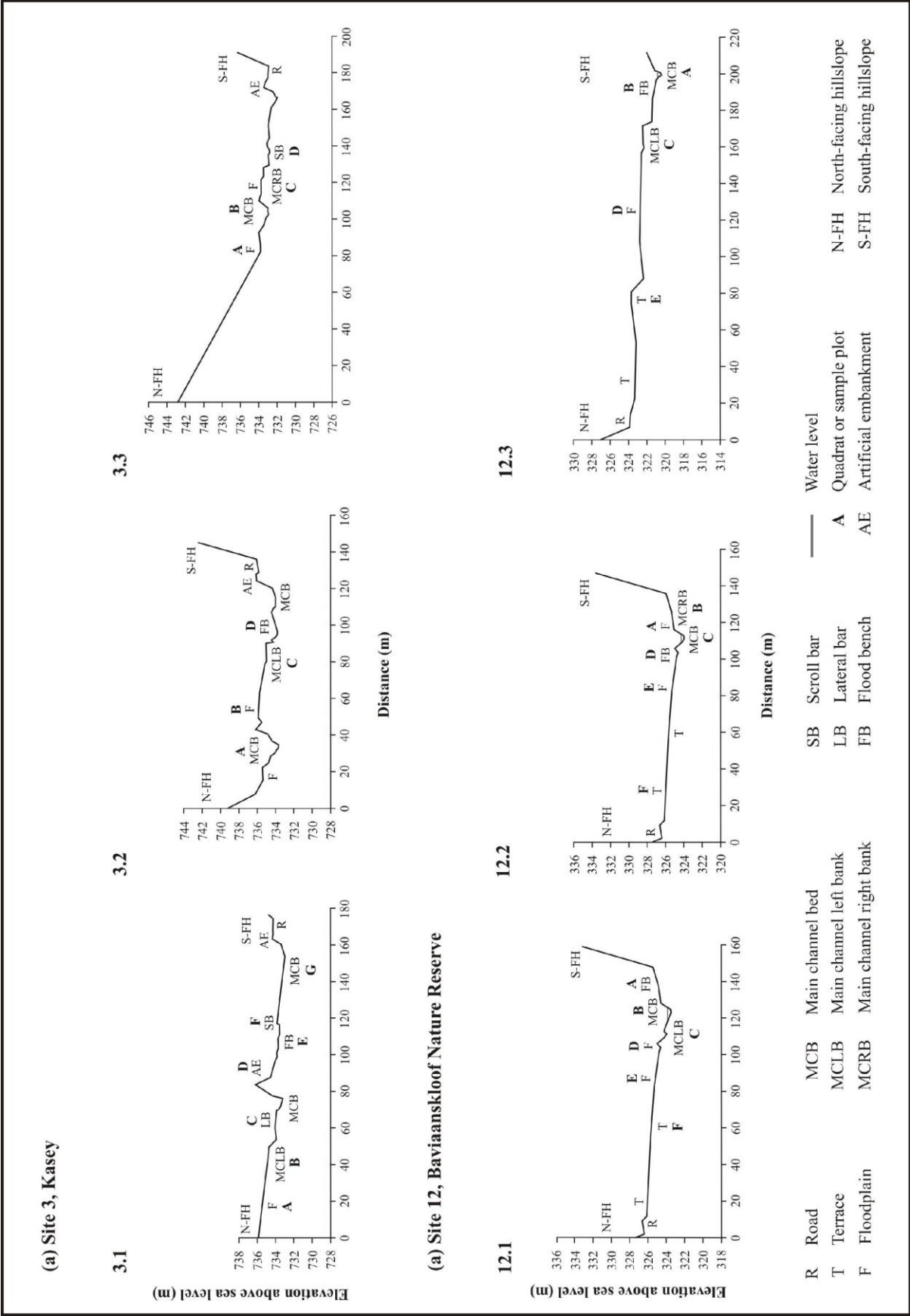
Confined valley setting			Semi-confined valley setting			Unconfined valley setting		
Plot	Size (m ²)	Landform or feature	Plot	Size (m ²)	Landform or feature	Plot	Size (m ²)	Landform or feature
2.1.A	64	Flood bench	1.1.A	64	Floodplain	4.1.A	64	Floodplain
2.1.B	20	Main channel left bank	1.1.B	64	Floodplain	4.1.B	16	Secondary channel
2.1.C	16	Main channel bed	1.1.C	16	Secondary channel	4.1.C	24	Secondary channel
2.1.D	64	Point bar	1.1.D	32	Secondary channel	4.1.D	16	Secondary channel
2.1.E	40	Scroll bar	1.1.E	56	Mid-channel bar	4.1.E	32	Secondary channel
2.1.F	64	Floodplain	1.1.F	48	Main channel bed	4.1.F	64	Mid-channel bar
2.1.G	64	Terrace	1.1.G	12	Main channel left	4.1.G	64	Floodplain
2.2.A	64	Flood bench	1.1.H	64	Floodplain	4.1.H	32	Main channel left
2.2.B	24	Main channel left bank	1.1.I	32	Terrace	4.1.I	64	Main channel bed
2.2.C	24	Main channel bed	1.2.A	64	Floodplain	4.1.J	48	Flood bench
2.2.D	16	Lateral bar	1.2.B	16	Secondary channel	4.1.K	64	Floodplain
2.2.E	48	Scroll bar	1.2.C	12	Secondary channel	4.1.L	64	Floodplain
2.2.F	64	Floodplain	1.2.D	32	Main channel bed	4.2.A	64	Floodplain
2.2.G	64	Terrace	1.2.E	64	Main channel bed	4.2.B	64	Island (mid-channel)
2.3.A	64	Flood bench	1.2.F	20	Main channel left	4.2.C	64	Flood bench
2.3.B	12	Scroll bar	1.2.G	32	Terrace	4.2.D	36	Main channel bed
2.3.C	20	Main channel bed	1.3.A	64	Floodplain	4.2.E	16	Main channel right
2.3.D	20	Main channel right	1.3.B	32	Secondary channel	4.2.F	32	Secondary channel
2.3.E	64	Floodplain	1.3.C	16	Secondary channel	4.2.G	24	Secondary channel
2.3.F	64	Terrace	1.3.D	16	Main channel bed	4.2.H	64	Floodplain
6.1.A	64	Flood bench	1.3.E	64	Main channel bed	4.2.I	64	Floodplain
6.1.B	24	Main channel right	1.3.F	24	Main channel left	4.2.J	64	Floodplain
6.1.C	40	Main channel bed	1.3.G	64	Floodplain	4.3.A	64	Island (mid-channel)
6.1.D	12	Floodplain	3.1.A	64	Floodplain	4.3.B	48	Flood bench
6.1.E	64	Floodplain	3.1.B	32	Main channel left	4.3.C	64	Main channel bed
6.1.F	64	Floodplain	3.1.C	64	Lateral bar	4.3.D	32	Main channel right
6.2.A	12	Main channel right	3.1.D	32	Artificial	4.3.E	64	Floodplain
6.2.B	24	Main channel bed	3.1.E	48	Flood bench	4.3.F	64	Floodplain
6.2.C	64	Flood bench	3.1.F	48	Scroll bar	4.3.G	64	Floodplain
6.2.D	16	Secondary channel	3.1.G	64	Main channel bed	4.3.H	16	Secondary channel
6.2.E	12	Secondary channel bed	3.2.A	24	Main channel bed	4.3.I	24	Secondary channel
6.2.F	64	Floodplain	3.2.B	64	Floodplain	5.1.A	12	Tributary channel
6.3.A	48	Flood bench	3.2.C	32	Main channel left	5.1.B	20	Tributary channel
6.3.B	12	Main channel right	3.2.D	48	Flood bench	5.1.C	64	Floodplain
6.3.C	40	Main channel bed	3.3.A	64	Floodplain	5.1.D	16	Main channel right
6.3.D	8	Secondary channel	3.3.B	20	Main channel bed	5.1.E	64	Main channel bed
6.3.E	16	Secondary channel bed	3.3.C	36	Main channel right	5.1.F	48	Artificial
6.3.F	64	Floodplain	3.3.D	64	Scroll bar	5.1.G	64	Floodplain
7.1.A	20	Secondary channel left	8.1.A	48	Flood bench	5.1.H	12	Tributary channel
7.1.B	48	Secondary channel bed	8.1.B	20	Main channel bed	5.1.I	28	Tributary channel
7.1.C	16	Main channel bed	8.1.C	12	Main channel left	5.1.J	64	Terrace
7.1.D	24	Main channel right	8.1.D	64	Floodplain	5.2.A	64	Floodplain
7.1.E	64	Flood bench	8.1.E	64	Floodplain	5.2.B	32	Tributary channel
7.2.A	48	Backwater area (main	8.1.F	56	Island (mid-channel)	5.2.C	12	Tributary channel
7.2.B	40	Main channel bed	8.1.G	8	Secondary channel	5.2.D	64	Floodplain
7.2.C	8	Main channel right	8.1.H	16	Secondary channel	5.2.E	64	Main channel bed
7.2.D	64	Flood bench	8.1.I	64	Flood bench	5.2.F	24	Main channel left
7.3.A	12	Main channel left bank	8.2.A	64	Floodplain	5.2.G	64	Floodplain
7.3.B	28	Main channel bed	8.2.B	8	Secondary channel	5.3.A	64	Floodplain
7.3.C	32	Flood bench	8.2.C	8	Secondary channel	5.3.B	16	Secondary channel
7.3.D	56	Floodplain	8.2.D	12	Main channel bed	5.3.C	12	Secondary channel
11.1.A	64	Floodplain	8.2.E	12	Main channel right	5.3.D	64	Floodplain
11.1.B	32	Main channel left bank	8.2.F	64	Flood bench	5.3.E	24	Main channel right
11.1.C	64	Main channel bed	8.2.G	64	Floodplain	5.3.F	64	Main channel bed
11.1.D	16	Lateral bar	8.3.A	12	Secondary channel	5.3.G	64	Floodplain
11.1.E	16	Secondary channel left	8.3.B	48	Secondary channel	5.3.H	40	Artificial
11.1.F	16	Flood bench	8.3.C	64	Floodplain	5.3.I	64	Floodplain
11.1.G	12	Secondary channel bed	8.3.D	16	Main channel left	5.3.J	28	Tributary channel

Confined valley setting			Semi-confined valley setting			Unconfined valley setting		
Plot	Size (m ²)	Landform or feature	Plot	Size (m ²)	Landform or feature	Plot	Size (m ²)	Landform or feature
11.1.H	64	Floodplain	8.3.E	48	Main channel bed	5.3.K	24	Tributary channel
11.2.A	32	Main channel bed	8.3.F	64	Floodplain	9.1.A	64	Terrace
11.2.B	32	Flood bench	12.1.A	40	Flood bench	9.1.B	24	Tributary channel
11.2.C	32	Main channel right	12.1.B	16	Main channel bed	9.1.C	16	Tributary channel
11.2.D	64	Floodplain	12.1.C	16	Main channel left	9.1.D	64	Terrace
11.2.E	64	Floodplain	12.1.D	64	Floodplain	9.1.E	64	Floodplain
11.3.A	20	Floodplain	12.1.E	64	Floodplain	9.1.F	32	Main channel left
11.3.B	64	Flood bench	12.1.F	64	Terrace	9.1.G	64	Island (mid-channel)
11.3.C	32	Main channel bed	12.2.A	64	Floodplain	9.1.H	64	Main channel bed
11.3.D	16	Main channel right	12.2.B	16	Main channel right	9.1.I	64	Floodplain
11.3.E	64	Floodplain	12.2.C	12	Main channel bed	9.1.J	64	Terrace
			12.2.D	64	Flood bench	9.2.A	64	Terrace
			12.2.E	64	Floodplain	9.2.B	32	Secondary channel
			12.2.F	64	Terrace	9.2.C	64	Secondary channel
			12.3.A	12	Main channel bed	9.2.D	64	Floodplain
			12.3.B	64	Flood bench	9.2.E	32	Main channel right
			12.3.C	20	Main channel left	9.2.F	32	Main channel bed
			12.3.D	64	Floodplain	9.2.G	64	Lateral bar
			12.3.E	64	Terrace	9.2.H	32	Flood bench
						9.2.I	32	Flood bench
						9.2.J	64	Floodplain
						9.2.K	64	Floodplain
						9.2.L	64	Terrace
						9.3.A	64	Terrace
						9.3.B	64	Terrace
						9.3.C	64	Floodplain
						9.3.D	20	Main channel right
						9.3.E	64	Main channel bed
						9.3.F	64	Floodplain
						9.3.G	8	Secondary channel
						9.3.H	16	Secondary channel
						9.3.I	64	Island (mid-channel)
						9.3.J	20	Main channel bed
						9.3.K	40	Main channel left
						9.3.L	64	Floodplain
						9.3.M	64	Terrace
						10.1.A	64	Terrace
						10.1.B	48	Main channel right
						10.1.C	32	Lateral bar
						10.1.D	48	Island (mid-channel)
						10.1.E	48	Main channel bed
						10.1.F	64	Flood bench
						10.1.G	64	Floodplain
						10.1.H	64	Floodplain
						10.1.I	64	Terrace
						10.1.J	64	Terrace
						10.2.A	64	Terrace
						10.2.B	64	Flood bench
						10.2.C	48	Island (mid-channel)
						10.2.D	24	Main channel right
						10.2.E	24	Main channel bed
						10.2.F	24	Flood bench
						10.2.G	64	Floodplain
						10.2.H	8	Secondary channel
						10.2.I	12	Secondary channel
						10.2.J	64	Floodplain
						10.2.K	64	Terrace
						10.3.A	64	Terrace
						10.3.B	32	Flood bench
						10.3.C	64	Flood bench
						10.3.D	32	Lateral bar
						10.3.E	16	Main channel bed
						10.3.F	32	Main channel left
						10.3.G	64	Floodplain
						10.3.H	64	Terrace
						10.3.I	64	Terrace
						13.1.A	64	Main channel bed
						13.1.B	48	Main channel right
						13.1.C	64	Floodplain
						13.1.D	12	Secondary channel
						13.1.E	16	Secondary channel
						13.1.F	64	Floodplain

Confined valley setting			Semi-confined valley setting			Unconfined valley setting		
Plot	Size (m ²)	Landform or feature	Plot	Size (m ²)	Landform or feature	Plot	Size (m ²)	Landform or feature
						13.2.A	12	Main channel left
						13.2.B	24	Main channel bed
						13.2.C	24	Flood bench
						13.2.D	64	Floodplain
						13.2.E	12	Secondary channel
						13.2.F	16	Secondary channel
						13.2.G	64	Floodplain
						13.3.A	64	Floodplain
						13.3.B	16	Main channel left
						13.3.C	32	Flood bench
						13.3.D	12	Main channel bed
						13.3.E	64	Floodplain
						13.3.F	64	Floodplain



Appendix 5.3: Valley floor cross-sections, geomorphic surfaces and quadrats, semi-confined study sites 3 and 12.





Appendix 5.5: NDVI and TC transformation summary statistics for the dry periods, Baviaanskloof.

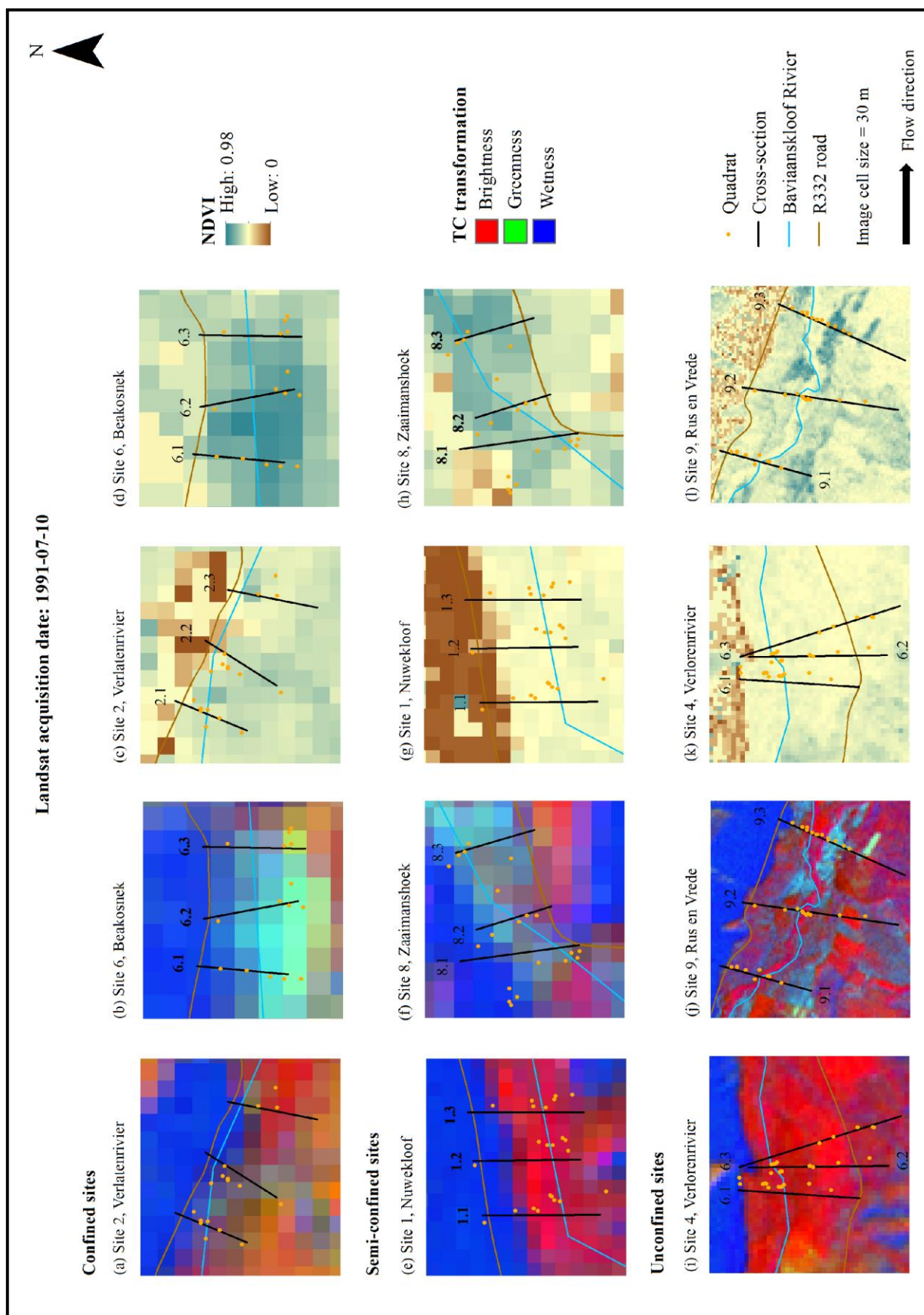
The * symbol denotes no data.

Valley setting	Study site	Variable	Landsat acquisition date: 1991-07-10				Landsat acquisition date: 1993-09-11			
			NDVI	Brightness	Greenness	Wetness	NDVI	Brightness	Greenness	Wetness
Confined	Site 2	Maximum	0.28	222.34	12.85	-20.94	0.33	227.01	24.38	-31.60
		Minimum	0.10	76.38	-7.13	-77.12	0.10	152.17	2.37	-53.03
		Average	0.20	119.59	1.07	-47.13	0.21	179.96	11.55	-43.49
		Standard deviation	0.05	43.54	5.51	17.21	0.07	29.25	6.81	7.32
	Site 6	Maximum	0.64	204.51	56.09	-9.52	0.56	175.50	34.13	-16.36
		Minimum	0.28	50.52	4.09	-73.22	0.35	96.00	10.01	-34.79
		Average	0.47	136.68	30.16	-30.05	0.41	134.69	23.94	-24.63
		Standard deviation	0.13	49.05	18.91	21.97	0.07	34.38	10.28	6.95
	Site 7	Maximum	0.33	27.97	-4.29	6.81	0.33	118.04	13.48	-12.88
		Minimum	-0.33	22.38	-9.93	2.99	-0.12	34.79	-14.82	-41.96
		Average	-0.08	25.29	-6.95	4.95	0.14	64.98	-5.10	-25.87
		Standard deviation	0.22	1.66	2.22	1.30	0.15	31.17	9.53	10.40
	Site 11	Maximum	0.31	200.14	8.61	-23.41	*	486.68	-26.53	64.11
		Minimum	0.07	92.28	-11.86	-75.52	*	240.03	-65.29	4.95
		Average	0.18	151.42	-1.99	-51.78	*	360.73	-44.75	34.23
		Standard deviation	0.08	34.39	6.93	14.50	*	75.60	11.12	15.39
Semi-confined	Site 1	Maximum	0.41	262.90	-0.84	1.00	0.25	239.43	8.71	-28.12
		Minimum	-0.27	22.39	-21.36	-85.16	0.06	96.21	-1.80	-41.65
		Average	0.05	178.08	-12.69	-59.21	0.15	182.71	2.99	-35.90
		Standard deviation	0.13	77.05	5.07	25.51	0.06	41.75	3.24	4.41
	Site 3	Maximum	0.44	248.96	1.84	-18.94	0.29	225.01	13.65	-26.83
		Minimum	0.06	44.30	-16.33	-88.91	0.05	104.96	-9.22	-42.99
		Average	0.16	179.65	-8.37	-61.52	0.13	188.17	1.10	-35.81
		Standard deviation	0.12	66.61	6.16	18.06	0.08	38.14	6.34	4.73
	Site 8	Maximum	0.60	158.33	31.46	2.79	0.62	200.72	30.46	-21.20
		Minimum	0.00	35.13	-6.74	-62.64	0.10	99.59	-0.97	-44.03
		Average	0.31	102.88	7.50	-26.20	0.34	144.75	17.05	-34.38
		Standard deviation	0.17	46.38	11.29	21.94	0.14	25.62	9.33	7.02
	Site 12	Maximum	0.51	249.66	31.44	-9.95	*	517.73	-41.12	83.50
		Minimum	0.10	54.83	-4.00	-83.57	*	290.57	-73.04	27.83
		Average	0.35	129.79	18.60	-28.96	*	420.73	-60.49	57.66
		Standard deviation	0.14	62.71	12.38	30.43	*	63.83	10.57	17.14
Unconfined	Site 4	Maximum	0.15	316.16	-6.12	-50.81	0.13	249.29	10.69	-41.25
		Minimum	0.04	122.81	-22.09	-106.02	0.05	193.01	-4.40	-52.15
		Average	0.08	223.86	-14.86	-84.81	0.09	226.07	2.30	-47.90
		Standard deviation	0.03	42.98	4.41	12.30	0.02	19.33	4.02	3.07
	Site 5	Maximum	0.26	259.70	4.67	-52.04	0.51	205.56	42.54	-26.29
		Minimum	0.03	132.35	-18.14	-93.51	0.04	157.28	-12.62	-49.16
		Average	0.09	190.75	-11.30	-73.30	0.11	181.78	0.72	-43.28
		Standard deviation	0.06	33.88	6.16	12.78	0.10	17.89	11.46	5.98
	Site 9	Maximum	0.50	245.42	24.30	-13.07	0.51	223.96	19.10	-19.82
		Minimum	0.01	75.27	-21.71	-100.73	-0.13	35.27	-13.39	-62.65
		Average	0.18	162.26	-3.75	-54.87	0.15	160.15	-0.44	-39.71
		Standard deviation	0.13	52.31	11.33	20.69	0.07	21.37	6.56	9.20
	Site 10	Maximum	0.51	251.44	24.34	-1.08	0.37	174.64	14.66	-13.13
		Minimum	0.04	86.70	-18.00	-80.83	0.05	98.24	-11.59	-45.49
		Average	0.22	155.32	-0.42	-50.32	0.15	132.22	-3.97	-25.23
		Standard deviation	0.13	52.31	11.33	20.69	0.07	21.37	6.56	9.20
	Site 13	Maximum	0.50	171.29	25.69	-23.19	*	469.47	-47.05	74.35
		Minimum	0.14	100.22	-4.23	-63.25	*	348.80	-68.46	36.25
		Average	0.32	131.41	10.62	-37.05	*	405.80	-54.41	50.06
		Standard deviation	0.11	25.52	8.67	13.79	*	41.32	7.33	12.15

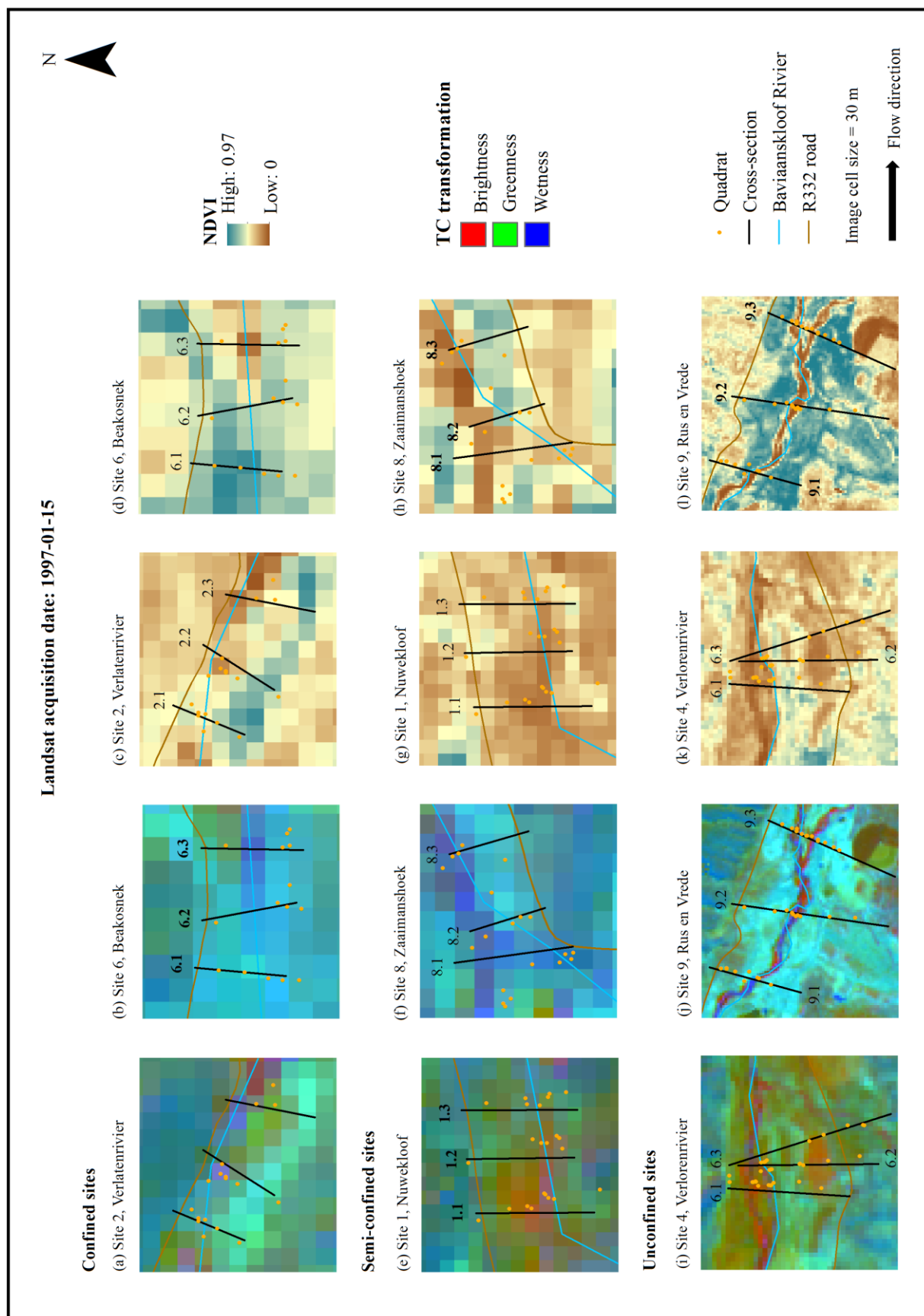
Appendix 5.6: NDVI and TC transformation summary statistics for the wet periods, Baviaanskloof.

Valley setting	Study site	Variable	Landsat acquisition date: 1997-01-15				Landsat acquisition date: 2003-02-12			
			NDVI	Brightness	Greenness	Wetness	NDVI	Brightness	Greenness	Wetness
Confined	Site 2	Maximum	0.61	197.98	50.94	-5.04	0.37	213.08	10.20	-84.17
		Minimum	0.15	106.30	5.05	-51.09	0.15	149.61	-6.43	-104.68
		Average	0.37	155.23	25.59	-28.10	0.25	184.05	1.32	-93.54
		Standard deviation	0.14	28.14	14.96	12.84	0.07	21.33	5.94	6.93
	Site 6	Maximum	0.74	162.60	53.77	10.18	0.80	146.91	58.94	-41.95
		Minimum	0.36	97.84	25.21	-36.86	0.38	117.02	9.48	-57.37
		Average	0.55	117.67	39.11	-6.98	0.64	137.34	37.16	-48.44
		Standard deviation	0.11	19.67	8.23	13.84	0.14	8.85	17.76	6.12
	Site 7	Maximum	0.43	120.76	16.03	-1.60	0.50	192.48	22.07	-56.03
		Minimum	0.06	23.15	-6.52	-41.28	0.25	142.52	7.58	-69.30
		Average	0.28	65.12	2.91	-18.11	0.36	166.75	14.10	-62.66
		Standard deviation	0.15	49.73	9.45	17.75	0.09	20.16	5.50	5.13
	Site 11	Maximum	0.56	166.27	42.29	-10.88	0.72	159.41	28.28	-62.87
		Minimum	0.03	118.11	-11.46	-44.70	0.23	118.21	-3.78	-83.56
		Average	0.40	145.55	28.25	-28.95	0.46	141.45	14.38	-70.34
		Standard deviation	0.14	13.57	14.60	9.25	0.12	13.11	8.98	6.90
Semi-confined	Site 1	Maximum	0.36	267.23	17.21	-22.74	0.35	277.68	4.11	-72.48
		Minimum	0.09	76.04	-8.39	-63.47	0.04	112.80	-18.34	-104.72
		Average	0.24	162.13	7.99	-41.95	0.14	192.70	-8.94	-91.28
		Standard deviation	0.08	52.73	7.83	11.47	0.08	45.39	5.71	11.63
	Site 3	Maximum	0.35	291.83	23.75	-34.95	0.29	241.24	5.86	-84.39
		Minimum	0.11	152.49	-7.84	-74.47	0.10	166.23	-10.76	-95.82
		Average	0.21	210.20	6.31	-53.09	0.19	198.28	-3.42	-89.18
		Standard deviation	0.11	55.51	13.10	14.79	0.08	32.73	6.14	4.93
	Site 8	Maximum	0.56	144.35	42.76	-3.38	0.78	165.93	42.77	-48.86
		Minimum	0.14	75.82	0.33	-19.30	0.27	119.74	-1.05	-86.13
		Average	0.37	124.80	22.84	-11.08	0.52	138.38	21.05	-66.15
		Standard deviation	0.14	19.81	14.80	5.12	0.17	11.40	16.61	11.69
	Site 12	Maximum	0.56	166.22	41.66	-14.15	0.78	155.93	41.42	-52.08
		Minimum	0.15	43.24	-1.41	-43.23	0.44	119.70	12.16	-78.48
		Average	0.36	126.30	20.96	-27.04	0.60	137.18	27.38	-64.27
		Standard deviation	0.14	33.67	15.78	8.59	0.10	12.65	10.83	9.19
Unconfined	Site 4	Maximum	0.47	274.15	36.90	-34.55	0.14	301.73	-6.22	-86.78
		Minimum	0.06	137.66	-18.27	-84.16	0.05	215.42	-22.12	-114.25
		Average	0.23	199.61	10.06	-56.48	0.09	253.24	-14.18	-99.77
		Standard deviation	0.11	36.71	15.06	13.87	0.02	25.35	3.94	8.44
	Site 5	Maximum	0.62	197.33	58.27	-17.45	0.21	251.08	-6.48	-79.62
		Minimum	0.12	136.20	-3.31	-71.70	0.06	178.78	-23.10	-113.08
		Average	0.28	164.56	14.34	-46.34	0.11	219.68	-12.96	-101.55
		Standard deviation	0.12	14.46	14.28	14.77	0.04	20.27	4.44	8.87
	Site 9	Maximum	0.77	210.86	68.77	8.68	0.74	250.32	24.85	-60.40
		Minimum	-0.01	89.45	-21.36	-71.20	0.06	104.25	-18.06	-116.36
		Average	0.41	148.33	27.14	-19.87	0.28	172.49	-2.05	-91.53
		Standard deviation	0.30	48.36	30.74	20.99	0.17	38.37	11.51	12.16
	Site 10	Maximum	0.76	277.23	59.96	11.79	0.69	254.87	29.06	-63.44
		Minimum	-0.02	101.20	-22.30	-68.40	0.06	128.66	-16.84	-111.44
		Average	0.32	162.43	15.63	-22.44	0.28	177.17	-1.15	-92.38
		Standard deviation	0.30	48.36	30.74	20.99	0.17	38.37	11.51	12.16
	Site 13	Maximum	0.64	162.87	54.24	-1.42	0.69	160.10	26.74	-59.68
		Minimum	0.24	119.78	13.96	-44.78	0.30	122.78	1.40	-88.56
		Average	0.52	136.61	38.93	-24.38	0.44	142.40	11.95	-74.52
		Standard deviation	0.12	14.40	11.56	12.04	0.11	11.16	8.08	9.81

Appendix 5.7: Colour composite images of NDVI and TC bands for quadrats at sites 1, 2, 4, 6, 8 and 9 during

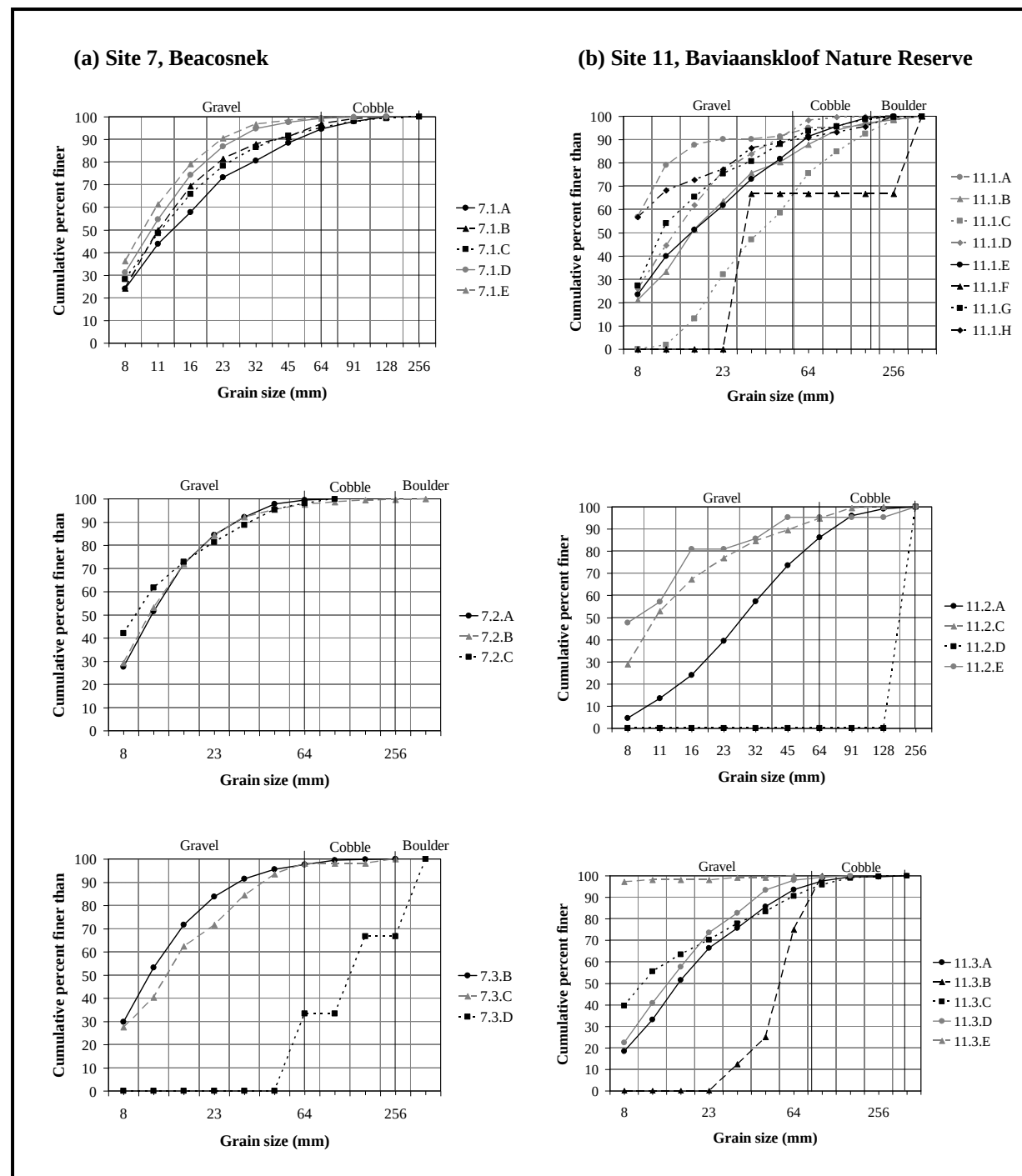


Appendix 5.8: Colour composite images of NDVI and TC bands for quadrats at sites 1, 2, 4, 6, 8 and 9 during a wet



Appendix 5.9: Grain size cumulative curves for coarse sediments, confined sites 7 and 11.

Quadrat codes and features as per Appendix 5.1.



Appendix 5.10: Grain size percentage data for coarse sediments, confined study sites.

FG = Fine gravel, MG = Medium gravel, CG = Coarse gravel, VCG = Very coarse gravel, SC = Small cobble, LC = Large cobble and B = Boulder. Quadrat codes and features as per Appendix 5.1. Excluded quadrats limited to fine sediments only.

Size class	FG	MG	MG	CG	CG	VCG	VCG	SC	SC	LC	B
Grain size, mm	8	11.3	16	22.6	32	45.3	64	90.5	128	256	>256
(phi-units)	(-3)	(-3.5)	(-4)	(-4.5)	(-5)	(-5.5)	(-6)	(-6.5)	(-7)	(-8)	(>-8)
2.1.A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	25.0	25.0	0.0
2.1.B	27.4	25.7	18.7	13.1	8.5	2.6	2.9	0.6	0.6	0.0	0.0
2.1.C	43.5	18.6	16.1	8.0	8.2	2.7	1.6	0.7	0.2	0.1	0.1
2.1.D	27.3	21.2	15.7	13.3	9.7	7.5	3.2	1.1	0.6	0.6	0.0
2.1.E	38.7	17.6	12.0	14.1	6.3	5.3	2.8	1.8	0.4	0.7	0.4
2.1.G	61.5	15.4	7.7	3.8	7.7	0.0	0.0	0.0	3.8	0.0	0.0
2.2.A	25.6	20.9	17.4	16.2	11.2	4.2	3.0	1.2	0.0	0.2	0.0
2.2.B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
2.2.C	48.3	13.8	13.8	4.1	7.6	4.1	3.4	3.4	0.0	0.0	1.4
2.2.D	34.2	22.8	26.6	6.3	5.1	3.8	1.3	0.0	0.0	0.0	0.0
2.2.E	50.7	10.9	14.5	4.3	3.6	5.1	4.3	3.6	2.2	0.7	0.0
2.2.F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0
2.2.G	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
2.3.A	4.8	29.4	22.2	13.5	10.3	9.5	5.6	3.2	0.8	0.8	0.0
2.3.B	38.6	16.3	17.1	7.7	9.3	5.7	3.3	0.8	0.8	0.4	0.0
2.3.C	33.8	21.8	20.3	13.6	5.4	2.3	1.8	0.5	0.3	0.3	0.0
2.3.D	45.5	0.0	27.3	9.1	9.1	9.1	0.0	0.0	0.0	0.0	0.0
2.3.E	81.6	10.2	4.1	0.0	0.0	0.0	0.0	2.0	2.0	0.0	0.0
2.3.F	39.4	22.3	12.8	16.0	3.2	4.3	0.0	1.1	1.1	0.0	0.0
6.1.B	0.0	0.0	0.0	0.0	0.0	25.0	0.0	0.0	25.0	25.0	25.0
6.1.C	21.4	16.1	17.1	17.5	11.5	9.7	4.6	1.5	0.5	0.2	0.0
6.2.A	18.8	27.1	17.3	10.8	14.4	5.8	5.1	0.4	0.4	0.0	0.0
6.2.B	44.3	19.4	11.6	11.1	3.0	5.5	2.8	1.7	0.3	0.0	0.3
6.2.C	31.3	21.0	13.1	6.8	10.2	8.5	5.7	2.3	1.1	0.0	0.0
6.2.D	0.0	0.0	0.0	21.4	28.6	21.4	14.3	14.3	0.0	0.0	0.0
6.2.E	20.9	15.0	12.6	17.5	11.7	8.3	7.3	4.4	1.5	1.0	0.0
6.2.F	21.7	0.0	8.7	6.5	8.7	10.9	19.6	8.7	15.2	0.0	0.0
6.3.A	0.0	0.0	0.0	0.0	16.7	33.3	0.0	0.0	0.0	16.7	33.3
6.3.B	0.0	0.0	14.3	28.6	14.3	0.0	21.4	21.4	0.0	0.0	0.0
6.3.C	21.9	18.1	16.7	14.0	14.0	9.6	3.2	1.4	0.9	0.2	0.0
6.3.D	0.0	0.0	0.0	0.0	0.0	0.0	33.3	33.3	33.3	0.0	0.0
6.3.E	14.3	8.2	10.2	8.2	10.2	12.2	16.3	10.2	6.1	4.1	0.0
6.3.F	29.6	24.7	18.5	6.2	2.5	7.4	6.2	1.2	2.5	1.2	0.0
7.1.A	24.0	19.8	14.0	15.3	7.4	7.9	6.2	3.3	2.1	0.0	0.0
7.1.B	24.2	25.8	19.4	12.1	6.5	3.2	5.6	2.4	0.8	0.0	0.0
7.1.C	28.2	20.4	17.3	12.4	8.3	5.0	3.5	2.9	1.2	0.8	0.0
7.1.D	31.3	23.4	19.5	12.7	7.8	2.7	1.8	0.6	0.2	0.0	0.0
7.1.E	36.3	25.0	17.9	11.4	6.0	1.8	1.0	0.7	0.0	0.0	0.0
7.2.A	27.5	23.9	20.6	12.4	7.8	5.5	1.8	0.5	0.0	0.0	0.0
7.2.B	29.3	23.9	18.8	12.4	7.8	3.2	2.2	1.1	0.8	0.3	0.3
7.2.C	42.1	19.6	11.2	8.4	7.5	6.5	2.8	1.9	0.0	0.0	0.0
7.3.B	29.7	23.5	18.4	12.2	7.7	4.1	2.1	1.9	0.2	0.2	0.0
7.3.C	27.5	12.8	22.0	9.2	12.8	9.2	4.6	0.0	0.0	1.8	0.0
7.3.D	0.0	0.0	0.0	0.0	0.0	0.0	33.3	0.0	33.3	0.0	33.3
11.1.A	56.8	22.2	8.6	2.5	0.0	1.2	3.7	0.0	1.2	2.5	1.2
11.1.B	21.2	12.1	18.2	12.1	12.1	4.5	7.6	6.1	3.0	1.5	1.5
11.1.C	0.0	1.9	11.3	18.9	15.1	11.3	17.0	9.4	7.5	5.7	1.9
11.1.D	25.9	18.7	17.2	14.7	7.2	6.9	7.7	1.3	0.2	0.2	0.0
11.1.E	23.5	16.5	11.3	10.4	11.3	8.7	9.6	4.3	3.5	0.9	0.0
11.1.F	0.0	0.0	0.0	0.0	66.7	0.0	0.0	0.0	0.0	0.0	33.3
11.1.G	27.3	26.7	11.3	10.0	5.3	7.3	5.7	2.0	3.0	1.0	0.3

Size class	FG	MG	MG	CG	CG	VCG	VCG	SC	SC	LC	B
Grain size, mm	8	11.3	16	22.6	32	45.3	64	90.5	128	256	>256
(phi-units)	(-3)	(-3.5)	(-4)	(-4.5)	(-5)	(-5.5)	(-6)	(-6.5)	(-7)	(-8)	(>-8)
11.1.H	56.8	11.4	4.5	4.5	9.1	2.3	2.3	2.3	2.3	4.5	0.0
11.2.A	4.5	8.9	10.6	15.4	17.9	16.3	12.6	9.8	3.3	0.8	0.0
11.2.C	28.8	24.0	14.4	9.6	7.7	4.8	5.3	4.8	0.5	0.0	0.0
11.2.D	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
11.2.E	47.6	9.5	23.8	0.0	4.8	9.5	0.0	0.0	0.0	4.8	0.0
11.3.A	18.3	14.9	18.3	14.9	9.4	9.9	7.9	4.0	2.0	0.0	0.5
11.3.B	0.0	0.0	0.0	0.0	12.5	12.5	50.0	25.0	0.0	0.0	0.0
11.3.C	39.6	15.8	7.9	6.8	7.5	5.7	7.2	5.3	3.0	0.8	0.4
11.3.D	22.4	18.3	16.9	15.8	9.2	10.7	4.6	1.3	0.7	0.0	0.0
11.3.E	97.2	0.9	0.0	0.0	0.9	0.0	0.9	0.0	0.0	0.0	0.0

Appendix 5.11: Coarse sediment summary statistics for confined study sites.

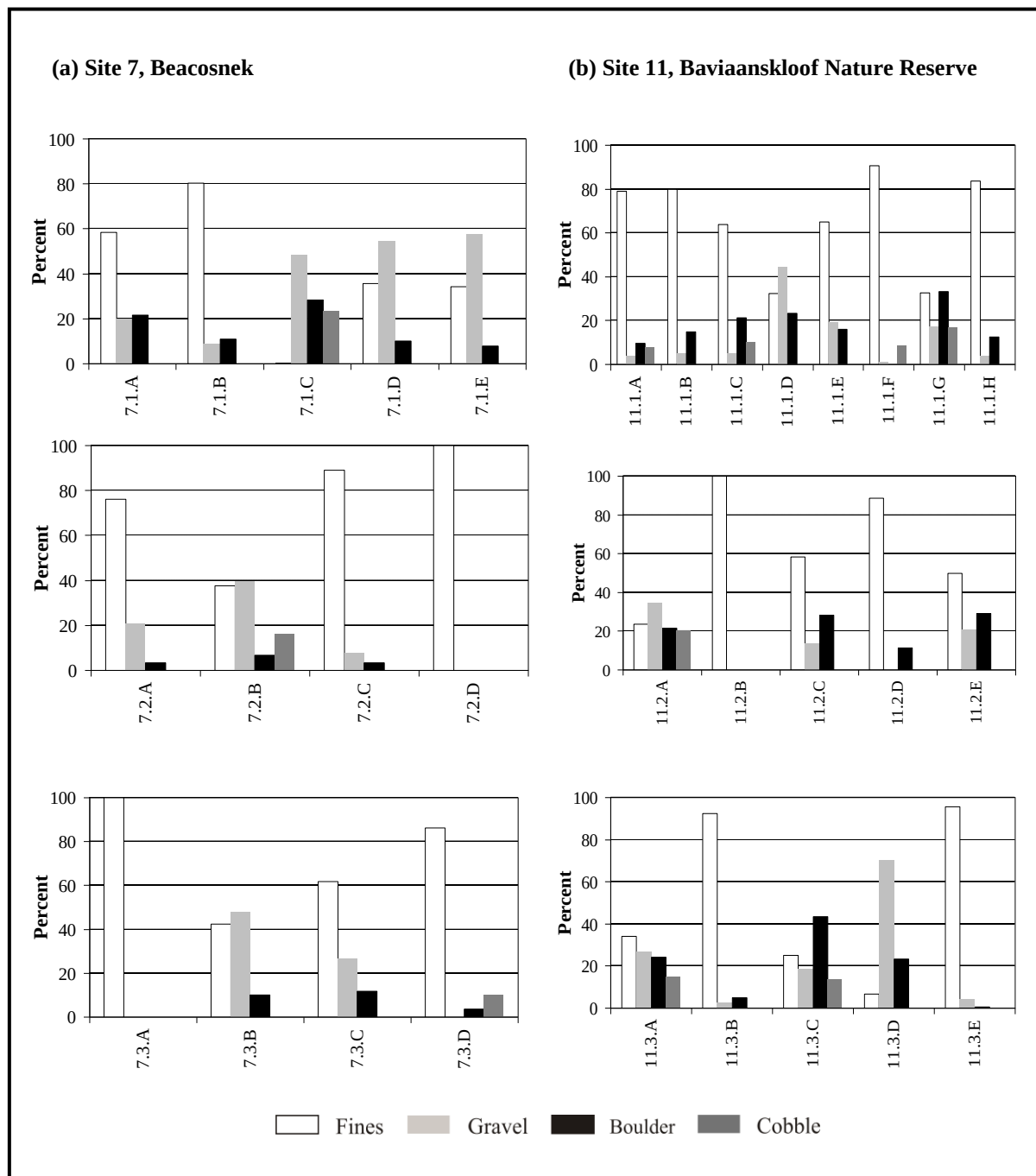
After Bunte and Abt (2001), Kondolf *et al.* (2003) and Mecklenburg (2006). Quadrat codes and features as per Appendix 5.1. Excluded quadrats limited to fine sediments only. Abbreviations (descriptions) from Blott and Pye (2001) and representing the following: VWS = Very well sorted, WS= Well sorted, MWS = Moderately well sorted, MS = Moderately sorted, PS = Poorly sorted, VPS = Very poorly sorted, VFS = Very fine skewed, FS = Fine skewed, S = Symmetrical, CS = Coarse skewed and VCS = Very coarse skewed.

Quadrat	Percentile values (mm)					Geometric method (mm)		
	D ₁₆	D ₃₅	Median or D ₅₀	D ₈₄	D ₉₅	Mean	Sorting	Skewness
2.1.A	71	81	90	200	240	119.16	1.74, MS	0.18, CS
2.1.B	7.1	8.8	11	22	40	12.50	1.77, MS	0.08, S
2.1.C	6.7	7.6	8.9	20	34	11.58	1.79, MS	0.17, CS
2.1.D	7.1	9	11	28	47	14.10	2.05, PS	0.14, CS
2.1.E	6.8	7.8	9.8	24	51	12.77	1.95, MS	0.16, CS
2.1.G	6.5	7.1	7.6	16	30	10.20	1.64, MS	0.2, CS
2.2.A	7.2	9.2	12	25	43	13.42	1.88, MS	0.07, S
2.2.B	270	290	300	340	360	302.99	1.12, VWS	0.01, S
2.2.C	6.6	7.4	8.3	27	63	13.35	2.26, PS	0.26, CS
2.2.D	6.9	8.1	10	16	32	10.51	1.52, MWS	0.04, S
2.2.E	6.6	7.3	8	32	74	14.53	2.61, PS	0.31, VCS
2.2.F	270	290	300	340	360	302.99	1.12, VWS	0.01, S
2.2.G	48	51	54	60	63	53.67	1.12, VWS	-0.01, S
2.3.A	9	11	14	37	63	18.25	2.1, PS	0.15, CS
2.3.B	6.8	7.8	10	26	46	13.30	2.04, PS	0.16, CS
2.3.C	6.9	8.1	10	19	33	11.45	1.67, MS	0.09, S
2.3.D	6.6	7.5	12	24	37	12.59	1.91, MS	0.03, S
2.3.E	6.3	6.8	7.2	8.6	15	7.36	1.17, VWS	0.03, S
2.3.F	6.7	7.7	9.3	19	36	11.28	1.72, MS	0.12, CS
6.1.B	40	100	130	290	340	107.70	2.74, PS	-0.09, S
6.1.C	7.4	10	14	32	51	15.39	2.09, PS	0.05, S
6.2.A	7.7	9.7	12	29	48	14.94	1.99, MS	0.13, CS
6.2.B	6.7	7.5	8.8	21	45	11.86	1.85, MS	0.18, CS
6.2.C	7	8.5	11	34	58	15.43	2.33, PS	0.18, CS
6.2.D	20	26	32	61	80	34.93	1.75, MS	0.05, S
6.2.E	7.5	11	16	42	74	17.75	2.38, PS	0.05, S
6.2.F	7.4	20	37	87	110	25.37	3.68, PS	-0.16, FS
6.3.A	32	39	45	310	340	99.60	4.15, VPS	0.35, VCS
6.3.B	16	20	27	70	83	33.47	2.14, PS	0.12, CS
6.3.C	7.4	10	14	31	48	15.15	2.05, PS	0.04, S
6.3.D	53	65	76	110	120	76.35	1.44, MWS	0, S
6.3.E	8.6	18	31	74	120	25.23	3, PS	-0.09, S
6.3.F	7	8.6	10	36	64	15.87	2.51, PS	0.24, CS
7.1.A	7.3	9.6	13	37	67	16.43	2.31, PS	0.12, CS
7.1.B	7.3	9.1	11	26	57	13.78	1.94, MS	0.13, CS
7.1.C	7.1	8.9	11	28	63	14.10	2.05, PS	0.14, CS
7.1.D	7	8.4	10	20	33	11.83	1.71, MS	0.11, CS

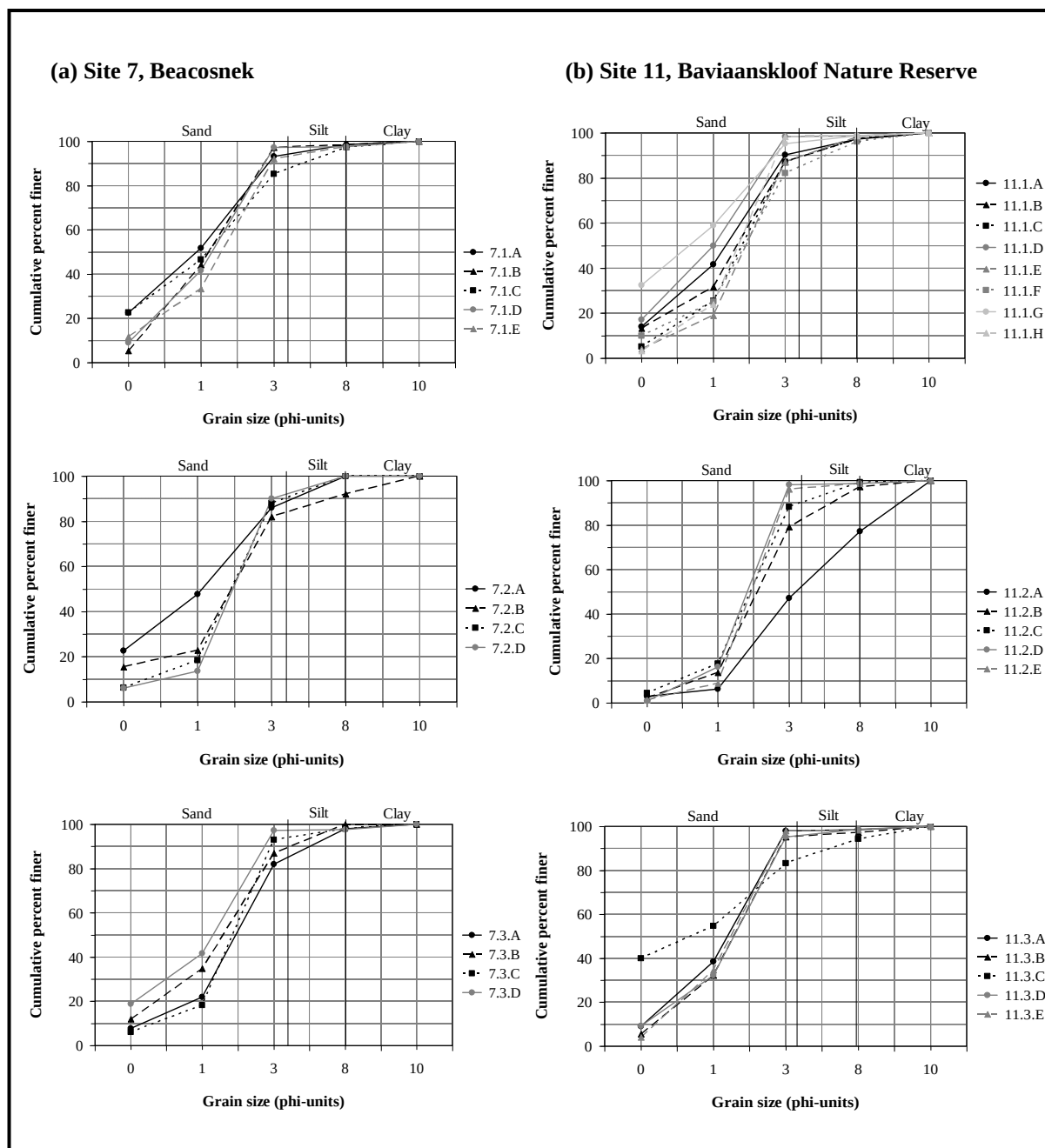
Quadrat	Percentile values (mm)					Geometric method (mm)		
	D ₁₆	D ₃₅	Median or D ₅₀	D ₈₄	D ₉₅	Mean	Sorting	Skewness
7.1.E	6.8	7.9	9.5	18	29	11.06	1.65, MS	0.1, CS
7.2.A	7.1	8.8	11	22	38	12.50	1.77, MS	0.08, S
7.2.B	7	8.6	11	22	43	12.41	1.79, MS	0.07, S
7.2.C	6.7	7.6	9.1	25	44	12.94	2.05, PS	0.2, CS
7.3.B	7	8.6	11	22	43	12.41	1.79, MS	0.07, S
7.3.C	7.1	9.6	13	32	50	15.07	2.15, PS	0.08, S
7.3.D	53	92	110	310	340	128.18	2.45, PS	0.08, S
11.1.A	6.5	7.2	7.7	14	64	9.54	1.5, MWS	0.16, CS
11.1.B	7.5	11	16	53	100	19.94	2.72, PS	0.1, CS
11.1.C	17	24	35	87	210	38.46	2.27, PS	0.05, S
11.1.D	7.2	9.3	12	32	55	15.18	2.17, PS	0.13, CS
11.1.E	7.3	10	15	49	86	18.91	2.66, PS	0.11, CS
11.1.F	24	27	29	310	340	86.26	5.95, VPS	0.45, VCS
11.1.G	7.1	8.8	10	37	80	16.21	2.55, PS	0.25, CS
11.1.H	6.5	7.2	7.7	29	120	13.73	2.48, PS	0.31, VCS
11.2.A	12	20	27	60	87	26.83	2.24, PS	0, S
11.2.C	7	8.7	11	31	65	14.73	2.19, PS	0.16, CS
11.2.D	190	200	210	240	250	213.54	1.12, VWS	0.02, S
11.2.E	6.6	7.4	8.7	28	45	13.59	2.27, PS	0.24, CS
11.3.A	7.7	11	16	43	72	18.20	2.38, PS	0.06, S
11.3.B	35	48	54	72	84	50.20	1.44, MWS	-0.06, S
11.3.C	6.7	7.7	9.9	46	85	17.56	3.06, PS	0.27, CS
11.3.D	7.4	10	13	33	51	15.63	2.15, PS	0.1, CS
11.3.E	6.3	6.7	7	7.7	7.9	6.96	1.11, VWS	-0.01, S

Appendix 5.12: Grain size percentage visual estimates for geomorphic landforms, confined sites 7 and 11.

Quadrat codes and features as per Appendix 5.1.



Appendix 5.13: Grain size cumulative curves for fine sediments, confined sites 7 and 11.
 Quadrat codes and features as per Appendix 5.1.



Appendix 5.14: Grain size percentage data for fine sediments, Baviaanskloof.

C = Clay, S = Silt, FS = Fine sand, MS = Medium sand and CS = Coarse sand. Quadrat codes and features as per Appendix 5.1.

Confined study sites						Semi-confined study sites						Unconfined study sites					
Size class	CS	MS	FS	S	C	Size class	CS	MS	FS	S	C	Size class	CS	MS	FS	S	C
Grain size (phi-units)	0	1	3	8	10	Grain size (phi-units)	0	1	3	8	10	Grain size (phi-units)	0	1	3	8	10
2.1.A	5.2	21.6	70.2	1.8	1.2	1.1.A	5.0	29.2	63.8	0.0	2.0	4.1.A	8.2	7.2	74.6	8.0	2.0
2.1.B	5.4	38.4	52.2	3.0	1.0	1.1.B	7.2	50.7	39.7	0.2	2.2	4.1.B	8.0	29.2	56.8	4.0	2.0
2.1.C	50.0	36.5	10.7	1.4	1.4	1.1.C	12.4	32.8	52.4	0.2	2.2	4.1.C	8.8	34.6	52.6	2.0	2.0
2.1.D	46.3	32.3	20.1	0.2	1.2	1.1.D	37.4	42.7	16.7	0.6	2.6	4.1.D	7.0	35.6	51.4	6.0	0.0
2.1.E	2.8	31.5	64.3	0.2	1.2	1.1.E	1.2	16.9	77.9	2.0	2.0	4.1.E	11.8	43.4	42.4	0.2	2.2
2.1.F	1.1	17.7	79.9	0.2	1.2	1.1.F	22.7	53.6	20.5	0.6	2.6	4.1.F	27.4	55.0	15.0	0.2	2.4
2.1.G	4.2	21.0	63.8	10.0	1.0	1.1.G	4.6	27.0	60.4	6.0	2.0	4.1.G	7.5	50.2	39.9	0.2	2.2
2.2.A	5.4	36.8	56.4	0.2	1.2	1.1.H	15.2	18.6	60.2	4.0	2.0	4.1.H	7.3	50.0	40.3	0.2	2.2
2.2.B	2.0	15.0	74.0	8.0	1.0	1.1.I	20.0	20.6	53.4	6.0	0.0	4.1.I	4.4	42.8	50.8	0.0	2.0
2.2.C	70.4	22.4	5.4	0.4	1.4	1.2.A	8.4	39.4	50.2	0.0	2.0	4.1.J	5.5	42.0	48.1	2.2	2.2
2.2.D	26.8	42.4	29.0	0.4	1.4	1.2.B	13.6	23.2	61.2	0.0	2.0	4.1.K	7.2	35.2	55.2	0.2	2.2
2.2.E	8.6	45.0	44.6	0.4	1.4	1.2.C	7.4	45.2	45.4	0.0	2.0	4.1.L	8.4	26.9	56.7	6.0	2.0
2.2.F	1.3	8.0	88.9	0.4	1.4	1.2.D	45.4	44.0	8.2	0.2	2.2	4.2.A	20.8	29.0	44.2	4.0	2.0
2.2.G	7.6	20.0	61.4	10.0	1.0	1.2.E	23.0	48.8	25.4	0.4	2.4	4.2.B	2.0	31.2	64.8	0.0	2.0
2.3.A	2.0	31.6	65.0	0.2	1.2	1.2.F	1.6	10.2	82.2	6.0	0.0	4.2.C	17.4	54.2	26.0	0.2	2.2
2.3.B	48.0	37.7	12.5	0.4	1.4	1.2.G	30.4	16.0	49.6	2.0	2.0	4.2.D	69.7	22.4	3.9	2.0	2.0
2.3.C	74.7	20.4	3.3	0.2	1.4	1.3.A	15.2	48.2	32.6	2.0	2.0	4.2.E	6.0	21.2	68.8	2.0	2.0
2.3.D	2.8	24.6	67.6	3.8	1.2	1.3.B	7.7	38.0	50.3	2.0	2.0	4.2.F	8.6	37.2	42.2	8.0	4.0
2.3.E	15.1	42.2	41.3	0.2	1.2	1.3.C	13.6	33.4	51.0	0.0	2.0	4.2.G	8.0	4.6	83.4	2.0	2.0
2.3.F	4.8	44.7	48.5	0.8	1.2	1.3.D	17.6	52.0	29.0	0.2	1.2	4.2.H	5.0	21.6	65.4	8.0	0.0
6.1.A	5.4	5.6	67.4	19.2	2.4	1.3.E	30.8	51.1	16.5	0.2	1.4	4.2.I	8.0	40.2	48.4	1.2	2.2
6.1.B	21.2	32.5	37.5	8.0	0.8	1.3.F	1.3	7.3	70.5	14.0	7.0	4.2.J	10.2	27.3	58.7	3.0	0.8
6.1.C	58.0	30.6	9.4	0.6	1.4	1.3.G	6.6	26.3	63.1	2.8	1.2	4.3.A	4.2	52.2	42.0	0.4	1.2
6.1.D	4.6	8.6	73.9	11.6	1.2	3.1.A	10.0	22.4	58.6	8.0	1.0	4.3.B	22.0	50.6	24.8	1.2	1.4
6.1.E	1.4	2.0	85.8	10.0	0.8	3.1.B	36.8	28.0	34.2	0.0	1.0	4.3.C	66.9	27.1	4.5	0.2	1.4
6.1.F	2.8	12.0	80.3	3.6	1.2	3.1.C	22.8	49.4	26.0	0.4	1.4	4.3.D	14.0	39.2	45.2	0.4	1.2
6.2.A	6.6	40.5	48.1	3.6	1.2	3.1.D	29.2	39.0	30.0	0.4	1.4	4.3.E	7.4	29.4	60.4	1.6	1.2
6.2.B	54.2	21.2	21.8	1.6	1.2	3.1.E	21.6	53.3	23.3	0.4	1.4	4.3.F	9.2	33.2	55.6	0.6	1.4
6.2.C	3.8	32.0	62.2	0.4	1.6	3.1.F	20.0	40.4	37.8	0.4	1.4	4.3.G	17.6	45.1	35.7	0.4	1.2
6.2.D	2.7	24.8	69.7	1.4	1.4	3.1.G	9.1	43.7	42.9	2.2	2.2	4.3.H	19.0	29.2	47.9	2.4	1.4
6.2.E	7.4	13.6	70.2	8.0	0.8	3.2.A	70.8	17.8	7.4	2.0	2.0	4.3.I	21.6	36.0	40.4	0.6	1.4
6.2.F	10.8	22.2	54.2	11.6	1.2	3.2.B	4.4	34.6	57.0	2.0	2.0	5.1.A	3.2	21.6	71.4	2.6	1.2
6.3.A	2.2	17.6	77.4	1.6	1.2	3.2.C	8.6	47.2	40.2	2.0	2.0	5.1.B	3.6	20.4	71.2	3.6	1.2
6.3.B	4.4	20.9	67.9	5.6	1.2	3.2.D	31.2	41.8	24.6	0.2	2.2	5.1.C	14.4	40.8	42.8	0.6	1.4
6.3.C	14.0	34.8	37.4	13.0	0.8	3.3.A	6.1	36.5	53.5	2.0	2.0	5.1.D	16.9	64.8	16.7	0.2	1.4
6.3.D	6.5	28.2	58.5	5.6	1.2	3.3.B	24.6	38.6	34.0	0.4	2.4	5.1.E	18.4	70.2	9.0	0.6	1.8
6.3.E	10.0	30.5	52.7	5.6	1.2	3.3.C	8.2	56.3	31.5	2.0	2.0	5.1.F	10.4	34.6	53.0	0.6	1.4
6.3.F	7.6	24.9	62.7	3.4	1.4	3.3.D	18.6	45.1	32.3	2.0	2.0	5.1.G	13.6	31.6	53.2	0.4	1.2
7.1.A	22.4	29.4	41.4	5.4	1.4	8.1.A	39.1	15.0	43.5	0.2	2.2	5.1.H	8.2	26.0	61.0	4.0	0.8
7.1.B	5.4	38.8	53.0	1.4	1.4	8.1.B	6.0	26.7	62.9	2.2	2.2	5.1.I	49.6	33.6	15.2	0.2	1.4
7.1.C	22.6	24.0	38.6	12.0	2.8	8.1.C	8.2	23.6	65.8	0.2	2.2	5.1.J	17.8	27.0	52.4	1.4	1.4
7.1.D	9.0	32.6	55.6	0.4	2.4	8.1.D	3.2	44.8	49.6	0.2	2.2	5.2.A	20.0	26.6	51.8	0.4	1.2
7.1.E	11.8	21.6	58.6	5.6	2.4	8.1.E	2.2	24.2	71.2	0.2	2.2	5.2.B	12.9	50.8	34.7	0.2	1.4
7.2.A	22.6	25.1	38.3	14.0	0.0	8.1.F	9.7	27.0	59.3	1.8	2.2	5.2.C	47.1	36.8	14.1	0.4	1.6
7.2.B	15.4	7.4	59.2	10.0	8.0	8.1.G	35.2	18.9	35.9	10.0	0.0	5.2.D	9.0	38.6	49.6	1.6	1.2
7.2.C	6.3	12.2	69.5	12.0	0.0	8.1.H	0.6	16.0	79.0	2.2	2.2	5.2.E	13.0	52.9	32.1	0.6	1.4
7.2.D	6.0	7.7	76.3	10.0	0.0	8.1.I	7.2	25.3	63.1	2.2	2.2	5.2.F	17.2	41.6	39.4	0.4	1.4
7.3.A	7.7	14.2	60.1	16.0	2.0	8.2.A	10.6	45.0	41.6	0.4	2.4	5.2.G	10.6	29.7	57.7	0.6	1.4
7.3.B	12.0	22.9	52.1	13.0	0.0	8.2.B	4.0	33.0	59.0	2.0	2.0	5.3.A	21.4	48.2	28.4	0.4	1.6
7.3.C	6.0	12.2	74.8	5.0	2.0	8.2.C	30.6	40.0	25.4	2.0	2.0	5.3.B	12.4	23.4	61.4	1.6	1.2
7.3.D	18.8	22.8	55.6	0.4	2.4	8.2.D	14.4	37.2	44.4	2.0	2.0	5.3.C	5.4	11.4	78.4	3.6	1.2
11.1.A	14.0	27.6	48.6	7.0	2.8	8.2.E	2.6	29.4	65.6	0.2	2.2	5.3.D	9.2	30.6	57.6	1.2	1.4
11.1.B	13.2	18.4	55.6	10.0	2.8	8.2.F	3.0	10.0	83.0	1.8	2.2	5.3.E	18.4	23.6	55.2	1.6	1.2
11.1.C	5.2	20.2	61.8	10.0	2.8	8.2.G	4.0	28.0	65.2	0.4	2.4	5.3.F	51.4	34.4	12.2	0.4	1.6
11.1.D	17.2	32.8	48.4	0.4	1.2	8.3.A	13.4	25.6	53.0	6.0	2.0	5.3.G	9.4	15.0	72.8	1.4	1.4
11.1.E	4.0	15.0	68.2	11.0	1.8	8.3.B	38.5	32.9	26.7	0.0	2.0	5.3.H	3.2	20.8	73.2	1.6	1.2
11.1.F	10.0	15.1	57.1	14.0	3.8	8.3.C	0.4	11.2	84.4	1.6	2.4	5.3.I	7.2	18.0	72.0	1.6	1.2
11.1.G	32.4	26.6	36.2	3.6	1.2	8.3.D	1.6	29.4	67.0	1.0	1.0	5.3.J	10.2	14.8	71.2	2.4	1.4
11.1.H	3.4	20.5	74.5	0.4	1.2	8.3.E	10.0	34.8	46.2	6.6	2.4	5.3.K	46.8	22.0	29.4	0.2	1.6
11.2.A	3.0	3.2	41.0	30.0	22.8	8.3.F	2.6	16.4	79.0	0.4	1.6	9.1.A	18.0	19.6	59.4	1.0	2.0
11.2.B	2.2	11.4	65.6	18.0	2.8	12.1.A	5.0	10.0	74.2	9.6	1.2	9.1.B	25.0	33.6	37.0	2.2	2.2
11.2.C	4.4	13.2	70.6	11.0	0.8	12.1.B	63.0	12.6	17.6	5.6	1.2	9.1.C	14.8	24.6	57.6	2.0	1.0

Confined study sites						Semi-confined study sites						Unconfined study sites					
Size class	CS	MS	FS	S	C	Size class	CS	MS	FS	S	C	Size class	CS	MS	FS	S	C
Grain size (phi-units)	0	1	3	8	10	Grain size (phi-units)	0	1	3	8	10	Grain size (phi-units)	0	1	3	8	10
11.2.D	0.9	15.4	81.9	0.6	1.2	12.1.C	12.2	41.4	39.6	5.6	1.2	9.1.D	21.2	5.0	63.8	10.0	0.0
11.2.E	1.2	7.7	87.3	2.6	1.2	12.1.D	10.6	46.2	41.6	0.2	1.4	9.1.E	4.2	25.2	67.6	1.0	2.0
11.3.A	9.0	29.4	59.6	0.6	1.4	12.1.E	10.1	16.6	66.5	6.0	0.8	9.1.F	14.8	34.0	49.2	0.0	2.0
11.3.B	5.6	26.6	63.0	2.0	2.8	12.1.F	5.6	22.0	70.4	0.6	1.4	9.1.G	16.8	10.0	43.1	24.0	6.0
11.3.C	40.0	14.7	28.5	11.0	5.8	12.2.A	6.6	12.7	65.9	12.0	2.8	9.1.H	0.8	14.2	81.0	2.0	2.0
11.3.D	9.2	23.0	62.9	3.6	1.2	12.2.B	2.6	6.0	82.6	8.0	0.8	9.1.I	2.6	4.2	90.2	3.0	0.0
11.3.E	4.0	30.6	63.4	0.4	1.6	12.2.C	27.6	22.6	42.6	6.4	0.8	9.1.J	13.6	6.4	77.6	0.2	2.2
						12.2.D	4.0	21.0	73.2	0.6	1.2	9.2.A	1.1	10.2	78.7	8.0	2.0
						12.2.E	5.2	42.0	50.8	0.6	1.4	9.2.B	10.4	7.6	52.0	20.0	10.0
						12.2.F	15.0	30.2	49.0	5.0	0.8	9.2.C	1.4	15.0	81.6	1.0	1.0
						12.3.A	6.8	35.6	39.8	15.0	2.8	9.2.D	8.0	21.0	68.6	0.2	2.2
						12.3.B	1.7	6.9	57.8	32.0	1.6	9.2.E	69.6	16.6	11.8	0.0	2.0
						12.3.C	2.4	10.0	67.8	16.0	3.8	9.2.F	3.1	22.9	70.1	2.0	2.0
						12.3.D	4.0	12.0	81.2	1.6	1.2	9.2.G	6.2	37.8	53.2	0.4	2.4
						12.3.E	21.2	40.2	37.0	0.2	1.4	9.2.H	12.0	32.6	53.0	0.2	2.2
												9.2.I	0.6	4.9	91.1	1.2	2.2
												9.2.J	0.4	1.0	92.5	6.0	0.0
												9.2.K	12.6	25.0	58.0	2.2	2.2
												9.2.L	5.0	13.2	69.8	10.0	2.0
												9.3.A	8.7	11.6	74.9	2.4	2.4
												9.3.B	11.0	37.3	47.3	2.2	2.2
												9.3.C	2.6	22.8	71.2	1.2	2.2
												9.3.D	4.4	15.0	74.6	6.0	0.0
												9.3.E	8.2	27.5	62.3	0.0	2.0
												9.3.F	1.0	17.6	71.4	10.0	0.0
												9.3.G	0.6	10.0	84.4	5.0	0.0
												9.3.H	6.8	31.4	58.8	2.0	1.0
												9.3.I	59.0	35.6	3.0	0.2	2.2
												9.3.J	5.4	23.6	69.0	0.0	2.0
												9.3.K	2.8	2.4	73.8	17.0	4.0
												9.3.L	9.7	19.3	65.0	6.0	0.0
												9.3.M	5.2	12.8	70.0	10.0	2.0
												10.1.A	4.0	37.2	56.8	0.0	2.0
												10.1.B	17.4	43.2	35.0	2.2	2.2
												10.1.C	4.0	41.6	51.6	0.4	2.4
												10.1.D	58.8	25.2	12.0	2.0	2.0
												10.1.E	1.1	14.6	80.3	3.0	1.0
												10.1.F	4.2	16.5	75.3	2.0	2.0
												10.1.G	29.6	34.0	33.6	0.4	2.4
												10.1.H	14.0	25.3	58.7	0.0	2.0
												10.1.I	11.6	20.0	64.4	2.0	2.0
												10.1.J	5.2	10.9	77.9	6.0	0.0
												10.2.A	4.0	27.4	56.6	12.0	0.0
												10.2.B	7.0	36.0	54.2	0.4	2.4
												10.2.C	10.9	32.2	54.5	0.2	2.2
												10.2.D	17.6	37.2	43.2	0.0	2.0
												10.2.E	3.0	19.2	74.7	0.8	2.2
												10.2.F	5.2	26.8	64.0	2.0	2.0
												10.2.G	4.2	7.6	80.2	8.0	0.0
												10.2.H	2.0	5.2	86.8	6.0	0.0
												10.2.I	5.0	10.4	76.6	8.0	0.0
												10.2.J	6.3	35.6	53.7	2.2	2.2
												10.2.K	3.0	10.0	82.2	3.6	1.2
												10.3.A	23.6	37.2	37.6	0.2	1.4
												10.3.B	32.6	25.5	40.1	1.6	0.2
												10.3.C	0.6	1.2	86.4	11.0	0.8
												10.3.D	66.7	18.8	10.7	3.0	0.8
												10.3.E	2.8	8.4	77.0	11.0	0.8
												10.3.F	11.1	34.2	52.7	0.6	1.4
												10.3.G	4.3	22.6	71.5	0.4	1.2
												10.3.H	9.2	30.0	57.8	1.0	2.0
												10.3.I	18.0	19.6	59.4	1.0	2.0
												13.1.A	12.0	15.2	56.0	14.0	2.8
												13.1.B	12.0	19.6	59.6	8.0	0.8
												13.1.C	2.0	34.0	62.0	0.6	1.4
												13.1.D	13.4	27.7	48.1	8.0	2.8
												13.1.E	23.2	35.4	38.6	1.6	1.2
												13.1.F	3.2	16.0	79.2	0.2	1.4
												13.2.A	3.4	20.0	62.8	11.0	2.8
												13.2.B	14.4	47.4	34.4	2.6	1.2

Confined study sites						Semi-confined study sites						Unconfined study sites					
Size class	CS	MS	FS	S	C	Size class	CS	MS	FS	S	C	Size class	CS	MS	FS	S	C
Grain size (phi-units)	0	1	3	8	10	Grain size (phi-units)	0	1	3	8	10	Grain size (phi-units)	0	1	3	8	10
												13.2.C	8.6	16.6	46.0	20.0	8.8
												13.2.D	1.2	16.4	79.6	1.6	1.2
												13.2.E	16.0	23.6	56.6	2.6	1.2
												13.2.F	5.1	31.1	61.9	0.6	1.4
												13.2.G	3.4	13.2	78.6	4.0	0.8
												13.3.A	6.0	5.6	85.6	1.4	1.4
												13.3.B	10.2	8.4	59.8	20.0	1.6
												13.3.C	10.2	19.3	49.7	18.0	2.8
												13.3.D	35.4	34.7	25.1	3.6	1.2
												13.3.E	2.7	22.2	72.3	1.6	1.2
												13.3.F	2.0	18.4	72.8	6.0	0.8

Appendix 5.15: Fine sediment summary statistics for confined study sites.

After Bunte and Abt (2001), Kondolf *et al.* (2003) and Mecklenburg (2006). Quadrat codes and features as per Appendix 5.1. Abbreviations represent the following: VWS = Very well sorted, WS= Well sorted, MWS = Moderately well sorted, MS = Moderately sorted, PS = Poorly sorted, VPS = Very poorly sorted, EPS = Extremely poorly sorted, VFS = Very fine skewed, FS = Fine skewed, S = Symmetrical, CS = Coarse skewed, VCS = Very coarse skewed, VP = Very platykurtic, P = Platykurtic, M = Mesokurtic, L = Leptokurtic, VL = Very leptokurtic and EL = Extremely leptokurtic.

Quadrat	Percentile values (phi-units)					Folk and Ward method (phi-units)				
	Φ_{10}	Φ_{16}	Median or Φ_{50}	Φ_{84}	Φ_{90}	Mean	Mode	Sorting	Skewness	Kurtosis
2.1.A	0.22	0.50		2.63	2.80	1.60	Unimodal	0.98, MS	-0.11, CS	0.83, P
2.1.B	0.12	0.28	1.66	2.54	2.77	1.35	Unimodal	1.02, PS	0.15, FS	0.73, P
2.1.C	-0.39	-0.93	1.24	0.93	1.66	0.20	Unimodal	0.77, MS	0.59, VFS	1.34, L
2.1.D	-0.38	-0.94	0.00	1.54	2.14	0.45	Unimodal	0.93, MS	0.59, VFS	1.13, L
2.1.E	0.23	0.42	0.12	2.55	2.73	1.48	Unimodal	0.96, MS	-0.01, S	0.74, P
2.1.F	0.51	0.85	1.49	2.63	2.78	1.75	Unimodal	0.85, MS	-0.1, CS	0.88, P
2.1.G	0.28	0.56	1.78	2.84	3.50	1.73	Unimodal	1.47, PS	0.17, FS	1.55, VL
2.2.A	0.12	0.29	1.78	2.48	2.69	1.35	Unimodal	0.99, MS	0.1, S	0.73, P
2.2.B	0.53	0.93	1.28	2.81	2.97	1.88	Unimodal	1.27, PS	0.17, FS	1.6, VL
2.2.C	-0.42	-2.43	1.89	-2.26	0.88	0.03	Unimodal	0.59, MWS	0.62, VFS	1.79, VL
2.2.D	-0.30	-0.25	-0.14	2.02	2.43	0.79	Unimodal	1.04, PS	0.37, VFS	0.91, M
2.2.E	0.03	0.16	0.55	2.36	2.63	1.15	Unimodal	1.01, PS	0.29, FS	0.79, P
2.2.F	1.02	1.15	0.92	2.68	2.82	1.92	Unimodal	0.76, MS	-0.09, S	0.9, P
2.2.G	0.12	0.42	1.92	2.84	3.50	1.66	Unimodal	1.54, PS	0.15, FS	1.5, VL
2.3.A	0.25	0.44	1.73	2.55	2.74	1.50	Unimodal	0.95, MS	-0.01, S	0.74, P
2.3.B	-0.38	-0.85	1.50	0.74	1.69	0.23	Unimodal	0.76, MS	0.54, VFS	1.26, L
2.3.C	-0.42	-2.88	0.05	0.46	0.75	-0.03	Unimodal	0.43, WS	0.53, VFS	1.75, VL
2.3.D	0.29	0.54	-0.16	2.67	2.85	1.63	Unimodal	0.98, MS	-0.07, S	0.79, P
2.3.E	-0.16	0.02	1.67	2.29	2.58	1.05	Unimodal	1.05, PS	0.28, FS	0.8, P
2.3.F	0.12	0.25	0.83	2.42	2.67	1.23	Unimodal	0.98, MS	0.29, FS	0.74, P
6.1.A	0.82	1.89	1.02	4.46	6.00	2.58	Bimodal	1.93, PS	0.4, VFS	2.02, VL
6.1.B	-0.26	-0.16	2.16	2.62	2.94	1.13	Unimodal	1.55, PS	0.41, VFS	1.16, L
6.1.C	-0.40	-1.37	0.89	0.02	1.30	0.14	Unimodal	0.73, MS	0.63, VFS	1.38, L
6.1.D	0.62	1.31	-0.07	2.91	4.20	1.99	Bimodal	1.41, PS	0.19, FS	1.91, VL
6.1.E	1.15	7.28	1.99	2.88	3.40	2.09	Unimodal	1.13, PS	0.28, FS	1.7, VL
6.1.F	0.59	1.09	2.09	2.72	2.87	1.87	Unimodal	0.85, MS	-0.1, CS	0.93, M
6.2.A	0.08	0.23	1.87	2.53	2.78	1.30	Unimodal	1.05, PS	0.22, FS	0.75, P
6.2.B	-0.40	-1.80	1.12	1.79	2.34	0.47	Unimodal	1.02, PS	0.73, VFS	1.07, M
6.2.C	0.19	0.38	-0.04	2.55	2.74	1.46	Unimodal	0.98, MS	0.01, S	0.74, P
6.2.D	0.30	0.54	1.46	2.62	2.79	1.60	Unimodal	0.95, MS	-0.08, S	0.8, P
6.2.E	0.19	0.63	1.65	2.79	2.97	1.75	Bimodal	1.38, PS	0.09, S	1.59, VL
6.2.F	-0.04	0.23	1.83	2.88	4.20	1.58	Bimodal	1.66, PS	0.19, FS	1.42, L
6.3.A	0.44	0.78	1.63	2.66	2.81	1.74	Unimodal	0.89, MS	-0.11, CS	0.88, P
6.3.B	0.27	0.56	1.78	2.73	2.91	1.67	Unimodal	1.24, PS	0.09, S	1.27, L
6.3.C	-0.14	0.06	1.73	2.88	4.45	1.33	Unimodal	1.72, PS	0.44, VFS	1.31, L
6.3.D	0.13	0.34	1.06	2.69	2.89	1.52	Unimodal	1.3, PS	0.15, FS	1.12, L
6.3.E	0.00	0.20	1.52	2.65	2.88	1.40	Unimodal	1.35, PS	0.19, FS	1.09, M
6.3.F	0.10	0.34	1.36	2.64	2.83	1.51	Unimodal	1.06, PS	-0.08, S	0.78, P
7.1.A	-0.27	-0.22	1.56	2.56	2.85	1.12	Unimodal	1.44, PS	0.34, VFS	1.01, M
7.1.B	0.12	0.27	0.94	2.50	2.73	1.33	Unimodal	1, PS	0.15, FS	0.73, P
7.1.C	-0.27	-0.28	1.22	2.94	4.99	1.32	Unimodal	1.9, PS	0.36, VFS	1.28, L
7.1.D	0.03	0.21	1.18	2.53	2.74	1.35	Unimodal	1.05, PS	0.05, S	0.75, P
7.1.E	-0.07	0.19	1.30	2.73	2.93	1.50	Bimodal	1.53, PS	0.15, FS	1.35, L
7.2.A	-0.27	-0.26	1.57	2.90	4.42	1.29	Unimodal	1.75, PS	0.36, VFS	1.16, L
7.2.B	-0.17	0.08	1.12	4.00	6.97	2.00	Bimodal	2.35, VPS	0.28, FS	2.19, VL
7.2.C	0.30	0.80	1.92	2.88	3.83	1.86	Bimodal	1.43, PS	0.13, FS	1.71, VL
7.2.D	0.52	1.06	1.91	2.84	3.00	1.95	Bimodal	1.29, PS	0.13, FS	1.74, VL
7.3.A	0.16	0.59	1.95	3.63	5.48	2.05	Bimodal	1.85, PS	0.26, FS	1.77, VL

Quadrat	Percentile values (phi-units)					Folk and Ward method (phi-units)				
	$\emptyset_{10}$	$\emptyset_{16}$	Median or $\emptyset_{50}$	$\emptyset_{84}$	$\emptyset_{90}$	Mean	Mode	Sorting	Skewness	Kurtosis
7.3.B	-0.08	0.17	1.94	2.88	4.15	1.55	Bimodal	1.64, PS	0.19, FS	1.32, L
7.3.C	0.33	0.82	1.58	2.76	2.92	1.81	Bimodal	1.25, PS	0.09, S	1.55, VL
7.3.D	-0.23	-0.12	1.85	2.53	2.74	1.25	Bimodal	1.15, PS	-0.04, S	0.7, P
11.1.A	-0.14	0.07	1.30	2.74	2.99	1.39	Unimodal	1.69, PS	0.28, FS	1.39, L
11.1.B	-0.12	0.15	1.35	2.88	4.39	1.57	Bimodal	1.77, PS	0.17, FS	1.53, VL
11.1.C	0.24	0.53	1.66	2.90	4.39	1.74	Unimodal	1.64, PS	0.2, FS	1.74, VL
11.1.D	-0.20	-0.04	1.80	2.40	2.65	1.12	Unimodal	1.1, PS	0.16, FS	0.73, P
11.1.E	0.40	0.80	1.00	2.91	4.26	1.87	Unimodal	1.5, PS	0.19, FS	1.8, VL
11.1.F	0.00	0.40	1.91	3.64	5.77	1.97	Bimodal	1.99, PS	0.27, FS	1.82, VL
11.1.G	-0.34	-0.62	1.87	2.38	2.71	0.93	Unimodal	1.17, PS	0.34, VFS	0.7, P
11.1.H	0.32	0.62	0.66	2.61	2.77	1.64	Unimodal	0.93, MS	-0.12, CS	0.86, P
11.2.A	1.19	1.48	1.70	8.60	9.09	4.50	Trimodal	3.12, VPS	0.4, VFS	0.64, VL
11.2.B	0.68	1.07	3.46	4.33	5.98	2.50	Unimodal	1.89, PS	0.42, VFS	1.91, VL
11.2.C	0.42	0.88	2.11	2.88	3.81	1.89	Unimodal	1.41, PS	0.17, FS	1.74, VL
11.2.D	0.59	0.98	1.92	2.65	2.80	1.82	Unimodal	0.82, MS	-0.09, S	0.89, P
11.2.E	1.03	1.16	1.82	2.72	2.86	1.94	Unimodal	0.76, MS	-0.08, S	0.89, P
11.3.A	0.03	0.24	1.94	2.53	2.73	1.39	Unimodal	1.05, PS	-0.02, S	0.76, P
11.3.B	0.17	0.39	1.39	2.64	2.83	1.53	Unimodal	1.02, PS	-0.05, S	0.77, P
11.3.C	-0.36	-1.63	1.57	3.36	6.07	1.25	Unimodal	2.23, VPS	0.61, VFS	1.36, L
11.3.D	0.03	0.29	0.68	2.64	2.83	1.50	Unimodal	1.07, PS	-0.1, S	0.79, P
11.3.E	0.20	0.39	1.56	2.56	2.75	1.48	Unimodal	0.98, MS	-0.01, S	0.74, P

Appendix 5.16: Soil nitrogen, phosphorus, organic carbon and pH per confinement setting, Baviaanskloof.

High or excessively high or values are indicated in bold. Quadrat codes and features as per Appendix 5.1.

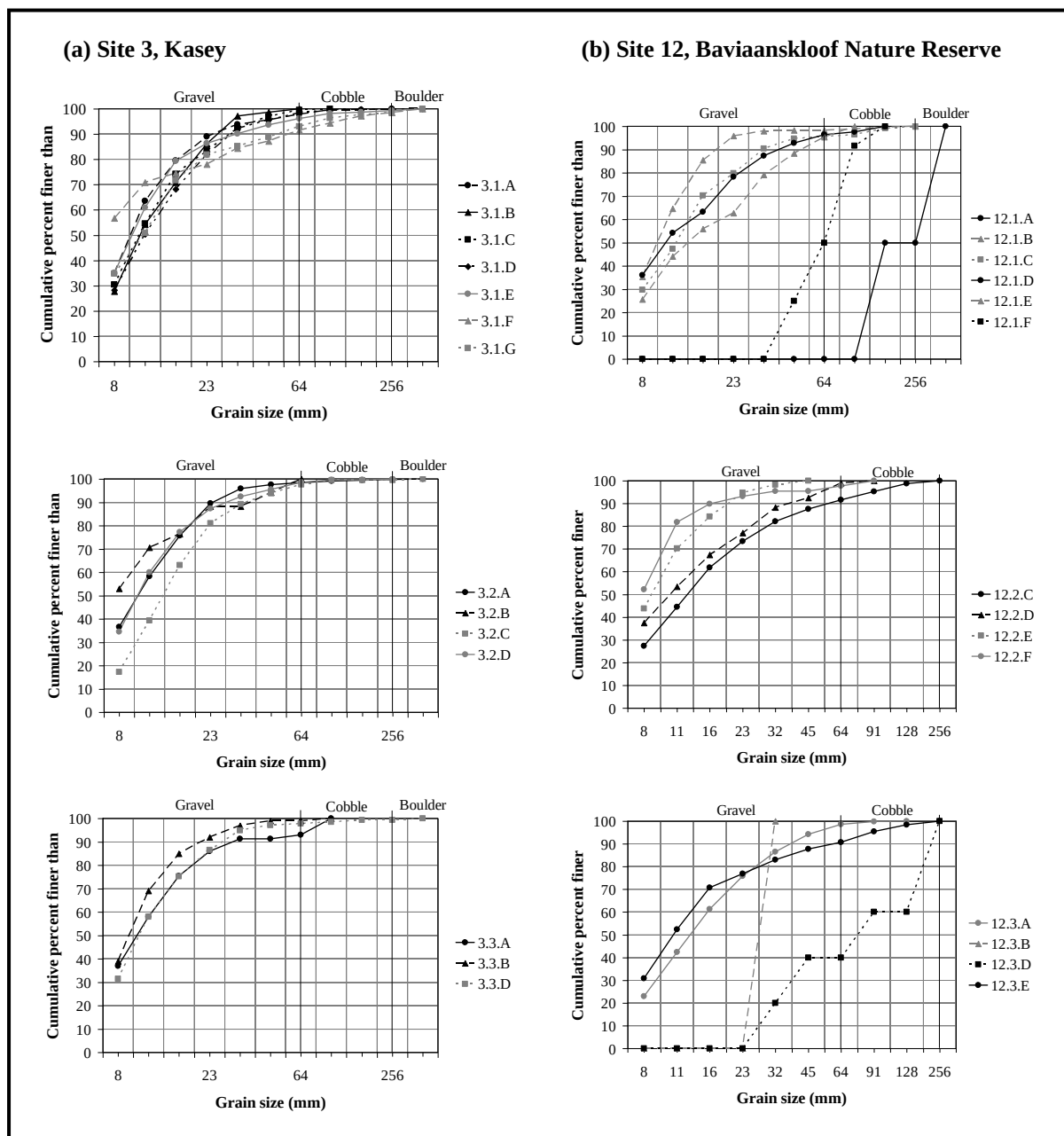
Confined valley setting					Semi-confined valley setting					Unconfined valley setting				
Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCl)	Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCl)	Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCl)
2.1.A	0.26	28.63	1.81	5.20	1.1.A	0.08	23.22	0.95	5.30	4.1.A	0.42	87.76	3.57	5.30
2.1.B	0.05	12.98	1.03	5.20	1.1.B	0.02	4.24	0.11	5.50	4.1.B	0.07	14.68	0.89	5.20
2.1.C	0.02	16.99	0.59	4.90	1.1.C	0.02	10.49	0.37	5.70	4.1.C	0.16	33.55	2.56	4.90
2.1.D	0.03	12.23	0.59	5.10	1.1.D	0.03	3.24	0.10	5.60	4.1.D	0.04	20.23	2.09	4.50
2.1.E	0.06	17.81	1.47	5.10	1.1.E	0.10	11.30	1.13	5.70	4.1.E	0.05	17.14	0.94	4.70
2.1.F	0.22	28.57	2.20	4.90	1.1.F	0.03	3.93	0.11	5.50	4.1.F	0.02	8.73	0.11	4.80
2.1.G	0.19	69.73	2.71	6.00	1.1.G	0.06	10.50	0.64	5.90	4.1.G	0.02	17.28	0.69	5.20
2.2.A	0.03	20.50	1.97	5.00	1.1.H	0.19	24.55	1.39	5.00	4.1.H	0.03	10.07	0.74	5.00
2.2.B	0.24	22.27	4.04	5.00	1.1.I	0.16	82.36	1.40	5.80	4.1.I	0.06	24.92	1.25	5.10
2.2.C	0.03	15.53	0.11	4.30	1.2.A	0.05	20.41	0.59	5.60	4.1.J	0.07	20.04	0.97	4.80
2.2.D	0.00	12.07	0.65	5.30	1.2.B	0.05	18.92	0.60	6.00	4.1.K	0.06	26.38	1.00	5.00
2.2.E	0.02	11.32	0.47	5.10	1.2.C	0.04	12.97	0.57	5.70	4.1.L	0.07	59.92	0.63	6.10
2.2.F	0.13	33.92	1.90	4.80	1.2.D	0.02	3.77	0.11	4.90	4.2.A	0.20	46.25	2.28	4.50
2.2.G	0.40	110.3	4.74	6.50	1.2.E	0.02	3.65	0.21	5.50	4.2.B	0.08	16.77	0.89	5.70
2.3.A	0.18	25.28	2.04	5.20	1.2.F	0.15	18.06	2.42	5.20	4.2.C	0.03	12.21	0.42	4.90
2.3.B	0.06	11.14	0.11	5.90	1.2.G	0.39	110.8	3.69	6.50	4.2.D	0.03	7.90	0.48	4.80
2.3.C	0.03	5.87	0.11	5.80	1.3.A	0.08	32.96	1.26	6.60	4.2.E	0.06	23.51	0.84	5.20
2.3.D	0.20	32.45	2.65	5.70	1.3.B	0.00	14.74	0.33	6.10	4.2.F	0.06	13.18	0.82	4.50
2.3.E	0.11	25.79	1.31	5.40	1.3.C	0.04	15.82	0.50	6.30	4.2.G	0.07	27.77	0.78	5.60
2.3.F	0.04	24.48	0.78	5.00	1.3.D	0.00	4.56	0.10	5.60	4.2.H	0.11	32.53	1.07	5.70
6.1.A	0.72	68.70	9.13	5.20	1.3.E	0.00	3.76	0.14	5.70	4.2.I	0.03	26.66	0.28	5.70
6.1.B	0.16	37.80	2.77	5.10	1.3.F	0.10	19.29	2.16	4.80	4.2.J	0.02	23.91	0.16	4.50
6.1.C	0.03	12.54	0.52	5.60	1.3.G	0.06	34.96	0.82	5.80	4.3.A	0.13	25.65	1.81	4.80
6.1.D	0.31	56.32	3.55	5.50	3.1.A	0.09	56.60	1.37	5.90	4.3.B	0.06	13.28	0.63	5.10
6.1.E	0.24	32.95	3.55	5.00	3.1.B	0.03	22.50	0.66	5.10	4.3.C	0.03	6.36	0.43	4.90
6.1.F	0.28	26.16	3.45	5.20	3.1.C	0.03	8.32	0.30	5.50	4.3.D	0.02	12.50	0.40	5.00
6.2.A	0.07	13.42	1.45	4.70	3.1.D	0.01	9.05	0.11	5.10	4.3.E	0.02	23.23	0.37	4.40
6.2.B	0.05	21.51	1.71	5.20	3.1.E	0.00	8.21	0.11	5.00	4.3.F	0.00	16.21	0.11	5.60
6.2.C	0.04	34.62	1.23	6.10	3.1.F	0.08	15.71	1.29	5.10	4.3.G	0.04	21.57	0.28	5.70
6.2.D	0.05	56.24	1.95	5.60	3.1.G	0.07	15.26	1.85	5.00	4.3.H	0.12	30.19	1.46	5.10
6.2.E	0.24	27.62	3.51	5.10	3.2.A	0.04	17.47	0.84	5.10	4.3.I	0.03	16.56	0.68	4.60
6.2.F	0.37	19.19	3.50	5.10	3.2.B	0.08	22.27	1.55	5.00	5.1.A	0.27	41.92	3.08	5.00
6.3.A	0.23	124.4	1.46	5.80	3.2.C	0.04	17.63	0.96	5.20	5.1.B	0.19	31.40	2.63	5.40
6.3.B	0.11	27.69	1.57	5.70	3.2.D	0.06	10.47	0.36	5.20	5.1.C	0.10	43.27	1.30	5.80
6.3.C	0.27	24.60	2.18	5.40	3.3.A	0.03	19.03	0.64	5.10	5.1.D	0.02	8.51	0.11	4.80
6.3.D	0.15	37.36	1.62	5.40	3.3.B	0.05	4.86	0.11	5.10	5.1.E	0.01	6.87	0.11	5.00
6.3.E	0.15	34.34	1.76	5.30	3.3.C	0.05	18.62	0.86	5.50	5.1.F	0.07	26.37	0.81	4.70
6.3.F	0.30	27.79	2.51	5.20	3.3.D	0.04	15.99	0.49	5.00	5.1.G	0.01	14.89	0.37	4.40
7.1.A	0.16	43.67	2.51	5.30	8.1.A	0.20	73.83	2.27	6.10	5.1.H	0.23	26.00	2.38	6.00
7.1.B	0.12	30.14	0.96	5.10	8.1.B	0.06	35.41	1.43	7.20	5.1.I	0.08	17.70	1.06	5.70
7.1.C	0.32	32.45	2.66	6.10	8.1.C	0.19	60.51	2.25	6.80	5.1.J	0.19	52.05	2.44	4.80
7.1.D	0.05	25.78	0.74	5.50	8.1.D	0.15	62.27	1.29	7.10	5.2.A	0.12	48.24	1.04	4.90
7.1.E	0.34	59.52	2.36	5.50	8.1.E	0.30	53.55	3.19	5.70	5.2.B	0.05	25.36	0.10	6.10
7.2.A	0.33	42.05	2.49	5.20	8.1.F	0.17	64.58	2.13	6.20	5.2.C	0.03	7.15	0.10	5.50
7.2.B	0.64	37.88	4.46	5.80	8.1.G	0.12	56.17	1.16	6.20	5.2.D	0.10	28.61	0.94	4.70
7.2.C	0.39	30.06	4.18	5.20	8.1.H	0.21	43.89	3.40	5.30	5.2.E	0.04	14.61	0.93	4.80
7.2.D	0.43	24.23	3.65	5.20	8.1.I	0.12	38.71	1.76	5.00	5.2.F	0.04	22.16	0.44	5.30
7.3.A	0.67	14.41	5.14	4.90	8.2.A	0.13	58.73	1.26	6.40	5.2.G	0.02	20.19	0.30	4.70
7.3.B	0.36	37.79	3.44	6.00	8.2.B	0.14	53.23	1.82	5.70	5.3.A	0.05	20.74	0.57	5.00
7.3.C	0.43	40.33	2.72	5.00	8.2.C	0.07	38.25	0.76	6.30	5.3.B	0.17	43.45	1.70	5.30
7.3.D	0.52	89.11	3.59	6.30	8.2.D	0.09	54.99	1.25	5.90	5.3.C	0.28	49.22	2.74	5.30
11.1.A	0.12	24.53	1.39	5.10	8.2.E	0.20	55.27	1.95	5.50	5.3.D	0.04	16.87	0.59	5.00
11.1.B	0.32	45.05	3.61	5.10	8.2.F	0.52	75.34	5.06	5.50	5.3.E	0.06	28.81	0.92	4.40
11.1.C	0.23	26.96	2.85	5.40	8.2.G	0.28	69.23	3.39	6.00	5.3.F	0.01	5.21	0.12	5.10
11.1.D	0.09	36.89	1.15	5.50	8.3.A	0.18	40.02	1.96	6.00	5.3.G	0.39	181.4	2.73	6.10
11.1.E	0.36	24.61	3.53	4.90	8.3.B	0.17	50.33	2.27	5.60	5.3.H	0.06	68.67	0.97	5.40
11.1.F	0.64	63.88	4.81	5.00	8.3.C	0.47	85.68	5.13	5.50	5.3.I	0.04	47.23	0.83	5.40
11.1.G	0.17	22.21	1.60	5.10	8.3.D	0.14	44.74	2.26	6.00	5.3.J	0.25	79.48	2.54	5.90
11.1.H	0.10	41.88	0.95	5.00	8.3.E	0.11	65.97	1.41	6.60	5.3.K	0.17	38.66	1.72	5.20
11.2.A	0.46	49.25	4.11	5.00	8.3.F	0.09	64.94	3.29	5.30	9.1.A	0.22	54.96	4.25	5.80

Confined valley setting					Semi-confined valley setting					Unconfined valley setting				
Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCI)	Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCI)	Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCI)
11.2.B	0.70	109.6	4.85	5.50	12.1.A	0.43	81.95	4.15	5.60	9.1.B	0.13	51.15	1.02	6.6
11.2.C	0.61	93.53	5.07	5.50	12.1.B	0.12	35.83	1.51	5.80	9.1.C	0.26	30.13	0.56	6.10
11.2.D	0.07	18.92	0.61	5.20	12.1.C	0.13	31.08	1.19	5.20	9.1.D	0.06	41.86	0.81	5.10
11.2.E	0.27	51.62	2.21	5.40	12.1.D	0.00	14.44	0.19	5.80	9.1.E	0.43	282.1	3.94	7.40
11.3.A	0.15	33.73	3.89	5.50	12.1.E	0.45	73.12	3.12	5.20	9.1.F	0.14	42.38	1.59	6.00
11.3.B	0.68	75.66	0.68	5.10	12.1.F	0.31	87.99	2.79	5.30	9.1.G	0.06	37.69	1.05	5.70
11.3.C	0.25	26.46	2.26	4.60	12.2.A	0.46	63.69	4.00	5.40	9.1.H	0.25	56.42	3.38	5.60
11.3.D	0.20	72.01	2.37	6.10	12.2.B	0.74	78.18	6.08	5.30	9.1.I	0.11	33.71	1.80	7.10
11.3.E	0.06	30.69	0.93	5.70	12.2.C	0.32	27.96	3.43	5.40	9.1.J	0.87	49.61	6.88	6.20
					12.2.D	0.17	27.78	1.83	5.60	9.2.A	1.11	87.71	4.75	5.70
					12.2.E	0.04	19.51	0.35	5.40	9.2.B	0.09	24.26	1.45	5.30
					12.2.F	0.12	31.45	1.40	5.20	9.2.C	0.27	59.69	2.33	4.80
					12.3.A	0.20	39.77	2.61	4.80	9.2.D	0.08	98.95	0.99	6.20
					12.3.B	0.70	32.20	6.65	4.50	9.2.E	0.11	36.11	1.25	5.70
					12.3.C	0.42	58.52	3.97	5.10	9.2.F	0.03	18.52	0.65	5.20
					12.3.D	0.31	15.75	2.23	6.00	9.2.G	0.11	45.91	1.35	5.60
					12.3.E	0.39	43.58	4.22	6.20	9.2.H	0.02	17.36	0.24	5.60
										9.2.I	0.06	18.77	0.50	4.90
										9.2.J	0.20	44.16	2.44	6.10
										9.2.K	0.25	118.7	3.33	5.30
										9.2.L	0.06	47.23	0.61	6.20
										9.3.A	0.41	177.7	3.84	5.70
										9.3.B	1.12	74.40	7.01	5.70
										9.3.C	0.19	55.58	2.43	6.10
										9.3.D	0.00	21.55	0.46	5.40
										9.3.E	0.11	47.73	1.97	5.60
										9.3.F	0.11	25.34	0.97	4.80
										9.3.G	0.10	54.18	1.92	5.50
										9.3.H	0.08	42.00	0.98	5.40
										9.3.I	0.06	52.13	0.68	6.10
										9.3.J	0.02	7.24	0.12	5.40
										9.3.K	0.06	28.76	0.88	6.50
										9.3.L	0.27	87.94	2.97	5.10
										9.3.M	0.15	59.19	1.43	7.20
										10.1.A	0.23	118.5	2.51	6.60
										10.1.B	0.03	42.78	0.52	6.30
										10.1.C	0.09	23.36	0.42	5.80
										10.1.D	0.02	19.24	0.36	6.00
										10.1.E	0.02	24.98	0.52	5.30
										10.1.F	0.09	50.20	1.38	5.70
										10.1.G	0.06	35.80	0.68	6.30
										10.1.H	0.41	73.74	3.71	5.90
										10.1.I	0.04	58.30	0.41	5.70
										10.1.J	0.13	74.33	0.91	6.10
										10.2.A	0.39	38.30	4.16	5.80
										10.2.B	0.36	56.19	4.58	5.10
										10.2.C	0.01	13.76	0.34	4.90
										10.2.D	0.10	25.32	1.05	5.60
										10.2.E	0.06	33.85	0.97	5.40
										10.2.F	0.16	31.92	2.11	5.80
										10.2.G	0.03	21.01	0.46	4.90
										10.2.H	0.35	37.20	2.63	5.60
										10.2.I	0.16	28.65	2.17	5.90
										10.2.J	0.30	44.85	2.46	5.60
										10.2.K	0.27	60.53	4.78	6.40
										10.3.A	0.17	23.51	1.29	5.20
										10.3.B	0.02	8.40	0.11	5.10
										10.3.C	0.02	21.34	0.30	4.30
										10.3.D	0.45	115.4	3.73	5.60
										10.3.E	0.03	23.33	0.61	5.20
										10.3.F	0.38	26.98	3.85	5.40
										10.3.G	0.08	33.63	0.62	5.00
										10.3.H	0.33	89.96	2.40	6.10
										10.3.I	0.13	51.15	1.02	6.60
										13.1.A	0.44	23.74	3.81	5.10
										13.1.B	0.33	46.18	3.35	5.90
										13.1.C	0.07	16.85	0.68	5.40
										13.1.D	0.23	37.31	1.99	5.20
										13.1.E	0.08	30.15	0.60	4.80
										13.1.F	0.68	73.75	5.04	7.10

Confined valley setting					Semi-confined valley setting					Unconfined valley setting				
Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCl)	Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCl)	Plot	N (%)	P Bray II (mg/ kg)	C (%)	pH (KCl)
										13.2.A	0.36	35.17	2.77	5.40
										13.2.B	0.09	14.43	0.86	5.10
										13.2.C	0.41	33.08	4.12	4.80
										13.2.D	0.08	21.26	0.88	5.20
										13.2.E	0.36	54.96	3.11	5.40
										13.2.F	0.11	37.10	0.94	5.30
										13.2.G	0.27	43.48	2.99	5.00
										13.3.A	1.02	42.67	7.95	5.20
										13.3.B	0.78	56.95	6.72	5.00
										13.3.C	0.42	26.11	4.01	5.00
										13.3.D	0.09	17.34	1.05	4.70
										13.3.E	0.08	10.58	0.55	5.50
										13.3.F	0.11	41.62	1.48	5.50

Appendix 5. 17: Grain size cumulative curves for coarse sediments, semi-confined sites 3 and 12.

Quadrat codes and features as per Appendix 5.1.



Appendix 5.18: Grain size percentage data for coarse sediments, semi-confined sites.

FG = Fine gravel, MG = Medium gravel, CG = Coarse gravel, VCG = Very coarse gravel, SC = Small cobble, LC = Large cobble and B = Boulder. Quadrat codes and features as per Appendix 5.1. Excluded quadrats limited to fine sediments only.

Size class	FG	MG	MG	CG	CG	VCG	VCG	SC	SC	LC	B
Grain size, mm	8	11.3	16	22.6	32	45.3	64	90.5	128	256	>256
(phi-units)	(-3)	(-3.5)	(-4)	(-4.5)	(-5)	(-5.5)	(-6)	(-6.5)	(-7)	(-8)	(>-8)
1.1.A	37.8	16.8	17.3	9.7	7.6	2.2	3.2	4.3	1.1	0.0	0.0
1.1.B	50.8	25.4	10.2	8.5	1.7	2.5	0.8	0.0	0.0	0.0	0.0
1.1.C	51.5	13.3	18.3	7.6	2.7	2.3	3.0	0.7	0.3	0.0	0.3
1.1.D	36.5	31.3	16.7	10.4	4.2	1.0	0.0	0.0	0.0	0.0	0.0
1.1.E	0.0	9.1	18.2	9.1	9.1	0.0	0.0	18.2	18.2	18.2	0.0
1.1.F	45.1	15.8	13.5	9.0	6.0	3.8	3.0	1.5	0.8	0.8	0.8
1.1.G	29.4	19.9	14.9	12.9	10.1	5.2	4.0	2.4	1.0	0.2	0.0
1.1.H	60.3	20.7	11.3	4.0	1.9	0.6	0.2	0.6	0.4	0.0	0.2
1.1.I	35.6	26.5	18.7	11.7	5.5	0.9	0.8	0.2	0.2	0.0	0.0
1.2.A	73.7	0.0	10.5	5.3	5.3	5.3	0.0	0.0	0.0	0.0	0.0
1.2.B	24.4	20.0	14.8	13.8	10.1	7.4	5.7	2.2	1.2	0.2	0.0
1.2.C	37.0	0.0	3.7	22.2	3.7	11.1	18.5	3.7	0.0	0.0	0.0
1.2.D	36.3	25.6	25.6	10.7	1.7	0.0	0.0	0.0	0.0	0.0	0.0
1.2.E	44.0	15.1	8.8	7.5	7.5	6.3	5.7	1.9	1.3	1.3	0.6
1.2.F	31.2	22.1	19.6	9.1	7.5	4.1	4.4	1.9	0.0	0.0	0.0
1.2.G	67.2	14.9	0.0	8.2	8.2	0.0	0.0	0.7	0.0	0.7	0.0
1.3.A	36.1	20.8	12.5	13.9	6.9	4.2	1.4	1.4	1.4	1.4	0.0
1.3.B	47.2	17.7	9.4	10.0	7.1	2.7	2.9	1.2	1.5	0.0	0.3
1.3.C	37.5	30.6	16.4	7.3	4.7	1.7	0.9	0.4	0.4	0.0	0.0
1.3.D	31.6	25.4	18.7	14.5	7.3	1.6	0.5	0.5	0.0	0.0	0.0
1.3.E	49.3	14.1	11.3	7.0	3.5	3.9	4.2	3.2	2.1	0.7	0.7
1.3.F	31.9	25.3	16.7	12.6	7.3	2.4	2.3	1.3	0.2	0.0	0.0
1.3.G	33.2	22.4	16.1	12.1	9.9	4.5	0.0	0.0	0.4	0.4	0.9
3.1.A	34.8	28.7	16.0	9.4	5.0	1.7	2.2	1.7	0.0	0.6	0.0
3.1.B	27.8	26.4	16.7	15.3	11.1	1.4	1.4	0.0	0.0	0.0	0.0
3.1.C	30.4	24.3	19.6	9.3	8.8	4.7	2.5	0.5	0.0	0.0	0.0
3.1.D	28.2	22.1	17.9	13.8	10.2	3.4	2.7	1.1	0.3	0.1	0.1
3.1.E	35.0	25.8	18.5	7.0	3.8	3.5	2.5	1.9	0.6	0.6	0.6
3.1.F	56.7	14.2	3.5	3.5	6.4	2.8	4.3	2.8	2.8	1.4	1.4
3.1.G	34.7	16.2	20.8	10.2	3.2	3.7	4.2	3.2	1.4	0.9	1.4
3.2.A	36.5	21.7	17.4	13.9	6.3	1.7	0.9	0.7	0.3	0.3	0.2
3.2.B	52.9	17.6	5.9	11.8	0.0	5.9	5.9	0.0	0.0	0.0	0.0
3.2.C	17.3	22.0	23.8	17.9	8.3	4.8	3.6	1.8	0.0	0.0	0.6
3.2.D	34.5	25.5	17.4	10.1	5.0	3.1	3.1	1.1	0.0	0.3	0.0
3.3.A	36.8	21.1	17.5	10.5	5.3	0.0	1.8	7.0	0.0	0.0	0.0
3.3.B	39.0	30.0	16.0	7.0	5.0	2.0	0.0	1.0	0.0	0.0	0.0
3.3.D	31.4	26.6	17.2	11.3	8.4	2.2	0.7	0.7	0.7	0.0	0.7
8.1.B	36.4	17.1	15.9	12.5	7.1	5.5	3.2	0.9	0.5	0.5	0.5
8.1.C	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0
8.1.F	44.2	36.3	6.2	7.1	2.7	1.8	0.9	0.9	0.0	0.0	0.0
8.1.G	33.7	17.9	18.8	9.9	9.9	5.2	2.4	1.2	0.6	0.0	0.4
8.1.I	16.2	12.8	18.4	12.4	15.0	10.3	8.5	3.8	2.1	0.4	0.0
8.2.A	0.0	0.0	80.0	0.0	0.0	20.0	0.0	0.0	0.0	0.0	0.0
8.2.C	16.6	10.7	15.0	9.1	17.1	14.4	11.2	4.3	1.6	0.0	0.0
8.2.D	51.2	14.0	4.7	20.9	4.7	3.7	0.0	0.5	0.5	0.0	0.0
8.2.F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0
8.2.G	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8.3.A	26.1	24.3	21.7	15.1	5.9	3.9	1.8	0.6	0.6	0.0	0.0
8.3.B	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.7	0.0	33.3	0.0
8.3.C	0.0	0.0	0.0	33.3	0.0	0.0	0.0	33.3	33.3	0.0	0.0
8.3.E	38.2	18.3	8.0	8.4	10.0	7.2	4.4	1.6	2.4	1.2	0.4
12.1.A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	0.0	50.0

Size class	FG	MG	MG	CG	CG	VCG	VCG	SC	SC	LC	B
Grain size, mm	8	11.3	16	22.6	32	45.3	64	90.5	128	256	>256
(phi-units)	(-3)	(-3.5)	(-4)	(-4.5)	(-5)	(-5.5)	(-6)	(-6.5)	(-7)	(-8)	(>-8)
12.1.B	35.4	29.2	20.8	10.4	2.1	0.4	0.0	0.4	0.8	0.4	0.0
12.1.C	29.8	17.5	22.8	9.6	10.5	4.4	0.9	0.9	2.6	0.9	0.0
12.1.D	36.1	18.1	9.0	15.1	9.0	5.4	3.6	1.2	2.4	0.0	0.0
12.1.E	25.6	18.6	11.6	7.0	16.3	9.3	7.0	4.7	0.0	0.0	0.0
12.1.F	0.0	0.0	0.0	0.0	0.0	25.0	25.0	41.7	8.3	0.0	0.0
12.2.C	27.2	17.3	17.3	11.5	8.7	5.4	4.2	3.5	3.5	1.3	0.0
12.2.D	37.4	16.0	13.9	9.6	11.2	4.3	6.4	1.1	0.0	0.0	0.0
12.2.E	43.9	26.3	14.0	10.5	3.5	1.8	0.0	0.0	0.0	0.0	0.0
12.2.F	52.3	29.5	8.0	3.4	2.3	0.0	2.3	2.3	0.0	0.0	0.0
12.3.A	23.0	19.4	18.8	14.7	10.7	7.6	4.3	1.3	0.2	0.0	0.0
12.3.B	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0
12.3.D	0.0	0.0	0.0	0.0	20.0	20.0	0.0	20.0	0.0	40.0	0.0
12.3.E	30.8	21.5	18.5	6.2	6.2	4.6	3.1	4.6	3.1	1.5	0.0

Appendix 5.19: Coarse sediment summary statistics for semi-confined study sites.

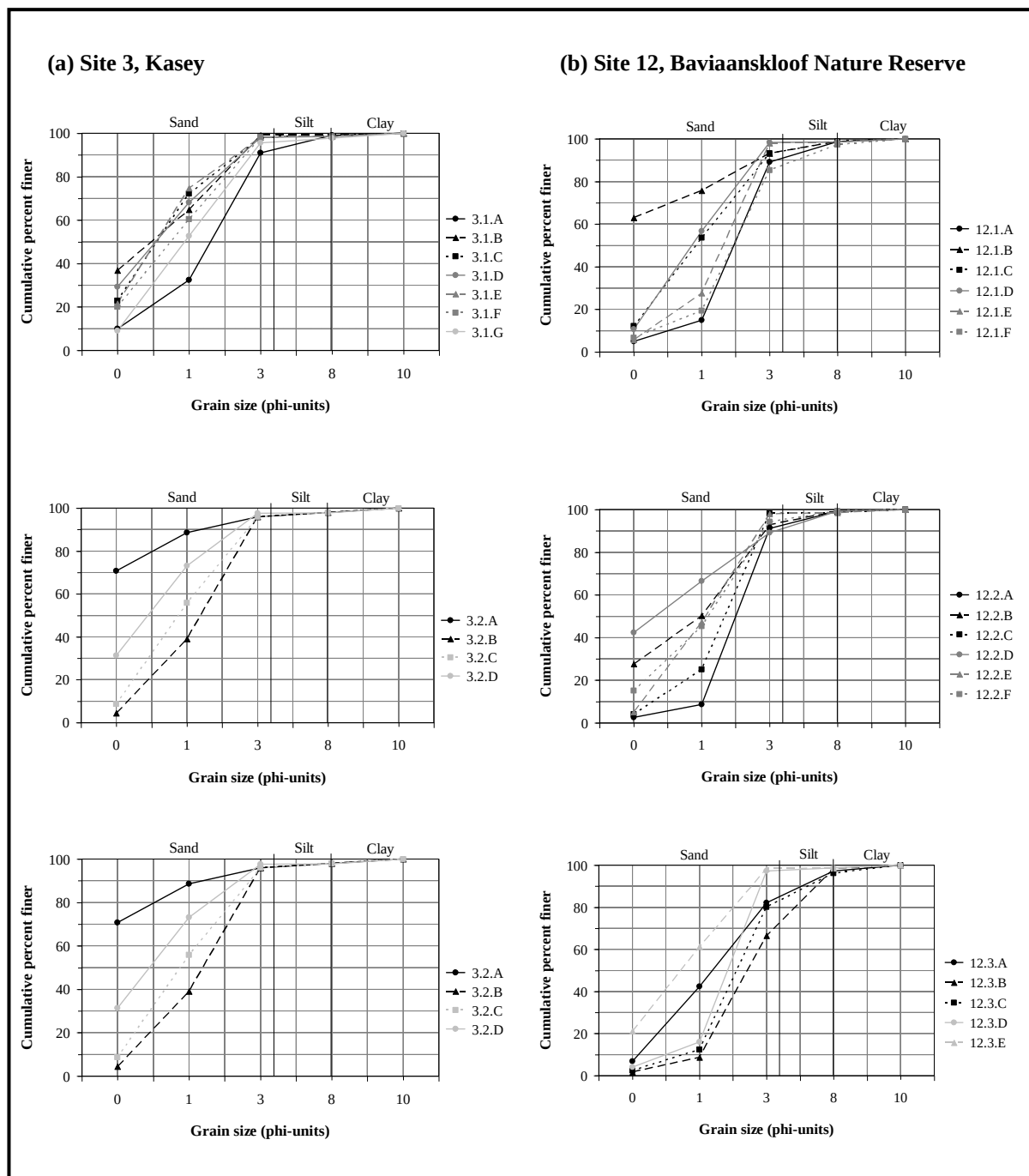
Bunte and Abt (2001), Kondolf *et al.* (2003) and Mecklenburg (2006). Quadrat codes and features as per Appendix 5.1. Excluded quadrats limited to fine sediments only. Abbreviations (descriptions) from Blott and Pye (2001) and representing the following: VWS = Very well sorted, WS= Well sorted, MWS = Moderately well sorted, MS = Moderately sorted, PS = Poorly sorted, VPS = Very poorly sorted, VFS = Very fine skewed, FS = Fine skewed, S = Symmetrical, CS = Coarse skewed and VCS = Very coarse skewed.

Quadrat	Percentile values (mm)					Geometric method (mm)		
	D ₁₆	D ₃₅	Median or D ₅₀	D ₈₄	D ₉₅	Mean	Sorting	Skewness
1.1.A	6.8	7.8	10	25	66	13.04	1.99, MS	0.15, CS
1.1.B	6.6	7.3	8	15	22	9.95	1.54, MS	0.16, CS
1.1.C	6.6	7.3	7.9	17	41	10.59	1.67, MS	0.2, CS
1.1.D	6.8	7.9	9.2	16	22	10.43	1.55, MS	0.09, S
1.1.E	13	21	70	190	230	49.70	4.05, VPS	-0.14, FS
1.1.F	6.6	7.5	8.8	23	55	12.32	1.97, MS	0.2, CS
1.1.G	7	8.7	11	28	56	14.00	2.06, PS	0.13, CS
1.1.H	6.5	7.1	7.6	12	20	8.83	1.37, MWS	0.13, CS
1.1.I	6.8	8	9.5	17	26	10.75	1.59, MS	0.09, S
1.2.A	6.4	6.9	7.3	16	33	10.12	1.67, MS	0.22, CS
1.2.B	7.2	9.5	13	33	59	15.41	2.17, PS	0.09, S
1.2.C	6.8	7.9	18	51	62	18.62	2.74, PS	0.02, S
1.2.D	6.8	7.9	9.5	15	20	10.10	1.49, MS	0.05, S
1.2.E	6.7	7.5	9.1	34	64	15.09	2.55, PS	0.26, CS
1.2.F	7	8.4	10	24	50	12.96	1.91, MS	0.15, CS
1.2.G	8.3	9.6	11	26	31	14.69	1.84, MS	0.18, CS
1.3.A	6.8	7.9	9.9	23	52	12.51	1.89, MS	0.14, CS
1.3.B	6.6	7.4	8.4	22	50	12.05	1.95, MS	0.22, CS
1.3.C	6.8	7.8	9.1	16	28	10.43	1.55, MS	0.1, S
1.3.D	6.9	8.3	10	19	28	11.45	1.67, MS	0.09, S
1.3.E	6.6	7.4	8.1	28	77	13.59	2.34, PS	0.28, CS
1.3.F	6.9	8.3	10	21	38	12.04	1.77, MS	0.12, CS
1.3.G	6.9	8.2	10	22	35	12.32	1.82, MS	0.13, CS
3.1.A	6.8	8	9.5	19	40	11.37	1.7, MS	0.12, CS
3.1.B	7.1	8.7	10	21	30	12.21	1.75, MS	0.13, CS
3.1.C	7	8.5	10	22	39	12.41	1.81, MS	0.13, CS
3.1.D	7.1	8.8	11	24	42	13.05	1.87, MS	0.1, S
3.1.E	6.8	8	9.6	20	54	11.66	1.75, MS	0.12, CS
3.1.F	6.5	7.2	7.7	31	98	14.20	2.61, PS	0.32, VCS
3.1.G	6.9	8	11	28	79	13.90	2.07, PS	0.13, CS
3.2.A	6.8	7.9	9.7	19	30	11.37	1.69, MS	0.1, S
3.2.B	6.5	7.3	7.9	20	47	11.40	1.87, MS	0.23, CS
3.2.C	7.8	10	13	25	49	13.96	1.79, MS	0.04, S
3.2.D	6.9	8.1	9.7	20	42	11.75	1.73, MS	0.12, CS
3.3.A	6.8	7.9	9.8	21	71	11.95	1.79, MS	0.12, CS
3.3.B	6.8	7.8	9	16	28	10.43	1.55, MS	0.11, CS
3.3.D	6.9	8.4	10	21	33	12.04	1.77, MS	0.12, CS
8.1.B	6.8	7.9	10	24	47	12.77	1.94, MS	0.14, CS

Quadrat	Percentile values (mm)					Geometric method (mm)		
	D ₁₆	D ₃₅	Median or D ₅₀	D ₈₄	D ₉₅	Mean	Sorting	Skewness
8.1.C	95	100	110	120	130	106.77	1.12, VWS	-0.04, S
8.1.F	6.7	7.5	8.4	14	26	9.69	1.46, MS	0.11, CS
8.1.G	6.9	8.2	11	25	44	13.13	1.93, MS	0.1, S
8.1.I	8	12	17	43	73	18.55	2.33, PS	0.04, S
8.2.A	12	13	14	34	41	20.20	1.8, MS	0.24, CS
8.2.C	7.9	13	21	47	69	19.27	2.45, PS	-0.04, S
8.2.D	6.6	7.3	7.9	20	31	11.49	1.86, MS	0.23, CS
8.2.F	68	72	76	85	88	76.03	1.12, VWS	0, S
8.2.G	17	18	19	21	22	18.89	1.11, VWS	-0.01, S
8.3.A	7.2	9	11	21	38	12.30	1.72, MS	0.07, S
8.3.B	69	77	83	220	240	123.21	1.93, MS	0.24, CS
8.3.C	19	65	76	110	120	45.72	2.72, PS	-0.25, FS
8.3.E	6.8	7.8	9.8	34	72	15.21	2.46, PS	0.23, CS
12.1.A	100	120	130	460	490	214.48	2.42, PS	0.27, CS
12.1.B	6.8	8	9.4	16	22	10.43	1.54, MS	0.07, S
12.1.C	7	8.8	12	26	70	13.49	1.94, MS	0.07, S
12.1.D	6.8	7.9	10	29	60	14.04	2.19, PS	0.19, CS
12.1.E	7.2	9.6	14	42	77	17.39	2.47, PS	0.11, CS
12.1.F	41	55	67	97	430	63.06	1.54, MS	-0.04, S
12.2.C	7.1	9.2	12	37	91	16.21	2.39, PS	0.15, CS
12.2.D	6.8	7.9	10	28	54	13.80	2.14, PS	0.18, CS
12.2.E	6.7	7.6	8.7	17	29	10.67	1.63, MS	0.14, CS
12.2.F	6.6	7.3	7.9	13	52	9.26	1.42, MS	0.13, CS
12.3.A	7.3	9.8	13	29	49	14.55	2.01, PS	0.06, S
12.3.B	25	29	32	460	490	107.24	7.83, VPS	0.47, VCS
12.3.D	32	69	190	390	470	111.71	4, PS	-0.22, FS
12.3.E	7	8.6	11	39	110	16.52	2.56, PS	0.2, CS

Appendix 5.21: Grain size cumulative curves for fine sediments, semi-confined sites 3 and 12.

Quadrat codes and features as per Appendix 5.1.



Appendix 5.22: Fine sediment summary statistics for semi-confined study sites.

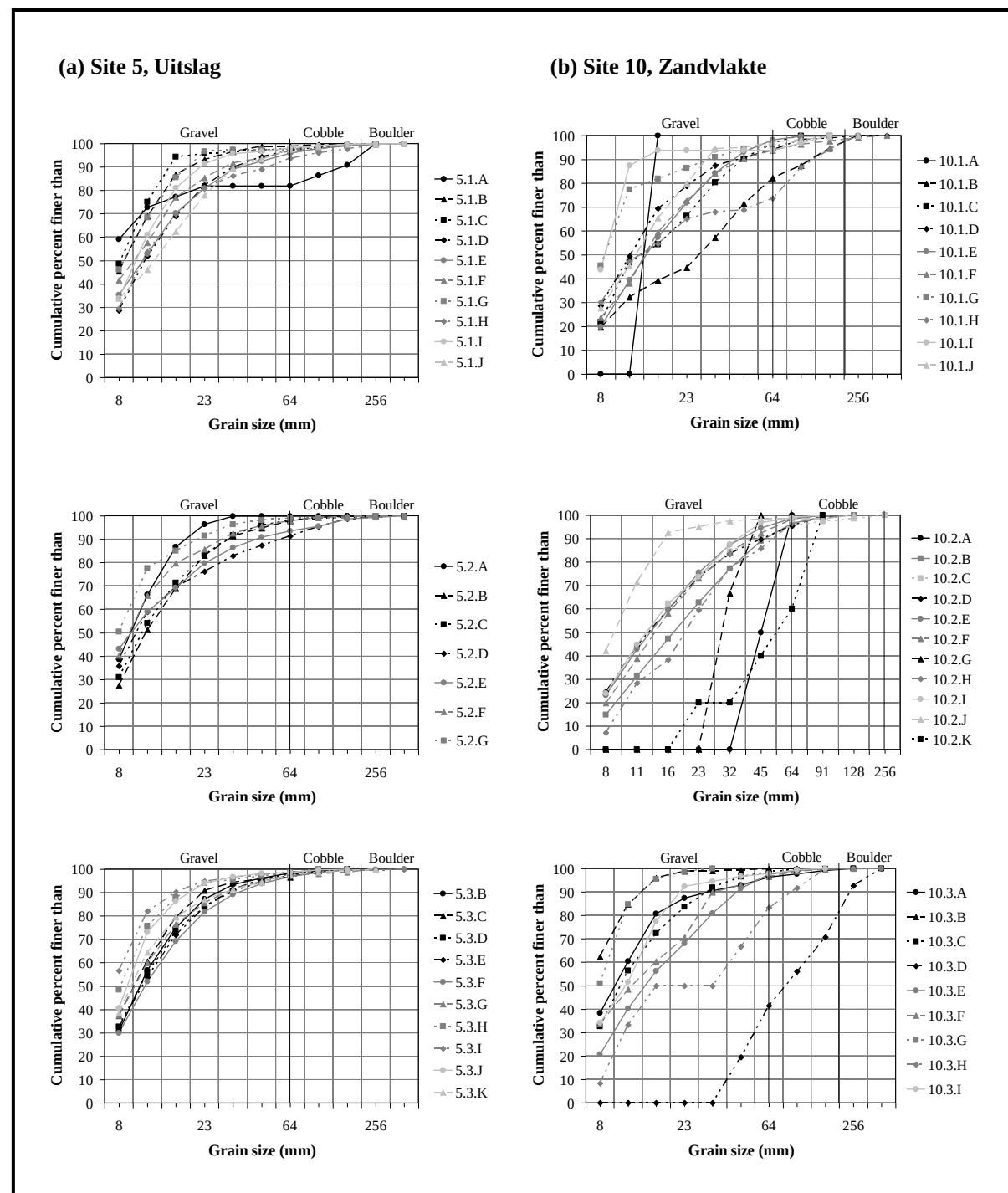
After Bunte and Abt (2001), Kondolf *et al.* (2003) and Mecklenburg (2006). Quadrat codes and features as per Appendix 5.1. Abbreviations (descriptions) represent the following: VWS = Very well sorted, WS= Well sorted, MWS = Moderately well sorted, MS = Moderately sorted, PS = Poorly sorted, VPS = Very poorly sorted, EPS = Extremely poorly sorted, VFS = Very fine skewed, FS = Fine skewed, S = Symmetrical, CS = Coarse skewed, VCS = Very coarse skewed, VP = Very platykurtic, P = Platykurtic, M = Mesokurtic, L = Leptokurtic, VL = Very leptokurtic and EL = Extremely leptokurtic.

Quadrat	Percentile values (phi-units)					Folk and Ward method (phi-units)				
	ϕ_{10}	ϕ_{16}	Median or ϕ_{50}	ϕ_{84}	ϕ_{90}	Mean	Mode	Sorting	Skewness	Kurtosis
1.1.A	0.17	0.38	1.49	2.56	2.75	1.48	Unimodal	0.99, MS	-0.03, S	0.75, P
1.1.B	0.06	0.17	0.84	2.32	2.62	1.11	Unimodal	0.99, MS	0.36, VFS	0.82, P
1.1.C	-0.09	0.11	1.18	2.48	2.71	1.26	Unimodal	1.08, PS	0.09, S	0.75, P
1.1.D	-0.36	-0.50	0.30	1.47	2.19	0.50	Unimodal	0.92, MS	0.45, VFS	1.26, L
1.1.E	0.52	0.88	1.82	2.69	2.85	1.80	Unimodal	0.87, MS	-0.1, S	0.88, P
1.1.F	-0.27	-0.12	0.51	1.75	2.34	0.71	Unimodal	0.96, MS	0.38, VFS	1.41, L
1.1.G	0.20	0.42	1.61	2.74	2.93	1.59	Unimodal	1.41, PS	0.2, FS	1.33, L
1.1.H	-0.17	0.04	1.54	2.67	2.87	1.42	Bimodal	1.35, PS	0.02, S	1.02, M
1.1.I	-0.24	-0.19	1.35	2.63	2.85	1.29	Bimodal	1.32, PS	0.06, S	0.84, P
1.2.A	0.04	0.19	1.09	2.44	2.68	1.24	Unimodal	1.03, PS	0.18, FS	0.76, P
1.2.B	-0.13	0.10	1.43	2.54	2.74	1.36	Bimodal	1.1, PS	-0.09, S	0.75, P
1.2.C	0.06	0.19	0.94	2.38	2.65	1.17	Unimodal	1.01, PS	0.29, FS	0.78, P
1.2.D	-0.38	-0.67	0.10	0.88	1.14	0.22	Unimodal	0.72, MS	0.46, VFS	1.29, L
1.2.E	-0.27	-0.14	0.55	1.96	2.43	0.79	Unimodal	1.01, PS	0.38, VFS	1.09, M
1.2.F	0.82	1.10	1.93	2.76	2.90	1.93	Unimodal	0.94, MS	0.04, S	1.18, L
1.2.G	-0.33	-0.90	1.15	2.52	2.76	1.14	Bimodal	1.2, PS	0.04, S	0.62, VP
1.3.A	-0.17	0.02	0.72	2.26	2.63	1.00	Unimodal	1.06, PS	0.37, VFS	0.89, P
1.3.B	0.06	0.22	1.17	2.52	2.76	1.31	Unimodal	1.05, PS	0.16, FS	0.75, P
1.3.C	-0.13	0.07	1.12	2.45	2.69	1.21	Unimodal	1.08, PS	0.11, FS	0.74, P
1.3.D	-0.21	-0.03	0.62	1.99	2.41	0.86	Unimodal	0.98, MS	0.36, VFS	1.03, M
1.3.E	-0.33	-0.29	0.38	1.25	1.98	0.47	Unimodal	0.83, MS	0.33, VFS	1.28, L
1.3.F	1.04	1.21	2.18	4.79	6.90	2.72	Unimodal	2.11, VPS	0.52, VFS	2.32, VL
1.3.G	0.13	0.36	1.54	2.62	2.81	1.51	Unimodal	1.03, PS	-0.06, S	0.77, P
3.1.A	0.00	-1.54	1.60	2.38	2.97	1.54	Unimodal	1.49, PS	0.14, FS	1.32, L
3.1.B	-0.35	0.38	0.47	2.63	2.47	0.77	Unimodal	1.08, PS	0.41, VFS	0.75, P
3.1.C	-0.27	0.33	0.55	2.59	2.37	0.77	Unimodal	0.99, MS	0.36, VFS	1.1, M
3.1.D	-0.32	0.29	0.53	2.45	2.45	0.79	Unimodal	1.05, PS	0.38, VFS	0.86, P
3.1.E	-0.26	0.57	0.53	2.62	2.30	0.73	Unimodal	0.95, MS	0.36, VFS	1.34, L
3.1.F	-0.24	0.23	0.74	2.60	2.57	0.96	Unimodal	1.07, PS	0.3, FS	0.79, P
3.1.G	0.02	-1.02	0.94	2.67	2.74	1.18	Unimodal	1.06, PS	0.3, FS	0.78, P
3.2.A	-0.42	0.96	-0.14	2.71	1.38	0.07	Unimodal	0.76, MS	0.69, VFS	2.37, VL
3.2.B	0.16	0.35	1.39	2.63	2.79	1.43	Unimodal	1.01, PS	0.07, S	0.72, P
3.2.C	0.03	0.12	0.88	2.37	2.70	1.15	Unimodal	1.04, PS	0.34, VFS	0.8, P
3.2.D	-0.33	0.36	0.45	2.59	2.38	0.70	Unimodal	1.02, PS	0.41, VFS	1.04, M
3.3.A	0.11	-0.37	1.28	2.06	2.78	1.37	Unimodal	1.03, PS	0.11, FS	0.74, P
3.3.B	-0.29	0.04	0.66	2.46	2.58	0.90	Unimodal	1.09, PS	0.33, VFS	0.79, P
3.3.C	0.03	0.46	0.74	2.59	2.62	1.04	Unimodal	1, MS	0.41, VFS	0.94, M
3.3.D	-0.22	1.07	0.70	2.71	2.63	0.96	Unimodal	1.08, PS	0.35, VFS	0.87, P
8.1.A	-0.36	0.43	0.73	2.60	2.65	0.94	Bimodal	1.17, PS	0.27, FS	0.63, VP
8.1.B	0.15	0.10	1.55	2.70	2.82	1.52	Unimodal	1.03, PS	-0.05, S	0.77, P
8.1.C	0.08	-0.68	1.55	1.95	2.77	1.49	Unimodal	1.04, PS	-0.1, CS	0.8, P
8.1.D	0.15	1.10	1.08	2.72	2.69	1.27	Unimodal	0.97, MS	0.27, FS	0.73, P
8.1.E	0.32	0.49	1.66	2.58	2.79	1.62	Unimodal	0.94, MS	-0.08, S	0.81, P
8.1.F	0.01	0.17	1.45	2.70	2.80	1.43	Unimodal	1.08, PS	-0.04, S	0.76, P
8.1.G	-0.35	0.82	0.78	2.65	3.00	1.06	Unimodal	1.63, PS	0.44, VFS	1.05, M
8.1.H	0.59	0.27	1.85	2.76	2.86	1.84	Unimodal	0.85, MS	-0.09, S	0.88, P
8.1.I	0.11	-0.74	1.56	2.12	2.82	1.51	Unimodal	1.05, PS	-0.07, S	0.78, P

Quadrat	Percentile values (phi-units)					Folk and Ward method (phi-units)				
	$\emptyset_{10}$	$\emptyset_{16}$	Median or $\emptyset_{50}$	$\emptyset_{84}$	$\emptyset_{90}$	Mean	Mode	Sorting	Skewness	Kurtosis
8.2.A	-0.03	-0.14	0.88	1.91	2.65	1.12	Unimodal	1.04, PS	0.3, VFS	0.8, P
8.2.B	0.18	-0.34	1.44	2.05	2.80	1.47	Unimodal	1, PS	0.04, S	0.73, P
8.2.C	-0.33	-0.11	0.49	1.78	2.53	0.77	Unimodal	1.08, PS	0.42, VFS	0.95, M
8.2.D	-0.15	-0.10	0.96	2.25	2.73	1.15	Unimodal	1.1, PS	0.23, FS	0.76, P
8.2.E	0.25	0.16	1.55	2.46	2.77	1.53	Unimodal	0.96, MS	-0.03, S	0.75, P
8.2.F	0.70	-3.08	1.89	-0.24	2.86	1.89	Unimodal	0.83, MS	-0.11, CS	0.94, M
8.2.G	0.21	0.33	1.55	2.58	2.78	1.53	Unimodal	0.98, MS	-0.04, S	0.76, P
8.3.A	-0.12	0.16	1.42	2.40	2.92	1.40	Bimodal	1.53, PS	0.2, FS	1.24, L
8.3.B	-0.36	-0.36	0.35	1.89	2.40	0.67	Unimodal	1.04, PS	0.47, VFS	0.91, M
8.3.C	0.86	0.27	1.91	2.55	2.86	1.91	Unimodal	0.79, MS	-0.08, S	0.89, P
8.3.D	0.29	-0.22	1.57	2.22	2.76	1.55	Unimodal	0.95, MS	-0.03, S	0.75, P
8.3.E	0.00	0.14	1.23	2.24	2.96	1.36	Unimodal	1.58, PS	0.35, VFS	1.37, L
8.3.F	0.45	-0.06	1.78	2.26	2.80	1.75	Unimodal	0.88, MS	-0.12, CS	0.9, P
12.1.A	0.50	1.03	1.94	2.86	3.41	1.94	Bimodal	1.37, PS	0.18, FS	1.82, VL
12.1.B	-0.41	-3.73	-0.10	1.95	2.64	0.50	Unimodal	1.34, PS	0.82, VFS	1.66, VL
12.1.C	-0.09	0.09	0.91	2.54	2.84	1.18	Unimodal	1.35, PS	0.42, VFS	1.13, L
12.1.D	-0.03	0.12	0.85	2.31	2.60	1.09	Unimodal	1.02, PS	0.31, VFS	0.81, P
12.1.E	0.00	0.47	1.70	2.60	2.90	1.59	Bimodal	1.31, PS	0.02, S	1.25, L
12.1.F	0.20	0.74	1.64	2.96	2.77	1.57	Unimodal	0.98, MS	-0.12, CS	0.83, P
12.2.A	0.27	1.18	1.93	2.83	4.99	1.88	Bimodal	1.64, PS	0.18, FS	1.94, VL
12.2.B	1.03	-0.51	2.00	2.59	2.97	2.00	Unimodal	1.16, PS	0.18, FS	1.68, VL
12.2.C	-0.31	0.57	0.99	2.61	2.87	1.12	Unimodal	1.47, PS	0.3, FS	0.95, M
12.2.D	0.29	-1.10	1.68	2.54	2.78	1.62	Unimodal	0.94, MS	-0.12, CS	0.86, P
12.2.E	0.11	0.26	1.11	2.45	2.68	1.27	Unimodal	0.99, MS	0.22, FS	0.73, P
12.2.F	-0.16	0.03	1.19	2.58	2.83	1.27	Unimodal	1.26, PS	0.18, FS	0.9, P
12.3.A	0.09	0.26	1.38	3.60	5.58	1.75	Unimodal	1.95, PS	0.46, VFS	1.42, L
12.3.B	1.05	1.26	2.43	5.75	6.66	3.14	Unimodal	2.17, VPS	0.46, VFS	1.03, M
12.3.C	0.76	1.11	2.11	4.19	6.04	2.46	Unimodal	1.88, PS	0.42, VFS	2.04, VL
12.3.D	0.50	1.00	1.84	2.67	2.82	1.84	Unimodal	0.85, MS	-0.11, CS	0.95, M
12.3.E	-0.26	-0.13	0.72	2.22	2.55	0.94	Unimodal	1.07, PS	0.3, VFS	0.8, P

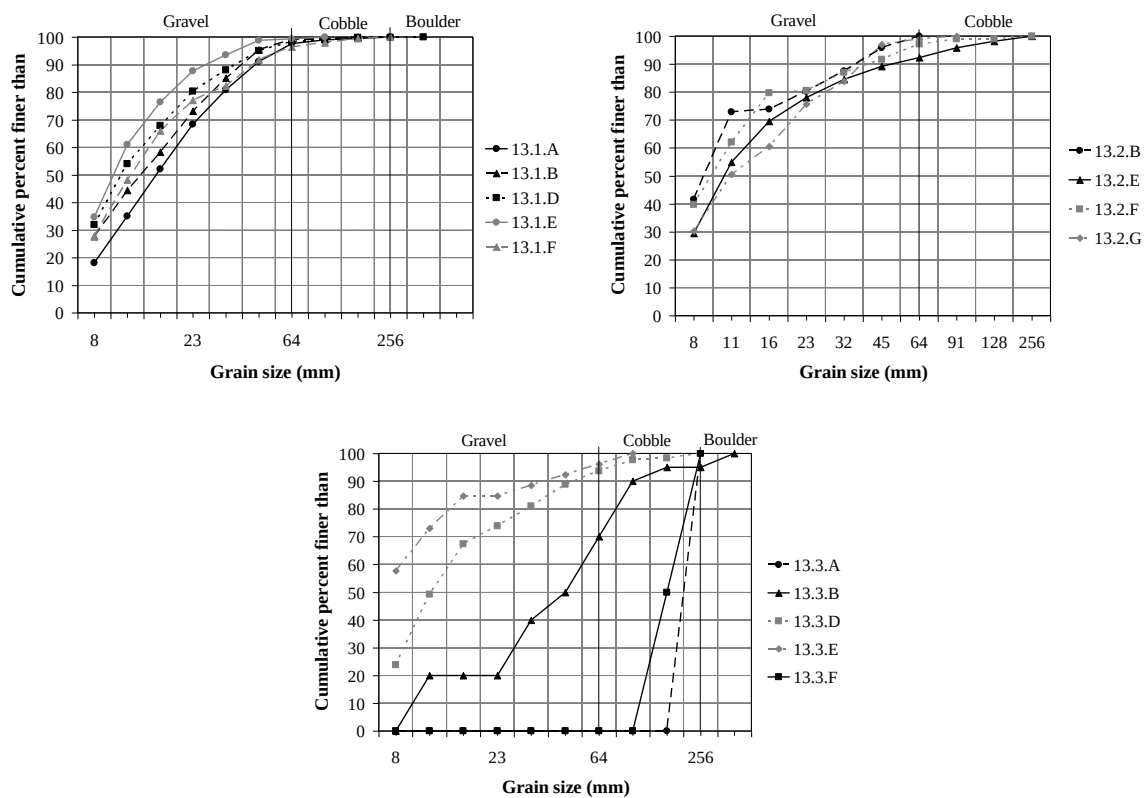
Appendix 5.23: Grain size cumulative curves for coarse sediments, unconfined sites 5, 10 and 13.

Quadrat codes and features as per Appendix 5.1.



Appendix 5.24: Continued

(c) Site 13, Baviaanskloof Nature Reserve



Appendix 5.25: Grain size percentage data for coarse sediments, unconfined study sites.

FG = Fine gravel, MG = Medium gravel, CG = Coarse gravel, VCG = Very coarse gravel, SC = Small cobble, LC = Large cobble and B = Boulder. Quadrat codes and features as per Appendix 5.1. Excluded quadrats limited to fine sediments only.

Size class	FG	MG	MG	CG	CG	VCG	VCG	SC	SC	LC	B
Grain size, mm	8	11.3	16	22.6	32	45.3	64	90.5	128	256	>256
(phi-units)	(-3)	(-3.5)	(-4)	(-4.5)	(-5)	(-5.5)	(-6)	(-6.5)	(-7)	(-8)	(>-8)
4.1.A	28.4	21.9	20.7	11.2	6.5	4.7	2.4	1.2	1.2	1.2	0.6
4.1.B	37.3	24.7	15.5	10.0	7.4	4.1	1.1	0.0	0.0	0.0	0.0
4.1.C	62.5	26.8	1.8	2.7	0.9	2.7	0.9	0.9	0.9	0.0	
4.1.D	42.9	14.3	19.0	11.1	7.1	2.9	1.1	1.1	0.3	0.2	0.0
4.1.E	21.2	18.0	15.3	13.9	8.6	7.0	8.0	4.3	2.7	1.1	0.0
4.1.F	24.3	19.2	17.8	14.6	10.7	7.9	2.9	1.3	1.0	0.2	0.0
4.1.G	37.5	0.0	25.0	6.3	0.0	12.5	6.3	0.0	6.3	6.3	0.0
4.1.H	27.0	20.3	15.8	13.5	9.0	4.5	4.1	2.3	1.4	1.8	0.5
4.1.I	37.7	25.4	18.3	12.1	2.6	0.8	1.8	0.5	0.1	0.3	0.3
4.1.J	33.5	12.2	12.5	15.5	12.2	6.1	6.1	0.6	0.3	0.6	0.3
4.1.K	50.0	29.2	8.3	6.9	0.0	2.8	1.4	0.0	1.4	0.0	0.0
4.1.L	28.6	19.0	19.7	10.9	8.8	6.1	4.1	0.7	0.0	2.0	0.0
4.2.A	25.2	20.7	18.4	13.8	8.0	6.7	5.7	1.4	0.2	0.0	0.0
4.2.B	44.4	18.5	11.1	3.7	3.7	0.0	0.0	0.0	7.4	11.1	0.0
4.2.C	23.9	21.1	19.1	5.7	10.0	7.7	6.2	2.9	1.4	0.5	1.4
4.2.D	23.9	20.8	19.1	16.4	9.7	6.1	2.8	1.1	0.0	0.0	0.1
4.2.E	38.9	18.5	9.6	9.8	11.9	8.1	2.2	0.4	0.4	0.0	0.2
4.2.F	28.2	21.4	19.4	10.7	7.8	4.4	2.9	3.9	0.5	1.0	0.0
4.2.G	58.1	7.0	14.0	9.3	2.3	4.7	2.3	2.3	0.0	0.0	0.0
4.2.I	68.7	19.3	4.8	2.4	0.0	0.0	0.0	0.0	3.6	0.0	1.2
4.2.J	50.0	0.0	0.0	0.0	0.0	50.0	0.0	0.0	0.0	0.0	0.0
4.3.A	0.0	0.0	0.0	20.0	20.0	0.0	40.0	20.0	0.0	0.0	0.0
4.3.B	39.8	0.0	9.1	9.1	12.5	11.4	9.1	1.1	3.4	2.3	2.3
4.3.C	17.3	19.5	16.5	12.9	11.7	8.5	8.2	3.5	1.4	0.5	0.1
4.3.D	50.1	10.2	13.8	7.7	4.1	6.4	4.9	1.3	0.5	0.8	0.3
4.3.E	31.4	18.8	18.8	11.0	7.8	5.1	5.1	1.6	0.0	0.4	0.0
4.3.F	50.0	26.9	3.8	7.7	0.0	0.0	3.8	0.0	0.0	7.7	0.0
4.3.G	25.9	0.0	22.4	6.9	5.2	19.0	6.9	8.6	1.7	1.7	1.7
4.3.H	65.4	7.7	5.0	3.8	4.6	5.4	4.6	1.5	1.2	0.4	0.4
4.3.I	26.7	21.9	16.3	11.6	8.2	7.0	6.0	0.8	0.8	0.6	0.2
5.1.A	59.1	13.6	4.5	4.5	0.0	0.0	0.0	4.5	4.5	9.1	0.0
5.1.B	45.4	23.6	17.8	6.3	3.4	2.3	0.0	0.6	0.6	0.0	0.0
5.1.C	48.6	26.4	19.3	1.4	0.7	0.7	0.7	0.7	0.7	0.7	0.0
5.1.D	28.7	23.2	17.2	13.1	7.6	4.6	2.8	1.2	1.2	0.4	0.0
5.1.E	35.3	17.5	17.5	10.6	8.2	3.4	3.4	2.1	1.0	0.7	0.3
5.1.F	41.7	16.0	19.4	8.3	6.3	2.1	3.1	0.7	2.1	0.0	0.3
5.1.G	46.1	22.3	17.1	11.2	0.7	0.0	0.0	0.4	1.1	0.7	0.4
5.1.H	29.5	24.3	16.2	11.0	5.2	2.9	4.6	2.3	1.7	1.7	0.6
5.1.I	33.9	27.2	20.0	10.5	4.1	1.0	1.4	0.9	0.7	0.2	0.1
5.1.J	33.8	12.3	16.2	15.5	11.6	3.9	4.2	1.1	1.1	0.0	0.4
5.2.A	38.6	27.6	20.5	9.7	3.4	0.1	0.0	0.0	0.1	0.0	0.0
5.2.B	27.4	23.8	17.7	14.1	8.4	3.3	3.1	1.5	0.3	0.2	0.1
5.2.C	30.9	23.2	17.3	12.0	8.4	4.3	2.2	0.8	0.4	0.5	0.1
5.2.D	35.8	23.2	10.6	6.6	6.6	4.6	4.0	4.0	3.3	0.7	0.7
5.2.E	43.1	15.7	10.5	10.5	6.5	4.6	2.6	2.0	3.3	0.7	0.7
5.2.F	40.3	25.6	13.7	6.0	6.9	3.1	2.3	1.3	0.6	0.0	0.2
5.2.G	50.5	27.1	7.5	6.5	4.7	1.9	0.9	0.0	0.0	0.9	0.0
5.3.A	39.4	20.4	7.3	8.8	2.9	3.6	5.8	6.6	2.2	2.2	0.7
5.3.B	30.7	26.0	18.0	12.5	6.1	2.8	2.2	1.4	0.3	0.0	0.0
5.3.C	37.3	23.2	19.0	11.3	3.5	1.4	0.7	2.8	0.7	0.0	0.0
5.3.D	32.5	22.9	17.9	10.6	6.6	4.0	2.8	1.4	1.2	0.0	0.0
5.3.E	32.2	21.5	18.0	12.1	7.5	4.3	2.2	1.2	0.7	0.1	0.1

Size class	FG	MG	MG	CG	CG	VCG	VCG	SC	SC	LC	B
Grain size, mm	8	11.3	16	22.6	32	45.3	64	90.5	128	256	>256
(phi-units)	(-3)	(-3.5)	(-4)	(-4.5)	(-5)	(-5.5)	(-6)	(-6.5)	(-7)	(-8)	(>-8)
5.3.F	30.0	21.9	17.4	12.5	7.5	4.7	2.9	1.7	1.2	0.2	0.2
5.3.G	37.5	22.4	16.4	9.2	5.9	3.3	2.6	0.7	0.7	1.3	0.0
5.3.H	48.5	27.3	12.1	6.1	1.5	1.5	1.5	1.5	0.0	0.0	0.0
5.3.I	56.6	25.4	8.1	4.6	1.7	1.2	1.2	0.0	0.6	0.0	0.6
5.3.J	40.5	32.6	13.3	7.6	2.7	1.5	0.4	1.1	0.4	0.0	0.0
5.3.K	38.6	25.8	15.2	7.5	4.2	3.1	3.2	1.1	0.6	0.6	0.0
9.1.A	28.1	19.0	16.7	12.8	7.8	7.4	2.8	1.7	2.2	1.5	0.0
9.1.B	22.6	19.4	15.0	13.4	10.5	8.5	6.5	3.4	0.4	0.3	0.1
9.1.C	29.9	21.6	16.1	9.1	10.1	6.0	3.6	1.6	1.1	1.0	0.0
9.1.D	33.6	20.3	20.7	9.6	2.6	1.1	3.3	2.6	1.8	3.3	1.1
9.1.F	21.7	15.3	11.5	10.8	15.9	9.6	7.0	5.1	2.5	0.6	0.0
9.1.G	28.9	21.5	15.9	12.9	8.7	5.7	3.4	1.7	0.9	0.3	0.0
9.1.H	32.0	19.0	15.3	11.5	8.0	7.0	5.7	0.7	0.4	0.4	0.1
9.2.A	56.8	15.4	8.2	4.1	5.4	3.6	2.9	2.5	0.5	0.5	0.0
9.2.C	14.1	9.3	14.4	16.9	16.7	11.0	10.5	3.4	2.8	0.6	0.3
9.2.D	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
9.2.E	15.7	15.5	14.3	16.5	15.7	12.3	7.3	1.8	0.6	0.2	0.1
9.2.F	25.3	21.2	18.6	13.9	9.9	5.5	3.4	1.4	0.3	0.3	0.2
9.2.G	41.6	19.7	13.6	8.1	7.0	3.1	3.1	2.4	1.1	0.2	0.2
9.2.H	24.1	22.6	19.0	15.7	10.5	6.3	1.0	0.6	0.2	0.0	0.0
9.2.I	46.5	10.6	11.6	6.0	9.0	7.3	5.0	2.7	1.0	0.3	0.0
9.2.K	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
9.2.L	20.0	14.0	20.5	15.3	15.3	6.5	3.3	2.8	1.9	0.5	0.0
9.3.A	0.0	0.0	22.2	27.8	0.0	0.0	22.2	22.2	5.6	0.0	0.0
9.3.D	61.2	12.2	6.1	7.3	6.1	3.3	2.0	1.2	0.4	0.0	0.0
9.3.E	24.2	19.2	15.5	13.9	11.2	8.7	4.4	2.4	0.4	0.0	0.0
9.3.F	35.6	20.0	15.2	9.5	6.2	8.6	3.6	1.4	0.0	0.0	0.0
9.3.G	0.0	0.0	0.0	0.0	0.0	0.0	33.3	0.0	33.3	33.3	0.0
9.3.H	72.2	13.9	5.6	0.0	2.8	2.8	0.0	2.8	0.0	0.0	0.0
9.3.I	20.4	13.3	11.2	7.1	6.1	10.2	11.2	11.2	4.1	4.1	1.0
9.3.J	18.9	17.2	12.3	11.7	11.1	12.8	8.4	5.8	1.1	0.5	0.1
9.3.K	48.4	23.0	14.9	8.4	3.1	0.5	0.7	0.3	0.7	0.0	0.0
9.3.L	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0
9.3.M	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.7	33.3	0.0	0.0
10.1.A	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10.1.B	19.6	12.5	7.1	5.4	12.5	14.3	10.7	5.4	7.1	5.4	0.0
10.1.C	21.7	25.0	7.6	12.0	14.1	9.8	6.5	3.3	0.0	0.0	0.0
10.1.D	28.8	20.6	20.2	9.3	8.6	3.2	3.2	4.4	0.8	0.8	0.2
10.1.E	19.8	19.6	18.0	14.4	12.5	8.9	5.0	1.4	0.3	0.2	0.0
10.1.F	23.7	14.4	21.5	13.0	11.4	6.3	3.5	2.5	1.2	1.6	0.8
10.1.G	45.5	31.8	4.5	4.5	4.5	3.4	1.1	2.3	2.3	0.0	0.0
10.1.H	30.2	17.0	7.5	10.4	2.8	0.9	4.7	13.2	7.5	5.7	0.0
10.1.I	43.8	43.8	6.3	0.0	0.0	0.0	0.0	3.1	3.1	0.0	0.0
10.1.J	27.7	17.7	20.0	14.5	14.5	0.5	2.3	0.9	1.4	0.5	0.0
10.2.A	0.0	0.0	0.0	0.0	0.0	50.0	50.0	0.0	0.0	0.0	0.0
10.2.B	14.9	16.4	15.9	15.6	14.5	11.7	7.5	2.8	0.6	0.1	0.0
10.2.C	23.8	20.4	18.1	11.7	10.6	5.3	5.7	1.9	1.1	1.5	0.0
10.2.D	24.7	19.5	15.8	13.8	9.7	6.2	5.9	3.9	0.6	0.0	0.0
10.2.E	23.1	19.6	16.8	16.0	11.9	7.0	4.2	1.1	0.2	0.0	0.0
10.2.F	19.8	18.9	19.4	14.9	11.3	8.1	5.9	1.8	0.0	0.0	0.0
10.2.G	0.0	0.0	0.0	0.0	66.7	33.3	0.0	0.0	0.0	0.0	0.0
10.2.H	7.1	21.3	9.9	21.3	17.7	8.5	10.6	2.1	1.4	0.0	0.0
10.2.I	24.0	20.7	17.5	11.5	13.8	9.2	2.3	0.9	0.0	0.0	0.0
10.2.J	42.0	29.4	21.0	2.5	2.5	0.8	0.0	0.0	1.7	0.0	0.0
10.2.K	0.0	0.0	0.0	20.0	0.0	20.0	20.0	40.0	0.0	0.0	0.0
10.3.A	38.3	22.1	20.3	6.8	3.2	2.3	3.6	1.4	1.4	0.9	0.0
10.3.B	62.5	22.2	11.4	2.7	0.2	0.2	0.5	0.2	0.0	0.0	0.0
10.3.C	32.6	23.7	16.0	11.4	8.1	4.6	2.2	0.7	0.4	0.2	0.1
10.3.D	0.0	0.0	0.0	0.0	0.0	19.5	22.0	14.6	14.6	22.0	7.3
10.3.E	20.6	19.8	15.9	11.9	12.8	10.6	6.1	1.6	0.7	0.1	0.1
10.3.F	33.7	14.7	11.9	10.2	19.2	3.1	3.6	2.4	0.7	0.5	0.0

Size class	FG	MG	MG	CG	CG	VCG	VCG	SC	SC	LC	B
Grain size, mm	8	11.3	16	22.6	32	45.3	64	90.5	128	256	>256
(phi-units)	(-3)	(-3.5)	(-4)	(-4.5)	(-5)	(-5.5)	(-6)	(-6.5)	(-7)	(-8)	(>-8)
10.3.G	51.0	33.8	10.8	3.2	1.3	0.0	0.0	0.0	0.0	0.0	0.0
10.3.H	8.3	25.0	16.7	0.0	0.0	16.7	16.7	8.3	8.3	0.0	0.0
10.3.I	34.1	17.6	25.8	14.8	2.2	2.2	1.1	1.6	0.5	0.0	0.0
13.1.A	18.1	16.8	17.1	16.3	12.4	10.4	6.5	1.3	0.5	0.5	0.0
13.1.B	27.8	16.7	13.9	14.8	12.0	10.2	3.7	0.0	0.9	0.0	0.0
13.1.D	31.9	22.1	13.8	12.4	7.7	7.0	3.3	0.7	0.7	0.0	0.2
13.1.E	34.7	26.3	15.4	11.3	5.9	5.3	0.6	0.6	0.0	0.0	0.0
13.1.F	27.9	20.3	17.8	11.2	5.1	9.6	4.6	1.5	1.5	0.5	0.0
13.2.B	41.7	31.3	1.0	6.3	7.3	8.3	4.2	0.0	0.0	0.0	0.0
13.2.E	29.5	25.4	14.6	8.6	6.3	4.8	3.2	3.5	2.2	1.9	0.0
13.2.F	39.8	22.2	17.6	0.9	6.5	4.6	5.6	1.9	0.0	0.9	0.0
13.2.G	30.3	20.2	10.1	15.2	8.1	13.1	2.0	1.0	0.0	0.0	0.0
13.3.A	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0
13.3.B	0.0	20.0	0.0	0.0	20.0	10.0	20.0	20.0	5.0	0.0	5.0
13.3.D	23.8	25.4	18.3	6.3	7.1	7.9	4.8	4.0	0.8	1.6	0.0
13.3.E	57.7	15.4	11.5	0.0	3.8	3.8	3.8	3.8	0.0	0.0	0.0
13.3.F	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	50.0	0.0

Appendix 5.26: Coarse sediment summary statistics for unconfined study sites.

After Bunte and Abt (2001), Kondolf *et al.* (2003) and Mecklenburg (2006). Quadrat codes and features as per Appendix 5.1. Excluded quadrats limited to fine sediments only.

Abbreviations (descriptions) from Blott and Pye (2001) and representing the following: VWS = Very well sorted, WS= Well sorted, MWS = Moderately well sorted, MS = Moderately sorted, PS = Poorly sorted, VPS = Very poorly sorted, VFS = Very fine skewed, FS = Fine skewed, S = Symmetrical, CS = Coarse skewed and VCS = Very coarse skewed.

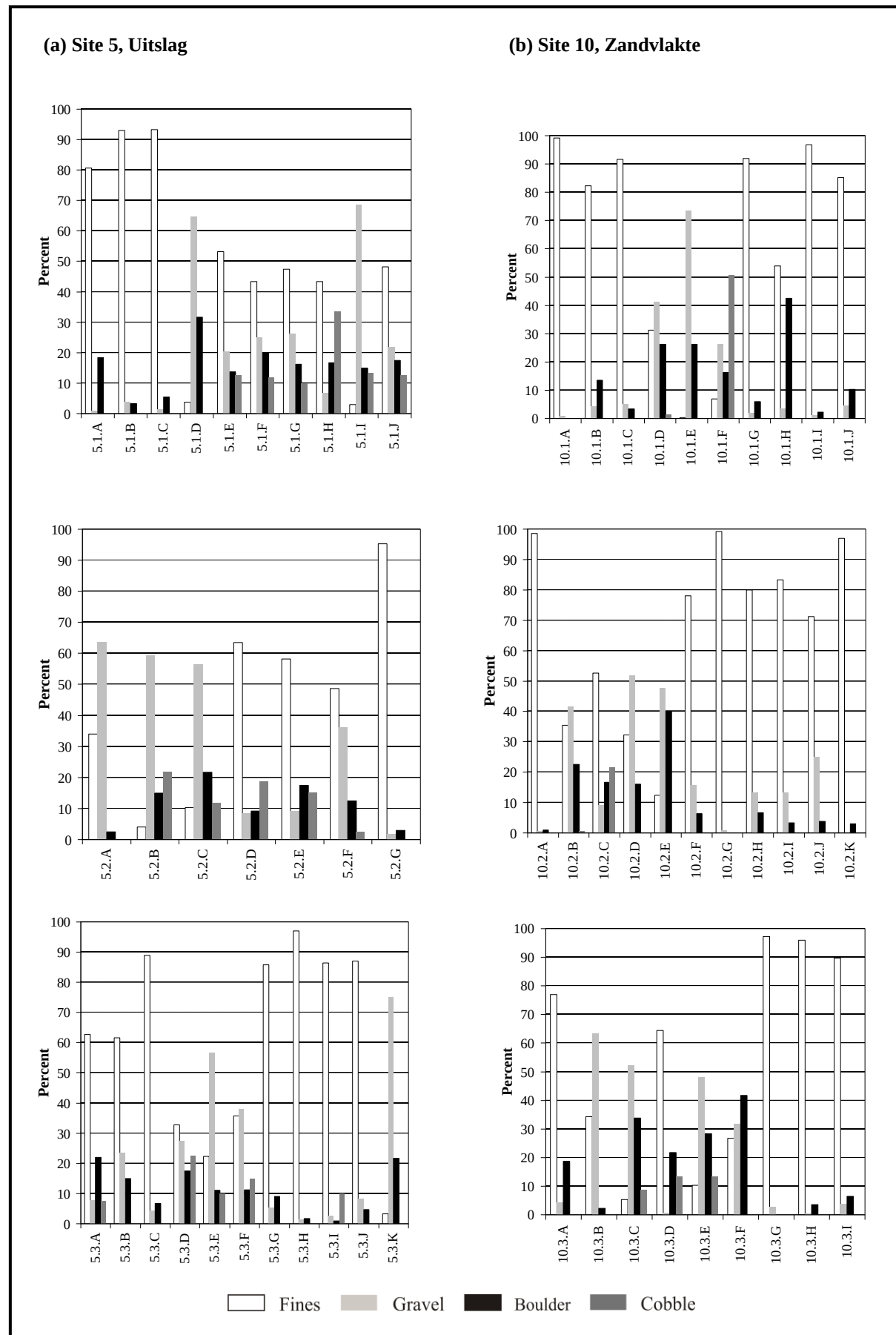
Quadrat	Percentile values (mm)					Geometric method (mm)		
	D ₁₆	D ₃₅	Median or D ₅₀	D ₈₄	D ₉₅	Mean	Sorting	Skewness
4.1.A	7.1	8.8	11	24	56	13.05	1.87, MS	0.1, S
4.1.B	6.8	7.9	9.4	20	32	11.66	1.76, MS	0.14, CS
4.1.C	6.5	7	7.6	10	33	8.06	1.24, VWS	0.06, S
4.1.D	6.7	7.6	9.4	20	34	11.58	1.77, MS	0.13, CS
4.1.E	7.5	10	14	45	82	18.37	2.54, PS	0.13, CS
4.1.F	7.3	9.6	13	29	47	14.55	2.01, PS	0.06, S
4.1.G	6.8	7.8	13	53	190	18.98	2.99, PS	0.17, CS
4.1.H	7.1	9.1	12	30	73	14.59	2.1, PS	0.11, CS
4.1.I	6.8	7.8	9.3	17	27	10.75	1.6, MWS	0.1, S
4.1.J	6.9	8.3	13	30	53	14.39	2.1, PS	0.06, S
4.1.K	6.6	7.3	8	14	34	9.61	1.48, MWS	0.14, CS
4.1.L	7	8.9	12	28	53	14.00	2.02, PS	0.09, S
4.2.A	7.2	9.3	12	29	52	14.45	2.04, PS	0.1, S
4.2.B	6.7	7.5	8.8	100	220	25.88	6.34, VPS	0.43, VCS
4.2.C	7.3	9.5	12	38	74	16.66	2.41, PS	0.17, CS
4.2.D	7.3	9.5	12	26	43	13.78	1.91, MS	0.08, S
4.2.E	6.8	7.8	9.7	28	42	13.80	2.16, PS	0.2, CS
4.2.F	7.1	8.9	11	27	66	13.85	2, MS	0.13, CS
4.2.G	6.5	7.1	7.7	19	44	11.11	1.83, MS	0.23, CS
4.2.I	6.4	6.9	7.4	10	21	8.00	1.25, VWS	0.08, S
4.2.J	6.6	7.3	8	40	43	16.25	3.11, PS	0.35, VCS
4.3.A	21	29	49	69	83	38.07	1.87, MS	-0.15, FS
4.3.B	6.7	7.7	17	49	120	18.12	2.71, PS	0.03, S
4.3.C	7.8	11	15	41	67	17.88	2.33, PS	0.09, S
4.3.D	6.6	7.3	8	27	55	13.35	2.29, PS	0.28, CS
4.3.E	54	110	210	310	340	129.38	2.68, PS	-0.24, FS
4.3.F	6.6	7.3	8	18	200	10.90	1.73, MS	0.2, CS
4.3.G	7.2	13	17	57	93	20.26	2.86, PS	0.08, S
4.3.H	6.4	7	7.5	26	57	12.90	2.32, PS	0.3, CS
4.3.I	7.1	9	11	31	55	14.84	2.18, PS	0.16, CS
5.1.A	6.5	7.1	7.7	75	210	22.08	5.46, VPS	0.44, VCS
5.1.B	6.6	7.5	8.5	15	27	9.95	1.53, MWS	0.11, CS
5.1.C	6.6	7.4	8.1	13	19	9.26	1.42, MWS	0.11, CS
5.1.D	7	8.7	11	24	48	12.96	1.88, MS	0.1, S
5.1.E	6.8	8	10	25	58	13.04	1.99, MS	0.15, CS
5.1.F	6.7	7.6	9.4	21	52	11.86	1.82, MS	0.14, CS
5.1.G	6.6	7.5	8.5	15	21	9.95	1.53, MWS	0.11, CS
5.1.H	7	8.6	10	27	78	13.75	2.06, PS	0.18, CS

Quadrat	Percentile values (mm)					Geometric method (mm)		
	D ₁₆	D ₃₅	Median or D ₅₀	D ₈₄	D ₉₅	Mean	Sorting	Skewness
5.1.I	6.9	8.1	9.7	18	30	11.14	1.63, MS	0.09, S
5.1.J	6.9	8.3	12	27	52	13.65	1.99, MS	0.07, S
5.2.A	6.8	7.8	9.1	15	21	10.10	1.49, MWS	0.08, S
5.2.B	7.1	8.9	11	23	46	12.78	1.82, MS	0.09, S
5.2.C	7	8.5	10	23	42	12.69	1.86, MS	0.14, CS
5.2.D	6.8	8	9.7	35	87	15.43	2.52, PS	0.24, CS
5.2.E	6.7	7.6	9.2	28	84	13.70	2.21, PS	0.22, CS
5.2.F	6.7	7.7	9	20	42	11.58	1.78, MS	0.16, CS
5.2.G	6.6	7.3	8	15	29	9.95	1.54, MWS	0.16, CS
5.3.A	6.7	7.7	9.4	49	92	18.12	3.31, PS	0.31, VCS
5.3.B	7	8.4	10	20	39	11.83	1.71, MS	0.11, CS
5.3.C	6.8	7.9	9.5	18	37	11.06	1.65, MS	0.1, S
5.3.D	6.9	8.3	10	22	47	12.32	1.82, MS	0.13, CS
5.3.E	6.9	8.3	10	22	43	12.32	1.82, MS	0.13, CS
5.3.F	7	8.6	11	25	51	13.23	1.92, MS	0.11, CS
5.3.G	6.8	7.8	9.6	21	47	11.95	1.8, MS	0.14, CS
5.3.H	6.6	7.4	8.1	14	29	9.61	1.48, MWS	0.13, CS
5.3.I	6.5	7.2	7.7	12	23	8.83	1.37, WS	0.12, CS
5.3.J	6.7	7.7	8.8	15	26	10.02	1.51, MWS	0.1, S
5.3.K	6.8	7.8	9.2	19	48	11.37	1.71, MS	0.14, CS
9.1.A	7.1	9	12	31	69	14.84	2.14, PS	0.12, CS
9.1.B	7.4	9.8	13	36	61	16.32	2.26, PS	0.12, CS
9.1.C	7	8.6	11	29	56	14.25	2.1, PS	0.14, CS
9.1.D	6.9	8.2	10	22	110	12.32	1.82, MS	0.13, CS
9.1.F	7.4	11	17	44	80	18.04	2.44, PS	0.03, S
9.1.G	7	8.8	11	27	52	13.75	2.01, PS	0.13, CS
9.1.H	6.9	8.4	11	29	52	14.15	2.12, PS	0.14, CS
9.2.A	6.5	7.2	7.7	21	54	11.68	1.96, MS	0.25, CS
9.2.C	8.5	15	20	47	79	19.99	2.35, PS	0, S
9.2.D	48	51	54	60	63	53.67	1.12, VWS	-0.01, S
9.2.E	8	12	17	38	57	17.44	2.18, PS	0.01, S
9.2.F	7.2	9.3	12	27	48	13.94	1.96, MS	0.09, S
9.2.G	6.7	7.6	9.2	23	57	12.41	1.94, MS	0.18, CS
9.2.H	7.3	9.3	12	24	38	13.24	1.82, MS	0.06, S
9.2.I	6.6	7.5	8.9	32	60	14.53	2.47, PS	0.26, CS
9.2.K	190	200	210	240	250	213.54	1.12, VWS	0.02, S
9.2.L	7.6	11	15	31	65	15.35	2.02, PS	0.01, S
9.3.A	14	19	22	77	93	32.83	2.54, PS	0.2, CS
9.3.D	6.5	7.1	7.6	19	39	11.11	1.83, MS	0.24, CS
9.3.E	7.3	9.6	13	32	54	15.28	2.12, PS	0.09, S
9.3.F	6.8	8	10	28	45	13.80	2.14, PS	0.18, CS
9.3.G	53	92	110	220	240	107.98	2.04, PS	-0.01, S
9.3.H	6.4	6.9	7.3	10	34	8.00	1.26, VWS	0.09, S
9.3.I	7.5	11	20	73	180	23.40	3.16, PS	0.07, S
9.3.J	7.7	11	17	45	74	18.61	2.43, PS	0.04, S
9.3.K	6.6	7.4	8.2	15	23	9.95	1.54, MWS	0.14, CS
9.3.L	48	51	54	60	63	53.67	1.12, VWS	-0.01, S
9.3.M	69	77	83	110	120	87.12	1.26, VWS	0.05, S
10.1.A	12	13	13	15	16	13.42	1.12, VWS	0.04, S

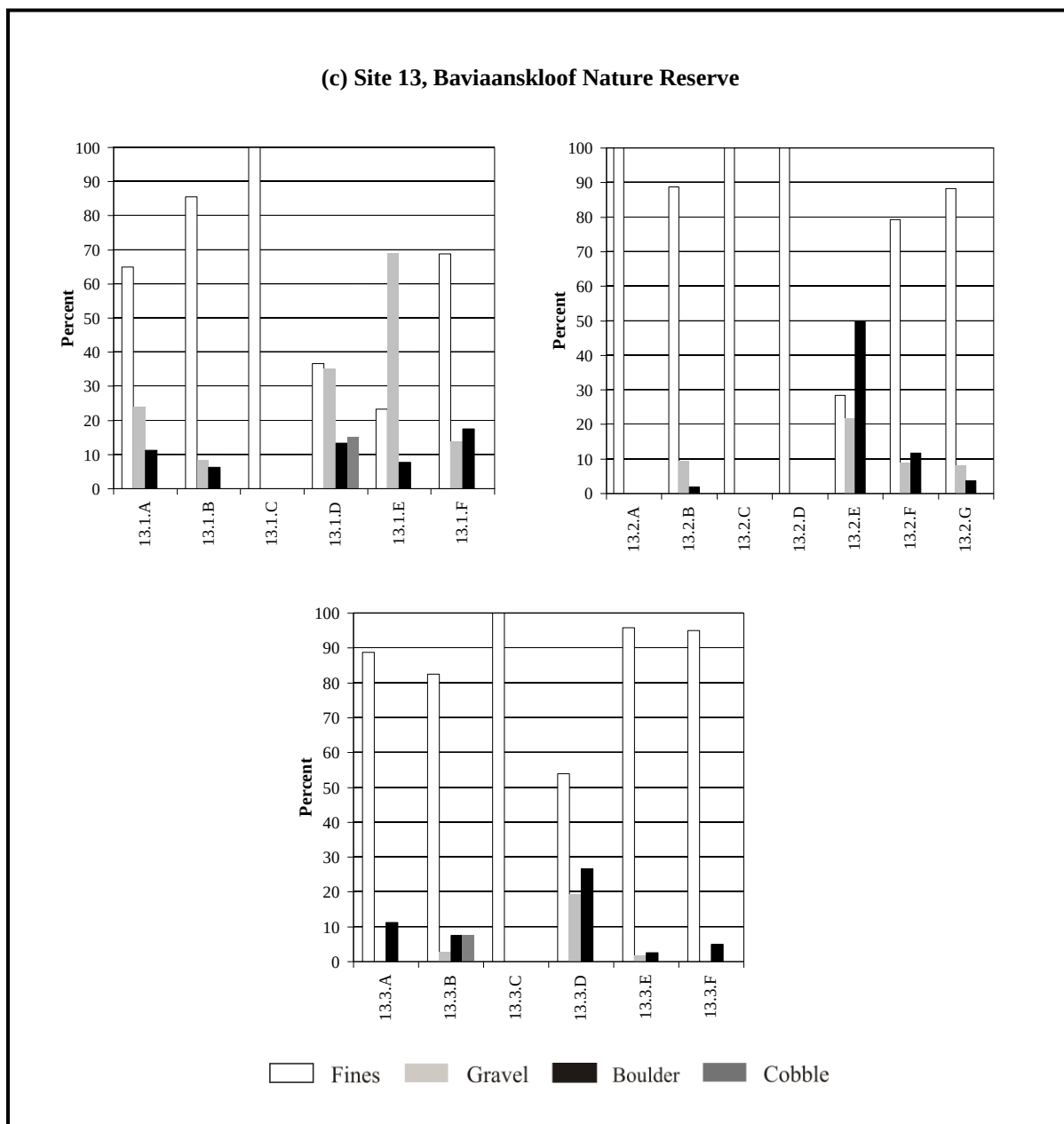
Quadrat	Percentile values (mm)					Geometric method (mm)		
	D ₁₆	D ₃₅	Median or D ₅₀	D ₈₄	D ₉₅	Mean	Sorting	Skewness
10.1.B	7.6	13	26	72	180	23.39	3.1, PS	-0.05, FS
10.1.C	7.4	9.5	13	36	58	16.32	2.26, PS	0.12, CS
10.1.D	7	8.8	11	28	70	14.00	2.06, PS	0.13, CS
10.1.E	7.6	10	14	32	51	15.59	2.06, PS	0.06, S
10.1.F	7.3	10	14	32	75	15.28	2.1, PS	0.05, S
10.1.G	6.6	7.5	8.4	19	56	11.20	1.77, MS	0.18, CS
10.1.H	7	8.8	13	84	190	24.25	4.16, VPS	0.26, CS
10.1.I	6.7	7.6	8.4	11	73	8.58	1.28, WS	0.02, S
10.1.J	7.1	9.1	12	24	45	13.05	1.85, MS	0.05, S
10.2.A	36	41	45	57	62	45.30	1.26, VWS	0.01, S
10.2.B	8.2	12	17	39	60	17.88	2.18, PS	0.03, S
10.2.C	7.3	9.5	12	31	62	15.04	2.11, PS	0.12, CS
10.2.D	7.2	9.5	13	33	62	15.41	2.17, PS	0.09, S
10.2.E	7.3	9.7	13	29	47	14.55	2.01, PS	0.06, S
10.2.F	7.6	10	14	32	53	15.59	2.06, PS	0.06, S
10.2.G	24	27	29	38	43	30.20	1.26, VWS	0.04, S
10.2.H	9.1	14	19	42	61	19.55	2.15, PS	0.02, S
10.2.I	7.3	9.5	12	29	42	14.55	2.03, PS	0.11, CS
10.2.J	6.7	7.6	8.7	14	22	9.69	1.45, MWS	0.08, S
10.2.K	21	41	54	79	86	40.73	2.02, PS	-0.16, FS
10.3.A	6.8	7.8	9.5	19	56	11.37	1.7, MS	0.12, CS
10.3.B	6.5	7	7.6	11	15	8.46	1.31, WS	0.1, S
10.3.C	6.9	8.3	10	22	40	12.32	1.82, MS	0.13, CS
10.3.D	42	58	78	220	290	96.12	2.34, PS	0.11, CS
10.3.E	7.5	10	14	35	55	16.20	2.18, PS	0.08, S
10.3.F	6.9	8.2	12	29	56	14.15	2.08, PS	0.09, S
10.3.G	6.6	7.3	8	11	16	8.52	1.29, WS	0.06, S
10.3.H	8.8	11	16	66	100	24.10	2.97, PS	0.19, CS
10.3.I	6.9	8.1	11	18	35	11.14	1.62, MWS	0.01, S
13.1.A	7.7	11	15	36	56	16.65	2.17, PS	0.06, S
13.1.B	7.1	9.3	13	32	49	15.07	2.15, PS	0.08, S
13.1.D	6.9	8.4	10	27	46	13.65	2.07, PS	0.18, CS
13.1.E	6.9	8	9.6	20	36	11.75	1.74, MS	0.13, CS
13.1.F	7.1	9	12	35	60	15.76	2.3, PS	0.14, CS
13.2.B	6.7	7.7	8.8	28	47	13.70	2.25, PS	0.24, CS
13.2.E	7	8.6	10	32	85	14.97	2.31, PS	0.22, CS
13.2.F	6.7	7.7	9.3	28	59	13.70	2.2, PS	0.21, CS
13.2.G	7	8.7	11	33	44	15.20	2.29, PS	0.17, CS
13.3.A	200	220	230	430	480	293.26	1.51, MWS	0.18, CS
13.3.B	10	30	48	89	390	29.83	3.33, PS	-0.21, FS
13.3.D	7.3	9.2	11	38	77	16.66	2.48, PS	0.21, CS
13.3.E	6.5	7.2	7.8	32	89	14.42	2.65, PS	0.32, VCS
13.3.F	110	190	230	450	490	222.49	2.02, PS	-0.02, FS

Appendix 5.27: Grain size percentage visual estimates for geomorphic landforms, unconfined sites 5, 10 and 13.

Quadrat codes and features as per Appendix 5.1

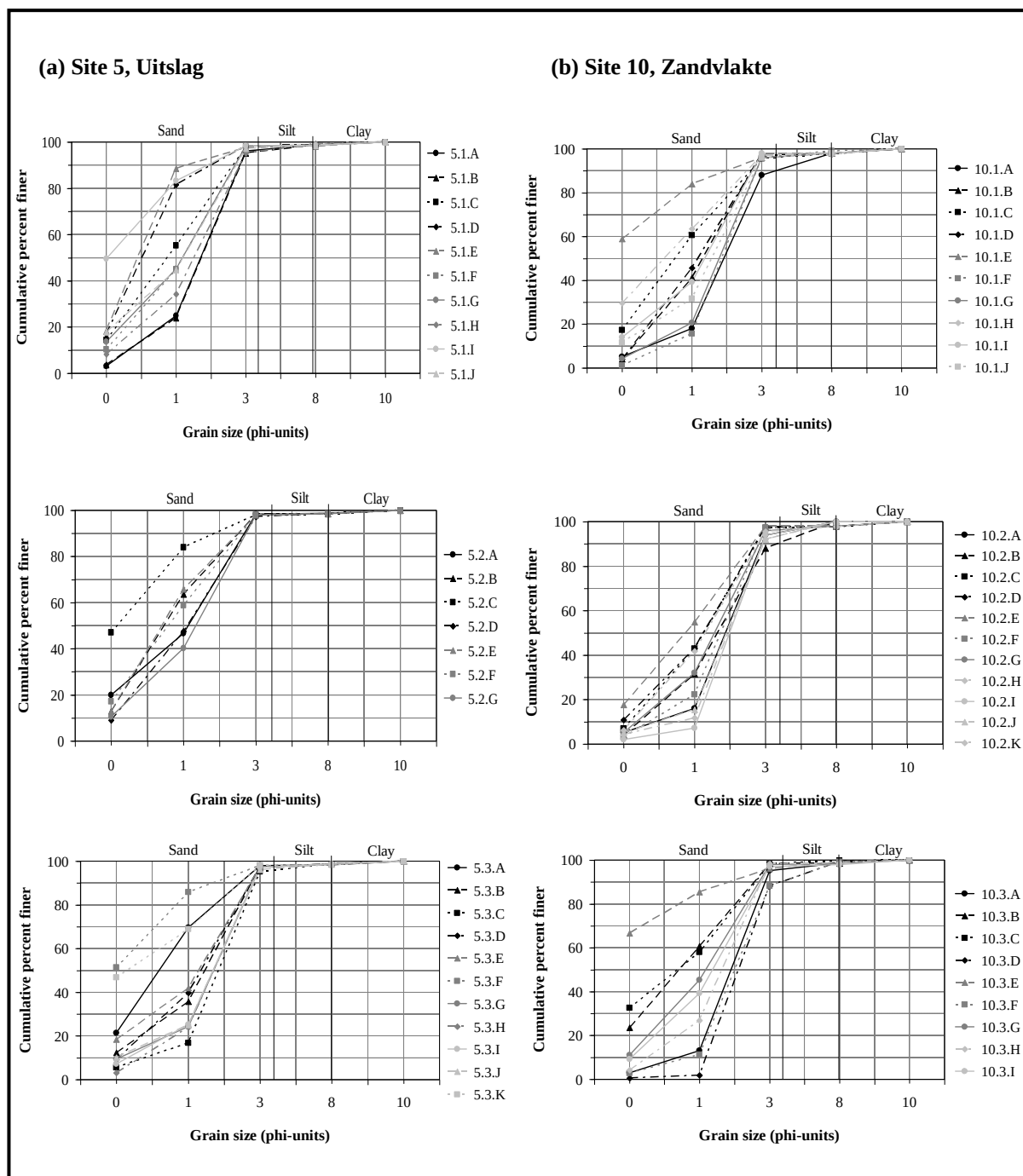


Appendix 5.28: continued



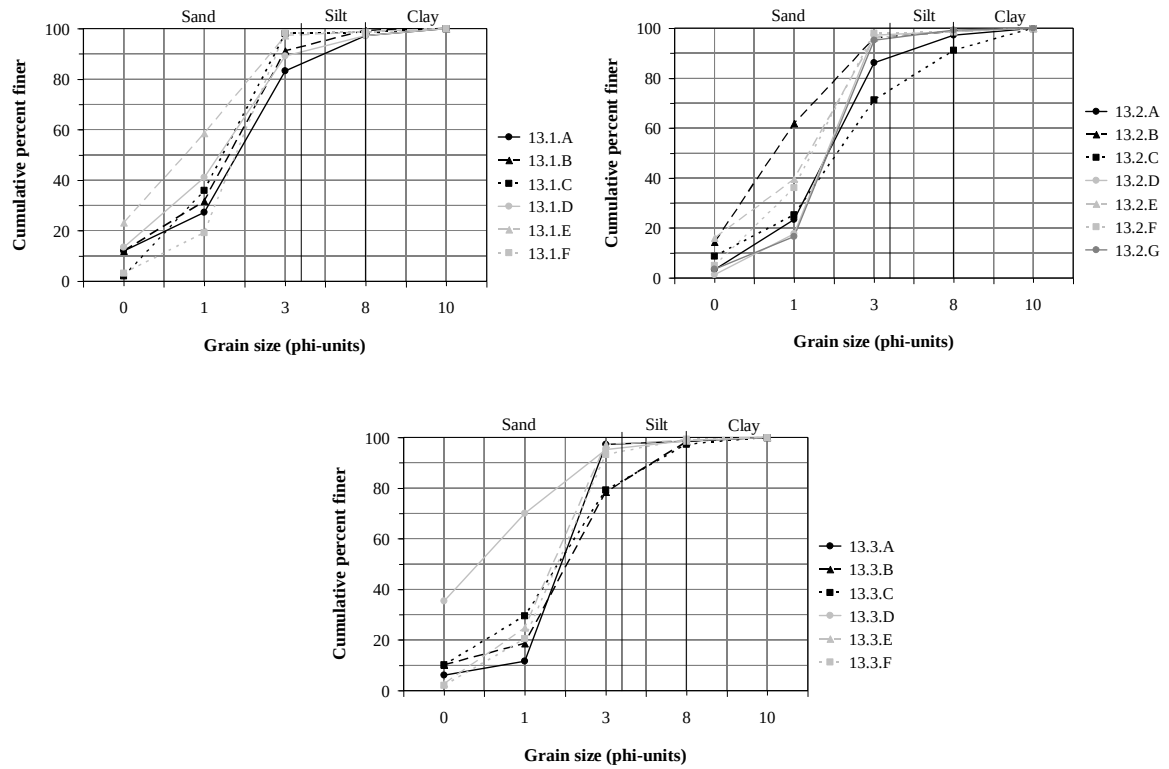
Appendix 5.29: Grain size cumulative curves for fine sediments, unconfined sites 5, 10 and 13.

Quadrat codes and features as per Appendix 5.1.



Appendix 5.30: Continued

(c) Site 13, Baviaanskloof Nature Reserve



Appendix 5.31: Fine sediment summary statistics for unconfined study sites.

After Bunte and Abt (2001), Kondolf *et al.* (2003) and Mecklenburg (2006). Quadrat codes and features as per Appendix 5.1. Abbreviations (descriptions) represent the following: VWS = Very well sorted, WS= Well sorted, MWS = Moderately well sorted, MS = Moderately sorted, PS = Poorly sorted, VPS = Very poorly sorted, EPS = Extremely poorly sorted, VFS = Very fine skewed, FS = Fine skewed, S = Symmetrical, CS = Coarse skewed, VCS = Very coarse skewed, VP = Very platykurtic, P = Platykurtic, M = Mesokurtic, L = Leptokurtic, VL = Very leptokurtic and EL = Extremely leptokurtic.

Quadrat	Percentile values (phi-units)					Folk and Ward method (phi-units)				
	Φ_{10}	Φ_{16}	Median or Φ_{50}	Φ_{84}	Φ_{90}	Mean	Mode	Sorting	Skewness	Kurtosis
4.1.A	0.25	1.08	1.93	2.84	3.00	1.93	Bimodal	1.41, PS	0.16,FS	1.92, VL
4.1.B	0.07	0.27	1.45	2.65	2.86	1.46	Unimodal	1.26, PS	0.14,FS	1.04, M
4.1.C	0.03	0.21	1.25	2.54	2.77	1.33	Unimodal	1.06, PS	0.09, S	0.75, P
4.1.D	0.08	0.25	1.29	2.61	2.84	1.38	Unimodal	1.19, PS	0.2,FS	0.93, M
4.1.E	-0.07	0.10	0.88	2.36	2.64	1.11	Unimodal	1.04, PS	0.29,FS	0.79, P
4.1.F	-0.31	-0.21	0.41	1.21	2.01	0.47	Unimodal	0.82, MS	0.3, VFS	1.39, L
4.1.G	0.05	0.17	0.85	2.32	2.62	1.11	Unimodal	1, MS	0.35, VFS	0.82, P
4.1.H	0.05	0.17	0.85	2.33	2.62	1.12	Unimodal	1, MS	0.35, VFS	0.81, P
4.1.I	0.13	0.27	1.11	2.45	2.69	1.28	Unimodal	0.98, MS	0.23,FS	0.73, P
4.1.J	0.11	0.25	1.11	2.52	2.77	1.29	Unimodal	1.02, PS	0.24,FS	0.74, P
4.1.K	0.08	0.25	1.28	2.51	2.72	1.34	Unimodal	1.03, PS	0.08, S	0.75, P
4.1.L	0.06	0.28	1.52	2.72	2.93	1.51	Unimodal	1.47, PS	0.19,FS	1.31, L
4.2.A	-0.25	-0.17	1.01	2.55	2.82	1.15	Unimodal	1.36, PS	0.28,FS	0.95, M
4.2.B	0.26	0.45	1.52	2.57	2.75	1.51	Unimodal	0.96, MS	-0.01, S	0.74, P
4.2.C	-0.21	-0.03	0.60	1.95	2.42	0.84	Unimodal	0.97, MS	0.38, VFS	1.15, L
4.2.D	-0.42	-2.39	-0.14	0.64	0.91	0.04	Unimodal	0.7, MWS	0.66, VFS	2.19, VL
4.2.E	0.19	0.47	1.66	2.65	2.83	1.60	Unimodal	1.01, PS	-0.12, CS	0.84, P
4.2.F	0.04	0.20	1.20	2.81	4.24	1.40	Unimodal	1.8, PS	0.43, VFS	1.59, VL
4.2.G	0.43	1.08	1.90	2.71	2.86	1.90	Bimodal	0.89, MS	-0.16, CS	1.08, M
4.2.H	0.23	0.51	1.72	2.76	2.94	1.66	Unimodal	1.3, PS	0.11,FS	1.28, L
4.2.I	0.05	0.20	1.07	2.48	2.73	1.25	Unimodal	1.04, PS	0.21,FS	0.76, P
4.2.J	-0.01	0.21	1.43	2.58	2.79	1.41	Unimodal	1.08, PS	-0.03, S	0.76, P
4.3.A	0.11	0.23	0.88	2.31	2.60	1.14	Unimodal	0.95, MS	0.38, VFS	0.78, P
4.3.B	-0.26	-0.12	0.55	1.92	2.40	0.78	Unimodal	0.99, MS	0.37, VFS	1.15, L
4.3.C	-0.41	-1.88	-0.12	0.63	0.85	0.05	Unimodal	0.54, MWS	0.58, VFS	1.3, L
4.3.D	-0.14	0.05	0.92	2.36	2.63	1.11	Unimodal	1.06, PS	0.24,FS	0.77, P
4.3.E	0.09	0.29	1.44	2.56	2.76	1.43	Unimodal	1.03, PS	-0.02, S	0.76, P
4.3.F	0.02	0.20	1.27	2.50	2.71	1.32	Unimodal	1.04, PS	0.05, S	0.75, P
4.3.G	-0.21	-0.04	0.72	2.19	2.53	0.96	Unimodal	1.04, PS	0.32, VFS	0.85, P
4.3.H	-0.23	-0.10	1.07	2.49	2.74	1.16	Unimodal	1.14, PS	0.12,FS	0.71, P
4.3.I	-0.26	-0.16	0.79	2.31	2.60	0.99	Unimodal	1.1, PS	0.26,FS	0.75, P
5.1.A	0.31	0.59	1.71	2.66	2.83	1.65	Unimodal	0.95, MS	-0.1, CS	0.84, P
5.1.B	0.31	0.61	1.73	2.69	2.85	1.67	Unimodal	0.96, MS	-0.11, CS	0.85, P
5.1.C	-0.15	0.04	0.87	2.35	2.63	1.09	Unimodal	1.06, PS	0.26,FS	0.78, P
5.1.D	-0.20	-0.01	0.51	1.28	2.00	0.59	Unimodal	0.77, MS	0.3,FS	1.56, VL
5.1.E	-0.22	-0.03	0.45	0.93	1.31	0.44	Unimodal	0.67, MWS	0.2,FS	1.6, VL
5.1.F	-0.02	0.16	1.19	2.47	2.70	1.27	Unimodal	1.05, PS	0.1, S	0.75, P
5.1.G	-0.13	0.08	1.18	2.46	2.68	1.24	Unimodal	1.08, PS	0.07, S	0.74, P
5.1.H	0.07	0.30	1.52	2.63	2.83	1.48	Unimodal	1.07, PS	-0.06, S	0.77, P
5.1.I	-0.39	-1.00	0.01	1.11	1.89	0.26	Unimodal	0.81, MS	0.61, VFS	1.23, L
5.1.J	-0.21	-0.07	1.20	2.50	2.73	1.21	Unimodal	1.13, PS	0.04, S	0.71, P
5.2.A	-0.24	-0.15	1.13	2.44	2.68	1.16	Unimodal	1.13, PS	0.05, S	0.69, P
5.2.B	-0.11	0.06	0.73	2.17	2.52	0.99	Unimodal	1, MS	0.35, VFS	0.9, P
5.2.C	-0.38	-0.84	0.08	1.00	1.87	0.26	Unimodal	0.79, MS	0.53, VFS	1.25, L
5.2.D	0.03	0.18	1.10	2.47	2.71	1.25	Unimodal	1.05, PS	0.18,FS	0.76, P
5.2.E	-0.11	0.06	0.70	2.13	2.50	0.96	Unimodal	0.99, MS	0.37, VFS	0.95, M
5.2.F	-0.20	-0.03	0.79	2.28	2.58	1.01	Unimodal	1.06, PS	0.29,FS	0.8, P

Quadrat	Percentile values (phi-units)					Folk and Ward method (phi-units)				
	Φ_{10}	Φ_{16}	Median or Φ_{50}	Φ_{84}	Φ_{90}	Mean	Mode	Sorting	Skewness	Kurtosis
5.2.G	-0.03	0.18	1.34	2.52	2.72	1.34	Unimodal	1.06, PS	0, S	0.75, P
5.3.A	-0.26	-0.11	0.59	2.01	2.44	0.83	Unimodal	1.01, PS	0.36, VFS	0.99, M
5.3.B	-0.09	0.15	1.46	2.57	2.77	1.40	Bimodal	1.09, PS	-0.09, S	0.76, P
5.3.C	0.40	0.93	1.85	2.71	2.87	1.83	Unimodal	0.91, MS	-0.14, CS	0.97, M
5.3.D	0.03	0.22	1.35	2.53	2.74	1.37	Unimodal	1.05, PS	0.01, S	0.75, P
5.3.E	-0.22	-0.10	1.29	2.52	2.74	1.25	Bimodal	1.14, PS	-0.02, S	0.7, P
5.3.F	-0.39	-1.03	-0.01	0.95	1.68	0.20	Unimodal	0.77, MS	0.6, VFS	1.29, L
5.3.G	0.04	0.44	1.70	2.64	2.80	1.59	Bimodal	1.03, PS	-0.18, CS	0.94, M
5.3.H	0.33	0.61	1.71	2.64	2.80	1.65	Unimodal	0.94, MS	-0.11, CS	0.86, P
5.3.I	0.15	0.49	1.69	2.63	2.80	1.60	Unimodal	1, PS	-0.15, CS	0.91, M
5.3.J	-0.01	0.39	1.70	2.66	2.83	1.58	Bimodal	1.05, PS	-0.19, CS	0.94, M
5.3.K	-0.38	-1.40	0.14	2.03	2.44	0.62	Unimodal	1.08, PS	0.62, VFS	0.8, P
9.1.A	-0.22	-0.10	1.42	2.56	2.76	1.31	Bimodal	1.15, PS	-0.1, CS	0.71, P
9.1.B	0.03	1.45	1.37	6.87	2.76	1.38	Unimodal	1.06, PS	0, S	0.76, P
9.1.C	-0.29	-0.27	0.74	2.37	2.70	0.98	Unimodal	1.15, PS	0.3, VFS	0.73, P
9.1.D	-0.16	0.05	1.37	2.55	2.76	1.32	Bimodal	1.12, PS	-0.05, S	0.73, P
9.1.E	-0.26	-1.04	1.75	2.81	3.00	1.48	Bimodal	1.62, PS	0, S	1.36, L
9.1.F	0.23	0.47	1.61	2.62	2.79	1.56	Unimodal	0.98, MS	-0.07, S	0.78, P
9.1.G	-0.16	0.04	1.05	2.43	2.67	1.17	Unimodal	1.08, PS	0.15,FS	0.74, P
9.1.H	-0.20	-0.08	2.07	5.92	7.14	2.65	Bimodal	2.79, VPS	0.37, VFS	1.1, M
9.1.I	0.65	1.02	1.86	2.70	2.85	1.86	Unimodal	0.83, MS	-0.09, S	0.89, P
9.1.J	1.07	1.20	1.96	2.71	2.84	1.96	Unimodal	0.74, MS	-0.08, S	0.88, P
9.2.A	-0.13	0.38	1.77	2.65	2.80	1.60	Bimodal	1.06, PS	-0.26, CS	1.03, M
9.2.B	0.88	1.12	1.98	2.85	3.00	1.98	Unimodal	1.3, PS	0.22,FS	1.85, VL
9.2.C	-0.02	0.74	2.23	6.50	7.97	3.15	Trimodal	2.83, VPS	0.47, VFS	1.27, L
9.2.D	0.57	0.97	1.82	2.66	2.80	1.82	Unimodal	0.83, MS	-0.09, S	0.9, P
9.2.E	0.10	0.38	1.61	2.60	2.78	1.53	Unimodal	1.03, PS	-0.13, CS	0.83, P
9.2.F	-0.42	-3.23	-0.14	0.87	1.64	0.12	Unimodal	0.76, MS	0.7, VFS	1.89, VL
9.2.G	0.30	0.57	1.69	2.66	2.83	1.64	Unimodal	0.96, MS	-0.09, S	0.82, P
9.2.H	0.10	0.26	1.23	2.50	2.73	1.33	Unimodal	1.02, PS	0.13,FS	0.74, P
9.2.I	-0.08	0.12	1.20	2.49	2.71	1.27	Unimodal	1.07, PS	0.08, S	0.75, P
9.2.J	1.10	1.23	1.98	2.72	2.86	1.98	Unimodal	0.69, MWS	-0.02, S	0.77, P
9.2.K	1.18	1.31	2.05	2.78	2.91	2.05	Unimodal	0.78, MS	0.15,FS	1.04, M
9.2.L	-0.10	0.14	1.43	2.60	2.81	1.39	Bimodal	1.11, PS	-0.05, S	0.75, P
9.3.A	0.38	0.83	1.91	2.89	3.99	1.88	Unimodal	1.49, PS	0.18,FS	1.85, VL
9.3.B	0.12	0.63	1.79	2.70	2.86	1.71	Bimodal	1, PS	-0.19, CS	0.98, M
9.3.C	-0.04	0.13	1.07	2.51	2.76	1.24	Unimodal	1.08, PS	0.19,FS	0.76, P
9.3.D	0.32	0.59	1.69	2.65	2.81	1.64	Unimodal	0.95, MS	-0.09, S	0.83, P
9.3.E	0.37	0.77	1.82	2.73	2.89	1.78	Unimodal	1.06, PS	0, S	1.16, L
9.3.F	0.07	0.28	1.46	2.55	2.74	1.43	Unimodal	1.04, PS	-0.05, S	0.77, P
9.3.G	0.51	0.85	1.88	2.83	3.00	1.85	Unimodal	1.29, PS	0.17,FS	1.54, VL
9.3.H	0.94	1.13	1.93	2.74	2.88	1.93	Unimodal	0.79, MS	-0.08, S	0.89, P
9.3.I	0.10	0.29	1.40	2.56	2.76	1.42	Unimodal	1.03, PS	0.01, S	0.75, P
9.3.J	-0.40	-1.21	-0.07	0.70	0.87	0.09	Unimodal	0.52, MWS	0.52, VFS	0.96, M
9.3.K	0.19	0.45	1.61	2.59	2.77	1.55	Unimodal	0.98, MS	-0.1, S	0.8, P
9.3.L	1.13	1.29	2.21	3.14	6.21	2.66	Bimodal	1.82, PS	0.52, VFS	2.04, VL
9.3.M	0.02	0.33	1.65	2.69	2.88	1.56	Bimodal	1.21, PS	-0.02, S	1.03, M
10.1.A	0.38	0.84	1.91	2.89	3.99	1.88	Unimodal	1.49, PS	0.18,FS	1.86, VL
10.1.B	0.16	0.32	1.31	2.51	2.72	1.38	Unimodal	0.98, MS	0.1,FS	0.72, P
10.1.C	-0.21	-0.03	0.75	2.34	2.68	1.02	Unimodal	1.1, PS	0.33, VFS	0.82, P
10.1.D	0.14	0.29	1.17	2.49	2.72	1.32	Unimodal	0.99, MS	0.2,FS	0.72, P
10.1.E	-0.40	-1.70	-0.07	0.99	2.00	0.19	Unimodal	0.83, MS	0.68, VFS	1.46, L
10.1.F	0.61	1.02	1.85	2.70	2.85	1.85	Unimodal	0.83, MS	-0.09, S	0.89, P
10.1.G	0.35	0.71	1.78	2.68	2.84	1.72	Unimodal	0.94, MS	-0.13, CS	0.9, M
10.1.H	-0.32	-0.40	0.60	2.21	2.57	0.86	Unimodal	1.11, PS	0.36, VFS	0.76, P
10.1.I	-0.14	0.08	1.37	2.52	2.73	1.32	Bimodal	1.1, PS	-0.05, S	0.74, P
10.1.J	-0.07	0.22	1.57	2.63	2.81	1.47	Bimodal	1.09, PS	-0.13, CS	0.79, P
10.2.A	0.44	0.99	1.87	2.74	2.90	1.87	Unimodal	1.02, PS	0.01, S	1.23, L
10.2.B	0.22	0.44	1.66	2.86	3.83	1.65	Unimodal	1.49, PS	0.22,FS	1.35, L
10.2.C	0.08	0.25	1.26	2.51	2.73	1.34	Unimodal	1.03, PS	0.1, S	0.75, P
10.2.D	-0.04	0.16	1.25	2.50	2.72	1.30	Unimodal	1.07, PS	0.05, S	0.75, P
10.2.E	-0.21	-0.04	0.87	2.35	2.63	1.06	Unimodal	1.09, PS	0.24,FS	0.76, P
10.2.F	0.36	0.67	1.74	2.65	2.81	1.69	Unimodal	0.93, MS	-0.12, CS	0.87, P

Quadrat	Percentile values (phi-units)					Folk and Ward method (phi-units)				
	$\emptyset_{10}$	$\emptyset_{16}$	Median or $\emptyset_{50}$	$\emptyset_{84}$	$\emptyset_{90}$	Mean	Mode	Sorting	Skewness	Kurtosis
10.2.G	0.18	0.40	1.56	2.63	2.81	1.53	Unimodal	1.01, PS	-0.05, S	0.76, P
10.2.H	0.76	1.10	1.95	2.80	2.95	1.95	Bimodal	1.14, PS	0.11,FS	1.56, VL
10.2.I	1.06	1.20	1.99	2.77	2.91	1.99	Unimodal	0.88, MS	0.07, S	1.16, L
10.2.J	0.48	1.02	1.90	2.79	2.95	1.90	Unimodal	1.18, PS	0.11,FS	1.53, VL
10.2.K	0.10	0.27	1.30	2.57	2.79	1.38	Unimodal	1.04, PS	0.1, S	0.74, P
10.3.A	0.70	1.07	1.90	2.73	2.87	1.90	Unimodal	0.84, MS	-0.11, CS	0.94, M
10.3.B	-0.28	-0.20	0.71	2.23	2.55	0.93	Unimodal	1.08, PS	0.3,FS	0.76, P
10.3.C	-0.34	-0.65	0.68	2.29	2.59	0.91	Unimodal	1.13, PS	0.3,FS	0.68, P
10.3.D	1.19	1.33	2.12	2.90	3.81	2.12	Unimodal	1.15, PS	0.29,FS	1.77, VL
10.3.E	-0.41	-2.69	-0.12	0.92	1.84	0.14	Unimodal	0.81, MS	0.71, VFS	1.77, VL
10.3.F	0.86	1.12	2.01	2.89	3.81	2.01	Unimodal	1.32, PS	0.2,FS	1.83, VL
10.3.G	-0.05	0.14	1.18	2.47	2.70	1.26	Unimodal	1.06, PS	0.1, S	0.75, P
10.3.H	0.25	0.52	1.65	2.60	2.77	1.59	Unimodal	0.95, MS	-0.1, CS	0.82, P
10.3.I	0.03	0.23	1.37	2.55	2.76	1.38	Unimodal	1.06, PS	0, S	0.75, P
13.1.A	-0.08	0.26	1.81	3.29	5.41	1.79	Bimodal	1.89, PS	0.21,FS	1.65, VL
13.1.B	-0.08	0.20	1.62	2.76	2.96	1.53	Bimodal	1.49, PS	0.11,FS	1.29, L
13.1.C	0.24	0.41	1.45	2.55	2.74	1.47	Unimodal	0.96, MS	0.03, S	0.73, P
13.1.D	-0.12	0.09	1.37	2.78	3.50	1.42	Unimodal	1.72, PS	0.28,FS	1.42, L
13.1.E	-0.28	-0.20	0.76	2.32	2.63	0.97	Unimodal	1.11, PS	0.28,FS	0.74, P
13.1.F	0.43	0.80	1.78	2.64	2.79	1.74	Unimodal	0.88, MS	-0.13, CS	0.91, M
13.2.A	0.33	0.63	1.85	2.93	4.72	1.80	Unimodal	1.62, PS	0.21,FS	1.77, VL
13.2.B	-0.15	0.03	0.75	2.29	2.64	1.02	Unimodal	1.06, PS	0.35, VFS	0.86, P
13.2.C	0.08	0.45	2.08	6.20	7.67	2.90	Trimodal	2.8, VPS	0.46, VFS	1.25, L
13.2.D	0.54	0.90	1.81	2.67	2.82	1.79	Unimodal	0.85, MS	-0.1, S	0.89, P
13.2.E	-0.18	0.00	1.37	2.57	2.78	1.31	Bimodal	1.14, PS	-0.05, S	0.72, P
13.2.F	0.16	0.35	1.45	2.55	2.74	1.45	Unimodal	0.99, MS	0, S	0.74, P
13.2.G	0.50	0.95	1.85	2.71	2.87	1.84	Unimodal	0.88, MS	-0.11, CS	0.93, M
13.3.A	0.71	1.10	1.90	2.69	2.83	1.90	Bimodal	0.86, MS	-0.15, CS	1.06, M
13.3.B	-0.01	0.70	2.05	4.40	5.88	2.38	Bimodal	2.04, VPS	0.32, VFS	1.81, VL
13.3.C	-0.01	0.30	1.83	4.33	5.98	2.15	Bimodal	2.16, VPS	0.35, VFS	1.51, VL
13.3.D	-0.35	-0.56	0.42	2.11	2.59	0.75	Unimodal	1.11, PS	0.46, VFS	0.91, M
13.3.E	0.33	0.60	1.69	2.63	2.80	1.64	Unimodal	0.94, MS	-0.1, S	0.84, P
13.3.F	0.43	0.76	1.81	2.75	2.91	1.77	Unimodal	1.15, PS	0.09, S	1.29, L

Appendix 6.1: Presence/absence of species in the Baviaanskloof per confinement setting.

Code refers to the first four letters of the species family name as per Appendix 6.2. The s in brackets denotes a seedling.

Code	Confinement setting	Confined valley				Semi-confined valley				Unconfined valley				
	Species per study site	2	6	7	11	1	3	8	12	4	5	9	10	13
Malv	<i>Abutilon sonneratianum</i>			*				*				*	*	
Agav	<i>Agave americana</i>					*		*				*		
Poac	<i>Agrostis lachnantha</i>			*	*								*	
Sapi	<i>Allophylus decipiens</i>													*
Asph	<i>Aloe ferox</i>									*		*	*	
Amar	<i>Ammocharis coranica</i>										*	*		
Malv	<i>Anisodonteia triloba</i>					*		*				*		
Rubi	<i>Anthospermum spathulatum</i>					*	*			*	*			
Mese	<i>Aptenia cordifolia</i>							*						
Aste	<i>Arctotheca calendula</i>	*	*	*	*	*	*	*	*	*	*	*	*	*
Aste	<i>Arctotheca</i> sp.2	*				*			*	*				
Papa	<i>Argemone ochroleuca</i>	*	*	*	*	*	*	*	*	*	*	*	*	*
Faba	<i>Argyrolobium</i> sp.2					*								
Poac	<i>Aristida congesta</i>	*				*	*			*	*	*	*	
Aspa	<i>Asparagus aethiopicus</i>				*	*	*				*	*	*	
Aspa	<i>Asparagus africanus</i>										*			
Aspa	<i>Asparagus capensis</i>					*		*	*	*	*	*	*	*
Aspa	<i>Asparagus retrofractus</i>					*				*			*	
Aspa	<i>Asparagus suaveolens</i>									*		*	*	
Chen	<i>Atriplex semibaccata</i>	*	*	*	*		*	*		*	*	*	*	*
Poac	<i>Avena fatua</i>					*								
Salv	<i>Azima tetracantha</i>	*	*			*	*	*	*		*	*	*	*
Lami	<i>Ballota africana</i>	*	*				*	*	*			*	*	*
Apia	<i>Berula erecta</i> subsp. <i>thunbergii</i>								*					*
Aste	<i>Bidens bipinnata</i>							*						
Acan	<i>Blepharis capensis</i>										*			
Amar	<i>Boophone disticha</i>											*		
Capp	<i>Boscia oleoides</i>											*		
Cras	<i>Bryophyllum delagoense</i>							*					*	
Budd	<i>Buddleja glomerata</i>						*							
Budd	<i>Buddleja saligna</i>	*	*				*						*	
Asph	<i>Bulbine abyssinica</i>					*								
Asph	<i>Bulbine favosa</i>										*	*	*	
Asph	<i>Bulbinella</i> sp.					*								
Capp	<i>Cadaba aphylla</i>											*	*	
Apoc	<i>Carissa bispinosa</i>	*			*						*			
Mese	<i>Carpobrotus deliciosus</i>	*	*	*	*	*	*	*	*					*
Ulma	<i>Celtis africana</i>		*		*			*					*	*
Poac	<i>Cenchrus ciliaris</i>				*					*			*	
Euph	<i>Chamaesyce inequilatera</i>												*	
Pter	<i>Cheilanthes hirta</i>	*			*	*	*			*	*	*		
Pter	<i>Cheilanthes viridis</i>				*									*
Chen	<i>Chenopodium album</i>													*
Chen	<i>Chenopodium ambrosioides</i>							*						
Chen	<i>Chenopodium carinatum</i>				*			*			*	*		
Chen	<i>Chenopodium mucronatum</i>	*		*	*	*		*	*	*	*	*	*	*
Chen	<i>Chenopodium murale</i>			*				*				*		
Poac	<i>Chloris virgata</i>									*				

Code	Confinement setting	Confined valley				Semi-confined valley				Unconfined valley				
	Species per study site	2	6	7	11	1	3	8	12	4	5	9	10	13
Aste	<i>Chrysanthemoides monilifera</i>						*	*						
Aste	<i>Chrysocoma ciliata</i>	*	*	*	*	*	*	*	*	*	*	*	*	*
Aste ¹	<i>Cineraria lobata</i>			*		*	*	*	*	*				
Aste	<i>Cirsium vulgare</i>											*		
Ranu	<i>Clematis brachiata</i>		*					*						
Rosa	<i>Cliffortia strobilifera</i>				*			*	*					
Euph	<i>Clutia daphnoides</i>					*				*	*			
Euph	<i>Clutia</i> sp.1												*	
Euph	<i>Clutia</i> sp.2	*				*	*			*				
Comm	<i>Commelina africana</i>							*				*		
Comm	<i>Commelina benghalensis</i>							*						
Conv	<i>Convolvulus</i> sp.									*				
Aste	<i>Conyza bonariensis</i>	*	*	*	*	*		*				*		*
Aste	<i>Conyza scabrida</i>	*	*	*	*			*	*					*
Bras	<i>Coronopus didymus</i>	*			*			*				*		
Aste	<i>Cotula australis</i>	*	*	*	*	*	*	*	*	*	*	*	*	*
Aste	<i>Cotula coronopifolia</i>			*				*						
Aste	<i>Cotula</i> sp.1										*			
Aste	<i>Cotula</i> sp.2									*				
Cras	<i>Cotyledon orbiculata</i>			*										
Cras	<i>Crassula capitella</i>										*			
Cras	<i>Crassula cultrata</i>			*		*								
Cras	<i>Crassula expansa</i>							*					*	
Cras	<i>Crassula muscosa</i>					*	*				*	*		
Cras	<i>Crassula</i> sp.1	*	*		*	*				*			*	
Cras	<i>Crassula</i> sp.2	*	*	*	*	*		*		*				*
Cras	<i>Crassula</i> sp.3	*									*		*	
Cras	<i>Crassula tetragona</i>		*											
Cras	<i>Crassula tetragona</i> var.1			*		*								
Cras	<i>Crassula tetragona</i> var.2			*			*	*			*			
Cucu	<i>Cucumis</i> sp.						*			*	*			
Poac	<i>Cymbopogon plurinodis</i>				*								*	
Apoc	<i>Cynanchum capense</i>		*	*	*			*	*			*	*	
Poac	<i>Cynodon dactylon</i>			*	*			*	*			*	*	*
Poac	<i>Cynodon incompletus</i>	*	*		*	*	*	*		*	*	*	*	*
Cype	<i>Cyperus denudatus</i>		*	*				*	*					*
Cype	<i>Cyperus rubicundus</i>					*				*		*		
Cype	<i>Cyperus</i> sp.1			*										*
Cype	<i>Cyperus</i> sp.2									*				
Cype	<i>Cyperus</i> sp.3				*									*
Cype	<i>Cyperus textilis</i>		*	*					*				*	*
Sola	<i>Datura stramonium</i>		*	*				*						
Poac	<i>Digitaria argyrogapta</i>												*	
Poac	<i>Digitaria eriantha</i>	*	*	*		*	*		*			*		
Eben	<i>Diospyros austro-africana</i>					*								
Eben	<i>Diospyros lycioides</i>	*	*		*	*	*	*	*	*	*	*	*	*
Sapi	<i>Dodonaea angustifolia</i>	*			*	*	*			*	*	*		
Hyac	<i>Drimia</i> sp.1					*								
Hyac	<i>Drimia</i> sp.2												*	
Mese	<i>Drosanthemum hispidum</i>				*	*		*	*			*	*	*
Mese	<i>Drosanthemum lique</i>	*			*	*	*		*	*	*	*	*	
Mese	<i>Drosanthemum</i> sp.									*	*	*	*	
Mese	<i>Eberlanza ferox</i>		*				*			*	*		*	
Bora	<i>Ehretia rigida</i>										*	*	*	
Poac	<i>Ehrharta calycinia</i>	*				*								
Poac	<i>Ehrharta</i> sp.	*			*	*			*					*

Code	Confinement setting	Confined valley				Semi-confined valley				Unconfined valley				
	Species per study site	2	6	7	11	1	3	8	12	4	5	9	10	13
Cype	<i>Eleocharis</i> sp.		*						*					*
Aste	<i>Elytropappus rhinocerotis</i>	*	*			*	*			*	*	*	*	
Poly	<i>Emex australis</i>	*			*	*	*	*	*	*	*	*	*	*
Poac [†]	<i>Eragrostis curvula</i>	*	*	*	*	*	*		*	*	*	*	*	*
Poac	<i>Eragrostis lehmanniana</i>	*	*	*	*	*	*	*	*	*	*	*	*	*
Poac	<i>Eragrostis obtusa</i>							*					*	
Aste	<i>Eriocephalus africanus</i>									*				
Aste	<i>Eriocephalus</i> sp.					*								
Erio	<i>Eriospermum</i> sp.											*		
Myrt	<i>Eucalyptus</i> sp.	*												
Eben	<i>Euclea undulata</i>												*	
Euph	<i>Euphorbia grandidens</i>											*		
Euph	<i>Euphorbia mauritanica</i>	*			*	*	*			*	*	*	*	*
Chen	<i>Exomis microphylla</i>				*			*	*			*		
Aste	<i>Felicia muricata</i>				*	*						*	*	
Aste	<i>Felicia</i> sp.				*									
Cype	<i>Ficinia</i> sp.									*				
Mora	<i>Ficus burtt-davyi</i>		*											
Mora	<i>Ficus sur</i>		*	*	*			*	*					*
Fuma	<i>Fumaria muralis</i>							*					*	
Aizo	<i>Galenia procumbens</i>	*	*		*	*	*	*		*	*	*	*	
Aizo	<i>Galenia pubescens</i>	*		*		*	*		*		*	*	*	*
Aste	<i>Galinsoga parviflora</i>												*	
Rubi	<i>Galium tomentosum</i>		*	*		*		*				*	*	
Aste	<i>Gazania krebsiana</i>					*	*			*	*			
Thym	<i>Gnidia</i> sp.											*		
Tili	<i>Grewia robusta</i>											*		
Cela	<i>Gymnosporia heterophylla</i>	*	*					*	*		*	*	*	*
Scro	<i>Hebenstretia robusta</i>		*	*		*	*			*				
Aste	<i>Helichrysum foetidum</i>			*		*								
Aste	<i>Helichrysum pumilio</i>	*		*		*	*		*	*	*	*		
Aste	<i>Helichrysum rosum</i>	*	*	*		*	*		*	*	*	*	*	*
Aste	<i>Helichrysum</i> sp.									*				
Aste	<i>Helichrysum zeyheri</i>	*		*	*				*	*				
Bras	<i>Heliophila pendula</i>						*	*			*			
Malv	<i>Hermannia althaeoides</i>		*	*	*	*		*				*		
Malv	<i>Hermannia desertorum</i>	*								*	*	*	*	
Malv	<i>Hermannia diffusa</i>						*				*			
Malv	<i>Hermannia pulchella</i>											*		
Malv	<i>Hermannia</i> sp.1	*				*	*				*			
Malv	<i>Hermannia</i> sp.2	*				*				*	*			
Malv	<i>Hermannia</i> sp.3					*	*	*						
Malv	<i>Hermannia velutina</i>					*								
Apia	<i>Hydrocotyle</i> sp.								*					
Poac	<i>Hyparrhenia hirta</i>	*				*				*				
Moll	<i>Hypertelis salsoloides</i>									*	*			
Moll	<i>Hypertelis</i> sp.					*					*			
Aste	<i>Hypochaeris radicata</i>	*				*	*			*		*		
Hypo	<i>Hypoxis</i> sp.							*						
Aste	<i>Ifloga glomerata</i>				*	*	*			*	*			
Faba	<i>Indigofera denudata</i>									*				
Faba	<i>Indigofera</i> sp.					*								
Cype	<i>Isolepis prolifera</i>		*	*					*					*
Bign	<i>Jacaranda mimosifolia</i>							*						
Scro	<i>Jamesbrittenia atropurpurea</i>									*	*		*	
Scro	<i>Jamesbrittenia phlogiflora</i>							*		*		*		

Code	Confinement setting	Confined valley				Semi-confined valley				Unconfined valley				
		2	6	7	11	1	3	8	12	4	5	9	10	13
Junc	<i>Juncus oxycarpus</i>		*											*
Acan	<i>Justicia orchoides</i>											*		
Cras	<i>Kalanchoe rotundifolia</i>													*
Cras ¹	<i>Kalanchoe</i> sp.							*						
Acha	<i>Kiggelaria africana</i>							*						
Aste	<i>Lactuca capensis</i>							*			*			
Faba	<i>Lebeckia</i> sp.					*				*				
Hyac	<i>Ledebouria</i> sp.											*	*	
Lami	<i>Leonotis ocymlifolia</i>		*	*		*		*	*	*	*	*	*	
Bras	<i>Lepidium africanum</i>	*	*	*	*	*	*	*	*	*	*	*	*	*
Aste	<i>Leysera gnaphalodes</i>	*	*	*	*	*		*		*	*	*	*	
Moll	<i>Limeum aethiopicum</i>				*	*				*	*	*	*	
Scro	<i>Limosella grandiflora</i>	*		*										
Lobe	<i>Lobelia anceps</i>		*	*										
Lobe	<i>Lobelia</i> sp.		*											
Faba	<i>Lotononis pungens</i>									*	*	*	*	
Sola	<i>Lycium cinereum</i>	*	*	*	*	*	*	*	*	*	*	*	*	*
Sola	<i>Lycium oxycarpum</i>	*	*	*	*	*	*	*		*	*	*	*	*
Mese	<i>Malephora crocea</i>											*	*	*
Malv	<i>Malva parviflora</i>							*	*		*	*		
Scro	<i>Manulea</i> sp.	*				*			*	*	*	*		
Faba	<i>Medicago laciniata</i>									*				
Meli	<i>Melianthus comosus</i>	*	*	*		*	*	*				*		
Poac	<i>Melica decumbens</i>		*			*								
Poac	<i>Melinis repens</i>		*				*			*	*		*	
Lami	<i>Mentha longifolia</i>	*	*	*	*			*	*				*	*
Mese	<i>Mesembryanthemum aitonis</i>				*							*	*	*
Mese	<i>Mesembryanthemum guecherianum</i>											*		
Mese	<i>Mestoklema elatum</i>	*	*	*	*	*		*			*	*	*	
Aste	<i>Metalasia</i> sp.2	*			*	*	*		*	*	*	*	*	
Aste	<i>Mikania capensis</i>								*					
Poac	<i>Miscanthus capensis</i>													*
Acan	<i>Monechma incanum</i>												*	
Lora	<i>Moquiniella rubra</i>							*				*		
Poly	<i>Muraltia spinosa</i> (= <i>Nylandtia spinosa</i>)					*								
Scro	<i>Nemesia capensis</i> (= <i>fruticans</i>)	*	*	*	*	*		*			*	*	*	
Rubi	<i>Nenax microphylla</i>										*	*		
Budd	<i>Nuxia floribunda</i>							*	*					
Meli	<i>Nymanina capensis</i>			*			*			*	*	*		
Nymp	<i>Nymphaea</i> sp.								*					
Aste	<i>Oedera genistifolia</i>						*		*	*	*	*		
Onra	<i>Oenothera</i> sp.							*		*				
Olea	<i>Olea europaea</i> subsp. <i>africana</i>		*								*			
Cact	<i>Opuntia ficus-indica</i>									*		*		
Aste	<i>Osteospermum</i> sp.1	*			*	*	*	*	*	*	*	*	*	*
Aste	<i>Othonna</i> sp.	*				*								
Oxal	<i>Oxalis commutata</i>	*	*			*					*	*	*	
Oxal	<i>Oxalis corniculata</i>	*							*		*			
Oxal	<i>Oxalis</i> sp.1	*		*		*								
Oxal	<i>Oxalis</i> sp.2	*	*	*	*	*	*	*	*	*	*	*	*	*
Poac	<i>Panicum deustum</i>	*	*	*	*	*	*	*	*	*	*	*	*	*
Poac	<i>Panicum</i> sp.	*	*			*		*	*		*	*		*
Sapi	<i>Pappea capensis</i>							*		*		*	*	

Code	Confinement setting	Confined valley				Semi-confined valley				Unconfined valley				
	Species per study site	2	6	7	11	1	3	8	12	4	5	9	10	13
Poac	<i>Paspalum dilatatum</i>											*		*
Poac	<i>Paspalum paspaloides</i> (= <i>distichum</i>)		*	*	*			*	*				*	*
Gera ₁	<i>Pelargonium glutinosum</i>	*				*	*	*		*	*			
Gera	<i>Pelargonium grossularioides</i>					*								
Gera	<i>Pelargonium odoratissimum</i>									*				
Gera	<i>Pelargonium reniforme</i>	*					*	*						
Gera	<i>Pelargonium</i> sp.1	*				*								
Gera	<i>Pelargonium</i> sp.2 (s)					*								
Gera	<i>Pelargonium trifidum</i>									*				
Gera	<i>Pelargonium zonale</i>	*		*	*			*						
Pter	<i>Pellaea calomelanos</i>			*	*						*	*		
Poac	<i>Pennisetum clandestinum</i>	*	*	*	*	*	*	*	*		*		*	*
Poac	<i>Pennisetum setaceum</i>	*		*	*		*		*		*			
Aste	<i>Pentzia incana</i>	*									*	*	*	
Poly	<i>Persicaria attenuata</i>	*	*	*					*					
Poly	<i>Persicaria decipiens</i>		*	*				*	*					*
Poly	<i>Persicaria</i> sp.			*										
Rham	<i>Phytolacca paniculata</i>													*
Scro	<i>Phyllopodium diffusum</i>		*	*						*				*
Sola	<i>Physalis peruviana</i>													*
Phyt	<i>Phytolacca dioica</i>							*						
Plan	<i>Plantago lanceolata</i>							*			*			
Plum	<i>Plumbago auriculata</i>				*				*				*	*
Cary	<i>Pollichia campestris</i>	*	*	*	*	*		*	*	*	*	*	*	*
Cary	<i>Polycarpon tetraphyllum</i>	*		*			*	*	*		*		*	*
Poly	<i>Polygala fruticosa</i>									*				
Poly	<i>Polygala myrtifolia</i>					*					*			
Poly	<i>Polygonum</i> sp.1							*						
Poly	<i>Polygonum</i> sp.2							*						
Port	<i>Portulacaria afra</i>			*								*	*	
Pota	<i>Potamogeton pusillus</i>								*					
Aste	<i>Pseudognaphalium luteo-album</i>	*	*	*	*			*	*			*	*	*
Mese	<i>Psilocaulon granulicaule</i>		*			*		*					*	*
Aste	<i>Pteronia incana</i>	*				*				*				
Aste	<i>Pteronia staehelinoides</i>					*								
Cela	<i>Putterlickia pyracantha</i>				*			*		*		*	*	
Ranu	<i>Ranunculus multifidus</i>		*	*				*	*					*
Bras	<i>Raphanus raphanistrum</i>	*						*				*	*	
Bras	<i>Raphanus</i> sp.		*	*				*				*	*	
Bign	<i>Rhigozum obovatum</i>											*		
Acan	<i>Rhinacanthus</i> sp.		*											
Mese	<i>Rhombophyllum</i> sp.											*	*	
Faba	<i>Rhynchosia caribaea</i>		*					*					*	
Euph	<i>Ricinus communis</i>							*						*
Bras	<i>Rorippa nasturtium-aquaticum</i>		*	*				*					*	
Poly	<i>Rumex crispus</i>		*						*					
Mese	<i>Ruschia rigens</i>					*	*							
Sali	<i>Salix mucronata</i>	*	*	*	*			*	*					*
Chen	<i>Salsola kali</i>	*	*	*	*		*	*	*	*		*	*	
Lami	<i>Salvia stenophylla</i>												*	
Lami	<i>Salvia verbenacea</i>	*				*	*	*		*	*		*	
Faba	<i>Schotia latifolia</i>											*		
Anac	<i>Searsia lancea</i>	*	*	*				*		*	*	*	*	
Anac	<i>Searsia longispina</i>										*			

Code	Confinement setting	Confined valley				Semi-confined valley				Unconfined valley				
	Species per study site	2	6	7	11	1	3	8	12	4	5	9	10	13
Anac	<i>Searsia lucida</i>	*	*	*	*	*	*		*	*	*	*	*	
Anac	<i>Searsia pallens</i>				*							*	*	
Anac	<i>Searsia pyroides</i>		*	*		*		*	*			*	*	*
Anac	<i>Searsia refracta</i>	*		*	*				*	*	*	*	*	
Anac	<i>Searsia tormentosa</i>												*	
Scro	<i>Selago saxatilis</i>	*				*	*			*	*	*	*	
Scro	<i>Selago</i> sp.										*		*	
Aste	<i>Senecio deltoideus</i>											*		*
Aste	<i>Senecio glutinosus</i>								*					*
Aste	<i>Senecio leptophyllus</i>	*	*	*	*	*		*	*					
Aste	<i>Senecio</i> sp.2					*								
Poac	<i>Setaria</i> sp.					*					*			
Malv	<i>Sida</i> sp.							*						
Cary	<i>Silene</i> sp.					*								
Bras	<i>Sisymbrium capense</i>	*	*	*	*	*	*	*						
Sola	<i>Solanum hermannii</i> (= <i>linnaeanum</i>)		*	*				*	*	*		*		*
Sola	<i>Solanum mauritianum</i>					*		*						
Sola	<i>Solanum nigrum</i>		*					*				*		*
Sola	<i>Solanum nodiflorum</i>			*										
Sola	<i>Solanum pseudocapsicum</i>							*						
Sola	<i>Solanum tomentosum</i>		*	*				*		*	*	*	*	
Aste	<i>Sonchus oleraceus</i>							*			*	*		
Unkn	Sp. 12				*			*						
Cucu	Sp. 7							*						
Apia	Sp.1					*		*						
Poac	Sp.10		*		*			*					*	
Scro	Sp.11	*		*				*		*				
Viol	Sp.13											*		
Aste	Sp.2					*								
Aste	Sp.4										*			
Aste	Sp.6					*								
Irid	Sp.8	*				*	*			*	*			
Poac	Sp.9			*	*	*	*	*				*	*	*
Poac	<i>Sporobolus africanus</i>	*									*			
Lami	<i>Stachys aethiopica</i>					*		*		*				
Apoc	<i>Stapelia olivacea</i>										*			
Cary	<i>Stellaria media</i>	*		*				*	*					*
Poac	<i>Stenotaphrum secundatum</i>							*						*
Poac	<i>Stipagrostis namaquensis</i>	*					*			*				
Aste	<i>Stoebe plumosa</i>	*		*						*	*			*
Scro	<i>Sutera</i> (= <i>Chaenostoma</i>) <i>halimifolia</i>	*	*		*	*	*	*	*	*	*	*	*	*
Scro	<i>Sutera</i> sp.					*				*				
Faba	<i>Sutherlandia</i> sp.					*								
Aste	<i>Tagetes minuta</i>		*	*				*	*					
Port	<i>Talinum</i> sp.									*				
Bign	<i>Tecoma stans</i>							*						
Aizo	<i>Tetragonia spicata</i>				*				*				*	*
Lami	<i>Teucrium</i> sp.	*	*					*		*	*	*	*	
Thel	<i>Thelypteris</i> sp.													*
Poac	<i>Themeda triandra</i>					*								
Sant	<i>Thesium</i> sp.1					*								
Mese	<i>Trichodiadema setuliferum</i>											*		
Aste	<i>Troglophyton capillaceum</i>	*	*	*	*	*	*	*	*	*	*	*	*	*
Hyac	<i>Urginea altissima</i>									*	*	*	*	
Urti	<i>Urtica urens</i>							*	*					*

Code	Confinement setting	Confined valley				Semi-confined valley				Unconfined valley				
	Species per study site	2	6	7	11	1	3	8	12	4	5	9	10	13
Mimo	<i>Vachellia (Acacia) karroo</i>	*	*	*	*		*	*	*	*	*	*	*	*
Verb	<i>Verbena bonariensis</i>			*	*			*				*	*	
Scro	<i>Veronica anagallis-aquatica</i>	*	*	*	*				*					*
Scro	<i>Veronica persica</i>							*						
Visc	<i>Viscum continuum</i>						*	*				*	*	
Visc	<i>Viscum obscurum</i>									*	*			
Visc	<i>Viscum rotundifolium</i>							*		*		*		*
Camp	<i>Wahlenbergia</i> sp.	*								*				
Camp	<i>Wahlenbergia undulata</i>									*	*			
Scro	<i>Walafria (= Selago) geniculata</i>	*			*	*				*	*	*		
Sola	<i>Withania somnifera</i>		*											
Aste	<i>Xanthium spinosum</i>								*					
Scro	<i>Zaluzianskya</i> sp.	*		*					*		*	*		
Zygo	<i>Zygophyllum foetidum</i>		*	*				*	*			*	*	*
Total		100	90	91	82	120	74	133	83	110	109	130	118	83
Grand total per setting		363				410				550				

Appendix 6.2: Descriptions of plant species in the study area.

Four letter family code name in brackets as per Appendix 6.1.

Family and species name	Growth form	Life cycle	Indigenous or Exotic	Weed or invader
Acanthaceae (Acan)				
<i>Blepharis capensis</i>	Shrub	Perennial	Indigenous	
<i>Justicia orchiioides</i>	Shrub	Perennial	Indigenous	
<i>Monechma incanum</i>	Shrub	Perennial	Indigenous	
<i>Rhinacanthus</i> sp.	Herb	Perennial	Indigenous	
Achariaceae (Acha) (= Kiggelariaceae)				
<i>Kiggelaria africana</i>	Tree	Perennial	Indigenous	
Agavaceae (Agav)				
<i>Agave americana</i>	Succulent shrub	Perennial	Exotic	Proposed invader
Aizoaceae (Aizo)				
<i>Galenia procumbens</i>	Shrub	Perennial	Indigenous	
<i>Galenia pubescens</i>	Herb	Perennial	Indigenous	
<i>Tetragonia spicata</i>	Shrub	Perennial	Indigenous	
Anacardiaceae (Anac)				
<i>Searsia lancea</i>	Shrub	Perennial	Indigenous	
<i>Searsia longispina</i>	Tree	Perennial	Indigenous	
<i>Searsia lucida</i>	Shrub	Perennial	Indigenous	
<i>Searsia pallens</i>	Tree	Perennial	Indigenous	
<i>Searsia pyroides</i>	Shrub	Perennial	Indigenous	
<i>Searsia refracta</i>	Shrub	Perennial	Indigenous	
<i>Searsia tomentosa</i>	Shrub	Perennial	Indigenous	
Amaryllidaceae (Amar)				
<i>Ammocharis coranica</i>	Geophytic herb	Perennial	Indigenous	
<i>Boophone disticha</i>	Geophytic herb	Perennial	Indigenous	
Apiaceae (Apia) (= Araliaceae)				
<i>Berula erecta</i> subsp. <i>thunbergii</i>	Herb	Perennial	Indigenous	
<i>Hydrocotyle</i> sp.	Helophytic herb	Perennial	Indigenous	
Sp.1	Herb	Perennial	Indigenous	
Apocynaceae (Apoc) (= Asclepiadaceae)				
<i>Carissa bispinosa</i>	Shrub	Perennial	Indigenous	
<i>Cynanchum capense</i>	Climber/herb	Perennial	Indigenous	
<i>Stapelia olivacea</i>	Succulent herb	Perennial	Indigenous	
Asparagaceae (Aspa)				
<i>Asparagus aethiopicus</i>	Climber/herb	Perennial	Indigenous	
<i>Asparagus africanus</i>	Climber/shrub	Perennial	Indigenous	
<i>Asparagus capensis</i>	Shrub	Perennial	Indigenous	
<i>Asparagus retrofractus</i>	Climber/shrub	Perennial	Indigenous	
<i>Asparagus suaveolens</i>	Shrub	Perennial	Indigenous	
Asphodelaceae (Asph)				
<i>Aloe ferox</i>	Succulent shrub	Perennial	Indigenous	
<i>Bulbine abyssinica</i>	Succulent herb	Perennial	Indigenous	
<i>Bulbine favosa</i>	Geophytic herb	Perennial	Indigenous	
<i>Bulbinella</i> sp.	Succulent herb	Perennial	Indigenous	
Asteraceae (Aste)				
<i>Arctotheca calendula</i>	Herb	Annual	Indigenous	
<i>Arctotheca</i> sp.2	Herb	Annual/perennial	Indigenous	
<i>Bidens bipinnata</i>	Herb	Annual	Exotic	
<i>Chrysanthemoides monilifera</i>	Shrub	Perennial	Indigenous	
<i>Chrysocoma ciliata</i>	Shrub	Perennial	Indigenous	
<i>Cineraria lobata</i>	Herb	Perennial	Indigenous	
<i>Cirsium vulgare</i>	Herb	Annual/biennial	Exotic	Weed
<i>Conyza bonariensis</i>	Herb	Annual	Exotic	

Family and species name	Growth form	Life cycle	Indigenous or Exotic	Weed or invader
<i>Conyza scabrida</i>	Shrub	Perennial	Exotic	
<i>Cotula australis</i>	Herb	Annual	Indigenous	
<i>Cotula coronopifolia</i>	Helophytic herb	Perennial	Indigenous	
<i>Cotula</i> sp.1	Herb	Annual	Indigenous	
<i>Cotula</i> sp.2	Herb	Annual	Indigenous	
<i>Elytropappus rhinocerotis</i>	Shrub	Perennial	Indigenous	
<i>Eriocephalus africanus</i>	Shrub	Perennial	Indigenous	
<i>Eriocephalus</i> sp.	Shrub	Perennial	Indigenous	
<i>Felicia muricata</i>	Shrub	Perennial	Indigenous	
<i>Felicia</i> sp.	Herb	Annual/biennial/perennial	Indigenous	
<i>Galinsoga parviflora</i>	Herb	Annual	Exotic	
<i>Gazania krebsiana</i>	Herb	Perennial	Indigenous	
<i>Helichrysum foetidum</i>	Herb	Biennial	Indigenous	
<i>Helichrysum pumilio</i>	Herb	Perennial	Indigenous	
<i>Helichrysum rosum</i>	Shrub	Perennial	Indigenous	
<i>Helichrysum</i> sp.	Herb	Annual/perennial	Indigenous	
<i>Helichrysum zeyheri</i>	Shrub	Perennial	Indigenous	
<i>Hypochaeris radicata</i>	Herb	Perennial	Exotic	
<i>Ifloga glomerata</i>	Herb	Annual	Indigenous	
<i>Lactuca capensis</i>	Herb	Perennial	Indigenous	
<i>Leysera gnaphalodes</i>	Shrub	Perennial	Indigenous	
<i>Metalasia</i> sp.2	Shrub	Perennial	Indigenous	
<i>Mikania capensis</i>	Climber/herb	Perennial	Indigenous	
<i>Oedera genistifolia</i>	Shrub	Perennial	Indigenous	
<i>Osteospermum</i> sp.1	Herb	Annual/perennial	Indigenous	
<i>Othonna</i> sp.	Herb/shrub	Annual/perennial	Indigenous	
<i>Pentzia incana</i>	Shrub	Perennial	Indigenous	
<i>Pseudognaphalium luteo-album</i>	Herb	Annual	Indigenous	
<i>Pteronia incana</i>	Shrub	Perennial	Indigenous	
<i>Pteronia staezelinoides</i>	Shrub	Perennial	Indigenous	
<i>Senecio deltoideus</i>	Scrambler/herb	Perennial	Indigenous	
<i>Senecio glutinosus</i>	Herb	Annual	Indigenous	
<i>Senecio leptophyllus</i>	Herb	Perennial	Indigenous	
<i>Senecio</i> sp.2	Herb	Annual/biennial/perennial	Indigenous	
<i>Sonchus oleraceus</i>	Herb	Annual	Exotic	
Sp.2	Herb	Annual/biennial/perennial	Unknown	
Sp.4	Shrub	Perennial	Unknown	
Sp.6	Herb	Annual/biennial/perennial	Unknown	
<i>Stoebe plumosa</i>	Shrub	Perennial	Indigenous	
<i>Tagetes minuta</i>	Herb	Annual	Exotic	
<i>Troglophyton capillaceum</i>	Herb	Annual	Indigenous	
<i>Xanthium spinosum</i>	Herb	Annual	Exotic	Weed
Bignoniaceae (Bign)				
<i>Jacaranda mimosifolia</i>	Tree	Perennial	Exotic	Invader
<i>Rhigozum obovatum</i>	Shrub	Perennial	Indigenous	
<i>Tecoma stans</i>	Tree	Perennial	Exotic	Weed
Boraginaceae (Bora)				
<i>Ehretia rigida</i>	Shrub	Perennial	Indigenous	
Brassicaceae (Bras)				
<i>Coronopus didymus</i>	Herb	Biennial	Indigenous	
<i>Heliophila pendula</i>	Herb	Annual	Indigenous	
<i>Lepidium africanum</i>	Herb	Biennial	Indigenous	
<i>Raphanus raphanistrum</i>	Herb	Annual	Exotic	
<i>Raphanus</i> sp.	Herb	Annual	Unknown	
<i>Rorippa nasturtium-aquaticum</i>	Herb	Perennial	Exotic	
<i>Sisymbrium capense</i>	Herb	Annual	Indigenous	
Buddlejaceae (Budd)				

Family and species name	Growth form	Life cycle	Indigenous or Exotic	Weed or invader
<i>Buddleja glomerata</i>	Shrub	Perennial	Indigenous	
<i>Buddleja saligna</i>	Shrub	Perennial	Indigenous	
<i>Nuxia floribunda</i>	Tree	Perennial	Indigenous	
Cactaceae (Cact)				
<i>Opuntia ficus-indica</i>	Succulent shrub	Perennial	Exotic	Weed
Campanulaceae (Camp)				
<i>Wahlenbergia</i> sp.	Herb	Annual/perennial	Indigenous	
<i>Wahlenbergia undulata</i>	Herb	Perennial	Indigenous	
Capparaceae (Capp)				
<i>Boscia oleoides</i>	Tree	Perennial	Indigenous	
<i>Cadaba aphylla</i>	Shrub	Perennial	Indigenous	
Caryophyllaceae (Cary) (= Illecebraceae)				
<i>Polycarpon tetraphyllum</i>	Herb	Annual	Indigenous	
<i>Pollichia campestris</i>	Herb	Perennial	Indigenous	
<i>Silene</i> sp.	Herb	Annual/perennial	Unknown	
<i>Stellaria media</i>	Herb	Annual	Indigenous	
Celastraceae (Cela)				
<i>Gymnosporia heterophylla</i>	Shrub	Perennial	Indigenous	
<i>Putterlickia pyracantha</i>	Shrub	Perennial	Indigenous	
Chenopodiaceae (Chen)				
<i>Atriplex semibaccata</i>	Shrub	Annual/perennial	Exotic	
<i>Chenopodium album</i>	Herb	Annual	Exotic	
<i>Chenopodium ambrosioides</i>	Herb	Annual	Exotic	
<i>Chenopodium carinatum</i>	Herb	Annual	Exotic	
<i>Chenopodium mucronatum</i>	Herb	Annual	Indigenous	
<i>Chenopodium murale</i>	Herb	Annual	Exotic	
<i>Exomis microphylla</i>	Shrub	Perennial	Indigenous	
<i>Salsola kali</i>	Herb	Annual	Exotic	Weed
Commelinaceae (Comm)				
<i>Commelina africana</i>	Herb	Perennial	Indigenous	
<i>Commelina benghalensis</i>	Herb	Annual	Indigenous	
Convulvulaceae (Conv)				
<i>Convolvulus</i> sp.	Climber/herb	Perennial	Unknown	
Crassulaceae (Cras)				
<i>Bryophyllum delagoense</i>	Succulent shrub	Perennial	Exotic	
<i>Cotyledon orbiculata</i>	Succulent shrub	Perennial	Indigenous	
<i>Crassula capitella</i>	Succulent herb	Perennial	Indigenous	
<i>Crassula cultrata</i>	Succulent shrub	Perennial	Indigenous	
<i>Crassula expansa</i>	Succulent herb	Perennial	Indigenous	
<i>Crassula muscosa</i>	Succulent herb	Perennial	Indigenous	
<i>Crassula</i> sp.1	Succulent shrub	Annual/perennial	Indigenous	
<i>Crassula</i> sp.2	Succulent herb	Annual/perennial	Indigenous	
<i>Crassula</i> sp.3	Succulent shrub	Annual/perennial	Indigenous	
<i>Crassula tetragona</i>	Succulent shrub	Perennial	Indigenous	
<i>Crassula tetragona</i> var.1	Succulent shrub/herb	Perennial	Indigenous	
<i>Crassula tetragona</i> var.2	Succulent shrub/herb	Perennial	Indigenous	
<i>Kalanchoe rotundifolia</i>	Succulent shrub	Perennial	Indigenous	
<i>Kalanchoe</i> sp.	Succulent shrub	Perennial	Indigenous	
Cucurbitaceae (Curu)				
<i>Cucumis</i> sp.	Scrambler/herb	Annual/perennial	Indigenous	
Sp. 7	Climber/unknown	Annual/perennial	Indigenous	
Cyperaceae (Cype)				
<i>Cyperus denudatus</i>	Herb	Perennial	Indigenous	
<i>Cyperus rubicundus</i>	Herb	Annual	Indigenous	
<i>Cyperus</i> sp.1	Herb	Annual/perennial	Indigenous	
<i>Cyperus</i> sp.2	Herb	Annual/perennial	Indigenous	
<i>Cyperus</i> sp.3	Herb	Annual/perennial	Indigenous	

Family and species name	Growth form	Life cycle	Indigenous or Exotic	Weed or invader
<i>Cyperus textilis</i>	Herb	Perennial	Indigenous	
<i>Eleocharis</i> sp.	Helophytic herb	Annual/perennial	Indigenous	
<i>Ficinia</i> sp.	Herb	Perennial	Indigenous	
<i>Isolepis prolifera</i>	Helophytic herb	Perennial	Indigenous	
Ebenaceae (Eben)				
<i>Diospyros austro-africana</i>	Shrub	Perennial	Indigenous	
<i>Diospyros lycioides</i>	Shrub	Perennial	Indigenous	
<i>Euclea undulata</i>	Shrub	Perennial	Indigenous	
Eriospermaceae (Erio)				
<i>Eriospermum</i> sp.	Geophytic herb	Perennial	Indigenous	
Euphorbiaceae (Euph)				
<i>Chamaesyce inequilatera</i>	Herb	Annual	Indigenous	
<i>Clutia daphnoides</i>	Shrub	Perennial	Indigenous	
<i>Clutia</i> sp.1	Herb/shrub	Perennial	Indigenous	
<i>Clutia</i> sp.2	Herb	Perennial	Indigenous	
<i>Euphorbia grandidens</i>	Tree	Perennial	Indigenous	
<i>Euphorbia mauritanica</i>	Succulent shrub	Perennial	Indigenous	
<i>Ricinus communis</i>	Shrub	Perennial	Exotic	
Fabaceae (Faba)				
<i>Schotia latifolia</i>	Tree	Perennial	Indigenous	
<i>Argyrolobium</i> sp.2	Herb	Annual/perennial	Indigenous	
<i>Indigofera denudata</i>	Helophytic herb	Perennial	Indigenous	
<i>Indigofera</i> sp.	Herb	Annual/perennial	Indigenous	
<i>Lebeckia</i> sp.	Herb	Annual/perennial	Indigenous	
<i>Lotononis pungens</i>	Herb	Perennial	Indigenous	
<i>Medicago laciniata</i>	Herb	Annual	Indigenous	
<i>Rhynchosia caribaea</i>	Climber/herb	Perennial	Indigenous	
<i>Sutherlandia</i> sp.	Shrub	Perennial	Indigenous	
Fumariaceae (Fuma)				
<i>Fumaria muralis</i>	Herb	Perennial	Exotic	
Geraniaceae (Gera)				
<i>Pelargonium glutinosum</i>	Shrub	Perennial	Indigenous	
<i>Pelargonium grossularioides</i>	Herb	Annual	Indigenous	
<i>Pelargonium odoratissimum</i>	Shrub	Perennial	Indigenous	
<i>Pelargonium reniforme</i>	Geophytic herb/shrub	Perennial	Indigenous	
<i>Pelargonium</i> sp.1	Herb	Annual/perennial	Indigenous	
<i>Pelargonium</i> sp.2 (seedling)	Herb	Annual/perennial	Indigenous	
<i>Pelargonium trifidum</i>	Geophytic herb/shrub	Perennial	Indigenous	
<i>Pelargonium zonale</i>	Shrub	Perennial	Indigenous	
Hyacinthaceae (Hyac)				
<i>Drimia</i> sp.1	Geophytic herb	Perennial	Indigenous	
<i>Drimia</i> sp.2	Geophytic herb	Perennial	Indigenous	
<i>Ledebouria</i> sp.	Geophytic herb	Perennial	Indigenous	
<i>Urginea altissima</i>	Geophytic herb	Perennial	Indigenous	
Hypoxidaceae (Hypo)				
<i>Hypoxis</i> sp.	Geophytic herb	Perennial	Indigenous	
Iridaceae (Irid)				
Sp.8	Geophytic herb	Perennial	Unknown	
Juncaceae (Junc)				
<i>Juncus oxycarpus</i>	Herb	Perennial	Indigenous	
Lamiaceae (Lami)				
<i>Ballota africana</i>	Herb	Perennial	Indigenous	
<i>Leonotis ocymifolia</i>	Shrub	Perennial	Indigenous	
<i>Mentha longifolia</i>	Herb	Perennial	Indigenous	
<i>Salvia stenophylla</i>	Hydrophytic herb	Perennial	Indigenous	
<i>Salvia verbenacea</i>	Herb	Perennial	Indigenous	

Family and species name	Growth form	Life cycle	Indigenous or Exotic	Weed or invader
<i>Stachys aethiopica</i>	Herb	Perennial	Indigenous	
<i>Teucrium</i> sp.	Herb	Perennial	Indigenous	
Lobeliaceae (Lobe)				
<i>Lobelia anceps</i>	Herb	Perennial	Indigenous	
<i>Lobelia</i> sp.	Hydrophytic herb	Annual/perennial	Indigenous	
<i>Moquiniella rubra</i>	Parasitic shrub	Perennial	Indigenous	
Malvaceae (Malv) (= Sterculiaceae)				
<i>Abutilon sonneratianum</i>	Shrub	Perennial	Indigenous	
<i>Anisodonteia triloba</i>	Shrub	Perennial	Indigenous	
<i>Hermannia althaeoides</i>	Herb/shrub	Perennial	Indigenous	
<i>Hermannia desertorum</i>	Shrub	Perennial	Indigenous	
<i>Hermannia diffusa</i>	Shrub	Perennial	Indigenous	
<i>Hermannia pulchella</i>	Shrub	Perennial	Indigenous	
<i>Hermannia</i> sp.1	Herb/shrub	Annual/perennial	Indigenous	
<i>Hermannia</i> sp.2	Herb	Annual/perennial	Indigenous	
<i>Hermannia</i> sp.3	Herb/shrub	Annual/perennial	Indigenous	
<i>Hermannia velutina</i>	Shrub	Perennial	Indigenous	
<i>Sida</i> sp.	Herb/shrub	Annual/perennial	Indigenous	
<i>Malva parviflora</i>	Herb	Annual	Indigenous	
Meliaceae (Meli)				
<i>Nymania capensis</i>	Shrub	Perennial	Indigenous	
Melanthaceae (Meli)				
<i>Melianthus comosus</i>	Shrub	Perennial	Indigenous	
Mesembryanthemaceae (Mese)				
<i>Aptenia cordifolia</i>	Succulent herb	Perennial	Indigenous	
<i>Carpobrotus deliciosus</i>	Succulent herb	Perennial	Indigenous	
<i>Drosanthemum hispidum</i>	Succulent shrub	Perennial	Indigenous	
<i>Drosanthemum lique</i>	Succulent shrub	Perennial	Indigenous	
<i>Drosanthemum</i> sp.	Succulent shrub	Perennial	Indigenous	
<i>Eberlanza ferox</i>	Succulent shrub	Perennial	Indigenous	
<i>Malephora crocea</i>	Succulent shrub	Perennial	Indigenous	
<i>Mesembryanthemum aitonis</i>	Succulent herb	Annual	Indigenous	
<i>Mesembryanthemum guecherianum</i>	Succulent herb	Annual/biennial	Indigenous	
<i>Mestoklema elatum</i>	Succulent shrub	Perennial	Indigenous	
<i>Psilocalon granulicaule</i>	Succulent herb	Annual/perennial	Indigenous	
<i>Rhombophyllum</i> sp.	Succulent shrub	Perennial	Indigenous	
<i>Ruschia rigens</i>	Succulent herb	Perennial	Indigenous	
Mimosoideae (Mimo) (= Leguminosae)				
<i>Vachellia (Acacia) karroo</i>	Tree	Perennial	Indigenous	
<i>Trichodiadema setuliferum</i>	Succulent herb	Perennial	Indigenous	
Molluginaceae (Moll)				
<i>Hypertelis salsoloides</i>	Shrub	Perennial	Indigenous	
<i>Hypertelis</i> sp.	Herb	Annual/perennial	Indigenous	
<i>Limeum aethiopicum</i>	Herb	Perennial	Indigenous	
Moraceae (Mora)				
<i>Ficus burtt-davyi</i>	Tree	Perennial	Indigenous	
<i>Ficus sur</i>	Tree	Perennial	Indigenous	
Myrtaceae (Myrt)				
<i>Eucalyptus</i> sp.	Tree	Perennial	Exotic	Invader
Nymphaeaceae (Nymp)				
<i>Nymphaea</i> sp.	Hydrophytic herb	Annual/perennial	Indigenous	
Oleaceae (Olea)				
<i>Olea europaea</i> subsp. <i>africana</i>	Tree	Perennial	Indigenous	
Onragaceae (Onra)				
<i>Oenothera</i> sp.	Herb	Annual/perennial	Exotic	
Oxalidaceae (Oxal)				
<i>Oxalis commutata</i>	Geophytic herb	Perennial	Indigenous	

Family and species name	Growth form	Life cycle	Indigenous or Exotic	Weed or invader
<i>Oxalis corniculata</i>	Geophytic herb	Perennial	Indigenous	
<i>Oxalis</i> sp.1	Geophytic herb	Perennial	Indigenous	
<i>Oxalis</i> sp.2	Geophytic herb	Perennial	Indigenous	
Papaveraceae (Papa)				
<i>Argemone ochroleuca</i>	Herb	Annual	Exotic	Weed
Phytolaccaceae (Phyt)				
<i>Phytolacca dioica</i>	Tree	Perennial	Exotic	
Plantaginaceae (Plan)				
<i>Plantago lanceolata</i>	Herb	Perennial	Exotic	
Plumbaginaceae (Plum)				
<i>Plumbago auriculata</i>	Shrub	Perennial	Indigenous	
Poaceae (Poac)				
<i>Agrostis lachnantha</i>	Graminoid	Annual	Indigenous	
<i>Aristida congesta</i>	Graminoid	Perennial	Indigenous	
<i>Avena fatua</i>	Graminoid	Annual	Exotic	
<i>Cenchrus ciliaris</i>	Graminoid	Perennial	Indigenous	
<i>Chloris virgata</i>	Graminoid	Annual	Indigenous	
<i>Cymbopogon plurinodis</i>	Graminoid	Perennial	Indigenous	
<i>Cynodon dactylon</i>	Graminoid	Perennial	Indigenous	Proposed invader
<i>Cynodon incompletus</i>	Graminoid	Perennial	Indigenous	
<i>Digitaria argyrograpta</i>	Graminoid	Perennial	Indigenous	
<i>Digitaria eriantha</i>	Graminoid	Perennial	Indigenous	
<i>Ehrharta calycinia</i>	Graminoid	Perennial	Indigenous	
<i>Ehrharta</i> sp.	Graminoid	Annual/perennial	Indigenous	
<i>Eragrostis curvula</i>	Graminoid	Perennial	Indigenous	
<i>Eragrostis lehmanniana</i>	Graminoid	Perennial	Indigenous	
<i>Eragrostis obtusa</i>	Graminoid	Perennial	Indigenous	
<i>Hyparrhenia hirta</i>	Graminoid	Perennial	Indigenous	
<i>Melica decumbens</i>	Graminoid	Perennial	Indigenous	
<i>Melinis repens</i>	Graminoid	Annual	Indigenous	
<i>Miscanthus capensis</i>	Graminoid	Perennial	Indigenous	
<i>Panicum deustum</i>	Graminoid	Perennial	Indigenous	
<i>Panicum</i> sp.	Graminoid	Annual/perennial	Indigenous	
<i>Paspalum dilatatum</i>	Graminoid	Perennial	Exotic	
<i>Paspalum paspaloides</i> (= <i>distichum</i>)	Graminoid	Perennial	Exotic	
<i>Pennisetum clandestinum</i>	Graminoid	Perennial	Exotic	Weed
<i>Pennisetum setaceum</i>	Graminoid	Perennial	Exotic	Weed
<i>Setaria</i> sp.	Graminoid	Annual/perennial	Indigenous	
Sp.10	Graminoid	Annual/perennial	Unknown	
Sp.9	Graminoid	Annual/perennial	Unknown	
<i>Sporobolus africanus</i>	Graminoid	Perennial	Indigenous	
<i>Stenotaphrum secundatum</i>	Graminoid	Perennial	Indigenous	
<i>Stipagrostis namaquensis</i>	Graminoid	Perennial	Indigenous	
<i>Themeda triandra</i>	Graminoid	Perennial	Indigenous	
Polygalaceae (Poly)				
<i>Muraltia spinosa</i> (= <i>Nylandtia spinosa</i>)	Shrub	Perennial	Indigenous	
<i>Polygala fruticosa</i>	Shrub	Perennial	Indigenous	
<i>Polygala myrtifolia</i>	Shrub	Perennial	Indigenous	
<i>Emex australis</i>	Herb	Annual	Indigenous	
<i>Persicaria attenuata</i>	Hydrophytic herb	Annual	Indigenous	
<i>Persicaria decipiens</i>	Helophytic herb	Annual	Indigenous	
<i>Persicaria</i> sp.	Helophytic herb	Annual	Indigenous	
<i>Polygonum</i> sp.1	Herb	Annual/perennial	Indigenous	
<i>Polygonum</i> sp.2	Scrambler/unknown	Annual/perennial	Indigenous	
<i>Rumex crispus</i>	Herb	Perennial	Exotic	Proposed invader

Family and species name	Growth form	Life cycle	Indigenous or Exotic	Weed or invader
Portulacaceae (Port)				
<i>Portulacaria afra</i>	Shrub	Perennial	Indigenous	
<i>Talinum</i> sp.	Herb	Annual	Indigenous	
Potamogetonaceae (Pota)				
<i>Potamogeton pusillus</i>	Hydrophytic herb	Annual	Indigenous	
Pteridaceae (Pter)				
<i>Cheilanthes hirta</i>	Herb	Perennial	Indigenous	
<i>Cheilanthes viridis</i>	Herb	Perennial	Indigenous	
<i>Pellaea calomelanos</i>	Herb	Perennial	Indigenous	
Ranunculaceae (Ranu)				
<i>Clematis brachiata</i>	Climber/herb	Perennial	Indigenous	
<i>Ranunculus multifidus</i>	Herb	Perennial	Indigenous	
Rhamnaceae (Rham)				
<i>Phyllica paniculata</i>	Shrub	Perennial	Indigenous	
Rosaceae (Rosa)				
<i>Cliffortia strobilifera</i>	Shrub	Perennial	Indigenous	
Rubiaceae (Rubi)				
<i>Anthospermum spathulatum</i>	Shrub	Perennial	Indigenous	
<i>Galium tomentosum</i>	Herb	Perennial	Indigenous	
<i>Nenax microphylla</i>	Shrub	Perennial	Indigenous	
Salicaceae (Sali)				
<i>Salix mucronata</i>	Tree	Perennial	Indigenous	
Salvadoraceae (Salv)				
<i>Azima tetracantha</i>	Shrub	Perennial	Indigenous	
Santalaceae (Sant)				
<i>Thesium</i> sp.1	Herb/shrub	Perennial	Indigenous	
Sapindaceae (Sapi)				
<i>Allophylus decipiens</i>	Shrub	Perennial	Indigenous	
<i>Dodonaea angustifolia</i>	Shrub	Perennial	Indigenous	
<i>Pappea capensis</i>	Shrub	Perennial	Indigenous	
Scrophulariaceae (Scro)				
<i>Hebenstretia robusta</i>	Shrub	Perennial	Indigenous	
<i>Jamesbrittenia atropurpurea</i>	Shrub	Perennial	Indigenous	
<i>Jamesbrittenia phlogiflora</i>	Shrub	Perennial	Indigenous	
<i>Limosella grandiflora</i>	Hydrophytic herb	Annual	Indigenous	
<i>Manulea</i> sp.	Herb	Annual/perennial	Indigenous	
<i>Nemesia capensis</i> (= <i>fruticans</i>)	Herb	Annual	Indigenous	
<i>Phyllopodium diffusum</i>	Herb	Annual	Indigenous	
<i>Selago saxatilis</i>	Shrub	Perennial	Indigenous	
<i>Selago</i> sp.	Shrub	Perennial	Indigenous	
Sp.11	Herb	Annual/perennial	Unknown	
<i>Sutera</i> (= <i>Chaenostoma</i>) <i>halimifolia</i>	Shrub/herb	Perennial	Indigenous	
<i>Sutera</i> sp.	Herb	Annual/perennial	Indigenous	
<i>Veronica anagallis-aquatica</i>	Herb	Annual	Indigenous	
<i>Veronica persica</i>	Herb	Annual	Exotic	
<i>Walafrida</i> (= <i>Selago</i>) <i>geniculata</i>	Shrub	Perennial	Indigenous	
<i>Zaluzianskya</i> sp.	Herb	Annual/perennial	Indigenous	
Solanaceae (Sola)				
<i>Datura stramonium</i>	Herb	Annual	Exotic	Weed
<i>Lycium cinereum</i>	Shrub	Perennial	Indigenous	
<i>Lycium oxycarpum</i>	Shrub	Perennial	Indigenous	
<i>Physalis peruviana</i>	Herb	Perennial	Exotic	
<i>Solanum hermannii</i> (= <i>linnaeanum</i>)	Shrub	Perennial	Exotic	
<i>Solanum mauritianum</i>	Shrub	Perennial	Exotic	Weed
<i>Solanum nigrum</i>	Herb	Annual	Exotic	
<i>Solanum nodiflorum</i>	Herb	Annual	Exotic	
<i>Solanum pseudocapsicum</i>	Shrub	Perennial	Exotic	Weed

Family and species name	Growth form	Life cycle	Indigenous or Exotic	Weed or invader
<i>Solanum tomentosum</i>	Shrub	Perennial	Indigenous	
<i>Withania somnifera</i>	Shrub	Perennial	Indigenous	
Thelypteridaceae (Thel)				
<i>Thelypteris</i> sp.	Herb	Annual/perennial	Indigenous	
Thymeleaceae (Thym)				
<i>Gnidia</i> sp.	Shrub	Perennial	Indigenous	
Tiliaceae (Tili)				
<i>Grewia robusta</i>	Shrub	Perennial	Indigenous	
Ulmaceae (Ulma)				
<i>Celtis africana</i>	Tree	Perennial	Indigenous	
Unknown (Unkn)				
Sp. 12	Hydrophytic herb	Annual/perennial	Unknown	
Urticaceae (Urti)				
<i>Urtica urens</i>	Herb	Annual	Exotic	
Verbenaceae (Verb)				
<i>Verbena bonariensis</i>	Herb	Annual	Exotic	Weed
Violaceae (Viol)				
Sp.13	Herb	Annual/perennial	Unknown	
Viscaceae (Visc)				
<i>Viscum continuum</i>	Parasitic shrub	Perennial	Indigenous	
<i>Viscum obscurum</i>	Parasitic shrub	Perennial	Indigenous	
<i>Viscum rotundifolium</i>	Parasitic shrub	Perennial	Indigenous	
Zygophyllaceae (Zygo)				
<i>Zygophyllum foetidum</i>	Climber/shrub	Perennial	Indigenous	