An Ecological and Hydrological Evaluation of the Effects of Restoration on Ecosystem Services in the Kromme River System, South Africa

by
Alanna Jane Rebelo

Dissertation presented for the degree of *Master of Science in Conservation Ecology, Faculty of Agriscience*, *at Stellenbosch University*

Promotors: Dr David le Maitre, Prof Karen Esler, Prof Richard Cowling

December 2012

Stellenbosch University http://scholar.sun.ac.za

The Upper Kromme River, from its watershed looking towards Cape St Francis

Stellenbosch University http://scholar.sun.ac.za

DECLARATION

By submitting this dissertation I declare that the entirety of the work contained therein is my own original work, that I am the owner of the copyright thereof and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Signature

Alanna Jane Rebelo

Name in Full

18 September 2012

Date

Copyright É Stellenbosch University
All rights reserved

Stellenbosch University http://scholar.sun.ac.za

ACKNOWLEDGMENTS

Thank-you to the following people:

- Dr David le Maitre (CSIR), Prof Karen Esler (SU), and Prof Richard Cowling (NMMU), my supervisors, for invaluable ideas, mentorship, guidance and assistance. This project would not have been at all possible without your valuable support, advice and suggestions
- It has been a fantastic experience working closely with Katie Gull and learning about economics as well as science. I am so grateful that I not only gained a wonderful colleague through this project, but also a great friend.
- Thank-you to the following people for collaborative efforts: Mark Horan, Sean Thornton-Dibb, Dr Caren Jarmain, Dr Shayne Jacobs and Julia Glenday.
- I would also like to thank ASSET Research, the WRC and the Core Team for this wonderful opportunity to participate in interdisciplinary research. A special thanks to Prof James Blignaut for all his encouragement and connections.
- A big thank-you goes to all the farmers of the Upper Kromme, for trusting Katie and myself, for giving us of their precious time, and for welcoming us into their homes. This thesis certainly could not have been done without their input.
- I am particularly indebted to Mr Christopher Cowling, Mr Japie Buckle and Mr Mike Powell, who have all given so much of their time to impart valuable insights, share contacts and give advice.
- Thanks also to the following people: Mr Cobus Ferreira, Mr Pierre Joubert, Mr Eric Roux, Mr Sam van der Merwe, Wayne Erlank, Mr Shannon Barkes, Mr Paul du Plessis, Tracey Steyn, Megan Nowell, Garth Stephenson, Matthew McConnachie, David Raymer, Prof Martin Kidd, Tracey Steyn, Dr Tony Rebelo, Mrs Leandri van der Elst, Mrs Monean Wenn, Mandy Alblast, Julia Glenday, Marijn Zwinkels, Dieter van den Broek, Lisa Nooij, Nikolett Czerski, and Mr Erik van den Berg (Aurecon).
- Thank you to Mrs Leandri van der Elst, Mrs Monean Wenn, Ms Celeste Mockey and Mr Erwine Scholtz for always being so willing to help me with administration and computer issues.

Stellenbosch University http://scholar.sun.ac.za

- Thank you to all my dedicated field assistants: Alexander Rebelo, Reghard DeBeer, Michelle Malan, Janet Rebelo, Bianca Bottega, Byron-Mahieu van der Linde
- Without the support of my close friends and family I could not have completed this project. Thanks to Dr Patricia Holmes, Dr Tony Rebelo, Janet Rebelo, Alex Rebelo, Shane De Stadler, Toni Scott, Bianca Bottega and last but certainly not least, Byron-Mahieu Van Der Linde.
- Finally I would like to thank my God, the First and the Last, the Truth and the Light, for this wonderful opportunity to study His creation and for His constant support, guidance, comfort and protection throughout the course of this project.

Thank-you to the following organizations for funding and support:

- ASSET Research (2010-2011)
- The Water Research Commission of South Africa (2010-2011)
- The Fynbos Forum Innovation Scholarship (Table Mountain Fund and WWF) (2011)
- The Dudley D'Ewes Scholarship (Cape Tercentenary Foundation) (2010-2011)
- The HB Thom Fund (2011)
- The Ernst and Ethel Eriksen Trust (2011)
- IALE-Africa Chapter (IALE Student Travel Award) (2011)

Stellenbosch University http://scholar.sun.ac.za

Thank-you to the following institutions for support:

- South African Weather Services (SAWS)
- Department of Conservation Ecology and Entomology (Stellenbosch University)
- Department of Water Affairs (DWA)
- Gamtoos Irrigation Board (GIB)
- PRESENCE/Living Lands Network
- Nelson Mandela Bay Municipality (NMBM)
- WaterWatch, Netherlands

Stellenbosch University http://scholar.sun.ac.za

ABSTRACT

Wetland systems provide vital hydrological ecosystem goods and services to mankind. When wetlands are transformed, through invasion by alien plants or replaced with agriculture, natural capital is lost, and the system is no longer able to provide the same quality of hydrological ecosystem services. Natural capital can be restored, but it involves substantial financial investment, and there is no guarantee that these hydrological ecosystem services will be fully recovered. This thesis aimed to investigate the hydrological impact of the land-cover changes in the Kromme River Catchment over the last 50 years, by using a combination of mapping and hydrological modelling techniques. We hypothesized that wetland loss in the Kromme has resulted in a shift in the flow regime, greater responsiveness to floods as a result of less storage, lower baseflow, and reduced water quality. We also hypothesised that the riparian invasion by *Acacia mearnsii* has caused flow reductions as a result of increased evaporation relative to the wetlands. Modelling results predict that over the past 50 years, the transformation of the floodplain wetlands in the Kromme River has shifted the flow regime, reducing baseflows and increasing the responsiveness of the catchment to extreme rainfall events. The invasion of *A. mearnsii* over time has also been predicted to have caused a reduction in river flow. Various restoration scenarios were considered, however if the Kromme were to be restored back to a land-cover state comparable to the 1950's, 26.9 km^2 (65.1%) of *A. mearnsii* would have to be cleared, and 5.2 km^2 (34.2%) of the wetlands would have to be restored. The hydrological benefits would include a predicted increase in riverflow (42 mm/a), baseflow (2.9 mm/a), an increase in flood protection and improved water quality. This restoration strategy could be regarded as a type of insurance plan, and the benefits gained in terms of increased ecosystem service delivery would be the insurance premium. In conclusion it appears that restoration, insuring natural capital in the Kromme River, would provide significant economic returns on investment.

Stellenbosch University http://scholar.sun.ac.za

OPSOMMING

Moeraslandstelsels voorsien die mens van noodsaaklike hidrologiese ekosisteemgoedere en -dienste. Wanneer moeraslande verander word, hetsy deur die indringing van uitheemse plante of vervanging met landboubedrywighede, gaan natuurlike kapitaal verlore en kan die stelsel nie meer dieselfde gehalte hidrologiese ekosisteemdienste lewer nie. Hoewel natuurlike kapitaal herwin kan word, behels dit beduidende finansiële belegging, en is daar boonop geen waarborg dat die hidrologiese ekosisteemdienste ten volle sal herstel nie. Hierdie tesis het ten doel gehad om die hidrologiese impak van die grondbedekkingsveranderinge in die Krommerivier-toeloopgebied oor die afgelope 50 jaar met behulp van ’n kombinasie van karterings- en hidrologiese modelleringstegnieke te ondersoek. Die hipotese was dat moeraslandverlies in die Kromme tot ’n verandering in die vloei-regime, hoër responsiwiteit op erge reënval as gevolg van minder bergingsruimte, ’n laer basisvloei en swakker watergehalte gelei het. Daar is voorts gehipoteseer dat die oewerindringing deur Acacia mearnsii ’n verlaging in vloei veroorsaak het weens ’n toename in verdamping uit die moeraslande. Modelleringsresultate dui daarop dat die transformasie van die vloedvlakte-moeraslande in die Krommerivier oor die afgelope 50 jaar die vloei-regime verander het, basisvloei verminder het en die toeloopgebied se responsiwiteit op erge reënval verhoog het. Die indringing van A. mearnsii het ook volgens aanduidings mettertyd ’n vermindering in riviervloei tot gevolg gehad. Verskeie herstelscenario’s is oorweeg. Om die grondbedekking in die Kromme te herstel tot wat dit in die 1950’s was, moet 26,9 km2 (65,1%) van die A. mearnsii verwyder en 5,2 km2 (34,2%) van die moerasland herwin word. Die hidrologiese voordele kan ’n verwagte toename in riviervloei (42 mm/a) en basisvloei (2,9 mm/a), ’n toename in vloedbeskerming sowel as beter watergehalte insluit. Hierdie herstelstrategie kan as ’n soort versekeringspolis beskou word, en die voordele verbonde aan beter ekosisteemdienslewering as die versekeringsuitbetalung. Ten slotte blyk dit dat die herstel van die Kromme, en die gepaardgaande versekering van natuurlike kapitaal, beduidende ekonomiese opbrengste op belegging sal meebring.

Stellenbosch University http://scholar.sun.ac.za

TABLE OF CONTENTS

Stellenbosch University http://scholar.sun.ac.za

LIST OF FIGURES

Stellenbosch University http://scholar.sun.ac.za

Stellenbosch University http://scholar.sun.ac.za

Stellenbosch University http://scholar.sun.ac.za

Stellenbosch University http://scholar.sun.ac.za

Stellenbosch University http://scholar.sun.ac.za

LIST OF TABLES

Stellenbosch University http://scholar.sun.ac.za

Stellenbosch University http://scholar.sun.ac.za

ABBREVIATIONS

CARA	The Conservation of Agricultural Resources Act
DWA	Department of Water Affairs
IAP	Invasive Alien Plant/s
LAI	Leaf Area Index
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
mcm	Million cubic metres
NEMA	National Environmental Management Act
NFA	National Forests Act
NGO	Non-Governmental Organisation
NWA	National Water Act
PES	Payment for Ecosystem Services
RNC	Restoring Natural Capital
SAWS	South African Weather Service
SEBAL	Surface Energy Balance Algorithm for Land
WfWater	Working for Water
WfWetlands	Working for Wetlands
WR2005	Water Resource 2005

Stellenbosch University http://scholar.sun.ac.za

CHAPTER 1: INTRODUCTION

Motivation

Restoration of Natural Capital (RNC) is a process through which not only the individual components of an ecosystem are restored, but also the flow of ecosystem goods and services (Aronson et al. 2007). Ecosystem services are the benefits that humans derive from nature that are essential to human existence (Daily et al. 2000, de Groot et al. 2002). The delivery of many ecosystem services has been repeatedly improved by restoration with many examples of successes worldwide (Aronson et al. 2007). Restoration has also been repeatedly shown to increase biodiversity and improve the socio-economic value of an ecosystem or area (Aronson et al. 2007, Blignaut & Aronson 2008, Blignaut et al. 2010). The concept of payments for ecosystem services (PES) was developed to give users of ecosystem services an incentive to pay for the benefits they derive from nature (World Bank 2004, Kosoy et al. 2008). PES requires interdisciplinary interaction, and provides a platform from which scientists, economists and beneficiaries can communicate and cooperate (World Bank 2004, Kosoy et al. 2008).

The most well known restoration project in South Africa, the Working for Water (WfWater) Programme, commenced the clearing of invasive alien plants (IAP) in 1995 (Hosking et al. 2002). The primary aim of WfWater is to contribute to economic empowerment, social equity and ecological integrity (Turpie et al. 2008, DWAF 2004). IAP clearing programmes are also a cost-effective way to protect water resources in South Africa (Le Maitre et al. 2002). However, recent research has shown that the WfWater Programme is sometimes inefficient, as follow-up IAP clearing treatment is often not done timeously (Hosking & du Preez. 2004, van Wilgen et al. 2012, McConnachie et al. 2012). There is a growing body of research on RNC and PES (Aronson et al. 2007), but according to Cowling et al. (2008), there has been a failure to link this restoration research with socio-economics and policy making (Aronson et al. 2010). This failure suggests that restoration projects have not been successful in effecting changes in the way ecosystem services are integrated into management practices (Cowling et al. 2008). A meta-

Stellenbosch University http://scholar.sun.ac.za

analysis of the pre-2009 restoration literature, 1582 peer-reviewed articles from 13 journals, revealed that the societal benefits of restoration are frequently underestimated and undervalued (Aronson et al. 2010). This has highlighted the overwhelming need for interdisciplinary research, and suitable management frameworks for this research that will maximize outcomes (Cowling et al. 2008).

Background

This master's study is part of a greater, interdisciplinary umbrella project undertaken by ASSET Research[1] and funded by the Water Research Commission, South Africa. There has been a large amount of ecological restoration work done in South Africa, however very few of these cases have documented the benefits of restoration. The purpose of the project was to provide evidence of the benefits of the restoration of natural capital and to address this information deficiency. Eight recently restored sites across South Africa were selected as case studies. These sites were, organised by biome: Oudtshoorn (Succulent Karoo), Namakwa Sands (Succulent Karoo), the Sabie River (Grassland (top) and Savanna (bottom)), the Drakensberg (Grassland), Lephalale (Savannah), the Agulhas Plain, Beaufort West (Nama Karoo), and the Kromme River (Fynbos). At each of these eight sites the following hypothesis was tested:

RNC improves water flow and water quality, land productivity, in some instances sequesters more carbon, and, in general, improves both the socio-economic value of the land in and the surroundings of the restoration site as well as the agricultural potential of the land.

This master's thesis investigates the hydrological benefits of restoration in the Kromme River system in the Eastern Cape of South Africa. The study was interdisciplinary in nature, and Katie Gull (Gull 2012) conducted the economics study of the Kromme system. As well as the hydrological science undertaken in this thesis, this research had a strong social science element. All of the farmers within the study area in the Kromme River were interviewed as part of this study (Appendix 1). This master's research also culminated in a farmer's workshop, where

[1] ASSET Research is an African research and development platform committed to the vision of a prosperous, clean and green economy in Africa. Website: http://www.assetresearch.org.za/

Stellenbosch University http://scholar.sun.ac.za

research findings were presented back to the farming community and workshops on the ecology of the Kromme system were held (Appendix 2).

Socio-economic setting

South Africa is a chronically water scarce country (Ashton 2002). The invasion of alien plant species, especially in river systems of South Africa, is a serious threat to water security (Dye & Jarmain 2004, Görgens and van Wilgen 2004). The coastal city of Port Elizabeth in the Eastern Cape of South Africa is in the midst of a water crisis and is searching for ways to augment its water supply to achieve water security. The Kromme River is a crucial water supply catchment for Port Elizabeth as the metropolis currently obtains roughly forty percent of its water from the Churchill and Impofu Dams collectively (DWA 2010).

Farmers have occupied the Kromme Catchment since the eighteenth century (Haigh et al. 2002, Raymer 2008). Since then, the hydrological regime has been altered by over-grazing, transformation of flood plains for crop production, invasion of alien trees in the floodplains (mainly Black Wattle, or *Acacia mearnsii*), canalization and straightening of the river, building infrastructure through and alongside the river, mechanical damage to the wetlands (ploughing) and the removal of a keystone wetland plant, palmiet (*Prionium serratum*). However, the growing recognition of the extensive damage being done by erosion of these wetlands resulted in restoration commencing in 1996 in the Kromme (Haigh et al. 2002). Gabions were constructed to prevent further erosion from headcuts, and *A. mearnsii* stands began to be cleared (Haigh et al. 2002). Further information on the detailed history of the Kromme is available in Appendix 3.

This study is of great socio-economic importance as our findings suggest that the effective control of *A. mearnsii* from the Kromme Catchment would make significant volumes of water available for downstream users –including the municipality of the city of Port Elizabeth.

Aim, key research question, hypotheses and significance of study

This masters study investigated the impact of restoration on several ecosystem services, including provisioning (water flow) and regulating (water purification, assurance of supply,

Stellenbosch University http://scholar.sun.ac.za

flood attenuation) services. As the restoration is a recent activity in the Kromme Catchment, we would not expect it to have demonstrated the full effects yet and there could be a time-lag of several years before benefits can directly be measured in the hydrological record. Thus this study examined the changes in the land-cover of the Kromme Catchment over the past 50 years and investigated the impact this had on the hydrology. The benefits of restoration were then inferred from the results. The central research question of this thesis is:

What was the hydrological impact of the land-cover changes in the Kromme River Catchment over the last 50 years?

To address this question, two steps had to be taken: firstly, the land-cover changes in the Kromme had to be quantified (Chapter 3), and secondly, matched to changes in the hydrological record (Chapter 4). However, no reliable flow record exists for the Kromme River, so the hydrology of the Kromme had to be modeled. A key issue in this study was how to calibrate the model if no riverflow data exist. This was addressed by ensuring that the key drivers of evaporation change, including the loss of palmiet wetlands (i.e. *P. serratum* dominated wetlands) and invasion by *A. mearnsii* would be modeled acceptably by comparing outputs with measurements available in the literature. No work has been done on the water use of palmiet wetlands, so the water-use of palmiet was studied to address this gap (Chapter 5). We supplemented the findings of the palmiet study with unpublished data on evaporation from palmiet wetlands and used this as input into the modelling chapter (Chapter 4).

The main hypotheses for this study are:

a) Wetland loss has resulted in: a shift in the flow regime, greater responsiveness to floods as a result of less storage and less baseflow and a reduction in water quality due to loss of filtering capacity of wetlands.
b) Riparian invasion by *A. mearnsii* has caused flow reduction as a result of increased evaporation relative to *P. serratum*.
c) Cultivation of floodplains has caused a decline in water quality.

Thesis structure

Stellenbosch University http://scholar.sun.ac.za

This thesis is composed of six different sections: three of these are synthesis chapters (introduction, literature review and conclusion) and three are research chapters (Figure 1.1). There is some overlap between the literature review and the introductions of the data chapters since each was written as a stand-alone publishable unit. Each chapter is briefly described below along with listings of the main contributors.

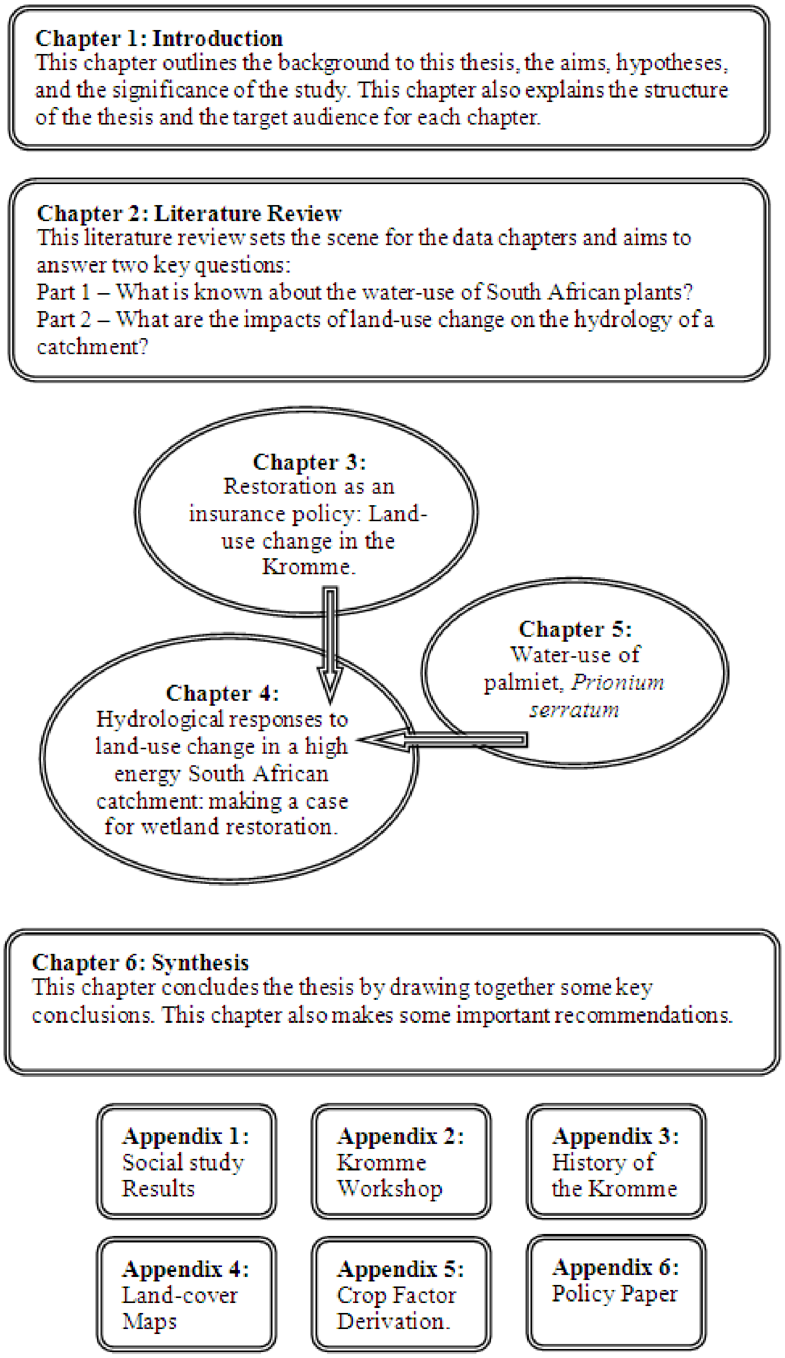


Figure 1.1: The visual framework of this thesis

Stellenbosch University http://scholar.sun.ac.za

Chapter 1: Introduction – This chapter sets the scene for the thesis, mentioning the motivation for the study and the umbrella project that this thesis falls under. It also briefly introduces the Kromme River catchment and its socio-economic setting, as well as some of the most important issues in the area. It outlines the specific aims of this master's thesis and introduces the research questions and structure of the thesis.

Chapter 2: Literature Review – This chapter reviews the broader literature base to set the scene for the three data chapters that follow. This chapter is divided into two main sections answering two specific questions. Firstly, to set the scene for Chapter 5: what information is available on the water use of South African vegetation types or land-cover types; specifically alien plant invasions and wetlands? Secondly, to set the scene for Chapter 3 and 4, what is known nationally and internationally about the impacts of changes in land-cover on hydrological ecosystem goods and services? The focus here is specifically on the transformation of floodplain wetlands into cultivated land (e.g. changes in flow regulation, impacts on water quality and sediments) and the impacts of riparian invasions on flow regimes (flow reductions and yield).

Chapter 3 – This chapter provides an in-depth view into what has happened to land-use in the Upper Kromme Catchment over the last 50 years. It specifically addresses the issues of alien invasion and wetland degradation. The output of this study included four high-resolution land-cover maps, from 2007, 1983, 1969, 1954 (Appendix 4). This is the first study of its kind and level of detail to be conducted in a South African catchment. This chapter has been submitted for peer-review for inclusion into a Springer Book entitled: Landscape Ecology for Sustainable Environment and Culture, edited by Prof Bojie Fu and Prof Bruce Jones. This chapter was co-authored by the following people: Dr David Le Maitre, Prof Karen Esler, and Prof Richard Cowling (co-supervisors).

Chapter 4 –This chapter uses the mapping data obtained in Chapter 3 and incorporates it into a hydrological model. It specifically investigates the impacts of land-cover change on hydrological ecosystem goods and services. It also incorporates data from Chapter 5. The details of how the crop factor for the Kromme wetlands was derived can be found in

Stellenbosch University http://scholar.sun.ac.za

Appendix 5. This chapter has been aimed at an international audience, and we plan to submit it to the Journal of Wetland Ecology and Management or an equivalent journal. This chapter was co-authored by the following people: Dr David Le Maitre, Prof Karen Esler, Prof Richard Cowling (co-supervisors), Mr Mark Horan and Mr Sean Thornton-Dibb (provided technical advice and input into the model development).

Chapter 5 – This chapter shifts focus and scale, and even study site, to one aspect of one species: the water-use of the wetland plant commonly known as palmiet (*P. serratum*). This study was undertaken because the hydrological model (Chapter 4) required a 'crop factor', a measure of water use which relates actual to potential evaporation, for each vegetation type found in the Kromme. There has been much research done on the water-use of agricultural species, and to a limited extent native dryland species, however very little work has been done on the water use of wetland species. This study looks at whether or not palmiet is a conservative water user, and how its water-use compares to other vegetation. This chapter may be submitted as a short research note to the South African Journal of Botany. This chapter was co-authored by the following people: Dr David Le Maitre, Prof Karen Esler, Prof Richard Cowling (co-supervisors) and Dr Caren Jarmain who provided Scintillometry and remote-sensing data, as well as help with methodology.

Chapter 6: Conclusion – This concluding chapter summarizes the major findings of this thesis and puts forward some management recommendations. It also reflects on gaps in the research and highlights areas for future study. It also mentions how this thesis attempts to address some of these gaps (Appendix ^)

Appendix 1 – Social Study: a background to the farmers of the Kromme is presented in this Appendix, as well as a summary of the activities taking place in the catchment and some of the opinions held by landowners. This Appendix also provides the main output of this study: the interactive land-cover map, with agricultural information overlaid.

Appendix 2 – Kromme Workshop: a summary of the farmers workshop held in March 2012 at Kareedouw.

Stellenbosch University http://scholar.sun.ac.za

Appendix 3 – The History of the Kromme. This work was included as an appendix so as not to detract from the flow of the thesis. It outlines the chronological history of the Kromme. It also presents a time-line of some of the major activities in the Kromme since 1775.

Appendix 4 – Land-cover Maps: the land-cover maps and corresponding aerial photographs are displayed in this Appendix.

Appendix 5 – Palmiet Crop Factor: this appendix shows the data analysis and derivation of the Crop Factor used in the hydrological modelling in Chapter 4.

Appendix 6 – Policy Paper: Urban water use. Authors: Alanna Rebelo and Katie Gull.

REFERENCES

Aronson J., S. J. Milton, and J. N. Blignaut (Eds). 2007. *Restoring natural capital: science, business, and practice*. Island Press, Washington, D. C.

Aronson, J., J. N. Blignaut, S. J. Milton, D. Le Maitre, K. J. Esler, A. Limouzin, C. Fontaine, M. P. de Wit, W. Mugido, P. Prinsloo, L. van der Elst, and N. Lederer. 2010. Are Socioeconomic Benefits of Restoration Adequately Quantified? A Meta-analysis of Recent Papers (2000–2008) in *Restoration Ecology* and 12 Other Scientific Journals. *Restoration Ecology*. **18**(2): 143-154.

Ashton, P. G. 2002. Avoiding conflicts over Africa’s water resources. *Ambio*. **31**(3): 236-242

Blignaut, J. and J. Aronson. 2008. Getting serious about maintaining biodiversity. *Conservation Letters*. **1**(1):12-17.

Blignaut, J., M. Mander, R. Schulze, M. Horan, C. Dickens, C. Pringle, K. Mavundla, I. Mahlangu, A. Wilson, M. McKenzie and S. McKean. 2010. Restoring and managing natural capital towards fostering economic development: Evidence from the Drakensberg, South Africa. *Ecological Economics*. **69**(6): 1313-1323.

Cowling R. M., B. Egoh, A. T. Knight, P.J. O'Farrell, B. Reyers, M. Rouget, D. J. Roux, and A. Welz, A.Wilhelm-Rechman. 2008. An operational model for mainstreaming ecosystem

Stellenbosch University http://scholar.sun.ac.za

services for implementation. *Proceedings of the National Academy of Sciences*. **105:** 9483-9488.

Daily, G.C., Soderquist, T., Aniyar, S., Arrow, K., Dasgupta, P., Ehrlich, P.R., Folke, C., Jansson, A.M., Jansson, B.O., Kautsky, N., Levin, S., Lubchenco, J., Maler, K.G., David, S., Starrett, D., Tilman, D., Walker, B., 2000. The value of nature and the nature of value. *Science.* **289**: 395–396.

de Groot, R. S., M. A. Wilson, and R. M. J. Boumans. 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics*. **41**: 393-408.

Department of Water Affairs and Forestry, South Africa. 2004. Internal Strategic Perspective: Orange River System Overarching. Prepared by PDNA, WRP Consulting Engineers (Pty) Ltd, WMB and Kwezi-V3 on behalf of the Directorate: National Water Resource Planning. DWAF Report No P RSA D000/00/0104.

Department of Water Affairs, South Africa. 2010. Algoa Reconciliation Strategy. Prepared by E van der Berg and Dr MJ Shand of Aurecon South Africa (Pty) Ltd, as part of the Water Reconciliation Strategy Study for the Algoa Water Supply Area. DWA Report No. WMA 15/M00/00/1409/04.

Dye, P., and C. Jarmain. 2004. Water use by black wattle (*Acacia mearnsii*): implications for the link between removal of invading trees and catchment streamflow response. *South African Journal of Science*. **100:** 40-44.

Görgens, A. H. M., and B. W. van Wilgen. 2004. Invasive alien plants and water resources in South Africa: current understanding, predictive ability and research challenges. *South African Journal of Science*. **100**: 27-33.

Gull, K. 2012. Water Supply in the Eastern Cape: An economic case study of land rehabilitation in the Kromme River Catchment. Masters of Commerce Thesis. University of Cape Town.

Haigh, E. A., P. L. Grundling, P. Illgner, J., Wilmotand, and J. Buckle. 2002. The Wetland Rehabilitation Project in the Kromme River System, Eastern Cape. Department of Water Affairs and Forestry Project X832633.

Hosking, S. G., and M. du Preez. 2004. A cost-benefit analysis of the *Working for Water Programme* on selected sites in South Africa. *Water SA* **30(**2): 143-152.

Stellenbosch University http://scholar.sun.ac.za

Hosking, S.G., Du Preez, M., Campbell, E.E., Wooldridge, T.H. and Du Plessis, L.L. 2002. Evaluating the Environmental use of water-selected case studies in the eastern and southern Cape. WRC Report Number: 1045/1/02.

Kosoy, N., E. Corbera, and K. Brown. 2008. Participation in payments for ecosystem services: case studies from the Lancadon rainforest, Mexico. *Geoforum*. **39**: 2073-2083.

Le Maitre, D. C., B. W. Van Wilgen, C. M. Gelderblom, C. Bailey, R. A. Chapman, and J. A. Nel. 2002. Invasive alien trees and water resources in South Africa: case studies of the costs and benefits of management. *Forest Ecology and Management.* **160**(3): 143-159.

McConnachie, M. M., R. M. Cowling, B. W. van Wilgen, D. A. McConnachie. 2012. Evaluating the cost-effectiveness of invasive alien plant clearing: a case study from South Africa. *Biological Conservation*. In Press.

Raymer, D. 2008. *Streams of Life*. Published by David Raymer, South Africa.

Turpie, J.K., C, Marais, and J. N. Blignaut. 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**: 788-798.

van Wilgen, B. W., G. G. Forsyth, D. C. Le Maitre, A. Wannenburgh, I. M. Kotzé, L. van den Berg, and L. Henderson. 2012. An assessment of the effectiveness of a large, national-scale invasive alien plant control strategy in South Africa. *Biological Conservation*. **148.** 28 – 38.

World Bank. 2004. Sustaining Forests: A Development Strategy. World Bank, Washington DC.

Stellenbosch University http://scholar.sun.ac.za

CHAPTER 2: LITERATURE REVIEW

Land transformation, which results in habitat loss, is currently the major threat to both species (Pimm & Raven 2000, Raimondo et al. 2009) and ecosystems (Vitousek et al. 1997, Rouget et al. 2004, Reyers et al. 2009). Though this transformation is perhaps essential for food and resource provision, the process of changing native land-cover into a specific land-use often has undesirable side-effects on hydrological ecosystem goods and services delivery (Vitouek et al. 1997, Falkenmark et al. 1999, Warburton et al. 2010). The reason for this is that the vegetation composition characteristic of different land-uses differentially affects the partitioning of rainfall between interception, transpiration, infiltration and runoff (Falkenmark et al. 1999, Costa et al. 2003). The native land-cover of the Kromme River System in the Eastern Cape Province of South Africa has been transformed into various agricultural land-uses, such as orchards and grazing (Chapter 3). The Kromme floodplain wetlands, crucial for providing hydrological ecosystem services to the Port Elizabeth Metropolis downstream, have been transformed by cultivation or invaded by woody alien trees, predominantly the Australian Black Wattle, *Acacia mearnsii* (Chapter 3). Perceptions of a marked decline in hydrological ecosystem services from the Kromme led to restoration efforts to mitigate this loss, beginning in 1996 (Haigh et al. 2002, Raymer 2008). To understand the hydrological change that has taken place in the Kromme catchment, it is important to know the properties and water-use characteristics of native South African plants, and those that, after land transformation, replace them.

This literature review has two main sections. The first section addresses what is known about the water-use of South African plants and woody invasive alien plants (IAPs). The second section reviews the local and international literature on the hydrological effects of land transformations.

Stellenbosch University http://scholar.sun.ac.za

Water-use of South African plants

The impacts of vegetation change, the result of succession or an alien invasion, on the hydrological regime is difficult to quantify because there is high variation in plant growth forms and physiology. The concept of 'limits to evaporation' was developed to simplify this complexity by identifying six key determinants of evaporation (Calder 1996, Calder 1999, Le Maitre 2004). These can be divided into two categories: physical and biological factors. Physical factors are, in order of magnitude of effect, soil moisture availability, energy availability and the effect of raindrop size on interception losses. The most important biological factors are plant size (e.g. height and root depth), and plant physiology (e.g. degree of drought tolerance) and the seasonality of the leaves (Calder 1999, Le Maitre 2004). In South Africa, a water-scarce country, the major limit to growth and evaporation is soil water availability (Dye & Jarmain 2004, Dye et al. 2008b).

A general principle exists with regards to plant water use: trees typically use more water than shrubs, which use more water than grasses (Bosch & Hewlett 1982, Dunin 2002). However some native South African plant groups, such as fynbos and grasslands, have features that limit water-use (Mooney et al. 1983). In the Cape Floristic Region, fynbos typically has leaves with low photosynthetic capacity, similar in structure and physiology to those in other Mediterranean-type climate regions (Mooney et al. 1983). As a result, fynbos uses water relatively conservatively and their leaves have relatively low stomatal conductances (von Willert et al. 1989, Mooney et al. 1983). In the Grassland Biome, transpiration rates are relatively high, but because grasses are dormant during the winter their annual transpiration is relatively low (Dye et al. 2008a, Dye et al. 2008b). In the more arid grasslands, rainfall is low, and so transpiration typically dominates the water balance (Snyman & Fouche 1991). There are some cases in the montane grasslands of the Drakensberg Mountains in South Africa, where energy is the major limit to transpiration (Everson et al. 1998). Evaporation and runoff each account for about half the rainfall during average rainfall years, whereas transpiration was found to dominate the water balance during dry years (Everson et al. 1998).

Stellenbosch University http://scholar.sun.ac.za

Water-use of invasive alien plants

There have been very few direct measurements of water use of IAPs in South Africa (Le Maitre 2004). Results of an international review of 40 studies worldwide reveal that the differences in water-use between IAPs and native plants of the same growth form appeared to arise at the leaf scale, where IAPs were measured to have higher stomatal conductances than indigenous species (Cavaleri & Sack 2010). However the dataset compared in this review used only a limited data set, and there are many studies that show that many other factors need to be taken into account, such as: whether a tree is evergreen or not, its rooting depth, the plant height and total leaf area (Everson et al. 2007, Clulow et al. 2011). In South Africa, most invasions are woody trees replacing shorter vegetation, which is generally composed of either herbaceous plants or low shrubs such as fynbos (Le Maitre et al. 2000). Greater water-use of South African IAPs is a result of higher transpiration rates of IAPs than that of native species (Dye et al. 2008a). Higher transpiration in IAPs has been attributed to competitive physiological and structural advantages, such as higher leaf surface area, active summer growth and deeper root systems (Levine et al. 2002, Morris et al. 2011). In South Africa and Lesotho, woody invasive alien trees were estimated to have invaded 10.1 million ha to some degree by 1997 (Le Maitre et al. 2000). These invasions were estimated to decrease the mean annual surface runoff by about 3300 million m^3 per annum. In the Kromme River, the greatest IAP threat is that of invasion by *A. mearnsii* (Haigh et al. 2002, Raymer 2008, Chapter 3). *A. mearnsii* has been found to be highly drought tolerant and so has been declared likely to persist under climate change scenarios of water shortages (Smith et al. 1998, Crous et al. 2011).

a. Non-riparian invasions

In the grasslands of the Seven Oak District, KwaZulu-Natal, the annual transpiration of the grassland (3-6.5 $mm.d^{-1}$) was found to be comparable to that of invasions of *A. mearnsii*, however that it was during the winter period, when the grass has senesced, that the trees used more water (Everson et al. 2007). In fynbos non-riparian sites, transpiration rates of *A. mearnsii* have been recorded between 1000-1400 mm per annum (Dye & Jarmain 2004). In non-riparian situations, indigenous vegetation typically has relatively low transpiration rates, so the invasion

Stellenbosch University http://scholar.sun.ac.za

or removal of *A. mearnsii* can result in differences in transpiration of up to 600 mm per annum (Dye & Jarmain 2004).

b. Riparian invasions

Direct measurements from the few studies done in South Africa have revealed that the water-use of *A. mearnsii* in the riparian zone is markedly higher than that of indigenous vegetation (Dye et al. 2001, Everson et al. 2001). The total evaporation of a dense, closed canopy stand of mature *A. mearnsii* in a riparian zone in the Western Cape was measured to be over 1500 mm per annum (Dye & Jarmain 2004). This value is comparable to evaporation from tropical forests (Dye & Jarmain 2004). Where a soil-water deficiency exists, the transpiration of stands of *A. mearnsii* may exceed the rainfall if groundwater supplies are available (Clulow et al. 2011). At the Two Streams Catchment, KwaZulu-Natal, *A. mearnsii* was measured to be using 1156 mm and 1171 mm for 2007 (rainfall 689 mm) and 2008 (rainfall 819 mm) respectively (Clulow et al. 2011). Annual transpiration of native riparian vegetation was compared to that of a riparian *A. mearnsii* invasion for two different riparian plant communities, one in the Fynbos Biome at a site in Jonkershoek, and the other in the Grassland Biome at Gilboa (Dye et al. 2001). In both Biomes, *A. mearnsii* was measured to have a higher annual transpiration than native riparian communities, yielding annual differences of 171 mm (1503 mm and 1332 mm respectively) in the Fynbos Biome, and 424 mm, (1260 mm and 836 mm respectively) in the Grassland Biome (Dye et al. 2001).

Water-use of wetlands and riparian plants

Historical diary excerpts written by early travellers in South Africa suggest that the floodplains of the Kromme River system may have once been covered entirely by peat wetlands, dominated by the wetland plant *Prionium serratum* (Skead 2009). Since the 1950's, the Kromme wetlands have largely been transformed into agriculture, and currently only 12% of what may once have existed remains (Chapter 3). There have been few direct measurements done on the water-use of South African riparian and wetland species, which causes complications in hydrological studies, such as this one, where accurate estimations of plant water-use is important for realistic output of riverflow. An international review on the role of wetlands in the

Stellenbosch University http://scholar.sun.ac.za

hydrological cycle concludes that there is clear evidence worldwide that wetlands are generally higher water-users than adjacent non-riparian vegetation, with 48 out of 74 studies concluding that wetlands increase average annual transpiration (Bullock & Acreman, 2003). However 10% of studies conclude the opposite (Bullock & Acreman, 2003).

In South Africa, it has been established that riparian vegetation – trees or wetlands that have permanent access to water in the root zone - has higher evaporation rates than non-riparian vegetation (Everson et al. 1998, Scott 1999, Dye et al. 2001, Everson et al. 2009). The limited research that has been done on South African wetlands has shown that wetlands are generally also high water-users as a result of the high evaporation rates of wetland plants such as reeds (*Phragmites mauritianus*) (Birkhead et al. 1997, Everson et al. 2001, Clulow et al. 2012). An early study in South Africa on riverflow in a marsh wetland system in KwaZulu-Natal in 1983, managed to link transpiration from the riparian zone with daily fluctuations in riverflow, demonstrating the high diurnal water-use of riparian species (Seyhan et al. 1983). There have been several studies on water-use of wetlands in South Africa which for this review have been presented by biome: the Fynbos and Grassland Biomes, and the Savanna Biome respectively.

a. Fynbos and Grassland Biomes

Annual transpiration was measured for two riparian tree communities, one in the Fynbos Biome at Jonkershoek, and the other in the Grassland Biome at Gilboa (Dye et al. 2001). The water use of these riparian tree communities was found to be high, at 1332 mm and 836 mm respectively (Dye et al. 2001). Upon comparing the water-use of riparian communities in two different biomes, Dye et al. (2001) concluded that water-use across different riparian plant communities cannot be generalised, as structural and physiological differences between them result in very different annual transpiration rates. Riparian vegetation, dominated by dense stands of *Setaria megaphylla*, of the grasslands from the Seven Oaks District of KwaZulu-Natal, was measured to have a very high water use, with a summer maximum of more than 6 mm. d^{-1} (Everson et al. 2007). This riparian zone (7.5 ha, 11% of the catchment area) was found to be important in riverflow generation relative to its area, contributing 21% to annual riverflow, compared to the upland areas (65 ha, 89% of the catchment area) (Everson et al. 2007). At another site in KwaZulu-Natal, total annual evaporation for the wetlands of the Mfabeni Mire

Stellenbosch University http://scholar.sun.ac.za

was measured to be approximately 900 mm, which was lower than expected due to cloud cover in the summer and in general a low evaporative demand for that year (Clulow et al. 2012). Clulow et al. (2012) emphasized that transpiration from different sites should not be compared without taking into account evaporative demand (vapour pressure deficit, VPD), as differing VPD at different sites, may cause an under or over-estimation of transpiration for short-term studies (Clulow et al. 2012).

b. Savanna Biome

In the Savanna Biome, transpiration for a common reed, *P. mauritianus*, was measured in the Sabie River, Kruger National Park (Birkhead et al. 1997). Transpiration of reeds was found to be high, 12 mm/day in summer and 7 mm/day in winter (Birkhead et al. 1997). A modelling verification study on water-use of the riparian wetlands of the Sabie River in Kruger National Park found that this same reed, *P. mauritianus*, had lower daily transpiration rates of 9 mm in summer and 4 mm in winter (Everson et al. 2001). The two studies used different techniques and the one used by Birkhead et al, (1997) definitely resulted in over-estimates (Everson et al. 2001). In the Sabie River, the riparian tree community, dominated by *Breonadia salicia* was found to use 36% less water (2.5 $mm.d^{-1}$) than that of the reeds (3.9 $mm.d^{-1}$) (Everson et al. 2001).

In the Limpopo Province, transpiration from floodplain and savanna vegetation in the Nylsvlei wetland was estimated to be between 920-1300 mm per annum, by using a combination of modelling techniques and energy balance measurements (Birkhead et al. 2007). In comparison from the North West Province, annual transpiration of a *Phragmites communis* dominated wetland in Orkney, was measured to be 1174 mm, using eddy covariance and Bowen ratio techniques (Dye et al. 2008b). The North West Province experiences summer rainfall, and thus daily transpiration was higher in summer (3 mm) than in winter (1.6 mm) (Dye et al. 2008b). Further west, in the Northern Cape Province, direct measurements have been taken on the water-use of South African riparian species from the Seekoei River, including species such as the native trees, *Rhus lancea*, *Acacia karoo*, and two wetland graminoids: *P. mauritianus* and Juncus species (Everson et al. 2010). Riparian water usage was measured to be 65% higher than that of the surrounding vegetation, and distinct seasonal differences were also found (Everson et al.

Stellenbosch University http://scholar.sun.ac.za

2010). Average daily evaporation of two riparian sites was found to both be 2.77 mm (Everson et al. 2010).

Impact of land-cover change on hydrology

The two greatest land-cover changes in the Kromme River have been the transformation of the floodplain wetlands into agriculture, and the invasion of the riparian zone by *A. mearnsii*. However, it is difficult to conclusively demonstrate causal relationships between these land-cover changes and the hydrology of the Kromme (Royappen et al. 2002). This review aims to shed some light on what hydrological changes should be expected from these two key land-cover changes. The first section reviews the literature of the impacts of the transformation of floodplain wetlands into cultivated land, the second reviews the available information on the impacts of a change from native vegetation to plantations on flow regimes, and the third reviews the impacts of riparian invasions on flow regimes.

For this section of the review it is necessary to clarify some hydrological concepts that will be discussed in further detail. In terms of the water balance, not all precipitation immediately enters the river channel and flows out of the catchment (Hewlett 1982). Water may be evaporated, immediately discharged from the catchment, temporarily stored, or percolated deep into subsurface storage (Hewlett 1982). Surface runoff or overland flow is defined as that part of precipitation that fails to infiltrate the soil, due to a range of physical and chemical factors, and flows over the surface until reaching the river channel (Hewlett 1982, Descheemaeker et al. 2006). Rainwater infiltrating the soil enters the sub-surface system and percolates through the soil and weathered rock, in some cases following preferential flow pathways, in others reaching the water table, before discharging into a river (Midgley & Scott 1994). Stormflow is the sum of the water from surface and subsurface stormflow that discharges during and after a rainfall event, and can be distinguished from the baseflow, the relatively steady flow which persists between events (Hewlett 1982, Lacey & Grayson 1998) using a range of techniques (Smakhtin 2001). Groundwater is defined as subsurface water located in the saturated zone. Other subsurface water is soil moisture (Le Maitre et al. 1999). The below ground movement of water is poorly understood (Royappen et al. 2002), but in a recent study groundwater discharge was found to

Stellenbosch University http://scholar.sun.ac.za

constitute a large portion of baseflow in many South African catchments (Le Maitre & Colvin 2008). A high proportion of baseflow is often associated with catchments with high rainfall or low evaporation and large water storage capacity, often where the underlying geology is granite or basalt (Mwakalila et al. 2002).

There is a set of principles governing hydrological impacts of land-use change within a catchment. Firstly, the location of a specific land-use or land-cover change within a catchment plays an important role in riverflow response (Warburton et al. 2012). The riparian zone for example, although it makes up only a fraction of the area of a catchment, is significant because changes in this zone have impacts disproportionate to the area of transformation (Scott 1999, Everson et al. 2007). Secondly, the relative contribution of land-use or a land-cover change to riverflow is not proportional to the area of that change (Bosch & Hewlett 1982, Warburton et al. 2012). Lastly, the relative contribution of each land-use to riverflow is not constant, but varies with mean annual precipitation (Warburton et al. 2012).

Transformation of floodplain wetlands into cultivated land

a. Changes in flow regulation

Wetlands are well known to be vital for flood attenuation in a landscape as in many instances they have been shown to have a buffering ability, reducing floods and delaying stormflow (Kotze & Breen 1994, Bullock & Acreman 2003, Kotze et al. 2005, Turpie et al. 2008, Russel 2009). In the Kromme River, we are aiming to determine whether the catchment's response to large rainfall events is consistent with what we would expect, given the land-cover changes. Catchment responses to large rainfall events are not much affected by vegetation due to saturation of the catchment, however where there is large storage, such as floodplain or peat-forming wetlands, this is different (Bragg 2002, Bullock & Acreman 2003, Scott et al. 2004, Stähli et al. 2011). There has been extensive research done on the hydrology of peat-forming wetlands in the Northern Hemisphere (Evans et al. 1999, Bragg 2002, Grayson et al. 2010). Peat-forming wetlands are well known to occur in systems characterised by 'boom and bust' type dynamics, with flashy stormflow hydrographs (Holden et al. 2007, Grayson et al. 2010).

Stellenbosch University http://scholar.sun.ac.za

Degraded peat-forming wetlands in northern England were found to be less able to absorb extreme rainfall events than those that had been restored (Grayson et al. 2010).

In a review of the international literature, land transformation from forest and grasslands to agriculture, crop and pasture lands was found to increase riverflow (Scanlon et al. 2007). However this may not be beneficial, as although there is little South African literature on the topic, it is likely that a land-use change to agriculture would decrease baseflow and potentially yield. In south-eastern Amazonia, a land-use change from native cerrado (characterized by grasses, small palms, shrubs and twisted or leaning trees) to agriculture, mostly pastures, decreased mean annual riverflow by 24% and increased high season flows (Costa et al. 2003). A modelling study in Ethiopia found that restoring land-use from agriculture, either cultivation, pasture lands or maize and some subsistence agriculture, back to indigenous woodland, semi-arid land characterised by dryland acacias, would decrease riverflow by 8% (Legesse et al. 2003). In a modelling study done in South Africa, degradation of native dryland vegetation by too-frequent burning and overgrazing was shown to increase riverflow (Mander et al. 2010). In a review of 169 studies worldwide, wetlands, although providing invaluable services to mankind, in most cases use more water than other land-uses, thereby reducing riverflow (Bullock & Acreman 2003).

With respect to understanding groundwater and surface interactions within wetlands, it is important to understand the connectivity and geology of each specific wetland (Devito et al. 1996). Many wetlands exist because they have formed atop impenetrable geological features, so there is little or no groundwater interaction (Devito et al. 1996, Bullock & Acreman 2003). However this is different for floodplain wetlands, such as those in the Kromme, which have are known to be connected and to recharge groundwater, especially during flood events (Bullock & Acreman 2003). In many wetlands documented to be valuable for groundwater recharge, the direction of flow between surface flow and groundwater varies depending on the hydrological conditions (Dubreuil 1985, Thompson & Hollis 1995, Wolski 2002). Bullock and Acreman (2003) reviewed 69 wetland studies pertaining to groundwater recharge. Half of these simply stated that groundwater recharge took place, a quarter stated that there was no recharge, six studies reported wetlands to recharge more, and nine studies that wetlands recharge less than

Stellenbosch University http://scholar.sun.ac.za

other land types (Bullock & Acreman 2003). A study of peat wetlands in the United Kingdom found that there was no significant flow regulation, and that groundwater discharge contributed very little to baseflow (Evans et al. 1999). However there are cases, such as in the floodplain wetlands of Nigeria, where wetlands have been found to increase baseflow (Sellars 1981).

b. Water quality and sediments

Wetlands have important functions in the hydrological cycle, as they have the ability to retain, or temporarily store, water and sediments (Begg 1986, McCarthy & Ellery 1998, Tooth et al. 2002, Humphries et al. 2010b). Sediments in the floodplain have been found to be an important sink for solutes, allowing river systems in good condition to improve water quality (Humphries et al. 2010a). Conclusions from a global review suggest that changes in land-use from forest and grasslands to agriculture (crop and pasture lands) may degrade water quality by mobilizing salts, causing salinization, and leaching of fertilizers (Scanlon et al. 2007). In Rwanda, marsh agricultural reclamation, drainage by Electrogas and increase in hydropower has degraded the water table of the marsh, the water quality of the marsh and decreased the water level in lakes downstream (Hategekimana & Twarabamenye 2007). In a South African study, road construction, invasion by alien plants and water use by local residents were found to have the greatest impact on the water quality of the eMthonjeni-Fairview Spring Wetland in Grahamstown, with the greatest damage caused to erosion control and toxicant removal services (Sinchembe & Ellery 2010). However riparian restoration in the USA, *inter alia* riparian fencing, protected stream crossings, and stream bank bioengineering, which create protective buffering between the dryland and water course, has been found to be successful in improving water quality, specifically phosphorous concentrations and bacterial counts (Meals 2001).

c. Geomorphology

The floodplains of the Kromme Catchment formed and accumulated sediments and wetlands over millennia, indeed the remaining palmiet wetlands are growing atop peat beds estimated to be some 0.5 to 2.8 m in depth, over 5600 years old (Toerien & Hill 1989, Haigh et al. 2002, Lewis 2008). The geomorphology of the Kromme River has since been modified, and at several points along the length of the river, there are large headcuts, eroding backwards into the exposed floodplain (Haigh et al. 2002). An underlying principle of geomorphology is that a landscape is

Stellenbosch University http://scholar.sun.ac.za

dynamic, erosion is a natural process and rehabilitation should be done with this in mind (Grenfell et al. 2009). Disturbance in the river channel, in the form of a road dissecting the river or the ploughing of the river bed, causes erosion and incision of the channel (Ellery et al. 2009). Accelerated erosion, for example, decreases water quality, causes sedimentation of dams and may result in a lowering of the water table (Bosch & Hewlett 1980). Typically, several drivers interact to bring about geomorphological change in a landscape and it is difficult to isolate their individual effects (Michalková et al. 2011).

In California, a Mediterranean-type climate region, land-use change over large areas altered erosion intensity which caused channel lengthening and a decrease in active channel width (Michalková et al. 2011). In South Africa and Australia, IAPs have been found to impact the geomorphology of river systems by modifying the river channel and their removal can lead to significant channel instability and mobilization of sediment (Beyers 1991, Rowntree 1991, Richardson et al. 1997, Bunn et al. 1998). In the Kromme River, IAPs shade out palmiet wetlands and have caused extensive erosion damage due to the species having a shallow spreading root system (Boland et al. 2006). The impacts of IAPs on riverine habitats show that invasion can lead to significant destabilisation of the floodplain sediments and result in erosion (Rowntree 1991). It is possible to mitigate these geomorphological impacts and one such example of this is in the Andes, where restoration of dense vegetation on mountain slopes slowed the rate of erosion (Vanacker et al. 2007). Other solutions included a decrease in rural population size coupled with reduced agriculture and a decrease in grazing pressure. This resulted in decreased erosion rates, the colonization of riverbanks by riparian vegetation and the narrowing of a river channel (Kondolf et al. 2007).

Impact of afforestation on flow regimes

There have been very few measurements of the impacts of invasions on runoff in South Africa, so when it comes to understanding their impacts, we have to draw inferences from the knowledge that we do possess. Most invasions in South Africa involve woody plants or trees, thus we can look at studies that have compared runoff from catchments with woody plants versus shorter vegetation, herbaceous plants (e.g. grasslands) or low shrubs (e.g. fynbos) (Calder 1996,

Stellenbosch University http://scholar.sun.ac.za

Calder 1999, Le Maitre 2004). A review on 94 catchment experiments around the world conclusively demonstrated that a reduction in vegetation cover will result in an increase in riverflow, and *vice versa* (Bosch & Hewlett 1982). Tall woody trees, such as pine and eucalyptus change the riverflow by 40 mm per 10% change in vegetation cover, whereas for deciduous hardwoods it is 25 mm and scrub 10 mm, respectively (Bosch & Hewlett 1982).

There have been many studies in South Africa on the impacts of plantations on riverflow, both in riparian and non-riparian settings, largely because the forestry industry is important for the economy but also accounts for the use of a relatively large proportion (4-8%) of South Africa's water resources (Bosch & von Gadow 1990, Jewitt 2002). Many South African studies have found that afforestation of catchments significantly reduces riverflow, showing that woody trees use more water that the native vegetation (van Lill et al. 1980, van Wyk 1986, Scott & Smith 1997, Scott & Lesch 1997, Scott et al. 1998, Scott et al. 2000). Several reviews have shown that where plantations replace shrubs or low vegetation they increase interception and transpiration, decrease total annual riverflow and baseflow and have a variable effect on stormflow, depending on the size of the rainfall event and the saturation of soil water reserves (Versfeld 1994, Forsyth et al. 1997, Vertessy et al. 2003, Scott et al. 2004). Dye (1996), noted that the rate at which transpiration increased after afforestation differed markedly between eucalypt and pine sites. In terms of what to expect when IAPs are cleared, studies show globally that deforestation increases riverflow (Bosch & Hewlett 1982, Zhang et al. 2001, Vertessy et al. 2003, Andreassian 2004, Bruijnzeel 2004, Scott et al. 2004, Legesse et al. 2010).

A paired catchment experiment was done in South Africa to determine the longer-term effects of afforestation with *Eucalyptus grandis* and *P. radiata* on riverflow (Scott & Prinsloo 2008). In both experiments, afforestation led to reductions in riverflow. However, this trend was reversed, riverflow tending towards pre-afforestation levels, as the trees matured; over 30 years for the pines, and 15 for eucalypts. Another study on afforestation with *Eucalyptus* and *Pinus* species in a South African catchment was found to significantly decrease riverflow after three and four years respectively. The stream dried up after nine and 12 years respectively (Scott & Lesch 1997). When the *Eucalyptus* plantations were clearfelled, full perennial riverflow did not return until five years later. Several studies done in New Zealand and Australia, found that greater

Stellenbosch University http://scholar.sun.ac.za

reductions in riverflow resulted after planting *P. radiata* than eucalyptus (Vertessy et al. 2003). Conversely, in South Africa greater reductions were found after *E. grandis* was planted than after that of *Pinus patula* and *P. radiata* (Scott & Smith 1997). Commercial plantations in South Africa were estimated to reduce the mean annual riverflow by 3.2% and baseflow by 7.8% (Scott et al. 1998).

Impact of riparian invasions on flow regimes

a. Runoff/Riverflow

Where woody trees replace indigenous vegetation types such as fynbos or grasslands, they are known to alter the hydrology of the catchment in a number of ways. This is because different growth forms; trees, shrubs or grasses, affect hydrology differently (Calder 2005). Firstly, IAPs are able to alter the rainfall interception in a catchment (Calder 2005). A change in interception can alter the ratio of evaporation to infiltration rates, which could in turn alter riverflow (Bosch & Hewlett 1982). Secondly, where woody alien trees replace indigenous grasslands or other short vegetation types, transpiration rates (soil water uptake) will exceed those of the indigenous vegetation. This is because the roots of the woody alien trees are able to reach groundwater reserves 10 m or more below the surface (Le Maitre et al. 1999, Le Maitre 2004). Thirdly, dense stands of IAPs generally have high annual transpiration rates, especially when compared to those of indigenous plants which become dormant in particular seasons, such as grasslands (Dye & Versfeld 2007, Everson et al. 2007). At a larger, catchment scale, these differences manifest as changes in evaporation and therefore changes in riverflow (Le Maitre 2004).

Modeling studies have estimated that invasion by IAPs will decrease riverflow (Le Maitre et al. 1996, Le Maitre et al. 2000, Le Maitre & Görgens 2001, Le Maitre et al. 2002). One study estimated that IAPs would decrease mean annual runoff by 3300 million m^3 per annum (Dye et al. 2008a). A few studies have used portable weirs to examine the short-term effects of the clearing of invasive wattle (Dye & Poulter 1995, Prinsloo & Scott 1999). Both of these studies found that the removal of invasive wattle resulted in riverflow increases, however due to their short-term nature neither of these studies took into account the water-use of the native vegetation that would eventually replace the wattle (Dye & Poulter 1995, Prinsloo & Scott 1999). Three

Stellenbosch University http://scholar.sun.ac.za

paired-catchment experiments showed that clearing indigenous forest or exotic trees in the riparian zone of a catchment disproportionately increases riverflow compared to clearing trees in another part of the catchment (Scott 1999).

b. Stormflow

IAPs also have an effect on stormflow, because litter cover, satiation of aquifers and soil water storage capacity all play a role in the stormflow process (Scott et al. 2004). Surface runoff, a component of stormflow, was found to decrease with vegetation rehabilitation, as it becomes negligible when vegetation cover exceeds 65% (Descheemaeker et al. 2006). This is because the vegetation stabilises and protects the soil, and organic matter improves its structure resulting in significant increase in infiltration and sustained riverflow. Furthermore, total vegetation cover was found to explain 80% of the variation in the rainfall/runoff relationship (Descheemaeker et al. 2006).

c. Groundwater and baseflow

Gush et al. (2002) concluded that our understanding of the hydrological processes with regard to the water use of trees from deep soil profiles was inadequate. Woody alien invasions are also thought to cause a general reduction in groundwater recharge (Parsons 2004). Clearing natural forests has been shown to increase baseflow; provided disturbance is kept to a minimum (Bruijnzeel 2004). However in Australia, natural forest growth stage had no effect on baseflow (Lacey & Grayson 1998). In general, afforestation and reforestation has been found to decrease baseflow (Hibbert 1971, McGuinnes & Harrold 1971, Smith & Scott 1992, Versfeld 1994, Forsyth et al. 1997, Scott & Lesch 1997, Scott et al. 1998, Andreassian 2004, Scott et al. 2004).

Conclusion

Invasion of fynbos and grasslands by woody IAPs are similar in structure and physiology to plantations of the same species, and plantations have been shown to increase evaporation, thereby decreasing riverflow. This analogy is also supported by the results of short-term studies on effects of clearing IAPs on transpiration and interception. Riparian and wetland vegetation have been shown to have higher evaporation rates, and therefore total water-use, than adjacent

Stellenbosch University http://scholar.sun.ac.za

dryland vegetation, ranging from around 1000-1200 mm annually. Invasions by IAPs in riparian and wetland settings use more water than native riparian plants; for *A. mearnsii* transpiration ranges from 1300-1500 mm/annum. Therefore where IAPs replace native riparian vegetation it is likely that a decrease in annual riverflow will result.

REFERENCES

Andreassian, V. 2004. Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology*. **291**: 1-27.

Begg, G. W. 1986. The wetlands of Natal (Part 1). An overview of their extent role and present status. Report 68. Pietermaritzburg: Natal Town and Regional Planning.

Beyers, G. 1991. A preliminary assessment of the geomorphological impact of alien vegetation in the Baviaanskloof region. Third Year Project, Department of Geography, Rhodes University, Grahamstown.

Birkhead, A. L., B. W. Olbrich, C. S. James, and K. H. Rogers. 1997. Developing an integrated approach to predicting the water use of riparian vegetation. Water Research Commission. WRC Report No: 474/1/97.

Birkhead, A. L., C. S. James, and M. T. Kleynhans. 2007. Hydrological and hydraulic modelling of the Nyl River floodplain. Part 2: Modelling hydraulic behavior. *Water SA*. **33**(1): 9-20.

Boland, D.J., M. I. H. Brooker, G. M. Chippendale, N. Hall, B. P. M. Hyland, R. D., Johnson, D. A. Kleinig, M. W., McDonald, and J. D. Turner. 2006. Forest Trees of Australia. CSIRO Publishing, Collingwood.

Bosch, J. M., and J. D. Hewlett. 1980. Sediment Control in South African forests and mountain catchments. *Suid-Afrikaanse Bosboutydskrif*. **115**: 50-55.

Bosch, J. M., and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*. **55**: 3-23.

Bosch, J. M., and K. von Gadow. 1990. Regulating afforestation for water conservation in South Africa. *Suid-Afrikaanse Bosboutydskrif*. **153**: 41-54.

Bragg, O. M. 2002. Hydrology of peat-forming wetlands in Scotland. *The science of the Total Environment*. **294**: 111-129.

Stellenbosch University http://scholar.sun.ac.za

Bruijnzeel, L. A. 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems and Environment*. **104**:185-228.

Bullock, A., and M. Acreman. 2003. The role of wetlands in the hydrological cycle. *Hydrology and Earth System Sciences*. **7**(3): 358-389.

Bunn, S. E., P. M. Davies, D. M. Kellaway, and I. P. Prosser. 1998. Influences of invasive macrophytes on channel morphology and hydrology in an open tropical lowland stream, and potential control by riparian shading. *Freshwater Biology*. **39**: 171-178.

Calder, I. R. 1996. Water use by forests at the plot and catchment scale. Commonwealth for review. Special issue on "*Forests and Climate*". **75**(1996): 19-30.

Calder, I. R. 1999. Blue Revolution. Earthscan. London. Pg 192.

Calder, I. R. 2005. Blue Revolution II: Land-use and integrated water resources management. Earthscan, London.

Cavaleri, M. A., and L. Sack. 2010. Comparative water use of native and invasive plants at multiple scales: a global meta-analysis. *Ecology*. **91**(9): 2705-2715.

Clulow, A. D., C. S. Everson, and M. B. Gush. 2011. The long-term impact of *Acacia mearnsii* trees on evaporation, stream flow, and ground water resources. Report No. TT 505/11, Water Research Commission, Pretoria.

Clulow, D., C. S. Everson, M. G. Mengistu, C. Jarmain, G. P. W. Jewitt, J. S. Price, and P. L. Grundling. 2012. Measurement and modelling of evaporation from a coastal wetland in Maputaland, South Africa. *Hydrology and Earth System Science*. **9**: 1741–1782.

Costa, M. H., A. Botta, and J. A. Cardille. 2003. Effects of large scale changes in land-cover on the discharge of the Tocantins River, south-eastern Amazonia. *Journal of Hydrology*. **283**: 206-217.

Crous, C. J., S. M. Jacobs and K. J. Esler. 2011. Drought-tolerance of an invasive alien tree, *Acacia mearnsii* and two native competitors in fynbos riparian ecotones. *Biological Invasions*. **14**: 619-631.

Descheemaeker, K., J. Nyssen, J. Poesen, D. Raes, M. Haile, B. Muys, and S. Deckers. 2006. Runoff processes on slopes with restored vegetation: a case study from the semi-arid Tigray highlands, Ethiopia. *Journal of Hydrology*. **331**: 219-241.

Stellenbosch University http://scholar.sun.ac.za

Devito, K. J., A. R. Hill, and N. Roulet. 1996. Groundwater-surface water interactions in headwater forested wetlands of the Canadian Shield. *Journal of Hydrology*. **181**: 127-147.

Dubreuil, P. L. 1985. Review of field observations of runoff generation in the tropics. *Journal of Hydrology*. **80:** 237-264.

Dunin, F. X. 2002. Integrating agroforestry and perennial pastures to mitigate water logging and secondary salinity. *Agricultural Water Management*. **53**: 259-270.

Dye P. J., Moses G., Vilakazi P., Ndlela R., Royappen M. 2001. Comparative water use of wattle thickets and indigenous plant communities at riparian sites in the Western Cape and KwaZulu-Natal. Water SA 27, 529–538.

Dye, P. and D: Versfeld. 2007. Managing the hydrological impacts of South African plantation forests: An overview. *Forest Ecology and Management.* **251**: 121– 128.

Dye, P. J. 1996. Climate, forest and streamflow relationships in South African afforested catchments. Commonwealth Forestry Reviews. **75**(1): 31-38.

Dye, P. J., and A. G. Poulter. 1995. A field demonstration of the effect on streamflow of clearing invasive pine and wattle trees from a riparian zone. *Southern African Forestry Journal*. **185**:1-7.

Dye, P. J., C. Jarmain, D. C. Le Maitre, C. S. Everson, M. B. Gush, A. Clulow. 2008b. Modelling vegetation water use for general application in different categories of vegetation. Water Research Commission, Pretoria, South Africa. WRC Report No: 1319/1/08.

Dye, P. J., M. B. Gush, C. S. Everson, C. Jarmain, A. Clulow, M, Mengistu, C. J. Geldenhuys, R. Wise, R. J. Scholes, S. Archibald, and M. J. Savage. 2008a. Water Use in Relation to Biomass of Indigenous Tree Species in Woodland, Forest and/or Plantation Conditions. Water Research Commission, Pretoria, South Africa. WRC Report No: 1462/1/08.

Dye, P., and C. Jarmain. 2004. Water use by black wattle (*Acacia mearnsii*): implications for the link between removal of invading trees and catchment streamflow response. *South African Journal of Science***. 100**: 40-44.

Ellery, W. N., M. Grenfell, S. Grenfell, D. C. Kotze, T. S. McCarthy, S. Tooth, P. L. Grundling, H. Beckedahl. D. Le Maitre, L. Ramsay. 2009. WET-Origins: Controls on the distribution and dynamics of wetlands in South Africa. C. Breen, J. Dini, W. Ellery, S. Mitchell, and

Stellenbosch University http://scholar.sun.ac.za

M. Uys (Eds). Water Research Commission, Pretoria, South Africa. WRC Report No. TT 334/09.

Evans, M. G., T. P. Burt, J. Holden, and J. K. Adamson. 1999. Runoff generation and water table fluctuations in blanket peat: evidence from UK data spanning the dry summer of 1995. *Journal of Hydrology*. **221**: 141-160.

Everson C.S., Gush, M.B., Moodley, M., Jarmain, C., Govender, M., Dye, P. 2007. Effective management of the riparian zone vegetation to significantly reduce the cost of catchment management and enable greater productivity of land resources. Report no. 1284/1/07, Water Research Commission, Pretoria, South Africa.

Everson, C. S., C. Burger, B. W. Olbrich, and M. B. Gush. 2001. Verification of estimates of water use from riverine vegetation on the Sabie river in the Kruger National park. Water Research Commission, Pretoria, South Africa. WRC Report No 877/1/01.

Everson, C. S., G. L. Molefe, and T. M. Everson. 1998. Monitoring and modelling components of the water balance in a grassland catchment in the summer rainfall area of South Africa. Water Research Commission, Pretoria, South Africa. WRC Report No. 493/1/98.

Everson, C., A. Clulow, and M. Mengitsu. 2009. Feasibility study on the determination of riparian evaporation on non-perennial systems. Water Research Commission, Pretoria, South Africa. WRC Report No: TT 424/09.

Everson, C., A. Clulow, and M. Mengitsu. 2010. Feasibility Study on the Determination of Riparian Evaporation in Non-perennial Systems. Water Research Commission, Pretoria, South Africa. WRC Report No. TT 424/09.

Falkenmark, M., L. Andersson, R. Castensson, K. Sundblad. 1999. Water: a reflection of land use Options for counteracting land and water mismanagement. Published by Swedish Natural Science Research Council. ISNB: 91 546 0358 7.

Forsyth, G. G., D. B. Versfeld, R. A. Chapman, and B. K. Fowles. 1997. The hydrological implications of Afforestation in the North-Eastern Cape: a survey of resources and assessment of the impacts of land-use change. Water Research Commission, Pretoria, South Africa. WRC Report No 511/1/97.

Grayson, R., J. Holden, and R. Rose. 2010. Long-term changes in storm hydrographs in response to peatland vegetation change. *Journal of Hydrology*. **389**: 336-343.

Stellenbosch University http://scholar.sun.ac.za

Grenfell, M. C., W. N. Ellery, and S. E. Grenfell. 2009. Valley morphology and sediment cascades within a wetland system in the KwaZulu-Natal Drakensberg Foothills, Eastern South Africa. *Catena*. **78**: 20-35.

Gush, M. B., D. F. Scott, G. P. W. Jewitt, R. E. Schulze, T. G. Lumsden, L. A. Hallowes, and A. H. M. Görgens. 2002. Estimation of streamflow reductions resulting from commercial Afforestation in South Africa. Water Research Commission, Pretoria, South Africa. WRC Report No: TT173/02.

Haigh, E. A., P. L. Grundling, P. Illgner, J., Wilmotand, and J. Buckle. 2002. The Wetland Rehabilitation Project in the Kromme River System, Eastern Cape. Department of Water Affairs and Forestry Project X832633.

Hategekimana, S., and E. Twarabamenye. 2007. The impact of wetlands degradation on water resources management in Rwanda: the case of Rugezi Marsh. *Journal of Agrarian Change*. **6**(4): 1-18.

Hewlett, J. D. 1982. Principles of forest hydrology. University of Georgia Press. Athens.

Hibbert, A. R. 1971. Increases in streamflow after converting chaparral to grass. *Water Resources Research*. **7**(1): 71–80.

Holden, J., Shotbolt, L., Bonn, A., Burt, T.P., Chapman, P.J., Dougill, A.J., Fraser, E.D.G., Hubacek, K., Irvine, B., Kirkby, M.J., Reed, M.S., Prell, C., Stagl, S., Stringer, L.C., Turner, A., Worrall, F., 2007. Environmental change in moorland landscapes. *Earth-Science Reviews*. **82** (1–2): 75–100.

Humphries, M. S., A. Kindness, W. N. Ellery, and J. C. Hughs. 2010b. Sediment geochemistry, mineral precipitation and clay neoformation on the Mkuze River floodplain, South Africa. *Geoderma*. 325-334.

Humphries, M. S., A. Kindness, W. N. Ellery, J. C. Hughes, and C. R. Benitez-Nelson. 2010a. ^{137}Cs and ^{210}Pb derived sediment accumulation rates and their role in the long-term development of the Mkuze River floodplain, South Africa. *Geomorphology*. **119**: 88-96.

Jewitt, G. 2002. Can integrated water resources sustain the provision of ecosystem goods and services? *Physics and Chemistry of the Earth.* **27**: 887-896.

Kondolf, G. M., H. Piégay, and N. Landon. 2007. Changes in the riparian zone of the lower Eygues River, France, since 1830. *Landscape Ecology*. **22**: 367-384.

Stellenbosch University http://scholar.sun.ac.za

Kotze, D. C., and C. M. Breen. 1994. Agricultural land-use impacts on wetland functional values. Water Research Commission, Pretoria, South Africa. WRC Report No 501/3/94.

Kotze, D. C., G. C. Marneweck, A. L. Batchelor, D. S. Lindley, and Collins, N. B. 2005. WET-EcoServices. A rapid assessment procedure for describing wetland benefits. Mondi Wetlands Project.

Lacey, G. C., and R. B. Grayson. 1998. Relating baseflow to catchment properties in south-eastern Australia. *Journal of Hydrology*. **204**: 231-250.

Le Maitre, D. C. 2004. Predicting invasive species impacts on hydrological processes: the consequences of plant physiology for landscape processes. *Weed Technology*. **18**: 1408-1410.

Le Maitre, D. C., and A. Görgens. 2001. Potential impacts of invasive alien plants on reservoir yields in South Africa. Tenth South African National Hydrology Symposium: 26-28 September 2001.

Le Maitre, D. C., and C. A. Colvin. 2008. Assessment of the contribution of groundwater discharges to rivers using monthly flow statistics and flow seasonality. *Water SA*. **34**(5): 549-564.

Le Maitre, D. C., B. W. Van Wilgen, C. M. Gelderblom, C. Bailey, R. A. Chapman, and J. A. Nel. 2002. Invasive alien trees and water resources in South Africa: case studies of the costs and benefits of management. *Forest Ecology and Management.* **160**(3): 143-159.

Le Maitre, D. C., B. W. van Wilgen, R. A. Chapman, and D. H. McKelly. 1996. Invasive plants and water resources in the Western Cape Province, South Africa: modelling the consequences of a lack of management. *Journal of Applied Ecology*. **33**: 161-172.

Le Maitre, D. C., D. B. Versfeld and R. A. Chapman. 2000. The impact of invading alien plants on surface water resources in South Africa: A preliminary assessment. *Water SA* **26** (3): 397-408. http:// www.wrc.org.za/archives/watersa%20archive/2000/July/1220.pdf

Le Maitre, D. C., D. F. Scott, and C. Colvin. 1999. A review of information on interactions between vegetation and groundwater. *Water SA*. **25**(2): 137-152.

Legesse, D. C., T. A. Abiye, C. Vallet-Coulomb, H. Abate. 2010. Streamflow sensitivity to climate and land-cover changes: Meki River, Ethiopia. *Hydrology and Earth System Sciences*. **14**: 2277-2287.

Stellenbosch University http://scholar.sun.ac.za

Legesse, D., C. Vallet-Coulomb, and F. Gasse. 2003. Hydrological response of a catchment to climate and land-use changes in Tropical Africa: case study South Central Ethiopia. *Journal of Hydrology*. **275**: 67-85.

Levine, J. M., M. Vilà, C. M. D'Antonio, J. S. Dukes, K. Grigulis, and S. Lavorel. 2002. Mechanisms underlying the impacts of exotic plant invasions. *Proceedings of the Royal Society of London*. **270**: 775-781.

Lewis, C. A. 2008. Geomorphology of the Eastern Cape, South Africa. Second Edition. NISC, Grahamstown. Pp 21-28.

Mander, M., J. Blignaut, M. Van Niekerk, R. Cowling, M. Horan, D. Knoesen, A. Mills, M. Powell, and R. Schulze. 2010. Baviaanskloof-Tsitsikamma Payments for Ecosystem Services: A feasibility assessment. Futureworks.

McCarthy, T. S. and W. N. Ellery. 1998. The Okavango Delta. *Transactions of the Royal Society of South Africa*. **53**: 157-182.

McGuinness, J. L., and L. Harrold. 1971. Reforestation influences on small watershed streamflow. *Water Resources Research*. **7**(4), 845–852.

Meals, D. W. 2001. Water quality response to riparian restoration in an agricultural watershed in Vermont, USA. *Water Science and Technology*. **43**(5): 175-182.

Michalková, M. H. Piégay, G. M. Kondolf and S. E. Greco. 2011. Lateral erosion of the Sacramento River, California (1942-1999), and responses of channel and floodplain lake o human influences. *Earth Surface Processes and Landforms*. **36**: 257-272.

Midgley, J. J., and D. F. Scott. 1994. The use of stable isotopes of water (D and ^{18}O) in hydrological studies in the Jonkershoek Valley. *Water SA*. **20**(2): 151-154.

Mooney, H. A., C. Field, S. L. Guloman, P. Rundel, and F. J. Kruger. 1983. Photosynthetic characteristic of South African sclerophylls. *Oecologia*. **58**: 398-401.

Morris, T. L., K. J. Esler, N. N. Barger, S. M. Jacobs and M. D. Cramer. 2011. Ecophysiological traits associated with the competitive ability of invasive Australian acacias. *Diversity and Distributions*. **17**: 898-910.

Mwakalila, S., G. Wyseure, and J. Feyen. 2002. The influence of physical catchment properties on Baseflow in semi-arid catchments. *Journal of Arid Environment*. **52**: 245–258.

Parsons, R. 2004. Surface Water: Groundwater Interaction in a South African Context – A Geohydrological Perspective. WRC Report Number TT 218/03.

Stellenbosch University http://scholar.sun.ac.za

Pimm S. L., and P. Raven. 2000. Extinction by numbers. *Nature*. **403**: 843-845.

Prinsloo, F. W., and D. F. Scott. 1999. Streamflow responses to the clearing of alien invasive trees from riparian zones at three sites in the Western Cape Province. *Southern African Forestry Journal*. **185**: 1-7.

Raimondo, D., L. Von Staden, W. Foden, J. E. Victor, N. A. Helme, R. C. Turner, D. A. Kamundi, and P. A. Manyama (eds). 2009. Red List of South African plants 2009. Strelitzia **25**. South African National Biodiversity Institute, Pretoria.

Raymer, D. 2008. *Streams of Life*. Published by David Raymer, South Africa.

Reyers, B., P. J. O'Farrell, R. M. Cowling, B. N. Egoh, D. C. Le Maitre, and J. H. J. Vlok. 2009. Ecosystem services, land-cover change, and stakeholders: finding a sustainable foothold for a semi-arid biodiversity hotspot. *Ecology and Society*. **14**(1): 38-61.

Richardson, D. M., I. A. W. Macdonald, J. H. Hoffmann, and L. Henderson. 1997. Alien plant invasions. In: *Vegetation of Southern Africa*. R. M. Cowling, D. M. Richardson, and S. M. Pierce (Eds). Cambridge, Cambridge University Press. Pp. 534–570.

Rouget, M, B. Reyers, Z. Jonas, P. Desmet, A. Driver, K. Maze, B. Egoh, and R. M. Cowling. 2004. *South African National spatial biodiversity assessment*. Technical Report. Volume 1: Terrestrial Component.

Rowntree, K. 1991. An assessment of the potential impact of alien invasive vegetation on the geomorphology of river channels in South Africa. *South African Journal of Aquatic Science*. **17** (1/2): 28-43.

Royappen, M., P. J. Dye, R. E. Schulze, and M. B. Gush. 2002. An Analysis of catchment attributes and hydrological response characteristics in a range of small catchments. Water Research Commission, Pretoria, South Africa. WRC Report No: 1193/1/02.

Russel, W. B. 2009. WET-RehabMethods: National guidelines and methods for wetland rehabilitation. C. Breen, J. Dini, W. Ellery, S. Mitchell, and M. Uys (Eds). Water Research Commission, Pretoria, South Africa. WRC Report No. 341/09.

Scanlon, B. R., I. Jolly, M. Sophocleous, and L. Zhang. 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality. *Water Resources Research*. **43**: 1-18.

Scott D. F., and F. W. Prinsloo. 2008. Longer-term effects of pine and eucalypt plantations on streamflow. *Water Resources Research*. **44**: 1-8.

Stellenbosch University http://scholar.sun.ac.za

Scott, D. F. 1999. Managing riparian zone vegetation to sustain streamflow: results of paired catchment experiments in South Africa. *Canadian Journal of Forestry Research*. **29**: 1149-1157.

Scott, D. F., and R. E. Smith. 1997. Preliminary empirical models to predict reductions in total and low flows resulting from afforestation. *Water SA*. **23**: 135–140.

Scott, D. F., and W. Lesch. 1997. Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, Mpumalanga province. *South African Journal of Hydrology*. **199**: 360-377.

Scott, D. F., D. C. Le Maitre, and D. H. K. Fairbanks. 1998. Forestry and streamflow reductions in South Africa. A reference system for assessing extent and distribution. *Water SA*. **24**: 187-199.

Scott, D. F., F. W. Prinsloo, G. Moses, M. Mehlomakulu, and A. D. A. Simmers. 2000. A re-analysis of the South African catchment Afforestation experimental data. Water Research Commission, Pretoria, South Africa. WRC Report No: 810/1/00.

Scott, D. F., L. A. Bruijnzeel, R. A. Vertessy, and I. R. Calder. 2004. Impacts of Forest Plantations on Streamflow. *Forest Hydrology*. **272**: 1-11.

Sellars, C. D. 1981. A floodplain storage model used to determine evaporation losses in the Upper Yobe River, Northern Nigeria. Journal of Hydrology. 52: 257-268.

Seyhan, E., A. S. Hope, and R. E. Schulze. 1983. Estimation of streamflow loss by evapotranspiration from a riparian zone. *South African Journal of Science*. **79:** 88-90.

Sinchembe, M., and W. N. Ellery. 2010. Human impacts on hydrological health and the provision of ecosystem services: a case study of the eMthonjeni-Fairview Spring Wetland, Grahamstown, South Africa. *African Journal of Aquatic Science*. **35**(3): 227-239.

Skead, C. J. (compiler). 2009. Historical plant incidence in southern Africa. *Strelitzia 24*. South African National Biodiversity Institute, Pretoria, South Africa.

Smakhtin, V. U. 2001. Low flow hydrology: a review. *Journal of Hydrology*. **240**: 147-186.

Smith, R. E., and D. F. Scott. 1992. The effects of afforestation on low flows in various regions of South Africa. *Water SA*. **18**: 185-194.

Smith, S. D., D. A. Devitt, A. Sala, J. R. Cleverly, and D. E. Busch. 1998. Water relations of riparian plants from warm desert regions. *Wetlands*. **18**(4): 687-696.

Stellenbosch University http://scholar.sun.ac.za

Snyman, H. A., and H. J. Fouche. 1991. Production and water-use efficiency of semiarid grasslands of South-Africa as affected by veld condition and rainfall. *Water SA*. **17**(4): 263-268.

Stähli, M., A. Badoux, A. Ludwig, K. Steiner, M. Zappa, and C. Hegg. 2011. One century of hydrological monitoring in two small catchments with different forest coverage. *Environmental Monitoring Assessment*. **174**: 91-106.

Thompson, J.R., and G. E. Hollis. 1995. Hydrological modelling and the sustainable development of the Hadejia-Nguru wetlands, Nigeria. *Hydrological Science Journal*. **40:** 97-108.

Toerien, D. K., and R. S. Hill. 1989. The geology of the Port Elizabeth areas, Explanation of Sheet 3324. Geological Survey South Africa. Pp 35.

Tooth, S., T. S. McCarthy, P. J. Hancox, D. Brandt, K. Buckley, E. Nortje, S. McQuade. 2002. The geomorphology of the Nyl River and floodplain in the semi-arid Northern Province, South Africa. *South African Geographical Journal*. 84:226-237.

Turpie, J.K., C, Marais, and J. N. Blignaut. 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**: 788-798.

van Lill, W. S., F. J. Kruger, and D. B. Van Wyk. 1980. The effect of afforestation with *Eucalyptus grandis Hill Ex Maiden* and *Pinus patula Schlecht. Et Cham.* on streamflow from experimental catchments at Mokobulaan, Transvaal. *Journal of Hydrology*. **48**: 107-118.

van Wyk, D. B. 1986. Some effects of afforestation on streamflow in the Western Cape Province, South Africa. *Water SA*. **13**(1): 31-36.

Vanacker, V., F. von Blanckenburg, G. Govers, A. Molina, J. Poesen, J. Deckers and P. Kubik. 2007. Restoring dense vegetation can slow mountain erosion to near natural benchmark levels**.** *Geology*. **35**(4): 303-306.

Versfeld, D. B. 1994. The forest industry and management for water conservation. Division of Forest Science and Technology, CSIR.

Vertessy, R. A., L. Zhang, and W. R. Dawes. 2003. Plantations, river flows and river salinity. *Australian Forestry*. **66**: 55-61.

Stellenbosch University http://scholar.sun.ac.za

Vitousek, P. M., H. A. Mooney, J. Lubchenco and J. M. Melillo. 1997. Human Domination of earth's ecosystems. *Science*. **277**: 494-499.

von Willert, D. J., M. Herppich, and J. M. Miller. 1989. Photosynthetic characteristic and leaf water relations of mountain fynbos vegetation in the Cedarberg area (South Africa). *South African Journal of Botany*. **55**(3): 288-298.

Warburton, R. E. Schulze, and G. P. W. Jewitt. 2010. Confirmation of *ACRU* model results for applications in land-use and climate change studies. *Hydrology and Earth System Science*. **14**: 2399–2414.

Warburton, R., E. Schulze, and G. P. W. Jewitt. 2012. Hydrological impacts of land-use change in three diverse South African catchments. *Journal of Hydrology*. **414-415**:118-135.

Wolski, A. 2002. Hydrological processes in the Okavango wetland, Botswana. *Proceedings of EGS.* Nice, April 2002.

Zhang, L., W. R. Dawes, and G. R Walker. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research*. **37**(3): 701-708.

Stellenbosch University http://scholar.sun.ac.za

CHAPTER 3

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

Rebelo, A.J. [1*], le Maitre, D. [2], Esler, K.J. [1, 3], and R. M. Cowling [4]

[1] Department of Conservation Ecology and Entomology, Stellenbosch University, Stellenbosch, South Africa
[2] Council for Scientific and Industrial Research (CSIR), Stellenbosch, South Africa
[3] Centre for Invasion Biology (C.I.B), Stellenbosch, South Africa
[4] Restoration Research Group, Department of Botany, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa

*Author for correspondence
E-mail: ARebelo@sun.ac.za
Tel: +2779 499 7235

Securing sufficient and reliable water supply is a priority for many countries worldwide, but their efforts are hindered by widespread landscape degradation and uncertainty around future climate change. We used historical aerial photographs and mapping techniques to investigate how a South African landscape has changed over the past century. The Kromme River system, a valuable water-providing catchment for the Nelson Mandela Bay metropolitan hub, has become heavily degraded. The floodplain wetlands, which historically occupied the entire valley floor, have been almost completely replaced by agriculture or invaded by the Australian Black Wattle, *Acacia mearnsii*. Some efforts have been made to restore the wetlands and control the invasive plants, but our results show that at the current rate of clearing it would take 30 years before *A. mearnsii* would be brought under control. We recommend that investment should be made, as a type of insurance against the loss of natural capital, based on restoring resilience in important water-providing catchments to hedge against future climatic uncertainties.

Keywords: floodplain wetlands, ecosystem goods and services, degradation, restoration, *Prionium serratum*, land-cover change, climate change.

Stellenbosch University http://scholar.sun.ac.za

Figure 3.1: The Kromme River in the Eastern Cape of South Africa as seen from its headwaters towards the coast. The Kromme is a narrow river valley, hence the name 'Langkloof', 100 km in length, bordered on each side by steep mountain ranges. The Kromme River has been heavily transformed by agriculture as shown in the foreground.

Diary Extract: C. I. La Trobe 1816

Upper Langkloof
'First impression of Langkloof: "a vale of perhaps 100 miles enclosed by mountains of different heights. On entering it we felt not a little disappointed ... we saw a long ridge of comparatively low hills, divided by narrow parallel kloofs, without wood or water, skirting a dull uncultivated vale...."'. (Skead 2009)
-The Langkloof is the local name for the Kromme River valley

INTRODUCTION

The concept of insurance, using financial capital as a safeguard against future undesirable and yet possible events, is well entrenched within modern society. It is considered wise to invest in and protect manufactured and human capital but the concept of protecting and investing in natural capital is met with great resistance. Natural capital is the ecosystem infrastructure that provides humankind with essential ecosystem goods and services (Aronson et al. 2007, Mander et al. 2010). The Kromme River system has valuable natural capital, including wetlands and aquifers, which provide water as well as regulating and storing services to the downstream

Stellenbosch University http://scholar.sun.ac.za

Nelson Mandela Bay metropolitan hub (Haigh et al. 2002, Raymer 2008). The Nelson Mandela Bay metropolitan hub has a history of struggling to match water supply with demand, largely due to its rapidly increasing population size as well as economic development (Raymer 2008). There is a strong correlation of 0.91 between population size and water demand, and it is already evident that water demand is set to outstrip supply for the hub in the near future (Eberhard 2009). This ever increasing demand for resources coupled with the uncertainty surrounding the predicted changes in climate, will be a recipe for disaster if it is not mitigated by investing in, and ensuring that, natural capital is maintained.

Natural Capital:

"Natural Capital is an economic metaphor for the stock of physical and biological natural resources that consist of:
Renewable natural capital *(living species and ecosystems);*
Nonrenewable natural capital *(subsoil assets, e.g. petroleum, coal, diamonds);*
Replenishable natural capital *(e.g., the atmosphere, potable water, fertile soils); and*
Cultivated natural capital *(e.g., crops and forest plantations)."*

(Aronson et al. 2007)

The on-going efforts to maintain economic growth and development are driving the intensification of agriculture and other ways of using landscapes. Land transformation, or habitat loss, is currently the major factor endangering species (Pimm & Raven 2000, Raimondo et al. 2009) and ecosystems (Rouget et al. 2004, MA 2006). This effect is exacerbated in semi-arid type environments with irregular rainfall, as there is often a mismatch between seasons when water is needed and when rainfall occurs (Kondolf 2011). This leads to measures aimed at capturing and using every drop of water available. Ecosystems need resilience to persist and humankind is making itself vulnerable by stripping ecosystems of this resilience by compromising their structural and functional integrity (eroding natural capital). This is particularly apparent in wetland and riparian ecosystems. Despite the uncertainty surrounding climate change, there is general agreement that it is likely to result in water shortages and an increase in floods in southern Africa (Midgley et al. 2005, Schulze 2005, Bates et al. 2008, Le Maitre et al. 2009). Alternatives to traditional infrastructure (like dams and inter-basin transfers) which involves using the infrastructure nature provides (such as wetlands and aquifers) are likely

Stellenbosch University http://scholar.sun.ac.za

to prove more effective in mitigating the effects of climate change and water scarcity (Matthews et al. 2011).

Ecosystem Goods and Services:
Ecosystem goods and services are the benefits that society derives either directly or indirectly from ecosystem functions (Daily et al. 2000, de Groot et al. 2002).
These goods and services can be classified into three main groups:
Provisioning services (e.g. water, food, fuel),
Regulatory services (carbon sequestration, water filtration, crop pollination),
Cultural services (fulfillment of human needs: spiritual, cultural, aesthetic, intellectual) (Aronson et al. 2007)

Wetlands continue to be destroyed worldwide, as well as in South Africa, a trend which sacrifices long term societal benefit for short term, largely private gains (Ashton 2002). Major threats to wetlands and associated river systems are agriculture, forestry, invasive alien species and poor land and fire management (Mooney et al. 1986, Rowntree 1991, Groombridge 1992, Rejmanek & Randall 1994, Grundling & Marnewick 1999, David et al. 2000, Brinson & Malvarez 2002, Collins 2005, Kotze et al. 2009). Invasive woody alien trees, such as *Acacia mearnsii*, commonly known as Black Wattle, are one of the greatest threats to South Africa's water supply because of high water consumption rates (Dye & Jarmain 2004). Alien plants had invaded about 10.1 million ha of South Africa and Lesotho to various degrees by 1996, resulting in the loss of an estimated 3300 million m^3 of water per annum (Le Maitre et al. 2000).

***Acacia mearnsii* (Black Wattle)**
A. mearnsii is arguably one of South Africa's most aggressive IAPs. It is a tall woody tree, a competitive invader with extremely rapid growth rates, high seed production and drought tolerance (Crous et al. 2011). It transpires large volumes of water and, together with other woody alien invasive plants, has been shown to decrease riverflow, baseflow and yield of South African River Systems (Bosch & Hewlett 1982, Dye 1996, Le Maitre et al. 2009). It has shallow root systems and thus is not able to withstand flood waters, resulting in trees being ripped out which causing significant channel instability and erosion in river systems (Scott et al. 2004, Grenfell et al. 2005). *A. mearnsii* shades out native plant species, such as the wetland plant, palmiet (*Prionium serratum*) (Boucher & Withers 2004, van Wilgen et al. 2008). *A. mearnsii* originates from Australia and is adapted to fire. This makes it very difficult to eradicate as burning simply stimulates the germination of its sizeable seed banks and many trees resprout. *A. mearnsii* poses a significant threat to attaining water security in South Africa.

Stellenbosch University http://scholar.sun.ac.za

Figure 3.2: The flowers and leaves of a Black Wattle (A. *mearnsii*) tree

Figure 3.3: An aerial photograph taken from a helicopter of Black Wattle (*A. mearnsii*) invading the Kromme River System, South Africa. A large expanse of the river has been cleared (foreground and right) but re-growth with the next flood or fire is inevitable due to accumulated seed-banks.

Restoration has had a highly successful return on investment worldwide as it has repeatedly been shown to improve the delivery of many ecosystem services (Aronson et al. 2007) and increase biodiversity (Aronson et al. 2007, Blignaut & Aronson 2008). In the 1990's South Africa recognized the threat to ecosystems and the economy by alien plants and have acknowledged the impact of alien invasion and poor management (van Wilgen et al. 1998). In 1996 a restoration programme called Working for Water (WfWater) commenced the clearing of

Stellenbosch University http://scholar.sun.ac.za

invasive alien plants (IAPs). It has been found to be economically viable and competitive to restore natural capital and infrastructure rather than using expensive, traditional engineering techniques (van Wilgen et al. 1998, van Wilgen et al. 2008). The Kromme River Catchment, a Mediterranean-type climate catchment in the Eastern Cape of South Africa, was selected as a priority location for WfWater, because of its importance in water provision for the Nelson Mandela Bay metropolitan hub. The water use of this metropolitan hub is predicted to increase from of 100 Mm^3 per annum in 2007 to about 130 Mm^3 per annum by 2017 (Murray et al. 2008). A major aim of the WfWater project is to make more water available by removing IAPs with high water consumption rates (McConnachie et al. 2012). However WfWater's ability to cope with the scale of the problem and its efficiency over the past 15 years has been called into question (van Wilgen et al. 1998, Hobbs 2004, van Wilgen et al. 2012, McConnachie et al. 2012).

Working for Water

In the 1990s South African scientists recognized the widespread damage to the landscape by alien invasion and acknowledged the urgent need for restoration. In 1996, the government's WfWater programme began clearing the invasive alien trees in the Kromme River System (McConnachie et al. 2012). WfWater aims to make more water available by clearing IAPs that use high amounts of water. It is run through the Department of Water and Environmental Affairs. Since WfWater started in 1995, more than one million hectares of IAPs have been cleared throughout the country. WfWater has also provided jobs and training to about 20 000 people a year. These people are drawn from the most marginalized areas, and of the total, 52% are women. Currently there are 300 projects across all nine South African provinces (DWAF 2006).

Figure 3.4: Workers from South Africa's WfWater Programme. WfWater, besides restoring the landscape by clearing IAPs, also empowers local people by creating jobs for unskilled workers

Stellenbosch University http://scholar.sun.ac.za

Here we assess how changes in the South African landscape as a result of increased 'progress and development' have affected the Kromme Catchment. We ask what changes are likely to happen in the future, not only in terms of continued land transformation, but coupled with climate change. Have recent attempts to restore this landscape been successful? Are current restoration programmes efficient? We attempt to discover the main driver of these changes to answer the question: how can these complex systems be managed in such a way that they become our insurance against climate change?

Stellenbosch University http://scholar.sun.ac.za

METHODS

Study site

The Kromme River (33˚S, 24˚E) is located in the Eastern Cape Province of South Africa (Figure 3.5). It is about 100 km in length from its upper reaches (550 m above sea level) to its estuary. The catchment is narrow and steep, bordered by the Suuranys Mountains (±1050 m) to the north, and the Tsitsikamma Mountains (±1500 m) to the south, both running from east to west.

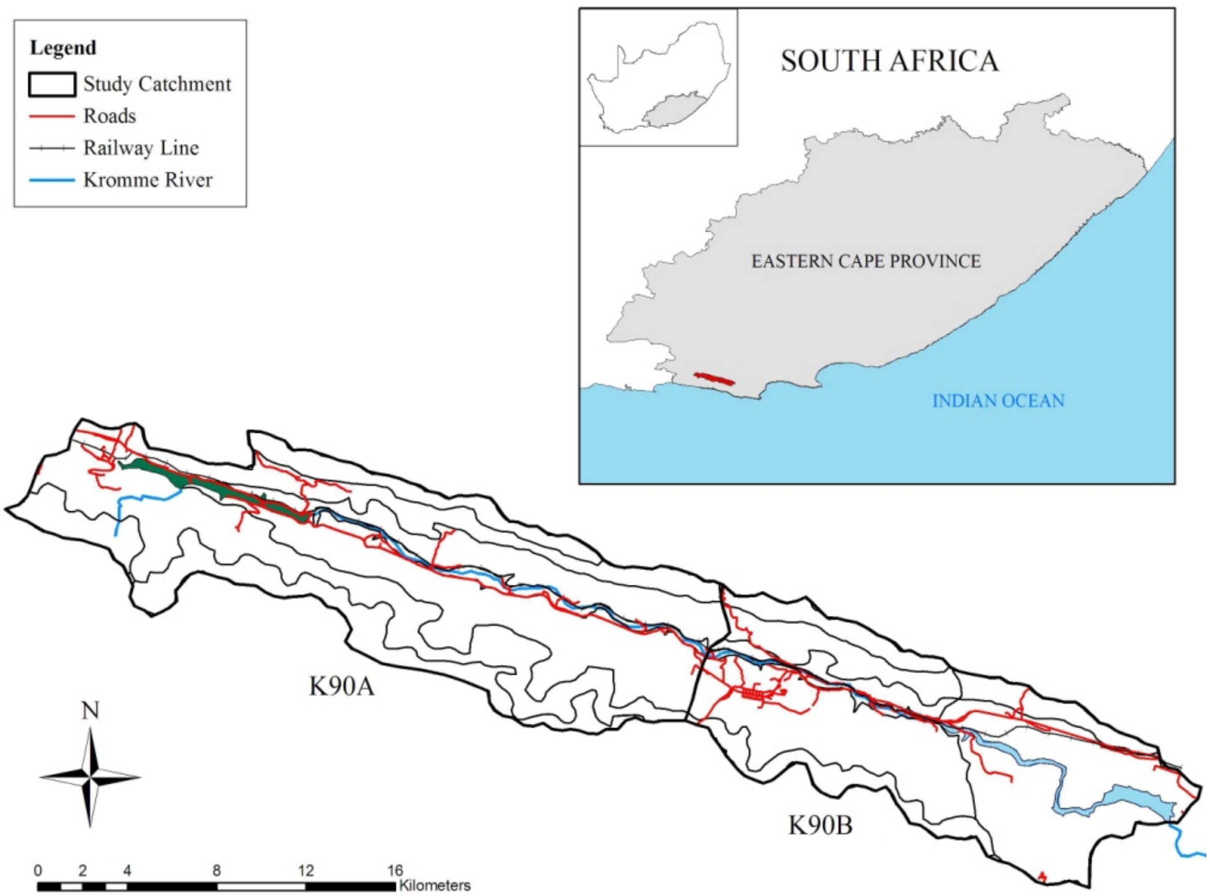


Figure 3.5: The location of the Kromme River study catchments (K90A and K90B) and the position of the Churchill Dam in the South Eastern corner of the catchment. The Kromme River is located in the Eastern Cape Province of South Africa and the Nelson Mandela Bay metropolitan area receives 24% of its water from the Churchill Dam. Solid black lines within the catchment delineate 11 subcatchments, ■ the remaining palmiet wetlands, ■ Churchill Dam.

Stellenbosch University http://scholar.sun.ac.za

Rainfall in the region is unpredictable, but tends to exhibit a bimodal pattern, with maximums in spring and autumn (Midgley et al. 1994). Mean annual precipitation (MAP) for the entire catchment is ±614 mm. Mean annual runoff (MAR) for the entire catchment is ±75 mm which is ±11% of the rainfall (Middleton & Bailey 2008).

The catchment has been heavily transformed by agriculture and alien invasion (Figure 3.6a). Groundwater recharge rates are estimated to be fairly high despite the relatively low rainfall, largely because of the shallow soils in the mountain slopes and the low water-use of fynbos (Figure 3.6b). Kareedouw (population under 1000) is the only town in the catchment (Figure 3.6c). The catchment consists predominantly of shales and sandstones of the Cape Supergroup (Toerien & Hill 1989) (Figure 3.6d). The Cape Fold Belt is part of an intensely folded range with dipping beds forming a trellis drainage pattern (Lewis 2008). There are six large and five minor tributaries entering from the southern mountain range, and seven large and numerous minor tributaries entering from the drier northern mountain range in the upper catchment (Haigh et al. 2002). Riverflow from the northern tributaries is mostly seasonal. Several of the tributaries have alluvial fans which limit the extent of the palmiet wetlands. Historically, the *P. serratum* stabilized the floodplain alluvium, forming peat basins which would have covered a large area of the floodplain (Haigh et al. 2002).

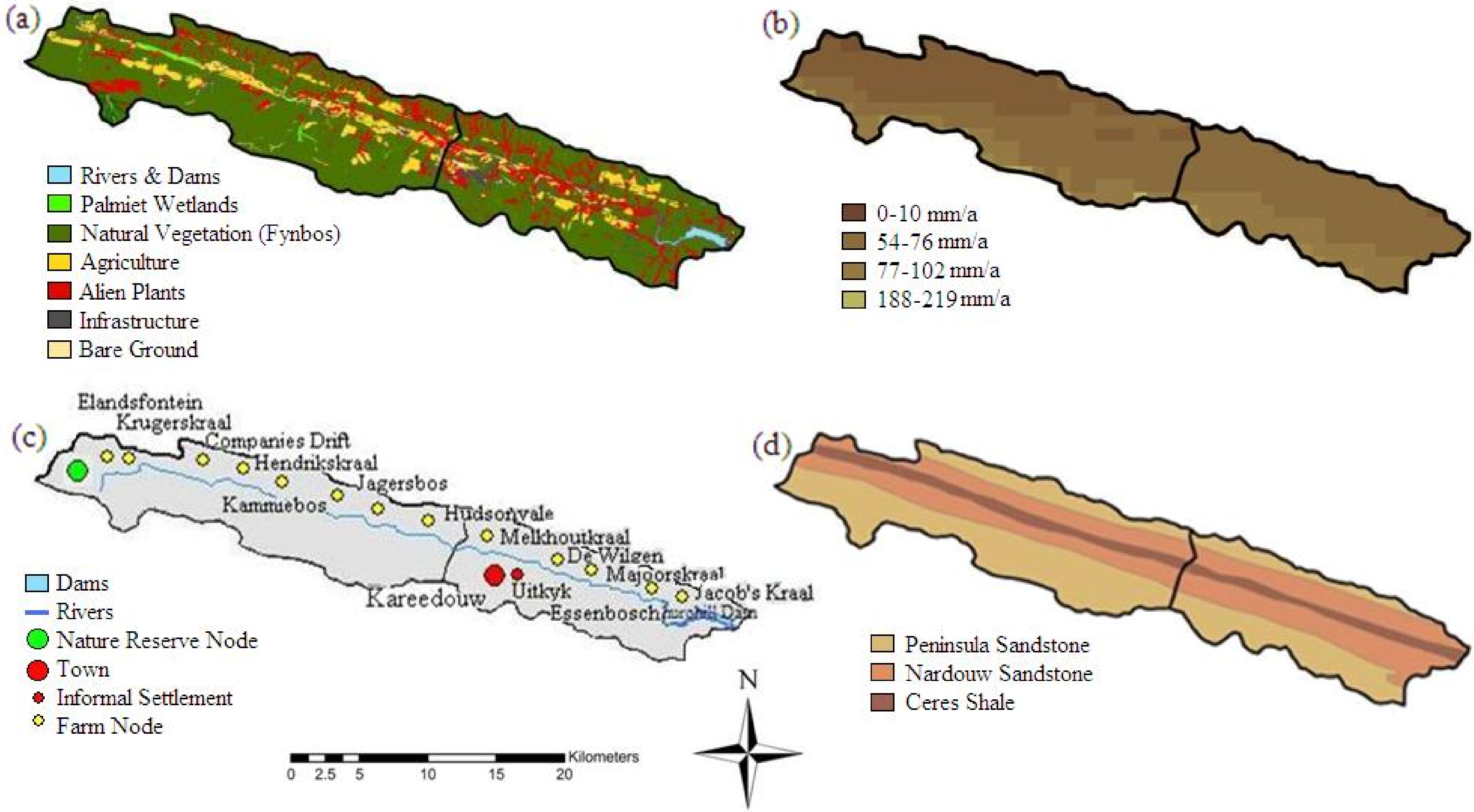


Figure 3.6: Characteristics of the upper Kromme Catchments: (a) vegetation and land-use, (b) ground water recharge (mm/annum), (c) towns and farms and (d) geology (Middleton & Bailey 2008).

Stellenbosch University http://scholar.sun.ac.za

Land-use in the Kromme was mapped at high resolution (~5m) spanning four decades: 1954, 1969, 1986, 2007. These time-slices were supplemented with a reference state based on a reconstruction of the land-cover of the Kromme system prior to European occupation, and using the Garden Route Initiative's Vegetation Map (Vlok et al. 2008). Land-use mapping was done using 1:20 000 aerial photographs in a GIS system (ArcMap) to divide the area into 15 pre-selected land-cover categories (Table 3.1). The Fynbos was divided into 10 types by (Vlok et al. 2008) but these were amalgamated into two categories for the modelling study based on whether the vegetation type classified as productive or unproductive for livestock. Areas of fynbos that was mapped as heavily degraded by over-grazing or altered fire regimes were kept as a separated class.

Areas that were invaded by alien plants were only distinguished if they had reached maturity and the density was greater than that of 80%. Canopy cover values lower than this are difficult to distinguish from indigenous vegetation in aerial photographs. There is a small degree of error, which varies depending on the difficulty of identifying and mapping each land-use category. The most difficult land-cover type to map was the mountain seep wetlands, as it is difficult to distinguish them from surrounding dryland fynbos. Indeed the sizes of these seep wetlands are likely to fluctuate seasonally and to be different each year. However this error was justified in that mapping was done for hydrological modelling purposes and the hydrological differences between fynbos and seep wetlands would be marginal when compared to other land-use types such as floodplain wetlands.

Mapping done using the most recent photographs was ground-truthed by mapping land-cover adjacent to the road that traverses the catchment. Some additional areas were verified using photographs and observations made during a helicopter trip over the catchment. The 2007 aerial photographs and map were used to cross-check identifications made from historical aerial photographs where the mapped classes could not be verified. Additional verification was done using maps compiled by different organizations and individuals: National Land Cover (NLC) (Van den Berg et al. 2008), maps showing extent, clearing and follow up done by WfWater, land-use maps for the Baviaanskloof Mega Reserve, and land-use maps for the Garden Route Initiative (GRI) (Vlok et al. 2008).

Stellenbosch University http://scholar.sun.ac.za

Table 3.1: The key to the different land-uses mapped in the Kromme Catchment, using aerial photograph based polygons captured using the ArcMAP software.

	Land-use	Description
1	Dams	Including small farm dams and a large municipal dam
2	Mountain Seep Wetlands	High altitude/gradient wetlands on the mountain slopes
3	Palmiet Wetlands	Wetlands in the valley, dominated by *Prionium serratum*
4	Riparian Vegetation	Woody vegetation in ravines, either thicket or Afromontane forest
5	Unproductive Fynbos	Seven Different unproductive fynbos and renosterveld vegetation types
6	Productive Fynbos	Three Different productive fynbos and renosterveld vegetation types
7	Degraded Fynbos	Degraded by heavy grazing or poor fire management
8	Irrigated Fields	Agriculture that has an irrigation system (sprinkler or central pivot)
9	Dryland Farming	Any agriculture that is not irrigated
10	Orchards	Orchards with irrigation systems
11	*Acacia mearnsii*	The dominant woody invasive alien plant in the catchment
12	Pinus species	The 2nd most common woody invasive alien plant in the catchment
13	Alien Plants	All other woody invasive plants, mainly Eucalyptus species
14	Infrastructure	All unnatural structures: houses, roads, railway lines, quarries
15	Open Soil	Open soil, sites of erosion or deposition in the river valley

Geomorphology changes

The total active channel length was measured along the centreline of the Kromme River from the aerial photographs from each of the four time slices.

RESULTS

Historical record and meteorological setting

Diary Extract: C. I. La Trobe 1816
East of Jagersbos
"... this country, unproductive as it generally is in means of subsistence for man and beast (is clothed) with an astonishing profusion of vegetable beauty. Hardly a spot exists upon which some curious and beautiful plant does not rear its head in its proper season; and in the midst of this brown desert we see the magnificent chandelier or red-star flower, measuring from four to five inches, to a foot and a half in the spread of its rays growing luxuriantly among the stones (*Brunsvigia littoralis*)". (Skead 2009)

Stellenbosch University http://scholar.sun.ac.za

This historical overview of the Kromme was compiled using two sources: Haigh et al. (2002) and Raymer (2008). The earliest record of agriculture in the catchment was in 1775 when a Mr Ferreira applied for grazing rights at Jagersbos. By this stage, settlers had already occupied the eastern part of the catchment. Orchards and grazing were the most common forms of land-use until 1930. In 1931 a particularly large flood destroyed many orchards along the river banks, causing severe erosion. After this, many farmers turned to pasture, dairy and meat production. This is also when *A. mearnsii* appeared for the first time along a stretch of the Kromme River. From 1931 to 1934, good rainfall years ensured *A. mearnsii* establishment. After the war ended in 1942, agricultural pressure increased. After orchards were swept away again in a flood in 1965, the farmers raised the banks of the river in an attempt to contain future floods. This caused significant channel erosion. By 1986, more than half of the valley floor had been converted to agriculture and *A. mearnsii* had formed dense stands on the floodplains. In 1996 WfWater began clearing the *A. mearnsii*, revealing the extent of the damage to the wetlands. In 2000 Working for Wetlands, a programme aimed at the rehabilitation of river systems, began building a series of weirs to prevent headcuts from eroding further upstream (Working for Wetlands 2010).

Diary Extract: C. J. F. Bunbury 30 March 1838
Langkloof
"The country was extremely arid except along the course of the little streams, and on the hills near the younger Kamper's residence the bushes had been burnt to a considerable extent, a practise general in this country and advantageous to the cattle but very provoking to the botanist". (Skead 2009)

Since 1931, the first recorded flood, there has been a major flood approximately every decade, the exceptions being the 1940's and the 1970's. In the 1980's there were two major flood episodes, the first being a series of three consecutive floods in 1981 and the second in 1983. The 1996 floods were described as the largest ever experienced in the catchment. In the past decade three major flood events have been recorded: 2004, 2006, and 2007. This year, 2012, the Kromme experienced a series of large flooding events. These results were not encorporated into this study.

Stellenbosch University http://scholar.sun.ac.za

Erosion Damage in the Kromme River

In the Kromme River, headcuts formed as a result of activities which disturbed the Kromme River's path. Examples from the Kromme were the building of a provincial road (the R62) and the building of the railway line through the wetlands, river or floodplain. The damage done was exacerbated by farmers allowing animals to graze in these disturbed areas, or ploughing these areas up for agriculture. These activities created 'nick-points' or weaknesses which led to rapid erosion and the loss of the eroded sand and gravel downstream. The nick-points migrate upstream and create progressively wider and deeper head-cuts and dongas over time. This process was rapidly accelerated during the large floods in the Kromme Catchment. The channels formed by the headcuts are detrimental because they drain groundwater from the surrounding alluvium, drying it out and reducing the lands productivity for agriculture or grazing. This process also destroys wetlands – which in a healthy state provide many services to society.

Figure 3.7: A damaged tributary in the Kromme River. The headcut moved backwards up the hill, eroding away sediment and vegetation

Stellenbosch University http://scholar.sun.ac.za

Figure 3.8: An aerial photograph taken from a helicopter of the main floodplain of the Kromme River after a large flood event. The floodplain was once covered by palmiet wetlands, specially adapted to withstand the force of the flood waters. The removal of the palmiet wetlands has destabilized the system, causing massive headcuts and lateral erosion which lowered the water table and reduced the agricultural potential of the land.

Figure 3.9: Cement weirs built along the Kromme River, Eastern Cape, South Africa. These weirs are built to restore the river by stopping the headcut from proceeding backwards up the river. This traps sediments and allows vegetation, such as *P. serratum* in this photograph, and eventually wetlands to recover

Stellenbosch University http://scholar.sun.ac.za

Overall it appears as though annual rainfall has decreased, albeit not significantly (R2=0.071), over the past century (Figure 3.10), with the seven lowest rainfall years all occurring during the past 40 years. Furthermore, the annual rainfall has not exceeded 823 mm in the last 30 years, compared with nineteen times in the preceding century. It appears as though extreme rainfall events are increasing in frequency, despite the fact that there is a decrease in annual rainfall in the past 40 years.

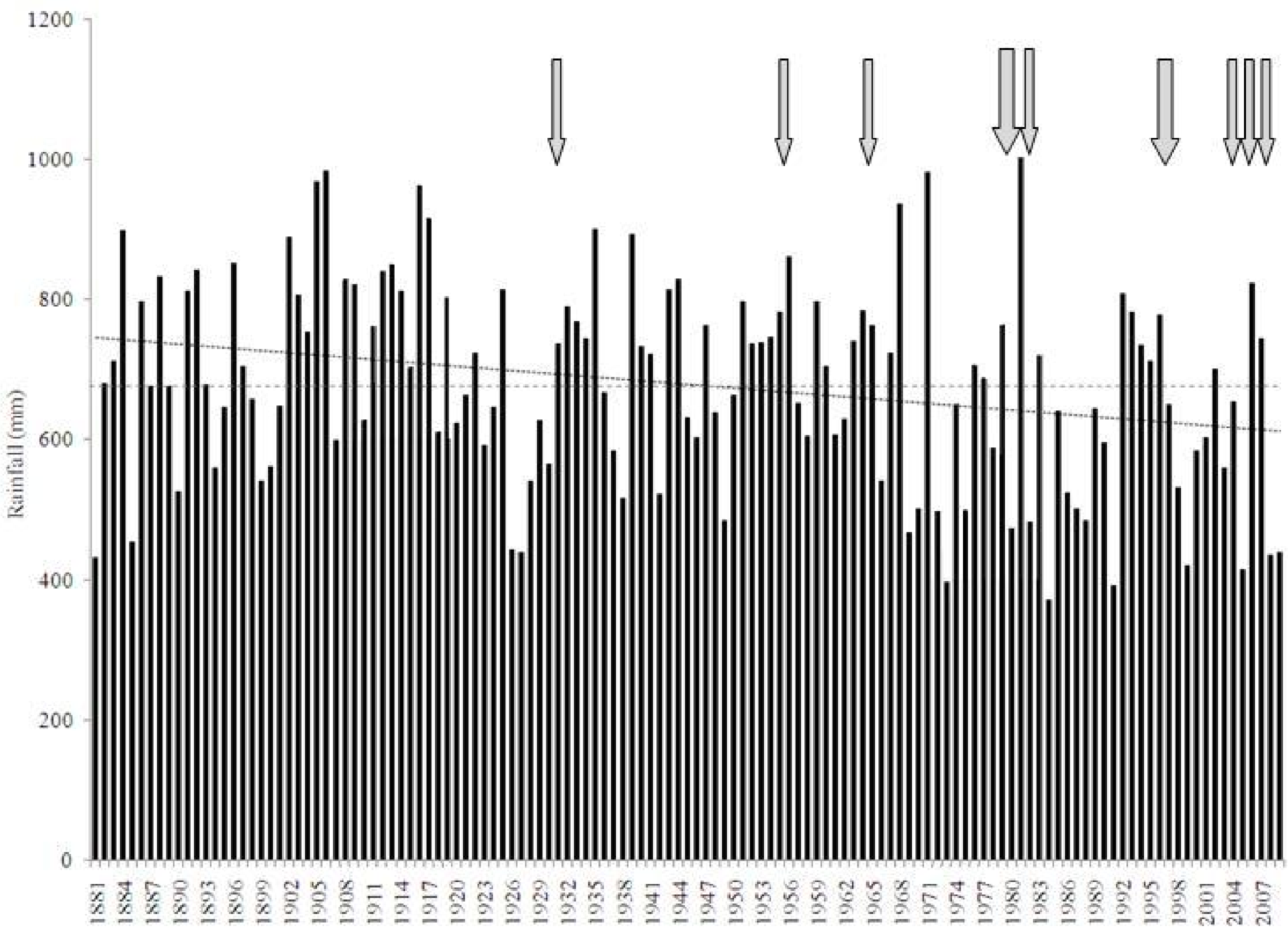


Figure 3.10: Annual precipitation in the upper Kromme from 1881 to 2007. The black stippled line is the trend line for rainfall. The horizontal gray stippled line indicates the overall mean rainfall per annum for this period (678 mm). Gray arrows indicate the occurrence of flood events according to the historical record (which only begins in the late 1920's), larger arrows represent larger floods

Land-use changes

Stellenbosch University http://scholar.sun.ac.za

Over time, both productive and unproductive fynbos vegetation groups have become degraded as a result of increasing grazing pressures and increases in fire frequency (Figure 3.11) Mountain seep wetlands have remained relatively unchanged over time, although they have become invaded by alien plants in some places. The most significant changes are in the relatively fertile floodplains which were dominated by palmiet wetlands. These wetlands have largely been replaced by agriculture, both irrigated and dryland, and also to a large extent by *A. mearnsii* invasion. *A. mearnsii* has also invaded ravines, replacing indigenous Afrotemperate forest.

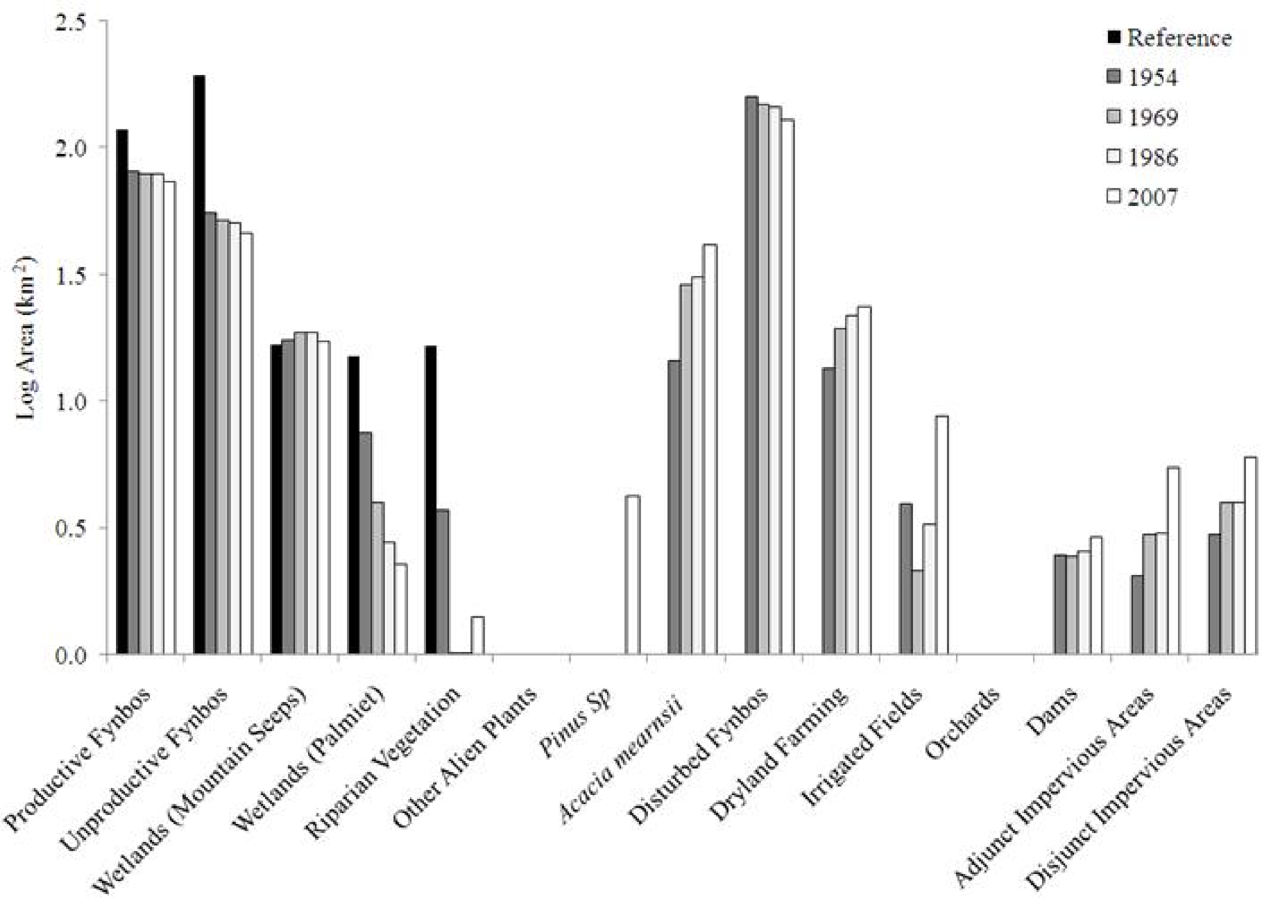


Figure 3.11: Landcover change in the Kromme Catchment from before 1954 to 2007

a. *Urban Sprawl*

The infrastructure of the town of Kareedouw has increased steadily from 1954 to the 1980's, however there is a dramatic change between 1986 and 2007 (Figure 3.12). This is the result of the ending of the Apartheid Regime in South Africa in 1994, which brought in new land tenure

Stellenbosch University http://scholar.sun.ac.za

and labour laws, leading to a movement of people from farms into nearby towns. During this time, four new townships were established around Kareedouw. *A. mearnsii* invasion increased steadily from 1954-2007. The palmiet wetlands in close proximity to the town had completely disappeared by 2007.

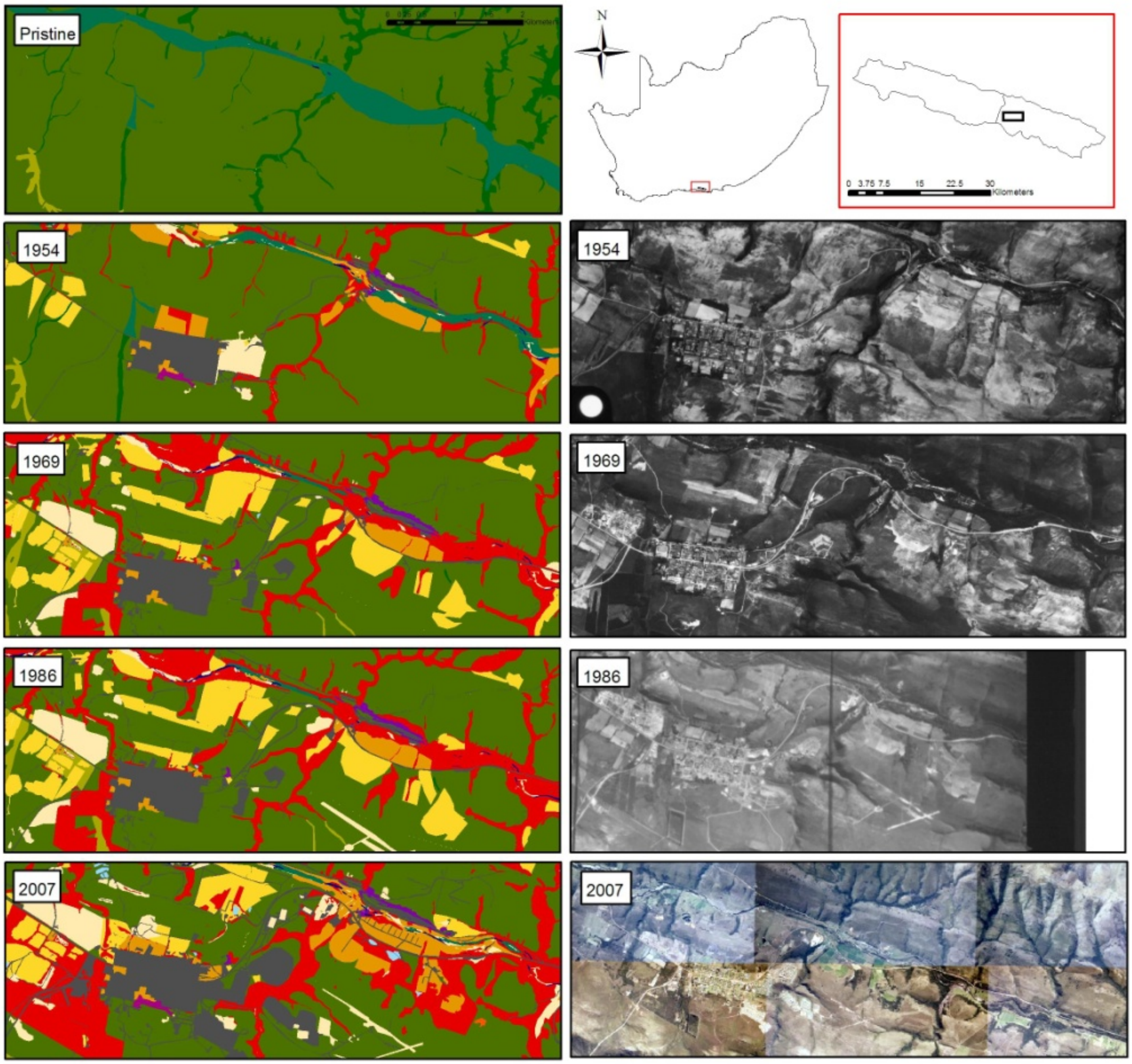


Figure 3.12: Snapshots capturing the spread of a rural town, Kareedouw from 1954 to 2007. Kareedouw is the only town in the Kromme River Catchment. Important land-use changes include: ■ *A. mearnsii*, ■ infrastructure, ■ dryland agriculture, ■ irrigated agriculture, ■ exposed soil, ■ palmiet wetlands and ■ fynbos

Stellenbosch University http://scholar.sun.ac.za

b. *Increase in Agriculture*

There was an increase in agriculture from 1954 to 2007, almost completely replacing palmiet wetlands along the entire length of the upper Kromme River (Figure 3.13). Large, functional palmiet wetlands remain at only one location along the Kromme, mostly displaced by agriculture. More recently there has been a shift from pasture crops to orchards by some farmers, especially in the Jagersbos area (Figure 3.14). *A. mearnsii* has invaded the area not claimed by agriculture. However by 2007 it had been largely removed from the main channel and floodplains themselves. Where *A. mearnsii* is cleared by WfWater, it is often immediately replaced by agriculture.

Stellenbosch University http://scholar.sun.ac.za

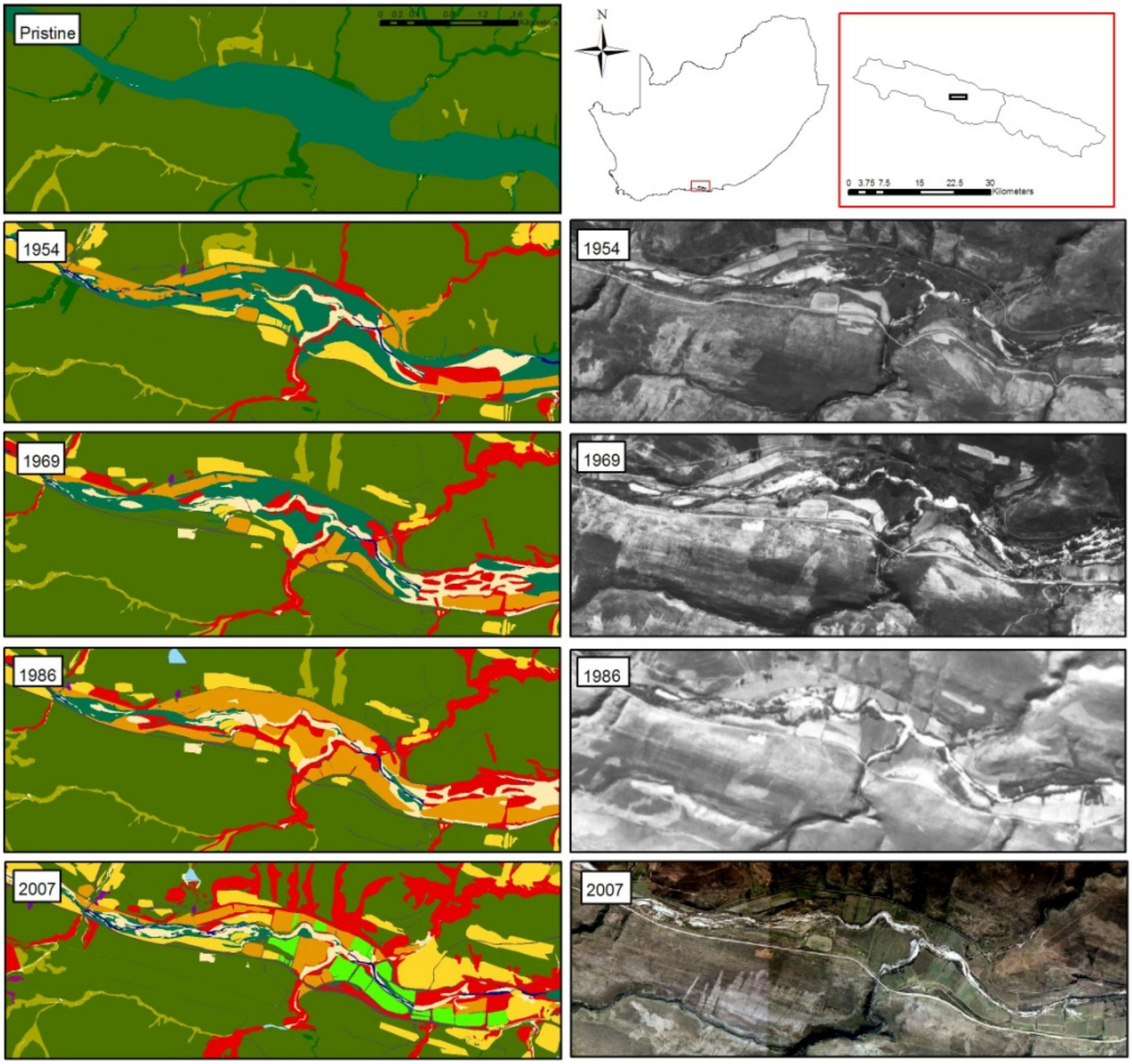


Figure 3.13: Snapshots capturing the increase in agriculture in the fertile floodplains at a farm called Jagersbos from 1954 to 2007 in the Kromme River Catchment. Important land-use changes include: ■ palmiet wetlands, ■ orchards, ■ dryland agriculture, ■ irrigated agriculture, ■ *A. mearnsii*, ■ exposed soil, ■ dams, and ■ fynbos

c. *Impact on Palmiet Wetlands*

Stellenbosch University http://scholar.sun.ac.za

Palmiet Wetlands

Prionium (palmiet) is a monotypic genus, recently moved from the family Juncaceae to Prionaceae (Munro & Linder 1997, Boucher & Withers 2004).Wetlands dominated by *Prionium serratum* (palmiet) have been neglected and under studied. They are widely distributed in the acid waters of the Fynbos Biome, from the Gifberg to Port Elizabeth, and have outliers in the Eastern Cape and southern KwaZulu-Natal (Rogers 1997, Boucher & Withers 2004). They are generally non-channeled or channeled valley bottom wetlands (Collins 2005). Palmiet wetlands are often underlain by a layer of peat, built up over thousands of years (Grundling 2004). *P. serratum* grows in dense stands that may appear to be separate plants, but are often clonal systems. Growth occurs throughout the year, flowering in spring and summer and fruit appears in March. *P. serratum* is completely salt and shade intolerant. *P. serratum* has adapted to fire, but alien plants invading wetlands cause their stems to lengthen in search of sunlight, which exposes it to increased fire damage. *P. serratum* is perceived by landowners to block rivers and is often removed in favour of agriculture. This causes destabilization of rivers and wetlands (Boucher & Withers 2004).

Figure 3.14: Palmiet, *Prionium serratum*, is a unique South African wetland plant, the only species in its family Prioniaceae. *P. serratum* has long, strap-like leaves and plants grow up to two metres tall

Stellenbosch University http://scholar.sun.ac.za

Figure 3.15: A typical palmiet wetland in Jonkershoek, in the Western Cape of South Africa. Palmiet wetlands are often underlain by a thick layer of peat, built up over thousands of years which perform many important functions including water storage and filtration.

The last remaining intact palmiet wetlands are located on a farm named Krugersland (Figure 3.16). These particular wetlands have been placed under protection and they are not permitted to be removed for agriculture. But the change in native land-cover to different land-uses surrounding these wetlands and encroaching upon these wetlands over time is pronounced.

Stellenbosch University http://scholar.sun.ac.za

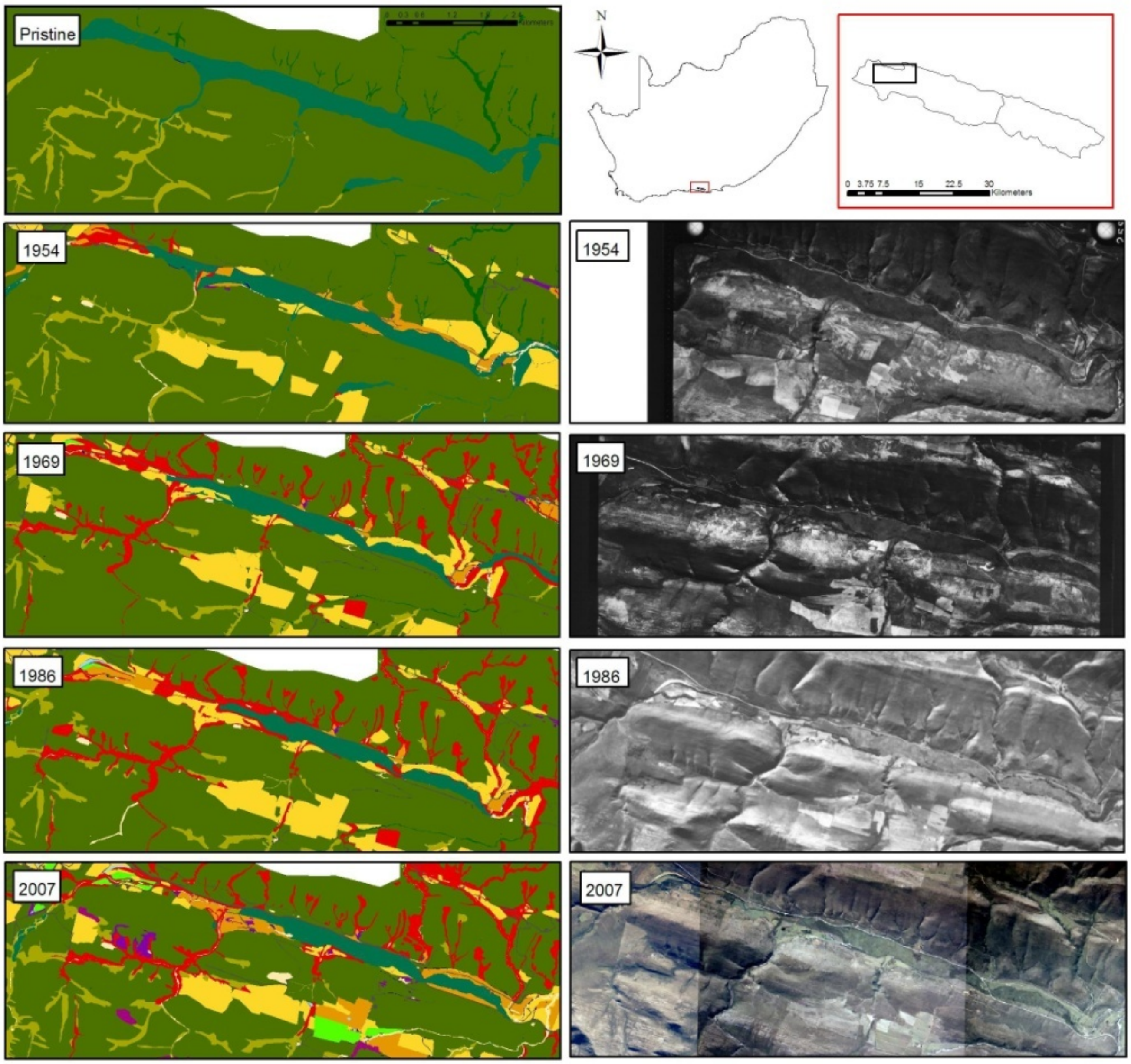


Figure 3.16: Snapshots capturing the change in extent and surrounding land-use of valuable palmiet peat wetlands due to an increase in agriculture and invasion of Black Wattle from 1954 to 2007. These wetlands occur on Krugersland Farm and are currently the last existing wetlands in the Kromme River. Important land-use changes include: ■ palmiet wetlands, ■ *A. mearnsii*, ■ dryland agriculture, ■ irrigated agriculture, ■ fynbos, and ■ other alien species.

Stellenbosch University http://scholar.sun.ac.za

Figure 3.17: The last remaining functional palmiet wetlands and peat beds in the Kromme River, Eastern Cape, South Africa. The wetlands would have historically covered the floodplains of the Kromme Riverbed, but have largely been removed in favour of agriculture

d. *Land-use change around the Churchill Dam*

The snapshots in Figure 3.19 show the change of land-use on municipal property surrounding the Churchill Dam. On the far right it is possible to see the plantations of *A. mearnsii* and Eucalyptus trees that were planted by the authorities themselves. This was later recognized to be a conflict of interest, and the plantations were removed. However the municipality has failed to take responsibility for these alien plants and they have spread.

The Churchill Dam
The building of the multi-arched Churchill Dam (able to hold 2.961 billion litres of water), began in 1940 and was completed in 1943. The first test of the Churchill Dam took place in 1944, which was a high rainfall year. The dam filled overnight to a depth of 27 m and a few days later overflowed (Raymer 2008). Today it is a very important water supply for the Nelson Mandela Metropolitan hub in the Eastern Cape of South Africa as it provides approximately 26% of the city's water supply. The Eastern Cape has been in a drought with the Churchill Dam being less than 30% full for the past few years. After the 2012 floods, it filled to 100% capacity for the first time in several years.

Stellenbosch University http://scholar.sun.ac.za

Figure 3.18: The multi-arched Churchill Dam on the Kromme River in the Eastern Cape of South Africa

Stellenbosch University http://scholar.sun.ac.za

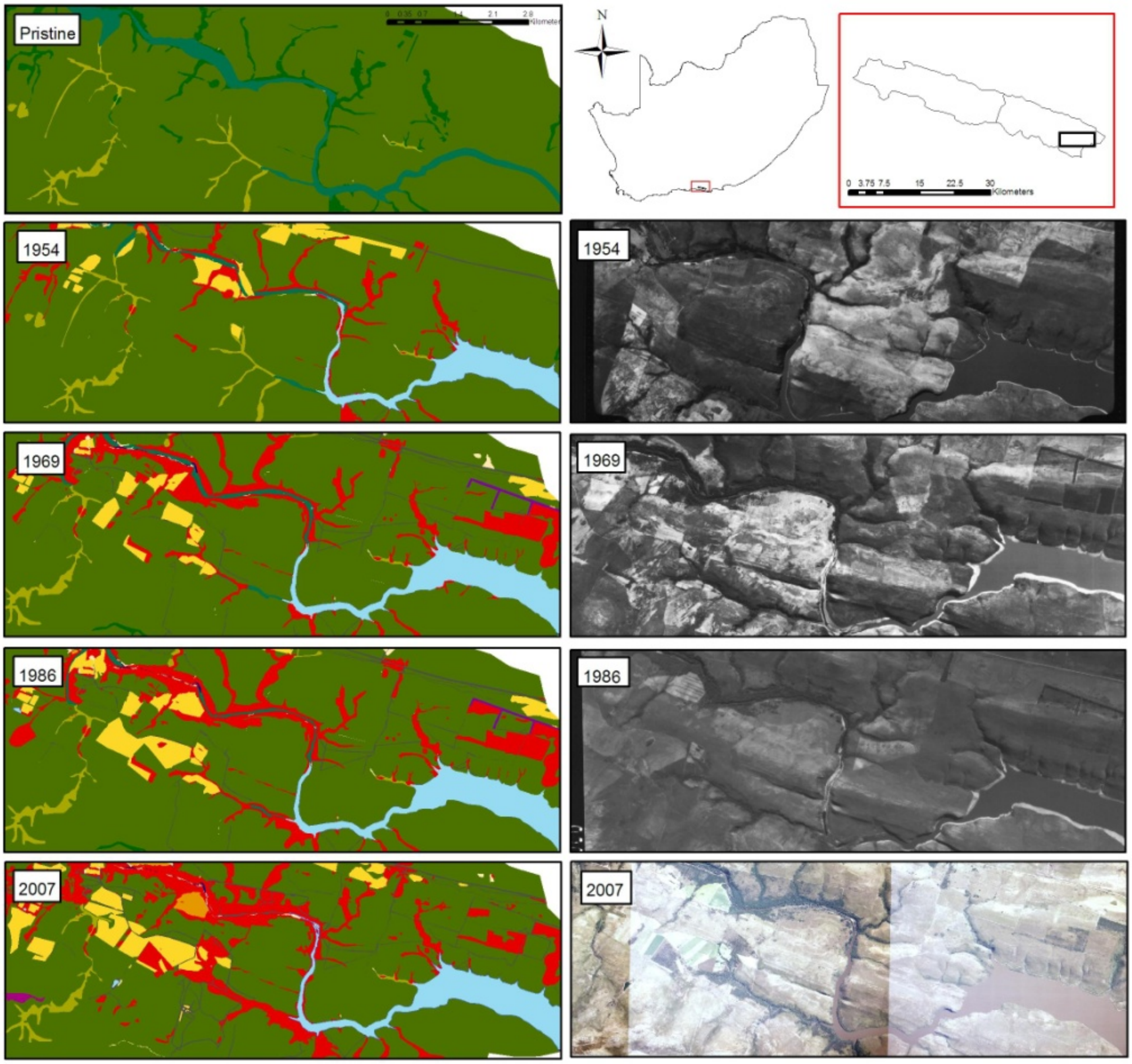


Figure 3.19: Snapshots capturing the change in agriculture and invasion of *A. mearnsii* in the vicinity of the Churchill Dam from 1954 to 2007. The Kromme River is an important water source for the nearby city of Port Elizabeth. Important land-use changes include: ■ dams, ■ *A. mearnsii*, ■ palmiet wetlands, ■ dryland agriculture, ■ fynbos, and ■ alien species.

e. *Geomorphological Changes: Changes in Channel Length*

The total channel length has increased from 1954 to 2007 (Figure 3.20). Very little change in the total channel length occurred between 1954 and 1986 with the most marked changes happening before and after this period. This implies that the river channel has become more

Stellenbosch University http://scholar.sun.ac.za

meandering with time, which may be a result in decreased channel stability brought about by the invasion of *A. mearnsii*.

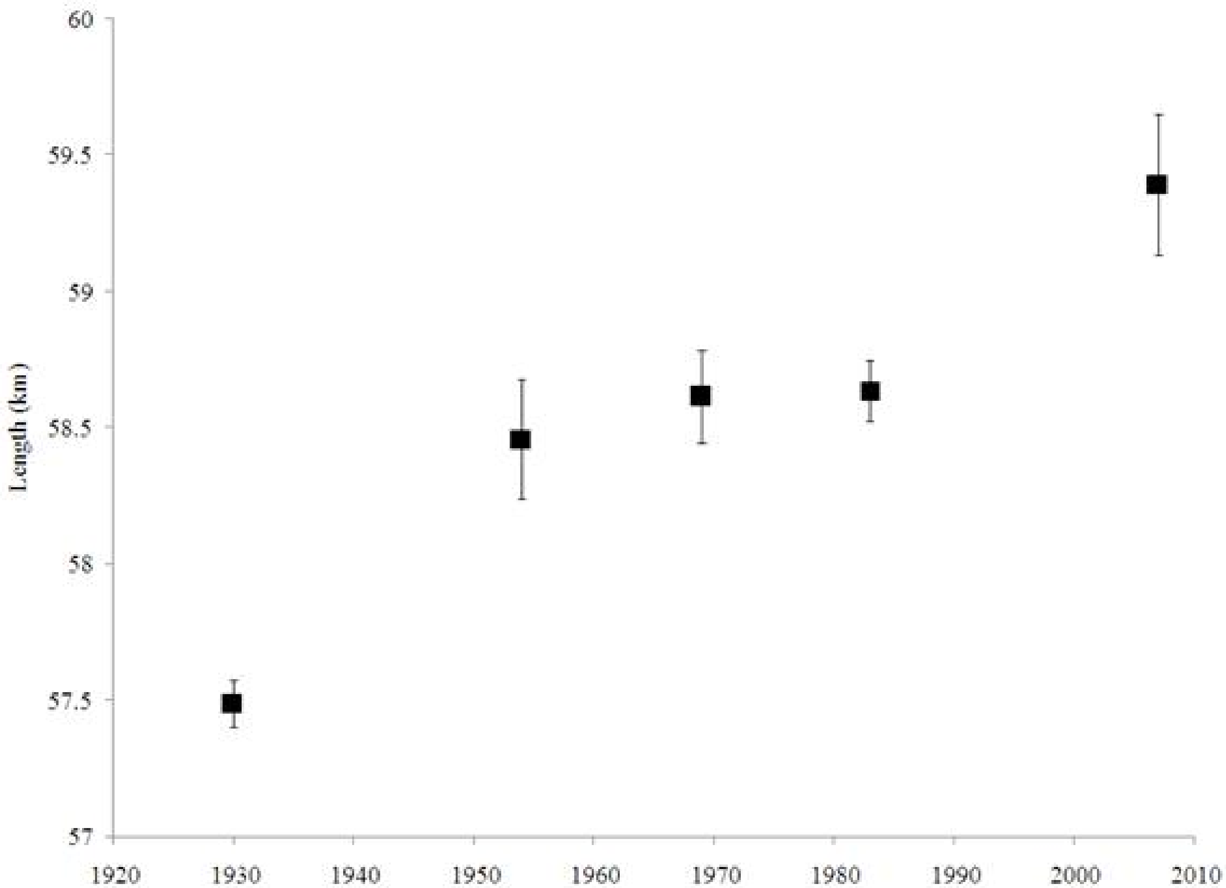


Figure 3.20: Change in the mean (±standard deviation) total channel length from 1954 to 2007 measured along the centreline for the length of the upper Kromme River.

f. *Rate of Spread of A. mearnsii*

The most dramatic increase in *A. mearnsii* invasion is 10.37 ha during the period 1986 to 2007 (Figure 3.21). However this is also the greatest time-step, with 24 years between the respective aerial photographs.

Stellenbosch University http://scholar.sun.ac.za

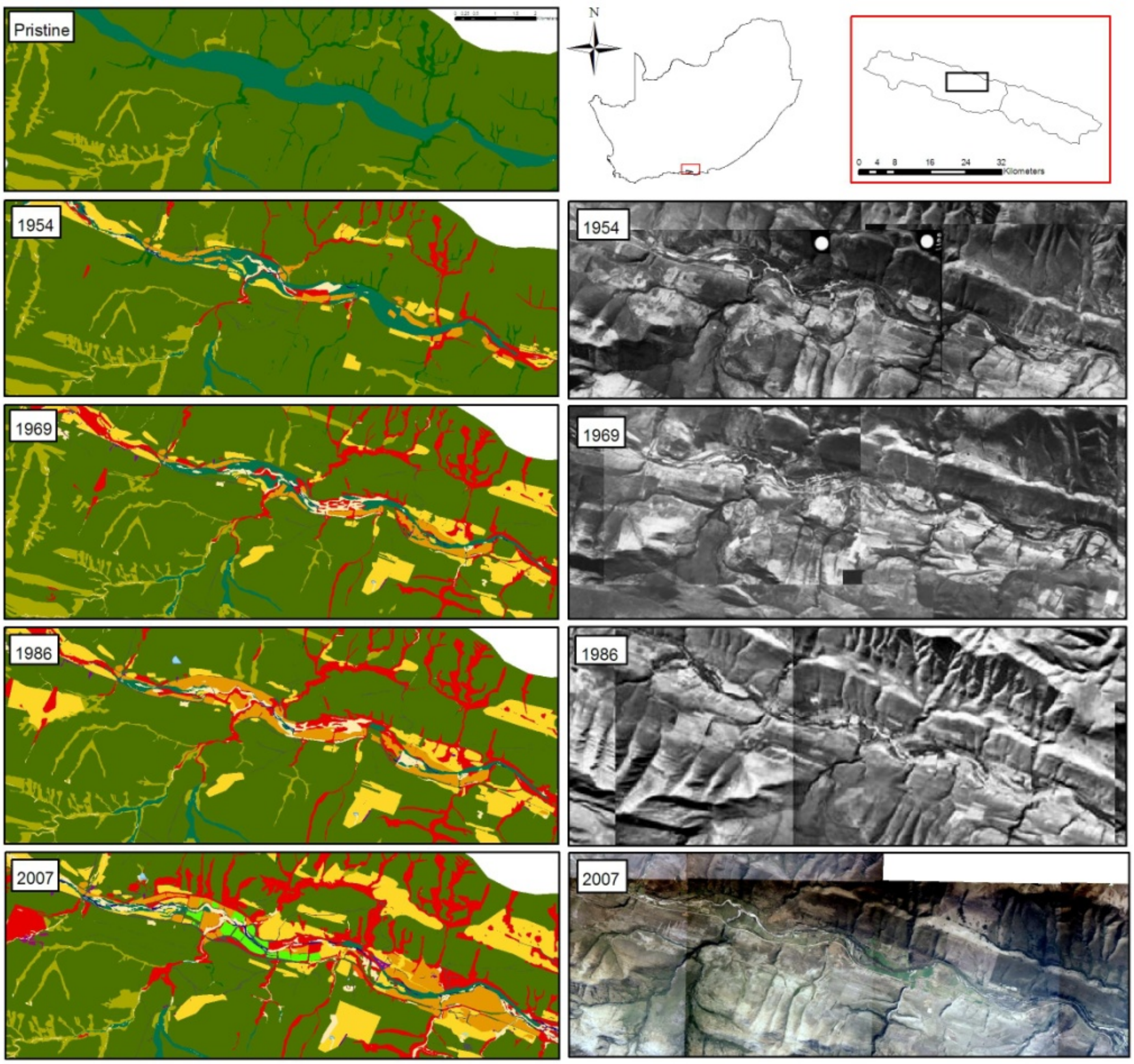


Figure 3.21: Snapshots capturing the rate of the invasion of *A. mearnsii* from 1954 to 2007 along the Kromme River. Important land-use changes include: ■ palmiet wetlands, ■ *A. mearnsii*, ■ dryland agriculture, ■ irrigated agriculture, ■ orchards, ■ exposed soil, ■ seep wetlands and ■ fynbos

The rate of invasion was greatest in the period between 1954 and 1969 at about 96 ha/a, which was its initial invasion phase. After this time, the invasion rates slowed to 12 ha/a perhaps indicating some threshold was reached. Between 1986 and 2007 the rate of invasion increases again to 43 ha/a, possibly indicating the stage when it began to invade old lands.

Stellenbosch University http://scholar.sun.ac.za

Table 3.2: The expansion and rate of invasion by *A. mearnsii* from 1954 to 2007 along the Kromme River.

	Reference	1954	1969	1986	2007	Mean
Acacia mearnsii (ha)	0.00	1440	2886	3097	4134	-
Rate of change (ha/decade)	-	1440	1447	211	1037	-
Number of years	-	54	15	17	21	-
Rate of change (ha/a)	-	27	96	12	49	**46.0**

g. *Effectiveness of Mitigation Attempts: Rate of Clearing by WfWater*

WfWater began alien clearing in the Kromme Catchment in 1996. The control programme involves an initial treatment followed by several, sometimes up to eight, further treatments before a given invasion is reduced to acceptable levels (McConnachie et al. 2012).

Table 3.3: The extent of the *A. mearnsii* alien invasion clearing by WfWater along the Kromme River from 2002 – 2010

Year	Area cleared (ha/a)
2002	93.61
2003	57.18
2004	77.19
2005	155.79
2006	143.7
2007	149.24
2008	147.08
2009	151.89
2010	269.39
Mean	*138.34*

Thus WfWater is clearing aliens at three times the rate of invasion.

Stellenbosch University http://scholar.sun.ac.za

DISCUSSION

Over the past half century wetlands, floodplains and fertile riverbeds, those areas in the catchment that are the most vital in terms of providing essential services to mankind, have been the most heavily impacted and transformed. Research has shown the transition from intact indigenous vegetation to landscapes heavily transformed by agriculture and IAPs results in significant hydrological changes (Prinsloo & Scott 1999, Jackson et al. 2001, Jewit 2002, Gleick 2003, Shiklomanov & Rodda 2003, Allan 2004, Scanlon et al. 2007, Gleick et al. 2011). The main drivers of land-use change and wetland transformation in the Kromme appear to be unsustainable agricultural practices and alien invasion of the riparian zone. These drivers cause erosion and headcuts, lowering of the water table, decreased riverflow due to increased transpiration and irrigation, greater flood damage, decreased baseflow and a decrease in water quality (Hibbert 1971, McGuinnes & Harrold 1971, Bosch & Hewlett 1982, Rowntree 1991, Smith & Scott 1992, Dye 1996, Scott & Lesch 1997, Scott 1999, Le Maitre & Görgens 2001, Le Maitre et al. 2002, Andreassian 2004, Dye & Jarmain 2004, Scott et al. 2004, Calder 2005, Grenfell et al. 2005).

Land-use change over large areas has been shown to alter erosion intensity, causing channel lengthening and a decrease in active channel width (Michalková et al. 2011). In South Africa and Australia, IAPs have been found to impact the geomorphology of rivers systems by modifying the river channel, while subsequent removal can lead to significant channel instability and mobilization of sediment (Beyers 1991, Rowntree 1991, Richardson et al. 1997, Bunn et al. 1998). With the destruction of wetlands in the Kromme, the river appears to have become more braided and sinuous with time. It is difficult to be certain about channel change because the Kromme River was originally a valley-bottom wetland with no channel visible at the surface. The decrease over time in the length of the Kromme River channel length is likely to be a result of alien invasion and concomitant wetland destruction.

What has happened in the Kromme may be a reasonable reflection of what is happening in other South African catchments (Mander et al. 2010). This damage to natural capital in catchments that are valuable for water provision is counter-productive. In the case of the

Stellenbosch University http://scholar.sun.ac.za

Kromme, farming is marginal and it is not an important agricultural catchment (Haigh et al. 2002). In such cases we would recommend prioritizing land-use at a catchment scale in terms of which ecosystem goods or services it is to provide. It is clear that high quality water-related ecosystem goods and services are not compatible with intensive agriculture in the floodplains of the same catchment. Yet this is the model that South Africa and many other countries appear to follow.

In the face of climate change, water resources in South Africa are likely to become scarcer and less predictable over time (WWAP 2009, Matthews et al. 2011). Specific predictions include an increase in summer rainfall, a decrease in winter rainfall, an increase in rainfall intensity in the east, a monthly rainfall change of 10 mm or more, and an increase in air temperature (mainly minimum temperature) by up to 2-3 °C (Midgley et al. 2005). Furthermore, climate change is likely to result in an increase in floods and droughts (Midgley et al. 2005). In the Kromme, rainfall is decreasing over time while major floods appear to be increasing. These predictions indicate a likely increase in extreme events, which a healthy, resilient, functioning river system may be able to absorb. However, with most of the wetlands in the Kromme transformed, the catchment may have lost its buffering ability and may no longer be able to absorb these extreme events. The wetlands that do remain are located upstream, near the headwaters, and as a result have no ability to filter and purify water downstream. However if *P. serratum* was restored further downstream, services that are crucial to downstream stakeholders –including water purification and flood attenuation, may be recovered with time (Aronson et al. 2007, Blignaut & Aronson 2008).

In an attempt to restore the Kromme Catchment, WfWater is clearing *A. mearnsii* at three times the average rate of invasion. However the available data do not differentiate between initial clearing and follow-up, so it is possible that their rate of clearing is slower than these data indicate. At their current rate of clearing it would take WfWater another 30 years to clear the Kromme, and this is just one of many South African catchments. Such a large investment in the Kromme over a long period of time with such a low rate of progress would suggest that the WfWater Programme could do with improvement (Hosking & du Preez, 2004, McConnachie et

Stellenbosch University http://scholar.sun.ac.za

al. 2012). Part of this may be the lack of communication: the failure to bridge the gap between managers, implementing agents and landowners and society at large (Cowling et al. 2008).

CONCLUSION

The question remains as to how these complex systems can be managed so that they are insured against future climate change. Managing the functioning of rivers requires holistic, integrated catchment management approaches as well as interdisciplinary co-operation (Dollar et al. 2007, Nel et al. 2007, Nel et al. 2009). Riparian systems have been described as complex adaptive systems and both a social learning process and an adaptive management approach is needed (Pahl-Wostl 2007). We recommend that important water providing catchments, where agriculture is marginal, should be prioritized for provision of water-related ecosystem services alone. Investment into improving the resilience of these systems as insurance against future climate changes is essential. This should be in the form of prohibiting unsustainable land management practices and enforcing the laws that protect rivers and wetlands, eradication of IAPs and rehabilitation of the river and wetlands. This investment in restoration of an important water-providing catchment cannot be done without education and a social learning process aimed at getting the land owners and others committed to participating in its restoration (Pahl-Wostl 2007, Cowling et al. 2008).

Stellenbosch University http://scholar.sun.ac.za

Figure 3.22: The headwaters of the Kromme River are in a pristine condition as they fall within the Formosa Nature Reserve, Eastern Cape, South Africa

REFERENCES

Allan, J.D. 2004. Landscapes and riverscapes: the influence of land use on stream ecosystems. *Annual Review of Ecology Evolution and Systematics*. **35**: 257–84.

Andreassian, V. 2004. Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology*. **291**: 1-27.

Aronson J., S. J. Milton, and J. N. Blignaut (eds). 2007. Restoring natural capital: science, business, and practice. Island Press, Washington, D. C.

Ashton, P. G. 2002. Avoiding conflicts over Africa's water resources. *Ambio*. **31**(3): 236-242

Bates, B. C., Z. W. Kundzewicz, S. Wu and J. P. Palutik (Eds). 2008. Climate change and water. Technical Paper of the Intergovernmental Panel on Climate Change, IPCC Secretariat, Geneva. Pp 210.

Beyers, G. 1991. A preliminary assessment of the geomorphological impact of alien vegetation in the Baviaanskloof region. Third Year Project, Department of Geography, Rhodes University, Grahamstown.

Stellenbosch University http://scholar.sun.ac.za

Blignaut, J. and J. Aronson. 2008. Getting serious about maintaining biodiversity. *Conservation Letters*. **1**(1):12-17.

Bosch, J. M., and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*. **55**: 3-23.

Boucher, C. and M. J. Withers. 2004. Notes on the ecology of *Prionium serratum* (palmiet), a Cape river specialist. *Veld & Flora*. **90**(1): 26-28.

Brinson, M. M. and A. I. Malvárez. 2002. Temperate freshwater wetlands: types, status and threats. *Environmental Conservation*. **29**: 115-133.

Bunn, S. E., P. M. Davies, D. M. Kellaway, and I. P. Prosser. 1998. Influence of invasive macrophytes on channel morphology and hydrology in an open tropical lowland stream, and potential control by riparian shading. *Freshwater Biology*. **39**: 171-178.

Calder, I. R. 2005. Blue Revolution II: Land use and integrated water resources management. Earthscan, London.

Collins, N. B. 2005. Wetlands: the basics and some more. Free State Department of Tourism, Environmental and Economic Affairs. http://www.csir.co.za/rhp/.

Cowling R. M., B. Egoh, A. T. Knight, P. J. O'Farrell, B. Reyers, M. Rouget, D. J. Roux, and A. Welz, A.Wilhelm-Rechman. 2008. An operational model for mainstreaming ecosystem services for implementation. *Proceedings of the National Academy of Sciences*. **105**: 9483-9488.

Crous, C. J., S. M. Jacobs and K. J. Esler. 2011. Drought-tolerance of an invasive alien tree, *Acacia mearnsii* and two native competitors in fynbos riparian ecotones. *Biological Invasions*. **14**: 619-631.

Daily, G.C., Soderquist, T., Aniyar, S., Arrow, K., Dasgupta, P., Ehrlich, P.R., Folke, C., Jansson, A.M., Jansson, B.O., Kautsky, N., Levin, S., Lubchenco, J., Maler, K.G., David, S., Starrett, D., Tilman, D., Walker, B., 2000. The value of nature and the nature of value. *Science*. **289**: 395–396.

David, P. B., B. B. Leslie, A. C. Kristine, and T. W. Andrew. 2000. Water Environment Federation. Proceedings of the Watershed Conference. Vancouver, British Columbia.

Stellenbosch University http://scholar.sun.ac.za

de Groot, R. S., M. A. Wilson, and R. M. J. Boumans. 2002. A typology for the classification, description and valuation of ecosystem functions, goods and services. *Ecological Economics*. **41**: 393-408.

Department of Water Affairs and Forestry, South Africa. 2006. Working for Water information pamphlet. October 2006. http://www.dwaf.gov.za/wfw/Docs/WfWadvertOct06.pdf

Dollar, E. S. J., C. S. James, K. H. Rogers, and M. C. Thoms. 2007. A framework for interdisciplinary understanding of rivers as ecosystems. *Geomorphology*. **89**: 147-162.

Dye, P. J. 1996. Climate, forest and streamflow relationships in South African afforested catchments. *Commonwealth Forestry Reviews*. **75**(1): 31-38.

Dye, P., and C. Jarmain. 2004. Water use by black wattle (*Acacia mearnsii*): implications for the link between removal of invading trees and catchment streamflow response. *South African Journal of Science*. **100**: 40-44.

Eberhard, R., 2009. Urban water demand scenarios for Nelson Mandela Bay Area. Presentation to Study Steering Committee by Palmer Development Group

Gleick, P. 2003. Global Freshwater Resources: Soft-Path Solutions for the 21st Century. *Science* **302**: 1524-1528.

Gleick, P. H., J. Christian-Smith, and H. Cooley. 2011. Water-use efficiency and productivity: rethinking the basin approach. *Water International*. **36**(7): 784–798.

Grenfell, M. C., W. N. Ellery, and R. A. Preston-Whyte. 2005. Wetlands as early warning (eco)systems for water resource management. *Water SA*. **31**(4): 465-472.

Groombridge, B. 1992. Global biodiversity, status of the earth’s living resources. World Conservation Monitoring Centre. Chapman and Hall, London. Pp. 297.

Grundling, P. L. 2004. Peatlands on the brink of the final phase in the extinction of a unique wetland type in southern Africa. Working for Wetlands Programme, National Botanical Institute, Pretoria. IMGG Scientific Symposium, September 2004. International Mire Conservation Group. Pp. 5.

Grundling, P. L. and G. C. Marnewick. 1999. Mapping, characterization and monitoring of the Highveld peatlands: compilation of existing data and evaluation of inventory methodology. Compiled for the Department of Agriculture, Directorate Land and Resources, Management on behalf of the Agricultural Research Council: Institute for Soil, Water and Climate.

Stellenbosch University http://scholar.sun.ac.za

Haigh, E. A., P. L. Grundling, and P. M. Illgner. 2002. Report on the scoping study on the status of the Kromme River peatland complex and recommended mitigatory measures. Department of Water Affairs and Forestry Project X832633.

Hibbert, A. R. 1971. Increases in streamflow after converting chaparral to grass. *Water Resources Research*. **7**(1): 71–80.

Hobbs, R.J., 2004. The Working for Water programme in South Africa: the science behind the success. *Diversity and Distributions*. **10**: 501-503.

Hosking, S. G., and M. du Preez. 2004. A cost-benefit analysis of the Working for Water Programme on selected sites in South Africa. *Water SA*. **30**(2): 143-152.

Jackson, R. B., S. R. Carpenter, C. N. Dahm, D. M. Mcknight, R. J. Naiman, S. L. Postel and S. W. Running .2001. Water in a Changing world. *Ecological Applications*. **11**(4): 1027–1045.

Jewitt, G. 2002. Can integrated water resources sustain the provision of ecosystem goods and services? *Physics and Chemistry of the Earth*. **27**: 887-896.

Kondolf, G. M. 2011. Mediterranean-climate episodic channels: long periods of boredom, brief moments of terror. The International Mediterranean Ecosystems Conference MEDECOS XII. 6-9 September 2011.

Kotze, D. C., C. M. Breen, I. Z. Nxele, and J. Kareko. 2009. WET-ManagementReview: The impact of natural resource management programmes on wetlands in South Africa. C. Breen, J. Dini, W. Ellery, S. Mitchell, and M. Uys (Eds). Water Research Commission, Pretoria, South Africa. WRC Report No. TT 335/09.

Le Maitre, D. C., and A. Görgens. 2001. Potential impacts of invasive alien plants on reservoir yields in South Africa. Tenth South African National Hydrology Symposium: 26-28 September 2001.

Le Maitre, D. C., B. W. Van Wilgen, C. M. Gelderblom, C. Bailey, R. A. Chapman, and J. A. Nel. 2002. Invasive alien trees and water resources in South Africa: case studies of the costs and benefits of management. *Forest Ecology and Management*. **160**(3): 143-159.

Le Maitre, D. C., C. Colvin, and A. Maherry. 2009. Water resources in the Klein Karoo: the challenge of sustainable development in a water-scarce area. South African Journal of *Science*. **105**: 39-48.

Stellenbosch University http://scholar.sun.ac.za

Le Maitre, D. C., D. B. Versfeld, and R. A. Chapman. 2000. The impact of invading alien plants on surface water resources in South Africa: a preliminary assessment. *Water SA*. **26**(3): 397-408.

Lewis, C. A. 2008. Geomorphology of the Eastern Cape, South Africa. Second Edition. NISC, Grahamstown. Pp 21-28.

Mander, M., J. Blignaut, M. Van Niekerk, R. Cowling, M. Horan, D. Knoesen, A. Mills, M. Powell, and R. Schulze. 2010. Baviaanskloof-Tsitsikamma Payments for Ecosystem Services: A feasibility assessment.

Matthews, J. H., B. A. J. Wickel, and S. Freeman. 2011. Converging currents in climate-relevant conservation: water, infrastructure, and institutions. *PLOS Biology*. **9**(9): 1-4.

McConnachie, M. M., R. M. Cowling, B. W. van Wilgen, D. A. McConnachie. 2012. Evaluating the cost-effectiveness of invasive alien plant clearing: a case study from South Africa. Biological Conservation. In Press.

McGuinness, J.L., and L. Harrold. 1971. Reforestation influences on small watershed streamflow. *Water Resources Research*. **7**(4), 845–852.

Michalková, M. H. Piégay, G. M. Kondolf and S. E. Greco. 2011. Lateral erosion of the Sacramento River, California (1942-1999), and responses of channel and floodplain lake o human influences. *Earth Surface Processes and Landforms*. **36**: 257-272.

Middleton, B. J. and A. K. Bailey. 2008. Water resources of South Africa, 2005 study (WR2005). WRC Report Number TT 380/08.

Midgley D. C., W. V. Pitman, and B. J. Middleton. 1994. Surface Water Resources of South Africa 1990 Volume III: Orange-Namaqualand. Report 1990 298/3.1/94. Water Research Commission.

Midgley, G. F., R. A. Chapman, B. Hewitson, P. Johnston, M. De Wit, G. Ziervogel, P. Mukheibir, I. Van Niekerk, M. Tadross, B. W. Van Wilgen, B. Kgope, P. Morant, A. Theron, R. J. Scholes, and G. G. Forsyth. 2005. A Status Quo, Vulnerability and Adaptation Assessment of the Physical and Socio-Economic Effects of Climate Change in the Western Cape. Report to the Western Cape Government, Cape Town, South Africa. Report No: ENV-S-C 2005-073. Stellenbosch: CSIR.

Millennium Ecosystem Assessment. Millennium Ecosystem Assessment Synthesis Reports. 2006.

Stellenbosch University http://scholar.sun.ac.za

Mooney, H. A., S. P. Hamberg, and J. A. Drake. 1986. The invasion of plants and animals. In: Ecology of biological invasions of North America and Hawaii. Mooney, H. A. and J. A. Drake (Eds). Springer-Verlag, New York.

Munro, S. L., and H. P. Linder. 1997. The embryology and systematic relationships of *Prionium serratum* (Juncaceae: Juncales). *American Journal of Botany*. **84**(6): 850-860.

Murray, R., M. Goedhart, and J. Baron. 2008. High-yielding groundwater areas around the Nelson Mandela Bay Municipality. Water Research Commission, Pretoria, South Africa. WRC Report No: TT 327/08.

Nel, J. L., B. Reyers, D. J. Roux, and R. M. Cowling. 2009. Expanding protected areas beyond their terrestrial comfort zone: identifying spatial options for river conservation. *Biological Conservation*. **142**: 1605-1616.

Nel, J. L., D. J. Roux, G. Maree, C. J. Kleynhans, J. Moolman, B. Reyers, M. Rouget, and R. M. Cowling. 2007. Rivers in peril inside and outside protected areas: a systematic approach to conservation assessment of river ecosystems. *Biodiversity Research*. **13**: 341-352.

Pahl-Wostl, C. 2007. The implications of complexity for integrated resources management. *Environmental Modelling and Software*. **22**: 561-569.

Pimm S. L., and P. Raven. 2000. Extinction by numbers. *Nature*. **403**: 843-845.

Prinsloo, F. W., and D. F. Scott. 1999. Streamflow responses to the clearing of alien invasive trees from riparian zones at three sites in the Western Cape Province. *Southern African Forestry Journal*. **185**: 1-7.

Raimondo, D., L. Von Staden, W. Foden, J. E. Victor, N. A. Helme, R. C. Turner, D. A. Kamundi, and P. A. Manyama (eds). 2009. Red List of South African plants 2009. Strelitzia 25. South African National Biodiversity Institute, Pretoria.

Raymer, D. 2008. Streams of Life. David Raymer.

Rejmánek, M., and R. Randall. 1994. Invasive alien plants in California: 1993 summary and comparison with other areas in North America. *Madrono.* **41**: 161–177.

Richardson, D. M., I. A. W. Macdonald, J. H. Hoffmann, and L. Henderson. 1997. Alien plant invasions. In: Vegetation of Southern Africa. R. M. Cowling, D. M. Richardson, and S. M. Pierce (Eds). Cambridge, Cambridge University Press. Pp. 534–570.

Rogers, K. H. 1997. Freshwater wetlands. In: Vegetation of Southern Africa. R. M. Cowling, D. M. Richardson, and S. M. Pierce (Eds). Cambridge University Press.

Stellenbosch University http://scholar.sun.ac.za

Rouget, M, B. Reyers, Z. Jonas, P. Desmet, A. Driver, K. Maze, B. Egoh, and R. M. Cowling. 2004. South African National spatial biodiversity assessment. Technical Report. Volume 1: Terrestrial Component.

Rowntree, K. 1991. An assessment of the potential impact of alien invasive vegetation on the geomorphology of river channels in South Africa. South African Journal of Aquatic *Science*. **17**(1/2): 28-43.

Scanlon, B. R., I. Jolly, M. Sophocleous, and L. Zhang. 2007. Global impacts of conversions from natural to agricultural ecosystems on water resources: quantity versus quality. *Water Resources Research*. **43**: 1-18.

Schulze, R. E. (Ed). 2005. Climate change and water resources in southern Africa: Studies on scenarios, impacts, vulnerabilities and adaptation. Water Research Commission, Pretoria, South Africa. WRC Report 1430/1/05.

Scott, D. F. 1999. Managing riparian zone vegetation to sustain streamflow: results of paired catchment experiments in South Africa. *Canadian Journal of Forestry Research*. **29**: 1149-1157.

Scott, D. F., and Lesch, W. 1997. Streamflow responses to afforestation with Eucalyptus grandis and Pinus patula and to felling in the Mokobulaan experimental catchments, Mpumalanga province, South Africa. *Journal of Hydrology*. **199**: 360-377.

Scott, D. F., L. A. Bruijnzeel, R. A. Vertessy, and I. R. Calder. 2004. Impacts of Forest Plantations on Streamflow. *Forest Hydrology*. **272**: 1-11.

Shiklomanov, I. A. and J. C. Rodda. (eds) 2003. World Water Resources at the Beginning of the Twenty-First Century. Cambridge University Press.

Skead, C. J. (compiler). 2009. Historical plant incidence in southern Africa. Strelitzia 24. South African National Biodiversity Institute, Pretoria, South Africa.

Smith, R. E., and D. F. Scott. 1992. The effects of afforestation on low flows in various regions of South Africa. *Water SA*. **18**: 185-194.

Toerien, D. K., and R. S. Hill. 1989. The geology of the Port Elizabeth areas, Explanation of Sheet 3324. Geological Survey South Africa. Pp 35.

Van den Berg, E. C., C. Plarre, H. M., Van den Berg, and M. W. Thompson. 2008. The South African National Land Cover 2000. Agricultural Research Council (ARC) and Council for Scientific and Industrial Research (CSIR), Pretoria. Report No. GW/A/2008/86.

Stellenbosch University http://scholar.sun.ac.za

van Wilgen, B. W., D. C. Le Maitre, A. Wannenburgh, I. M. Kotze, L. van den Berg, L. Henderson. 2012. An assessment of the effectiveness of a large, national-scale invasive alien plant control strategy in South Africa. *Biological Conservation*. **148**: 28-38.

van Wilgen, B. W., D. C. Le Maitre, and R. M. Cowling. 1998. Ecosystem services, efficiency, sustainability and equity: South Africa's Working for Water Programme. *Trends in Ecology and Evolution*. **13**: 378.

van Wilgen, B.W., B. Reyers, D. C. Le Maitre, D. M. Richardson, and L. Schonegevel. 2008. A biome scale assessment of the impact of invasive alien plants on ecosystem services in South Africa. *Journal of Environmental Management*. **89**: 336-349.

Vlok, J., D. Euston-Brown, T. Wolf. 2008. A vegetation map for the Garden Route Initiative. Unpublished 1:50 000 maps and reports supported by CAPE FSP task team.

Working for Wetlands, Strategy 2006-2010. Available: http://wetlands.sanbi.org/articles2/File/WfWet%20Strategy.pdf

World Water Assessment Program. 2009. The United Nations world water development report: water in a changing world. Paris: UNESCO and Earthscan. Pp 318.

Stellenbosch University http://scholar.sun.ac.za

CHAPTER 4

Hydrological responses to land-cover change in a high energy South African catchment: Making a case for wetland restoration

Rebelo, A.J. [1]*, le Maitre, D. [2], Esler, K.J. [1, 3], Cowling [4], R.M., Horan, M.J.C [5], and S.L.C. Thornton-Dibb [5].

[1] Department of Conservation Ecology and Entomology, Stellenbosch University, Stellenbosch, South Africa
[2] Council for Scientific and Industrial Research (CSIR), Stellenbosch, South Africa
[3] Centre for Invasion Biology (C.I.B), Stellenbosch, South Africa
[4] Restoration Research Group, Department of Botany, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa
[5] Department of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, Pietermaritzburg, South Africa

*Author for correspondence
E-mail: ARebelo@sun.ac.za
Tel: +2779 499 7235

Wetlands are invaluable life support systems as they provide humankind with many essential services. However wetlands across the globe are threatened by land transformation and it is estimated that more than half of South Africa's wetlands have been thus destroyed. We argue that to meet rising demands for water, investment in natural infrastructure should be made for providing and storing water rather than using traditional, expensive engineering methods. Using modelling, we show that restoration of the natural infrastructure of a South African catchment characterised by cycles of boom and bust is able to provide competitive water related ecosystem services. Theoretically, if wetlands were restored to the extent they occupied in the catchment in 1969, they would potentially be able to provide an extra 5 mm baseflow per annum during the 3 dry months alone, translating into a flow increase of at least 6120 m^3 each year in the dry season. Wetland restoration would also improve the catchment's ability to absorb extreme rainfall events, decreasing flood damage and improving water quality. If the woody invasive alien plants were cleared from the riparian zone of this catchment (4134 ha currently invaded), an increase in riverflow of more than 42 mm per annum, which is equivalent to 32610 m^3 per annum (±30%), could be expected.

Keywords: restoration, degradation, land-cover change, extreme events, baseflow, yield

Stellenbosch University http://scholar.sun.ac.za

INTRODUCTION

"When one tugs at a single string in nature, he finds it connected to the rest of the world"
– John Muir

Wetlands across the globe are valuable as they have the ability to retain or temporarily store water and sediments, and in doing so provide society with many ecosystem goods and services (Begg 1986, McCarthy & Ellery 1998, Tooth et al. 2002, MA 2005, Zedler & Kercher 2005, Humphries et al. 2010, Driver et al. 2012, Simonit & Perrings 2011). Some of the ecosystem services are regulating services such as flood attenuation (Kotze & Breen 1994, Bullock & Acreman 2003, Kotze et al. 2005, Vörösmarty et al. 2005, Turpie et al. 2008, Russel 2009, Simonit & Perrings 2011), increasing baseflow or dry season flow (Sellars 1981, Finlayson & D'Cruz. 2005), recharging of groundwater aquifers (Thompson & Hollis 1995, Wolski 2002, Bullock & Acreman 2003, Finlayson & D'Cruz. 2005), as well as nutrient and waste assimilation, which improves water quality (Kotze & Breen 1994, Cowan 1995, Kotze et al. 2005, Finlayson & D'Cruz. 2005, Vörösmarty et al. 2005). There are many human and environmental driving forces that cause damage or changes to wetlands, and this may affect their ability to optimally perform these functions (Moser et al. 1996, MA 2005, Nelson 2005, Zedler & Kercher 2005, Vörösmarty et al. 2005, Finlayson & D'Cruz. 2005). For all their positive aspects, wetlands are generally also relatively high water-users, a trade-off that needs to be taken into consideration (Birkhead et al. 1997, Everson et al. 2001, Bullock & Acreman 2003, Clulow et al. 2012).

Southern African wetland systems have not been as well studied as their Northern Hemisphere counterparts (Ellery et al. 2009). A lack of knowledge about Southern Hemisphere riparian systems combined with inappropriate management has caused significant damage (Kondolf 2011). In South Africa, wetlands and their associated river systems, despite their inherent value, are in a critical state (Nel et al. 2007, Nel & Driver 2012) with 65% estimated to be threatened (Nel & Driver 2012) and over half estimated to have been destroyed (Cowan 1995, Driver et al. 2012). Floodplain wetlands are recognised to be the most threatened and least protected wetland type in South Africa (Nel & Driver 2012). Palmiet wetlands, characterised by the dominance of palmiet (*Prionium serratum*), are associated with the acid-waters of the Fynbos Biome with outliers in Pondoland and southern KwaZulu-Natal (Rogers 1997, Boucher & Withers 2004) in South Africa. Palmiet wetlands are channelled, or sometimes

Stellenbosch University http://scholar.sun.ac.za

non-channelled, valley bottom wetlands and rivers often have fringes of palmiet along their banks (Collins 2005). Some palmiet wetlands have formed on top of peat beds built up over thousands of years (Haigh et al. 2002). These peat deposits play a major role in water filtration and carbon sequestration (Gorham 1995, Grundling 2004, House & Brovkin 2005, MA 2005).

Land-cover changes have been identified as among the most important drivers of ecosystem transformation (Nelson 2005, Reyers et al. 2009). Changes in land-cover from woody vegetation to pasture or grassland increases riverflow (Bosch & Hewlett 1982, Zhang et al. 2001, Vertessy et al. 2003, Andreassian 2004, Bruijnzeel 2004, Scott et al. 2004, Legesse et al. 2010). Reforestation or afforestation decreases riverflow and total annual baseflow (van Lill et al. 1980, van Wyk 1986, Scott & Smith 1997, Scott & Lesch 1997, Scott et al. 1998, Scott et al. 2000) and has a variable effect on stormflow, depending on the size of the rainfall event and the saturation of soil (Versfeld 1994, Dye 1996, Forsyth et al. 1997, Vertessy et al. 2003, Scott et al. 2004). This decrease in riverflow and baseflow is largely due to changes in vegetation structure to tall, deep-rooted, evergreen vegetation from seasonally dormant grassland or shrublands, which changes rainfall partitioning between evaporation and runoff at both habitat and landscape scales (Scott et al. 2004, Calder 2005). The location of the specific land-use practices within a catchment plays an important role in the response of the riverflow with riparian areas being particularly sensitive to changes (Scott 1999, Everson et al. 2007, Warburton et al. 2012). In South Africa, models of the hydrological impacts of invasive alien plants (IAPs), especially woody trees in riparian zones, have projected that they decrease riverflow (Le Maitre et al. 1996, Le Maitre et al. 2000, Le Maitre & Görgens 2001, Le Maitre et al. 2002). By analogy with plantations, IAPs also are predicted to decrease groundwater recharge (Le Maitre et al. 1999, Calder 2005). IAPs have been found to affect water quality by redistributing sediments (Rowntree 1991), and have been modelled to decrease yields of water supply schemes (Le Maitre & Görgens 2001). Clearing woody IAPs, especially from riparian zones and wetlands, has been shown to recover these ecosystem goods and services (Dye & Poulter 1995, Prinsloo & Scott 1999, Scott 1999).

The Kromme River System in the Eastern Cape of South Africa, like other rivers in the country, is characterised by long periods of typical flows punctuated by heavy floods (Haigh et al. 2002). Native ecosystems have adapted to this episodic nature of flow, sediment transport and channel evolution and when this natural flux has been suppressed, invasive alien species

Stellenbosch University http://scholar.sun.ac.za

(IAPs) can outcompete native species (Moser et al. 1996, MA 2005, Russel 2009, Kondolf 2011). The Kromme is situated in a long narrow river valley, bordered on both sides by steep mountain ranges (Haigh et al. 2002). According to records dating from the mid 18^{th} Century (Skead 2009), palmiet wetlands once filled the valley bottom and flood plains but have now been converted to cultivated lands or displaced by IAPs, mainly *Acacia mearnsii* (Chapter 3). Palmiet wetlands stabilise the alluvium and their removal, although it was intended to make what was perceived to be the best agricultural land available, has resulted in extensive erosion in this high energy system, similar to what has happened to floodplain wetlands elsewhere (MA 2005, Nelson 2005, Haigh et al. 2002, Raymer 2008, Russel 2009). South Africa has legislation with explicit provision for protecting river systems and their floodplains; however, enforcement of these laws remains problematic (Roux et al. 2006, Armstrong 2009). After 1995 two restoration programmes commenced work in the catchment: Working for Water (Hobbs 2004, van Wilgen et al. 2012, McConnachie et al. 2012) and Working for Wetlands, clearing IAPs and rehabilitating wetlands, respectively.

The aim of this study is to improve the understanding of the dynamics of the interactions between changes in land-use and the hydrological responses of a catchment. We use a hydrological model to address the following question: what impact has wetland degradation had on the surface runoff in the Kromme Catchment? This understanding can be used to predict the long-term hydrological impacts of the restoration of the Kromme wetlands, which will help to make a case for restoration. Three aspects of hydrology were investigated: firstly riverflow (i.e. surface runoff and baseflow, secondly stormflows (i.e. floods), and lastly water quality. A change from wetlands to another land-cover, such as agriculture or *A. mearnsii*, is predicted to reduce the riverflow component of the water balance by increasing evaporation losses. The destruction of the wetlands is predicted to have caused a decrease in the water storage and filtering capacity of the catchment. We further predict that this will reduce the water quality, reduce baseflow by decreasing water storage and retention in the catchment, and decrease the catchment's capacity to absorb extreme events, resulting in an increase in rainfall-event runoff responses and more severe floods (Russel 2009).

Stellenbosch University http://scholar.sun.ac.za

METHODS

Study site

The Kromme River (33˚S, 24˚E) is located in the Eastern Cape Province of South Africa (Figure 4.1). It is about 100 km in length from its upper reaches (550 m above sea level) to its estuary. The catchment is narrow and steep, bordered by the Suuranys Mountains (±1050 m) to the north, and the Tsitsikamma Mountains (±1500 m) to the south, both running from east to west. The Kromme River is divided into five quaternary catchments: K90A-E. This study focuses on the Upper Kromme which is made up of the two uppermost quaternary catchments: K90A and K90B (Figure 4.1).

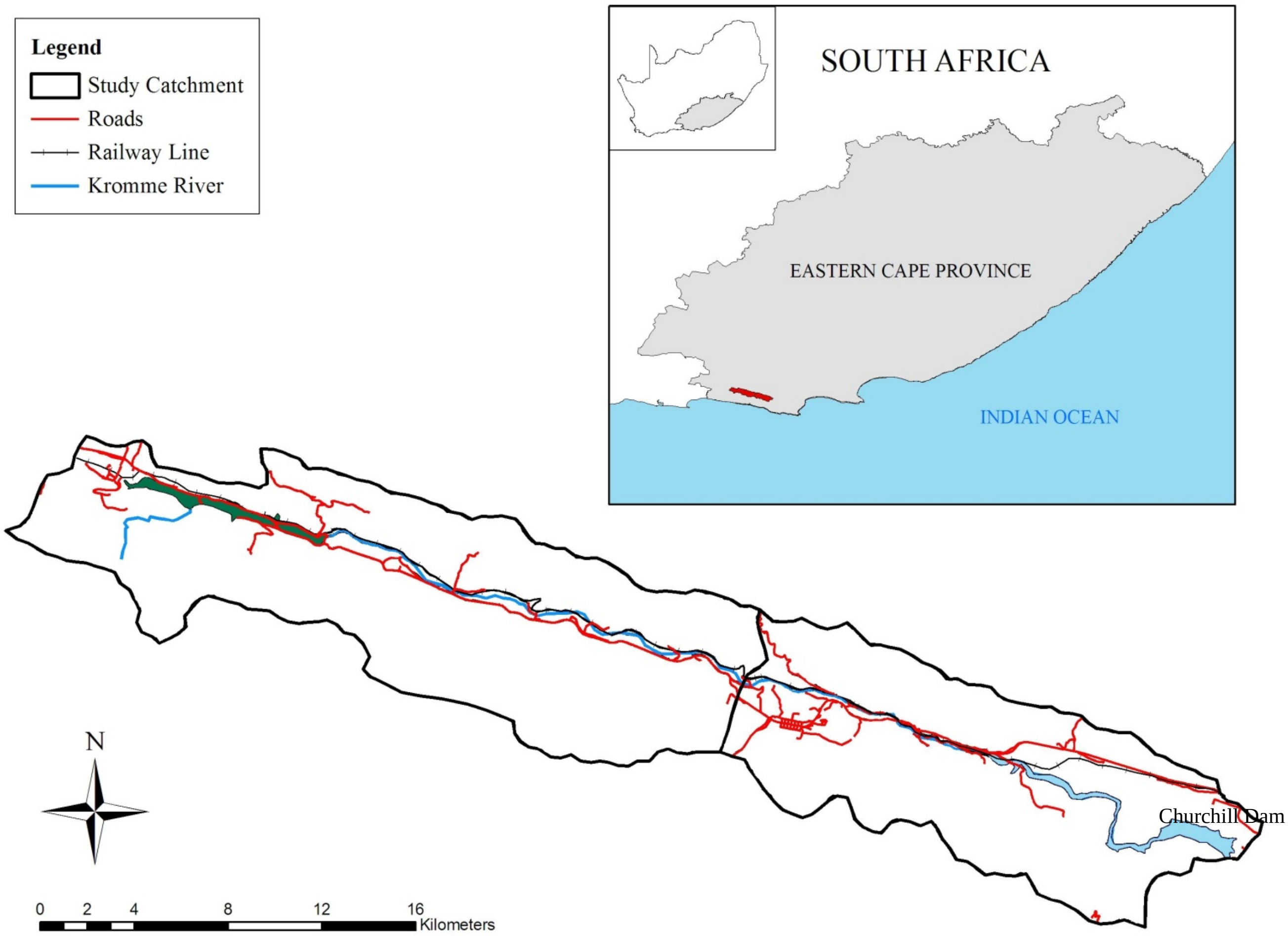


Figure 4.1: The location of the Kromme River study catchments (K90A (left) and K90B (right)) and the position of the Churchill Dam. The Kromme River is located in the Eastern Cape Province of South Africa and the Nelson Mandela Bay metropolitan area receives 24% of its water from the Churchill Dam.

Stellenbosch University http://scholar.sun.ac.za

Rainfall in the region is unpredictable, but tends to exhibit a bimodal pattern, with high rainfall in spring and autumn (Midgley et al. 1994). Mean annual precipitation (MAP) for the entire catchment is ±614 mm. Mean annual runoff (MAR) for the entire catchment is ±75 mm, which is ±11% of the rainfall (WR2005) (Middleton & Bailey 2008).

The catchment has been heavily transformed by agriculture and IAPs, particularly the river floodplains where *A. mearnsii* was nearly ubiquitous before clearing started in the 1990's (Chapter 3) (Figure 4.2a). Groundwater recharge rates are estimated to be fairly high despite the relatively low rainfall, largely because of the shallow soils in the mountain slopes, the low water-use of fynbos and the highly-fractured underlying sandstones (Figure 4.2b, Colvin et al. 2007, Roets et al. 2008). Kareedouw (population under 1000) is the only town in the catchment (Figure 4.2c). The catchment geology consists predominantly of shales and sandstones of the Cape Supergroup (Toerien & Hill 1989) (Figure 4.2d). The Cape Fold Belt is part of an intensely folded range with dipping beds forming a trellis drainage pattern (Lewis 2008). The trellis of K90A and B consists of six large and five minor tributaries entering from the southern mountain range, and seven large and numerous minor tributaries entering from the drier northern mountain range (Haigh et al. 2002). Riverflow from the northern tributaries is mostly seasonal. Several of the tributaries have alluvial fans which limit the extent of the palmiet wetlands. Historically, the palmiet stabilised the floodplain alluvium, forming peat basins which would have covered a large area of the flood plain (Haigh et al. 2002).

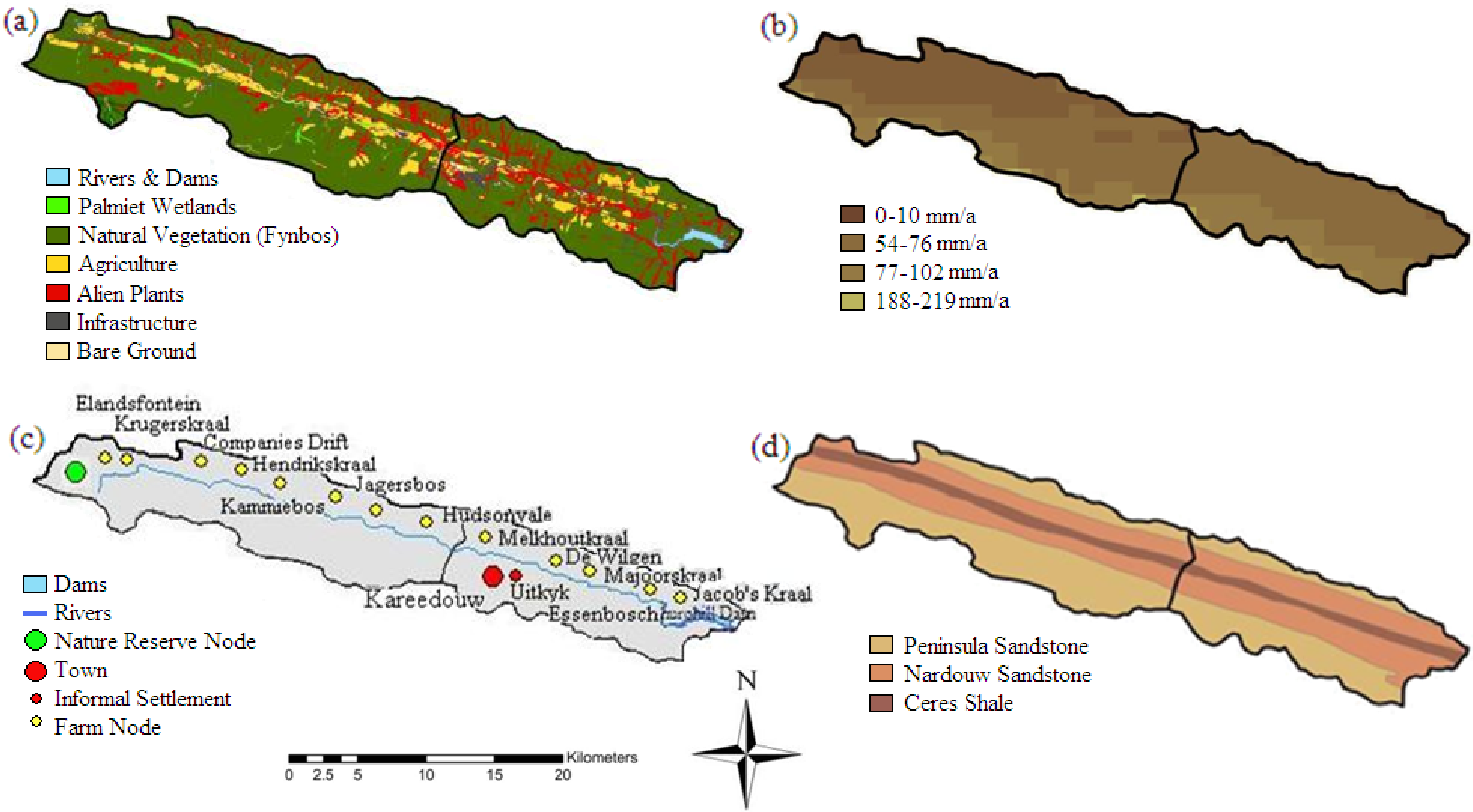


Figure 4.2: Characteristics of the upper Kromme Catchments: (a) vegetation and land-use, (b) ground water recharge (mm/annum), (c) towns and farms and (d) geology (Middleton & Bailey 2008).

Stellenbosch University http://scholar.sun.ac.za

Mapping

Land-use in the Kromme was mapped at high resolution (~5 m) using aerial photography taken in 1954, 1969, 1986, 2007 and a reference state. This reference state is a reconstruction of the Kromme before European occupation using a vegetation map of the Baviaanskloof Mega Reserve (Vlok et al. 2008). Mapping was done using 1:20 000 aerial photographs in a GIS system (ArcMap) according to 15 pre-selected land-use categories. For a detailed description of land-use changes in the Kromme, see Chapter 3.

Using hydrological modelling to investigate impacts of land-use change

Riverflow measurements in the Kromme are made at the Churchill dam at the outlet of catchment K90B. There is no gauge to measure the inflow, so it is estimated by measuring changes in the level of the water in the dam, subtracting measured outflows and estimated evaporation and adding measured rainfall. However, even small errors in the water level, evaporation or rainfall values can result in large errors in the estimated inflow. The errors are particularly important during low flows and negative inflow values were frequently calculated. Consequently, this flow record was deemed too unreliable to use for catchment runoff estimation; it was not used in a prior study because of the errors (A.H.M. Görgens, pers. comm. 2010). This means that the only way to estimate impacts of the loss of wetlands, and increases in the area invaded by *A. mearnsii*, on riverflow is to use hydrological modelling to generate a flow record. Hydrological modelling has been used frequently in the past to assess water resource availability in both pristine and transformed ecosystems (Hughes 2004). It has also been used to assess the consequences of development scenarios (Schulze 2000). Traditional modelling methods are only able to offer measures of reliability in situations where the model can be calibrated and the simulated data could be compared with observed data. This could not be done in this case, but we provide evidence that the estimates of the changes in actual riverflow are defensible in a later section (see *Calibration and Validation*). The modelling of the changes was facilitated by the fact that default parameter values were available for most of the land-cover types from an unpublished hydrological modelling study done for the catchments of Kromme, Kouga and Baviaanskloof River systems using the same model (Mander et al. 2010).

Stellenbosch University http://scholar.sun.ac.za

The ACRU agrohydrological model

The Agricultural Catchments Research Unit (ACRU) model has been developed over a period of 30 years by the School of Bioresources Engineering and Environmental Hydrology (BEEH) at the University of KwaZulu-Natal in South Africa. This particular model was chosen because of its simple user interface, its large database of vegetation and soil parameters developed for South African conditions, and because it is appropriate for a catchment of this size. The ACRU model is a physical-conceptual model with a daily time step. It is based on multi-layer soil water budgeting (Figure 4.3) and is consequently sensitive to land-use changes, irrigation demand and the onset and degree of water stress. ACRU has been used in numerous studies in South Africa and elsewhere for various purposes including investigating the impacts of land-use change (Jewitt et al. 2004, Schulze 2000) and impacts of climate change (Schulze et al. 2005) on hydrological resources. It has also been tested against field measurements (Schulze 1995, Jewitt & Schulze 1999, Smithers and Schulze 2004). Documentation on the latest available ACRU Model was published in Warburton et al. (2010). However, this particular study is the first to use the new wetland and riparian routines of the version 4 of the ACRU Model, a script which allows excess riverflow to flood adjacent riparian or wetland Hydrological Response Units (HRU's) (Gray 2011).

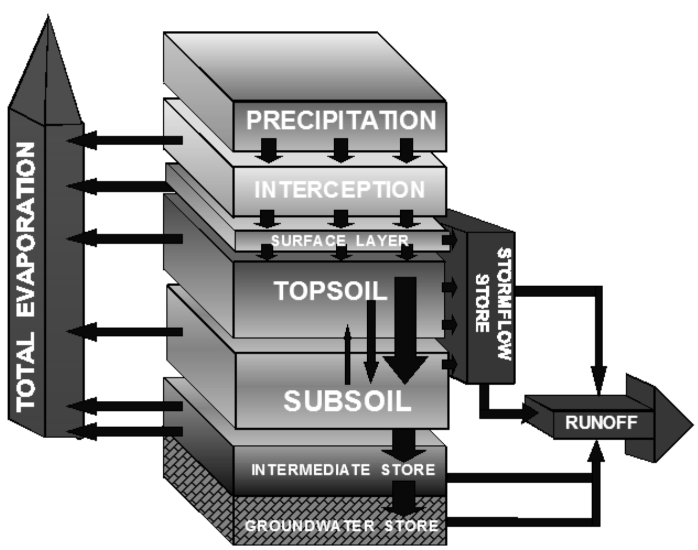


Figure 4.3: A diagram of the multi-layer water budgeting performed by ACRU. The thickness of the arrows represents the relative proportion of water moving through the system (Diagram from: Schulze 1995, Smithers and Schulze 2004).

Stellenbosch University http://scholar.sun.ac.za

Model set-up

a. Sub-catchments

The study catchment (quaternary catchments K90A and K90B) was sub-divided into 11 hydrologically similar sub-catchments (A1-4 and B1-7) (Figure 4.4). The main factor guiding the delineation was altitude, because rainfall is positively correlated with altitude. Catchment responses to rainfall are non-linear, so a single mean rainfall value would not adequately estimate hydrological processes over the whole catchment. This is especially true for catchments with marked rainfall gradients. These sub-catchments were based on those delineated by Schulze et al. (2008), as rainfall, geology and soils had already been taken into account during this process. However the sub-catchments were further divided based on hydrology, where an extra three sub-catchments were delineated to represent the flood plain.

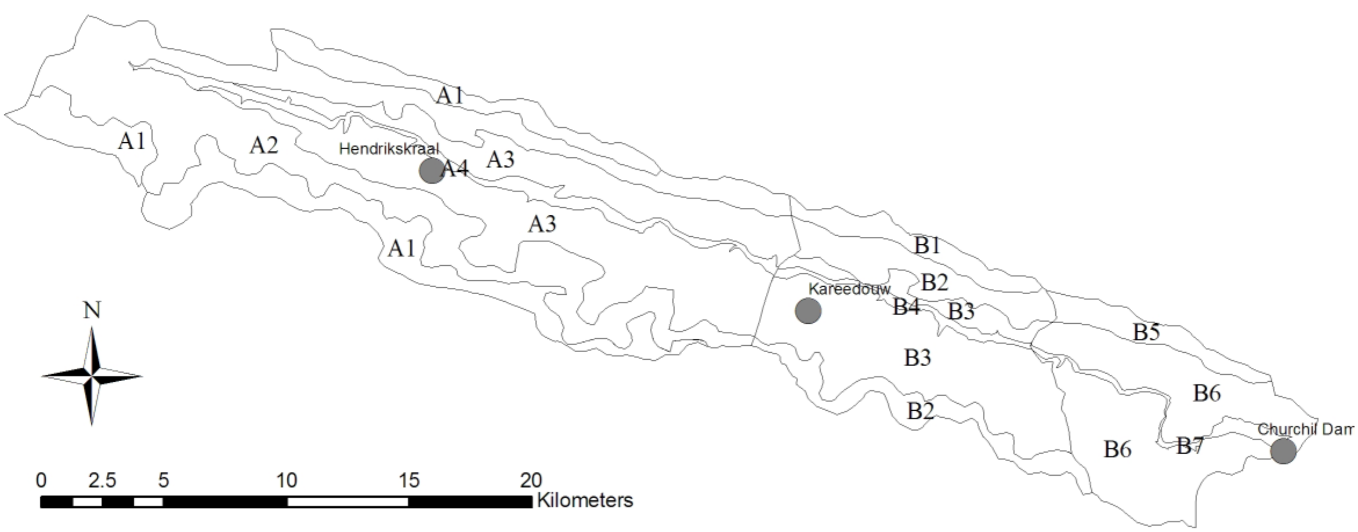


Figure 4.4: The upper Kromme was divided into 11 study sub-catchments (A1-4, B1-7). The position of the 3 rainfall stations within the study catchments are marked by shaded circles.

b. Hydrological response units (HRU's)

Sub-catchments were each divided up into 15 different Hydrological Response Units (HRU), which are areas of the subcatchment that are treated as a unit due to hydrological, geological, and vegetation similarities, using 1:20 000 colour aerial photographs in a GIS system, ArcMap (Table 4.1). Vegetation types were divided into two categories according to whether the vegetation type was classified as relatively productive (on relatively fertile soils) or unproductive

Stellenbosch University http://scholar.sun.ac.za

(on highly infertile soils, mainly associated with thin soils overlying the exposed quartzitic sandstones in the upper regions of the catchment). Productive fynbos groups are those that contain vegetation that has a relatively high nutrient content and are consequently known to be able to support grazing by livestock. Unproductive fynbos groups have comparatively low nutrient content and cannot support large livestock. Lastly, fynbos that was heavily degraded by over-grazing or altered fire regimes was separated from these two groups.

Table 4.1: The subcatchments of the upper Kromme were each further divided into 15 different hydrological response units (HRU's) which were mapped in the Kromme using aerial photo interpretation and captured as spatial data layers using ArcMap.

HRU	Land-use	Description
1	Dams	Including small farm dams and a large municipal dam
2	Mountain Seep Wetlands	High altitude/gradient wetlands on the mountain slopes
3	Palmiet Wetlands	Wetlands in the valley, dominated by *Prionium serratum*
4	Riparian Vegetation	Woody vegetation in ravines, either thicket or afromontane forest
5	Unproductive Fynbos	Seven different unproductive fynbos and renosterveld vegetation types
6	Productive Fynbos	Three different productive fynbos and renosterveld vegetation types
7	Degraded Fynbos	Degraded by heavy grazing or poor fire management
8	Irrigated Fields	Agriculture that has an irrigation system (sprinkler or central pivot)
9	Dryland Farming	Any agriculture that is not irrigated
10	Orchards	Orchards with irrigation systems
11	*Acacia mearnsii*	The dominant woody invasive alien plant in the catchment
12	*Pinus Sp*	The second most common woody invasive alien plant in the catchment
13	Other Alien Plants	All other woody invasive plants, mainly *Eucalyptus* species
14	Disjunct Impervious	All unnatural structures: houses, roads, railway lines, quarries
15	Adjunct Impervious	Open soil, sites of erosion or deposition in or adjacent to the river

c. Configuration

Different land-uses, or HRU's, were captured in a flow network (Figure 4.5). HRU's were linked together in such a way that water flows (rainfall, evaporation and riverflow) in the Kromme River were represented in this model as accurately as possible. Irrigated fields were "fed" with irrigation water from the nearest dam.

Stellenbosch University http://scholar.sun.ac.za

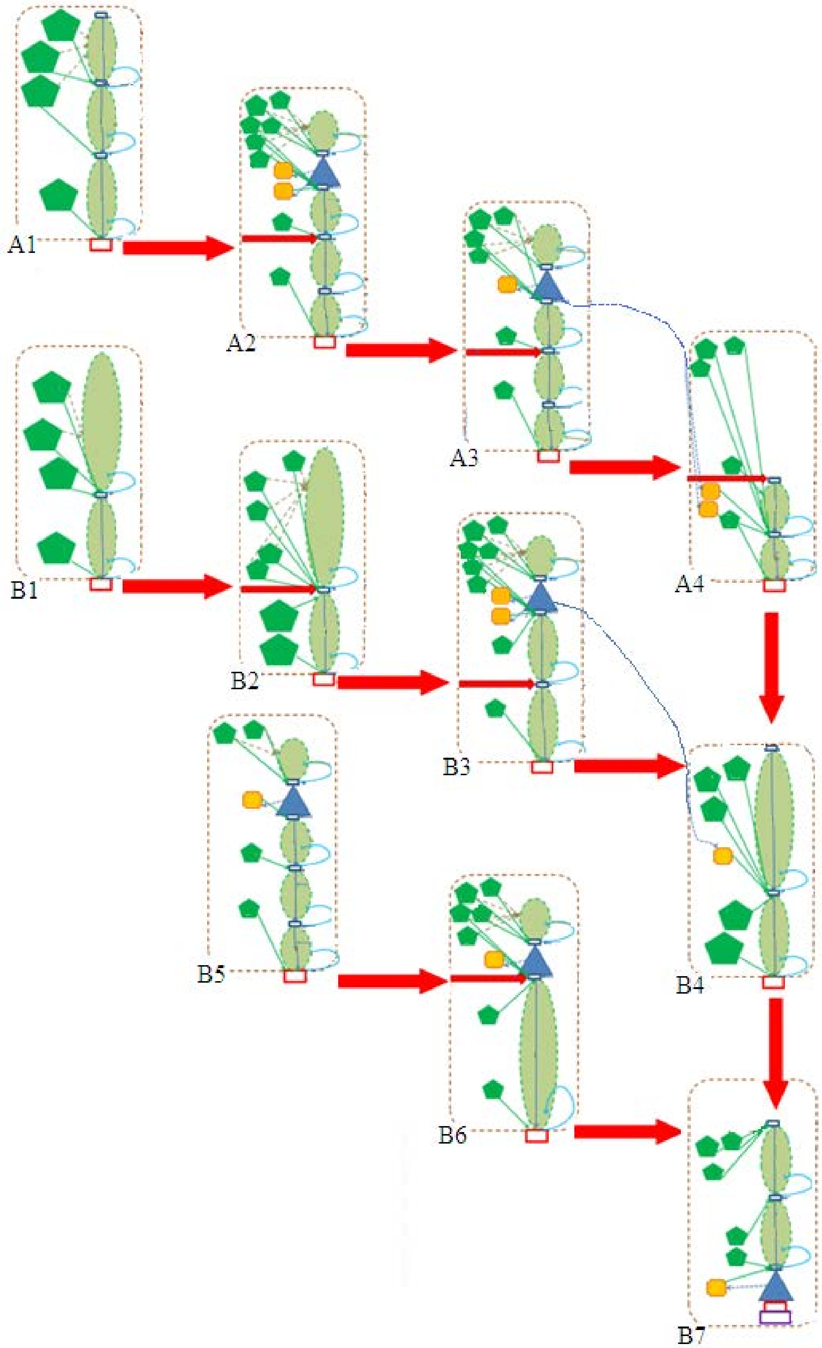


Figure 4.5: The 11 subcatchments of the upper Kromme River were routed to form of a hydrological network. Within each subcatchment, the 15 HRU's were configured according to the above design. Key: ---Subcatchments, light blue and red arrows indicate riverflow, dark blue stippled lines (affiliated with irrigated HRU's) indicate water abstraction for irrigation, HRU's, irrigated HRU's, ▲ dam and the large light green ovals represent wetlands and riparian zones. The red boxes represent subcatchment nodes and the purple box the catchment node.

Stellenbosch University http://scholar.sun.ac.za

d. Data sources

i. Rainfall

Rainfall records from all available sources were screened for errors and missing data and only the most reliable records were used (Lynch 2003). From a set of nine stations, we selected three that best represented each of the eleven sub-catchments (Figure 4.4). We obtained data for the Hendrikskraal and Kareedouw rainfall gauging stations from the Lynch database (Lynch 2003), and from the Churchill Dam rainfall gauging station from the Department of Water Affairs. We generated a rainfall correction surface for the catchment from altitude using a digital elevation model (DEM), and calculated the mean rainfall for each of the three subcatchment segments: A1-4, B1-4 and B5-7 (Figures 4.4 & 4.6).

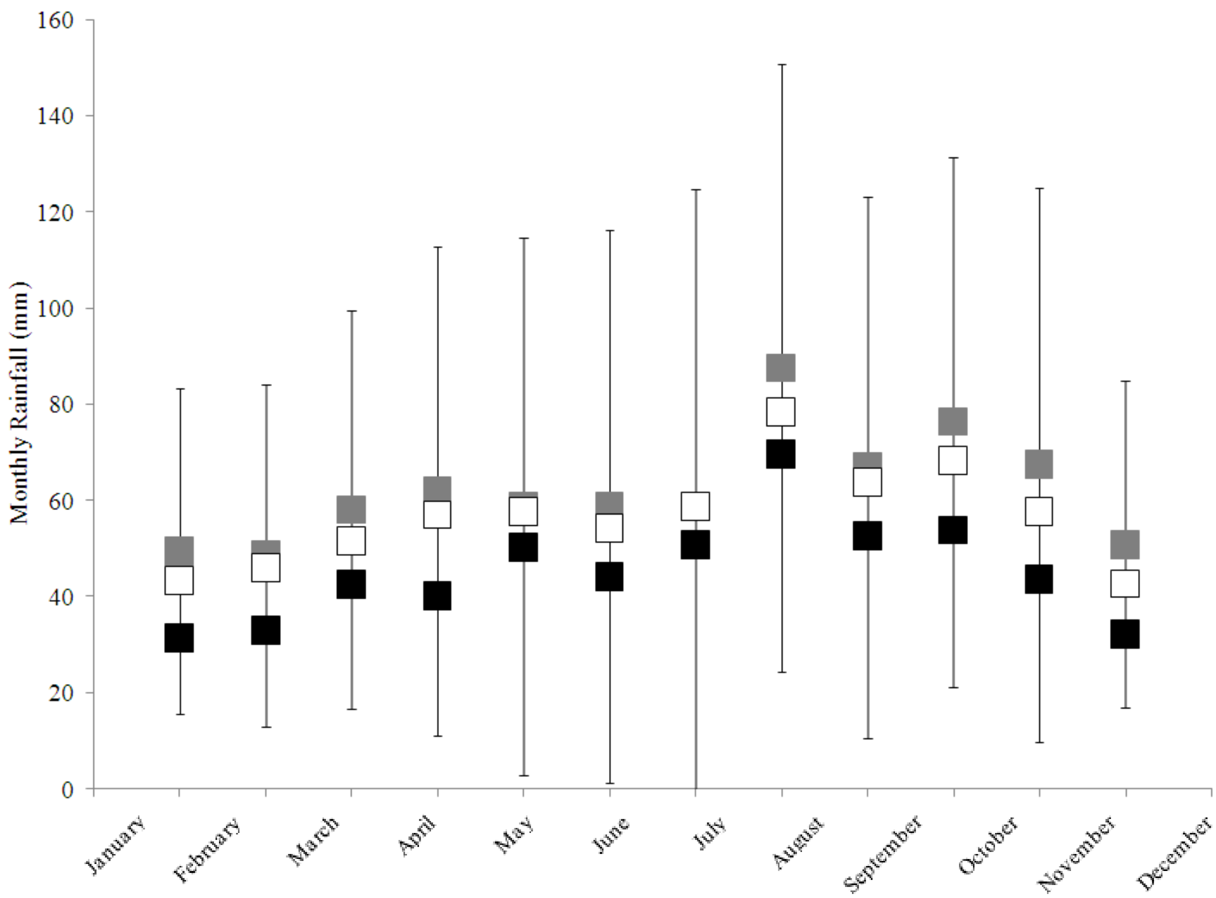


Figure 4.6: Mean monthly rainfall from 1950 to 2000 driving the three sub-catchment segments: A1-4, B1-4 and B5-7. Gauges are placed at Hendrikskraal ■, the town of Kareedouw ■ and at the Churchill Dam □.

Stellenbosch University http://scholar.sun.ac.za

ii. Soils and geology

Soil and geological data for the ACRU model were extracted for each of the eleven sub-catchments from the electronic data provided by the South African Atlas of Climatology and Agrohydrology (Schulze et al. 2008).

iii. Water bodies and irrigation

Surface areas obtained from the mapping survey (Chapter 3) for each of the farm dams and for the municipal dam were used to calculate the volumes using formulae presented in the ACRU Manual (Schulze 1995). The most general dam form was used for calculations as this allows for dams which do not have a standard shape and where detailed measurements are not available: $Capacity = Area \times Depth$. Irrigation data were obtained via interviews of farmers in the Kromme in 2010[2].

iv. Wetland and riparian routines

Palmiet wetlands were modelled using the new $ACRU_4$ wetland routine (Horan pers comm. 2012) and a crop factor derived in this study (Chapter 5, Appendix 5). Where *A. mearnsii* replaced palmiet wetlands, it was also modelled using the new ACRU wetland routine. Riparian zones and seep wetlands were modelled using the riparian routines. This was to allow the hillslope flow, in the form of underground seepage through the B-Horizon, to be modelled.

v. Vegetation parameters

The ACRU model outputs both evaporation and riverflow. It calculates total evaporation from estimates of both evaporation from the soil (E_s) and vegetation (E_t). The model estimates the potential E_t for each vegetation type using the Hargreaves and Samani (1985) equation which requires only daily minimum and maximum temperature inputs. It then uses a water use coefficient (crop factor) to approximate an actual Et, which is then further adjusted for soil moisture availability (Schulze 1995). The ACRU model takes into account three processes when modelling evaporation from plants: canopy interception, evaporation from vegetated surfaces and evaporation from soil surfaces (Schulze 1995). Evaporation is influenced by soil water uptake via the plants roots from soil horizon A and B (Schulze 1995). The monthly values for crop factor, infiltration co-efficient, root mass distribution, amongst other values, for each

[2] The data obtained in the farmer surveys conducted in 2011 are contained in a separate database and will not be published due to sensitive nature of the data.

Stellenbosch University http://scholar.sun.ac.za

vegetation type –derived from a vegetation map by Vlok et al. (2008) – were obtained from the ACRU model database, having being compiled for a similar hydrological study in the same region by Mander et al. (2010). The crop factor for *P. serratum*, which was used to approximate water use of the palmiet wetlands, was developed from MODIS satellite data (Appendix 5).

Scenarios

A model was built for each of four different land-cover scenarios, representing the actual land-cover from four different periods in the Kromme: 2007, 1986, 1969 and 1954. The data on the state of the catchment in each period are described in Chapter 3 of this thesis.

Calibration and Validation

The ACRU Model attempts to capture and represent water flows and the controls on them but it does require calibration against observed data to confirm that the correct values for the various parameters have been chosen. However, for the Kromme River there are no reliable flow measurements. The output was instead compared with results from another independent modelling study, namely the Water Resources 1990 assessment (Midgley et al. 1994)) and with the dam inflow data as downloaded from the Department of Water Affairs (DWA) database (http://www.dwaf.gov.za/hydrology/).

Traditional calibration and validation could not be done in this case, but we do have limited data for the key land-cover changes, namely the loss of the palmiet wetlands and invasion by *A. mearnsii*, that can be compared with the model outputs. Evaporation from palmiet wetlands was measured using infra-red scintillometry (Jarmain pers. comm. 2011) and also using the remote-sensing based SEBAL model (Appendix 5). Measurements of evaporation from riparian invasions of *A. mearnsii* are available from a number of studies in South Africa (Dye et al. 2001, Dye & Jarmain 2004, Clulow et al. 2009, Clulow et al. 2011). These measurements can be compared with the ACRU output values for evaporation for the hydrological response units (HRUs) with those land-cover types. If the ACRU output values are reasonable predictions for evaporation from key land-cover types, this provides evidence that the estimates of the changes in modelled riverflows are defensible.

Stellenbosch University http://scholar.sun.ac.za

Responses to extreme events

The responses to flood events can still be studied using the estimated dam inflows instead of the modelled data, because the effects of errors in the dam inflow calculations will be small relative to the inflow volumes. We used the measured inflows after extreme events to assess whether the catchment's ability to absorb extreme flood events had been altered by the changes in landcover. For the flood analysis, 20 of the largest individual rainfall events were selected in each of five decades from 1950 to 2000. The corresponding riverflow response for each rainfall event was calculated from the DWA data set. To determine whether or not extreme flood events have become more prevalent with time, a standard least squares fit was applied to each correlation using STATISTICA Version 10. Significance of the differences between correlations were then determined based on whether or not confidence intervals overlapped in a range plot.

Stellenbosch University http://scholar.sun.ac.za

RESULTS

The most significant changes in the land-cover of the Kromme Catchment between 1954 and 2007 were an increase in the area of productive and unproductive fynbos that has become degraded by overgrazing and too-frequent burning, an increase in the cover of *A. mearnsii*, a decrease in palmiet wetlands (85%) and riparian vegetation (92%), and a proliferation of different forms of agriculture (Figure 4.7). Four different hydrological models were built according to each of the four different land-cover scenarios: 1954, 1969, 1986, 2007. These four scenarios formed along a degradation gradient, ranging from:

1. representative of the state of the land in 1950s:
   (low degradation, wetlands relatively intact, low intensity agriculture)
2. representative of the 1960/1970s,
3. representative of the 1980s and lastly
4. representative of the 1990/2000s:
   (most degraded, wetlands most transformed, high intensity agriculture)

Stellenbosch University http://scholar.sun.ac.za

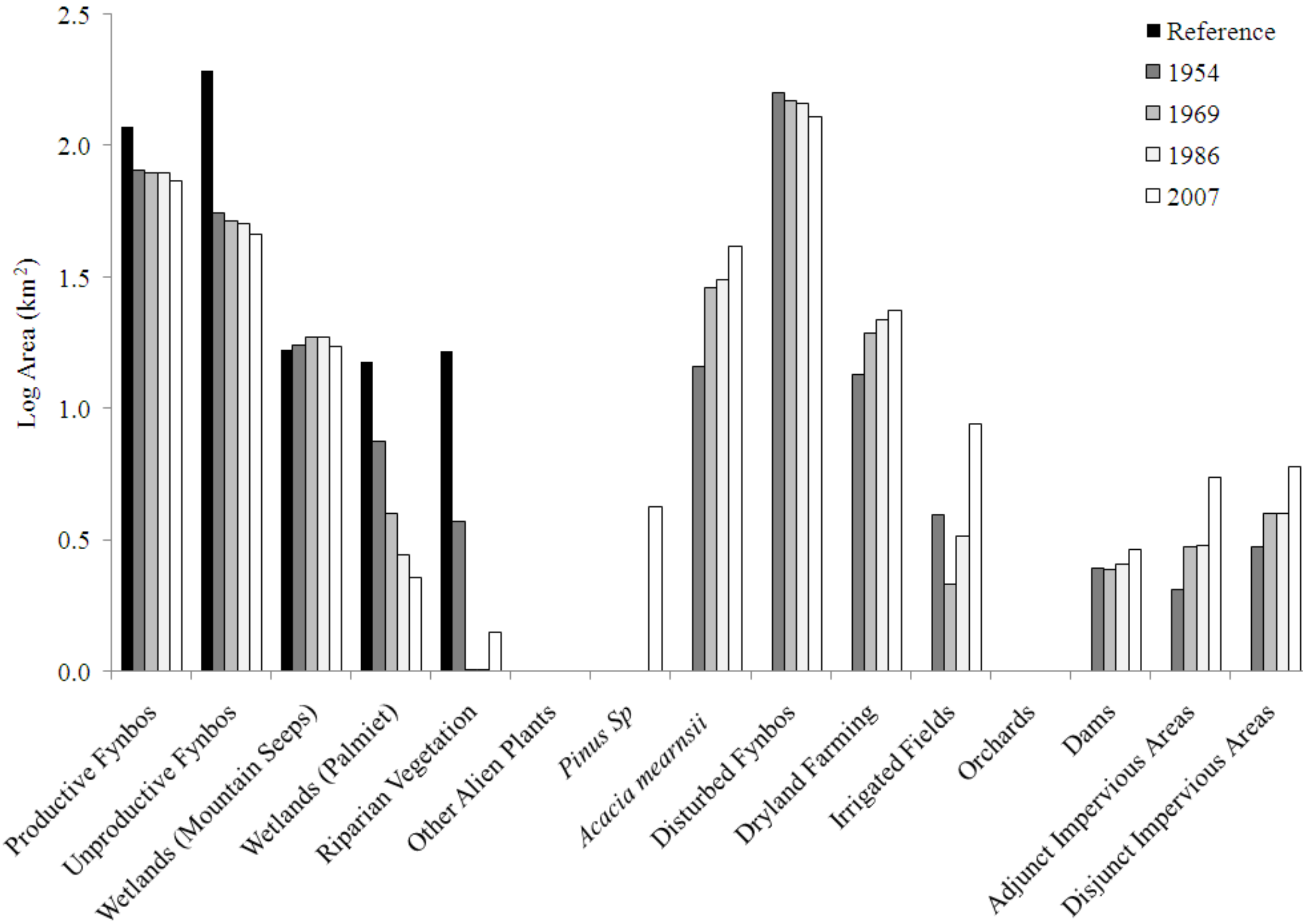


Figure 4.7: Land-use change in the Kromme from before 1954 to 2007

Effect on Riverflow

The changes in riverflows due to rainfall can be confounded by multi-year variability in rainfall and trends in rainfall so we first examined the rainfall records for evidence of change. Rainfall in the Kromme has decreased and become more variable over the four decades (Table 4.2.1). MAP was highest in the period 1950-1970, and lowest from 1980-2000. The Kromme River has a relatively high modelled rainfall-to-runoff-ratio of around 26% compared to 21% and 19% for the water resources studies: WR90 and WR2005 respectively (Middleton & Bailey 2008). The difference may be explained by the WR2005 being based on a MAP of 745 mm, 131 mm higher than that of this study (614 mm); however different models, modelling approaches and assumptions about vegetation water-use may also account for these differences. The MAP

Stellenbosch University http://scholar.sun.ac.za

used in this study was calculated using more rainfall gauging stations than the water resources study and was extrapolated using a rainfall correction surface and weighted according to the area of the catchment the rain gauge represented. When the MAP of 614 mm is used to calculate the ratio for the water resources studies, the new ratios range from 21-28% which are very comparable to the ratios calculated for this study. In the Kromme this modelled rainfall/runoff ratio based on its state in 1954 was 26.2% and has declined to 24.6% for its state in 2007. Thus the decrease in MAR of 42 mm per annum is greater than what would be expected given the decrease in rainfall. This is confirmed by a second analysis where the rainfall input records is kept constant and the large decrease in runoff is still apparent (Table 4.2.2). Thus the model behaved as expected and the decrease in runoff over time relative to the rainfall can be attributed largely to land-cover changes in the Kromme.

Table 4.2.1: Mean annual rainfall and modelled riverflow in the Kromme River for four different 20 year time periods. Different rainfall data were used for each model, thus the impacts of land-use change alone cannot be isolated. Means are ± standard deviation.

Landcover	Rainfall Dates	Mean Annual Precipitation (mm)	Mean Annual Runoff (mm)	Rainfall / Runoff (%)
1954	1950-1970	668.7±130.73	175.4±96.93	26.2
1969	1960-1980	617.6±169.48	160.9±87.47	26.1
1986	1970-1990	561.0±178.60	138.5±82.10	24.7
2007	1980-2000	542.6±178.70	133.4±80.05	24.6

Table 4.2.2: Mean annual rainfall and modelled riverflow for the Kromme River for four different landcover scenarios each spanning 50-year periods. Landcover scenarios were modelled along a degradation gradient, from (1) least degraded to (4) most degraded. Rainfall input data (614.0±165.56) were identical in this section, the same 50 year dataset being used in each scenario. This allows the impacts of land-use change alone to be isolated. Means are ± standard deviation.

Degradation gradient ↓

Landcover Scenario	Rainfall Dates	Mean Annual Runoff (mm)	Rainfall / Runoff (%)
1	1950-2000	188.1±95.87	30.6
2	1950-2000	169.0±86.63	27.5
3	1950-2000	147.2±81.83	24.0
4	1950-2000	146.1±79.97	23.8

The differences in runoff between scenarios appear relatively small, but when converted into volumes the differences become more evident. The differences in land-cover between the 1954

Stellenbosch University http://scholar.sun.ac.za

and 2007 scenarios resulted in a modelled decrease in MAR of 42 mm, which translates to 15.18 million cubic metres (mcm) in total over 50 years, or 0.3 mcm per annum. Scenario 1, representing the Kromme in its least degraded state in the last 50 years, produced consistently higher runoff per annum for the given rainfall input (Figure 4.8). Scenario 4, representing the Kromme in its most degraded state in the last 50 years, produced consistently lower runoff per annum for the given rainfall input. Line (a) shows the potential yield with the minimal number of years where there was failure to meet the demand for yield (3 years out of 27) under Scenario 1. Line (b) shows the potential harvestable yield with minimal failures (1 year out of 18) under Scenario 4. There is a difference in 10 mcm per annum in potential yield between the two different scenarios. Line (c) shows the point in the 1980s after which the actual yield drawn from the Kromme declined and never again exceeded line (b). This may be a result of a reduction in yield that the Kromme is able to supply. However it is also around the time that the Impofu Dam was built (Appendix 3), and this change may have decreased the pressure of abstraction from the Churchill Dam. This graph shows that the ACRU modelled results have a high level of agreement with the actual river flow data from the DWA and that runoff from the upper Kromme River has been in steady decline over the past 50 years.

Stellenbosch University http://scholar.sun.ac.za

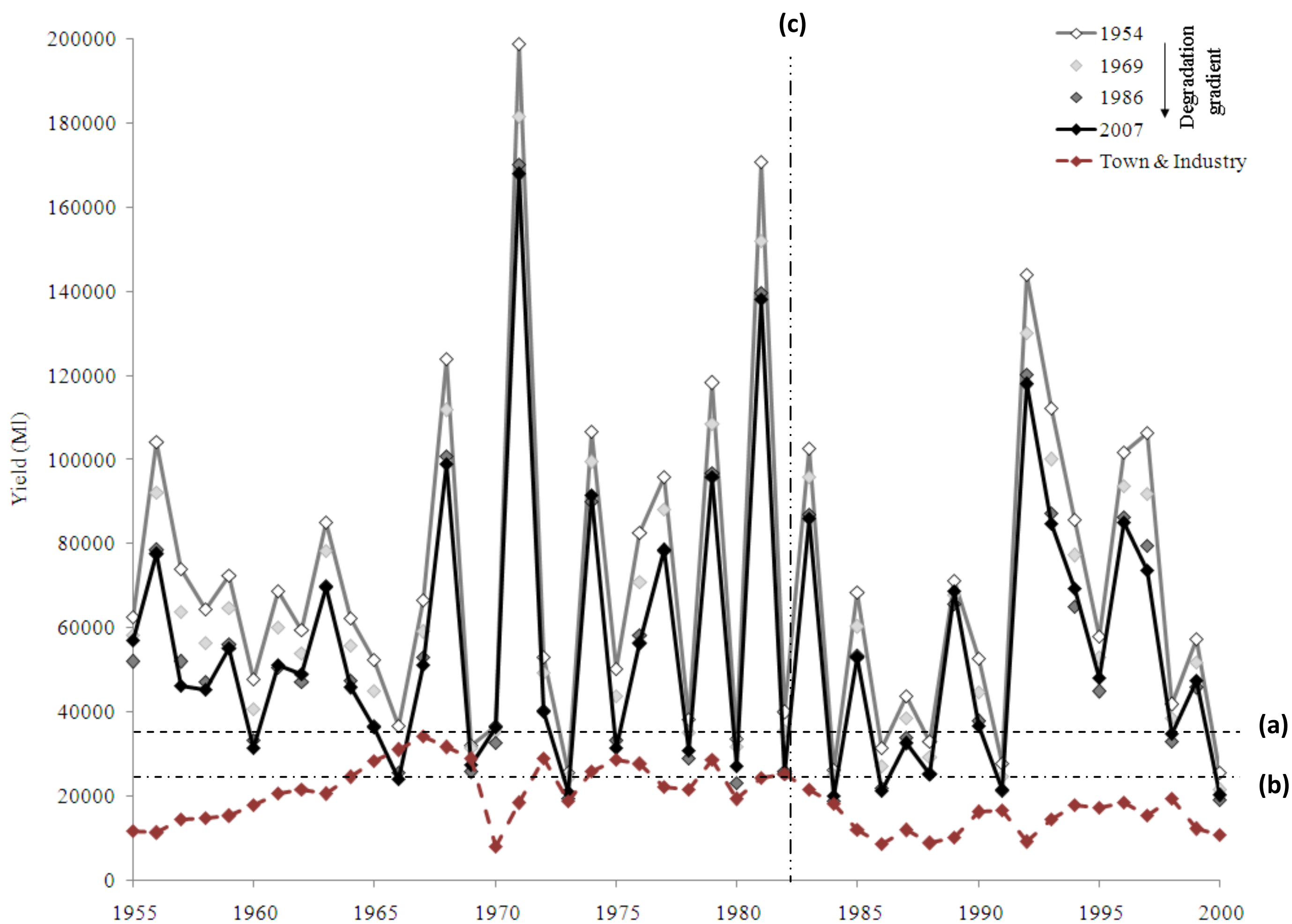


Figure 4.8: ACRU simulations of the total riverflows in the Kromme Catchment annually under four different degradation scenarios from 1955-2000. Landcover scenarios were modelled along a degradation gradient, from least degraded to most degraded. The same 50 year rainfall data record was used in each scenario. This allows the impacts of land-use change alone to be isolated. The yield, or offtake from the dam for industry and for the Nelson Mandela Bay metropolitan area is also shown.

Effect on Baseflow

Baseflow, that portion of riverflow resulting from groundwater and catchment water storage, was calculated from the modeled data for the three driest months in the Kromme: December, January and February. The model behaved as expected: for the least degraded state, the baseflow was highest and made up the greatest percentage of the mean annual runoff (Table 4.3). The modeled baseflow decreased along the degradation gradient, predominantly the result of wetland transformation, *A. mearnsii* invasion and an increase in the area under agriculture. The increase

Stellenbosch University http://scholar.sun.ac.za

in the standard deviation of the modeled results with the degradation gradient suggests that baseflow would also become more variable and less predictable with increased degradation.

Table 4.3: Simulated monthly baseflow (mean ± standard deviation) for each landcover scenario each spanning 50-years periods. Landcover scenarios were modelled along a degradation gradient, from (1) least degraded to (4) most degraded. Rainfall input data (614.0±165.56) were identical in this section, the same 50 year data record used in each scenario. This allows the impacts of land-use change alone to be isolated.

	Landcover Scenario	Rainfall Dates	Mean Monthly Baseflow (mm)	Mean Annual Baseflow (mm)	% of MAR
Degradation gradient ↓	1	1950-2000	9.42 ± 7.263	113.10	60.1
	2	1950-2000	8.27 ± 6.993	99.25	58.7
	3	1950-2000	6.57 ± 7.070	78.88	53.6
	4	1950-2000	6.58 ± 9.221	78.95	54.0

The way the catchment responds to rainfall events according to the ACRU model differs among the four different degradation scenarios. Scenario 4, the most degraded, responded the most to high rainfall events (Figure 4.9). Conversely, during the dry season it had the lowest riverflow. However in Scenario 1, the least degraded, the catchment was best able to absorb high rainfall events, shown by the less dramatic response to these high rainfall events compared to the other 3 scenarios. During the dry season Scenario 1 generated the highest riverflow. The model results suggest that as the catchment has become more degraded with time (from 1954 to 2007), so the baseflow during the dry months has decreased and the riverflow during the extreme rainfall events/high rainfall season has increased.

Stellenbosch University http://scholar.sun.ac.za

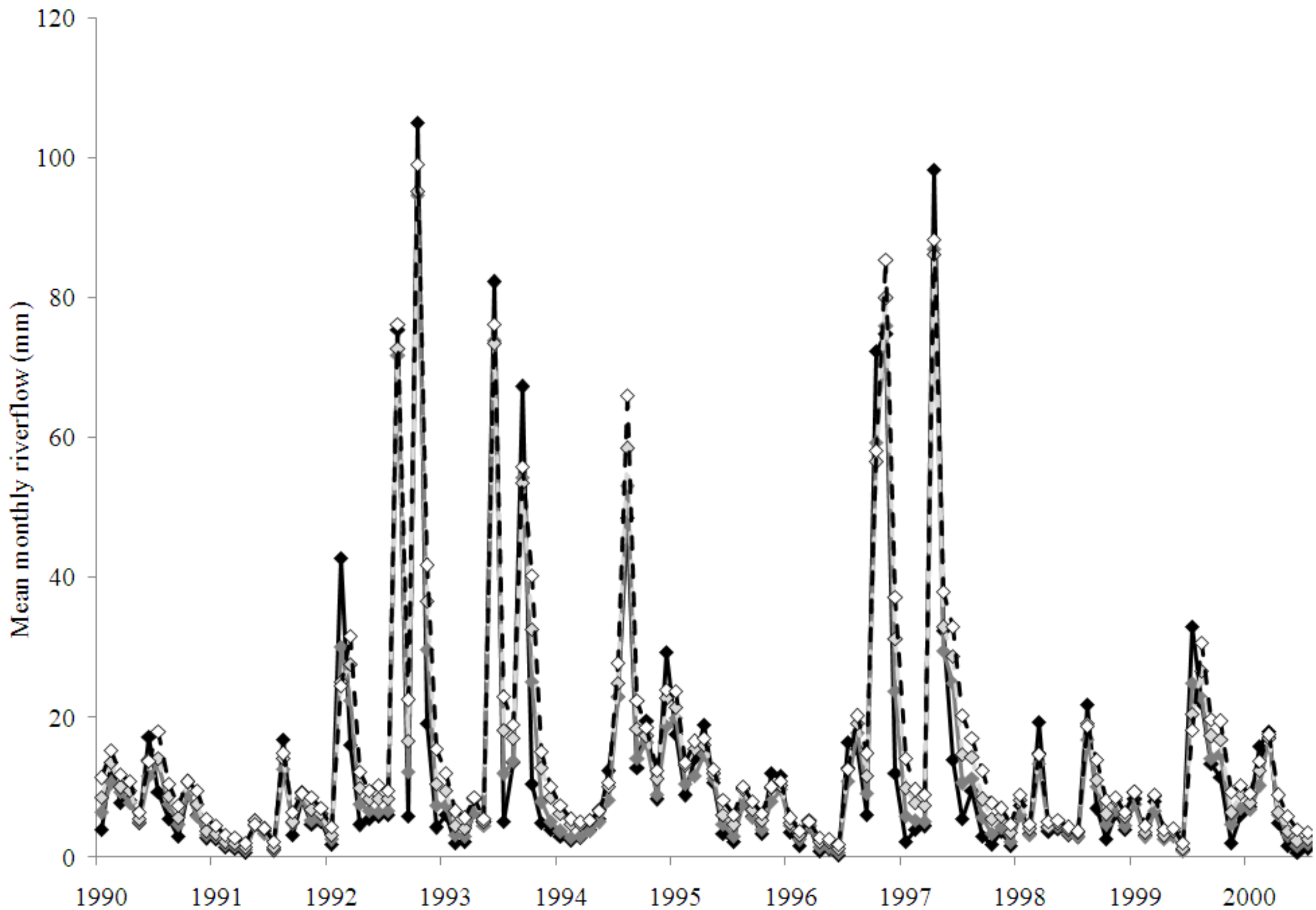


Figure 4.9: Mean monthly riverflow from 1990 to 2000 for each of the four modelling scenarios (♦ 2007, ♦ 1986, ♦ 1969, ◊ 1954).

Effect on Extreme Events

Analysis of the rainfall and riverflow and the cumulative deviations from the respective mean values showed that the Kromme has had extended periods of above average rainfall, from 1950-1970, punctuated by relatively brief but intense periods of drought, from 1980-1990 (Figure 4.10). In 1983 the most extreme rainfall event in over 50 years occurred in the Kromme, where more than half of the MAP (614 mm) was received in 8 days, a total of 332.37 mm. This resulted in catastrophic floods. Four of the ten most extreme rainfall events occurred in the 1970s, and two in each of the 1950s, 1980s and 1990s. There were 2786 rainfall events between 1950 and 2000. The mean magnitude of rainfall event was 11 mm. There were 28 rainfall events greater than 101 mm. There is a slight decrease in the magnitude of all rainfall events over time.

Stellenbosch University http://scholar.sun.ac.za

In addition, extreme rainfall events appeared to decrease rather than increase with time, although the rate of decrease was low (Figure 4.10).

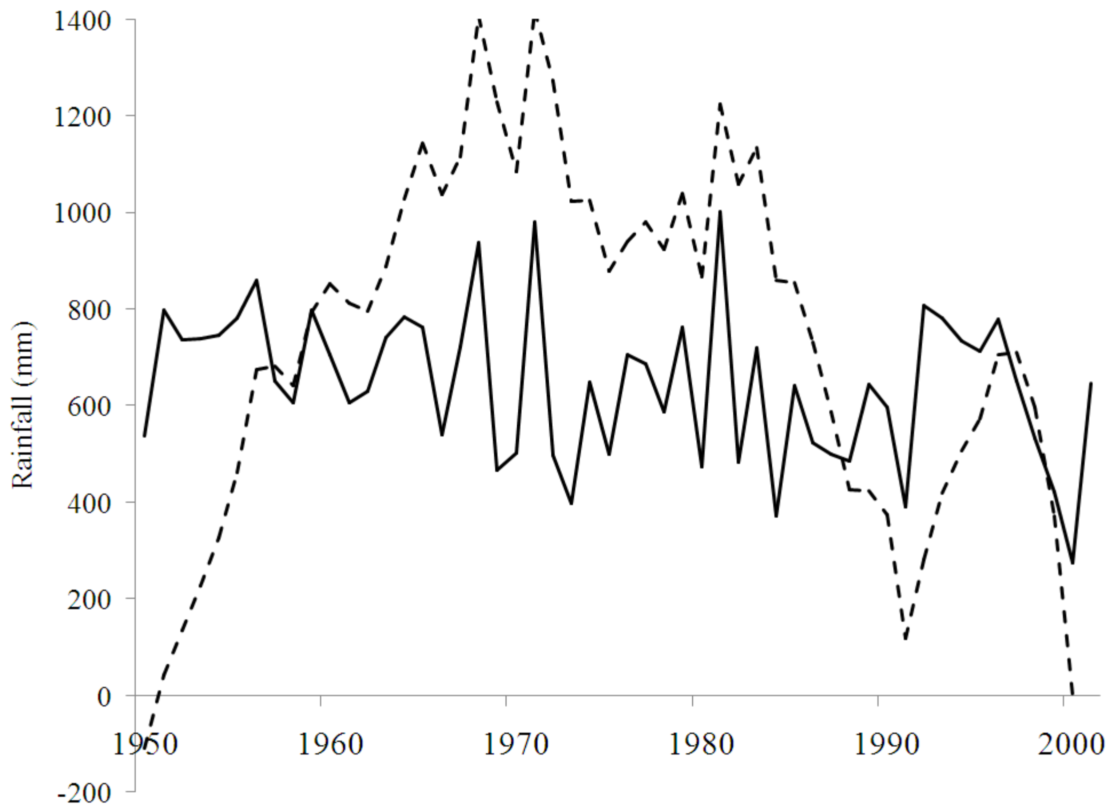


Figure 4.10: Mean annual rainfall (solid line) and its cumulative deviation from the mean (stippled line) in the upper Kromme River between 1950 and 2000.

The ability of the upper Kromme River catchment to absorb rainfall has decreased over time, despite the attempt to artificially retain it by increasing the number of farm dams (Figure 4.11). The relationship between rainfall and riverflow has changed over time, the catchment producing more runoff/riverflow for each rainfall event. This can be seen by the gradient of the trendline for each decade. In the 1950s the gradient was low (0.05) but increased to 0.89 in the 1980s where it peaked and then decreased to 0.66 in the 1990s. The removal of the outlier, point (a), reduced this gradient to 0.68, only slightly greater than the gradient of the 1990s. Outlier (a) is the largest rainfall event in the Kromme Catchment in the last 50 years, 332 mm over a period of eight days. The 1950s had the weakest correlation coefficient, followed by the 1960s. The trendlines of all other decades were acceptable fits. Range plots showed that each time period

Stellenbosch University http://scholar.sun.ac.za

was differed significantly from the next, with the exception of 1960s from 1970s, 1980s from 1990s and 1970s from 1990s.

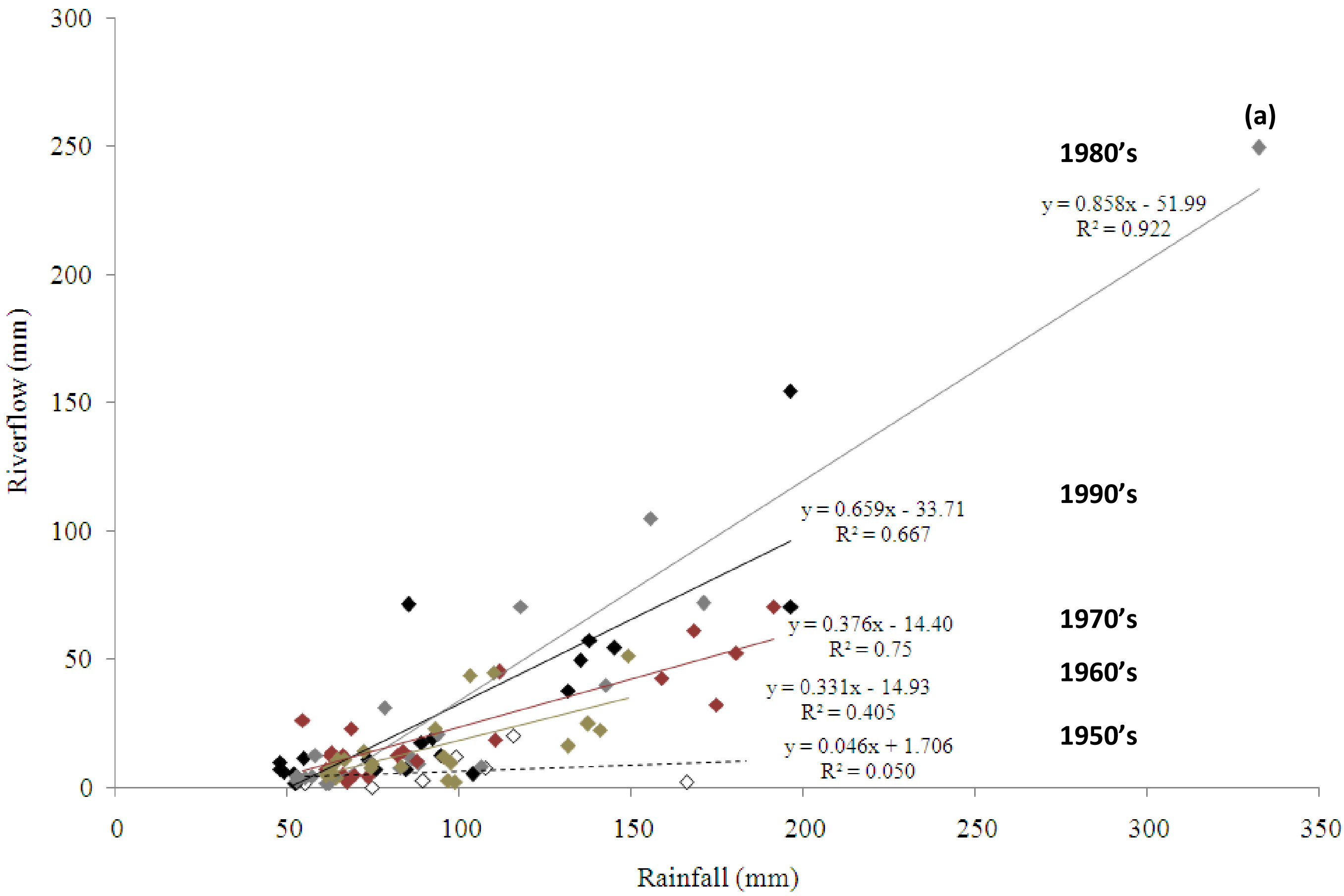


Figure 4.11: An assessment of the ability of the Upper Kromme River catchment to absorb and regulate the flows from extreme rainfall events over the past five decades. Note: DWA data and not ACRU Modelled data were used in this section.

Effect on Water Quality

There are no water quality data for the Kromme River before 2000 although water treatment works were constructed in the 1940s. However, data on the amount of chemicals used to treat the water are available from 1985 (Figure 4.12). It is possible to deduce the state of the quality of the water by examining the volumes of the chemicals added to the water, as they would increase in response to a decline in water quality. Water quality of the Kromme River declined from 1985 to 1995 (section A), necessitating ever greater amounts of chemicals. At this point there was an

Stellenbosch University http://scholar.sun.ac.za

abrupt change in the amount of chemicals used and a slower rate of increase from then to 2010 (section B). Chemicals used to treat impoundment water are constantly being improved to decrease running costs. At the Churchill Dam, chemicals have changed over time from 'Flocotan' (an aluminium sulphate) to 'powder allum' (a different form of aluminium sulphate), and finally to a liquid allum called PAC 'Poly Aluminium chloride'. This latest shift to PAC, a far cheaper and easier chemical to use, coincided with the shift seen in the graph –demarcated by section A and B. Thus the specific impacts of restoration on water quality cannot be quantified, however it is clear that the need for, and thus the cost of, water treatment has increased overall from 1985-2010.

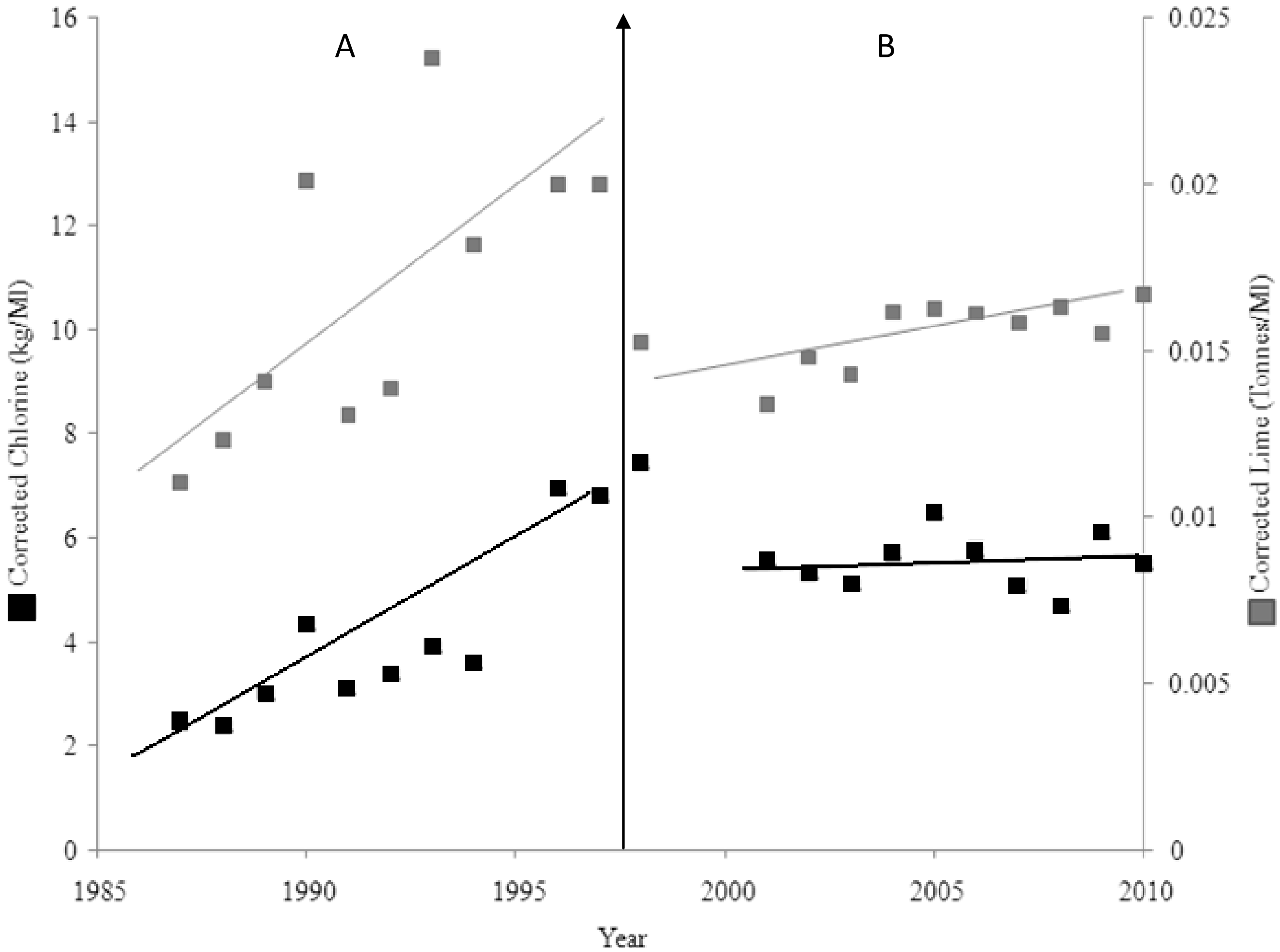


Figure 4.12: Water treatment chemical input (corrected ■ Chlorine and ■ Lime) into the Churchill Dam from 1985-2010.

Stellenbosch University http://scholar.sun.ac.za

Model reliability

A comparison of the cumulative riverflow showed that the different flow estimates are actually quite similar (Figure 4.13). The close similarity between the flows based on the observed (DWA), modelled (WR90) and post-1980 land-cover scenarios (ACRU) suggests that they are all reasonable estimates of the actual riverflow.

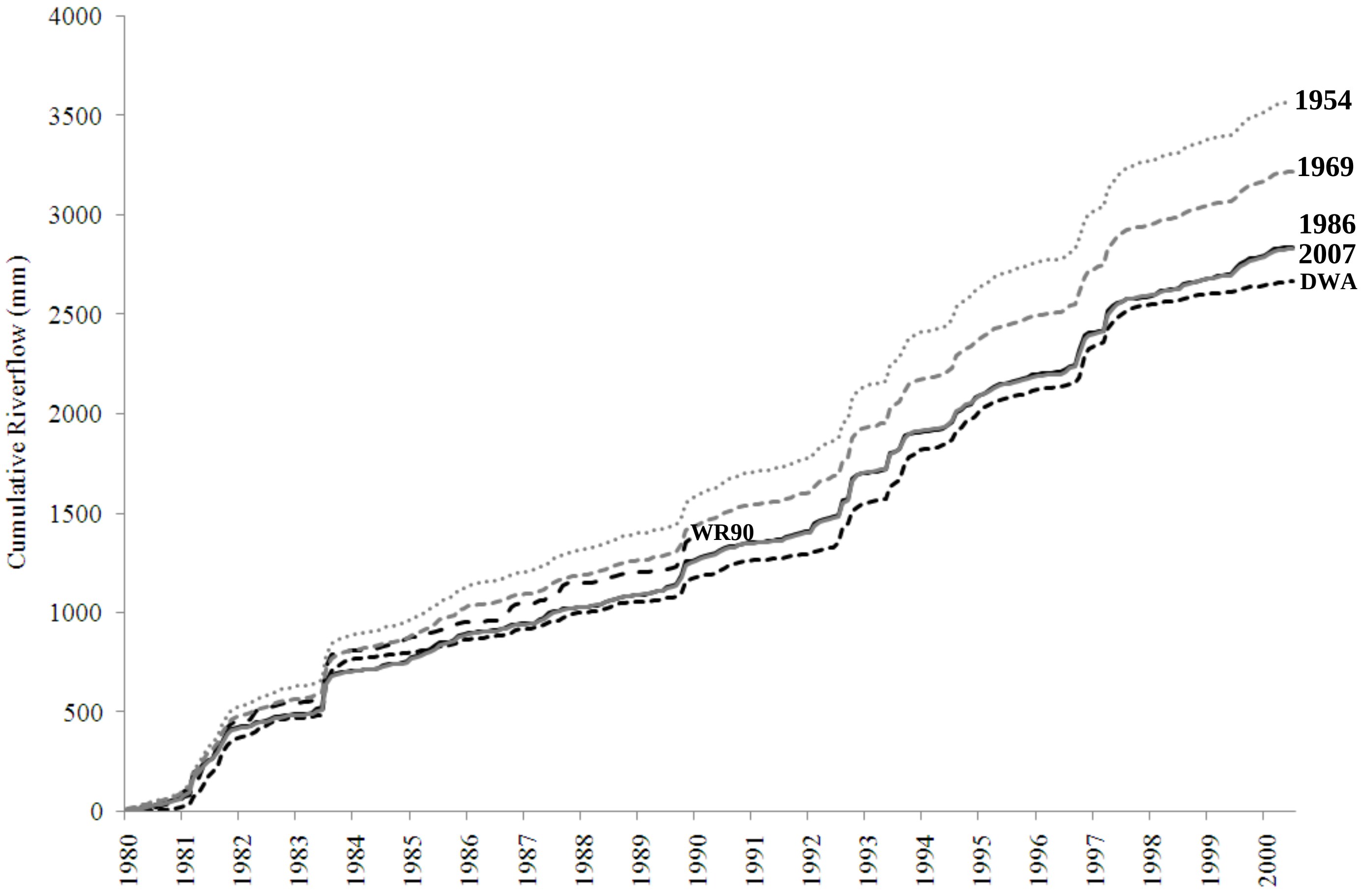


Figure 4.13: Modelled cumulative riverflow from 1980 to 2000 in the upper Kromme River for each of the four different landcover scenarios (1954, 1969, 1986, 2007) and for two independent modelling studies: --- DWA dam recipe calculations, --- WR90 modelled estimates.

Stellenbosch University http://scholar.sun.ac.za

DISCUSSION

Wetland transformation

Wetland transformation is not expected to have had a discernible impact on overall runoff as this will have been masked by much greater changes caused by *A. mearnsii* invasion. However, changes to the wetlands are predicted to have had an impact on baseflow (Begg 1986, McCarthy & Ellery 1998, Tooth et al. 2002, Humphries et al. 2010). When the bulk of the Kromme wetlands were removed, runoff, instead of being captured in wetland sediments, would have left the catchment as riverflow in the wet season, some of which would be stored instead in the Churchill Dam. In a dam, water is subject to high evaporation rates and as a result high volumes of water are lost to the atmosphere (Everson et al. 1998, Everson 1999).

The ACRU model appears to simulate the expected changes well, projecting a marked decrease in baseflow with time. This is due to the decline in the extent of the wetlands by 5.2 km^2 (69.6%) between 1954 (7.54 km^2) and 2007 (2.34 km^2) and the concomitant reduction in catchment storage. This makes a strong case for the restoration of wetlands, as they have the ability to provide low cost water during the dry season. Theoretically, if the wetlands were restored to the extent they occupied in 1969, they would potentially be able to provide an extra 5 mm baseflow per annum during the 3 dry months alone. This would translate into a flow increase of at least 6120 m^3 each year in the dry season. Contrary to these results, a review of 169 wetland studies worldwide, albeit dominated by Northern Hemisphere case studies, found that in most cases wetlands decreased baseflow, with exceptions of floodplain and peatland wetlands where connections to aquifers were strong (Bullock & Acreman 2003). We hypothesize that the latter is the case with the floodplain peatland wetlands of the Kromme River (Haigh et al. 2002).

Wetlands are renowned globally for their role in flood attenuation in a landscape (Kotze & Breen 1994, Kotze et al. 2005, Turpie et al. 2008, Russel 2009). From the time-series analysis of rainfall it is evident that this catchment often experiences long periods of drought, punctuated with periods of heavy rainfall, often accompanied by flooding. The Kromme Catchment is a high energy catchment, and it needs to have a high resilience to be able to withstand the frequent heavy floods. The removal of wetlands has decreased the catchment’s ability to absorb extreme

Stellenbosch University http://scholar.sun.ac.za

rainfall events, causing significant soil erosion (Chapter 3). It is not clear what caused the slight improvement in the catchment's buffering capacity after the 1980s; it may have been a result of the wetland rehabilitation that commenced in the Kromme in the early 2000s, however the gradients of these correlations were too similar to draw any conclusions about restoration. Results from the international review of wetlands corroborate these results, as in most cases wetlands have been shown to reduce flood peaks or delay stormflow (Bullock & Acreman 2003). In African studies, wetlands in Zimbabwe were found to have an insignificant effect on flood magnitude (Bullock 1992), whereas wetlands in West Africa were found to flatten flood peaks (John et al. 1993).

Wetland restoration may have improved water quality in the Kromme. It is evident that the rate of increase in the new chemicals at the Churchill Dam was lower than that of the old chemicals. The question remains as to whether this reflects a slower rate of decline in water quality as a result of the wetland rehabilitation upstream of the dam. Certainly this rehabilitation would have an effect on the sediment load arriving at the dam, but this cannot be causally linked to the water treatment at the dam. It is possible that the change in water treatment may be the result of changes in user water quality requirements rather than the water purification plant managers responding to upstream changes in water quality. However a study done in the USA has shown that wetlands do improve water quality and that a loss of wetlands would increase sediment loads as well as total phosphorus and nitrogen (Wang et al. 2010).

Our results present a compelling case for investing in wetland restoration as an insurance against future extreme rainfall events– especially in the face of uncertainties associated with anthropogenic climate change (Schulze et al. 2005). An increase in temperature of 1.5 °C, a predicted temperature rise for the African continent as a result of climate change, has been modelled to result in a decrease in simulated discharge of about 15% in a study in South Central Ethiopia (Legesse et al. 2003). Climate change could have profound implications for water security in the Nelson Mandela Bay metropolitan hub in the future.

Invasive alien plants (IAPs)

Stellenbosch University http://scholar.sun.ac.za

A. mearnsii is an aggressive invader, predominately invading the river course, which gives it access to water all year round. It is an extremely high water user, recorded as transpiring and intercepting up to 1500 mm per annum in riparian zones in fynbos (Dye & Jarmain 2004). This is approximately 600 mm higher than that of dryland fynbos and about 170 mm more than a restioid wetland in a winter rainfall area similar to the Kromme (Dye & Jarmain 2004, Everson et al. 1998). It is a highly drought-tolerant species with a high level of anatomical plasticity (Crous et al. 2011, Crous et al. 2012). Furthermore *A. mearnsii* shades out the palmiet in the wetlands (Boucher & Withers 2004) as it invades along the floodplain. Once the wetland plants have been displaced, the peat beds are exposed, rapidly dry out and erode away. Since *A. mearnsii* is arguably the main driver in the destruction of the remaining palmiet wetlands, it is likely to be indirectly causing a decrease in the catchment’s ability to absorb extreme rainfall events and the degradation of its water filtering service.

The model predicts a decrease in the flows in the Kromme from 1954 to 2007. Riverflow changes are likely to have been a result of the two biggest land-use changes: invading *A. mearnsii* and the degradation of fynbos on the mountain slopes, which are likely to have caused conflicting changes to riverflow. An increase in the extent of degraded natural vegetation, as a result of too-frequent burning and overgrazing is well established to cause an increase in runoff, which contributes to increased riverflow and therefore yield (Mander et al. 2010). The loss of the palmiet wetlands and their replacement by cultivated lands and erosion should also have decreased evaporation and increased total runoff. The net decrease suggests that the increase in the extent of *A. mearnsii* invasions, and thus its water-use, has exceeded the gains from the extensive area of damaged mountain fynbos and the reduction in the palmiet wetlands. Even if *A. mearnsii* is not completely eradicated, but simply cleared to the extent of the 1954 invasion, the ACRU model predicts that there would be an increase in riverflow of more than 42 mm per annum with a resultant increase in yield of 32610 m^3 per annum. These results compare well with the findings of an international review looking at the impacts of land-cover change from that of low native vegetation (i.e. shrubs) to that of afforestation (i.e. trees) (Bosch & Hewlett 1982). It was found that woody trees, such as pine and eucalyptus, change the riverflow by approximately 40 mm per 10% change in vegetation cover (Bosch & Hewlett 1982).

Stellenbosch University http://scholar.sun.ac.za

South Africa is a chronically water scarce country (Ashton 2002). The Nelson Mandela Bay metropolitan hub is in a water crisis and is seeking to increase its water supply and security of that supply (DWA 2010). The data from this study suggest that restoration of the wetlands in the municipality's main supply catchment, the Kromme River, could increase runoff and help to alleviate the water supply situation. In the Kromme, wetlands currently continue to be destroyed, sacrificing long term societal benefit, for short term private gains. It is during the dry season and droughts that water security is a major problem for both the city and for local farmers, and it is wetlands that provide water during the dry season (Sellars 1981). Denuding/burning the catchment would not increase water supply, as it would not provide water in the dry season; the more variable MAR becomes, the lower the potential yield from the catchment becomes. Many studies have shown temporal variation of riverflow to be an important consideration in water management (e.g. Bruijnzeel 2004, Vogel et al. 2007, Mander et al. 2010).

The model shortcomings and uncertainty estimates

Table 4.4 shows the evaporation output from the Kromme ACRU Model for three vegetation types (HRU's): *P. serratum*, *A. mearnsii* and fynbos. It also displays the results, with MAP and other pertinent information, from other studies done on these vegetation types in South Africa. At first glance it may appear as though the Kromme ACRU Model is underestimating evaporation from these key HRU's (Table 4.4). However, when the MAP from these studies is compared, the Kromme is receiving less than half the MAP than that of the other fynbos research sites, and about 200 mm less than that of grassland research sites. From this, it appears as though the evaporation that ACRU models for these vegetation types are reasonable, and it then follows that riverflow estimates will be defensible. Furthermore the order of magnitude of the evaporation that ACRU outputs for these vegetation types are logical; *A. mearnsii* is using ±200 mm more than that of the indigenous riparian vegetation (*P. serratum*), which in turn is using ±260 mm more than that of the dryland fynbos. The only other major factor that is not taken into account is that of the influence of groundwater (undoubtedly a significant factor in the hydrological dynamics of the Kromme floodplain) as ACRU does not adequately model soil-groundwater interactions.

Stellenbosch University http://scholar.sun.ac.za

Table 4.4: A comparison of the ACRU Model evaporation outputs for key vegetation types (HRU's) from the Upper Kromme (Eastern Cape), with that of measurements done in other studies in South Africa (Dye et al. 2001, Dye & Jarmain 2004, Clulow et al. 2011). All evaporation and rainfall (MAP) values are reported in mm per annum. Provinces: EC (Eastern Cape, WC (Western Cape), and KZN (KwaZulu-Natal).

	Location	**Province**	**Biome**	**MAP**	***P. serratum***	***A. mearnsii***	**Fynbos**
ACRU Output	Kromme River	EC	Fynbos	614	694.6±21.46	899.4±44.66	430.39
Appendix 5	Jonkershoek	WC	Fynbos	1630	1043	-	-
Dye et al. 2001	Jonkershoek	WC	Fynbos	1324	-	1503-	1332
Dye & Jarmain 2004	Jonkershoek	WC	Fynbos	1324	-	1503	600-850
Dye et al. 2001	Gilboa	KZN	Grassland	867	-	1260	-
Dye & Jarmain 2004	Gilboa	KZN	Grassland	867	-	1260	-
Dye & Jarmain 2004	Seven-Oaks	KZN	Grassland	842	-	1223	-
Clulow et al. 2011	Two-Streams	KZN	Grassland	754	-	1164	-

A qualitative assessment of the uncertainty of the model output was undertaken by comparing ACRU simulations to those of DWA and WR2005 (Middleton & Bailey 2008) (Figure 4.13) and to compare evaporative outputs of key HRU's from the ACRU model to measurements done in other studies (Table 4.4). One major shortcoming in this modelling study is that of taking into account soil-groundwater interactions as ACRU does not adequately model this. A second shortcoming in this study was in terms of irrigated agriculture; it appears that dams were drying up and crops not being properly irrigated as a result (crop water-use was lower than expected). This may mean that farmers are extracting water from the Kromme River illegally or the model is over-estimating crop water-use. This would not have been taken into account in the modelling as irrigation amounts were based on estimates from the farmers themselves, as the Department of Water Affairs have no reliable measurements, or even estimates. This lack of information may have confounded the results of this study, as underestimating water-use of crops would have a noticeable impact on riverflow. However at least this underestimation would be consistent for all of the four scenarios modelled in this study, and so the comparison between land-cover scenarios is still reasonably robust, even if absolute values are questionable.

Stellenbosch University http://scholar.sun.ac.za

CONCLUSION

Although the conclusions reached in this study are based primarily on the outputs of a model, we have found them to be consistent with the data and findings of other studies and argue that the results are robust enough to make a strong case that similar changes have occurred in the actual riverflow of the Kromme.

The findings also make a strong case for restoration of the wetlands and removal of *A. mearnsii*. When land-use change and climate change are superimposed on ecosystems that are naturally unstable and highly variable, they react extremely unpredictably and are exceptionally difficult to manage. These systems need to be managed and restored carefully so that some acceptable degree of resilience is recovered such that there is some protection from future climate change and uncertainty.

Stellenbosch University http://scholar.sun.ac.za

REFERENCES

Andreassian, V. 2004. Waters and forests: from historical controversy to scientific debate. *Journal of Hydrology*. **291**: 1-27.

Armstrong, A. 2009. WET-Legal: Wetland rehabilitation and the law in South Africa. WRC Report No. TT 338/09. C. Breen, J. Dini, W. Ellery, S. Mitchell, and M. Uys (Eds). Water Research Commission, Pretoria.

Ashton, P. G. 2002. Avoiding conflicts over Africa's water resources. *Ambio*. **31**(3): 236-242

Begg, G. W. 1986. The wetlands of Natal (Part 1). An overview of their extent role and present status. Report 68. Pietermaritzburg: Natal Town and Regional Planning.

Birkhead, A. L., B. W. Olbrich, C. S. James, and K. H. Rogers. 1997. Developing an integrated approach to predicting the water use of riparian vegetation. Water Research Commission. WRC Report No: 474/1/97.

Bosch, J. M., and J. D. Hewlett. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology*. **55**: 3-23.

Boucher, C. and M. J. Withers. 2004. Notes on the ecology of *Prionium serratum* (palmiet), a Cape river specialist. *Veld & Flora*. **90**(1): 26-28.

Bruijnzeel, L. A. 2004. Hydrological functions of tropical forests: not seeing the soil for the trees? *Agriculture, Ecosystems and Environment*. **104**:185-228.

Bullock, A., and M. Acreman. 2003. The role of wetlands in the hydrological cycle. *Hydrology and Earth System Sciences*. **7**(3): 358-389.

Bullock, A. 1992. The role of dambos in determining river flow regimes in Zimbabwe. *Journal of Hydrology*. **134**: 349-372.

Calder, I. R. 2005. Blue Revolution II: Land use and integrated water resources management. Earthscan, London.

Clulow, A., C. Everson, and M. Gush. 2009. The long-term impact of *Acacia mearnsii* trees on evaporation, streamflow, and ground water resources. WRC Report. CSIR.

Clulow, D., C. S. Everson, M. G. Mengistu, C. Jarmain, G. P. W. Jewitt, J. S. Price, and P. L. Grundling. 2012. Measurement and modelling of evaporation from a coastal wetland in Maputaland, South Africa. *Hydrology and Earth System Science*. **9**: 1741–1782.

Stellenbosch University http://scholar.sun.ac.za

Clulow, A.D., C. S. Everson, and M. B. Gush. 2011. The long-term impact of *Acacia mearnsii* trees on evaporation, streamflow, and ground water resources. Water Research Commission, Pretoria, South Africa. WRC Report: TT 505/11.

Collins, N. B. 2005. Wetlands: the basics and some more. Free State Department of Tourism, Environmental and Economic Affairs. http://www.csir.co.za/rhp/.

Colvin, C, D. C. Le Maitre, I. Saayman, and S. Hughes. 2007. An introduction to aquifer dependent ecosystems in South Africa. WRC Report TT 301/07, Water Research Commission, Pretoria.

Cowan, G. 1995. Wetlands of South Africa. Department of Environmental Affairs and Tourism. Pp. 1-51.

Crous, C. J., S. M. Jacobs and K. J. Esler. 2011. Drought-tolerance of an invasive alien tree, *Acacia mearnsii* and two native competitors in fynbos riparian ecotones. *Biological Invasions*. 14: 567-577.

Crous, C. J., S. M. Jacobs and K. J. Esler. 2012. Wood anatomical traits as a measure of plant responses to water availability: invasive *Acacia mearnsii* De Wild. compared with native tree species in fynbos riparian ecotones, South Africa. *Trees - Structure and Function*. DOI: 10.1007/s00468-012-0726-3.

Department of Water Affairs, South Africa. 2010. Algoa Reconciliation Strategy. Prepared by E van der Berg and Dr MJ Shand of Aurecon South Africa (Pty) Ltd, as part of the Water Reconciliation Strategy Study for the Algoa Water Supply Area. DWA Report No. WMA 15/M00/00/1409/04.

Driver A., K. J. Sink, J. N. Nel, S. Holness, L. Van Niekerk, F. Daniels, Z. Jonas, P. A. Majiedt, L. Harris, and K. Maze. 2012. *National Biodiversity Assessment 2011: An assessment of South Africa's biodiversity and ecosystems. Synthesis Report*. South African National Biodiversity Institute and Department of Environmental Affairs, Pretoria.

Dye, P. J. 1996. Climate, forest and streamflow relationships in South African afforested catchments. Commonwealth Forestry Reviews. **75**(1): 31-38.

Dye P.J., Moses G., Vilakazi P., Ndlela R., Royappen M. 2001. Comparative water use of wattle thickets and indigenous plant communities at riparian sites in the Western Cape and KwaZulu-Natal. Water SA 27, 529–538.

Stellenbosch University http://scholar.sun.ac.za

Dye P. J., and A. G. Poulter A.G. 1995. Field demonstrations of the effect on streamflow of clearing invasive pine and wattles trees from a riparian zone. *South African Forestry Journal*. **173**: 27–30.

Dye, P., and C. Jarmain. 2004. Water use by black wattle (*Acacia mearnsii*): implications for the link between removal of invading trees and catchment streamflow response. *South African Journal of Science***. 100:** 40-44.

Ellery, W. N., M. Grenfell, S. Grenfell, D. C. Kotze, T. S. McCarthy, S. Tooth, P. L. Grundling, H. Beckedahl. D. Le Maitre, L. Ramsay. 2009. WET-Origins: Controls on the distribution and dynamics of wetlands in South Africa. WRC Report No. TT 334/09. C. Breen, J. Dini, W. Ellery, S. Mitchell, and M. Uys (Eds). Water Research Commission, Pretoria.

Everson, C. S. 1999. Evaporation from the Orange River: Quantifying open water resources. Water Research Commission, Pretoria, South Africa. WRC Report No 683/1/99.

Everson, C. S., G. L. Molefe, and T. M. Everson. 1998. Monitoring and modelling components of the water balance in a grassland catchment in the summer rainfall area of South Africa. Water Research Commission, Pretoria, South Africa. WRC Report No. 493/1/98.

Everson, C. S., C. Burger, B. W. Olbrich, and M. B. Gush. 2001. Verification of estimates of water use from riverine vegetation on the Sabie river in the Kruger National park. Water Research Commission, Pretoria, South Africa. WRC Report No 877/1/01.

Everson C.S., Gush, M.B., Moodley, M., Jarmain, C., Govender, M., Dye, P. 2007. Effective management of the riparian zone vegetation to significantly reduce the cost of catchment management and enable greater productivity of land resources. Report no. 1284/1/07, Water Research Commission, Pretoria, South Africa.

Finlayson, M. C., and R. D'Cruz. 2005. Inland Water Systems. Chapter 20, Millennium Ecosystem Assessment. Pp 551-583.

Forsyth, G. G., D. B. Versfeld, R. A. Chapman, and B. K. Fowles. 1997. The hydrological implications of Afforestation in the North-Eastern Cape: a survey of resources and assessment of the impacts of land-use change. Water Research Commission, Pretoria, South Africa. WRC Report No 511/1/97.

Görgens, A.H.M, Aurecon, Cape Town, pers. comm. 2010

Stellenbosch University http://scholar.sun.ac.za

Gorham, E. 1995. The biogeochemistry of northern peatlands and its possible responses to global warming. In: Biotic feedbacks in the global climate systems. Woodwell, G. M., and F. T. Mackenzie (Eds). New York: Oxford University Press. Pp. 169-187.

Gray, R. P. 2011. Techniques for assessing the impacts of wetlands on hydrological responses under varying climatic conditions. Unpublished MSc Dissertation, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal.

Grundling, P. L. 2004. Peatlands on the brink of the final phase in the extinction of a unique wetland type in southern Africa. Working for Wetlands Programme, National Botanical Institute, Pretoria. IMGG Scientific Symposium, September 2004. International Mire Conservation Group. Pp. 5.

Haigh, E. A., P. L. Grundling, and P. M. Illgner. 2002. Report on the scoping study on the status of the Kromme River peatland complex and recommended mitigatory measures. Department of Water Affairs and Forestry Project X832633.

Hargreaves, G. H., and Z. A. Samani. 1985. Reference crop evapotranspiration from temperature. *Transactions of the American Society for Agriculture and Engineering*. **1**: 96–99.

Hobbs, R. J. 2004. The Working for Water programme in South Africa: the science behind the success. *Diversity and Distributions*. **10**: 501-503.

Horan, M. pers comm. 2012. BEEH, University of KwaZulu Natal, Pietermaritzburg.

House, J. and V. Brovkin. 2005. Climate and Air Quality. Chapter 13, Millennium Ecosystem Assessment. Pp 355-390.

Hughes, D. A. 2004. Incorporating ground water recharge and discharge functions into an existing monthly rainfall-runoff model. *Hydrological Sciences Journal*. **2004** (2): 297-311.

Humphries, M. S., A. Kindness, W. N. Ellery, and J. C. Hughs. 2010. Sediment geochemistry, mineral precipitation and clay neoformation on the Mkuze River floodplain, South Africa. *Geoderma*. 325-334.

Jarmain, C. pers. comm. 2011

Jewitt, G. P. W., J. A. Garratt, I. R. Calder, and L. Fuller. 2004. Water resources planning and modelling tools for the assessment of land use change in the Luvuvhu Catchment, South Africa. *Physics and Chemistry of the Earth*. **29:** 1233–1241.

Stellenbosch University http://scholar.sun.ac.za

Jewitt, G. P. W., and R. E. Schulze. 1999. Verification of the ACRU model for forest hydrology applications. *Water SA*. 25(4): 483-489.

John, D.M., C. Leveque, and L. E. Newton. 1993. Chapter on West Africa. In: *Wetlands of the World I: Inventory, ecology and management*. D.F. Whigham, D. Dykyjova and S. Hejny (Eds). Kluwer, Dordrecht, The Netherlands.

Kondolf, G. M. 2011. Mediterranean-climate episodic channels: long periods of boredom, brief moments of terror. The International Mediterranean Ecosystems Conference MEDECOS XII. 6-9 September 2011.

Kotze, D. C., and C. M. Breen. 1994. Agricultural land-use impacts on wetland functional values. Water Research Commission, Pretoria, South Africa. WRC Report No 501/3/94.

Kotze, D. C., G. C. Marneweck, A. L. Batchelor, D. S. Lindley, and Collins, N. B. 2005. WET-EcoServices. A rapid assessment procedure for describing wetland benefits. Mondi Wetlands Project.

Le Maitre, D. C., and A. Görgens. 2001. Potential impacts of invasive alien plants on reservoir yields in South Africa. Tenth South African National Hydrology Symposium: 26-28 September 2001.

Le Maitre, D. C., B. W. van Wilgen, R. A. Chapman, and D. H. McKelly. 1996. Invasive plants and water resources in the Western Cape Province, South Africa: modelling the consequences of a lack of management. *Journal of Applied Ecology*. **33**: 161-172.

Le Maitre, D. C., D. F. Scott, and C. Colvin. 1999. A review of information on interactions between vegetation and groundwater. *Water SA*. **25**(2): 137-152.

Le Maitre, D. C., D. B. Versfeld and R. A. Chapman. 2000. The impact of invading alien plants on surface water resources in South Africa: A preliminary assessment. *Water SA* **26** (3): 397-408. http:// www.wrc.org.za/archives/watersa%20archive/2000/July/1220.pdf

Le Maitre, D. C., B. W. Van Wilgen, C. M. Gelderblom, C. Bailey, R. A. Chapman, and J. A. Nel. 2002. Invasive alien trees and water resources in South Africa: case studies of the costs and benefits of management. *Forest Ecology and Management.* **160**(3): 143-159.

Legesse, D. C., T. A. Abiye, C. Vallet-Coulomb, H. Abate. 2010. Streamflow sensitivity to climate and land-cover changes: Meki River, Ethiopia. *Hydrology and Earth System Sciences*. **14**: 2277-2287.

Stellenbosch University http://scholar.sun.ac.za

Legesse, D., C. Vallet-Coulomb, F. Gasse. 2003. Hydrological response of a catchment to climate and land use changes in Tropical Africa: case study South Central Ethiopia. *Journal of Hydrology*. **275**: 67-85.

Lewis, C. A. 2008. Geomorphology of the Eastern Cape, South Africa. Second Edition. NISC, Grahamstown. Pp 21-28.

Lynch, S. D. 2003. Development of a raster database of annual, monthly and daily rainfall for Southern Africa. Water Research Commission, Pretoria, South Africa. WRC Report 1156/1/03. Pp 78.

Mander, M., J. Blignaut, M. Van Niekerk, R. Cowling, M. Horan, D. Knoesen, A. Mills, M. Powell, and R. Schulze. 2010. Baviaanskloof-Tsitsikamma Payments for Ecosystem Services: A feasibility assessment.

McCarthy, T. S. and W. N. Ellery. 1998. The Okavango Delta. *Transactions of the Royal Society of South Africa*. **53**: 157-182.

McConnachie, M. M., R. M. Cowling, B. W. van Wilgen, D. A. McConnachie. 2012. Evaluating the cost-effectiveness of invasive alien plant clearing: a case study from South Africa. *Biological Conservation*. In Press.

Middleton, B. J. and A. K. Bailey. 2008. Water resources of South Africa, 2005 study (WR2005). WRC Report Number TT 380/08.

Midgley, D. C., W. V. Pitman, and B. J. Middleton. 1994. Surface Water Resources of South Africa 1990 Volume III: Orange-Namaqualand. Report 1990 298/3.1/94. Water Research Commission.

Millennium Ecosystem Assessment. 2005. Ecosystems and well-being: Wetlands and water Synthesis. World Resources Institute, Washington, DC.

Moser, M., P. Crowford, and F. Scott. 1996. A global review of wetland loss degradation. In: Papers, Technical Session B. Vol. 10/12B, Proceedings of the 6th Meeting of the Conference of Contracting Parties, Brisbane, Australia, 19-27 March 1996. Ramsar Convention Bureau, Gland, Switzerland. Pp 21-31.

Nel J. L., and A. Driver. 2012. South African National Biodiversity Assessment 2011: Technical Report. Volume 2: Freshwater Component. CSIR Report Number CSIR/NRE/ECO/IR/2012/0022/A. Council for Scientific and Industrial Research, Stellenbosch.

Stellenbosch University http://scholar.sun.ac.za

Nel, J. L., D. J. Roux, G. Maree, C. J. Kleynhans, J. Moolman, B. Reyers, M. Rouget, and R. M. Cowling. 2007. Rivers in peril inside and outside protected areas: a systematic approach to conservation assessment of river ecosystems. *Biodiversity Research*. **13**: 341-352.

Nelson, G. C. 2005. Drivers of Ecosystem Change: Summary Chapter. Chapter 3, Millennium Ecosystem Assessment. Pp 73-76.

Prinsloo, F. W., and D. F. Scott. 1999. Streamflow responses to the clearing of alien invasive trees from riparian zones at three sites in the Western Cape Province. *Southern African Forestry Journal*. **185**: 1-7.

Raymer, D. 2008. *Streams of Life*. Published by David Raymer, South Africa.

Reyers, B., P. J. O'Farrell, R. M. Cowling, B. N. Egoh, D. C. Le Maitre, and J. H. J. Vlok. 2009. Ecosystem services, land-cover change, and stakeholders: finding a sustainable foothold for a semi-arid biodiversity hotspot. *Ecology and Society*. **14**(1): 38-61.

Roets, W., Y. Xu, L. Raitt, and L. Bredonck. 2008. Groundwater discharges to aquatic ecosystems associated with the Table Mountain Group (TMG) aquifer: A conceptual model. *Water SA*. **34**: 77-88.

Rogers, K. H. 1997. Freshwater wetlands. In: Vegetation of Southern Africa. R. M. Cowling, D. M. Richardson, and S. M. Pierce (Eds). Cambridge University Press.

Roux, D., J. Nel, H. MacKay, and A. Driver. 2006. Policy objectives for conserving freshwater ecosystems: how many rivers, which ones, and what level of protection are required. WISA 2006 Biannual Conference and Exhibition. http://hdl.handle.net.10204/1206

Rowntree, K. 1991. An assessment of the potential impact of alien invasive vegetation on the geomorphology of river channels in South Africa. *South African Journal of Aquatic Science*. **17** (1/2): 28-43.

Russel, W. B. 2009. WET-RehabMethods: National guidelines and methods for wetland rehabilitation. WRC Report No. 341/09. C. Breen, J. Dini, W. Ellery, S. Mitchell, and M. Uys (Eds). Water Research Commission, Pretoria.

Schulze, R. E. 1995. Hydrology and Agrohydrology: A Text to Accompany the *ACRU* 3.00 Agrohydrological Modelling System. Water Research Commission, South Africa. Pp 552.

Schulze, R. E. 2000. Modelling hydrological responses to land use and climate change: a southern African Perspective. *Ambio: Journal of the Human Environment*. 29: 12–22.

Stellenbosch University http://scholar.sun.ac.za

Schulze, R. E., Lumsden, T. G., Horan, M. J. C., Warburton, M. L., and Maharaj, M. 2005. An assessment of impacts of climate change on agrohydrological responses over Southern Africa, in: Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation, edited by: Schulze, R. E., Water Research Commission, South Africa, Report: 1430/1/05, 141–189.

Schulze, R. E., Maharaj, M., Warburton, M. L., Gers, C. J., Horan, M. J. C., Kunz, R. P., and Clark, D. J. 2008. Electronic data accompanying the South African Atlas of Climatology and Agrohydrology, Water Research Commission, South Africa, Report: 1489/1/08.

Scott, D. F., and R. E. Smith. 1997. Preliminary empirical models to predict reductions in total and low flows resulting from afforestation. *Water SA*. **23**: 135–140.

Scott, D. F., and W. Lesch. 1997. Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, Mpumalanga province. *South African Journal of Hydrology*. **199**: 360-377.

Scott, D. F. 1999. Managing riparian zone vegetation to sustain streamflow: results of paired catchment experiments in South Africa. *Canadian Journal of Forestry Research*. **29**: 1149-1157.

Scott, D. F., D. C. Le Maitre, and D. H. K. Fairbanks. 1998. Forestry and streamflow reductions in South Africa. A reference system for assessing extent and distribution. *Water SA*. **24**: 187-199.

Scott, D. F., F. W. Prinsloo, G. Moses, M. Mehlomakulu, and A. D. A. Simmers. 2000. A re-analysis of the South African catchment Afforestation experimental data. Water Research Commission, Pretoria, South Africa. WRC Report No: 810/1/00.

Scott, D. F., L. A. Bruijnzeel, R. A. Vertessy, I. R. Calder. 2004. Impacts of Forest Plantations on Streamflow. *Forest Hydrology*. **272**: 1-11.

Sellars, C. D. 1981. A floodplain storage model used to determine evaporation losses in the Upper Yobe River, Northern Nigeria. Journal of Hydrology. 52: 257-268.

Simonit, S. and C. Perrings. 2011. Sustainability and the value of the ‘regulating’ services: Wetlands and water quality in Lake Victoria. *Ecological Economics* **70**: 1189–1199.

Skead, C. J. (compiler). 2009. Historical plant incidence in southern Africa. *Strelitzia 24*. South African National Biodiversity Institute, Pretoria, South Africa.

Stellenbosch University http://scholar.sun.ac.za

Smithers, J. C. and Schulze, R. E. 2004. *ACRU* Agrohydrological Modelling System: User Manual Version 4.00, School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal, South Africa.

Thompson, J.R., and G. E. Hollis. 1995. Hydrological modelling and the sustainable development of the Hadejia-Nguru wetlands, Nigeria. *Hydrological Science Journal*. **40:** 97-108.

Toerien, D. K., and R. S. Hill. 1989. The geology of the Port Elizabeth areas, Explanation of Sheet 3324. Geological Survey South Africa. Pp 35.

Tooth, S., T. S. McCarthy, P. J. Hancox, D. Brandt, K. Buckley, E. Nortje, S. McQuade. 2002. The geomorphology of the Nyl River and floodplain in the semi-arid Northern Province, South Africa. *South African Geographical Journal*. 84:226-237.

Turpie, J.K., C, Marais, and J. N. Blignaut. 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**: 788-798.

van Lill, W. S., F. J. Kruger, and D. B. Van Wyk. 1980. The effect of afforestation with *Eucalyptus grandis Hill Ex Maiden* and *Pinus patula Schlecht. Et Cham.* on streamflow from experimental catchments at Mokobulaan, Transvaal. *Journal of Hydrology*. **48**: 107-118.

van Wilgen, B. W., D. C. Le Maitre, A. Wannenburgh, I. M. Kotze, L. van den Berg, L. Henderson. 2012. An assessment of the effectiveness of a large, national-scale invasive alien plant control strategy in South Africa. *Biological Conservation*. **148**: 28-38.

van Wyk, D. B. 1986. Some effects of afforestation on streamflow in the Western Cape Province, South Africa. *Water SA*. **13**(1): 31-36.

Versfeld, D. B. 1994. The forest industry and management for water conservation. Division of Forest Science and Technology, CSIR.

Vertessy R. A., L. Zhang, and W. R. Dawes. 2003. Plantations, river flows and river salinity. *Australian Forestry*. **66**: 55-61.

Vlok, J. H. J., D. I. W. Euston-Brown, and T. Wolf. 2008. A vegetation map for the Garden Route Initiative. Unpublished 1:50 000 maps and report supported by CAPE FSP task team.

Stellenbosch University http://scholar.sun.ac.za

Vogel, C., S. C. Moser, R. E. Kasperson, and G. D. Dabelko. 2007. Linking vulnerability, adaptation, and resilience science to practice: Pathways, players, and partnerships. *Global Environmental Change*. **17**: 349–364.

Vörösmarty, C. J., C. Lévêque, and C. Revenga. 2005. Fresh Water. Chapter 7, Millennium Ecosystem Assessment. Pp 165-207.

Wang, X., S. Shang, Z. Qu, T. Liu, A. M. Melesse, W. Yang. 2010. Simulated wetland conservation-restoration effects on water quantity and quality at watershed scale. *Journal of Environmental Management*. **91**: 1511-1525.

Warburton, R. E. Schulze, and G. P. W. Jewitt. 2010. Confirmation of *ACRU* model results for applications in land use and climate change studies. *Hydrology and Earth System Science*. **14**: 2399–2414.

Warburton, R. E. Schulze, and G. P. W. Jewitt. 2012. Hydrological impacts of land use change in three diverse South African catchments. *Journal of Hydrology*. **414-415**:118-135.

Wolski, A. 2002. Hydrological processes in the Okavango wetland, Botswana. *Proceedings of EGS.* Nice, April 2002.

Zedler, J. B., and S. Kercher. 2005. Wetland Resources: Status, Trends, Ecosystem Services, and Restorability. *Annual Review of Environmental Resources*. **30**: 39-74.

Zhang, L., W. R. Dawes, and G. R Walker. 2001. Response of mean annual evapotranspiration to vegetation changes at catchment scale. *Water Resources Research*. **37**(3): 701-708.

Stellenbosch University http://scholar.sun.ac.za

CHAPTER 5

Does palmiet (*Prionium serratum*) use water conservatively?

Rebelo, A.J. [1]*, Jarmain, C., Le Maitre, D. L. [2], Esler, K.J. [1, 3] and R. M. Cowling [4]

[1] Department of Conservation Ecology and Entomology, Stellenbosch University, Stellenbosch, South Africa
[2] Council for Scientific and Industrial Research (CSIR), Stellenbosch, South Africa
[3] Centre for Invasion Biology (C.I.B), Stellenbosch, South Africa
[4] Restoration Research Group, Department of Botany, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa

*Author for correspondence
E-mail: ARebelo@sun.ac.za
Tel: +2779 499 7235

Palmiet, *Prionium serratum*, is a valuable wetland plant which occurs mostly in the Fynbos Biome, in the southern and south-western part of South Africa. It is generally perceived as undesirable by South African riparian landowners, clogging rivers and impeding riverflow. So it is often removed and replaced by agriculture. Very little is known about this important wetland plant. This study investigated its water relations, by measuring stomatal conductance. *P. serratum* has a lower stomatal conductance range than that of non-riparian fynbos vegetation, which is counter-intuitive given that its evaporation is not water-limited. We conclude that although the water-use of *P. serratum* is a cost that needs to be considered in comparing its benefits with that of cropland, the ecosystem goods and services that *P. serratum* wetlands have been shown to provide far outweigh the short-term financial gains of cropland.

Keywords: *Prionium serratum*, palmiet, stomata, evaporation, stomatal conductance, water-use.

Stellenbosch University http://scholar.sun.ac.za

INTRODUCTION

Palmiet (*Prionium serratum*, Prioniaceae) is a common and prominent riparian wetland plant, occurring in river floodplains and along river fringes in the southern and south-western part of South Africa (Boucher & Withers 2004). It is perceived by many riparian landowners as a high water-user causing blockages in rivers, and is therefore often removed so that the floodplain sediments can be cultivated or converted into pasture. However, the loss of *P. serratum* makes these lands vulnerable to erosion during floods, destabilizing and modifying river systems and further degrading the wetlands (Chapter 4, Boucher & Withers 2004). This chapter investigates the water-use of *P. serratum*, specifically the seasonal and annual patterns in stomatal conductance and its response to key drivers.

P. serratum is widely distributed in the acid waters of wetlands in the Fynbos Biome, from the Gifberg to Port Elizabeth, with outliers in the Eastern Cape and southern KwaZulu-Natal (Rogers 1997, Boucher & Withers 2004). *Prionium* is a monotypic genus, recently moved from the family Juncaceae to Prionaceae (Munro & Linder 1997). *P. serratum* grows in dense stands of what appear to be separate plants but are often simply individual ramets in large clones (Boucher & Withers 2004). These wetlands may be underlain by a layer of peat and accumulated sediments, built up over thousands of years (Haigh et al. 2002, Grundling 2004). It grows throughout the year, with flowering in spring and summer and fruit appearing in March (Boucher & Withers 2004). It is completely intolerant of saline water and full shade (Boucher & Withers 2004). *P. serratum* resprouts after fires but can be killed by fire where shading by IAPs has caused it to grow long stems in search of full sunlight.

Soil water availability is a major factor limiting to plant growth in most of South Africa (Dye et al. 2008). Like other Mediterranean vegetation, fynbos has conservative water-use with relatively low stomatal conductances and photosynthetic capacities (von Willert et al. 1989, Mooney et al. 1983). However, riparian plants with permanent access to water in the root zone have much higher evaporation rates than non-riparian counterparts (Everson et al. 1998, Scott 1999, Dye et al. 2001, Everson et al. 2007, Everson et al. 2009, Clulow 2011). The limited research conducted on South African wetlands has shown that these habitats are generally high

Stellenbosch University http://scholar.sun.ac.za

water-users as a result of the high evaporation rates of wetland plants such as reeds (*Phragmites mauritianus*) (Wilson & Dincer 1976, Seyhan et al. 1983, Meigh 1995, Birkhead et al. 1997, Everson et al. 2001, Birkhead et al. 2007, Dye et al. 2008, Clulow et al. 2012). Other important factors affecting annual water-use are the proportion of the year that leaves are maintained, the aerodynamic resistance of the canopy (Dye et al. 2008), and the topographic aspect (Everson et al. 1998).

This chapter reports on measurements of the stomatal conductance of *P. serratum* using porometry and climatic factors which are known to control stomatal conductances and, thus, transpiration rates. The results are compared with the stomatal conductances of other fynbos plant species. Many methods have been developed to measure the water-use of different plant species at the leaf, plant, and ecosystem scale. Scaling up from leaf scale (stomatal conductance) to canopy scale is very difficult and can lead to substantial errors; so it is not attempted in this study (Jarvis & McNaughton 1986, Pearcy et al. 1989). Furthermore, it is important to consider that all evaporation/plant water-use measurements involve some estimation, and all are subject to error.

It is widely accepted that restoring wetlands is beneficial in terms of habitat provision, sediment stabilisation and accretion, which create storage capacity for water and increase the ability of the floodplain to absorb floods and retain groundwater to sustain dry season flows (Begg 1986, Kotze & Breen 1994, McCarthy & Ellery 1998, Tooth et al. 2002, Bullock & Acreman 2003, Kotze et al. 2005, Turpie et al. 2008, Russel 2009, Humphries et al. 2010). However the high evaporation rates of wetland plants, such as *P. serratum*, may reduce water availability and the cost of such losses needs to be taken into consideration when evaluating restoration options.

The aim of this study was investigate the water-use of *P. serratum* and seasonal/spatial variation of its water-use. It was initially hoped that this study would provide an estimate of annual water-use of *P. serratum* for the hydrological modelling in Chapter 4. However it quickly became apparent that the errors involved in the scaling-up process, from stomatal conductance to transpiration, were too great for results to be robust enough to use (Pearcy et a. 1989).

Stellenbosch University http://scholar.sun.ac.za

METHODS

Study sites

We located, as a study site, a palmiet wetland in the Jonkershoek valley in the Western Cape Province of South Africa (33°58'38" S, 18°56'48" E) (Figure 5.1). The area receives a mean annual precipitation (MAP) of ± 1427 mm (Scott 1999). The catchment is protected as part of a nature reserve; however the adjacent slopes have been used for pine plantation forestry for decades. This wetland was used to obtain field-based measurements of water-use from *P. serratum*.

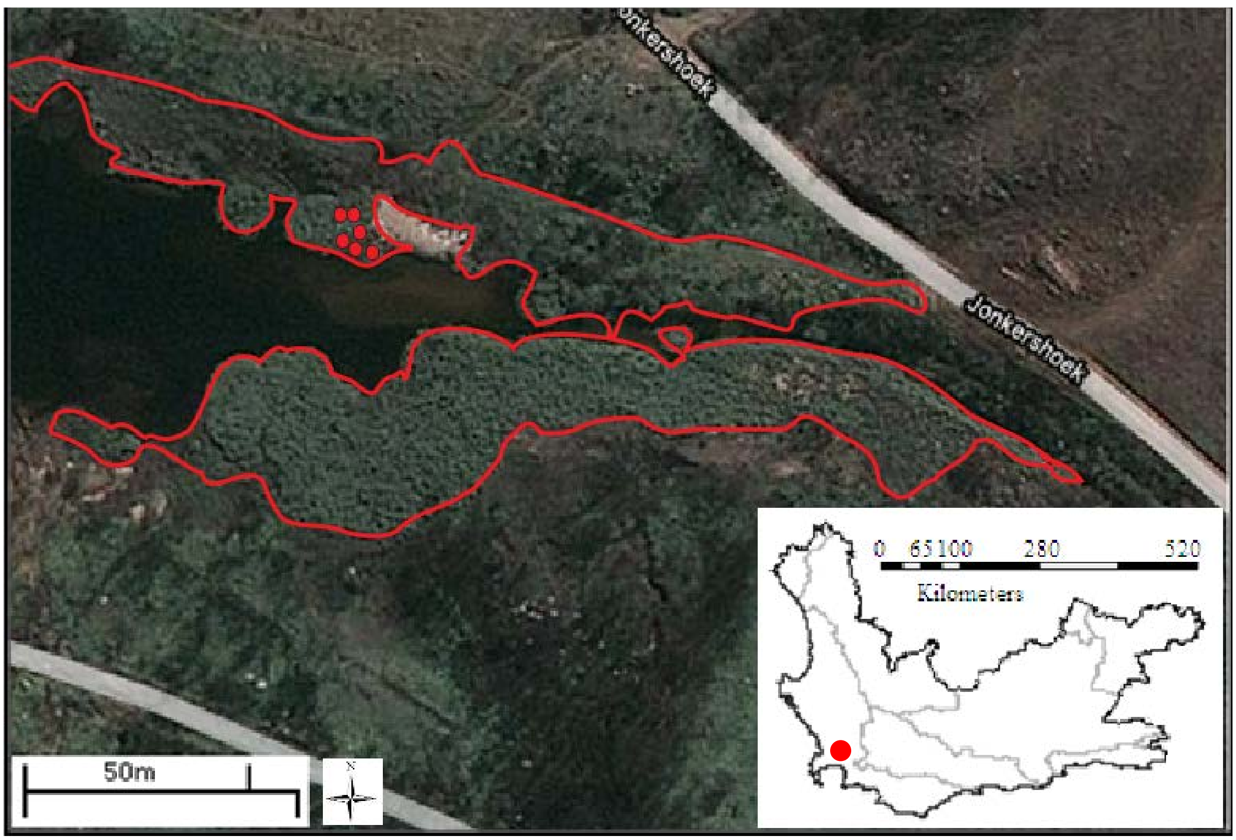


Figure 5.1: The location of the study palmiet wetland in a satellite image of Jonkershoek in the Western Cape (inset). The extent of the palmiet wetlands are delineated in red, and the approximate location of the 6 study plants are marked.

Stellenbosch University http://scholar.sun.ac.za

Leaf Anatomy

An epidermal peel was done for the adaxial and abaxial surface of a *P. serratum* leaf and examined under a light microscope at 4x, 10x and 40x magnifications. Stomata were counted on both surfaces. A cross section through a leaf of *P. serratum* was made, examined and photographed at 4x, 10x and 40x magnifications.

Porometer measurements of stomatal conductance

The stomatal conductance of *P. serratum* ($m^2.s.mol^{-1}$) was measured on 6 plants at Jonkershoek wetland over three different seasons: in spring of 2010 (November), summer of 2011 (February/March) and winter of 2011 (June). Sampling took place over three days in each season. Measurements were taken hourly starting as early as 07h00 and as late as 19h00 depending on the duration of full sunlight in each season. Measurements were made using a porometer for Stomatal Conductance Measurements (SC1 Leaf Porometer -Decagon Devices 2012). Leaf temperature was also recorded using the porometer. From the 6 study plants, 3 were chosen which were situated away from the water such that their roots would not be constantly inundated. The other three were chosen along the edge of the water such that their roots would constantly be submerged in water. On each plant, two leaves were sampled, one from the bottom of the plant (older) and one from the top of the plant (younger). Both the top and bottom surface of each leaf was measured and whether it was positioned such that it was in the sun or shade was recorded. Preliminary measurements indicated that leaf age and whether the leaf was positioned on the north/south/east or west of the plant did not significantly affect stomatal conductances. Hence leaf age and aspect where not taken into consideration in the actual fieldwork.

Measurements could only be taken once there was sufficient solar radiation to initiate photosynthesis and for the stomata to open. Winter measurements were extremely difficult to take, especially early in the morning, and were not possible during wet weather. As a result data were only obtained for two days in winter. Stomatal conductance measurements were only accurate to within 10% (Decagon Devices 2012).

Stellenbosch University http://scholar.sun.ac.za

Since it is difficult to scale stomatal conductance up to plant or stand-level, it was therefore not possible to compare our data with evaporation data for other species or systems (Pearcy et al. 1989). Hence we compared our data with stomatal conductance data collected for other fynbos species, as no stomatal conductance data exist for South African wetland plants, in order to determine the relative levels of water-use by *P. serratum*.

Statistical Analyses

STATISTICA Version 10 was used to check all data for normality. All the data were found to be normally distributed. A mixed model repeated measures analysis of variance (ANOVA) was done to determine the significance of the difference between stomatal conductance measurements for specific variables at different times of day and in different seasons. A 'Classification And Regression Tree' (CART) Analysis (Breiman et al. 1984), was used to determine which climatic variables affected stomatal conductance.

Leaf area index

The leaf area index (LAI) of a plant is a measure of the area of leaves of the plant per unit of ground area. It is often used to assess biomass, canopy cover and to make transpiration or productivity estimates (Jarvis & Leverenz 1983, Decagon Devices 2010). The LAI of *P. serratum* was measured on a cloudy day in autumn, using an ACCUPAR LP-80 Leaf Area Index Meter (Decagon Devices 2010).

Stellenbosch University http://scholar.sun.ac.za

RESULTS

The results are divided into two sections: the first is on *P. serratum* anatomy and the second on *P. serratum* water-use characteristics.

Anatomy of palmiet stomata

The number of stomata does not differ between adaxial and abaxial leaf surfaces. From an epidermal peel of both the abaxial and adaxial surface of *P. serratum* leaves, stomata do not appear to be sunken (Figure 5.2). Stomatal guard cells are easily made out at a magnification of 10x.

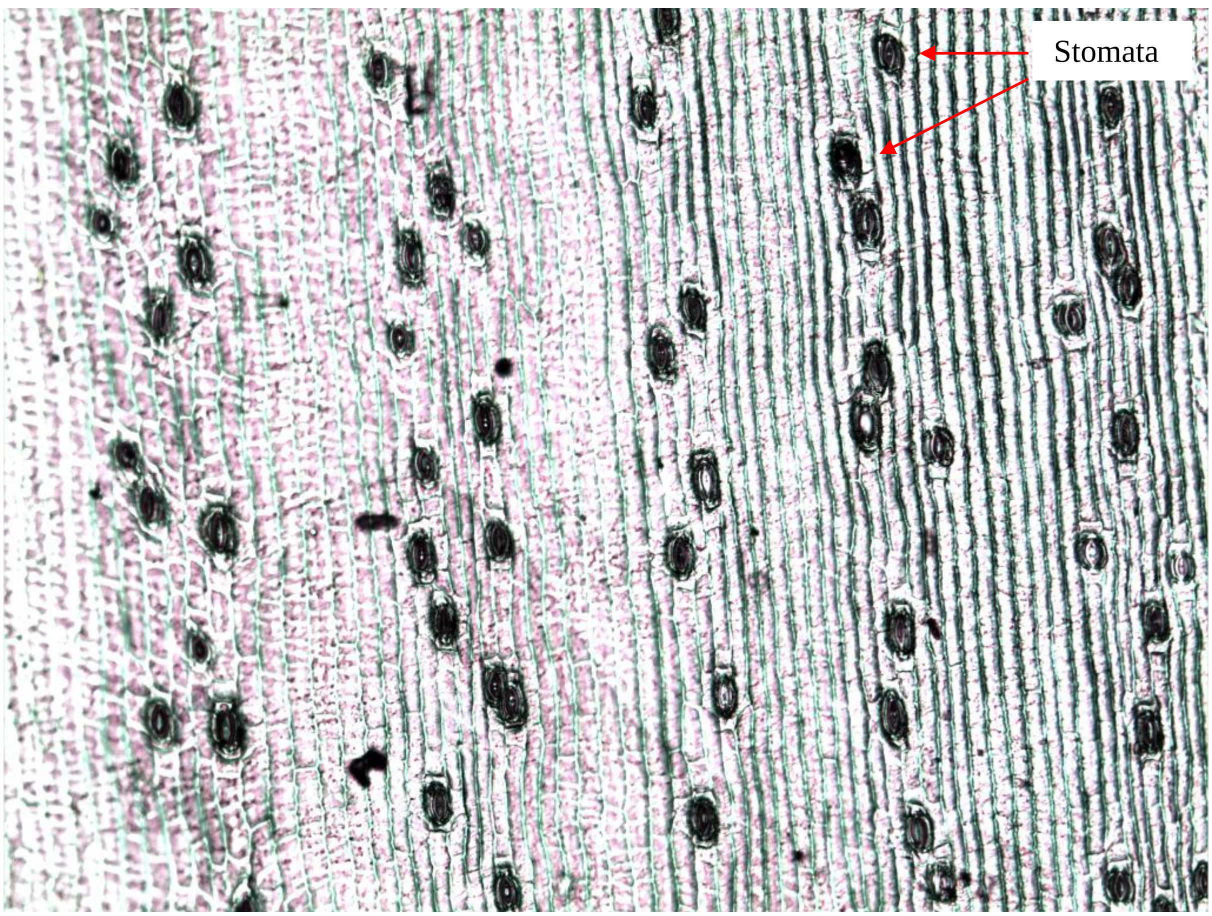


Figure 5.2: Epidermal peel of adaxial surface palmiet (*Prionium serratum*) leaf (10x)

Stellenbosch University http://scholar.sun.ac.za

A more detailed cross section through a *P. serratum* leaf shows that it has large stomatal cavities and from these sections it appears to have sunken stomata, despite the contradictory evidence from the epidermal peels (Figure 5.3 & 5.4). There is no obvious explanation as to why *P. serratum* should have sunken stomata, as it is a wetland not a desert plant. One explanation may be as an adaptation to the intermittent dry periods that wetlands periodically experience.

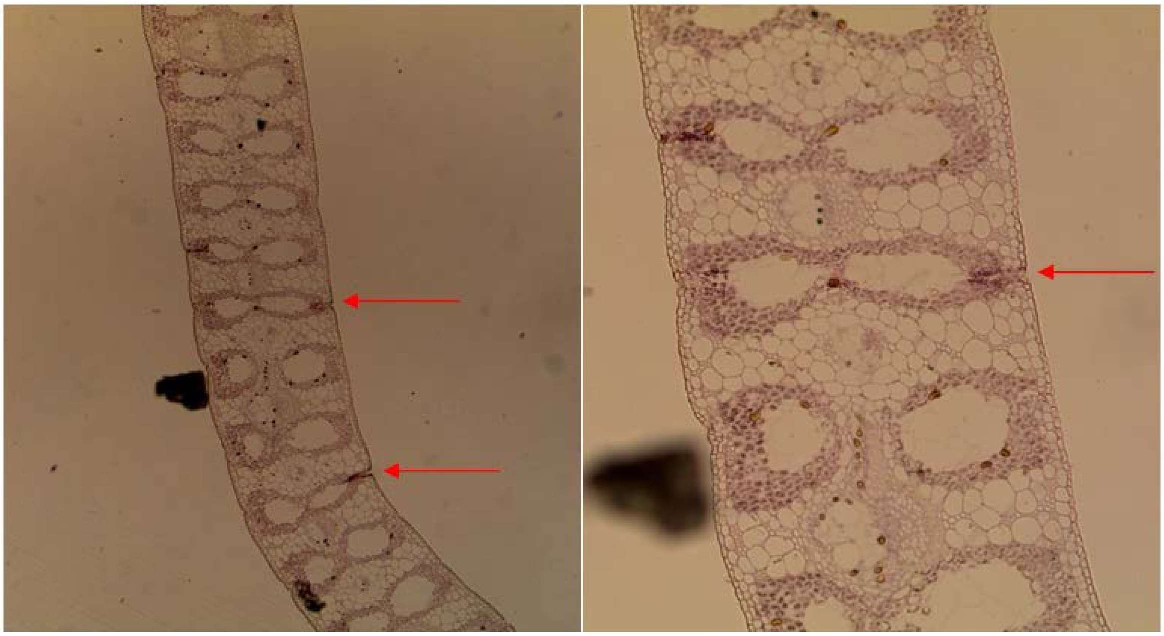


Figure 5.3: Cross section through palmiet (*Prionium serratum*) leaf on left (4x), and right (10x). Arrow indicates the position of stomatal apertures.

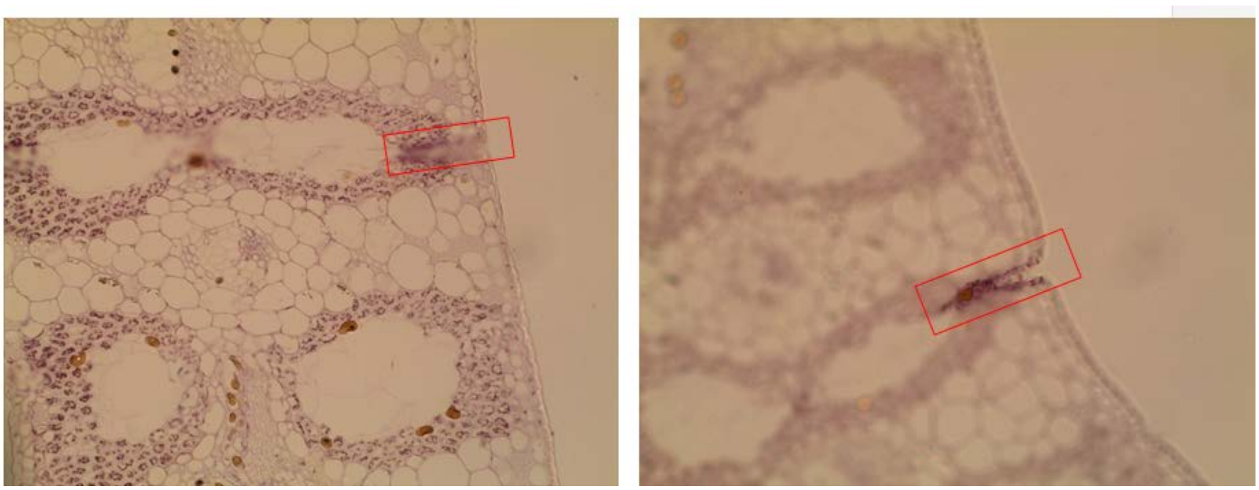


Figure 5.4: Two cross sections through a palmiet (*Prionium serratum*) leaf (20x). Red squares indicate the position of stomatal apertures.

Stellenbosch University http://scholar.sun.ac.za

Stomatal conductance of P. serratum

In an average stand of *P. serratum*, the mean (± standard deviation) number of plants per m^2 (n=10) is 7.0±1.76. The mean (n=10) number of living leaves per plant is 48.3±13.56, and dead leaves is 8.3±5.03. The mean (n=50) length of leaves is 89.7±11.75 cm. These values translate into a LAI of 11.2±1.10 (n=25) as measured by the LAI meter.

i. Spatial variation in P. serratum *water-use*

There was no significant difference in stomatal conductance among *P. serratum* plants that were inundated with water and those that were not inundated, or between the abaxial and adaxial surfaces of *P. serratum* leaves. There was no significant difference in stomatal conductance between sunny and cloudy days, and between leaves that were positioned in the sun or shade. However once the sun had set, stomatal conductance declined significantly (Figure 5.5).

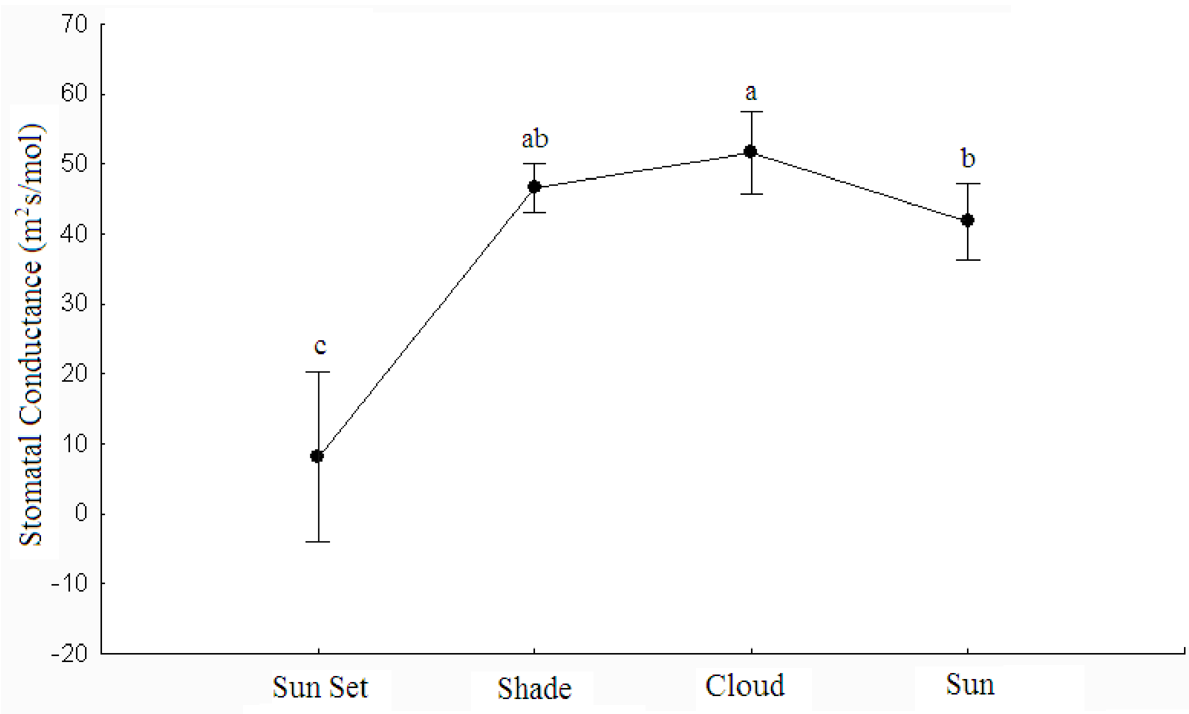


Figure 5.5: The effect of presence or absence of the sunlight on stomatal conductance of palmiet (*Prionium serratum*) in Jonkershoek, Western Cape. Points with the same letters denote no significant difference.

Stellenbosch University http://scholar.sun.ac.za

ii. Temporal variation in P. serratum *water-use*

The mean hourly stomatal conductance did not differ significantly among measurements made at different times of the day. However the diurnal patterns of stomatal conductance differed significantly among seasons (Figure 5.6), with those in in winter being significantly different from those during the summer and spring. In spring, stomatal conductance was low in the early morning and increased toward sun-set. In summer the stomatal conductance was similar throughout the day while in winter it started relatively high in the morning and ended with low values.

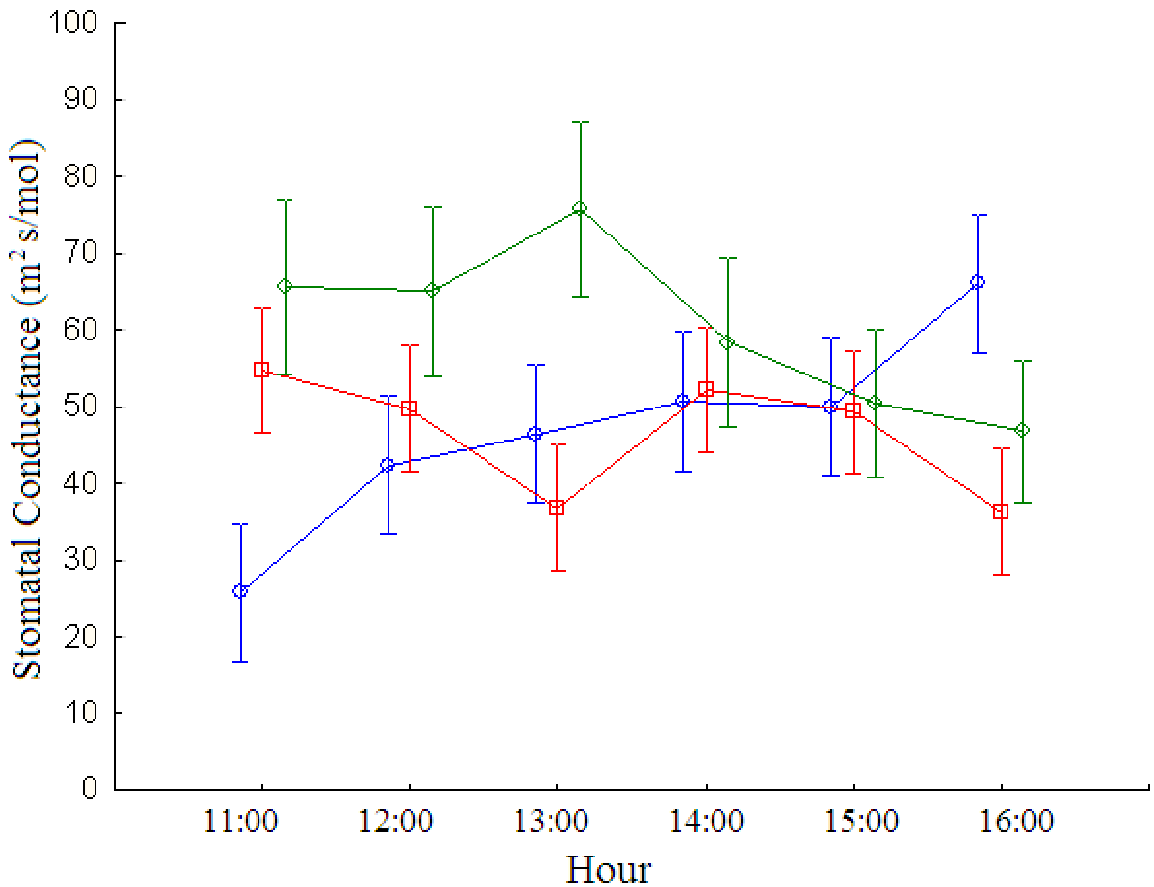


Figure 5.6: The effect of time of day and season on stomatal conductance of palmiet (*Prionium serratum*) in Jonkershoek, Western Cape. The blue line is the diurnal pattern for spring, the red for summer and the green for autumn/winter. For the sake of comparison, time was restricted to the hours 11:00 to 16:00 as for some days in winter, stomatal conductance could only be measured between those hours.

Stellenbosch University http://scholar.sun.ac.za

A CART analysis importance plot indicated that the three most important variables controlling stomatal conductance are the presence or absence of the sun (i.e. whether the sun had set or not), the season and the time of day (Figure 5.7).

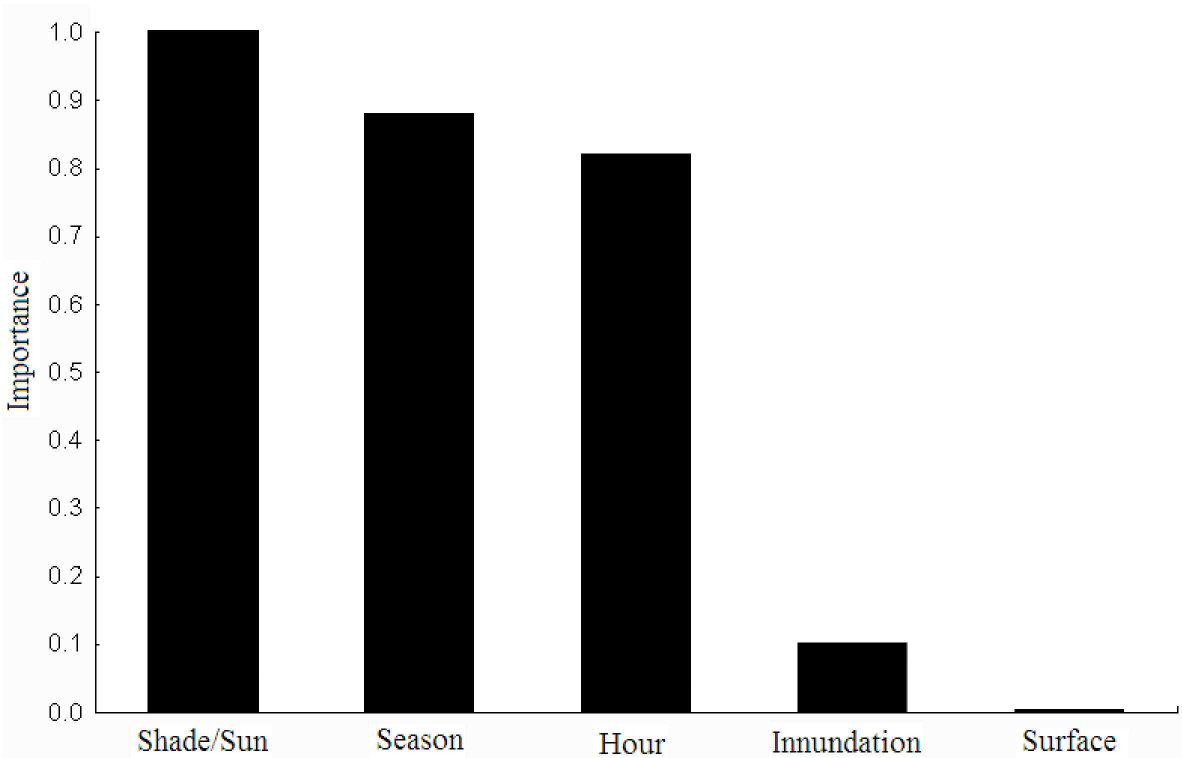


Figure 5.7: The relative importance of the effects of each variable (the effect of whether the sun had risen or not (shade/sun), the season, the time of day (hour), whether or not the plant was permanently inundated with water and the abaxial and adaxial surfaces of the leaves) on the stomatal conductance of palmiet (*Prionium serratum*) in Jonkershoek, Western Cape.

iii. Climatological influence on P. serratum *water-use*

Wind speed, saturated vapour pressure, temperature, vapour pressure deficit, radiation, potential evaporation and relative humidity had no significant effect on the stomatal conductance of *P. serratum*. Vapour pressure (VP) was the only environmental variable that had a significant positive effect on stomatal conductance (P=0.05, t=1.94).

iv. Stomatal Conductance

P. serratum has a mean stomatal conductance range of 18-112 $mmol.m^{-2}.s^{-1}$.

Stellenbosch University http://scholar.sun.ac.za

DISCUSSION

Stomatal Conductance

P. serratum appears to have a lower stomatal conductance than most other terrestrial fynbos plants (Table 5.1). This is counter-intuitive given that *P. serratum* is a wetland plant and in this study all plants appeared to have access to water and showed no signs of water stress.

Table 5.1: Ranges of leaf conductances (mmol.m^{-2}.s^{-1}) for different growth forms of fynbos from the Cape Floristic Region, South Africa. Table adapted from von Willert et al. (1989) and Miller (1984).

Source	Location	Tall shrub	Mid Shrub	Restioid	Geophyte	Graminoid	*P. serratum*
Miller 1984	Algeria: *Waboomveld*	75-217	31-665	134-339	110-146	-	-
	Algeria: *23 years of age*	43-264	71-598	283-445	-	-	-
	Jonkershoek: *Waboomveld*	90-452	90-452	-	-	-	-
	Jonkershoek: *Swartboskloof*	45-904	37-1100	-	-	252-358	-
	Jonkershoek: *Langrivier*	77-528	191-213	265-427	195	-	-
	Jakkalsrivier	60-143	425	350	-	105	-
	Pella	126-455	57-646	219-585	-	-	-
von Willert et al. 1989	Cedarberg	68-157	61-125	89-139	226	91	-
This study	Jonkershoek	-	-	-	-	-	18-112

P. serratum stomatal conductance compares well with the stomatal conductance of *Cannomois acuminata* which has been measured to be 89-139 mmol.m^{-2}.s^{-1} (von Willert et al. 1989). The *C. acuminata* restiod vegetation from the Cedarberg area is comparable to the riparian, fynbos, wetland communities in Jonkershoek which had an annual evaporation of about 1332 mm per annum (MAP 1324 mm) (Dye et al. 2001). If we assume that palmiet and restioids

Stellenbosch University http://scholar.sun.ac.za

respond in the same way to climatic factors, these findings suggest that the annual evaporation of palmiet stands in Jonkershoek could be about the same.

Leaf Area Index

Obtaining a LAI for plants like grasses is difficult because of the vertical arrangement of the leaves. LAI can be measured in two ways: the total leaf area per unit ground (as in this study) or as the projected leaf area per unit ground area (Dye et al. 2008). In the case of graminoids, the latter is usually much lower and more comparable to measurements on other species, meaning that the comparisons given here should be treated with caution (Dye et al. 2008). In a study of grasslands, LAI values were found to be very low, ranging from 0.3 to 2.0, whilst those of woody coniferous open-canopy forests range from 0.2 to 0.9 (Breuer et al. 2003). However another study found maximum LAI of conifer stands to vary from 3.5-20 (Leverenz & Hinckley 1990). A study done on *Arundo Donax* found LAI values to range from 3.4-6.1 (Watts & Moore 2010). LAI varied from 1-5 in a remote-sensing survey of the grassland and plantations of the Mistley-Canema Estate in KwaZulu-Natal (Bulcock & Jewitt 2010). The LAI of *P. serratum* is high, comparable with LAI values for dense, closed canopy forests, but this may also be a result of the vertical and overlapping arrangement of the leaves (Eschenbach & Kappen 1996). Fynbos has been measured to have an LAI of between 2-3 (Miller 1984). Sugarcane has been measured to have a LAI of up to 6, and *Acacia mearnsii* to have a LAI of 2-3 (Dye et al. 2008).

CONCLUSION

From the stomatal conductance measurements in this study it appears that *P. serratum* is a relatively low water-user for a wetland plant. However, stomatal conductance measurements are difficult to perform, and the porometer can be inconsistent, so follow-up verification work is recommended. In terms of morphology, it is possible that *P. serratum* has special morphological adaptations, such as sunken stomata, for periods of drought, when rivers or wetlands dry up. These adaptations may have allowed the species to persist in extremely dry years. Thus, although appearing counter-intuitive as *P. serratum* grows exclusively in areas that are inundated, these adaptations are essential for the long-term survival of the species. In conclusion, the water-use of

Stellenbosch University http://scholar.sun.ac.za

P. serratum is a cost to consider when assessing the costs and benefits of a wetland compared to that of cropland. However when the other ecosystem goods and services that wetlands provide are factored in, the benefits of a wetland far outweigh those of cropland. We recommend that riparian landowners protect and preserve the wetlands and riparian zones surrounding their water-resources, and restrict agriculture to non-riparian land where the hydrological side-effects will not be as pronounced.

REFERENCES

Begg, G. W. 1986. The wetlands of Natal (Part 1). An overview of their extent role and present status. Report 68. Pietermaritzburg: Natal Town and Regional Planning.

Birkhead, A. L., B. W. Olbrich, C. S. James, and K. H. Rogers. 1997. Developing an integrated approach to predicting the water use of riparian vegetation. Water Research Commission. WRC Report No: 474/1/97.

Birkhead, A. L., C. S. James, and M. T. Kleynhans. 2007. Hydrological and hydraulic modelling of the Nyl River floodplain. Part 2: Modelling hydraulic behavior. *Water SA*. **33**(1): 9-20.

Boucher, C. and M. J. Withers. 2004. Notes on the ecology of *Prionium serratum* (palmiet), a Cape river specialist. *Veld & Flora*. **90**(1): 26-28.

Breiman, L., Friedman, J. H., Olshen, R. A., and C. J. Stone. 1984. Classification and regression trees. Monterey, CA: Wadsworth & Brooks/Cole Advanced Books & Software.

Breuer, L., K. Eckhardt, and H. G. Frede. 2003. Plant parameter values for models in temperate climates. *Ecological Modelling*. **169**: 237-293.

Bullock, A., and M. Acreman. 2003. The role of wetlands in the hydrological cycle. *Hydrology and Earth System Sciences*. **7**(3): 358-389.

Bulcock, H. H., and G. P. W. Jewitt. 2010. Spatial mapping of leaf area index using hyperspectral remote sensing for hydrological applications with a particular focus on canopy interception. *Hydrology and Earth System Sciences*. **14**: 383–392.

Clulow, D., C. S. Everson, M. G. Mengistu, C. Jarmain, G. P. W. Jewitt, J. S. Price, and P. L. Grundling. 2012. Measurement and modelling of evaporation from a coastal wetland in Maputaland, South Africa. *Hydrology and Earth System Science*. **9**: 1741–1782.

Stellenbosch University http://scholar.sun.ac.za

Clulow, A.D., C. S. Everson, and M. B. Gush. 2011. The long-term impact of *Acacia mearnsii* trees on evaporation, streamflow, and ground water resources. Water Research Commission, Pretoria, South Africa. WRC Report: TT 505/11.

Decagon Devices. 2010. Leaf Area Index Meter –ACCUPAR LP-80: Operators Manual Version 10. Decagon Devices, Inc., 2365 NE Hopkins Court. www.decagon.com.

Decagon Devices. 2012. Leaf Porometer: Operators Manual Version 11. Decagon Devices, Inc., 2365 NE Hopkins Court. www.decagon.com.

Dye, P. J., G. Moses, P. Vilakazi, R. Ndlela, and M. Royappen. 2001. Comparative water use of wattle thickets and indigenous plant communities at riparian sites in the Western Cape and KwaZulu-Natal. *Water SA*. **27**(4): 529-536.

Dye, P. J., C. Jarmain, D. C. Le Maitre, C. S. Everson, M. B. Gush, A. Clulow. 2008. Modelling vegetation water use for general application in different categories of vegetation. Water Research Commission, Pretoria, South Africa. WRC Report No: 1319/1/08.

Eschenbach, C. and L. Kappen. 1996. Leaf area index determination in an alder forest: a comparison of three methods. *Journal of Experimental Botany*. **47**(302): 1457-1462.

Everson, C. S., M. Gush, M. Moodley, C. Jarmain, and P. Dye. 2007. Effective management of the riparian zone vegetation to significantly reduce the cost of catchment management and enable greater productivity of land resources. Water Research Commission, Pretoria, South Africa. WRC Report No 1284/1/07.

Everson, C. S., G. L. Molefe, and T. M. Everson. 1998. Monitoring and modelling components of the water balance in a grassland catchment in the summer rainfall area of South Africa. Water Research Commission, Pretoria, South Africa. WRC Report No. 493/1/98.

Everson, C. S., C. Burger, B. W. Olbrich, and M. B. Gush. 2001. Verification of estimates of water use from riverine vegetation on the Sabie river in the Kruger National park. Water Research Commission, Pretoria, South Africa. WRC Report No 877/1/01.

Everson, C., A. Clulow, and M. Mengitsu. 2009. Feasibility study on the determination of riparian evaporation on non-perennial systems. Water Research Commission, Pretoria, South Africa. WRC Report No: TT 424/09.

Grundling, P. L. 2004. Peatlands on the brink of the final phase in the extinction of a unique wetland type in southern Africa. Working for Wetlands Programme, National Botanical

Stellenbosch University http://scholar.sun.ac.za

Institute, Pretoria. IMGG Scientific Symposium, September 2004. International Mire Conservation Group. Pp. 5.

Haigh, E. A., P. L. Grundling, and P. M. Illgner. 2002. Report on the scoping study on the status of the Kromme River peatland complex and recommended mitigatory measures. Department of Water Affairs and Forestry Project X832633.

Humphries, M. S., A. Kindness, W. N. Ellery, and J. C. Hughs. 2010. Sediment geochemistry, mineral precipitation and clay neoformation on the Mkuze River floodplain, South Africa. *Geoderma*. 325-334.

Jarvis, P. G., and J. W. Leverenz. 1983. Productivity of temperate, deciduous and evergreen forests. In: Lange O. L. (Ed). Physiological plant ecology. IV. Encyclopedia of plant physiology, Vol. 12D. New York: Springer-Verlag. Pp: 233–280.

Jarvis, P. G., and K. G. McNaughton. 1986. Stomatal control of transpiration: scaling up from leaf to region. *Advances in Ecological Research*. **15**: 1-49.

Kotze, D. C., and C. M. Breen. 1994. Agricultural land-use impacts on wetland functional values. Water Research Commission, Pretoria, South Africa. WRC Report No 501/3/94.

Kotze, D. C., G. C. Marneweck, A. L. Batchelor, D. S. Lindley, and Collins, N. B. 2005. WET-EcoServices. A rapid assessment procedure for describing wetland benefits. Mondi Wetlands Project.

Leverenz J. W., and T. M. Hinckley. 1990. Shoot structure, leaf area index and productivity of evergreen conifer-stands. *Tree Physiology*. **6**:135–149.

McCarthy, T. S. and W. N. Ellery. 1998. The Okavango Delta. *Transactions of the Royal Society of South Africa*. **53**: 157-182.

Meigh, J. 1995. The impact of small farm reservoirs on urban water supplies in Botswana. *Natural Resources Forum.* **19:** 71-83.

Miller, J. M., P. C. Miller, and P. M. Miller. 1984. Leaf conductance and xylem pressure potentials in fynbos plant species. *South African Journal of Science*. **80**: 381-385.

Mooney, H. A., C. Field, S. L. Guloman, P. Rundel, and F. J. Kruger. 1983. Photosynthetic characteristic of South African sclerophylls. *Oecologia*. **58**: 398-401.

Munro, S. L. and H. P. Linder. 1997. The embryology and systematic relationships of *Prionium serratum* (Juncaceae: Juncales). *American Journal of Botany*. 84(6): 850-860.

Stellenbosch University http://scholar.sun.ac.za

Pahl-Wostl, C. 2007. The implications of complexity for integrated resources management. *Environmental Modelling and Software*. **22**: 561-569.

Pearcy, R. W., J. Ehleringer, H. A. Mooney, and P. W. Rundel (Eds). 1989. Plant physiological ecology: field methods and instrumentation. Chapman and Hall. Pp 48-52.

Rogers, K. H. 1997. Freshwater wetlands. In: *Vegetation of Southern Africa*. R. M. Cowling, D. M. Richardson, and S. M. Pierce (Eds). Cambridge University Press.

Russel, W. B. 2009. WET-RehabMethods: National guidelines and methods for wetland rehabilitation. C. Breen, J. Dini, W. Ellery, S. Mitchell, and M. Uys (Eds). Water Research Commission, Pretoria, South Africa. WRC Report No. 341/09.

Scott, D. F. 1999. Managing riparian zone vegetation to sustain streamflow: results of paired catchment experiments in South Africa. *Canadian Journal of Forestry Research*. **29**: 1149-1157.

Seyhan, E., A. S. Hope, and R. E. Schulze. 1983. Estimation of streamflow loss by evapotranspiration from a riparian zone. *South African Journal of Science.* **79:** 88-90.

Tooth, S., T. S. McCarthy, P. J. Hancox, D. Brandt, K. Buckley, E. Nortje, S. McQuade. 2002. The geomorphology of the Nyl River and floodplain in the semi-arid Northern Province, South Africa. *South African Geographical Journal*. 84:226-237.

Turpie, J.K., C, Marais, and J. N. Blignaut. 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**: 788-798.

von Willert, D. J., M. Herppich, and J. M. Miller. 1989. Photosynthetic characteristic and leaf water relations of mountain fynbos vegetation in the Cedarberg area (South Africa). *South African Journal of Botany*. **55**(3): 288-298.

Watts, D. A. and G. W. Moore. 2010. Water-Use Dynamics of an Invasive Reed, *Arundo donax*, from Leaf to Stand. *Wetlands*. **31**: 725–734.

Wilson, B. H., and T. Dincer. 1976. An introduction to the hydrology and hydrography of the Okavango Delta. *Proceedings of the Symposium on the Okavango Delta and its future utilisation*, Botswana Society, Gaborone, **33:** 48.

Stellenbosch University http://scholar.sun.ac.za

CHAPTER 6: CONCLUSIONS AND SYNTHESIS

The aim of this thesis was to investigate the impact of restoration on key ecosystem provisioning and regulating services, by estimating the impacts of degradation in the Kromme River, South Africa. The land-cover change over the past 50 years was investigated and their impact on hydrology was modelled. The benefits of restoration can now be inferred from the results. The central research question of this thesis was:

What was the hydrological impact of the landcover changes in the Kromme River Catchment over the last 50 years?

This synthesis chapter highlights the main conclusions of this study, as well as making some recommendations for various management and political levels.

MAIN CONCLUSIONS

Land-cover change

In the past 50 years, the Kromme River's wetlands, floodplains and relatively fertile riverbeds, the areas in the catchment that are the most vital in terms of providing essential services to mankind, have been the most damaged and transformed. Two key land-cover changes were identified: the loss of palmiet floodplain wetlands, and the invasion of *A. mearnsii*, primarily in the riparian zones (Chapter 3)

Hydrological impacts

The hydrological modelling predicted that the transformation of the floodplain wetlands in the Kromme River has shifted the flow regime, reducing baseflows and increasing the responsiveness of the catchment to extreme rainfall events (i.e. greater floods) (Chapter 4). There are also data which indicate a decline in water quality (Chapter 4). The invasion of *A. mearnsii* over time has caused a reduction in riverflow. However it is very difficult to differentiate between the hydrological impacts of the wetland transformation and that of the *A. mearnsii*

Stellenbosch University http://scholar.sun.ac.za

invasion, as the invasion by *A. mearnsii* is a key driver for wetland loss. Regardless, the hydrological impacts of degradation in the Kromme River are substantial.

Working for Water

At their current rate of clearing (3x the rate of invasion), it would take WfWater another 30 years to effectively control *A. mearnsii* in the Kromme (Chapter 3). On a positive note, WfWater appear to have been relatively successful at follow-up in the Upper Kromme (Chapter 3, McConnachie et al. 2012), however the rate of clearing is still too slow to perhaps be economically effective. It may be better to make a greater investment into clearing as much as possible, as early as possible, so that control would not have to be stretched out for as long as 30 years. A further observation relating to the control of IAPs, which I do not mention in my chapter, is that biological control has not yet been introduced into the Kromme, and this is something that should be rectified as soon as possible.

Water-use of Palmiet

P. serratum appears to have a relatively low stomatal conductance for a wetland plant. It has sunken stomata which may have evolved for periods of drought, when rivers or wetlands dry up. These adaptations may have allowed the species to persist in extremely dry years. However the evaporation from palmiet wetlands is still relatively high (Appendix 5) and thus the water-use of *P. serratum* is an additional cost to consider when evaluating the costs and benefits of a wetland compared to that of agriculture (Chapter 5).

Benefit of restoration

Using hydrological modelling of different scenarios, it is possible to hypothetically reverse the impacts of degradation and to infer the hydrological benefits of restoration. If the Kromme Catchment were to be restored back to the land-cover state of 1986 (i.e. clear 10.4 km^2 (25.2% of the current extent of the invasion) of *A. mearnsii*, restore 0.5 km^2 (3.3% of original extent) of palmiet wetlands), the hydrological benefits would be so small, they would not be worth the investment in restoration (Chapter 4). If the Kromme Catchment were restored back to the land-cover state of 1969 (i.e. clear 12.5 km^2 (30.2%) of *A. mearnsii*, restore 1.6 km^2 (10.5%) palmiet wetlands), the hydrological benefits would include a predicted increase in riverflow (27.5 mm/a), baseflow (1.69 mm/a), an increase in flood protection and improved water quality (Chapter 4). If

Stellenbosch University http://scholar.sun.ac.za

finances were invested in the Kromme Catchment such that it was restored back to the land-cover state of 1954 (i.e. clear 26.9 km^2 (65.1%) of *A. mearnsii*, restore 5.2 km^2 (34.2%) palmiet wetlands), the hydrological benefits would include a predicted increase in riverflow (42 mm/a), baseflow (2.9 mm/a), an increase in flood protection and improved water quality (Chapter 4). Finally, if the Kromme were restored back to its reference condition, which in reality is impossible due to the large scale wetland degradation and loss of peat beds, it would involve restoring between 5.2-12.8 km^2 (34.2-100%) of the palmiet wetlands, clearing 41.3 km^2 (100%) of *A. mearnsii* and ceasing all intensive cultivation in the floodplains (32.2 km^2) (100%). The actual hydrological benefits would include ecosystem goods and services in excess of those modelled for the 1954 scenario (Chapter 4). These actions could be regarded as the type of insurance plan taken out, and the benefits gained in terms of increased ecosystem service delivery would be the insurance premium. In conclusion it appears that restoration, or financial investment into the Kromme River, would provide significant economic returns on investment.

SHORTCOMINGS

1. ACRU Model restrictions

The ACRU model did not adequately take into account groundwater dynamics in the Kromme, which is a problem considering the high levels of groundwater recharge of floodplain wetlands. Neither did the model take into account structural damage to the river, in the form of erosion dongas and headcuts, which would undoubtedly have some of the greatest hydrological impacts in the Kromme. A model is never a substitute for real data; however its results still provide insights and may be useful. However as a result of the limitations of this model, it is likely that the hydrological benefits of restoration in this study are under-estimations of their true value.

2. Data limitations

The South African Department of Water Affairs did not have the requisite data on water-use of the Kromme farmers, despite being mandated by South African legislation to collect these data. As a result I had to rely on the landowners for details of their water-use (Appendix 3). Recent research has shown that not all farmers tell the truth (St. John et al. 2010). Indeed my

Stellenbosch University http://scholar.sun.ac.za

research suggested that farmers had underestimated their water-use for agriculture in the Kromme River, as the model predicted that farm dams were drying up, and output from the model indicates that crop water-use was uncharacteristically low (Chapter 4). This may imply that farmers are possibly using far more water than they are legally entitled to, and may be directly abstracting from the Kromme River itself.

RECOMMENDATIONS

Communication

Restoration has been highly successful worldwide and has repeatedly been shown to improve the delivery of many ecosystem services (Aronson et al. 2007, Blignaut & Aronson 2008). However, there has been a failure to link this research with socio-economics and policy making. This failure suggests that such research has had little impact on local communities and few studies have been successful in implementing changes, with regards to the use of ecosystem services (Cowling et al. 2008). Communication between scientists and managers, and scientists and landowners needs to be improved. There are projects trying to address this gap, such as the umbrella project that this thesis falls under: ASSET Research, which has produced several policy papers as output from several of its funded masters studies (Appendix 6). This could be further encouraged by providing incentives for young scientists doing postgraduate studies to write up their research in a popular format, for magazines read by managers and landowners. The Conservation Ecology Department at Stellenbosch University have implemented such a programme, whereby postgraduate students are required to disseminate their research through several popular mediums in order to graduate. There are also projects willing to fund this type of dissemination and community interaction, and a grant was given by ASSET Research for the results of this masters research to be presented back to the farmers in the Kromme (Appendix 2)

A second communication gap has been identified in this study between the management of Working for Water and landowners. This lack of communication has often resulted in disagreements over whose role it is to do follow-up treatments in the Kromme. This issue has been pinpointed as one of the major reasons why follow-up is not timeously done in some cases in South Africa, and why reinvasion occurs (McConnachie et al. 2012, van Wilgen et al. 2012).

Stellenbosch University http://scholar.sun.ac.za

A social change

South Africa is a water scarce country and as a result of a series of poor management decisions, unsustainable land use and invasion by woody alien trees, water security has declined. For centuries South African landscapes and rivers have been viewed through the lens of ideas and preferences inherited from the North (Kondolf 2011). South Africa has been viewed as "barren" and "vaal" (bland) due to its lack of woody trees and powerful river systems. Since the 1820 settlers arrived, Europeans have brought numerous plant and animal species from other countries for many reasons, including: timber, horticulture, crops, accidental introduction and ornamental purposes. Invasion of South African by these species has changed landscapes, causing hydrological impacts that we bear the brunt of today. To truly succeed in restoring the South African landscape, we will require more than isolated restoration attempts (van Wilgen et al. 2012). A true recovery of the system will require a social change, a shift in mindset that can only be brought about by strategic social marketing and a social learning process (Leigh 2005, Pahl-Wostl 2007). There is also a great need for economic systems to be completely restructured so that ecosystem services are appropriately valued and included in financial audits at all levels (local, regional and national) (Cowling et al. 2008). Together with Living Lands[3], a network of researchers, farmers and managers in the region, we have embarked on such a learning process with relevent stakeholders in the Kromme (Appendix 2).

Valuing water appropriately

Wastage of water in South Africa through leaks, unnecessary over-consumption and through losses associated with water hungry IAPs is pervasive. It has been argued (Andrews 2012) that the price of water should be increased, on a sliding scale, to reflect its true value: a resource that humankind cannot survive without; and to foster or encourage an appropriate sense of the value of water in society. It is also suggested that a payments for ecosystem services (PES) scheme be considered for the Kromme, Kouga and Baviaanskloof region (Mander et al. 2010, Andrews 2012). If a market for the trading of water-rights was opened, and a cap-and-trade system

[3] Living Lands is an NPO conserving and restoring living landscapes –including environmental, social and economic aspects. http://www.earthcollective.net/livinglands/

Stellenbosch University http://scholar.sun.ac.za

(Stavins 2001) for water introduced, it may encourage and provide incentive for farmers to become more sustainable water-users, as well as to discourage unsustainable farming practices (Andrews 2012). However this would require not only buy-in from the associated municipality, the Department of Water Affairs and land-owners, but also accurate monitoring of the water-use of each farmer (Andrews 2012). It has also been suggested that IAPs should be controlled no matter the cost and that an alien control charge should be included as part of water resource management fees (Blignaut et al. 2007).

Water-use monitoring and support

In Australia, field techniques (such as heat-flux towers and Scintillometry) coupled with remote sensing techniques have been incorporated into the Australian Water Resources Assessment. This assessment releases an annual estimate of the water balance for the continent for planning and policy purposes (Glenn et al. 2011). Despite attempts by the South African Department of Water Affairs to gauge water usage and to enforce water usage restrictions as per their mandate, very little is known about actual water-use by South African landowners. Additionally very little is known about South Africa's water resources in general as not all river systems are gauged, in the case of the Kromme River, data are poorly kept and existing equipment poorly maintained. Remote sensing is a potential solution to these logistical challenges, and whilst it may not be a silver bullet, it could assist farmers and government to optimise, manage and control water use in South Africa. There are energy-balance-based algorithms for estimating the evaporation from areas of land using satellite images which can help to establish links between land-use, water allocation and water-use (Bastiaanssen et al. 1998, Bastiaanssen et al. 2005). Coupled to ground techniques, heat-flux towers or scintilometers, for validation, it could prove a reasonably cheap, highly accurate and high resolution measure of water-use of landowners and industry in South Africa. It is also recommended that for every cement weir that Working for Wetlands builds, the Department of Water Affairs should capitalize on this and install a gauging weir for monitoring riverflow.

Enforcement of legislation

South Africa has some of the best environmental legislation in the world including *inter alia*: the National Environmental Management Act 1998 (NEMA), the National Water Act 36 of 1998

Stellenbosch University http://scholar.sun.ac.za

(NWA), the Conservation of Agricultural Resources Act 43 of 1983 (CARA), the National Forests Act 84 of 1998 (NFA) (Roux et al. 2006, Armstrong 2009). However, enforcement of these laws remains problematic (Armstrong 2009). Immediate action needs to be taken such that the environment can be protected from offenders. There are many landowners in South Africa who are violating citizens' constitutional rights to clean air, fresh water and biodiversity, making short-term personal profits at society's long-term cost. Promoting sustainable farming will take two approaches: providing incentives (carrots) and compliance and law enforcement (sticks). It is recommended that a scientific officer with legal training be appointed in every secondary catchment in South Africa to follow up on water-related violations and to ensure that legislation is enforced.

Investing for the future

Climate change is likely to lead to water shortages and more intense and unpredictable rainfall events, resulting in increased floods (Schulze et al. 2005, Matthews et al. 2011, Trenberth 2011). In the face of growing uncertainty surrounding future climate change, it would be wise to take out an insurance policy by investing in and restoring our natural infrastructure while we still can. It has been recommended that alternatives to new infrastructure (such as water filtration and desalination plants) be considered, that society builds with nature: attempting to use the natural infrastructure (wetlands, aquifers) that nature provides (Matthews et al. 2011). As a matter of urgency, South Africa should be investing in ecosystems by increasing protected areas, with river and wetland systems being the highest priority (Nel et al. 2009).

There are examples of success stories of investing in natural infrastructure from all around the world. One such example is of the Seattle Municipality, North America (Cosman et al. 2012). In the 1980s Seattle was one of the unhealthiest cities in North America, with the highest rate of disease (outbreaks of typhoid and cholera), as a result of poor quality and limited water supply. After years of water-shortages and a fire destroying most of the city, the municipality decided to invest in a catchment, and purchase it for the sole purpose of water-provision. The Cedar River Catchment was bought from farmers and restored, and within 10 years the catchment provided a secure supply of high quality water, the outbreaks of disease ceased, improving the health of the citizens of the Seattle Municipality. In addition, the city was saved billions of dollars in the long

Stellenbosch University http://scholar.sun.ac.za

term. This is because the use of natural systems for water provision services proved substantially cheaper than creating an artificial system, such as a new water filtration plant (Cosman et al, 2012). It is recommended that South African government follow a similar approach: that is to decide which catchments are priority catchments in terms of water-provision, and invest in these catchments. It is becoming increasingly apparent that unsustainable and commercial farming practises are not compatible with high quality, secure water provision. The South African government should decide whether to farm "water" in these catchments, or maintain agriculture and forestry, as these catchments cannot support both services. We recommend that important water providing catchments, especially where agriculture and forestry are marginal, should be prioritized for provision of water-related ecosystem services alone.

Conclusion

This study could be greatly strengthened by being repeated in a transformed catchment that has a high quality historical hydrological record. An ideal catchment would be one where alien invasion has taken place, and where restoration has followed, as the hydrological effects would all have been captured in this hydrological record. The modelling results from this study have been interesting, but a key question that arises out of this thesis is: is it possible to accurately quantify the hydrological benefits of restoration at a landscape scale?

REFERENCES

Andrews, M. 2012. Payments for Ecosystem Services in the Kromme, Kouga and Baviaanskloof: the feasibility of a cap-and-trade system. Fynbos Forum Conference 2012, Stilbaai, South Africa.

Armstrong, A. 2009. WET-Legal: Wetland rehabilitation and the law in South Africa. C. Breen, J. Dini, W. Ellery, S. Mitchell, and M. Uys (Eds). Water Research Commission, Pretoria, South Africa. WRC Report No. TT 338/09.

Aronson J., S. J. Milton, and J. N. Blignaut (Eds). 2007. *Restoring natural capital: science, business, and practice*. Island Press, Washington, D. C.

Bastiaanssen, W. G. M., E. J. M. Noordman, H. Pelgrum, G. Davids, B. P. Thoreson, and R. G. Allen. 2005. SEBAL model with remotely sensed data to improve water-resources

Stellenbosch University http://scholar.sun.ac.za

management under actual field conditions. *Journal of Irrigation and Drainage Engineering*. **131**(1): 85-93.

Bastiaanssen, W. G. M., M. Meneti, R. A. Feddes, and A. A. M. Holtslag. 1998. A remote sensing surface energy balance algorithm for land (SEBAL). 1. Formulation. *Journal of Hydrology*. **212-213**: 198-212.

Blignaut, J. and J. Aronson. 2008. Getting serious about maintaining biodiversity. *Conservation Letters*. **1**(1):12-17.

Blignaut, J. N., C. Marais, and J. K. Turpie. 2007. Determining a charge for the clearing of invasive alien plant species (IAPs) to augment water supply in South Africa. *Water SA*. **33**(1): 27-34.

Cosman, D., R. Schmidt, J. Harrison-Cox, and D. Batker. 2012. How water utilities can spearhead natural capital accounting. *The Solutions Journal*. **2**(6): 28-31.

Cowling R. M., B. Egoh, A. T. Knight, P.J. O'Farrell, B. Reyers, M. Rouget, D. J. Roux, and A. Welz, A.Wilhelm-Rechman. 2008. An operational model for mainstreaming ecosystem services for implementation. *Proceedings of the National Academy of Sciences*. **105:** 9483-9488.

Glenn, E. P., T. M. Doody, J. P. Guerschman, A. R. Huete, E. A. King, T. R. McVicar, A. I. J. M. Van Dijk, T. G. Van Niel, M. Yebra, and Y. Zhang. 2011. Actual evapotranspiration estimation by ground and remote sensing methods: the Australian experience. *Hydrological Processes*. **25**: 4103-4116.

Kondolf, G. M. 2011. Mediterranean-climate episodic channels: long periods of boredom, brief moments of terror. The International Mediterranean Ecosystems Conference MEDECOS XII. 6-9 September 2011.

Leigh, P. 2005. The ecological crisis, the human condition, and community-based restoration as an instrument for its cure. *Ethics in Science and Environmental Politics*. **2005**: 3-15.

Mander, M., J. Blignaut, M. Van Niekerk, R. Cowling, M. Horan, D. Knoesen, A. Mills, M. Powell, and R. Schulze. 2010. Baviaanskloof-Tsitsikamma Payments for Ecosystem Services: A feasibility assessment. Futureworks.

Matthews, J. H., B. A. J. Wickel, and S. Freeman. 2011. Converging currents in climate-relevant conservation: water, infrastructure, and institutions. *PLOS Biology*. **9**(9): 1-4.

Stellenbosch University http://scholar.sun.ac.za

McConnachie, M. M., R. M. Cowling, B. W. van Wilgen, D. A. McConnachie. 2012. Evaluating the cost-effectiveness of invasive alien plant clearing: a case study from South Africa. *Biological Conservation*. In Press.

Nel, J. L., B. Reyers, D. J. Roux, and R. M. Cowling. 2009. Expanding protected areas beyond their terrestrial comfort zone: identifying spatial options for river conservation. *Biological Conservation*. **142**: 1605-1616.

Roux, D., J. Nel, H. MacKay, and A. Driver. 2006. Policy objectives for conserving freshwater ecosystems: how many rivers, which ones, and what level of protection are required. WISA 2006 Biannual Conference and Exhibition. http://hdl.handle.net.10204/1206

Schulze, R. E., Lumsden, T. G., Horan, M. J. C., Warburton, M. L., and Maharaj, M. 2005. An assessment of impacts of climate change on agrohydrological responses over Southern Africa. In: *Climate Change and Water Resources in Southern Africa: Studies on Scenarios, Impacts, Vulnerabilities and Adaptation*. Schulze, R. E(Ed). Water Research Commission, South Africa.

St. John, F. A. V., G. Edwards-Jones, J. M. Gibbons, and J. P. G. Jones. 2010. Testing novel methods for assessing rule breaking in conservation. *Biological Conservation*. **143**: 1025–1030.

Stavins, R. N. 2001. Experience with market-based policy instruments. *Discussion Paper 01-58* (Washington, D.C.: Resources for the Future). "Market-based instruments are regulations that encourage behavior through market signals rather than through explicit directives regarding pollution control levels or methods". http://www.rff.org/Publications/Pages/PublicationDetails.aspx?PublicationID=17130

Trenberth, K. E. 2011. Changes in precipitation with climate change. *Climate Research*. **47**: 123-138.

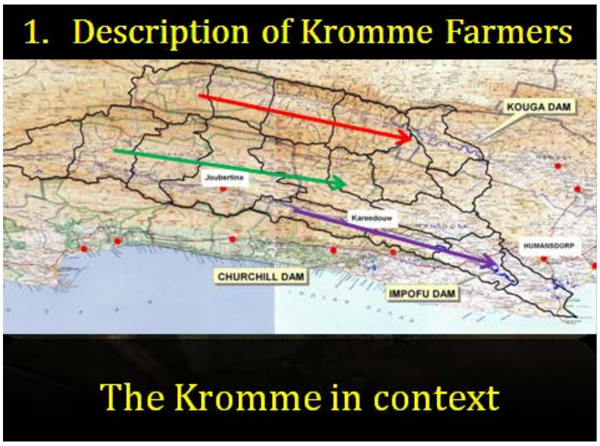
van Wilgen, B. W., D. C. Le Maitre, A. Wannenburgh, I. M. Kotze, L. van den Berg, L. Henderson. 2012. An assessment of the effectiveness of a large, national-scale invasive alien plant control strategy in South Africa. *Biological Conservation*. **148**: 28-38.

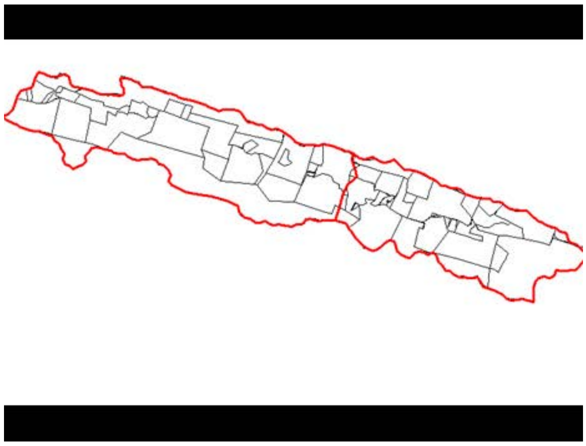
APPENDIX 1

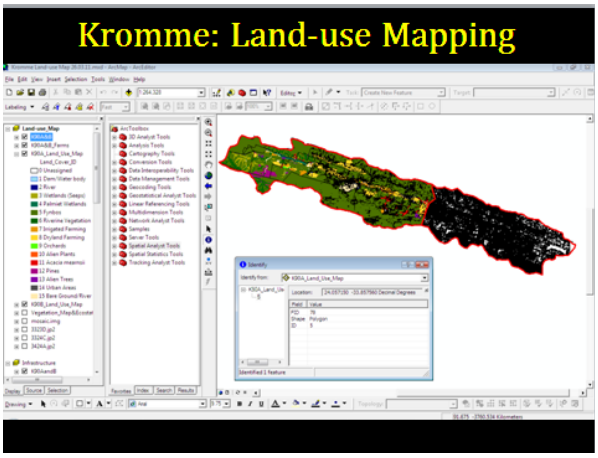
A social study of the farmers of the Kromme

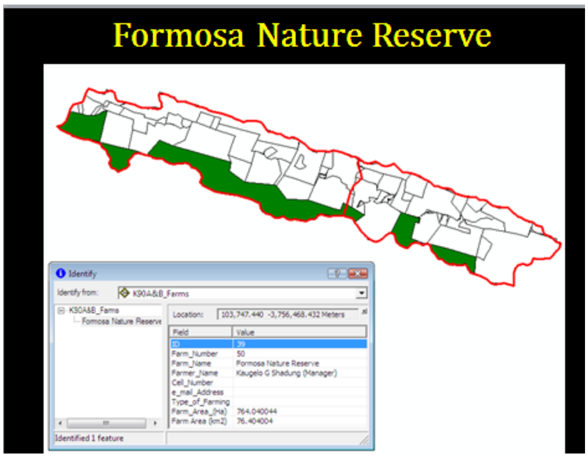
This Appendix is split into two sections. The first is a description of the farmers of the Kromme in a powerpoint format. Each farm has a slide for a) its location within the catchment, b) a photo of the farm, c) a photo of the farmer –if possible. The slides that show the map also show an attribute table with pertinent information about the farm and its land-uses, as well as details about the farmers. This database is not displayed in full in this thesis, so as to protect the farmers' details. The second section is a summary of the farming activities and opinions of farmers in the Kromme. Another output of this social study was a detailed land-use map, aimed at the farmers (Figure A1.1). This was distributed to interested farmers at the workshop in March 2012 (Appendix 4). All of our data were obtained in lengthy private interviews at each of the farmers' homes.

SECTION 1: Description of the Kromme Farmers

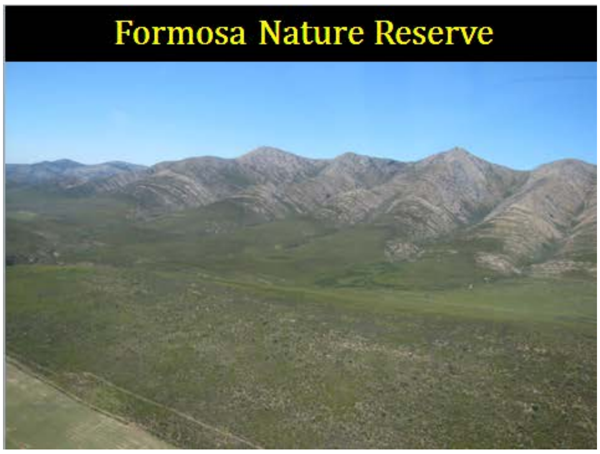


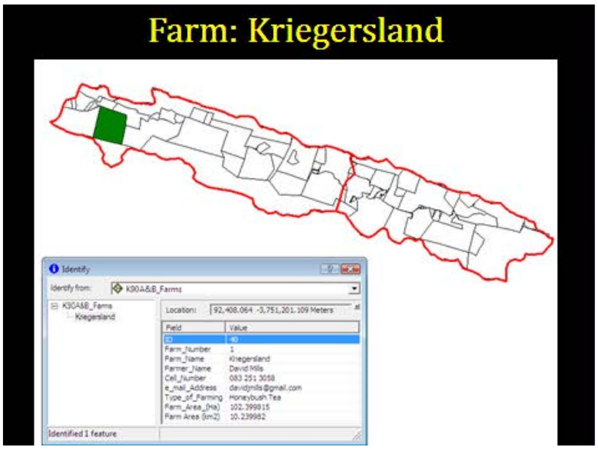



Kromme: Land-use Mapping


Formosa Nature Reserve


Formosa Nature Reserve


Formosa Nature Reserve


Farm: Kriegersland


Farm: Kriegersland

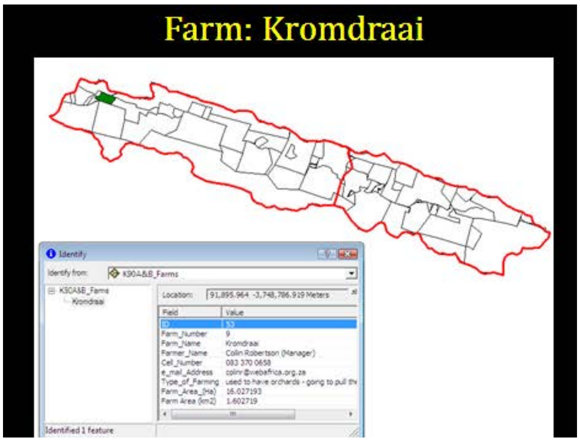

Farm: The Heights


Farm: The Heights

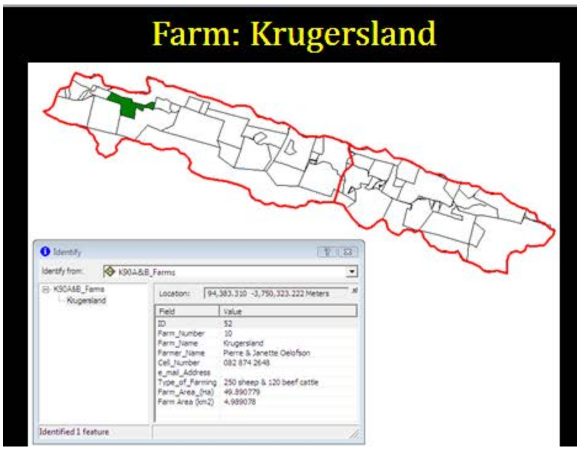

Farm: The Heights


Farm: The Heights


Farm: The Heights


Farm: Kromdraai
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Kromdraai
Location: 91,895.964 -3,748,786.919 Meters
Field Value
ID 53
Farm_Number 9
Farm_Name Kromdraai
Farmer_Name Collin Robertson (Manager)
Cell_Number 083 370 0658
e_mail_Address colinr@webafrica.org.za
Type_of_Farming used to have orchards - going to pull the
Farm_Area_(Ha) 16.027193
Farm Area (km2) 1.602719
Identified 1 feature


Farm: Kromdraai

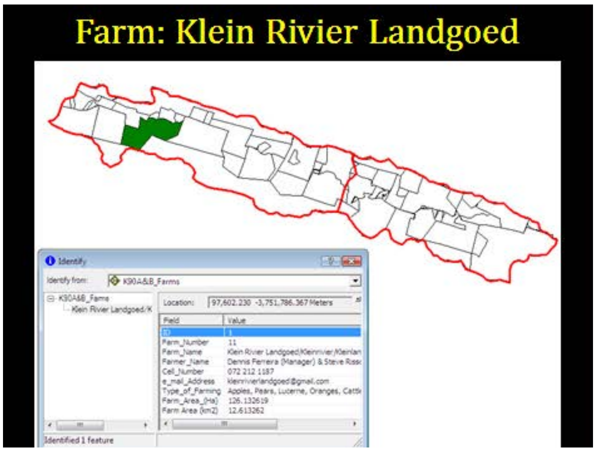

Farm: Krugersland
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Krugersland
Location: 94,383.310 -3,750,323.222 Meters
Field Value
ID 52
Farm_Number 10
Farm_Name Krugersland
Farmer_Name Pierre & Janette Oelofson
Cell_Number 082 874 2648
e_mail_Address
Type_of_Farming 250 sheep & 120 beef cattle
Farm_Area_(Ha) 49.890779
Farm Area (km2) 4.989078
Identified 1 feature


Farm: Krugersland


Farm: Krugersland


Farm: Krugersland

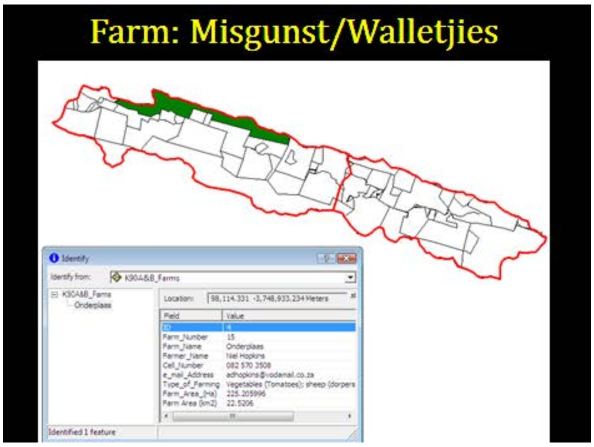

Farm: Krugersland


Farm: Klein Rivier Landgoed
Identify
Identify from:
K90A&B_Farms
K90A&B_Farms
Klein Rivier Landgoed/K
Location:
97,602.230 -3,751,786.367 Meters
Field
Value
Farm_Number
11
Farm_Name
Klein Rivier Landgoed/Kleinrivier
Farmer_Name
Dennis Ferreira (Manager)
Cell_Number
072 212 1187
e_mail_Address
kleinrivierlandgoed@gmail.com
Type_of_Farming
Apples, Pears, Lucerne, Oranges
Farm_Area_(Ha)
126.132619
Farm Area (km2)
12.613262
Identified 1 feature


Farm: Klein Rivier Landgoed

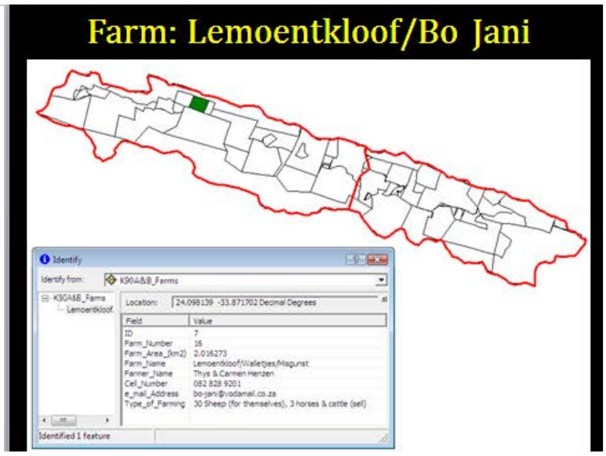

Farm: Klein Rivier Landgoed


Farm: Klein Rivier Landgoed


Farm: Misgunst/Walletjies
Identify
Identify from:
K90A&B_Farms
K90A&B_Farms
Location:
98,114.331 -3,748,933.234 Meters
Field
Value
ID
4
Farm_Number
15
Farm_Name
Farmer_Name
Niel Hopkins
Cell_Number
082 570 3508
e_mail_Address
Type_of_Farming
Vegetables (Tomatoes); sheep (dorpers
Farm_Area_(Ha)
225.205996
Farm Area (km2)
22.5206
Identified 1 feature

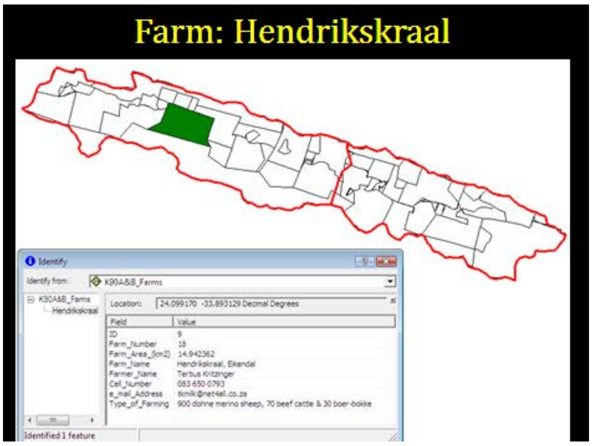

Farm: Misgunst/Walletjies


Farm: Misgunst/Walletjies


Farm: Lemoentkloof/Bo Jani
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Lemoentkloof.
Location: 24.098139 -33.871702 Decimal Degrees
Field Value
ID 7
Farm_Number 16
Farm_Area_(km2) 2.016273
Farm_Name Lemoentkloof/Walletjies/Misgunst
Farmer_Name Thys & Carmen Henzen
Cell_Number 082 828 9201
e_mail_Address bo-jani@vodamail.co.za
Type_of_Farming 30 Sheep (for themselves), 3 horses & cattle (sell)
Identified 1 feature


Farm: Lemoentkloof/Bo Jani


Farm: Lemoentkloof/Bo Jani


Farm: Hendrikskraal
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Hendrikskraal
Location: 24.099170 -33.893129 Decimal Degrees
Field Value
ID 9
Farm_Number 18
Farm_Area_(km2) 14.942362
Farm_Name Hendrikskraal, Eikendal
Farmer_Name Tertius Kritzinger
Cell_Number 083 650 0793
e_mail_Address tkmik@net4all.co.za
Type_of_Farming 900 dohne merino sheep, 70 beef cattle & 30 boer-bokke
Identified 1 feature

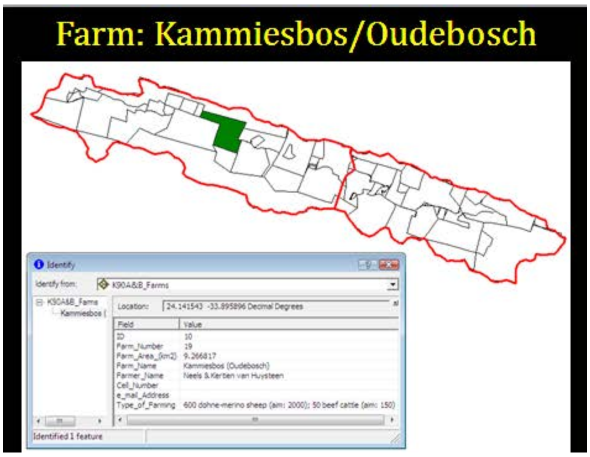

Farm: Hendrikskraal

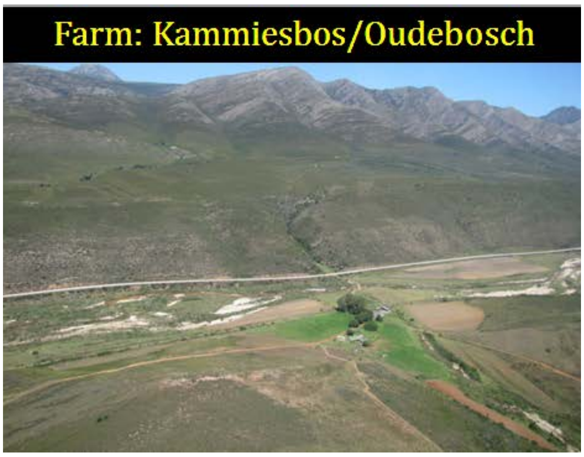

Farm: Hendrikskraal


Farm: Hendrikskraal


Farm: Hendrikskraal


Farm: Hendrikskraal


Farm: Kammiesbos/Oudebosch
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Kammiesbos (
Location: 24.141543 -33.895896 Decimal Degrees
Field Value
ID 10
Farm_Number 19
Farm_Area_(km2) 9.266817
Farm_Name Kammiesbos (Oudebosch)
Farmer_Name Neels & Kerten van Huysteen
Cell_Number
e_mail_Address
Type_of_Farming 600 dohne-merino sheep (aim: 2000); 50 beef cattle (aim: 150)
Identified 1 feature


Farm: Kammiesbos/Oudebosch


Farm: Kammiesbos/Oudebosch

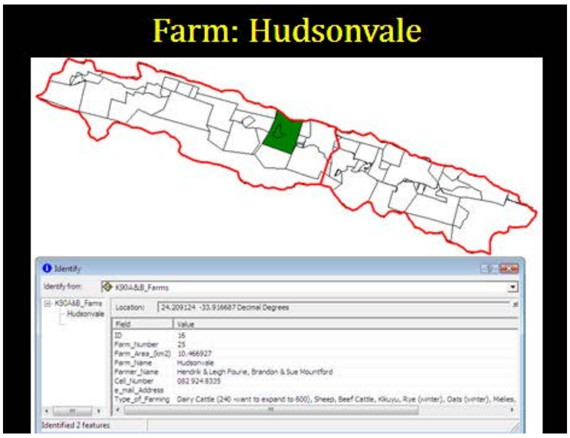

Farm: Jagersbos
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Jagersbos
Location: 24.167529 -33.916458 Decimal Degrees
Field Value
ID 12
Farm_Number 21
Farm_Area_(km2) 9.308838
Farm_Name Jagersbos
Farmer_Name Jacobus Havenga (Manager), Du Toit (Owners)
Cell_Number 072 679 7204
e_mail_Address
Type_of_Farming Swart (45) and Rooi (72) Angus (Cattle), Orchards (Pears (24ha), Plums (9.27ha), Lemons), Kikuyu, Lucerne
Identified 1 feature


Farm: Jagersbos


Farm: Jagersbos

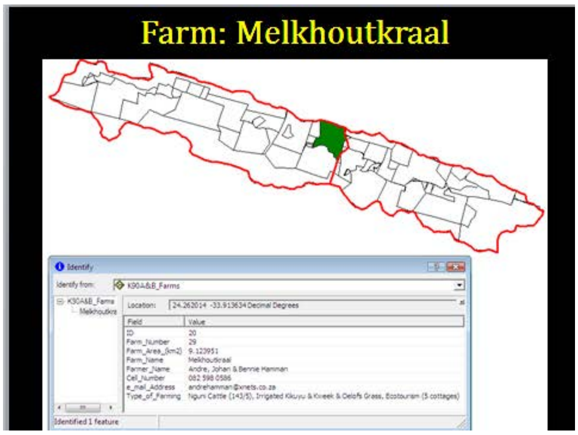

Farm: Jagersbos

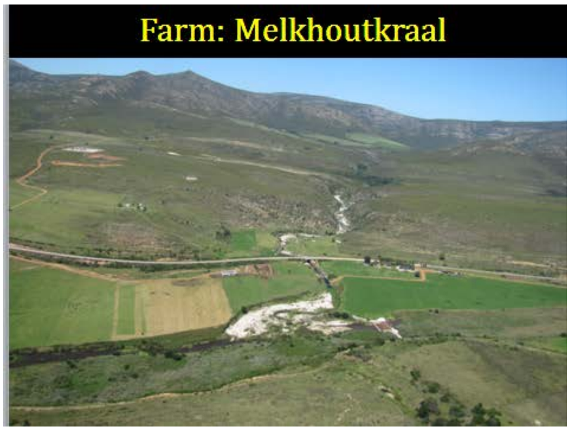

Farm: Jagersbos


Farm: Hudsonvale
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Hudsonvale
Location: 24.209124 -33.916687 Decimal Degrees
Field Value
ID 16
Farm_Number 25
Farm_Area_(km2) 10.466927
Farm_Name Hudsonvale
Farmer_Name Hendrik & Leigh Fourie, Brandon & Sue Mountford
Cell_Number 082 924 8335
e_mail_Address
Type_of_Farming Dairy Cattle (240 -want to expand to 600), Sheep, Beef Cattle, Kikuyu, Rye (winter), Oats (winter), Mielies,
Identified 2 features


Farm: Hudsonvale


Farm: Hudsonvale


Farm: Melkhoutkraal
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Location: 24.262014 -33.913634 Decimal Degrees
Field Value
ID 20
Farm_Number 29
Farm_Area_(km2) 9.123951
Farm_Name Melkhoutkraal
Farmer_Name Andre, Johan & Bennie Hamman
Cell_Number 082 598 0586
e_mail_Address andrehamman@xnets.co.za
Type_of_Farming Nguni Cattle (143/5), Irrigated Kikuyu & Kweek & Delofs Grass, Ecotourism (5 cottages)
Identified 1 feature

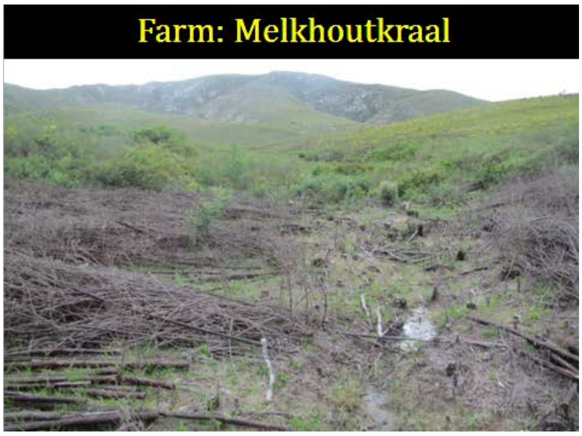

Farm: Melkhoutkraal

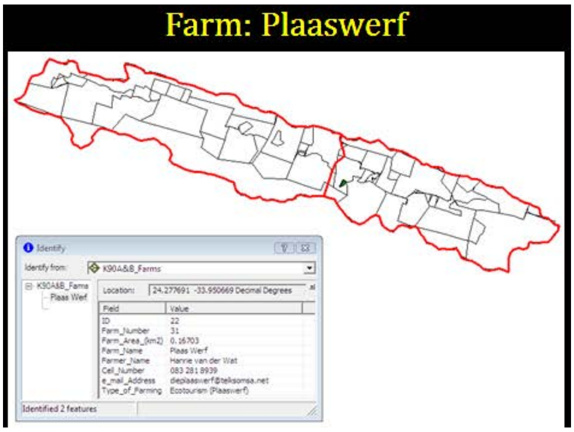

Farm: Melkhoutkraal

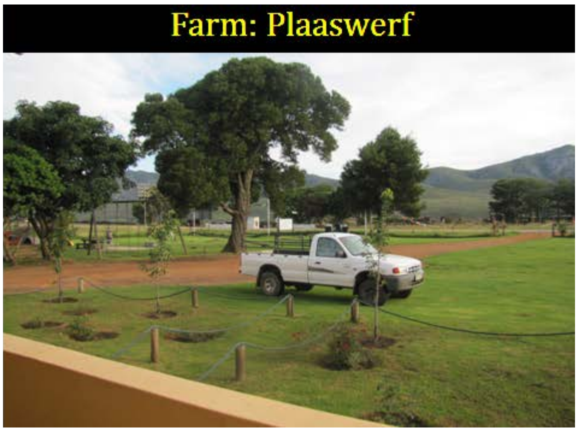

Farm: Melkhoutkraal


Farm: Melkhoutkraal

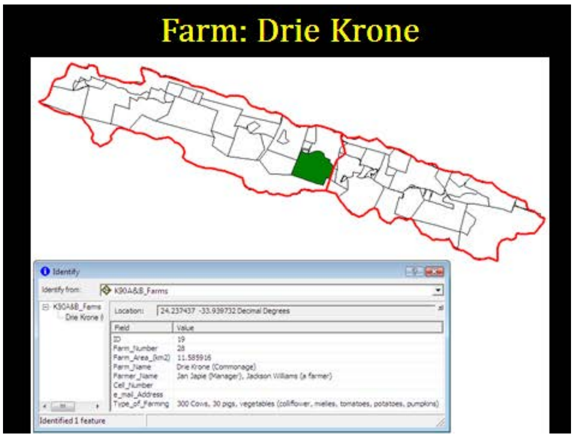

Farm: Melkhoutkraal


Farm: Melkhoutkraal

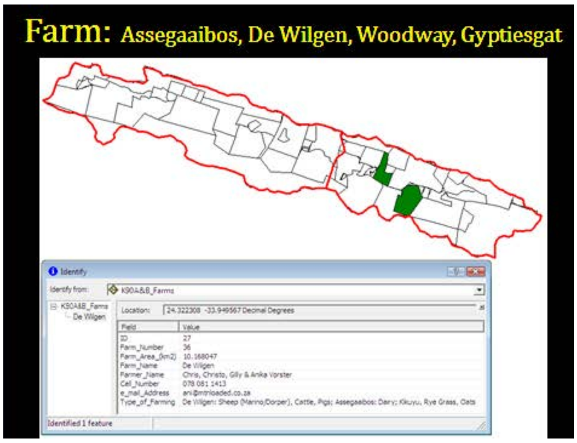

Farm: Plaaswerf
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Plaas Werf
Location: 24.277691 -33.950669 Decimal Degrees
Field Value
ID 22
Farm_Number 31
Farm_Area_(km2) 0.16703
Farm_Name Plaas Werf
Farmer_Name Hannie van der Wat
Cell_Number 083 281 8939
e_mail_Address dieplaaswerf@telkomsa.net
Type_of_Farming Ecotourism (Plaaswerf)
Identified 2 features

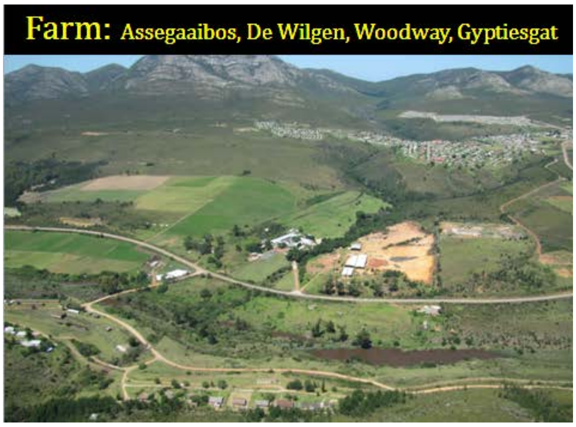

Farm: Plaaswerf

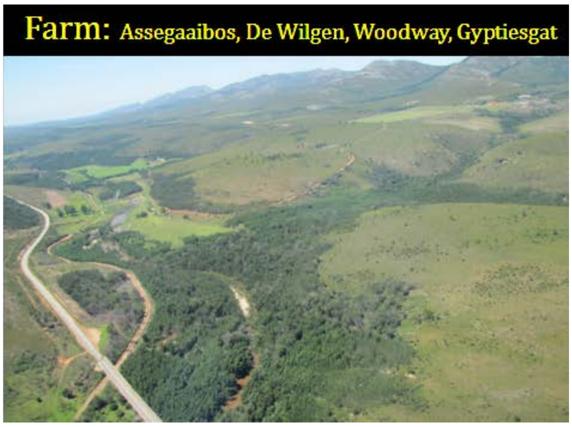

Farm: Plaaswerf

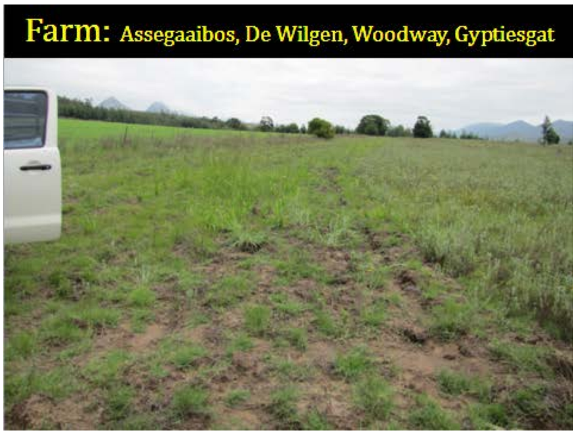

Farm: Drie Krone
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Drie Krone
Location: 24.237437 -33.939732 Decimal Degrees
Field Value
ID 19
Farm_Number 28
Farm_Area_(km2) 11.585916
Farm_Name Drie Krone (Commonage)
Farmer_Name Jan Japie (Manager), Jackson Williams (a farmer)
Cell_Number
e_mail_Address
Type_of_Farming 300 Cows, 30 pigs, vegetables (colliflower, mielies, tomatoes, potatoes, pumpkins)
Identified 1 feature

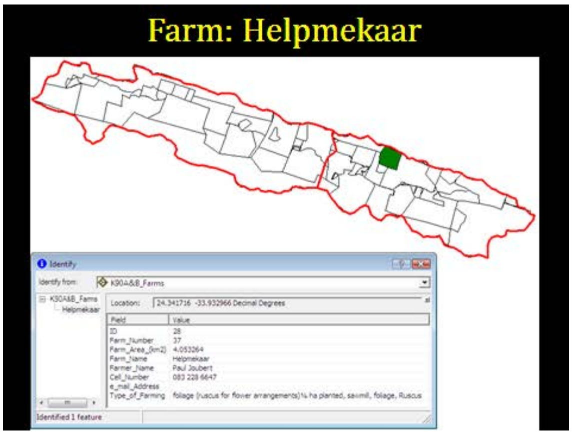

Farm: Drie Krone


Farm: Assegaaibos, De Wilgen, Woodway, Gyptiesgat
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
De Wilgen
Location: 24.322308 -33.949567 Decimal Degrees
Field
Value
ID 27
Farm_Number 36
Farm_Area_(km2) 10.168047
Farm_Name De Wilgen
Farmer_Name Chris, Christo, Gilly & Anika Vorster
Cell_Number 078 081 1413
e_mail_Address ani@mtnloaded.co.za
Type_of_Farming De Wilgen: Sheep (Merino/Dorper), Cattle, Pigs; Assegaaibos: Dairy; Kikuyu, Rye Grass, Oats
Identified 1 feature


Farm: Assegaaibos, De Wilgen, Woodway, Gyptiesgat

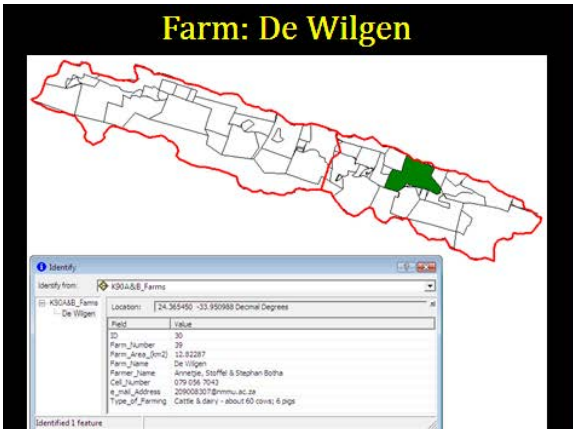

Farm: Assegaaibos, De Wilgen, Woodway, Gyptiesgat


Farm: Assegaaibos, De Wilgen, Woodway, Gyptiesgat


Farm: Helpmekaar
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Helpmekaar
Location: 24.341716 -33.932966 Decimal Degrees
Field
Value
ID 28
Farm_Number 37
Farm_Area_(km2) 4.053264
Farm_Name Helpmekaar
Farmer_Name Paul Joubert
Cell_Number 083 228 6647
e_mail_Address
Type_of_Farming foliage (ruscus for flower arrangements)¼ ha planted, sawmill, foliage, Ruscus
Identified 1 feature


Farm: Helpmekaar


Farm: Helpmekaar

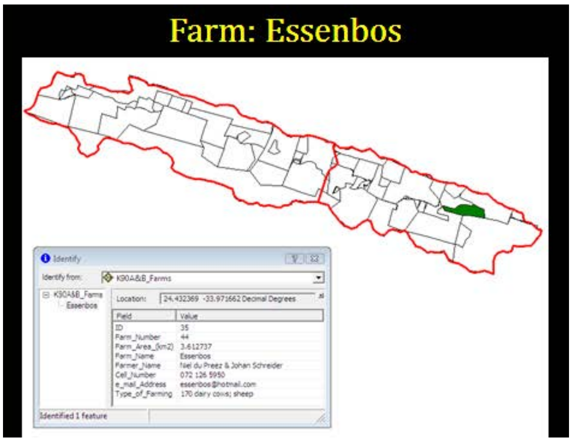

Farm: De Wilgen
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
De Wilgen
Location: 24.365450 -33.950988 Decimal Degrees
Field Value
ID 30
Farm_Number 39
Farm_Area_(km2) 12.82287
Farm_Name De Wilgen
Farmer_Name Annetjie, Stoffel & Stephan Botha
Cell_Number 079 056 7043
e_mail_Address 209008307@nmmu.ac.za
Type_of_Farming Cattle & dairy - about 60 cows; 6 pigs
Identified 1 feature


Farm: De Wilgen

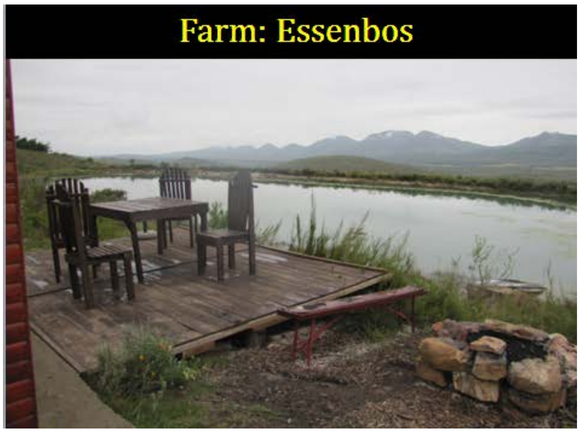

Farm: De Wilgen

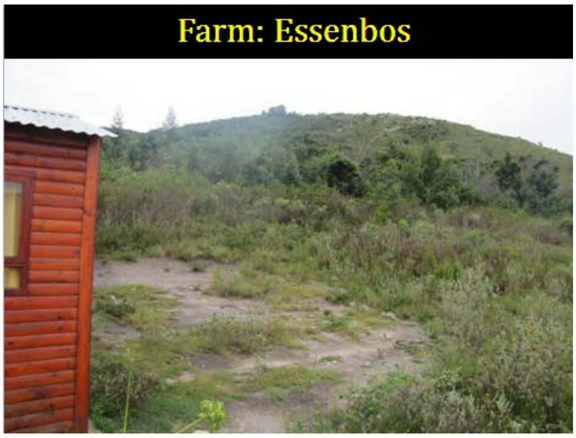

Farm: De Wilgen


Farm: De Wilgen


Farm: Essenbos
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Essenbos
Location: 24.432369 -33.971662 Decimal Degrees
Field Value
ID 35
Farm_Number 44
Farm_Area_(km2) 3.612737
Farm_Name Essenbos
Farmer_Name Niel du Preez & Johan Schreider
Cell_Number 072 126 5950
e_mail_Address essenbos@hotmail.com
Type_of_Farming 170 dairy cows; sheep
Identified 1 feature


Farm: Essenbos

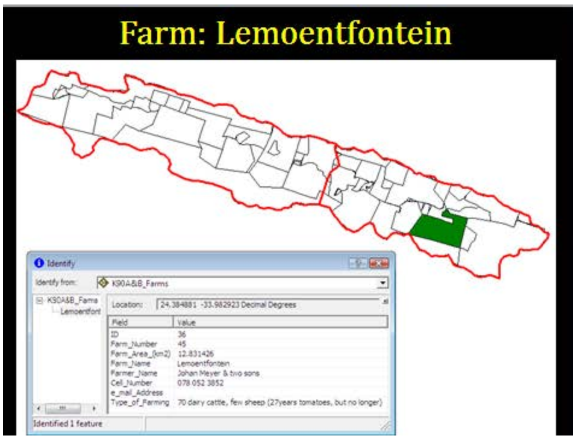

Farm: Essenbos

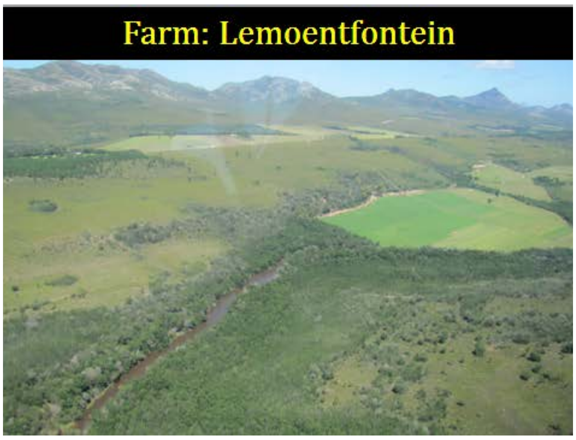

Farm: Essenbos


Farm: Essenbos


Farm: Essenbos

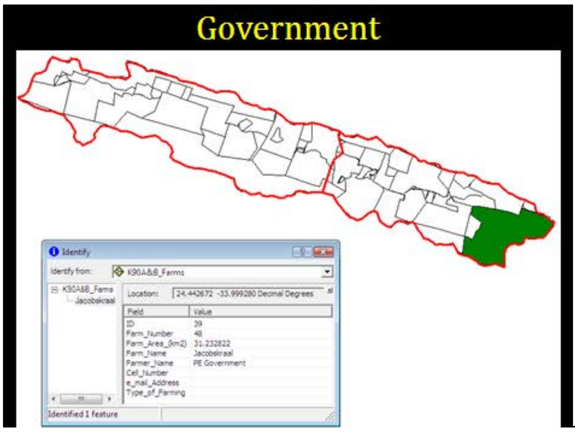

Farm: Essenbos


Farm: Lemoentfontein
Identify
Identify from: K90A&B_Farms
K90A&B_Farms
Lemoentfont
Location: 24.384881 -33.982923 Decimal Degrees
Field Value
ID 36
Farm_Number 45
Farm_Area_(km2) 12.831426
Farm_Name Lemoentfontein
Farmer_Name Johan Meyer & two sons
Cell_Number 078 052 3852
e_mail_Address
Type_of_Farming 70 dairy cattle, few sheep (27years tomatoes, but no longer)
Identified 1 feature

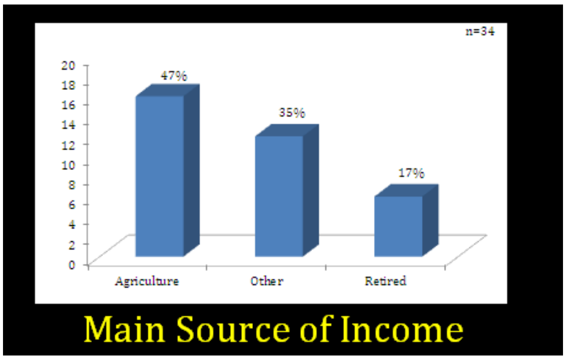

Farm: Lemoentfontein

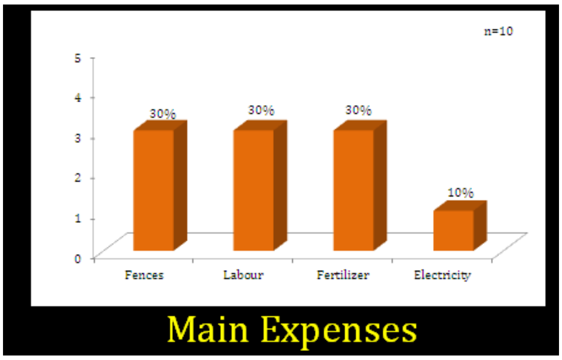

Farm: Lemoentfontein

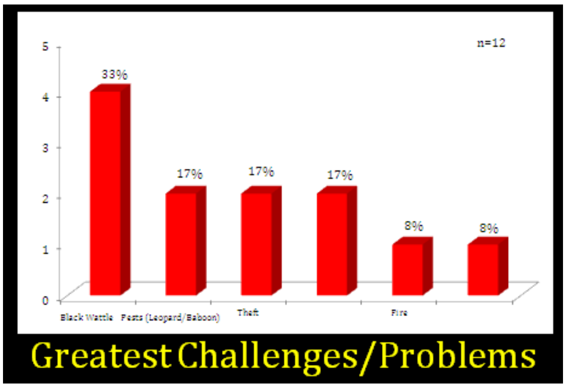

Farm: Lemoentfontein

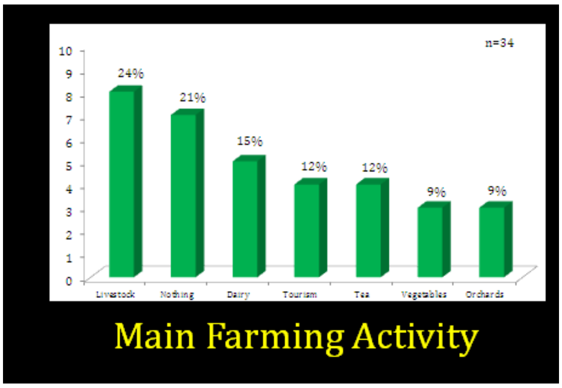


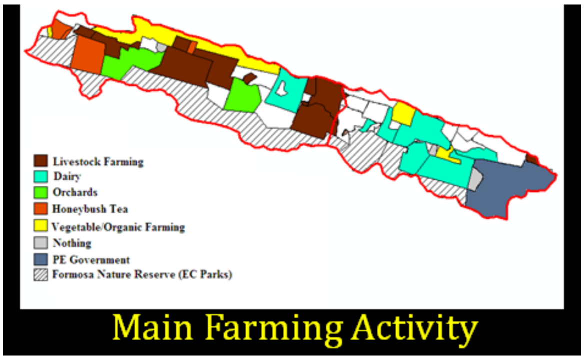
SECTION 2: Summary of the Activities in the Kromme

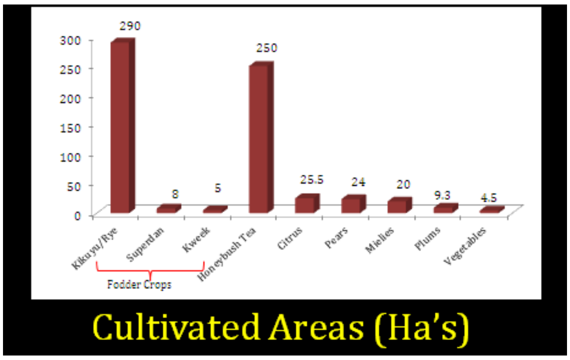


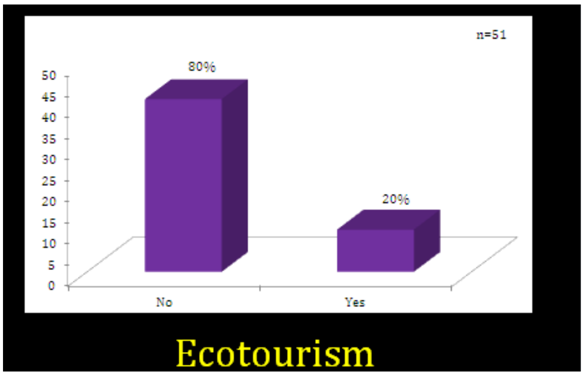


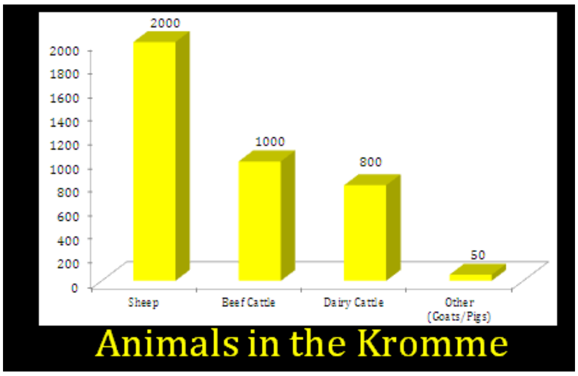


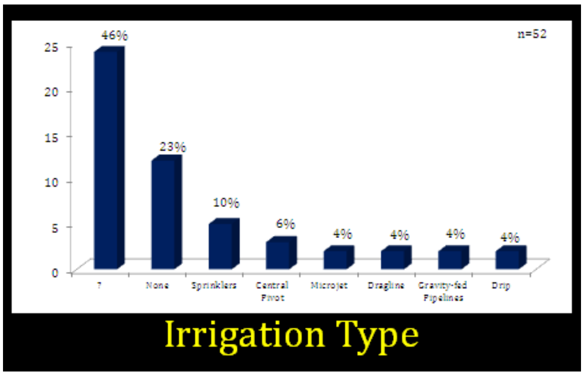


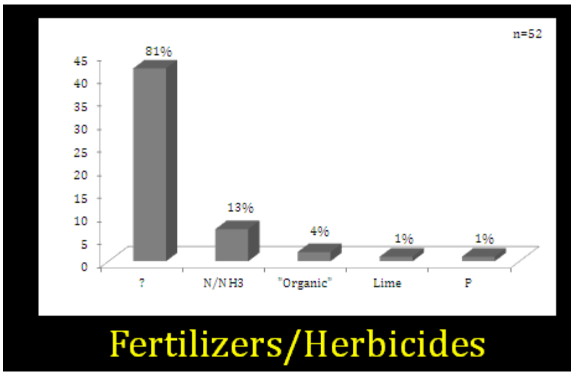

Livestock Farming
Dairy
Orchards
Honeybush Tea
Vegetable/Organic Farming
Nothing
PE Government
Formosa Nature Reserve (EC Parks)
Main Farming Activity

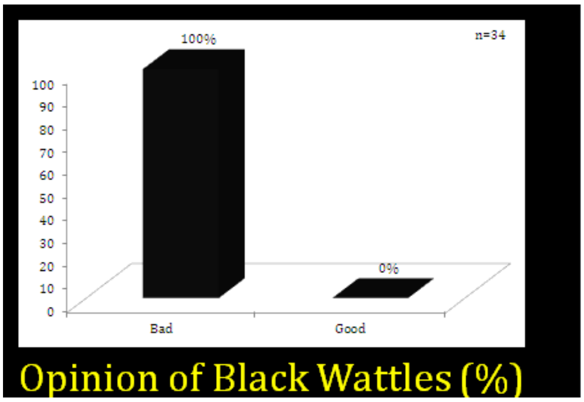

290
8
5
250
25.5
24
20
9.3
4.5
Kikuyu/Rye
Superdan
Kweek
Honeybush Tea
Citrus
Pears
Mielies
Plums
Vegetables
Fodder Crops
Cultivated Areas (Ha's)

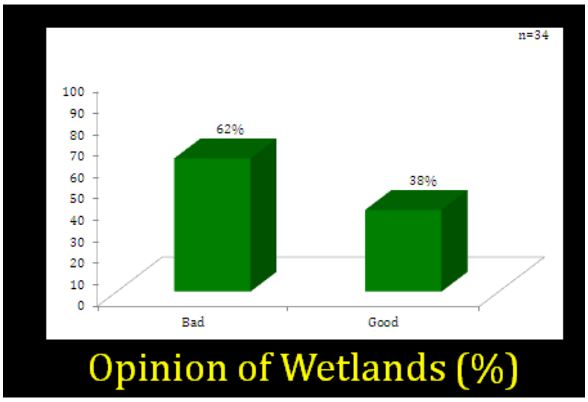

n=51
80%
20%
No
Yes
Ecotourism

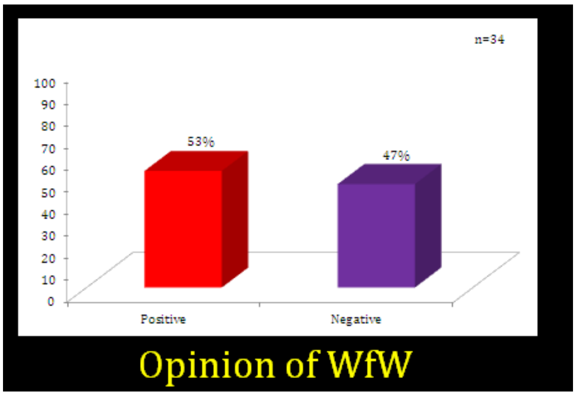

2000
1000
800
50
Sheep
Beef Cattle
Dairy Cattle
Other (Goats/Pigs)
Animals in the Kromme


n=52
46%
23%
10%
6%
4%
4%
4%
4%
?
None
Sprinklers
Central Pivot
Microjet
Dragline
Gravity-fed Pipelines
Drip
Irrigation Type


n=52
81%
13%
4%
1%
1%
?
N/NH3
"Organic"
Lime
P
Fertilizers/Herbicides


n=34
100%
0%
Bad
Good
Opinion of Black Wattles (%)

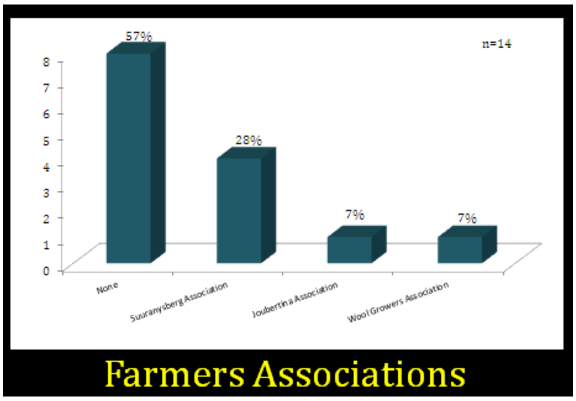

n=34
62%
38%
Bad
Good
Opinion of Wetlands (%)



Main Issues:

1. Communication
2. Theft by Labourers
3. Land Unusable
4. Slow
5. Inefficient (no follow-up)

Opinion of WfW/GIB



Main Issues:

1. Communication
2. Theft by Labourers
3. Land Unusable
4. Slow
5. Inefficient (no follow-up)

Opinion of WfW/GIB

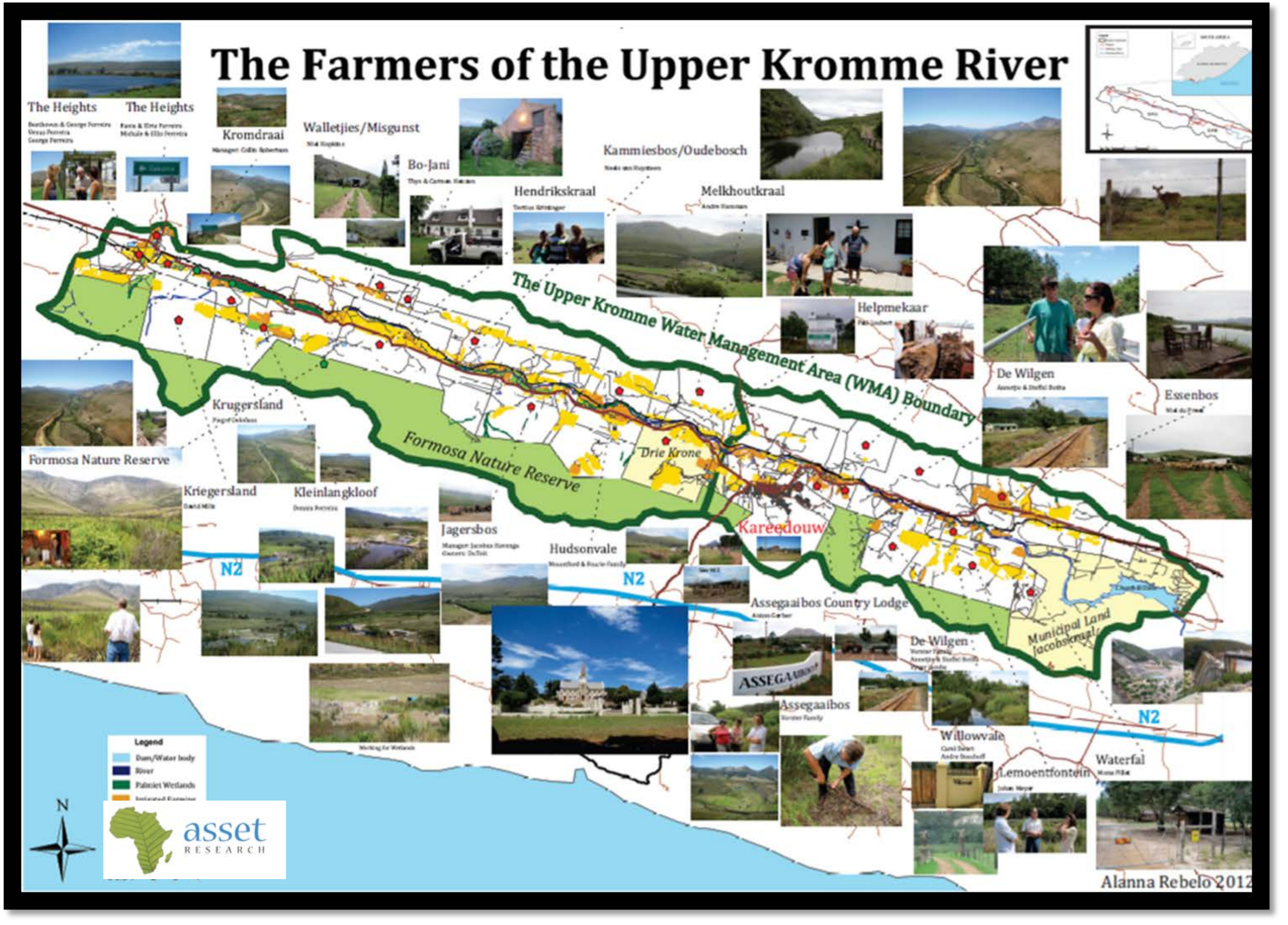


Figure A1.1: A detailed map of the farming in the Upper Kromme River

Stellenbosch University http://scholar.sun.ac.za

ACKNOWLEDGEMENTS

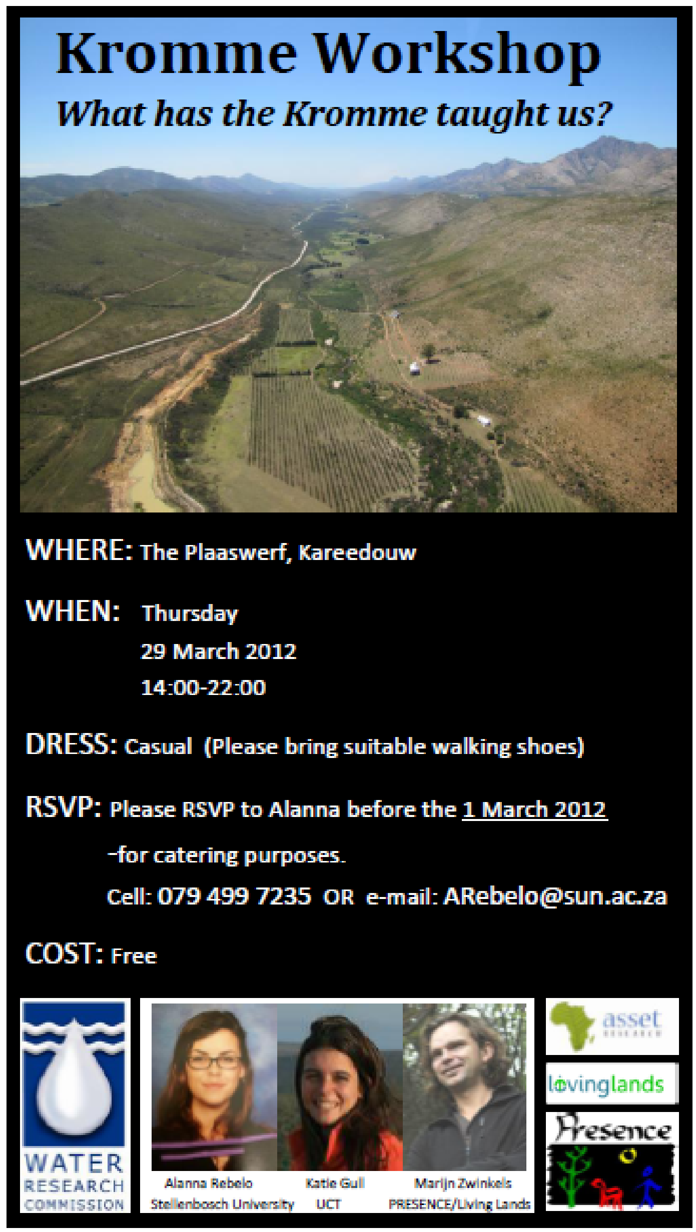
I would like to thank Katie Gull, who travelled the whole of the Kromme catchment with me for several days, spending hours drinking coffee with the Kromme farmers, trying to get to the bottom of the economic/social/hydrological setting in the Kromme. I would also like to thank the wonderful farmers themselves for their patience, hospitality and openness.

Stellenbosch University http://scholar.sun.ac.za

APPENDIX 2

The Kromme Workshop

The Kromme Workshop was held in Kareedouw, the town in the Kromme Catchment, for farmers of the Upper Kromme. Farmers were consulted in person, month in advance as to what date and time would suit them best. The following invitation, in the appropriate language, was then hand-delivered to each farmer. This Appendix contains a workshop report, summarizing key points and showcasing the day using photos.



Stellenbosch University http://scholar.sun.ac.za

29 March 2012

Kromme Workshop

Alanna Rebelo

Workshop Summary: The Workshop in Photos

Set-up: A lot of work was put in by many!

Programme (Summarised)

1. Registration & Tea
2. Networking
3. Voice of the Land (Alanna & Katie's presentations)
4. Discussion
5. Fieldtrip
6. Tea
7. Dialogue (Open session)
8. Spitbraai

Main Objectives

1. Feed back Kromme results
2. Gain a better understanding of the area
3. Allow free sharing of opinions, ideas & feelings

Workshop "Rules"

1. Nothing is "right" or "wrong"
2. Everyone is an expert
3. Respect
4. Freedom of language (English/Afrikaans)
5. *Your* learning, *your* responsibility
6. No phones

Stellenbosch University http://scholar.sun.ac.za

Networking

Workshop participants were given a short exercise where each was to choose another participant they did not know, and answer the following questions:

- Name & Organization/Farm
- What is your expectation for this workshop?
- What makes the Kromme special for you?

The Workshop Begins!

Three short presentations were given:

1. Are palmiet wetlands important?
2. What damage does Black Wattle cause?
3. The economics of the Kromme

Discussion

The presentations were followed by a constructive and informative discussion around biological control, alien invasive plants and fire management as an eradication strategy.

The farmers of the Upper Kromme also expressed their frustration concerning water rights of the Kromme River. They are forced to purchase water from the Department of Water Affairs, however they are required to improve their farming practises to improve water quantity and quality for the municipality downstream, with no financial recompense.

It was noted that working together as unit (i.e. forming a committee for the Upper Kromme), would considerably improve their ability to be able to approach government about these issues and seek resolution.

Stellenbosch University http://scholar.sun.ac.za



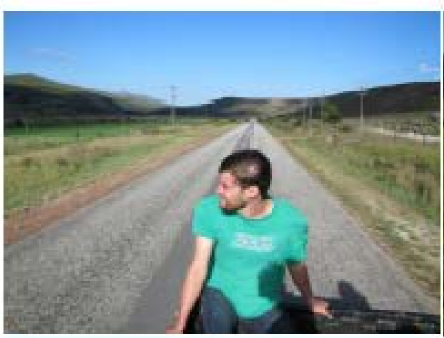



The Fieldtrip

The fieldtrip took place at Hudsonvale Farm.

Two short talks were given:

1. Wetland and erosion control structures –Mr Japie Buckle
2. Fynbos: why should farmers care? –Prof Richard Cowling







Stellenbosch University http://scholar.sun.ac.za

Open Session: Discussion

Two short talks were given:

1. The Living Lands Project in the Baviaanskloof was also presented in this session
   -by Marijn Zwinkels
2. Opportunities and assistance for farmers was also briefly presented
   –by Alanna Rebelo

Main Objectives:

1. Find ways to assist Kromme farmers
2. Find opportunities to restore the land
3. To find a solutions where *both:*
   a. Farmers are able to generate income
   b. The land is used in a more sustainable manner
4. To start a process where all stakeholders can learn together

Stellenbosch University http://scholar.sun.ac.za

Main Messages, Actions & Next Steps

☑ **The need to start a "Kromme River Communication Forum" or committee.**

-This would provide a place where farmers/landowners could communicate and discuss main objectives and organise further actions (Mr Andre Hamman – Melkhoutkraal Farm).

-A forum like this would lead to better co-operation between the landowners and WfWetlands, WfWater and other organisations since there is no farmers association representing the farmers' interests (Mr Japie Buckle –Working for Wetlands).

-This would soon be necessary anyway (DWA requires a Water Users Association to be established in each South Africa Catchment) (Dieter van den Broeck).

-The strong opinion was to form a committee immediately (Mr George Ferreira, Mr Johan Hamman, Mr Andre Boshoff, Mr Niels van Huysteen, Mr Thys Henzen)

-It was pointed out that the function, goals and objectives for this committee should be defined. A spokesperson should also be selected, who should communicate with WfWater on behalf of the farmers (Mr Anton Gerber – Assegaaibos Lodge).

-Some initial issues:

- Alien clearing is not done in a scientific way
- Follow-ups are not done on time and sometimes not at all.
- Communication with WfWater is lacking

-Two farmers were selected as representatives for the new committee:

Mr Johan Hamman (Melkhoutkraal)
Mr George Ferreira (The Heights)

☑ **The need to improve communication within the farming community**

-It was suggested that a local newspaper be used to publish relevant communications (Mr Andre Hamman, Melkhoutkraal Farm)

-Newspapers that were suggested were: "Die Burger" and "The Kouga Express" as they are widely known and read in the area.

-However concerns were expressed in terms of the research perhaps alerting government to the potential of the area, and planting ideas for the government to reclaim farms in the area (Mr Chris Vorster -De Wligen Farm).

☑ **The Kromme Farmers to Reduce Water Use**

-The importance of protecting water supplies and the importance of working together towards this goal was highlighted (Mr Andre Hamman, Melkhoutkraal Farm)-

☑ **Learning by example: a trip to the Baviaanskloof Farmers**

-Once the farmers had leant that Living Lands had worked together with farmers in another catchment (the Baviaanskloof) they were very curious to see the results and meet with the farmers themselves. It was agreed that Learning Lands would organise such a trip in the future (Mr Chris Vorster -De Wligen Farm)

Stellenbosch University http://scholar.sun.ac.za

Time to Relax: Spitbraai

Acknowledgements

Organisers:
Ms Alanna Rebelo
Mr Marijn Zwinkels
Mr Byron-Mahieu van der Linde

Speakers:
Prof Richard Cowling
Mr Japie Buckle
Ms Alanna Rebelo
Mr Marijn Zwinkels

Workshop Facilitator:
Mr Dieter van den Broeck

Camera & Video:
Mr Byron-Mahieu van der Linde

Living Lands Volunteers:
Ms Lisa Nooij
Ms Nikolett Czegledi

Organisations:
Living Lands
CAPE
WoFIRE
WfWater (Cape Town)
WaterWheel (Lani van Vuuren)
EC Parks

Main Funder:
ASSET Research

Journalists:
Mr Roelof Bezuidenhout (Farmers Weekly)

Stellenbosch University http://scholar.sun.ac.za

APPENDIX 3

A history of the land-use of the Kromme

Present land-use

The total area of the Kromme River Catchment is 155 631 ha (Mander et al. 2010). The area is extensively transformed, especially in the lower estuarine reaches where there are a number of tourist resorts. The catchment is invaded with alien plants, with over 60% reported to be infested over a decade ago (Carpenter 1999). The upper reaches of the river are mostly privately owned and farmed (28 544 ha) (with drylands or old cultivated fields comprising 9 862 ha), and only 8 062 ha are owned by the state. Farming in the catchment is predominantly intensive fruit, vegetable and large livestock farming. Some farmers are taking advantage of ecotourism and a few game and holiday farms have been developed to attract tourists. There are few towns and informal settlements in the catchment, the largest Kareedouw, comprising 3 708 ha. Wetlands are extensive, making up 1 077 ha of the catchment; however most are heavily degraded or completely transformed. There are large areas of degraded vegetation, making up 13 325 ha, whilst 3 350 ha of this is reported to be as a result of alien invasion (SANParks 2009, Skowno 2008).

Large areas of natural vegetation do still exist (10 205 ha), some within the Formosa Nature Reserve in the upper reaches of the river (Figure A3.1). Fynbos is the dominant vegetation type (56 804 ha), followed by grassland (15 479 ha), thicket (12 087 ha), renosterveld (11 366 ha) and forest (2 734 ha) (Vlok et al. 2008). The dominant vegetation on the peat beds is palmiet (*P. serratum*) with smaller patches of ferns, grasses, reeds and sedges (Haigh et al. 2002). Peat beds develop above the alluvial fans where the sub basins form. The peatland complex, fen, have formed over a period of 5000 years. Two western peat basins cover 240 ha, whilst an eastern peat basin covers 150 ha. The mean thickness of the peat is approximately 1.6 m, ranging from 0.5 m to 2.8 m. The total volume of peat was estimated to be 12.9 Mm^3. Peat beds are being destroyed by agriculture, ploughing of the wetlands, the removal of palmiet, water abstraction, draining,

Stellenbosch University http://scholar.sun.ac.za

donga and headcut erosion, the construction of dams, roads, railway lines and fences, alien plant invasion and peat fires (Haigh et al. 2002).

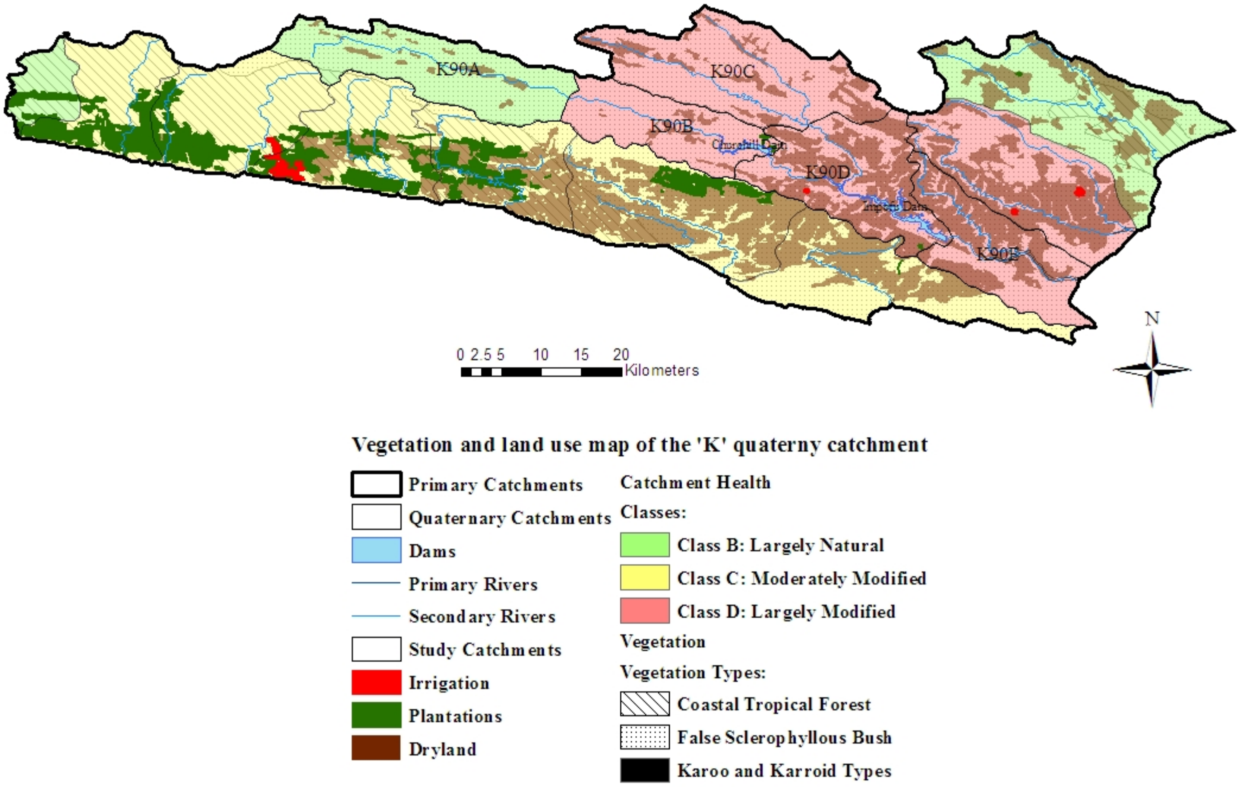


Figure A3.1: Catchments K90A-E (Eastern Cape) divided into land-use types (irrigation, plantation, dryland), catchment health and broad vegetation type (Middleton & Bailey 2008).

The Kromme River System has two major impoundments; the Churchill Dam (with the adjacent Churchill Water Treatment Works) and the Impofu Dam (with the adjacent Elandsjagt Water Treatment Works) (Figure A3.2).

Stellenbosch University http://scholar.sun.ac.za

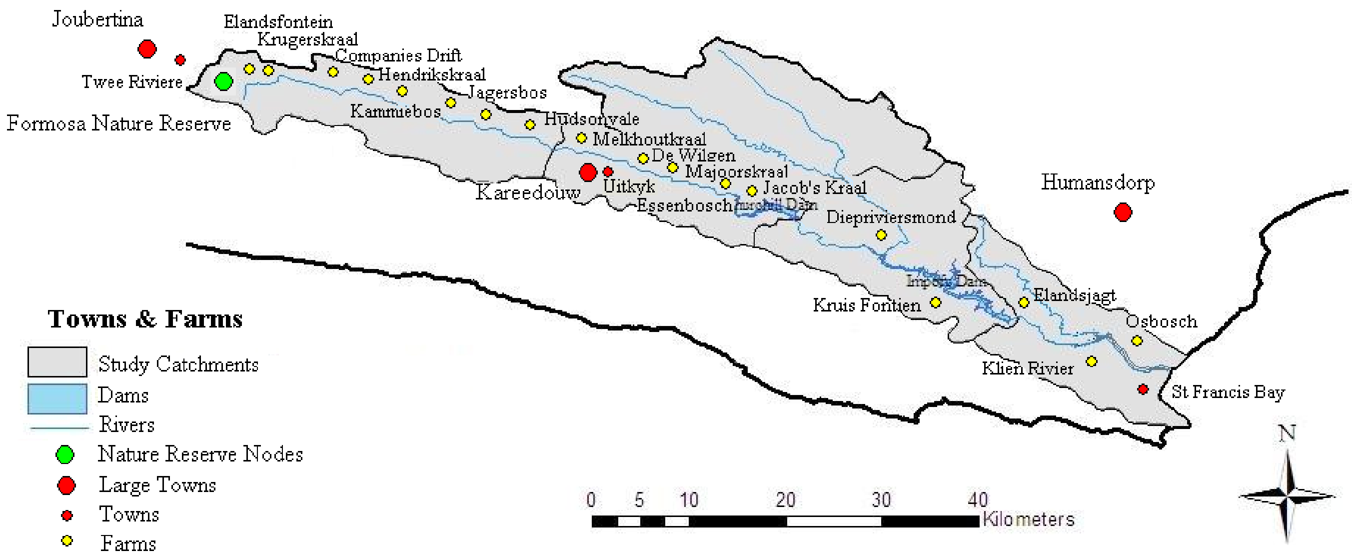


Figure A3.2: Towns, settlements and farmsteads along the Kromme River, in catchments K90A-E (Eastern Cape).

History

This history was compiled using three primary sources, Haigh et al. (2008), Raymer (2008) and Skead (2009). Haigh et al. (2008) used a number of sources, including the National Archives in Cape Town, travel writings of early explorers, annual reports from the Cape Colony and Cape Province and interview conducted with land owners. Raymer (2008) used a number of newspaper articles, the City Engineers Annual Reports (1907-1991), the Mayor's Annual Reports (1903-1945), Official Council Brochures, Municipal Files and Departmental Records (1930-2006), and various Bills, Acts, and Proceedings of Select Committees of Parliament. Skead (2009) is a compilation of records and diary extracts of travellers and settlers in South Africa dating from 1700 to 1848.

Pre-1940: Colonization era

Settlers began acquiring grazing rights for the region as early as 1775. According to records, timber began to be shipped from the Kromme Catchment to Cape Town, via newly built harbours in Plettenberg Bay and Mossel Bay in 1787. Before the 1820s Port Elizabeth (PE) comprised only Port Fredrick, a mission station at Bethelsdorp. However in the 1820s, the British Settlers

Stellenbosch University http://scholar.sun.ac.za

landed in PE and the population began to grow until, in 1861, the PE Municipality was formed. In 1869, a precursor to the R62 was built from Avontuur to Kareedouw, which only crossed the Kromme River twice, by bridge and by causeway. The previous route required travellers to cross the river eight times. Before the 1880s, no house in PE had running water.

In the first half of the twentieth century, the most common farming practices in the region were orchards and grazing. In 1905, Kareedouw, the main town in the Kromme River valley, became established. The following year the railway line through the catchment (at the base of the Suuranysberg watershed) was completed, with a station at Jagerbos. This allowed for an intensification of farming. Planning for the construction of the Churchill Dam began as early as 1928. In 1930, 1931, 1932, 1936 exhaustive surveys, studies and reports on the Kromme River system were undertaken in preparation for the dam. Between 1930 and 1940, farming in the region changed to soft fruit orchards on the fertile floodplains, which had previously been wetlands. However in 1931, massive floods ripped out orchards along the Kromme River banks and caused severe erosion. As a result, many farmers turned to pasture, meat and dairy production. After the 1931 floods, black wattle trees were reported to have appeared in great numbers all along the course of the Kromme River. Four good years of rainfall following the 1931 flood ensured black wattle establishment. In 1935, famers started planting kikuyu (*Pennisetum clandestinum*) on the floodplains as a pasture grass. Indigenous rooigras (*Themeda triandra*) was ploughed over for the production of grains and vegetables.

In 1937, the proceedings for the construction of the Churchill Dam commenced at the Water Court. The following year, authority was granted for the building of the dam. In 1939 the contract for the building of the dam was awarded. The preparation and set up at the proposed dam building site commenced in 1940.

Diary Extracts (Source: Skead 2009)

1772-1773 Thunberg, C. P.

Upper Langkloof, near Uniondale:

"The land in the Lange Kloof is bare, and without any shrubs or bushes, but abounds much in grass."

Stellenbosch University http://scholar.sun.ac.za

1772-1773 Thunberg, C. P.

Essenbosch, 33km west northwest of Humansdorp:

"...arrived at Essebosch, a fine forest in almost a plain and level country"
"The bread tree (*Encephalartos caffer*) is a species of palm or cycad which grows on the hills below the mountains, in these tracts"
"The berries of the guarri bush (Euclea undulata) had a sweet taste and were eaten by the Hottentots"
"...we proceeded to Essebosch, a pretty, neat, little wood which has acquired its name from the large trees, *essenboom* or ash trees, Ekebergia capensis, that grew there, the leaf of which resembles the European ash. Large fig trees too, *Ficus capensis*, the fruit of which is eaten by the baboons, grew here in abundance."

1775 Sparrman, A.

Upper Langkloof, Uniondale

"In the neighbourhood of the Brak-rivier which, he says, is where the Langkloof begins, as well as in other places in the Langkloof they made great complaints about the piss-grass mentioned as growing in Attaquaskloof [40 km northwest of Mossel Bay] though nobody could, with any degree of certainty, point out any particular herb as coming under that denomination".

Essenbosch

"The name of Essen-bosch is given to a kind of woody tract along the Essen River which, as well as the wood, has taken its name from the *esse* or ash tree, *Ekebergia capensis*".

1804 Lichtenstein

Near Kromme River, eastern Langkloof

"We rested near the river under the shade of some small trees of *kruppelholz, Protea conocarpa* [*Leucospermum conocarpodendron*]".

1816 La Trobe, C. I.

Upper Langkloof, after passing over the mountains at Perdekop

"Barren as these mountains in general appear, they yet afford a rich harvest for the botanist, and we found several curious plants unknown to our best botanist, Mr Melville. In some places, the rugged sides of the hills are clothed with aloes and other larger plants, and as we proceeded we saw on many hills the so-called *wageboom* growing dispersed [*Protea nitida*] resembling a planted orchard, the trees standing fifteen or twenty paces asunder".

First impression of Langkloof: "a vale of perhaps 100 miles enclosed by mountains of different heights. On entering it we felt not a little disappointed ... we saw a long ridge of comparatively low hills, divided by narrow parallel kloofs, without wood or water, skirting a dull uncultivated vale...".

Essenbosch

Pitched tent "... on a grassy spot surrounded with bushes and defended by high trees against wind..."

Stellenbosch University http://scholar.sun.ac.za

1816 La Trobe, C. I.

East of Jagersbosch

"... we saw a country before us apparently level but full of dells and gullies. The great variety of bushes and flowering shrubs on all sides attracted our attention. Large aloes [*Aloe ferox*] are interspersed among the bushes and, with their broad leaves, form a striking contrast to the many small-leaved evergreens which surround them. Some of them were in full bloom, towering above the thicket, and one, more perfect than the rest, was brought into the wagons".

"... this country, unproductive as it generally is in means of subsistence for man and beast [is clothed] with an astonishing profusion of vegetable beauty. Hardly a spot exists upon which some curious and beautiful plant does not rear its head in its proper season; and in the midst of this brown desert we see the magnificent chandelier or red-star flower, measuring from four to five inches, to a foot and a half in the spread of its rays growing luxuriantly among the stones [*Brunsvigia littoralis*]".

1820 Moodie, J. W. D.

Langkloof

"I had now entered the Langkloof... which extends for more than 100 miles between two parallel ranges of mountains, or rather mountains on one side and high grassy hills on the other".

West of Gamtoos River

"The eastern extremity of the Lange Kloof opens into the valley of the Kromme River [18 km west of Humansdorp], and here the scenery again becomes interesting and romantic... The pasturage along the banks of the Kromme River is everywhere of that coarse description which is distinguished by the term 'sour' by the colonists".

1838 Backhouse, J.

Upper Langkloof over the mountains behind George:

"In the evening we pursued our journey in the Lange Kloof which is an extensive valley between ranges of lofty hills with farms at distant intervals wherever there are little streams to fertilize the ground which is generally dry pasture compose more of bushes than of grass".

Lower Langkloof, near Krom River:

"We emerged from the Lange Kloof by a steep descent to the upper part of the Krom Rivier... The vale of the Krom Rivier is narrow. In some places the head of the river extends from the hills on one side to those of the other side and is choked with palmit [*Prionium serratum*]. The quantity of water was so small as only just to be traced in a flowing state in a few places". [27 November]
"The hills, both here and in the adjacent parts of the Lange Kloof were besprinkled with a glaucous-leaved protea forming a small tree [probably *Protea nitida*]"
"In a stony place on one of the hills the noble Cyrtanthus obliquus was in flower."

Stellenbosch University http://scholar.sun.ac.za

1838 Backhouse, J.

Krom Rivier:

"Three Fingo women stopped where we outspanned... they were eating the root of *Cussonia*, an arborescent shrub belonging to the same natural order as the ivy; the leaves were palmate and the root is about as thick as a man's arm, tender and white."
"The Coloured people eat likewise the roots of the blue waterlily, *Nymphacaea capensis [Nymphaea nouchali]*, which abounds in some of the pools of the Krom Rivier, along with *Villarsia indica* [*Nymphoides indica*] a smaller plant with yellow-fringed blossoms. The magnificent flowers of the blue waterlily exhale an odour resembling that of the violet".
"Fine specimens of *Virgilia capensis* [*Virgilia oroboides*], a small tree with fragrant, pink, pea-like flowers were growing near some streamlets".
"The blue Africa lily, *Agapanthus umbellatus* [*Agapanthus praecox*] was in flower in moist places".
"An aloe with a trunk rising to 8 feet high, though not in flower, formed a striking feature among the bushes on the adjoining hills".

1838 Bunbury, C. J. F.

Langkloof:

"The country was extremely arid except along the course of the little streams, and on the hills near the younger Kamper's residence the bushes had been burnt to a considerable extent, a practise general in this country and advantageous to the cattle but very provoking to the botanist". (30 March)
"Here, however was plenty of that curious plant called by the colonists *paarde kapok*, or horse-cotton, *Lanaria plumosa* [*Lanaria lanata*] with its stem and flowers enveloped in a dense woolly coat of singular whiteness. A beautiful everlasting, the *Helichrysum foetidum* bearing a profusion of golden yellow flowers, is common along the edges of streams in the Long Kloof, together with the graceful and pretty shrub *Gnidia oppositifolia*"
"On the parched and barren hills which bound the Long Kloof, a few species of everlastings were the chief plants in flower at this season; and another of the same tribe, *Metalasia muricata* is as common along the road all through this kloof and indeed throughout the Districts of Zwellendam and George, as the ragwort is in England".
"Different species of Restio form the principal part of the herbage, both on the hills and along the sides of the streams. In most rivers is an abundance of our common reedmace or bulrush *Typha latifolia* which appears to be as truly wild here as in Europe".

Central portion of the Langkloof:

"This long valley, although crossed by numerous streams, is on the whole of a remarkably arid and monotonous appearance. Indeed, short of actual desert, I can hardly imagine anything more wearisome: not a tree, not a house, or a trace of civilization for miles together; scarcely a bush above 3 feet high; nor a tinge of green except along the margins of streams whose course is indicated by a narrow strip of reeds and rushes. A great part of the ground is covered exclusively with the melancholy grey rhinoceros bush [*Elytropappus rhinocerotis*]. The mountains on the south are extremely steep and rugged ... like the cliffs of Table Mountain, without a tree or blade of grass. The streams ... are numerous and, though small, are never entirely dried up. An industrious and enterprising people would have turned them to good account in irrigating land. As it is, I travelled through the Long Kloof at two different seasons, and both times it appeared equally barren". (31 March)

Stellenbosch University http://scholar.sun.ac.za

1838 Bunbury, C. J. F.

Krom Rivier valley 64 km east of Diep River at Jagersbosch:

"... rugged stony and barren hills ... the hill immediately behind the house which abounds with Proteaceae and heaths, and promises a good harvest of plants in a more favourable season. I gathered a leucospermum [*Leucospermum cuneiforme*]" which I had not before seen in flower. I have seen no acacias since we crossed the Great Doorn River on the morning of 29 March".
"The hills near Jagersbosch abound with the small tree called *wagenboom* [*Protea nitida*] which was indeed common in many parts of the country we had traversed, but this was the first time I saw it in flower. It is one of the largest kind of Protea, for though it does not attain such a height as the silver tree, it is fully as thick in the trunk. A beautiful sugarbird of a golden-green colour with scarlet breast was here perched on its flowers, climbing about them and thrusting its slender beak into every floret."
"The moist hollows between the hills, as well as the valley of the Kromme River, were nearly filled with the palmiet rush [*Prionium serratum*], a common plant throughout the country we had traversed from the Hottentot Holland Mountains eastward. It is eminently a social plant growing very thick together and forming large masses unmixed with anything else. In its herbage and general appearance it is quite unlike a rush and has more the look of an aloe or of the crown of a pineapple mounted upon a thick, black spongy stem which varies in height from less than a foot to 3 or 4 feet according to the depth of water in which it grows".

1839 Krauss, F. In Sphor

Upper Langkloof:

Krauss went down into the Langkloof. "The main vegetation was again *kreupelbome,* [*Leucospermum cuneiforme*] but also bulbous plants and particularly the beautiful amaryllis [*Amaryllis belladonna*] adorned the countryside".
"On March 3rd I travelled from the Landkloof across a steep rise into teh narrow valley of the Kromme River ... the river was densely overgrown with palmiet reeds and is very marshy".

Jagersbosch:

Arrived at Jagersbosch, deep in the mountains: "... here I found a few specimens of a pretty plant with a flower rising from the centre [*Cussonia spicata*]".

1940-1996: Degradation era

After 1942, agricultural activities tended towards the production of soft fruit and vegetables, but dairy and sheep farming remained important. With the increase in economic pressure, destructive framing practises, such as over-grazing and the draining of floodplains for larger

Stellenbosch University http://scholar.sun.ac.za

orchards, increased. When the first aerial photographs were taken in 1942, the Kromme River Catchment was already transformed to a degree by agricultural activities. In 1943, the construction of the multi-arched Churchill Dam (able to hold 2.961 billion litres of water), was completed. The first test of the Churchill Dam took place in 1944, which was a high rainfall year. The dam filled overnight to a depth of 27 m and a few days later overflowed.

In 1945 people began to harvest the black wattle bark for use in the tannery in George. The Kromme River Scheme (Churchill Dam and the Churchill Water Treatment Works) only officially opened in 1948 because it was only fully commissioned in 1947 as a result of the war. Only a year later, in 1949, a second pipeline to Churchill Dam was proposed. In the 1950s extensive bridge construction began. Between the period of 1954 and 2003, the Kromme River straightened out and became less braided and sinuous. In this same period the channel was recorded to have doubled in overall width. Several years prior to 1954, the rainfall was unusually high and in 1956 a massive flood event occurred. The Churchill Water Treatment Works were also flooded and supply was disrupted. The second pipeline to the Churchill Dam was commissioned the same year. In 1957, pipe-laying commenced, cutting the river eleven times. The same year, extensive cracking of the downstream face of the Churchill Dam occurred.

In the 1960s extensive road construction began, and from 1961-1969, the old road was re-laid and tarred. This construction damaged the catchment, as a stream was re-routed for a bridge to be built, and the whole process resulted in sedimentation. In 1961 a pump station was constructed, and the following year the second pipeline became fully operational. The same year a carbonation bay (to stabilize raw water) was constructed at the Churchill Dam. In 1963 a safety report on Churchill Dam was released and work on strengthening the dam was completed the same year.

In 1964 and 1965, there was heavy rainfall which resulted in a massive flood which swept away orchards and fences. After this flood event, farmers in the catchment raised the banks of the river, causing massive erosion, in a futile attempt to reduce future damage. In 1968 there was another year of heavy rainfall and another massive flood event. During the period 1970 to 1986, the deterioration of wetlands increased markedly. In 1970, preparations for a second dam lower

Stellenbosch University http://scholar.sun.ac.za

down on the Kromme River began. Further years of heavy rainfall occurred in 1971, when the Churchill pipelines were again disrupted, in 1974 when a headcut was reported to have moved back 500 m, and in 1977 when the Churchill pipe bridge was reported to have been washed away. In 1979 construction on the second dam on the Kromme River commenced.

Between the years 1980 and 1985, a drought occurred, which reduced the vegetation cover of the catchment. In 1981 the biggest series of floods in record occurred, with three floods in one year. The impacts of this flood event were exacerbated as a result of the low vegetation cover from the drought. The Churchill pipelines were also washed away. The year before the floods, a contract for maintenance work on the Churchill Dam and pipes was awarded, thus maintenance and inspections began in 1981. In 1982, Elandsjagt Dam was completed and in another major flood the following year, the dam was filled.

Between the period 1983 to 1990, side roads leading to several farms (Walletjies, Kammiesbos, Jagerbos and Hudsonvale) were built. In 1985, Elandsjagt Water Treatment Works officially opened. By 1986, half of the valley floor had reportedly been transformed. In 1988 the walls of the Churchill Dam cracked a second time as a result of an alkali aggregate reaction. Another year of drought followed in 1989. Post apartheid, in 1994, an influx of people into Kareedouw, the biggest town in the Kromme River valley, began. Some 70% of the people are unemployed and living off grants. In 1996, the largest recorded floods occurred, breaching the tar roads and causing severe damage to infrastructure and farms downstream.

Post-1996: Restoration era

In 1996, WfWater began clearing aliens in the Kromme River Catchment. This clearing revealed the extent of the damage to the wetlands, which included extensive instream gullying (especially in the peat basins) and widespread river bank erosion. In 2000, a project called Working for Wetlands began mechanical restoration of the Kromme River. A series of rock gabions built in the upper catchment were completed in 2002. A gabion and two concrete/rock structures were built in Companjesdrift and completed in 2005. A rock gabion weir and spillway were built at Hudsonvale between 2000 and 2003. Three concrete structures and three spillways were built at Krugersland in 2001 and completed in 2003. According to a survey conducted in

Stellenbosch University http://scholar.sun.ac.za

2001, 65% of the Kromme River Catchment was natural, 29% agricultural, 6% degraded, and almost 1% urban. In 2001, wetlands on the farm Hudsonvale were deemed to be in good condition, due in part to the kikuyu pastures in the seasonal zone, but mostly a result of the rehabilitation structure completed by WfWetlands.

In 2001 another flood occurred. By 2003, over half of the land adjacent to the marsh wetlands in Krugersland was transformed. The land at Companjesdrift was invaded by alien vegetation by 2000 and the marsh had been destroyed. By 2003, all wetlands had been converted to floodplains/riparian zones. In 2003, 13 weirs were constructed, and in 2004, a further five. In 2004, flash floods damaged the Churchill pipelines. Between 2004 and 2006, two weirs were constructed and in 2005 two gabions built above the tributary at Hendrikskraal. In 2005 five weirs were constructed and between 2006 and 2007, a concrete/gabion structure was built at Kammiesbos. In 2006, extant marshes persisted at Krugersland, and Companjesdrift was in good-excellent condition due to removal of alien vegetation and rehabilitation structures constructed. Another large flood event occurred in 2006. Construction for the desludging process began in 2005 and was completed in 2006. A smaller flood followed in 2007, and a further four gabions were constructed.

In 2007 a survey showed that from the palmiet wetlands at the upper reaches of the Kromme River, to the town of Kareedouw, intensive farming of vegetables and livestock occur. From Kareedouw to the charcoal factory, there are six oxidation ponds, factories and low-cost housing areas. From the charcoal factory to the Churchill Dam, land-use is primarily agricultural and grazing, although stretches of palmiet do occur. From Churchill to Impofu Dam, the land is largely inaccessible due to the confined nature of the valley, with steep mountain ridges to the east and west, and the two dams forming physical barriers to the north and south respectively. However one dairy farm exists in the area. From the stretch of river from Impofu Dam to the estuary, the primary land-use is dairy farming. The primary land-use in the Diep River Catchment is cattle farming. The most recent assessment of land-use in the Kromme River Catchment prior to this study, can be seen in Figure A3.1.

Stellenbosch University http://scholar.sun.ac.za

REFERENCES

Carpenter, R. C. 1999. An economic analysis of eradicating alien vegetation as an alternative to conventional water supply schemes: a case of the Krom and Kouga. MSc Thesis. Rhodes University, Grahamstown, South Africa.

Haigh, E. A., P. L. Grundling, and P. M. Illgner. 2002. Report on the scoping study on the status of the Kromme River peatland complex and recommended mitigatory measures. Department of Water Affairs and Forestry Project X832633.

Haigh E. A., P. M. Illgner, J. Wilmot, and J Buckle. 2008. The wetland rehabilitation project in the Kromme River Wetland, Eastern Cape. Report.

Mander, M., J. Blignaut, M. Van Niekerk, R. Cowling, M. Horan, D. Knoesen, A. Mills, M. Powell, and R. Schulze. 2010. Baviaanskloof-Tsitsikamma Payments for Ecosystem Services: A feasibility assessment. Futureworks.

Middleton, B. J. and A. K. Bailey. 2008. Water resources of South Africa, 2005 study (WR2005). WRC Report Number TT 380/08.

Raymer, D. 2008. *Streams of Life*. Published by David Raymer, South Africa.

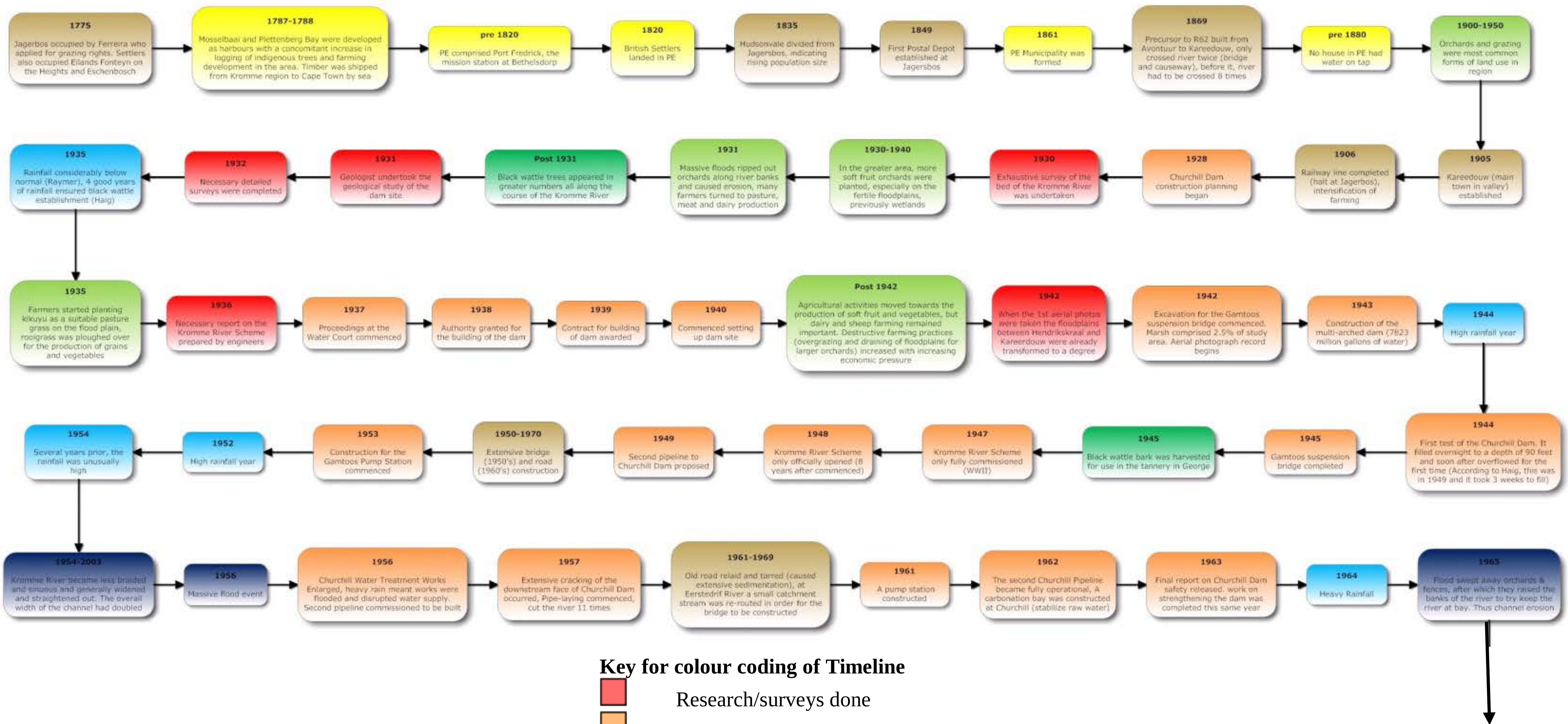
SANParks, 2009. *Garden Route Initiative: Park Planning and Development*. GIS data.Scholes 2001

Skead, C. J. (compiler). 2009. Historical plant incidence in southern Africa. *Strelitzia 24*. South African National Biodiversity Institute, Pretoria, South Africa.

Skowno, A. 2008. Baviaanskloof Mega-Reserve Biodiversity Assessment, Report for BMR project May 2008.

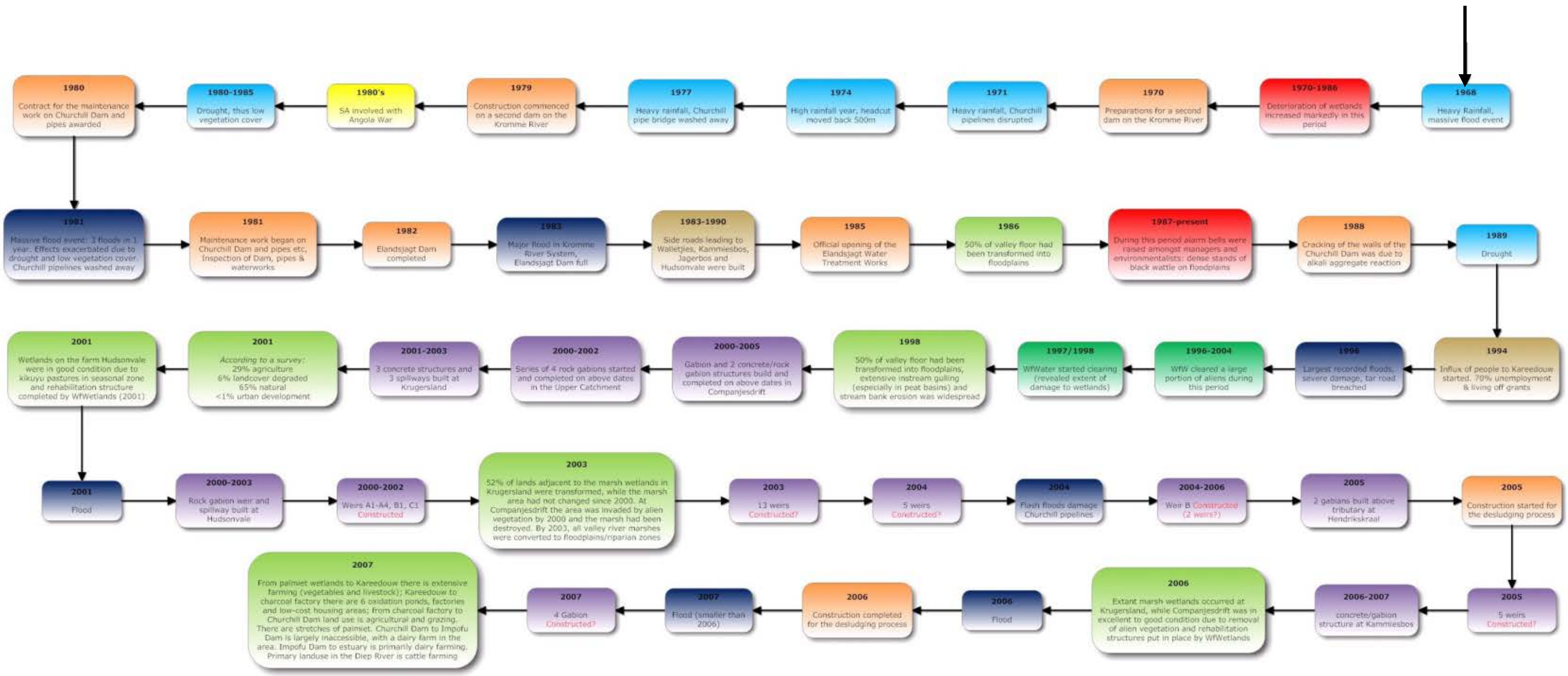
Vlok, J. H. J., D. I. W. Euston-Brown, and T. Wolf. 2008. A vegetation map for the Garden Route Initiative. Unpublished 1:50 000 maps and report supported by CAPE FSP task team.

Figure A3.3: Chronology of Kromme River Catchment 1940-2010



Key for colour coding of Timeline

- Research/surveys done
- Waterworks building (dams etc)
- Eastern Cape developments
- Land use
- Alien plants
- Meteorological data
- Rainfall data
- Restoration/rehabilitation
- Roads, railways & construction



Key for colour coding of Timeline

- Research/surveys done
- Waterworks building (dams etc)
- Eastern Cape developments
- Land use
- Alien plants
- Meteorological data
- Rainfall data
- Restoration/rehabilitation
- Roads, railways & construction

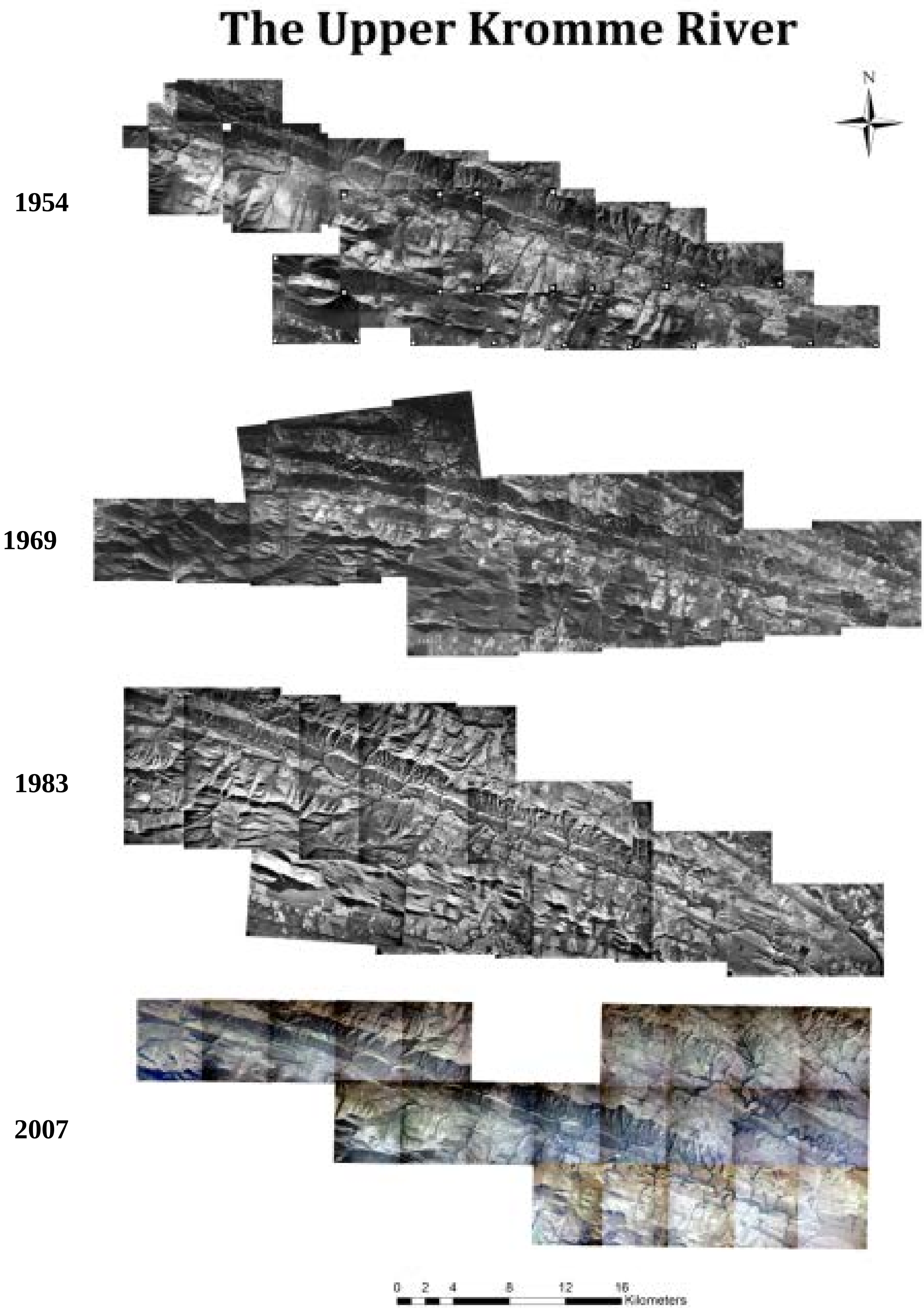
Stellenbosch University http://scholar.sun.ac.za

APPENDIX 4

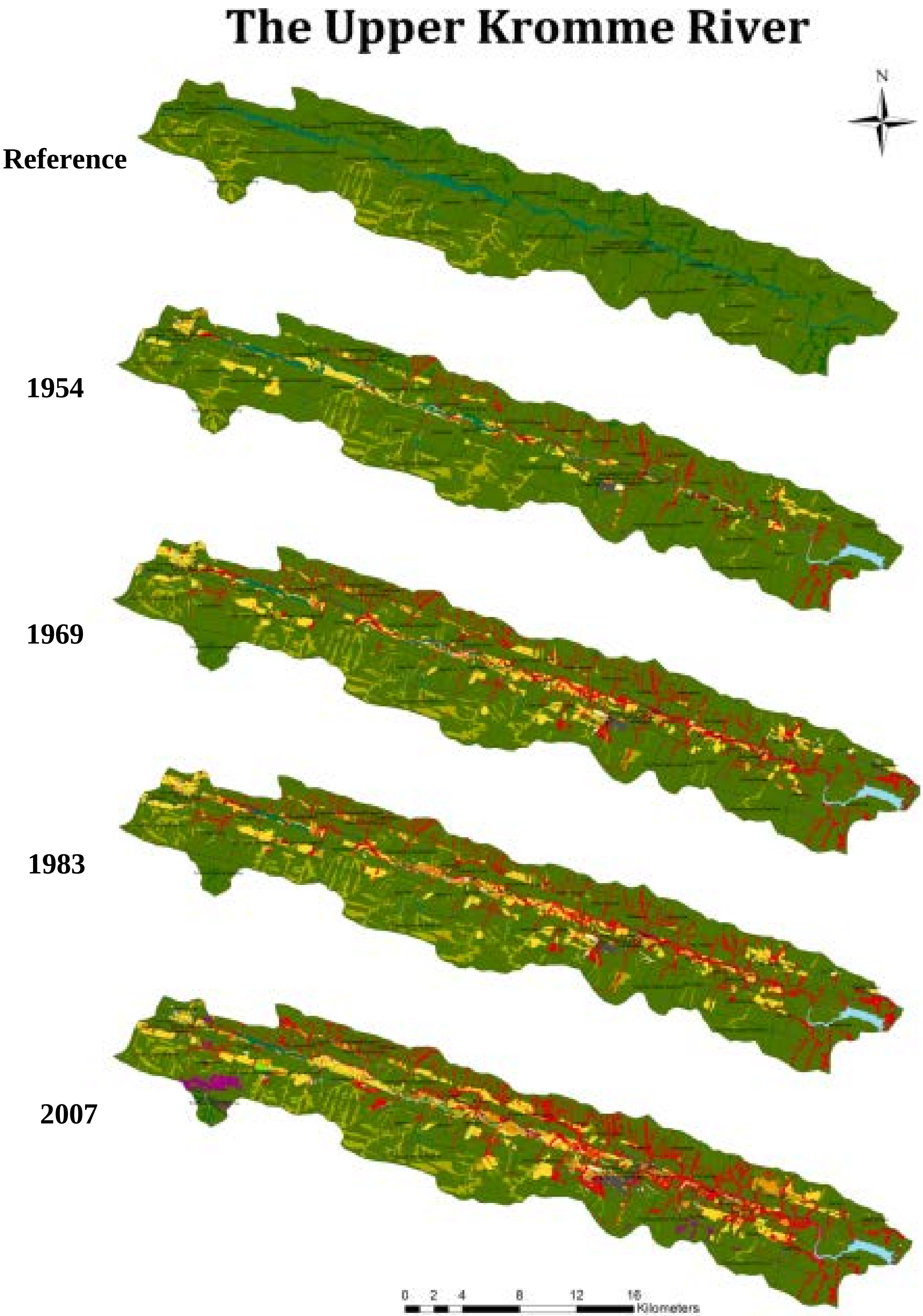
Mapping outputs for the Kromme River

This masters study resulted in the creation of a detailed land-use map for the Kromme (2007) and land-use maps for 1983, 1969, 1954 and a reference map. This Appendix showcases these maps and the mosaicked aerial photographs used for the creation of these maps.

Stellenbosch University http://scholar.sun.ac.za



Stellenbosch University http://scholar.sun.ac.za



Stellenbosch University http://scholar.sun.ac.za

APPENDIX 5

Calculating a Crop Factor for Palmiet (*Prionium serratum*)

INTRODUCTION

Many methods have been developed to measure the water-use of different plant species at the leaf, plant, and ecosystem scale. Scaling up from leaf scale (stomatal conductance) to canopy scale is very difficult and can lead to substantial errors (Jarvis & McNaughton 1986, Pearcy et al. 1989). At the other end of the scale, estimates of evaporation over large areas derived from modelling techniques such as SEBAL (Surface Energy Balance Algorithm for Land), which estimates evaporation from satellite imagery and climatic variables such as solar radiation and vapour pressure (Bastiaanssen et al. 1998), also involve assumptions which can lead to substantial errors.

METHODS

Evaporation at the Franschhoek Wetland

The Franschhoek palmiet wetland is also located in the Western Cape Province of South Africa, nearby the Jonkershoek wetland (33°57’50” S, 19°10’00” E) (Figure A5.1). Thus this wetland has similar rainfall to the Jonkershoek wetland. Dr C. Jarmain (unpublished data) carried out measurements at this wetland using an energy balance technique (scintilometry). Measurements were taken using a large aperture scintilometer at 10 minute intervals for 17 days, from 13 – 29 October 2008. Data collected using a scintilometer (model BLS900) and weather station data were used to estimate the daily energy balance which was then used to estimate the total daily evaporation (ET):

$$\lambda E = R_n - G - H$$

$$ET = \lambda E / \lambda_v$$

Stellenbosch University http://scholar.sun.ac.za

λE refers to the latend energy flux density, (Rn) net solar radiation, (G)soil heat flux density, (H) sensible heat flux density (all in $w.m^{-2}$), and λ_v the latent heat of vaporisation ($J.kg^{-1}$). Scintilometry data were then scaled up to daily values and compared with remote-sensing data.

We also obtained satellite-based estimates of evaporation for this wetland from two sources, both based on the Surface Energy Balance Algorithm for Land (SEBAL) Model. The one dataset came from a study which covered the main wine growing area of the Western Cape and used Landsat 7-ETM imagery (Jarmain et al. 2007). The data have a spatial resolution of 30 m and cover the period from September to April for 2004-2005, 2005-2006 and 2006-2007. The other data came from a study of evaporation using Monthly Moderate Resolution Imaging Spectroradiometer (MODIS) data with a spatial resolution of 250 m (Meininger and Jarmain 2009). These data covered three separate rainfall years, a low rainfall year (2000-2001), an average rainfall year (2002-2003), and a high rainfall year (2006-2007). In the first data set (2000-2001), three months were excluded due to cloud cover obscuring the study site. In the second data set (2002-2003), two months were excluded due to cloud cover. In the last data set (2006-2007) only one month was excluded due to cloud cover.

Reference evaporation (Et_0) was obtained from a nearby weather station (Villiersdorp). A crop factor for palmiet (Kc) was then calculated using the following formula:

$$Kc = Et / Et_0$$

Crop resistance or Kr ($s.m^{-1}$) was also calculated using the MODIS data by an independent project. Crop resistance was converted to stomatal conductance ($m.s^{-1}$) for comparison with porometry data (Allen et al. 1998).

$$Kr = 1 / Kc$$

Stellenbosch University http://scholar.sun.ac.za

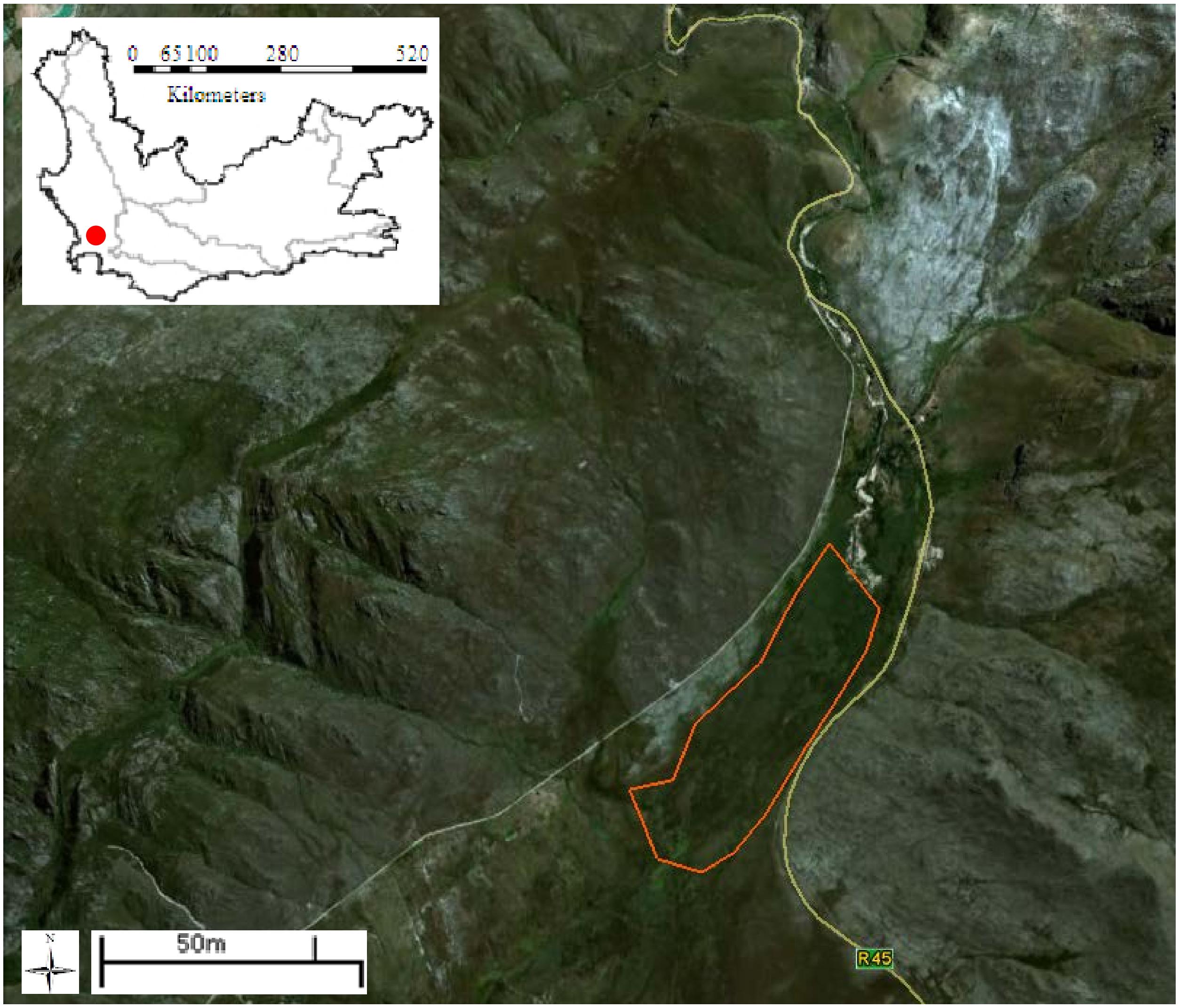


Figure A5.1: A satellite image of the Franschhoek palmiet wetland in the Western Cape (inset)

RESULTS

Scintilometry

Evaporation of palmiet at a wetland/stand scale is very closely linked to solar radiation (Figure A5.2; Jarmain unpublished). Evaporation is low throughout the night, however in spring, from about 07:00 it starts increasing and reaches a peak of 0.78 mm/hour around midday. Evaporation then decreases until 18:00 when it reaches its night time constant evaporation rate.

Stellenbosch University http://scholar.sun.ac.za

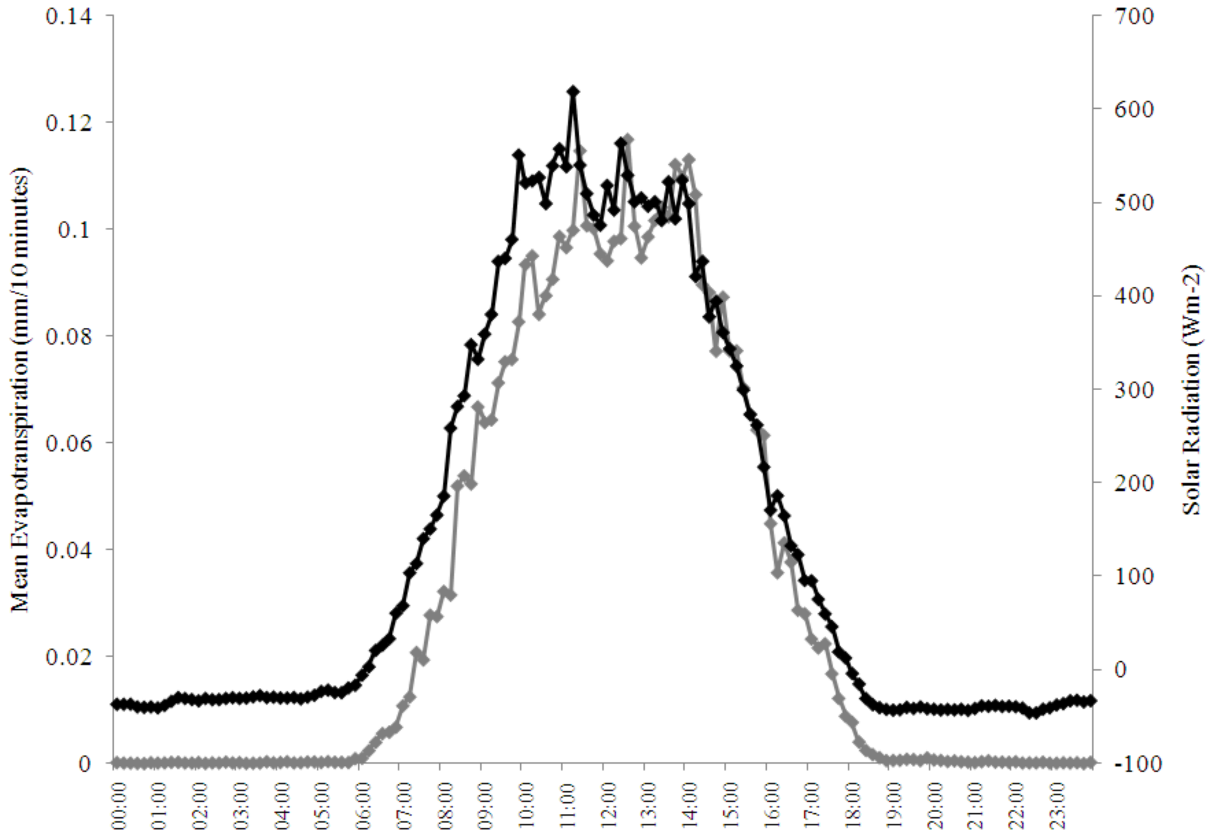


Figure A5.2: Mean daily evaporation from the Franschhoek palmiet wetland over 17 days in spring, measured using scintilometry over 24 hours at 10 minute intervals. The black line is evaporation and the gray line is solar radiation.

a. Landscape scale: Remote-Sensing

The MODIS based evaporation data show that that palmiet uses more water over the period October to February (spring and summer) than it does during the winter months (May to August) (Figure A5.3).

Stellenbosch University http://scholar.sun.ac.za

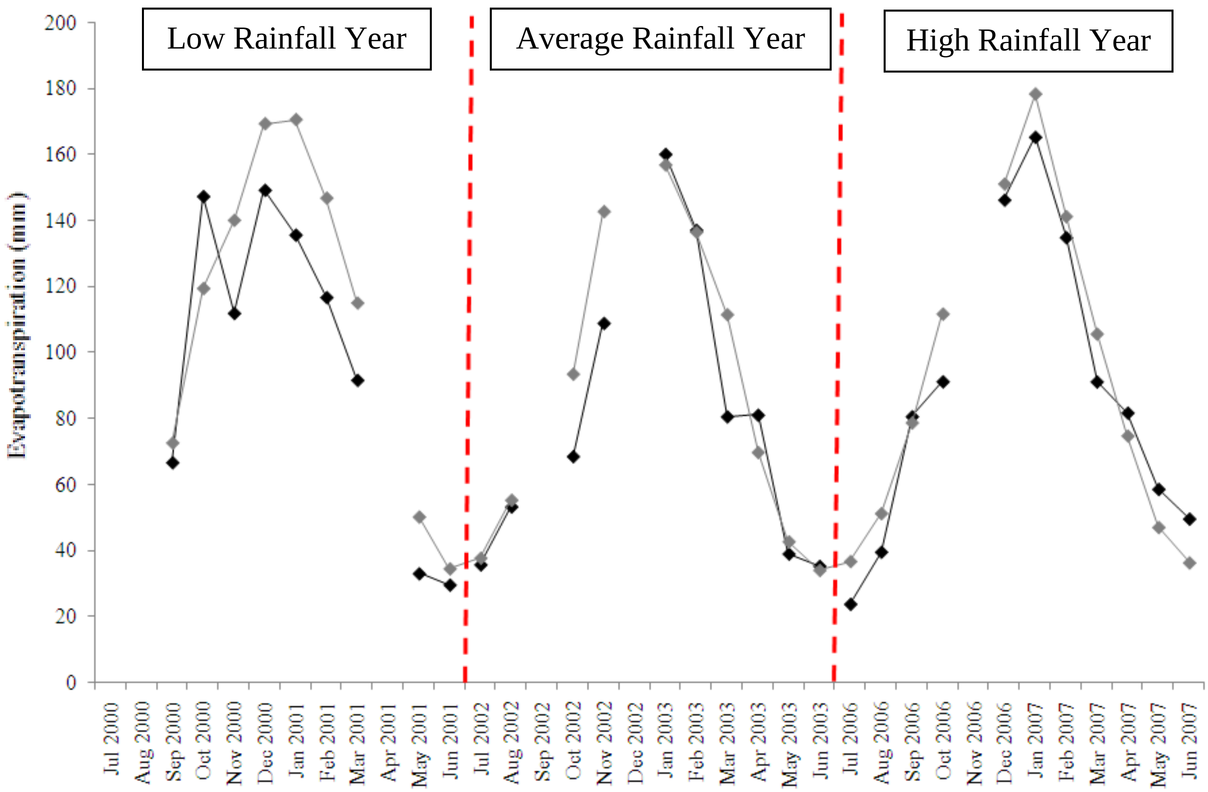


Figure A5.3: Seasonal and annual variation in monthly MODIS evaporation values for palmiet in the Franschhoek palmiet wetland from 2000-2007. Black lines show evaporation and gray lines show reference evaporation. Stippled, red vertical lines indicate a jump in the horizontal time scale.

During the high and average rainfall year the evaporation from palmiet peaked in the early summer, however during the low rainfall year this peak in stomatal conductance was not apparent (Figure A5.4).

Stellenbosch University http://scholar.sun.ac.za

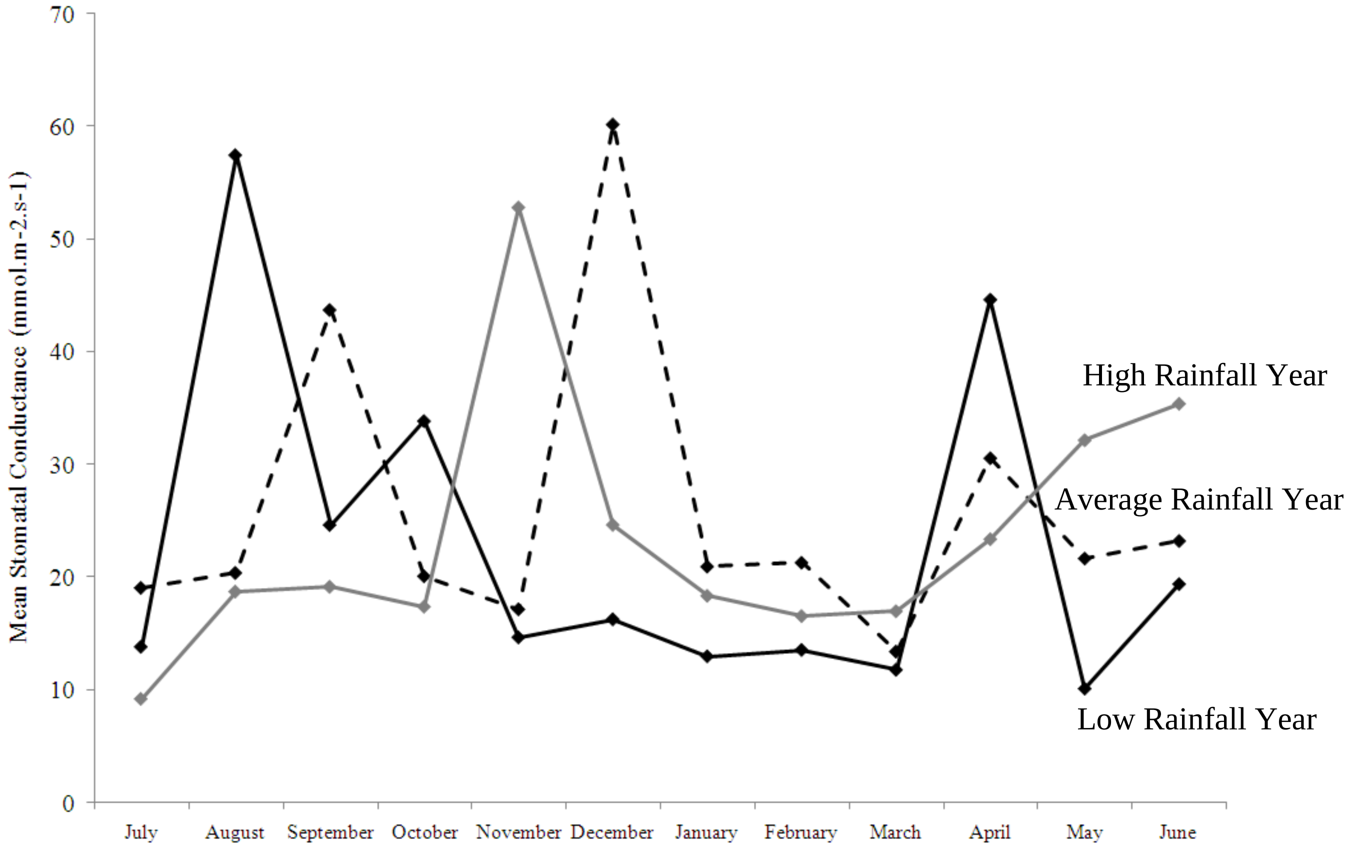


Figure A5.4: Seasonal and annual variation in monthly MODIS stomatal conductance values for palmiet in the Franschhoek palmiet wetland from 2000-2007. The black stippled line is the average rainfall year (2002-2003), the gray line is the high rainfall year (2006-2007), and the solid black line is the low rainfall year (2000-2001).

The evaporation rates estimated using the Landsat images confirms the characteristic peak over the early summer months (Figure A5.5). No estimates were made during the winter months. The Landsat estimates of the monthly summer evaporation were slightly higher than that of MODIS (±50 mm). It is interesting to note that the evaporation of palmiet is in excess of that of the reference evaporation (Figure A5.5).

Stellenbosch University http://scholar.sun.ac.za

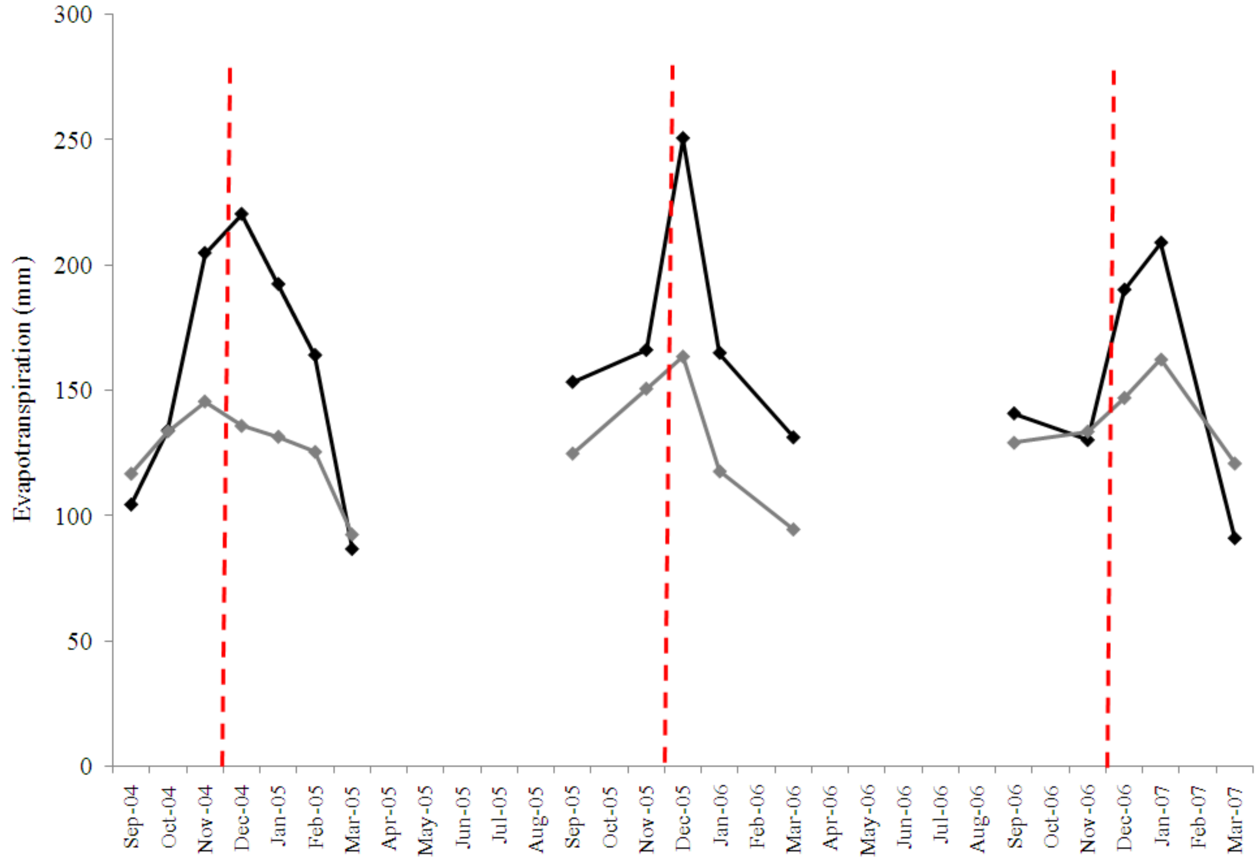


Figure A5.5: Seasonal and annual variation in monthly Landsat evaporation values for palmiet in the Franschhoek palmiet wetland from 2004-2007. Black lines show SEBAL estimates of evaporation and gray lines show reference evaporation.

Driving Factors

For the Landsat data, both rainfall and solar radiation appear to be driving Et (Figure A5.6).

Stellenbosch University http://scholar.sun.ac.za

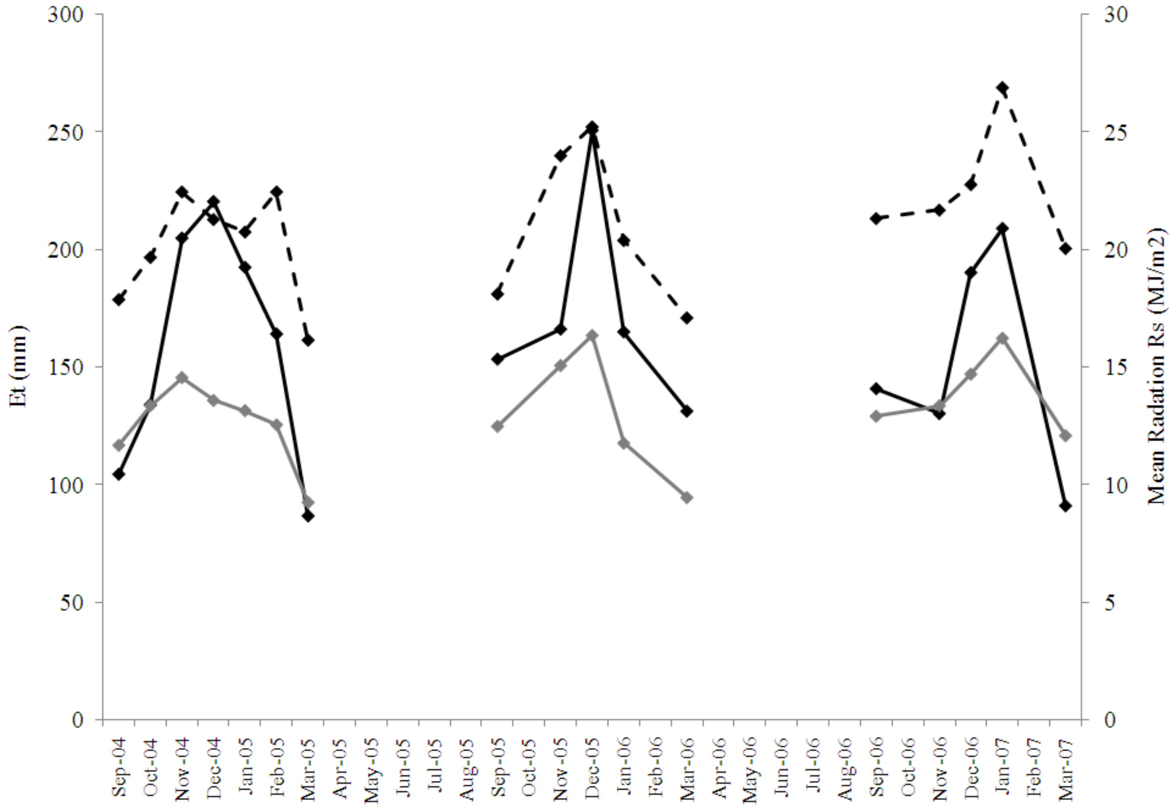


Figure A5.6: The relationships between SEBAL evaporation estimates and solar radiation for palmiet in the Franschhoek palmiet wetland. Black lines again indicate estimated evaporation and gray lines reference evaporation. Black stippled lines indicate solar radiation.

Crop Factor for palmiet

There is a high level of agreement between the crop factor for the MODIS and Landsat data which supports the use of the crop factor for MODIS in the hydrological modelling study in Chapter 4 (Table A5.1).

Stellenbosch University http://scholar.sun.ac.za

Table A5.1: The calculated crop factor for palmiet.

	MODIS Kc	Landsat Kc
January	1.002827	1.3835622
February	1.092371	1.3067137
March	1.044104	1.0256552
April	1.2048355	
May	1.0971023	
June	1.150314	
July	0.9433495	
August	1.0090625	
September	1.123157	1.0707617
October	1.0727197	1.0025311
November	1.0006825	1.1609746
December	1.013613	1.4825863

Water-use of palmiet

The Landsat-based evaporation estimate for palmiet appeared to be an over-estimate relative to the MODIS estimate. The annual evaporation of palmiet was estimated as 1526 mm by the scintillometry measurements during one season of the year, 1042 mm by MODIS and 1623 mm by Landsat. Since scintillometry measurements were only taken during spring, it is likely that the annual evaporation calculated using only spring data will be over-exaggerated. Therefore the evaporation of Landsat would also appear to be an over-estimate of palmiet's actual evaporation. Evaporation measured from *Phragmites mauritianus*, another South African wetland plant, suggest an evaporation of anywhere between 900-1300 mm/a, depending on the rainfall for the region (Birkhead et al. 1997, Everson et al. 2001, Clulow et al. 2012). This is much closer to the MODIS estimate for palmiet, suggesting that it is more accurate (Everson et al. 2001). The MODIS-based values for stomatal conductance appeared to under-estimate the stomatal conductance of palmiet relative to the porometry data (Table A5.2).

Stellenbosch University http://scholar.sun.ac.za

Table A5.2: A comparison of water-use values, in terms of evaporation (Et) and various conductances (Cond.) across all scales and methods used in this study. MODIS stomatal conductance was averaged for each month over the 3 years.

	Scintilometry Et (mm)	Landsat Et (mm)	MODIS Et (mm)	Porometry Stomatal Cond. (mmol.m-2.s-1)	MODIS Stomatal Cond. (mmol.m-2.s-1)
January		188.61	153.60		17.41
February		163.91	129.47	40.89	17.12
March		102.90	87.67	46.08	14.04
April			81.27		32.85
May			43.39		21.30
June			38.00	59.86	25.99
July			29.59		14.02
August			46.27		32.18
September		132.75	73.51		29.16
October	127.20	133.95	102.23	48.50	23.77
November		166.90	110.29	36.85	28.20
December		220.21	147.65	31.86	33.69
Annual estimate	1526.40	1623.73	1042.94		

ACKNOWLEDGMENTS

A special thanks to Dr Caren Jarmain for help in this part of my thesis. I could not have done any of this work without your support and tutelage. Thank you also to Garth Stephenson of the GIS Consultancy at Stellenbosch University. Also to the CSIR for support with remote-sensing. Thank you to Dr Caren Jarmain, Dr Wouter Meininger and WaterWatch (Netherlands) for supplying data. I would also like to acknowledge help from my supervisors: Dr David le Maitre, Prof Karen Esler and Prof Richard Cowling for their help and support, as well as Dr Shayne Jacobs (SU) for lending my equipment for porometry.

REFERENCES

Allen, R. G., L. S. Pereira, D. Raes, and M. Smith. 1998. FAO Irrigation and Drainage Paper No. 56: Crop evapotranspiration (guidelines for computing crop water requirements). ISBN 92-5-104219-5. Pp 290.

Stellenbosch University http://scholar.sun.ac.za

Bastiaanssen, W. G. M., M. Meneti, R. A. Feddes, and A. A. M. Holtslag. 1998. A remote sensing surface energy balance algorithm for land (SEBAL). 1. Formulation. *Journal of Hydrology*. **212-213**: 198-212.

Birkhead, A. L., B. W. Olbrich, C. S. James, and K. H. Rogers. 1997. Developing an integrated approach to predicting the water use of riparian vegetation. Water Research Commission. WRC Report No: 474/1/97.

Clulow, D., C. S. Everson, M. G. Mengistu, C. Jarmain, G. P. W. Jewitt, J. S. Price, and P. L. Grundling. 2012. Measurement and modelling of evaporation from a coastal wetland in Maputaland, South Africa. *Hydrology and Earth System Science*. **9**: 1741–1782.

Jarmain, C. Unpublished data.

Everson, C. S., C. Burger, B. W. Olbrich, and M. B. Gush. 2001. Verification of estimates of water use from riverine vegetation on the Sabie river in the Kruger National park. Water Research Commission, Pretoria, South Africa. WRC Report No 877/1/01.

Jarmain, C., A. Klaasse, W. G. M. Bastiaanssen, and A. S. Roux. 2007. Remote sensing tools for water use efficiency of grapes in the Winelands region, Western Cape. Proceedings of the 13th SANCIAHS symposium, Cape Town, 6–7 September 2007.

Jarvis, P. G., and K. G. McNaughton. 1986. Stomatal control of transpiration: scaling up from leaf to region. *Advances in Ecological Research*. **15**: 1-49.

Meininger, W., and C. Jarmain. 2009. Development of remote sensing tools for monitoring the hydrological benefits of the Working for Water Program. Report prepared for the Working for Water Programme, Working for Water, Cape Town.

Pearcy, R. W., J. Ehleringer, H. A. Mooney, and P. W. Rundel (Eds). 1989. Plant physiological ecology: field methods and instrumentation. Chapman and Hall. Pp 48-52.

Stellenbosch University http://scholar.sun.ac.za

APPENDIX 6

Kromme Policy Paper

TIPS
TRADE & INDUSTRIAL POLICY STRATEGIES

asset
RESEARCH

POLICY BRIEF

Urban water use

INTRODUCTION

There has been a global shift in the way that water provision for urban water use is viewed. Governments are increasingly choosing to invest in environmental health. By protecting river systems, governments can reduce management costs. In this brief, examples of international case studies related to such government interventions are presented, followed by a South African case study: the Kromme River.

BACKGROUND

INTERNATIONAL CASE STUDIES

Seattle Municipality: Purchase of the Cedar River Catchment for its water supply by Seattle, one of the unhealthiest cities in the US before the 1890s, made the city one of the healthiest in the US within 10 years.

Before the purchase of the Cedar River Catchment, Seattle was an unhealthy city with epidemics of cholera and typhoid and major water shortages. Purchasing a catchment solely for water provision (i.e. all agriculture and forestry was ceased) was considered expensive and risky at the time, but the endeavour was a huge success.

Within 10 years clean water began to flow once more, and outbreaks of cholera and typhoid ceased. This endeavour not only provided the city with clean water and improved the health of its citizens, it also saved the city hundreds of millions of dollars in the long term. This is because the use of natural systems for water provision services proved substantially cheaper than creating an artificial system, such as a water filtration plant (Cosman et al, 2012).

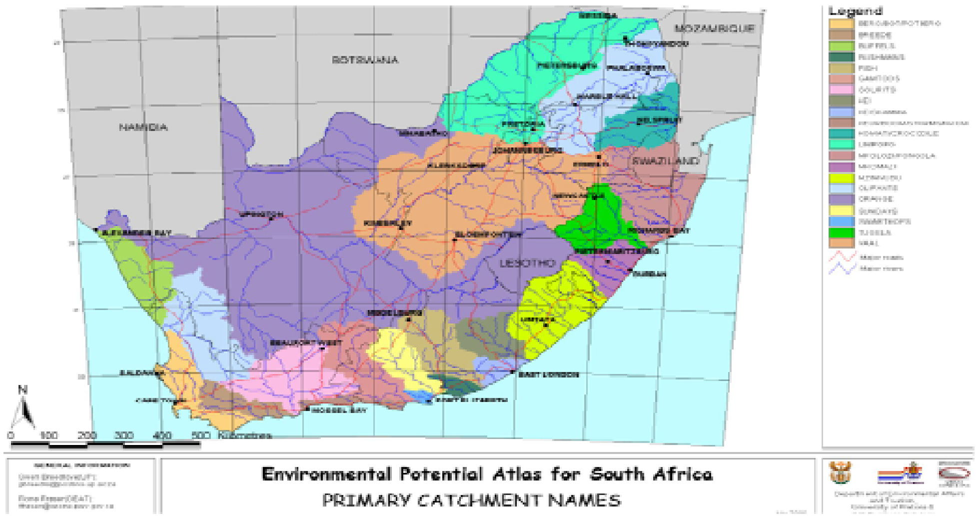
RECOMMENDATIONS – SPECIFIC TO NELSON MANDELA BAY

- **Protect what we have:** Protecting our natural resources will ensure their services are delivered in perpetuity. The Kromme case study, which illustrates this, may be applied to other catchments in South Africa.
- **Forming partnerships:** Landowners (service providers) are based in water-providing catchments and their actions have an impact on the water produced that municipalities (end-users) benefit from. Municipalities need to form partnerships with landowners to assure the supply of high quality of water.
- **Align incentives:** All stakeholders must work towards the same goal. Landowners must be willing to restore and protect the catchment and the end-users must be willing to pay for the delivery of services (e.g. clean and reliable water flow).
- **Communication is vital:** All government departments, implementing agents, conservation initiatives, landowners, and scientists must make earnest attempts to achieve effective communication when it comes to working in important water-producing catchments.
- **Biodiversity Stewardship Programme:** Tax and financial incentives are available to landowners who sign up to the Biodiversity Stewardship Programme through which landowners in ecologically important areas are required to manage invasive alien plants. This programme is one vehicle for such partnerships between landowners and government.
- **Law enforcement:** South Africa has sound laws for the protection of natural resources but these need to be enforced to avoid the degradation of natural resources.

Authors: Alanna Rebelo and Katie Gull March 2012

Stellenbosch University http://scholar.sun.ac.za

WHAT IS A CATCHMENT AREA?



A catchment is an area, often surrounded by mountains, whose rainfall all drains into one body of water, such as the ocean, an estuary, or a dam. A catchment consists of mountains, the lowlands/flood plains and all the rivers running through this area. South Africa is divided up broadly into 19 primary catchments, as shown in the picture, above. Each of these 19 catchments is further divided up into quaternary catchments, which is the scale at which water management, in terms of urban water use, should take place.

New York Municipality: The municipality invested US$1.5 billion in maintaining and restoring its Catskill Catchment and saved $6 billion in the cost of a filtration plant plus operating costs (Cosman et al, 2012). New York City is supplied with water from the Catskill Catchment via the Catskill Aqueduct.

Kampala, Uganda: The Nakivubo Swamp provides wastewater purification services and nutrient retention services, valued at US$1-US$1.75 million a year. Using the existing swamp is far cheaper than the expansion and maintenance of new wastewater facilities. Despite these findings, policymakers have neglected to protect the area and the wetlands' ability to remove nutrients and pollutants has been greatly reduced – costing the country millions of dollars each year. However, after 2008 a new plan was proposed to reverse this (Kozak, 2012).

A CASE STUDY OF THE KROMME RIVER

The Kromme River in the Eastern Cape provides 40% of the water (Raymer, 2010), and it provides the cheapest* and best quality water in the Western System to the Nelson Mandela Bay Municipality (NMBM). However, the catchment that supplies the Kromme with water is in An extremely bad condition at present.

**The average operational cost of water from the Churchill Water Treatment Works is $R0.54/m^3$ compared to $R0.83/m^3$ in Elandsjacht and $R0.93/m^3$ at Loerie.*

The upper Kromme River valley is divided up into relatively small farms, with the main activities being dairy, livestock and fruit farming. Agriculture in this arid environment has low profit margins. The land has been poorly managed, resulting in erosion of arable soil and about 85% of the once extensive wetlands have been destroyed (ASSET Research, 2012). Loss of wetlands is serious as these provide services such as the maintenance of water quality, silt retention, flood protection, low flow augmentation and a place of refuge for animals. Since the wetlands in the Kromme have been destroyed, the flood damage is reported to have become more severe.

These services, invisible to the economy when the system is healthy, require expensive engineering solutions to replace them. This is a case where the cost of uninformed decisions by a few private landowners is carried by the citizens of Port Elizabeth over a long-time horizon.

Other factors contributing to the loss of services from the Kromme are the alien black wattles, which first appeared in the catchment in the 1940s. Currently 41ha of this area are invaded, mostly in the river itself, which equates to more than 11% of the catchment (ASSET Research. 2012). These trees use more water than indigenous vegetation (Dye and Jarmain, 2004) and landowners have reported that smaller rivers have ceased flowing as a result of these trees using the water. The river itself has also been

Stellenbosch University http://scholar.sun.ac.za

HEADCUTS – DONGAS AND GULLIES

A headcut is caused by an activity which disturbs a rivers path. Examples are building a road or railway line through a wetland, river or floodplain, allowing animals to graze in these areas, or ploughing these areas up. These activities cause damage called a 'nick-point' to the path that water flows along, and as more and more water flows past the point of damage, it will start to wash the loose sand and gravel downstream. This causes the nick-point to start moving backwards and become bigger with time. This process happens much faster during big floods. Headcuts are bad because they drain the water from the surrounding land, so it can no longer be as productive for agriculture or grazing. It also destroys wetlands –which provide many services.

Source image: Image: http://deq.mt.gov/statesuperfund/ubmc/images/virtour/full/22b_full.jpg

structurally damaged. Many parts have been canalised and poor road construction and illegal farming in the river have taken their toll. The Conservation of Agricultural Resources Act (Republic of South Africa, 1984) prohibits certain practises and yet is not being enforced in the Kromme. These activities cause headcuts, which steadily erode their way upstream impairing the land's ability to hold water and causing loss of top soil. This is detrimental to both agriculture and water users downstream.

All of this damage has a direct impact on NMBM's water supply. Resource abuse has negatively affected the quantity and quality of water the city receives, requiring costly engineering interventions and alternative water sources being developed sooner than would otherwise be necessary. The attempts by landowners in the Kromme to increase their short-term financial gain has had adverse implications in the long-term for the public water resources and has at the same time reduced the capacity of the agricultural land to support the farmers' livelihoods.

WHAT IS RESTORATION?

When humans get ill, they go to a doctor who fixes them so their bodies can function properly again. When land, rivers and mountains are damaged or "ill", they also need to be fixed so that they can function properly again. South Africa and all its people rely on the ability of the land to function properly. They need its fresh, clean water, its healthy soil for agriculture, and especially need its ability to protect the population from extreme events, particularly in the face of climate change.

There are many ways to "fix" or "restore" the environment. Some ways include cutting down alien (from another country) trees and plants that use up all the water. Other types of restoration include fixing up damaged wetlands by building concrete structures to stop the soil being washed away. It could also be re-growing plants in areas where animals have been allowed to overgraze and all that remains is bare soil.

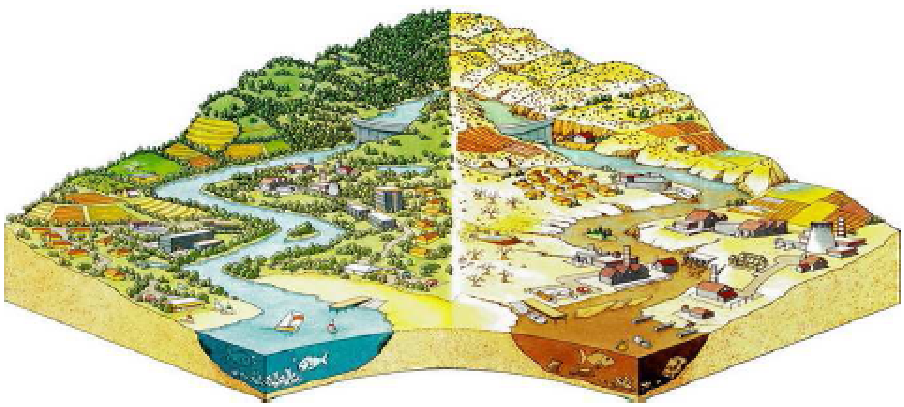
WHAT IS BEING DONE?

Working for Water: In the 1990s scientists recognised the widespread damage to the land and the urgent need for restoration. In 1996, the government's Working for Water (WfWater) programme began clearing the invasive alien trees in the Kromme.

WfWater aims to make more water available by clearing invasive alien plants that use high amounts of water. It is run through the Department of Water Affairs. Since WfWater started in 1995, more than one million hectares of invasive alien plants have been cleared throughout the country. WfWater has also provided jobs and training to about 20 000 people a year. These people are drawn from the most marginalised areas, and of the total, 52% are women. Currently there are 300 projects in all nine provinces.

Stellenbosch University http://scholar.sun.ac.za

INTEGRATED CATCHMENT MANAGEMENT



Integrated catchment management is a form of management and planning where a catchment as a whole is looked after instead of the more traditional piecemeal approach. This is based on the fact that all aspects of nature are intimately connected. It is not possible to separate land management from water management and successfully look after natural resources. *Image from: Waterwatch Queensland (http://www.georgesriver.org.au/IgnitionSuite/uploads/images/poster_healthycatchment%20qld%20waterwatch%20sml.jpg)*

Working for Wetlands: The Working for Wetlands (WfWetlands) project was started in 2000 by the South African National Biodiversity Institute (SANBI) on behalf of the Departments of Environmental Affairs, Department of Agriculture, Forestry and Fisheries and Department of Water Affairs (DWA). It aims to fix up the wetlands of South Africa as well as draw unemployed people into the productive sector of the economy. There are 40 projects running and in 2009, 95 wetlands were rehabilitated in all nine provinces, jobs were created for 1500 people and 250 small businesses were supported. In 2000, Working for Wetlands began to physically rehabilitate the Kromme, building cement structures to stop the headcuts moving further up the river, preventing the loss of more arable land.

Biodiversity Stewardship Initiatives: The Biodiversity Stewardship Initiative (BSI) is an initiative of Environmental Affairs and Tourism (DEAT) as well as key conservation organisations such as Eastern Cape Parks. The BSI allows landowners with land that has rich biodiversity to enter into an agreement to secure legal protection for their land. The initiative offers support and advice from nature conservation agencies and funding from government to protect valuable resources. It employs landowners to look after their land in a way that will protect these resources in perpetuity. An estimated R22 million has been spent on the restoration of the wetlands (WfWetlands) and over R12 million devoted to the removal of invasive trees (WfWater). Restoration in the Kromme catchment is regarded as an investment, it will improve the ecosystem and preserve services for posterity.

Integrated Catchment Management: This integrated catchment management is currently not well integrated due to poor communication. Landowners should be included in the process and agricultural practices need to change to provide a lasting legacy. In addition, integrated catchment management needs to be made financially viable and appealing to landowners if the benefits of restoration are to be sustained. Because restoration and integrated catchment management will benefit the end-users, a suggestion is that landowners should be paid to manage their land in such a way that the ecosystem services their land provides are optimised for downstream users in the long term. Essentially they would be paid for providing good quality water, or "farming water".

ANALYSIS

A cost-benefit analysis, as performed in Kromme River Catchment to assess the economic viability of restoration activities should be undertaken in each case to determine the viability of any planned intervention. The additional yield resulting from clearing one hectare of alien invasive plants in the Kromme amounts to 3207m^3 of water per year. On average, about 140ha of invasive woody trees are removed each year. Thus the NMBM can expect an additional 440 000m^3 flowing into the Churchill Dam each year. The economic value or NMBM's willingness to pay for this additional water amounts to around R540 000 per annum. However, private landowners also benefit from the restoration in terms of increased land productivity and on-farm increased water availability.

Stellenbosch University http://scholar.sun.ac.za

The government's Water for Work programme (left) and Working for Wetlands programme (right)

CONCLUSIONS

An important finding of this study was that the benefits of the restoration are not economically viable over a 25 year period *for water production alone*. Other services that are also provided by restoration such as improvements in water quality, the security of the water source, increased agricultural productivity and increased flood protection contribute to the viability. Restoration programmes protect the catchments and provide employment and capacity building opportunities. The restoration in the Kromme area provides around 500 jobs per annum and spends R4 000 on wages for every hectare cleared.

WfWetlands provides an additional 100 jobs per annum. Government's New Growth Plan aims to create five-million new jobs by 2020 (National Planning Commission, 2011). Restoration of catchments could therefore help meet these targets while addressing other issues such as securing long-term sustainable water supply for cities.

REFERENCES

Cosman, D., Schmidt, R., Harrison-Cox, J. and Batker, D. 2012. How water utilities can spearhead natural capital accounting. *The Solutions Journal*, 2(6):28-31.

Dye, P. and Jarmain, C. 2004. Water use by black wattle (*Acacia mearnsii*): implications for the link between removal of invading trees and catchment streamflow response. *South African Journal of Science*, 100:40-44.

Gull, K. 2012. MSc Dissertation, University of Cape Town.

Kozak, J. 2012. Local policymakers can lead the transformation – how government values nature. *The Solutions Journal*, 2(6):32-34.

National Planning Commission. 2011. National Development Plan: Vision for 2030. Pretoria: National Planning Commission.

Raymer, D. 2010. pers. comm.

ASSET Research. 2012. The Impact of Re-Establishing Indigenous Plants and Restoring the Natural Landscape on Sustainable Rural Employment and Land Productivity through Payment for Environmental Services, Phase 2: fieldwork report. Project K5/1803. Pretoria.

Republic of South Africa. 1984. Conservation of Agricultural Resources Act, Act 43 of 1984. Pretoria: Government Gazette.

ABOUT THIS POLICY BRIEF

This Policy Brief was prepared by Alanna Rebelo, University of Stellenbosch and ASSET Research, arebelo@sun.ac.za and Katie Gull, University of Cape Town and ASSET Research, katie_gull@hotmail.com

The South African Water Research Commission provided financial support for this study, under contract K5/1803, *The impact of re-establishing indigenous plants and restoring the natural landscape on sustainable rural employment and land productivity through payment for environmental services*, (Water Research Commission 2009, Water Research Commission Knowledge Review 2008/09. Water Research Commission, Pretoria, South Africa. ISBN: 978-1-77005-894-1), awarded to ASSET Research. ASSET Research is an economy/ecology think-tank that seeks to internalise the importance of natural assets – such as water, energy, biodiversity and fertile land – in the search for alternative development paths.

TIPS supported the development of five policy briefs based on the findings of the research. TIPS is a research institution active in South Africa and the region that facilitates policy development.

The authors would like to thank the Water Research Commission and TIPS for their support and Dr Steve Mitchell and Leandri van der Elst for editing and proofreading of the manuscript.

TIPS TRADE & INDUSTRIAL POLICY STRATEGIES **www.tips.org.za**

WATER RESEARCH COMMISSION **www.wrc.org.za**

asset RESEARCH **www.assetresearch.org.za**

Stellenbosch University http://scholar.sun.ac.za

View of the Jonkershoek Dam, Western Cape