DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND ITS REHABILITATION FOR IMPROVED WATER SECURITY

by

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in Hydrology
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PREFACE

The research contained in this thesis was completed by the candidate while based in the Discipline of Hydrology, School of Agricultural, Earth and Environmental Sciences of the College of Agriculture, Engineering and Science, University of KwaZulu-Natal, Pietermaritzburg, South Africa. The research was financially supported by the Water Research Commission and the Green Fund of the Development Bank of South Africa.

The contents of this work have not been submitted in any form to another university and, except where the work of others is acknowledged in the text, the results reported are due to investigations by the candidate.

Signed: Graham P. W. Jewitt

Date: January 2018

DECLARATION 1: PLAGIARISM

Note that two declaration sections are required if there are papers emanating from the thesis. The first (obligatory) declaration concerns plagiarism and the second declaration specifies your role in the published papers.

I, Catherine Jane Hughes declare that:

(i) the research reported in this thesis, except where otherwise indicated or acknowledged, is my original work;

(ii) this thesis has not been submitted in full or in part for any degree or examination to any other university;

(iii) this thesis does not contain other persons' data, pictures, graphs or other information, unless specifically acknowledged as being sourced from other persons;

(iv) this thesis does not contain other persons' writing, unless specifically acknowledged as being sourced from other researchers. Where other written sources have been quoted, then:

a) their words have been re-written but the general information attributed to them has been referenced;

b) where their exact words have been used, their writing has been placed inside quotation marks, and referenced;

(v) where I have used material for which publications followed, I have indicated in detail my role in the work;

(vi) this thesis is primarily a collection of material, prepared by myself, published as journal articles or presented as a poster and oral presentations at conferences. In some cases, additional material has been included;

(vii) this thesis does not contain text, graphics or tables copied and pasted from the Internet, unless specifically acknowledged, and the source being detailed in the thesis and in the References sections.

Signed: Catherine Jane Hughes

Date: August 2018

DECLARATION 2: PUBLICATIONS

My role in each section, paper and presentation is indicated.

CHAPTER 2: OVERVIEW OF LITERATURE – ECOSYSTEM SERVICES AND REHABILITATION

The overview of literature was compiled by Hughes, C.J. as part of Water Research Commission Project K5/2156. Technical support and review was provided by Schulze, R.E. and Jewitt, G.P.W.

CHAPTER 3: ESTIMATION OF WATER FLOW RESPONSES TO CHANGES IN LAND COVER IN SELECTED LOCATIONS IN SOUTH AFRICA

Accepted by Koedoe *and peer reviewed.*

The analysis and compilation of this study was conducted by Hughes, C.J. (corresponding author) as part of Water Research Commission Project K5/2156. Technical support and review was provided by Schulze, R.E. and Jewitt, G.P.W.

CHAPTER 4: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 1: CONTEXT AND MODELLING APPROACH

and

CHAPTER 5: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 2: OUTPUTS

Both accepted by WaterSA *and peer reviewed.*

- Hughes, C.J. 2016. High resolution spatial and temporal modelling and mapping of land protection and rehabilitation scenarios to support water-related ecosystem services. African Congress for Conservation Biology Conference. El Jadida, Morocco. Presented by Hughes, C.J.
- Hughes, C.J. and Jewitt, G.P.W. 2015. Rehabilitation for improved water service delivery: Hydrological modelling of ecological infrastructure in the uMngeni catchment, South Africa. Society for Ecological Restoration Conference. Manchester, United Kingdom. Presented by Hughes, C.J.
- Hughes, C.J., de Winnaar, G., Warburton-Toucher, M. and Jewitt, G.P.W. 2015. Hydrological ecosystem service delivery in the upper uMngeni catchment – water security from ecological infrastructure. IAHS Conference. Prague, Czech Republic. Presented by Hughes, C.J.
- Hughes, C.J. and Jewitt, G.P.W. 2014. Land use change and ecological infrastructure: Improving hydrological ecosystem service delivery in the uMngeni catchment. SANCIAHS Conference. Cape Town, South Africa. Presented by Hughes, C.J.

The research is based on a large-scale hydrological modelling exercise using the *ACRU* model. The original configuration of the uMngeni catchment was compiled by Warburton (2011), but the import of the configuration into *ACRU4*, the update of the model to reflect current land use, revision of parameters (particularly for invasive alien wattle) and addition of sediment-related parameters to the model was carried out by myself. I also conducted the post-modelling data analysis with the selected *ACRU* outputs in MS Excel, and processed the results for mapping. The GIS maps presented in this report were compiled by Gary de Winnaar of GroundTruth. I compiled the papers and am corresponding author. This work was funded by the Development Bank of South Africa's Green Fund, in collaboration with the Department of Environmental Affairs. The project was completed by a team comprised of experts from the CWRR, South African National Biodiversity Institute, the Institute of Natural Resources, FutureWorks, GroundTruth and Zunckel Ecological and Environmental Services.

This work represents one of the first catchment-wide hydrological and economic modelling and mapping studies which was directly informed by an officially constituted partnership of corporate, academic, municipal and Non-Governmental Organization entities which has recognized the potential value of investment in ecological infrastructure towards water security. The author played a key role not only in the modelling study, but also with the project management and stakeholder engagement aspects of the project. Beyond the modelling aspects described in these two papers, the work further contributed to a wider paper detailing two case studies in this field in South Africa:

Mander, M., Jewitt, G., Dini, J., Glenday, J., Blignaut, J., Hughes, C., Marais, C., Maze, K., van der Waal, B. and Mills, A. 2017. Modelling potential hydrological returns from investing in ecological infrastructure: Case studies from the Baviaanskloof-Tsitsikamma and uMngeni catchments, South Africa. *Ecosystem Services*. Volume 27, Part B, 261-271.

Upon submitting this exercise as a single draft to a journal paper, it was established that a single paper would not allow for sufficient expansion on methods and results. Therefore, the entire study was separated into two parts, which allowed for further explanation of method, parameterization and results.

CHAPTER 6: MITIGATING THE IMPACTS OF GLOBALIZATION ON WATER SECURITY IN SOUTH AFRICA – A LANDSCAPE LEVEL INTEGRATED ECOSYSTEM SERVICES APPROACH

The paper was written by Hughes, C.J., with review provided by Bragg, C. (who also contributed to some of the discussion on globalization), and Jewitt, G.P.W. From a globalization perspective, the uMngeni case study was considered to provide an effective illustration of the use of investment in ecological infrastructure as a means to meet the needs for water security of a growing population – hence the reintroduction of the uMngeni methodology into a third paper, and the links to this catchment almost throughout the thesis.

Signed: Catherine Jane Hughes

Date: August 2018

ABSTRACT

Water is fundamental not only for biological function, hygiene, recreation and many cultural traditions, but is also vital for the survival of any business or economy. Ecological infrastructure - the nature-based equivalent of built infrastructure - delivers water, soil, clean air and other ecosystem services to society, and needs to be maintained in order to sustain the supply of sufficient, good quality water, as well as to provide food security and protection from floods, droughts and other extreme events. This thesis aimed to illustrate that improvement in water-related ecosystem service delivery can be achieved through conservation and rehabilitation of ecological infrastructure.

The overview of literature focused on defining what is meant by "water-related ecosystem services", and then on different forms of human-induced degradation that affect the delivery of these by ecological infrastructure. The first modelling study provided an understanding of the differing hydrological responses to alien plant invasion and livestock overgrazing across South Africa. The second modelling exercise focused on the uMngeni catchment, in which high-resolution land cover data and a daily time-step hydrological model were used. We concentrated on three water-related ecosystem services, namely water supply, sustained baseflow and avoidance of excessive sediment loss. This study provided a hydrologically informed assessment of what the potential benefits of either conservation (of the status quo), or of rehabilitation of ecological infrastructure, could be.

The final section of this thesis explored some of the wider issues associated with globalization and urbanization in the uMngeni catchment, and their impacts on water-related ecosystem service delivery by ecological infrastructure. The thesis concludes with observations on the need for stakeholders to work together towards optimal investment decision-making with regard to ecological infrastructure projects, which may protect people from water-related risk, as well as ensure food security.

EXTENDED ABSTRACT

Water is life. It is fundamental not only for biological function, hygiene, recreation and many cultural traditions, but is also vital for the survival of any business or economy. Ecological infrastructure, the nature-based equivalent of built infrastructure, delivers water, soil, clean air and other ecosystem services to society, and needs to be maintained in order to sustain the supply of sufficient, good quality water, as well as to provide food security and protection from floods, droughts and other extreme events.

This study aims to illustrate, firstly at a high level and then through a relevant case study, that improvement in water-related ecosystem service delivery can be achieved through conservation and rehabilitation of ecological infrastructure.

The overview of literature focuses on defining what is meant by "water-related ecosystem services", and then the different forms of human-induced degradation that affect the delivery of these by ecological infrastructure. It then explores the potential for rehabilitation of degraded lands to reinstate water-related ecosystem service delivery.

The first modelling study aims to provide an understanding of the differing hydrological responses to alien plant invasion and grassland degradation across South Africa, which is the focus of government-led clearing and rehabilitation programmes. Seven locations were selected to represent different climatic regimes across the country, and the *ACRU* daily time-step hydrological model was then used to simulate hydrological responses, based on each catchment's natural soils, vegetation and climate.

The potential hydrological impacts of three highly problematic invasive alien plant species in South Africa were modelled. These trees have a marked effect on baseflow volumes, particularly in the Western Cape, with a potential monthly reduction of up to 4.5 m^3/ha/d. Based on the modelling, these trees do not, however, appear to show conclusive impacts on stormflow. Grassland degradation due to livestock overgrazing, has a major effect on stormflow volumes - increasing volumes by up to 100% in the rainy season months in KwaZulu-Natal, and in turn has potential for increasing sediment and nutrient transport. Baseflow volumes are also impacted upon negatively by overgrazing, which reduces the

amount of water recharged below ground, with a reduction of up to 1.2 m^3/ha/d. A sensitivity analysis highlighted the importance of the crop coefficient (CAY) and coefficient of initial abstraction (COIAM) parameters in the *ACRU* model, and highlights a need for further investigation to confirm the validity of the parameters used in the simulation exercise.

South Africa is a semi-arid country which frequently faces water shortages, and experienced a severe drought in the 2016 and 2017 rainfall seasons. Government is under pressure to continue to deliver clean water to the growing population at a high assurance of supply. Studies now show that the delivery of water may be sustained not only through built infrastructure such as dams and pipelines, but also through investment in Ecological Infrastructure (EI).

A daily time-step hydrological model was used to map areas which should be prioritised for protection or rehabilitation to sustain the delivery of water-related ecosystem services within the uMngeni catchment. We focused on three water-related ecosystem services, i.e.:

- water supply;
- sustained baseflow; and
- erosion control/avoidance of excessive sediment losses.
- The two key types of degradation were modelled, namely overgrazing and the invasion of upland areas by Black Wattle (*Acacia mearnsii*).

Part 1 of this paper in 2 parts provides a discussion on the role of EI in delivering water-related ecosystem services, describes the motivation for the study, and the methods used in modelling and mapping the catchment. Part 2 explores and illustrates the current level of delivery of water-related ecosystem services in different parts of the catchment, with potential hydrological benefits of rehabilitation and protection of EI in the uMngeni Catchment.

The Mpendle, Lions River, Karkloof, Inanda and Durban sub-catchments are important areas for the generation of streamflows which accumulate downstream (i.e. water yield in the catchment) when annual totals are considered. Modelled annual sediment yield (in tonnes) from naturally vegetated areas is most severe in the lower catchment areas with steeper slopes such as Inanda, and in the high altitude areas which have both steeper slopes and higher rainfall. The central and eastern parts of the uMngeni Catchment were found to contribute the greatest yield of sediment from degraded areas with low protective vegetation cover.

This combined modelling and mapping exercise highlighted areas of priority ecosystem service delivery, such as higher altitude grassland areas, which could be recommended for formal conservation, or protection under private partnerships. Generally, these areas confirm the intuitive sense of catchment stakeholders, but provide a robust and more defendable analysis through which water volumes are quantifiable, and potential investment into catchment interventions are justified.

South Africa is a major economic hub, with the port of Durban being the most active on the African continent. However, with the re-entry of the country into the global markets and the resulting economic opportunities, the increasing trend of globalization has led to industrialization and urbanization, which has increased the size and severity of the economy's ecological footprint. The final section of this thesis explores some of the wider issues associated with globalization and urbanization in the uMngeni catchment, and their impacts on water-related ecosystem service delivery by ecological infrastructure, and water security. The uMngeni Ecological Infrastructure Partnership is provided as a case study for mitigation of environmental degradation in urban centres due to population and economic growth, and we explore how enhancing stakeholder frameworks at a catchment scale, as well as integrated hydrological modelling to identify key areas for rehabilitation, can sustain ecosystem services and indeed human life. This is a theme which resonates throughout many developing countries. The chapter concludes with observations on the need for stakeholders to work together towards optimal investment decision-making, which may both protect the catchment's people from water-related risk, and ensure its success as a global commercial centre.

ACKNOWLEDGEMENTS

Firstly I would like to thank Myles Mander for first introducing me to the concept of ecosystem services, as well as Professor Roland Schulze for inspiring me to take my first steps into the world of hydrology, and his patience with me as a biologist. For technical support for my project, as well as project concepts, I would like to thank Dr Christo Marais, Prof Terry Everson and Prof Colin Everson. Thanks to Trevor Coleman being a fantastic mentor during my consulting days, and for always giving me a push to "just get it done" when required.

My thanks go to Dr Michele Warburton-Toucher for generously sharing her *ACRU* configuration of the uMngeni catchment, and many additional moments of technical assistance, as well as Mark Horan, David Clark, Sean Thornton-Dibb and Richard Kunz for answering technical questions during my short time at the Centre for Water Resources Research.

For the epic journey that was the uMngeni Green Fund project I would like to thank Gary de Winnaar for technical support and friendship, as well as the uMngeni Ecological Infrastructure Partnership student team for moral support and good times, especially Sanele Ngubane, Sesethu Matta and Hlengiwe Ndlovu. To Duncan Hay - thanks for your heartfelt effort and passion for the uMngeni, and your continued backing far beyond this project.

Some special people need to be thanked for cups of coffee and long chats – Dr Sabine Stuart-Hill, Stefanie Schütte and – my Swedish sister and fellow fan of the ecosystem services concept – Dr Rebecka Malinga.

My two long-suffering supervisors, Prof Graham Jewitt and Prof Roland Schulze – thanks for all the support and patience over the years, and your slightly intimidating technical wisdom.

My many friends who have seen me through on this journey – thank you for your constant presence.

Finally, thanks to my family. My mum, Lee, my brother Mitchell and my dad George, who is my role model and the inspiration for my love of nature. I love you all endlessly.

TABLE OF CONTENTS

Page

LIST OF TABLES

Table **Page**

LIST OF FIGURES

LIST OF ABBREVIATIONS

ACRU	Agricultural Catchments Research Unit
ARC	Agricultural Research Council
CAY	Crop coefficient
COIAM	Coefficient of initial abstraction
COLON	Percentage root colonization in the subsoil horizon
CSIR	Council for Scientific and Industrial Research
CWRR	Centre for Water Resources Research
DEA	Department of Environmental Affairs
DWA	Department of Water Affairs
EI	Ecological Infrastructure
EKZNW	Ezemvelo KZN Wildlife
ET	Evapotranspiration
GIS	Geographical Information System
GTI	GeoTerraImage
HRU	Hydrological Response Unit
IAP	Invasive Alien Plant
IAHS	International Association of Hydrological Sciences
IMF	International Monetary Fund
KZN	KwaZulu-Natal
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MASL	Metres above Sea Level
MDGs	Millennium Development Goals
MUSLE	Modified Universal Soil Loss Equation
NLC	National Land Cover
NRLD	National Review on Land Degradation
NWRS	National Water Resource Strategy
PCSUCO	Percentage of surface cover
ROOTA	Fraction of roots active in the topsoil
RDM	Resource Directed Measures
SA	South Africa
SADC	Southern African Development Community

SANBI	South African National Biodiversity Institute
SANCIAHS	South African National Committee of the International Association of Hydrological Scientists
SCS	Soil Conservation Service
SDF	Spatial Development Framework
SDGs	Sustainable Development Goals
SER	Society for Ecological Restoration
SIP	Strategic Integrated Project
UEIP	uMngeni Ecological Infrastructure Partnership
UKZN	University of KwaZulu-Natal
UN	United Nations
UNCCD	United Nations Convention to Combat Desertification
UNEP	United Nations Environmental Program
USA	United States of America
VEGINT	Interception loss
WC	Western Cape
WfW	Working for Water
WWF-SA	World Wide Fund for Nature – South Africa
WRC	Water Research Commission

CHAPTER 1: INTRODUCTION

Rationale for the research

In around 2010, while I was working in environmental consultancy, a new colleague introduced me to the concept of ecosystem services. Very little in the field of conservation or environmental management had made so much sense to me, both in terms of the justification for the preservation of the environment, but also how this justification was communicated to the public – i.e. how the public could benefit from these services provided by nature. It also further developed in my mind the Earth and people as a system, and how everything was interlinked.

What struck me the most about this concept were the water-related aspects, and how human action and land management could so significantly alter the quality and quantity of water received by downstream communities and the ecosystem itself. I felt this was something I wanted to use for furthering environmental management principles in the development projects I was involved with at the time, but also in a personal capacity, and particularly in South Africa. In this country, in-depth hydrological modelling work towards ecosystem service change investigation at sub-catchment scale has, to date, been uncommon, but where it has been undertaken it has been successful and informative (e.g. Blignaut et al. 2010, Mander et al. 2010, Le Maitre et al. 2014). Much of this work – although not always labelled under the ecosystem services umbrella - has also been carried out in support of the Department of Environmental Affairs' Working for Water programme (Cullis et al. 2008, Le Maitre et al. 2013), which was also a great inspiration for my work as an example of concurrent social, environmental and economic gains through an environmental approach.

Justification

Healthy ecological infrastructure, the nature-based equivalent of built infrastructure, plays a vital role in supplying water and other water-related ecosystem services to people in South Africa's catchments. Human-induced land cover changes can alter ecological infrastructure significantly, and can have a major negative effect on water supply and quality in our rivers, lakes and dams. As a result, many areas, even those with relatively high rainfall, face water storage and distribution challenges. However, in areas in which land cover change has caused a loss of ecosystem functionality, it may be possible to rehabilitate ecological infrastructure such that delivery of these services may be reinstated, either partially or entirely.

Aims

This body of work aims to illustrate, through review of literature, interaction with experts in the field, and hydrological modelling, that water security can be enhanced through improvement in water-related ecosystem service delivery as a result of the rehabilitation of degraded ecological infrastructure. Taking care of a catchment's natural assets can therefore delay or even prevent the need for the construction of costly infrastructure such as dams and desalination plants.

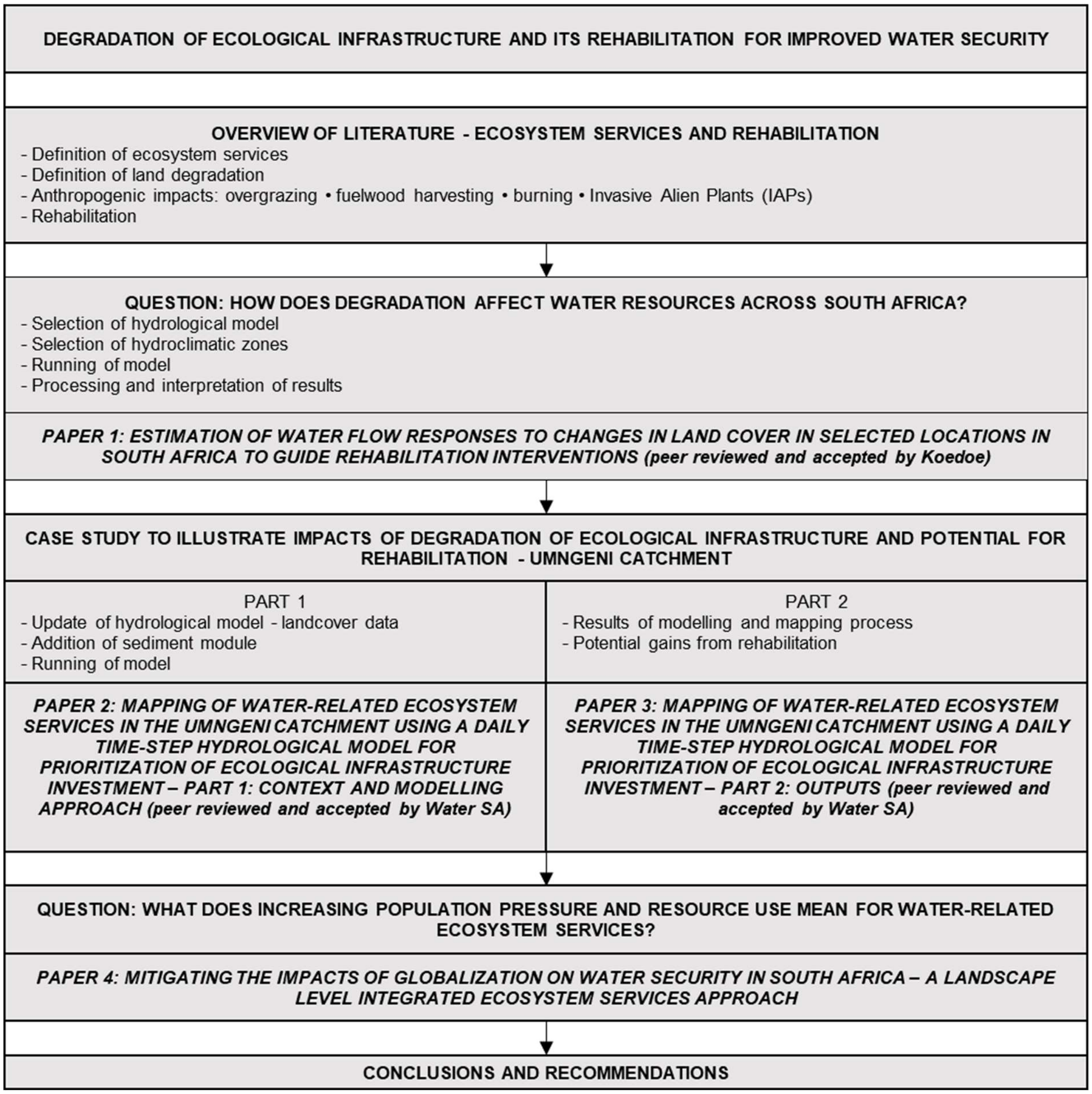
Objectives

The following objectives have allowed me to achieve this aim:

- Gaining an improvement in understanding of the link between land degradation and water security through literature review and interaction with experts in the field;
- Use of a validated and widely verified hydrological model to explore the targeted land cover changes (overgrazing and invasive alien plants) and their specific effects on the delivery of water within a catchment in different parts of South Africa, which has diverse climates and soils;
- Using this hydrological model to map and illustrate priority areas in a selected case study catchment, the uMngeni catchment in KwaZulu-Natal;
- Exploring how this model can be used to simulate the effect of overgrazed lands on water-related ecosystem services, showing the potential gains through rehabilitation;
- Exploring how this model can be used to simulate the effect of invasive alien plants on water-related ecosystem services, showing the potential gains through rehabilitation;
- Drawing conclusions on hydrological gains through security and rehabilitation of ecological infrastructure; and
- Exploring the possibilities for mitigation of the effects of globalization and urbanization on water security in South Africa through investment in ecological infrastructure, using the uMngeni Catchment as a case study.

Thesis structure

The following diagram provides an overall graphical representation of the structure of the thesis to achieve these objectives, and the diagram is provided at the beginning of each section to orientate the reader.



DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND ITS REHABILITATION FOR IMPROVED WATER SECURITY

OVERVIEW OF LITERATURE - ECOSYSTEM SERVICES AND REHABILITATION
- Definition of ecosystem services
- Definition of land degradation
- Anthropogenic impacts: overgrazing • fuelwood harvesting • burning • Invasive Alien Plants (IAPs)
- Rehabilitation

QUESTION: HOW DOES DEGRADATION AFFECT WATER RESOURCES ACROSS SOUTH AFRICA?
- Selection of hydrological model
- Selection of hydroclimatic zones
- Running of model
- Processing and interpretation of results

PAPER 1: ESTIMATION OF WATER FLOW RESPONSES TO CHANGES IN LAND COVER IN SELECTED LOCATIONS IN SOUTH AFRICA TO GUIDE REHABILITATION INTERVENTIONS (peer reviewed and accepted by Koedoe)

CASE STUDY TO ILLUSTRATE IMPACTS OF DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND POTENTIAL FOR REHABILITATION - UMNGENI CATCHMENT

PART 1
- Update of hydrological model - landcover data
- Addition of sediment module
- Running of model

PART 2
- Results of modelling and mapping process
- Potential gains from rehabilitation

PAPER 2: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 1: CONTEXT AND MODELLING APPROACH (peer reviewed and accepted by Water SA)

PAPER 3: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 2: OUTPUTS (peer reviewed and accepted by Water SA)

QUESTION: WHAT DOES INCREASING POPULATION PRESSURE AND RESOURCE USE MEAN FOR WATER-RELATED ECOSYSTEM SERVICES?

PAPER 4: MITIGATING THE IMPACTS OF GLOBALIZATION ON WATER SECURITY IN SOUTH AFRICA – A LANDSCAPE LEVEL INTEGRATED ECOSYSTEM SERVICES APPROACH

CONCLUSIONS AND RECOMMENDATIONS

Figure 1: Thesis structure

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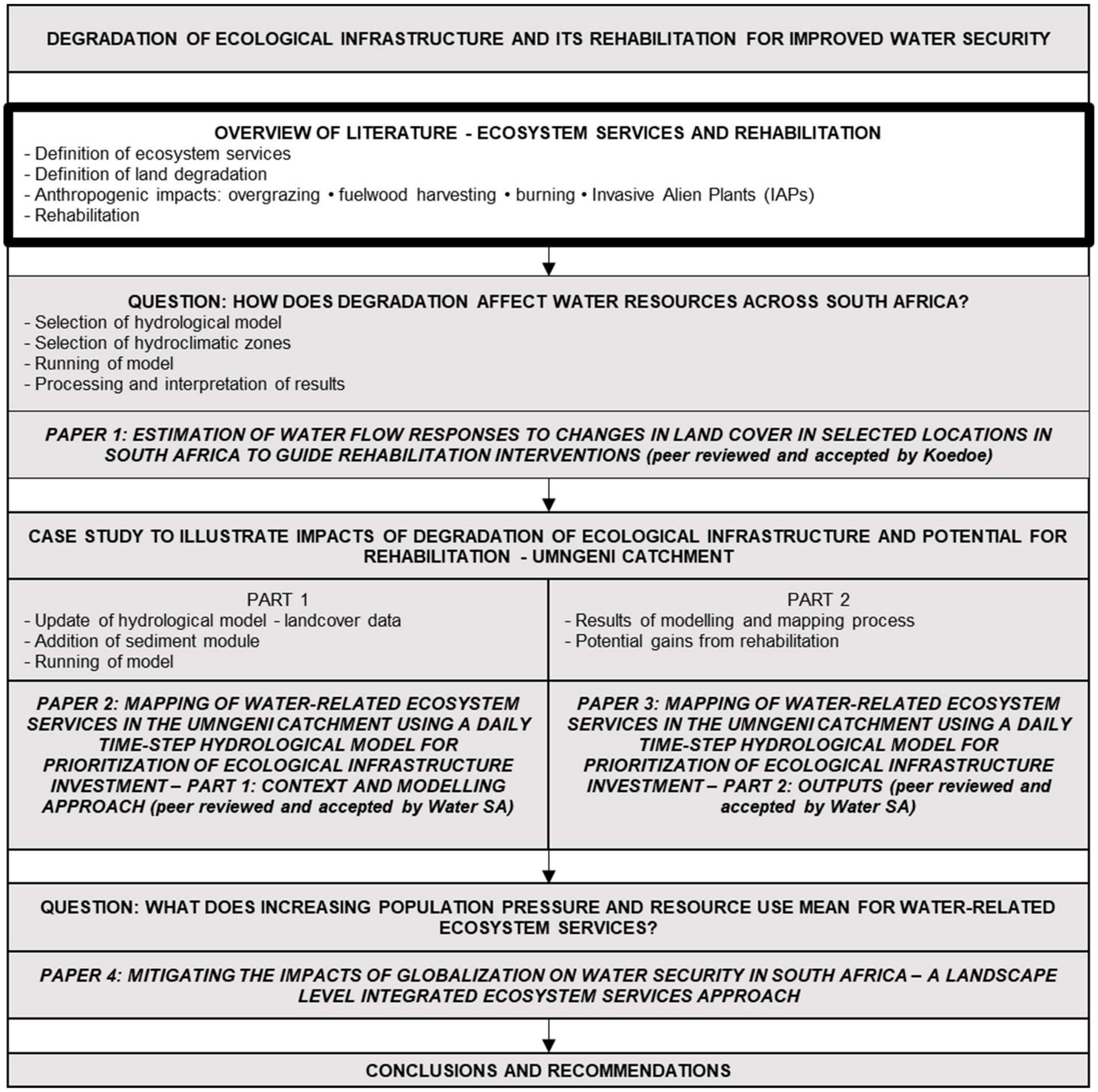
DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND ITS REHABILITATION FOR IMPROVED WATER SECURITY
OVERVIEW OF LITERATURE - ECOSYSTEM SERVICES AND REHABILITATION
- Definition of ecosystem services
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QUESTION: HOW DOES DEGRADATION AFFECT WATER RESOURCES ACROSS SOUTH AFRICA?
- Selection of hydrological model
- Selection of hydroclimatic zones
- Running of model
- Processing and interpretation of results
PAPER 1: ESTIMATION OF WATER FLOW RESPONSES TO CHANGES IN LAND COVER IN SELECTED LOCATIONS IN SOUTH AFRICA TO GUIDE REHABILITATION INTERVENTIONS (peer reviewed and accepted by Koedoe)
CASE STUDY TO ILLUSTRATE IMPACTS OF DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND POTENTIAL FOR REHABILITATION - UMNGENI CATCHMENT
PART 1
- Update of hydrological model - landcover data
- Addition of sediment module
- Running of model
PART 2
- Results of modelling and mapping process
- Potential gains from rehabilitation
PAPER 2: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 1: CONTEXT AND MODELLING APPROACH (peer reviewed and accepted by Water SA)
PAPER 3: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 2: OUTPUTS (peer reviewed and accepted by Water SA)
QUESTION: WHAT DOES INCREASING POPULATION PRESSURE AND RESOURCE USE MEAN FOR WATER-RELATED ECOSYSTEM SERVICES?
PAPER 4: MITIGATING THE IMPACTS OF GLOBALIZATION ON WATER SECURITY IN SOUTH AFRICA – A LANDSCAPE LEVEL INTEGRATED ECOSYSTEM SERVICES APPROACH
CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 2: OVERVIEW OF LITERATURE – ECOSYSTEM SERVICES AND REHABILITATION

Introduction

"Water security is defined as the capacity of a population to safeguard sustainable access to adequate quantities of acceptable quality water for sustaining livelihoods, human well-being, and socio-economic development, for ensuring protection against water-borne pollution and water-related disasters, and for preserving ecosystems in a climate of peace and political stability." (UN-Water 2013)

The Earth's natural land cover has been significantly altered over time, usually to meet the needs of a growing society, to the point at which it may be facing catastrophic risk (Steffen et al. 2015, Rockström et al. 2009, Warburton et al. 2012). As a consequence of land cover alterations and degradation of ecological infrastructure[1], hydrological responses have changed, and water security in many of South Africa's catchments has become threatened. These hydrological changes can include a reduction in water production from water source areas and delivery of water in our country's rivers, a change in the components of runoff, temporal water flow patterns, and a change in water quality. Even in areas which have a relatively high rainfall, decision makers face many challenges with regard to water management due to aging infrastructure, lack of awareness of the value of water and the need to conserve water resources, lack of human and financial resources and skills, as well as ineffective capture and storage of rainfall (DWA 2013). The country's communities and ecosystems therefore do not always have access to adequate water in regard to both quality and quantity. This is particularly pertinent in times of drought, which in some parts of South Africa are projected to become more frequent under climate change (Kusangaya et al. 2014).

Security of fresh water is of particular concern in South Africa, which has a mean annual rainfall of 450 mm per annum, when compared to a world average of 860 mm (King et al. 2011). This rainfall is furthermore not spread evenly throughout the country, neither spatially nor temporally, and under climate change is likely to become more variable on both annual (year-to-year) and monthly time scales (Schulze and Kunz 2011a, b). Together with the low

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[1] "naturally functioning ecosystems that produce and deliver valuable services to people" (Jewitt et al. 2015)

and erratic rainfall of the country, the conversion of rainfall to runoff within South Africa is only 9% on average (Whitmore 1971), and the inter-annual variability of runoff has been found to be between 2 and 5 times that of rainfall (Schulze 2008). The natural water scarcity in the country is compounded by human activities such as agriculture (which was allocated as much as 62% of the available water supply in the year 2000), urbanization (23%), mining and industry (6%; King et al. 2011).

Regardless of water availability, poor water quality can also affect human and ecosystem health and function (Rijsberman 2006). Furthermore, with the changing weather and climate patterns already being attributed to global climate change, the rainfall seasons on which agricultural and water supply systems rely may shift (Schulze and Kunz 2011b). There is thus a need for water resource managers to better understand hydrological systems in terms of water supply (rainfall and runoff), demand by water users and factors which can alter catchment yield so that water resources may be managed sustainably. It is also important to understand how to rehabilitate systems which have been negatively altered.

There is currently a lack of knowledge with regard to the socio-economic and environmental benefits which may be gained through the rehabilitation of altered ecosystems (Aronson et al. 2010). This work aims to contribute further research into the hydrological benefits of rehabilitation, with a focus on overgrazed lands and invasive alien plant species – mainly in terms of gains in water volume in the catchment. Links may, however, also be drawn between volume gains, particularly in terms of baseflow, and water quality, as well as to economic benefits such as job creation and avoided infrastructure costs.

This chapter focuses on the degradation of ecological infrastructure with a view to understanding the hydrological effects of these impacts, and aims to explore options for rehabilitation of hydrological ecosystem services, and ultimately the sustainable supply of water to people and ecosystems.

How does ecological infrastructure provide water-related services to society?

Brauman et al. (2007) describe water-related ecosystem services as those which encompass the benefits to society produced by terrestrial ecosystem effects on fresh water. The authors further group these services into five types, namely:

- The supply of water for extraction;
- In-stream water supply;
- Mitigation of potential negative effects of water (e.g. flooding, landslides);
- Cultural benefits derived from water use; and
- Services which perform a supporting function, such as nutrient cycling and aquatic primary production.

A simplified interpretation of how ecological infrastructure delivers these services and how these can benefit society from a water perspective is shown in Figure 2. The links between ecosystem services and ecological infrastructure are further explored in Figure 3, which illustrates the complexities of system thresholds and feedbacks inherent in the relationships between ecological infrastructure and ecosystem services (e.g. Suding et al. 2004). These should particularly be borne in mind when planning restoration action, as further explored later in this chapter.

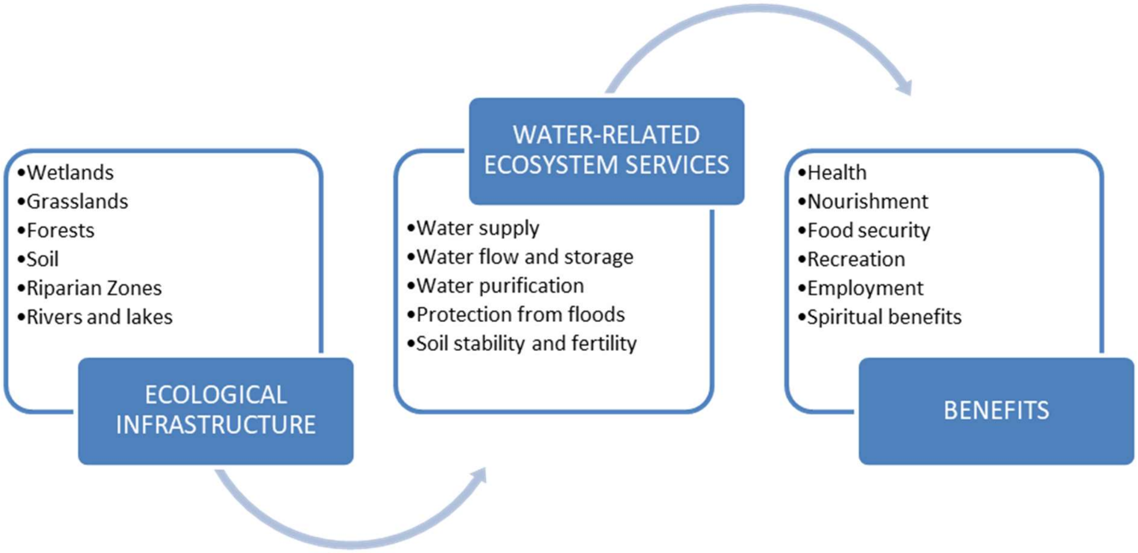

Figure 2: Simplified diagram of the provision of water-related ecosystem services and benefits by ecological infrastructure

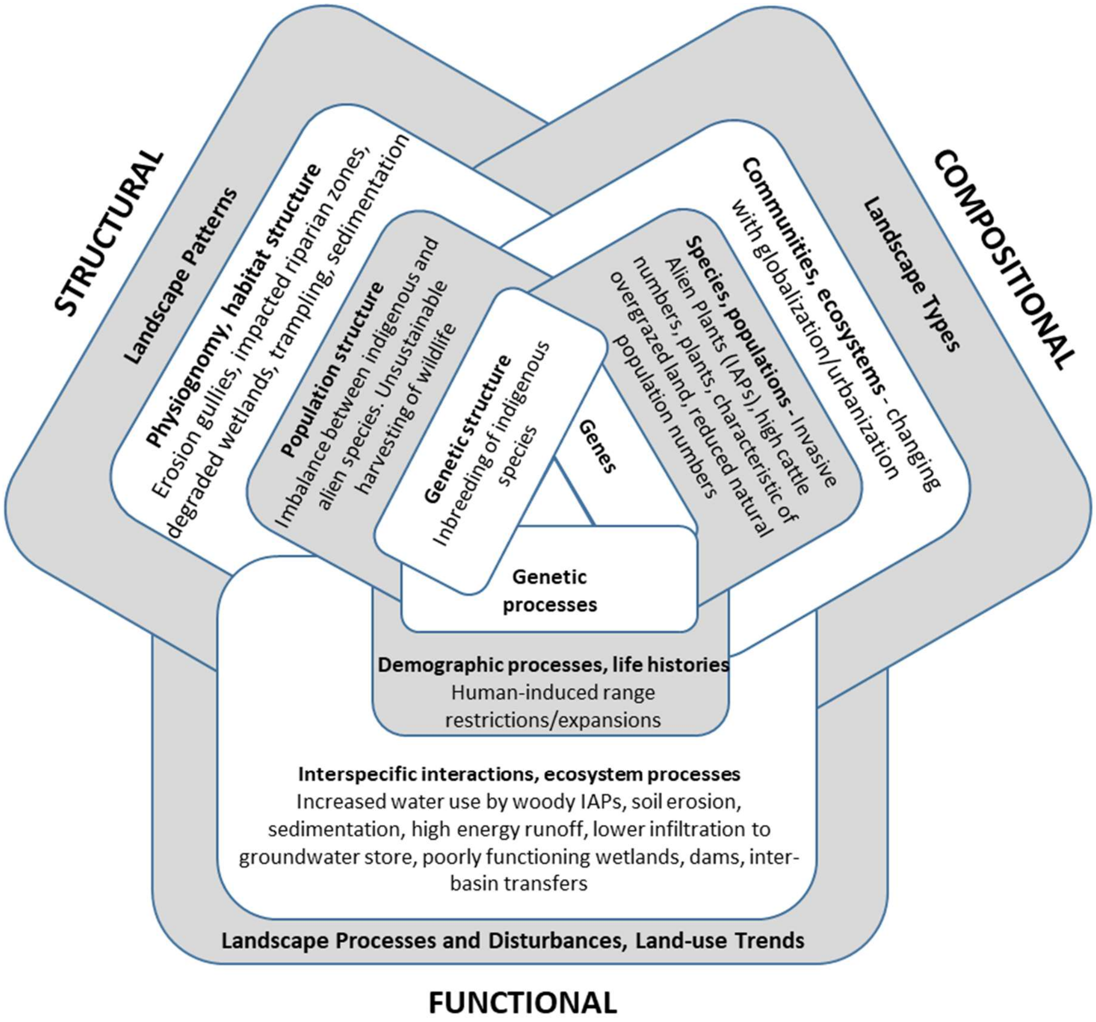

Figure 3. Adaptation of Noss's diagram (1990) of compositional, structural, and functional biodiversity indicating the impacts of degradation on various levels on EI, and the complexities of interactions between abiotic and biotic ecosystem factors

Once ecological infrastructure has been degraded through poor land use management, there is likely to be a reduction in the delivery of some or all of these water-related ecosystem services (Le Maitre et al. 2007). Furthermore, once land has become degraded, the livelihoods and quality of life of people who depend on it are likely to be significantly compromised (Blignaut et al. 2008).

A closer look at land degradation

Land degradation, and in turn the degradation of ecological infrastructure through society's actions, has had a marked impact on natural hydrological responses (Rockström et al. 2009). The intensity of the impact is dependent on the particular human-induced change and its location within a catchment (Warburton et al. 2012). Projected climate changes for South Africa broadly include higher temperatures, more variable rainfall patterns and more extreme rainfall events (Kusangaya et al. 2014).

Land degradation can be highly context dependent, and will vary between ecosystems and climates (Rutherford et al. 2012). The term degradation furthermore has different meanings from a biodiversity perspective (e.g. reduced ecosystem productivity) and from an agricultural perspective, e.g. less productive rangeland (Rutherford and Powrie 2010a).

Scholes and Biggs (2005) define land degradation as land uses which result in a persistent loss in ecosystem productivity and, more technically, as extractive use by humans at a rate which exceeds the natural replenishment. In a southern African context, it is often associated with high human population densities and poverty in rural areas (Scholes and Biggs 2005). It is also useful to note the definition of degradation as provided in the South African National Review on Land Degradation (NRLD), as compiled by Hoffman et al. (1999), namely: "reduction or loss, in arid, semi-arid and dry sub-humid areas, of the biological or economic productivity and complexity of rainfed cropland, irrigated cropland, or range, pasture, forest and woodlands resulting from land uses or from a process or combination of processes, including processes arising from human activities and habitation patterns such as:

- Soil erosion caused by wind and/or water;
- Deterioration of the physical, chemical and biological or economic properties of soil; and
- Long-term loss of natural vegetation".

Land degradation includes a variety of processes, including changes in plant species composition, surface cover and soil erosion, and results in reduced biological and economic productivity of the area concerned (Wessels 2011). The NRLD (Hoffmann et al. 1999) directed attention to severe land degradation in the former homelands of South Africa, which are generally seen as communal areas which are characterized by dense populations, overgrazing, soil erosion, excessive harvesting of firewood and an increase in plant species which are not palatable to livestock. Degraded land can refer to land which has been burned too frequently in an attempt to increase grazing resources (Blignaut et al. 2008). Wessels (2011) attributes land degradation to a combination of unemployment, poverty and an absence or failure of land-use regulation. In a South African context it is also important to bear in mind the political history and inequality of the country, and the unethical confining of certain population groups to specific areas, which has led to over-utilization of limited resources (Hoffmann et al. 1999). Land degradation has a marked effect on the land and vegetation-related aspects of the hydrological cycle, and on the partitioning of water within the cycle, which are depicted in Figure 4. The land surface forms the interface between precipitation and the soil, sub-soil and groundwater zone. At the surface, precipitation is partitioned into interception[2] by vegetation, soil water evaporation, infiltration and surface runoff, and below the surface, into transpiration and recharge to below the root zone and into groundwater. A degraded land surface is likely to vastly alter each of these processes.

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[2] Interception can be defined as the process and the amount of rain stored on leaves and branches and eventually evaporated into the atmosphere (after Langbein and Izeri 1960).

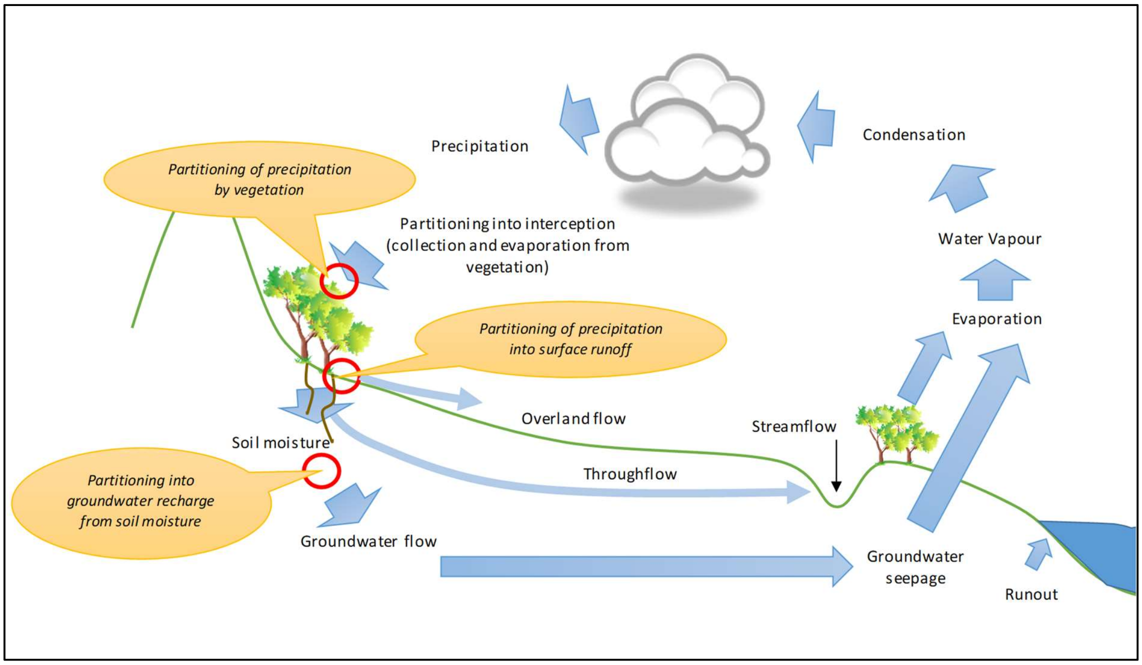

Figure 4: The hydrological cycle (after Rockström et al. 1999, Ward and Robinson 2000 and Jewitt 2005)

Land degradation alters the balance between infiltration and stormflow, i.e. overland and near-surface flow (Le Maitre et al. 2007), and it could therefore be argued that the two most important hydrological changes brought about through land degradation are:

- Reduced interception and infiltration rates; and
- Sediment mobilization through stormflow.

These are further explored below, and this network of effects is depicted in Figure 5.

Reduced interception and infiltration rates

The loss of aerial and surface vegetation cover through various types of degradation (Figure 5) reduces canopy interception and transpiration, and thus increases the partitioning of water into soil water evaporation, surface and near-surface runoff, implying that more water is directed off the surface and thus does not reach the water stores and paths below the vegetation's root zone (Maloti Drakensberg Transfrontier Project 2007).

Reduced infiltrability of the soil results in reduced retention of water in the catchment, and thus affects the replenishment of soil moisture, sub-surface flows and partitioning of soil water into groundwater recharge (Le Maitre et al. 1999, Reyers et al. 2009) from which sustained baseflows are derived. This implies that the movement of water (unsaturated flow) through the hillslope is critical (Lorentz et al. 2008), particularly during intense rainfall events in which a large amount of rain falls in a short period. Reduction in groundwater recharge could be problematic in the long term over large parts of southern Africa, as over 75% of the western part of this region is dependent on groundwater as a primary water source for agricultural and domestic use (Scholes 2009), assuming that recharge to groundwater currently takes place in these areas under undisturbed conditions.

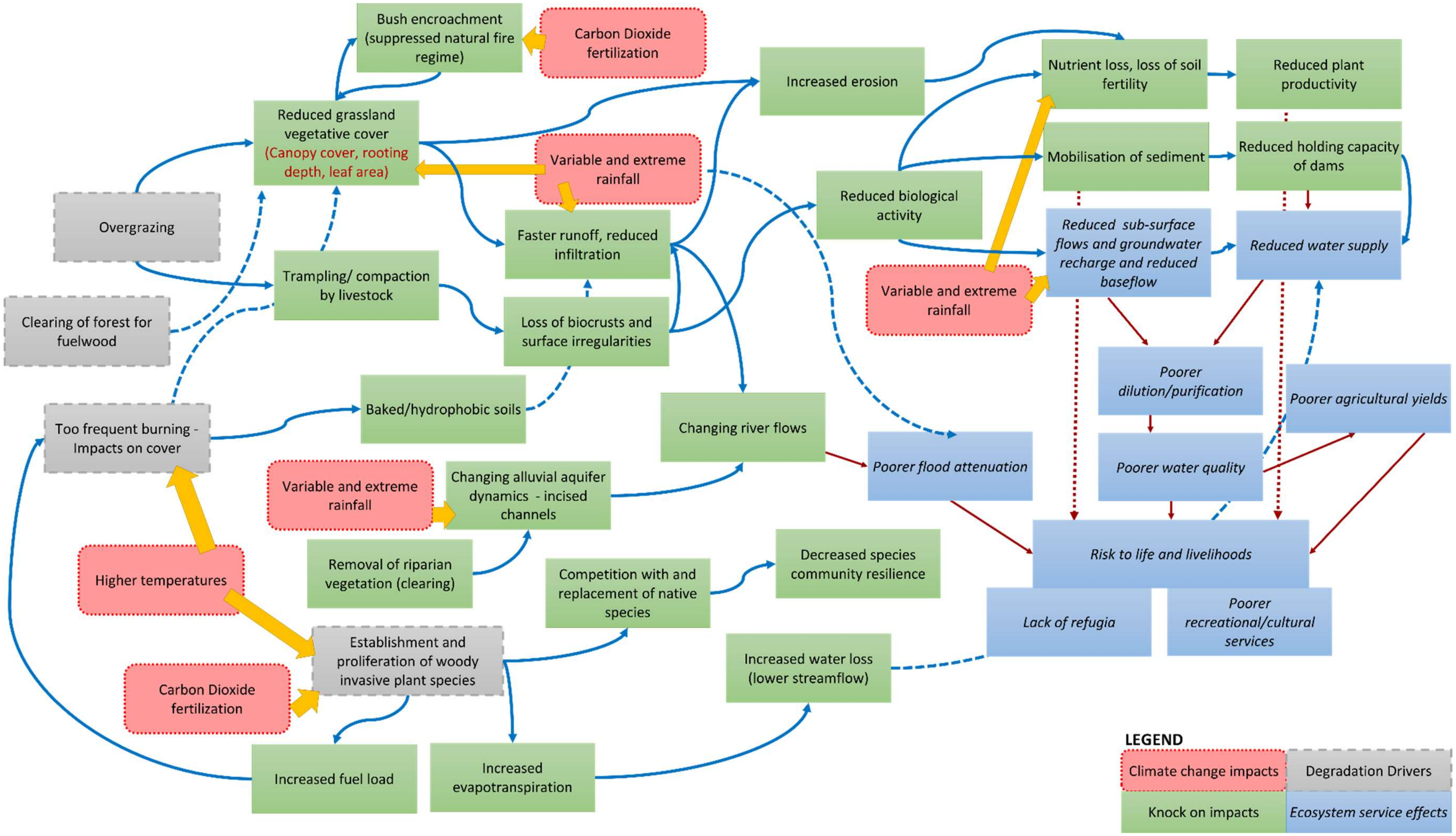

Figure 5: Interpretation of the impacts of land cover and climate change, and subsequent effects on ecological infrastructure and water-related ecosystem services

Rain falling on fine soil particles may furthermore result in re-deposition of these particles into a hard crust, "cap" or "scald" which is inhospitable to seedling establishment (preventing re-vegetation) and which further reduces infiltration (Scholes 2009)[3] (Figure 5).

Sediment (topsoil) mobilization through stormflow

Sediment mobilization implies soil loss and an increase in stream sediment yields through a change in flow patterns (Le Maitre et al. 2007). Degraded land can be exposed to higher rates of soil water evaporation, resulting in a faster rate of drying in the topsoil horizon (Snyman and du Preez 2005). This drier topsoil is easily mobilized by wind and rain, and can be moved downslope with the increased surface runoff (Figure 5), removing with it the soil's natural organic materials and nutrients, thus lowering soil fertility in the upland areas (Moore 2001), and depositing the nutrients into water courses and water impoundments. Gully erosion may also occur, and this is a key feature of degraded South African landscapes (Mararakanye and Le Roux 2012), causing large-scale soil loss.

If upstream intensive agricultural and/or anthropogenic activities such as effluent-producing industries or waste water treatment works exist in the catchment, then transport of soluble nitrates as well as phosphates – the latter, importantly, being sediment-bound (Pettersson et al., 1988).- is likely, leading to eutrophication in downstream water courses (Hughes et al. 2013). It is also possible that salinization could occur in upland degraded soils (particularly through high concentrations of phosphates, sodium, potassium and magnesium), leading to increased cation exchange capacity and nutrient imbalances (Rutherford et al. 2012).

Of concern with regard to water volumes is that mobilized sediment is transported to rivers and into dams, where a fraction is deposited and occupies space (Figure 5). Man-made dams are designed to contain and consistently supply water to domestic, industrial and agricultural users. Sedimentation may thus reduce the capacity and lifespan of the dams (Csiki and Rhoads 2010) and lead to more frequent spilling and/or the need for costly dredging, and such runoff is not effectively captured and less water is available for distribution to water users. Water supply

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[3] Scholes (2009) hypothesizes that a threshold of soil exposure (i.e. area not covered by vegetation) must exist beyond which the rate of scald formation cannot be naturally re-vegetated. This threshold has reportedly not been quantified, and is highly likely to vary between seasons and soil types.

may become less reliable from a service delivery perspective, which is a key concern in South Africa. Furthermore, in rivers, natural pans and wetlands, sediment deposition may affect ecosystem function and fish health, altering the benthic structure and ecological balance of the water course (Holmes et al. 2005).

Specific changes in water-related ecosystem services in response to specific anthropogenic activities are explored individually below. The hydrological response and ecosystem consequence of each is detailed in Table 1.

Table 1: Degradation drivers, their hydrological and ecological consequences, and examples of rehabilitation activities used to address delivery of key water-related ecosystem services

Degradation driver	Primary impact	Hydrological response	Ecosystem consequence	Rehabilitation action	Measurement for modelling and monitoring	References
▪ Overgrazing	▪ Reduction in vegetative cover - reduction in above-ground biomass and surface litter/mulch	▪ Reduced interception ▪ Reduced infiltration ▪ Sediment mobilization (erosion) ▪ Increased evaporation of soil moisture and reduced topsoil moisture content ▪ Higher speed runoff ▪ Reduced groundwater recharge	▪ More flow pulses in river ▪ Lower overall water levels in rivers and groundwater aquifer ▪ Poorer water quality in water courses due to sedimentation ▪ Topsoil nutrient loss ▪ Soil salinization	▪ Re-seeding of grasses ▪ Rotational grazing (as opposed to inextensive, unmanaged grazing) ▪ Planting of small perennial trees which persist above the browse line, as well as hardy shrubs ▪ Mulching, gypsum treatments ▪ Mechanical efforts – filling in with soil/gabions ▪ Avoidance of nutrient-exhaustive cropping ▪ Efficient use of fertilizer ▪ Introduction of legumes ▪ In aquatic systems – water circulation through mechanical means, manipulation of zooplankton	▪ Baseflow ▪ Stormflow ▪ Streamflow ▪ Groundwater storage ▪ Sediment yield ▪ Soil moisture in topsoil and sub-soil horizons ▪ Peak discharge	▪ Hughes et al. 2013 ▪ Rutherford et al. 2012 ▪ Blignaut et al. 2008 ▪ King and Hobbs 2006 ▪ Schulze et al. 2007 ▪ Beukes and Cowling 2003 ▪ Ahmad et al. 1998 ▪ Bradshaw 1996
	▪ Bush encroachment/ densification (indigenous, woody species)	▪ Higher evapotranspiration (increased water use) ▪ ▪ Reduced soil water content ▪ Reduced organic matter ▪ Reduced soil aggregate stability	▪ Reduced vegetative cover, alteration of species composition and food chain ▪ Decreased stormwater flow and recharge	▪ Thinning/"Debushing" ▪ Lower savanna burning frequency ▪ Lower stocking rates ▪ Manipulating competitive dynamics (e.g. altering the disturbance regime to favour desirable species)	▪ Species counts ▪ Evapotranspiration	▪ King and Hobbs 2006 ▪ Podwojewski et al. 2014 ▪ Smit 2004 ▪ van Vegten 1984
	▪ Soil compaction	▪ Reduced infiltration ▪ More rapid runoff	▪ As for "reduction in vegetative cover"	▪ Vegetation, addition of organic matter ▪ Mechanical treatment	▪ Baseflow ▪ Stormflow ▪ Streamflow ▪ Groundwater storage ▪ Sediment yield ▪ Soil moisture in A and B horizons ▪ Peak flow	▪ Bradshaw 1996 ▪ Trimble and Mendel 1995
▪ Injudicious frequent burning	▪ Reduction in vegetative cover	▪ Reduced interception ▪ Reduced infiltration	▪ As for "reduction in vegetative cover"	▪ Changing burning frequency and timing (e.g. changing	▪ Baseflow ▪ Stormflow	▪ Blignaut et al. 2008

Degradation driver	Primary impact	Hydrological response	Ecosystem consequence	Rehabilitation action	Measurement for modelling and monitoring	References
regime (too frequent, wrong timing, fire too hot)	▪ Hydrophobic soils/water repellency	▪ Sediment mobilization (erosion) ▪ Increased evaporation of soil moisture and reduced topsoil moisture content ▪ Higher speed runoff, flooding ▪ Reduced groundwater recharge	▪ Destruction of above-ground organic material and soil carbon ▪ Reduced cation exchange capacity (destruction of humus compounds, increase of soil pH through deposition of positive ions with ash)	annual winter burn to bi-annual spring burn in Drakensberg) ▪ Hillslope: o Post-fire seeding with grasses (with fertilizer) o Contour furrowing and trenching o Use of contour-felled logs o Mulching o Scarification and ripping o Use of geotextiles for stability o Temporary fencing o Sand or soil bags ▪ Channel o Straw/log/rock dams o Stabilizers – rocks and logs o Channel clearing ▪ Roads and paths o Cross drains o Culvert upgrade and repair o Outsloping	▪ Streamflow ▪ Groundwater storage ▪ Sediment yield ▪ Soil moisture in A and B horizons ▪ Carbon and other chemistry measurement ▪ Peak flow	▪ Schulze et al. 2007 ▪ Neary et al. 2005
▪ Invasive alien plant species	▪ Replacement of native species	▪ Significant increased water uptake through evapotranspiration (reduced streamflow), particularly in the riparian zone	▪ Reduced water availability to ecosystem ▪ Out-competition of native species ▪ Disruption of food chain	▪ Manipulating competitive dynamics ▪ Mechanical, chemical, biological, integrated clearing ▪ Selective and controlled burning	▪ Species counts ▪ Remote sensing ▪ Streamflow	▪ Te Beest et al. 2012 ▪ Marais and Wannenburgh 2008 ▪ King and Hobbs 2006

Overgrazing/overstocking

Trimble and Mendel (1995) list the following potential effects of cattle grazing, which range from those which affect specific points within the catchment to those which affect the catchment as a whole (refer to Figure 5):

- *Compaction of soil* which can cause a smoother and less penetrable surface and increased runoff (converting the runoff regime from one of variable source areas to one of general unsaturated overland flow) due to ineffective "trapping" of precipitation by vegetation cover or natural surface roughness (irregular features) in the topsoil; weakening of biological resistance to trampling. Compaction of soils lead to runoff generation either through the rainfall intensity exceeding the infiltration rate ("Hortonian" overland flow; Horton 1945) or the infiltration rate exceeding the percolation rates through the soil. Compaction therefore restricts the movement of water through the soil profile, causing runoff;
- *Reduction in soil organisms* which increase soil porosity, permeability, structure and fertility;
- *Reduction in above-ground and surface vegetative cover* which enhances soil loss;
- *Reduction in infiltration*, e.g. for "moderate/light" grazing a reduction to 75% of the ungrazed condition, and for "heavy" grazing a reduction to 66% of the "moderate/light" condition, or half of the ungrazed condition, particularly during wet periods; and
- *Damage to streams, ponds and riparian areas*, e.g. breaking of river banks, roughening of water course, removal of vegetation and soil.

Heavy grazing has a marked effect on ecological infrastructure, and on grassland in particular, resulting in a significant decline in annual and perennial canopy cover and forb/grass, leafy stem, tussock and stoloniferous plant species (Rutherford and Powrie 2010b; 2011). This renders the soil susceptible to wind and water erosion. In fact, Dlamini et al. (2011) have shown a strong correlation between the proportion of vegetation and the amount of sheet erosion.

Particularly pertinent to savanna grassland areas, Scholes (2009) further identifies an increase in the cover and biomass of woody plants over time in overgrazed lands, this process being known as shrub or bush encroachment, which in turn leads to reduced grass cover and enhanced soil exposure. Therefore, heavy grazing is likely to reduce the stabilizing grass cover, while possibly allowing for bush encroachment by woody species. This further implies a loss of natural biodiversity and alterations to the ecosystem, which may compromise its ability to deliver ecosystem services.

A significant change in vegetation can cause a change in catchment flows – either positive or negative. Degradation due to uncontrolled harvesting of trees for fuel is also form of deforestation which results in a reduction in above-ground biomass and root zone depth, and can cause an immediate increase in runoff (Bosch and Hewlett 1982). This is an increasingly widespread issue in sub-Saharan Africa, where wood is still the predominant cooking fuel (Schlag and Zuzarte 2008). Fuelwood harvesting can cause reduced water uptake by plants, lower evapotranspiration and higher annual mean river discharge (Chidumayo 2013). However, although this impact may release more water to the stream through surface runoff in the short term, it also implies that lower infiltration is likely to result, which is likely to lead to decreased low flows and groundwater recharge. In addition, the discharged water is likely to be of lower quality due to sediment content, and may be less suitable for many other uses.

Too frequent burning of grasslands

In South Africa, fire is vital for grassland ecosystem health. It also allows land managers to manipulate grassland areas towards various management objectives (Titshall et al. 2000, Snyman 2003, SANBI 2013). New vegetation growth is stimulated and moribund material removed, nutrients released, and the succession of different types and a diversity of vegetation (and control of invasive and weed species) is facilitated (SANBI 2013). South African law requires careful fire management planning by land managers, and fire frequency needs to be carefully controlled. Although well-timed fires are important for grassland ecosystem health, too frequent burning can be detrimental to grassland ecosystems[4].

Blignaut et al. (2010) carried out a modelling study in the Drakensberg to investigate the use of hydrological modelling as a tool for ecosystem services trading. Hydrological effects of

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[4] The effects of too infrequent burning are not discussed here.

degradation through too-frequent grassland burning were identified during this research, as listed below:

- A reduction in above-ground biomass, which in turn lowers transpiration and canopy interception, and reduces the canopy's protective properties, thereby contributing to the soil loss process. This was also discussed by Scott (1993), who found a 16% increase in total flow which he attributed to a reduction in transpiration and interception after burning in natural catchments, and by Lane et al. (2006), who found increases of between 40 and 94% in certain Australian catchments following a severe fire; and
- A reduction in surface litter/mulch , which may raise rates of evaporation from the soil surface (drying the topsoil), reduce the infiltrability of the soil, and thereby enhance soil erosion; and
- An increase in soil hydrophobicity/water repellency. Scott (1993) and Smith et al. (2011) found an increase in stormflow and soil loss from plantation catchments due to water repellency caused by fire and reduced infiltration.

The consequences of the above effects include higher stormflows, higher sediment yields and lower baseflows, all of which are directly linked to changes in water-related ecosystem services, which have been found to be very important components of wider ecosystems (Reyers et al. 2009).

Establishment of alien invasive plant species

The establishment and proliferation of non-indigenous plants, particularly of woody species which are more notable water users than grasslands, can reduce water availability in the catchment (Van Wilgen et al. 2008) in terms of changes to overland flow, interflow and groundwater flow. Woody species can change the amount of groundwater recharge in the catchment through the changes they make to the processes of interception, evapotranspiration, infiltration, runoff, and soil water uptake through deep roots in the unsaturated zone, and they can also directly withdraw groundwater from shallow aquifers and saturated strata (Le Maitre et al. 1999). Through some of the above processes they thereby reduce the amount of precipitation which is eventually partitioned from the atmosphere to the water table (Le Maitre et al. 1999). This affects water provision (a water-related ecosystem service, see Figure 2) to the aquatic ecosystem and downstream communities.

Certain *Eucalyptus* species and *Acacia mearnsii* in particular are deep rooted plants (Robinson et al. 2006, Clulow et al. 2010) capable of withdrawing more water from the sub-soil when compared to shallower-rooted indigenous vegetation. In fact, root depth in species such as *Acacia* spp. and *Prosopis* spp. can reach between 3 and 20 m, with *Eucalyptus* spp. roots having even been shown to extend to 60 m in one case (Le Maitre et al. 1999). These inherently invasive plants, which are generally grown in commercial forestry plantations, also have relatively high leaf area indices (Scott and Lesch 1997, Asner et al. 2003) which are likely to enhance evapotranspiration and intercept more rainfall prior to its reaching the soil (Gordon 1998), although the increased evapotranspiration (a more continual process) is thought to have a larger impact than increased interception - a more episodic process (Scott and Lesch 1997). The higher interception and enhanced evapotranspiration by these invasive species implies that natural runoff processes are not maintained, and downstream ecological functioning may be compromised. Problematic alien invasive plant genera at national level include *Eucalyptus*, *Populus* and *Acacia* (Van Wilgen and Wannenburgh 2016), and as such these are the most targeted by the South African government's Working for Water (WfW) Programme's alien plant clearing efforts[5]. *Pinus* and *Hakea* are specifically targeted in the Western Cape, *Lantana camara* and *Chromolaena odorata* in the savanna and grassland areas, and *Prosopis* in the arid areas of the country (Van Wilgen and Wannenburgh 2016).

Of major concern in South Africa is the invasion of riverine riparian zones (important corridors of ecological infrastructure) by non-indigenous species, particularly because of their very high rates of evapotranspiration, as mentioned above, and because of abundant soil water in the riverine riparian zone (Dye and Jarmain 2004). The invasive plants have access to additional water from the available groundwater within the riparian zone largely derived from the discharges of groundwater and lateral flow from adjacent hillslopes into the floodplain (Le Maitre et al. 1999, Görgens and van Wilgen 2004, Lorentz et al. 2008, Van Wilgen et al. 2008). A change in the water table due to abstraction of water by invasive alien plants will depend on

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[5] The Working for Water (WfW) programme was launched in 1995 and is administered by the Department of Environmental Affairs. The programme has succeeded in clearing more than a million hectares of invasive alien plants within the borders of South Africa using mechanical, biological, chemical and integrated methods, and providing employment and training to 20000 people from previously disadvantaged backgrounds (Department of Environmental Affairs, 2014).

how direct the connection is between the surface and the groundwater resource, and in South Africa, where an estimated 90% of the land area is underlain by fractured aquifers, this implies a fairly direct connection (Le Maitre et al. 1999).

Over much of the year, for many trees in the riparian zone, evapotranspiration is limited by atmospheric water demand, and this can result in a faster than normal loss of streamflow from the catchment and a reduction in low- and annual-season streamflows (with low referring to the dry winter season in most parts of South Africa). However, several studies have been completed with regard to the effects that invasive alien trees have on water resources, particularly in South Africa and Australia, which indicate that this relationship is more complex. It should firstly be noted that transpiration by riparian trees may be limited by stomatal closure when there is a large differerence between the amount of moisture in the air and how much moisture the air can hold when it is saturated (i.e. a high Vapour Pressure Deficit, VPD), as Dzikiti et al. (2016) found for at least one Eucalypt species, as illustrated by hourly sap flow data. Furthermore, transpiration may also be limited by water availability as determined by elevation above water level, i.e. the position of the tree on the stream bank and whether it has permanent access to water (e.g. willow trees as explained in Doody and Benyon 2011), or depth to the water table for species in the *Prosopis* genus (Stromberg et al. 1993), which are problematic in South African groundwater-dependent ecosystems.

Rehabilitation of human-induced land cover changes

Connections within the hydrological cycle along various corridors and between various components of ecological infrastructure are particularly important as they contribute to the flow of energy, matter and organisms in an ecosystem (Noss 1990, Pringle 2001). Hydrological connections are not only important within the river channel itself (between upstream and downstream), but in lateral relationships between the river and its adjacent floodplain's aquatic habitats, as well as vertical connectivity with the groundwater zone (Newson 2010, Hermoso et al. 2012a). It has been suggested that, with regard to protection of freshwater systems, focus should be placed on three aspects, namely whole catchment management, maintenance of natural flow patterns and the prevention of establishment of invasive species (Saunders et al. 2002).

In order to sustain and improve water-related ecosystem services which have been altered due to anthropogenic degradation, rehabilitation may be required. Bradshaw (1997) lists the four common terms used in connection with ecological restoration, namely restoration, rehabilitation, remediation and reclamation, and updated definitions are provided below.

- **Restoration** - "The action of returning something to a former owner, place, or condition" (Oxford Dictionary 2014). **Ecological restoration** is "the process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed" (Society for Ecological Restoration 2004);
- **Rehabilitation** – "Return (something, especially a building or environmental feature) to its former condition: *the campaign aims to rehabilitate the river's flood plain" (*Oxford Dictionary 2014). **Rehabilitation** also focuses on pre-existing condition, but emphasizes the reparation of ecosystem processes, productivity and services, whereas restoration goals include the re-establishment of biotic integrity in terms of species composition and community structure (Society for Ecological Restoration 2004);
- **Remediation** – "The action of remedying something, in particular of reversing or stopping environmental damage" (Oxford Dictionary 2014)
- **Reclamation** – "Bring (waste land or land formerly under water) under cultivation" (Oxford Dictionary 2014). It focuses on stabilization of terrain, assurance of safety and aesthetics, and a return of the land to a useful purpose. Re-vegetation may include the use of only a single species, and as such this process may not be ecologically driven (Society for Ecological Restoration 2004).

With regard to the term “restoration”, Bradshaw (1997) refers to an older definition as implying that the land is brought back to an original or perfect state, whereas “rehabilitation” does not imply this perfection, and is perhaps more appropriate for use in natural resource management activities in South Africa, as it is unlikely that functionality will ever be completely attained. Bradshaw (1996) provides a useful graphic which illustrates these different terms, as shown in Figure 6.

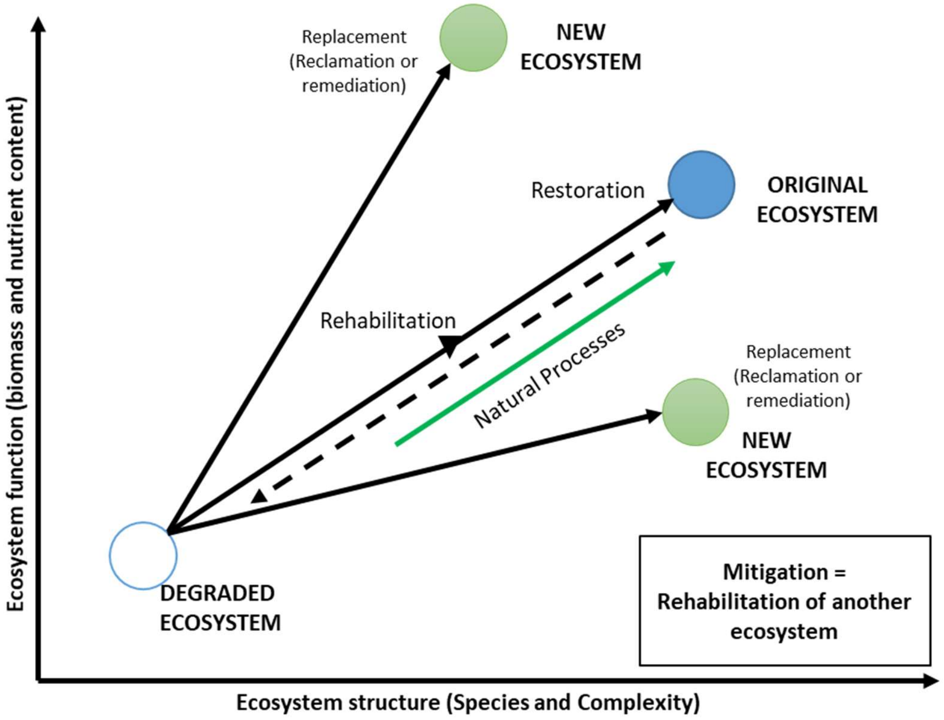

Figure 6: Differences between restoration, rehabilitation and replacement of an ecosystem (after Bradshaw 1996)

Land rehabilitation not only improves the ability of ecological infrastructure to effectively produce agricultural and other food sources, but also enhances the delivery of water-related ecosystem services and resilience to climate change (Blignaut et al. 2008). Rehabilitation addresses both the improvement of ecology and economics, i.e. the natural environment is improved, and simultaneously there is a quantifiable benefit to human beings (Blignaut et al. 2008).

A selection of examples of rehabilitation activities that can be employed towards reinstatement of ecological infrastructure and water-related ecosystem services is provided in Table 1. This table also lists the identified degradation effects, as well as recommended measurements to assess and monitor this effect during rehabilitation efforts.

Kauffman et al. (1997) emphasize that the first and most critical step in the rehabilitation process is to ensure that activities causing degradation or those preventing recovery are stopped, which they refer to as passive or natural restoration (Kauffman et al. 1997). Once active rehabilitation is introduced, emphasis can in turn be placed on structure or function (Noss 1990), with structural efforts placed on static patterns (i.e. mechanical manipulation such as providing flood attenuation structures) and functional efforts focusing on dynamic processes within the system, such as restriction of grazer access to allow plants to re-establish (King and Hobbs 2006). Spatial connectivity is extremely important in terms of the maintenance of ecological processes, particularly in freshwater systems (Hermoso et al. 2012a), and this should be borne in mind when rehabilitation is considered. Poff et al. (1997) place particular emphasis on streamflow as the most important factor in maintaining species diversity and river function, and recommend that rehabilitation should focus on streamflow maintenance as a priority. In terms of the rehabilitation of ecological infrastructure, therefore, it is important that an attempt be made to reinstate water-related ecosystem services, with focus on:

- Returning the physical aspects of the area to a functional state (channels, wetlands, eroded areas, etc.);
- Reinstating the chemical and nutrient components of the habitat; and
- Replacing missing species or removing invasive alien species (Bradshaw 1996).

Particularly where soil compaction and erosion have taken place due to anthropogenic land use, mechanical rehabilitation efforts could be required. King and Hobbs (2006) refer to this structural repair effort as a “quick fix”, in which a pre-disturbance appearance could be reached, but in which dynamic processes within the system (ecosystem function) may not be attained, and long-term rehabilitation goals may not be predictable, consistent or sustainable (Suding et al. 2004). With regard to erosion gullies and rills, these can be filled mechanically with soils and gabions (abiotically), and this may be effective to a degree; however, it will also be necessary to address issues of soil-water interactions - infiltration in particular (King and Hobbs 2006). Biotic interventions are likely to be required in this case, as organic matter is vital for soil aggregate stability and prevention of erosion (Podwojewski et al. 2014). In riparian areas, it may be necessary to add woody debris to the water channel, which can assist with channel development, as well as sediment accumulation and hydrologic routing (Kauffman et al. 1997). Especially with regard to overgrazed or injudiciously burned land, it is vital that a vegetative cover be re-established. Rehabilitation should aim at reinstating prior conditions, including the establishment of multiple species representative of the original vegetation's diversity (active, biotic intervention; Kauffman et al. 1997), although this could occur naturally over time. In order to improve nutrient retention in agricultural lands, it is recommended that crop and grazing rotation be practiced, particularly for nutrient-exhaustive crops. Furthermore, where artificial fertilizers are applied, this should be done in a balanced (Nitrogen to Phosphate ratios) and efficient manner (Ahmad et al. 1998) to ensure nutrient retention in the soil.

Rehabilitation of invasive alien plant infested lands, and in turn their delivery of water-related ecosystem services, can have a direct and quantifiable economic benefit to beneficiaries. Although sufficient streamflow from a system is important, the sustained flow of water of high quality is also important (Mander et al. 2010). The Working for Water programme is responsible in South Africa for the rehabilitation of areas invaded by non-indigenous plant species through mechanical, chemical, biological and integrated means (Department of Environmental Affairs 2014). Van Wilgen and Wannenburgh (2016) report that 2.5 million hectares have been cleared to date, with follow up activities having taken place on average 2.7 times over the past two decades. The water benefits of this programme were estimated to be 50 – 130 million m^3 per year (Görgens and van Wilgen 2004) across South Africa. In certain areas of the country which rely on groundwater and where riparian zones are invaded by plants such as mesquite (*Prosopis* spp.), the benefits of removal of these plants has been estimated at as much as 134 million m^3 per year in these groundwater-dependent areas (Görgens and van Wilgen 2004).

Optimization of rehabilitation interventions

In South Africa, there are both limited human and financial resources available for environmental management and rehabilitation of ecological infrastructure. While environmental actions are recognized as vital, it is important that any investments made in a catchment towards improving water yield, sustainable flows and water quality are made sensibly and with the strongest possible likelihood of success. Although Alexander and Allan

(2007) report in their review of ecological rehabilitation efforts in the United States that fewer than half of ecological rehabilitation projects are in fact *ecologically* effective, De Groot et al. (2013), after a review of more than 200 studies of conservation and rehabilitation efforts, report that the majority of the rehabilitation projects provided net benefits, and recommended that these be considered as profitable and high-yielding investments.Localized interventions in riverine riparian areas in particular can arise from a lack of understanding of ecological process and can, in fact, sometimes be more harmful than helpful (Hermoso et al. 2012a, b). Hermoso et al. (2012a, b) therefore emphasize the need for systematic rehabilitation planning which takes connectivity into account, with resources needing to be directed towards specific actions and locations that can produce the maximum benefit, taking into account the scale of planning and the scale of the intervention, particularly because ecosystem responses to land use changes vary over space and time (De Fries et al. 2004, Newson 2010). Linked to this is the fact that social aspects (governance, land tenure, community dynamics), as well as consultation and mutual learning with stakeholders, are vital to the success of rehabilitation actions (Reyers et al. 2009).

In addition, it is important to note that environmental management decisions, specifically the establishment of protected areas, are often undertaken as a result of political, economic or cultural motivation rather than a conservation goal (Saunders et al. 2002). As such, the most appropriate management activity for a particular area may not be adopted because the land is not readily available. For example, removal of invasive alien plants and/or rehabilitation activities which take place on communal land in South Africa will be a far different activity from that undertaken on state or privately owned land (Smit 2004). Consideration of socio-economic issues and buy-in from stakeholders is therefore vital if rehabilitation and environmental management efforts are to be successful. Based on lessons learnt during a recently completed study of investment into ecological infrastructure in the uMngeni catchment for the enhancement of water security (Jewitt et al. 2015), it can be said that a combination of biophysical and economic modelling and mapping, thorough groundtruthing and exceptionally strong stakeholder and expert consultation is required for the prioritization of investment interventions such that rehabilitation objectives may be optimally realized towards water security and the development of South Africa's Green Economy[6] (Sitas et al. 2014, Ntshotsho et al. 2015)..

Conclusion

Land degradation due to human activities can affect the functionality of ecological infrastructure and water-related ecosystem service delivery. These ecosystem imbalances affect water and other resource supplies to downstream users, which is particularly relevant to a developing country such as South Africa, in which sensitive ecosystems and local communities (often practising subsistence agriculture) rely directly on catchment resources (Singh et al. 2011). In addition, climate change induced rainfall and temperature patterns are likely to exacerbate these impacts.

Given the lack of resources available for rehabilitation activities within South Africa due to more pressing needs such as economic development and health care, methods for prioritization of these actions based on different objectives and with cost considerations in mind are likely to be extremely useful to land use planners, water resource managers and policy makers. The need to integrate ecological connectivity into environmental planning efforts is an emerging research area (Hermoso et al. 2012a), as ecological understanding of land use changes and their effects are strongly linked to successful rehabilitation of ecosystems and the services they deliver (Bradshaw 1996). It is furthermore important that rehabilitation efforts be continually improved upon through an adaptive cycle based on learnings gained through monitoring and evaluation (Hermoso et al. 2012b), and further research into the combination of ecological and socio-economic considerations when planning rehabilitation strategies and actions is urgently required. Although the water benefits of rehabilitation activities can be self-evident, the many social, ecological and land care benefits have not yet been adequately highlighted, linked or quantified (Turpie 2004, Aronson et al. 2010, Rebelo et al. 2015). Blignaut et al. (2008) conclude that although watershed rehabilitation and maintenance is unlikely to result in the complete elimination of water supply shortages, it is part of a suite of water resource management actions which will assist managers in the optimization of water supply. A combination of research including hydrological modelling, field observations and extensive

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[6] "A Green Economy is defined as one that results in improved human wellbeing and social equity, whilst significantly reducing environmental risks and ecological scarcities." (UNEP, 2011)

stakeholder engagement with this concept in mind will allow catchment managers to better direct their rehabilitation efforts for improved water sustainability.

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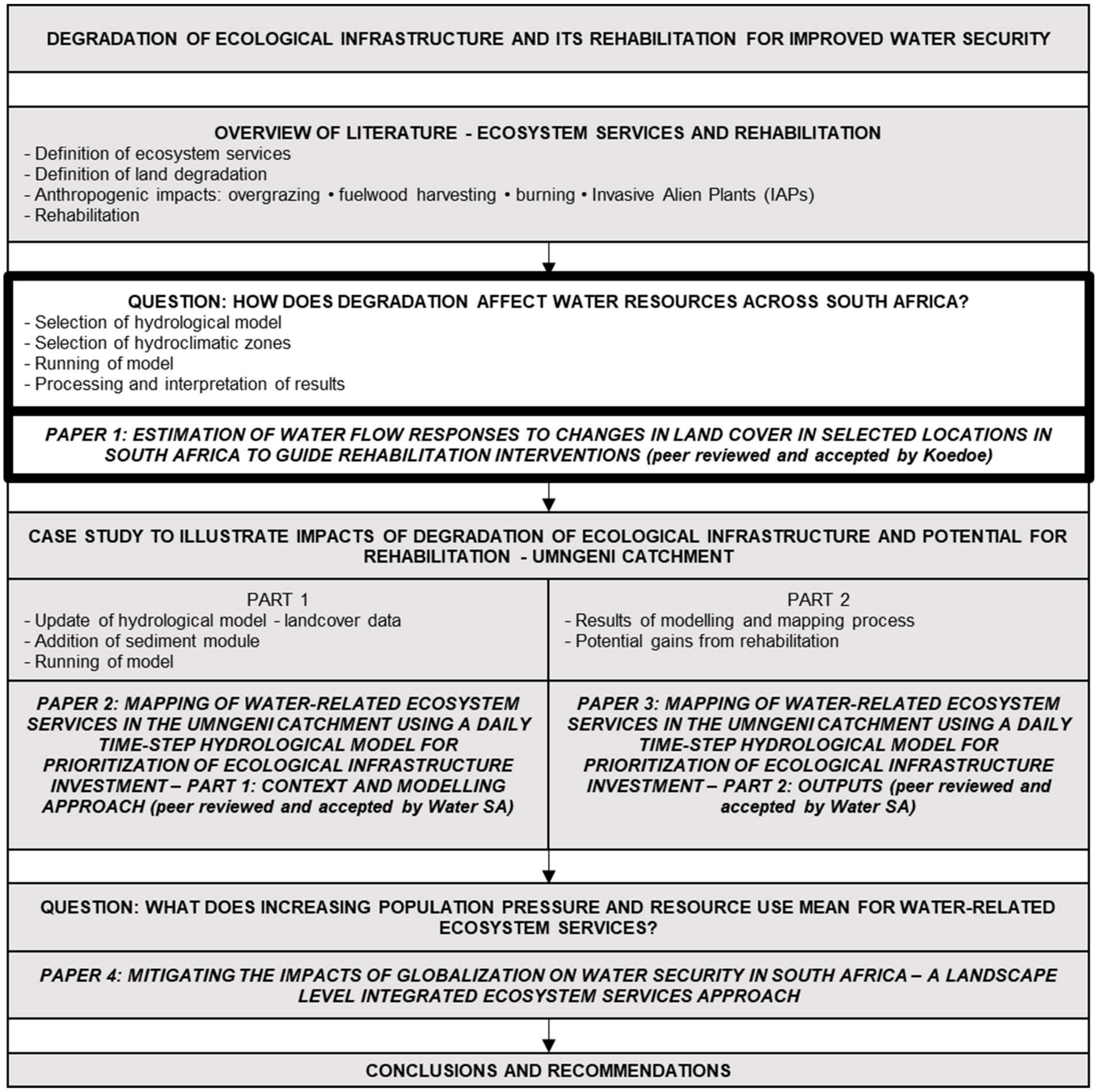

DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND ITS REHABILITATION FOR IMPROVED WATER SECURITY

OVERVIEW OF LITERATURE - ECOSYSTEM SERVICES AND REHABILITATION

- Definition of ecosystem services
- Definition of land degradation
- Anthropogenic impacts: overgrazing • fuelwood harvesting • burning • Invasive Alien Plants (IAPs)
- Rehabilitation

QUESTION: HOW DOES DEGRADATION AFFECT WATER RESOURCES ACROSS SOUTH AFRICA?

- Selection of hydrological model
- Selection of hydroclimatic zones
- Running of model
- Processing and interpretation of results

PAPER 1: ESTIMATION OF WATER FLOW RESPONSES TO CHANGES IN LAND COVER IN SELECTED LOCATIONS IN SOUTH AFRICA TO GUIDE REHABILITATION INTERVENTIONS (peer reviewed and accepted by Koedoe)

CASE STUDY TO ILLUSTRATE IMPACTS OF DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND POTENTIAL FOR REHABILITATION - UMNGENI CATCHMENT

PART 1	PART 2
- Update of hydrological model - landcover data - Addition of sediment module - Running of model	- Results of modelling and mapping process - Potential gains from rehabilitation
PAPER 2: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 1: CONTEXT AND MODELLING APPROACH (peer reviewed and accepted by Water SA)	***PAPER 3: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 2: OUTPUTS (peer reviewed and accepted by Water SA)***

QUESTION: WHAT DOES INCREASING POPULATION PRESSURE AND RESOURCE USE MEAN FOR WATER-RELATED ECOSYSTEM SERVICES?

PAPER 4: MITIGATING THE IMPACTS OF GLOBALIZATION ON WATER SECURITY IN SOUTH AFRICA – A LANDSCAPE LEVEL INTEGRATED ECOSYSTEM SERVICES APPROACH

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 3: ESTIMATION OF WATER FLOW RESPONSES TO CHANGES IN LAND COVER IN SELECTED LOCATIONS IN SOUTH AFRICA TO GUIDE REHABILITATION INTERVENTIONS

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Abstract

This study aims to provide an understanding of the differing hydrological responses to alien plant invasion and grassland degradation across South Africa, which is the focus of government-led clearing and rehabilitation programmes. Seven locations were selected to represent different climatic regimes across the country, and the *ACRU* daily time-step hydrological model was then used to simulate hydrological responses, based on each catchment's natural soils, vegetation and climate.

The potential hydrological impacts of three highly problematic invasive alien plant species in South Africa were modelled. These trees have a marked effect on baseflow volumes, particularly in the Western Cape, with a potential monthly reduction of up to 4.5 m^3/ha/d. Based on the modelling, these trees do not, however, appear to show conclusive impacts on stormflow. Grassland degradation due to livestock overgrazing, has a major effect on stormflow volumes - increasing volumes by up to 100% in the rainy season months in KwaZulu-Natal, and in turn has potential for increasing sediment and nutrient transport. Baseflow volumes are also impacted upon negatively by overgrazing, which reduces the amount of water recharged below ground, with a reduction of up to 1.2 m^3/ha/d. A sensitivity analysis highlighted the importance of the crop coefficient (CAY) and coefficient of initial abstraction (COIAM) parameters in the *ACRU* model, and highlights a need for further investigation to confirm the validity of the parameters used in the simulation exercise.

Introduction

South Africa's National Development Plan 2030 (National Planning Commission 2012) indicates that the country is currently on an upward path to development and economic growth. Associated with this economic development is likely to be large-scale change in the land cover (physical properties of the earth's surface) within the country's boundaries through the conversion of natural land to agricultural, residential and industrial uses. Each of these land cover conversions implies a change in the hydrological characteristics of the area, such as the partitioning of precipitation into interception, infiltration and runoff which, in addition to being determined by climatic characteristics, is influenced by vegetation and soil (Le Maitre et al. 2009). In South Africa, given this growth trajectory, both human resources and finance may prove insufficient to ensure a sustainable supply of good quality water to a growing population. It is therefore important to make well-informed water-related decisions. These include decisions regarding new infrastructure developments and rehabilitation activities which can play a role in securing water quality and quantity in catchments (Jewitt et al. 2015), such as the important work towards removal of invasive alien (non-indigenous) plants (IAPs, see Figure 7a), as carried out by South Africa's Natural Resource Management programmes, including the Working for Water initiative (Van Wilgen et al. 2008).

A consequence of the above-mentioned changes in land cover, if poorly managed, can be land degradation. Land degradation, and in turn the degradation of ecological infrastructure through anthropogenic activities, has had a marked impact on natural hydrological responses (Le Maitre et al. 1999, Rockström et al. 2009). Several deep-rooted commercial forestry tree species have become highly problematic IAPs in South Africa. The impact of degradation due to IAP invasions on the hydrological characteristics of an area are relatively well reported (e.g. Dye 1996, Dzikiti et al. 2013, Le Maitre et al. 2016). Three genera of major concern include *Eucalyptus* spp., *Pinus* spp. and *Acacia* spp.. These genera often invade riparian areas (Figure 8) where sources of sub-surface water are not as limited as in upland areas (Everson et al. 2014). Furthermore, these trees have effects on interception, evapotranspiration, runoff, infiltration, and uptake of water through the presence of their deep roots in the unsaturated soil zone. They can withdraw groundwater directly from shallow aquifers and saturated strata (Dye 1996), thereby lowering the amount of water which is stored in the water table and/or reaches the catchment's streams (Le Maitre et al. 1999).

Some South African grasslands also have a history of poor rangeland management and overgrazing (Vetter et al. 2006). Heavy utilization of grazing land causes a reduction in both perennial and annual canopy cover and vegetation species diversity (Rutherford and Powrie 2010, 2011; see Figure 7b). Overgrazing can lead to soil compaction through cattle trampling, a reduction in basal cover and canopy interception (as there is less vegetation), as well as well as the development of an impermeable crust through direct rain drop exposure and reduced infiltration through the soil (Mills and Fey 2003 2004; Vetter et al. 2006). This leads to increased surface runoff and reduced water entering the unsaturated zone and hence underlying groundwater stores (Le Maitre et al. 1999, Snyman 1999; Reyers et al. 2009; Abdalla et al. 2018). In many places, the decline in basal cover (Rutherford and Powrie 2013), may result in higher energy runoff, with associated sediment and nutrient mobilization and loss.

The hydrological effects of overgrazing in grasslands, according to the Maloti Drakensberg Transfrontier Project (2007) and supported by Trimble and Mendel (1995), Sahin and Hall (1996), Illius and O’Connor (1999), Birkett et al. (2016), Vandandorj et al. (2017) and Gaitán et al. (2018), are summarized below:

- A reduction in above-ground biomass, which in turn results in a decrease in transpiration at rates that are dependent on whether the original natural veld had a relatively high or low biomass, as well as a decrease in canopy interception and the canopy’s protective properties in regard to soil loss;
- A reduction in litter or mulch on the soil surface, which results in increases in the rate of soil water evaporation, thus drying out the topsoil horizon more rapidly and exposing the soil to more severe erosion; and
- A possible compaction of the soil surface through trampling by livestock, which can result in an increase in stormflow and a reduction in the infiltration of rain into the soil.

Thus, actions are required to rehabilitate such lands where they are in poor condition (Rutherford and Powrie 2013). However, it should be noted that in other areas, such as those dominated by renosterveld and in the Succulent Karoo, the replacement of perennial with annual or unpalatable plants can be an indicator of overgrazing (Thompson et al. 2009) and the assumptions above may not be valid.

(a) (b)

Figure 7: Examples of land degradation mechanisms (a) Invasive *Eucalyptus grandis* trees in a tributary of the Kusane River, which joins the Karkloof River in KwaZulu-Natal (Photo: G Jewitt), and (b) overgrazed lands in the foothills of the Drakensberg mountains in KwaZulu-Natal (Photo: C Hughes)

The consequences of degradation of some parts of the landscape are more significant than others. In particular, catchment headwaters and riparian zones have been highlighted (Newsom, 2010). Gregory et al. (1991) define riparian zones as the interface between terrestrial and aquatic ecosystems. South Africa is faced with invasions of alien plants in the country's riparian zones at a large scale (Görgens and van Wilgen 2004, Le Maitre et al. 2016). This is problematic particularly because of the high rates of evapotranspiration characteristic of many IAPs. In the riparian zone, IAPs have access to additional water from the lateral discharges from hillslopes, and may in reality have access to water from groundwater in the riparian zone (Le Maitre et al. 1999, Görgens and van Wilgen 2004, Van Wilgen et al. 2008). This implies that the IAPs are capable of significantly reducing available water in the country's catchments, in turn resulting in a decline in the provision of water-related ecosystem services.

Figure 8: A cleared riparian zone within a forestry plantation in KwaZulu-Natal (Photo: C Hughes)

Limiting and restoring catchment degradation is closely aligned with global interest in the concept of ecosystem services (Costanza et al. 1997; Balmford et al. 2002), investment in ecological infrastructure (EI) (Jewitt et al. 2015; De Castro Dias et al. 2016), and payment for ecosystem services as an incentive for improved land practice (Deng et al. 2016, Sgroi et al. 2016). These are generally captured under the general theme of Nature Based Solutions (WWAP, 2018). In South Africa in particular, there is a national effort towards land rehabilitation, IAP clearing and job creation through public works to improve the delivery of ecosystem services to society (Blignaut et al. 2008, Turpie et al. 2008) and through EI, this has recently become embedded in national water resources policy (DWS, 2018). Illustrating the potential water flow responses to degradation and the potential benefits of such interventions in various parts of the country with different hydroclimates will provide useful information to guide implementation of this policy. Hydrological modelling provides an appropriate approach to provide such information.

Methodology

Scientists understand that the effects of degradation are different in different environments. Key effects of degradation are apparent in hydrological responses which, in turn, are strongly influenced by climate and rainfall in different environments. With a view to assessing how degradation can alter hydrological responses in different areas, seven locations based on the zones identified by Smithers and Schulze (2003) were used to represent different hydroclimatic regimes (Figure 11). The attributes for a hypothetical catchment, representative of each zone, were drawn from South Africa's Quinary catchment database developed by Schulze et al. (2010; Table 2) and the *ACRU* Agrohydrological model was applied to assess the impacts of for several degradation scenarios in each of these zones, relative to a baseline condition.

The ACRU Agrohydrological Model

ACRU is a multi-purpose and multi-level daily time step soil water budgeting model developed, validated and widely verified in South Africa (Schulze 1995 and updates, Figure 9). The model is able to simulate the hydrological effects of IAPs and overgrazed land in terms of changes in baseflows and stormflows, as a result of changes to above ground biomass, root depth/distribution and water use by plants. *ACRU* also accounts for the topographic position of riparian areas within the hydrological landscape and resultant changes in water availability from the system (Warburton et al. 2010, Le Maitre et al. 2014, Rebelo 2015). Within the model, the user is able to specify the hydrological characteristics (vegetation, soils, etc.) for distinct Hydrological Response Units (HRUs), such as riparian zones, to test responses to land cover change.

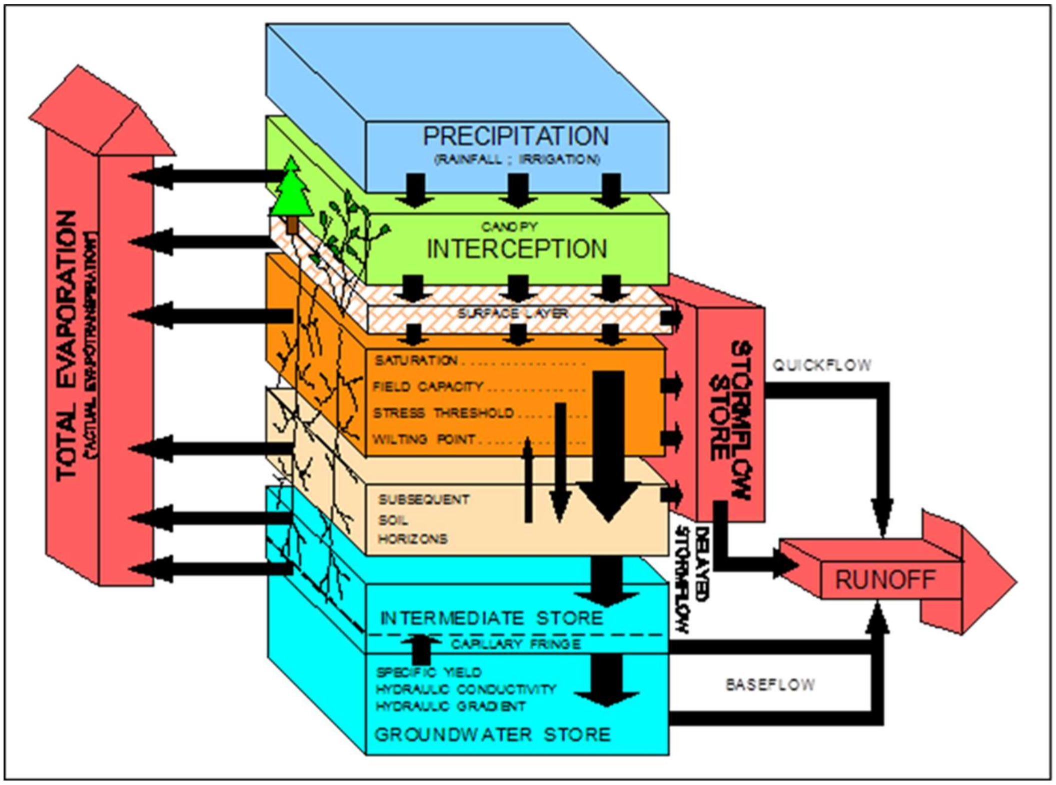

Figure 9: Schematic representation of the *ACRU* model's water budget (Schulze, 1995)

In each of the scenarios, responses in terms of streamflow and its components (stormflow and baseflow) were assessed, and it is important to understand the manner in which they are derived in the *ACRU* model. Baseflow is modelled explicitly, with the value derived from soil water which has percolated out of the base of the sub-soil (B) horizon, and into a baseflow store (Schulze and Smithers 2004). The store which collects baseflow is connected in the model to the stream channel, and releases water slowly into the stream at a rate which depends, *inter alia*, on the quantity of water in the groundwater store (Schulze and Smithers 2004). Stormflow, i.e. surface and near-surface flow, is generated from characteristics of the rainfall, vegetation and antecedent soil moisture, and "quickflow" represents that portion of stormflow generated from a rainfall event on a given day which exits the catchment on the same day on which it was generated, plus any amount which may have been accumulated from preceding days' stormflows (Schulze and Smithers 2004). Thus, stormflow can be rapid or delayed.

To simulate the movement of sub-surface flow from upland areas into the riparian zone for the IAP analysis, hillslope relationships were introduced using the *ACRU* model. A hillslope relationship can be defined as the hydrological connectivity between upland areas and the river or riparian area downslope, and is most commonly used to describe the development of water tables between the hillslope and the riparian zone, resulting in a measurable runoff response (McGuire and McDonnell 2010). Within the *ACRU* model configuration, a riparian zone can be selected as a specialized HRU within a catchment, and if a hillslope relationship is specified, then the sub-surface flow from the upland HRU is directed to the downslope riparian zone's sub-soil horizon, on the assumption that the riparian zone is underlain by an impervious layer, thus simulating the hydrological connectivity between the two hydrological response units (MBB 1997, Thornton-Dibb et al. 2010; Figure 10). A standard riparian zone size was used for these hypothetical catchments, i.e. no field-based delineation was carried out.

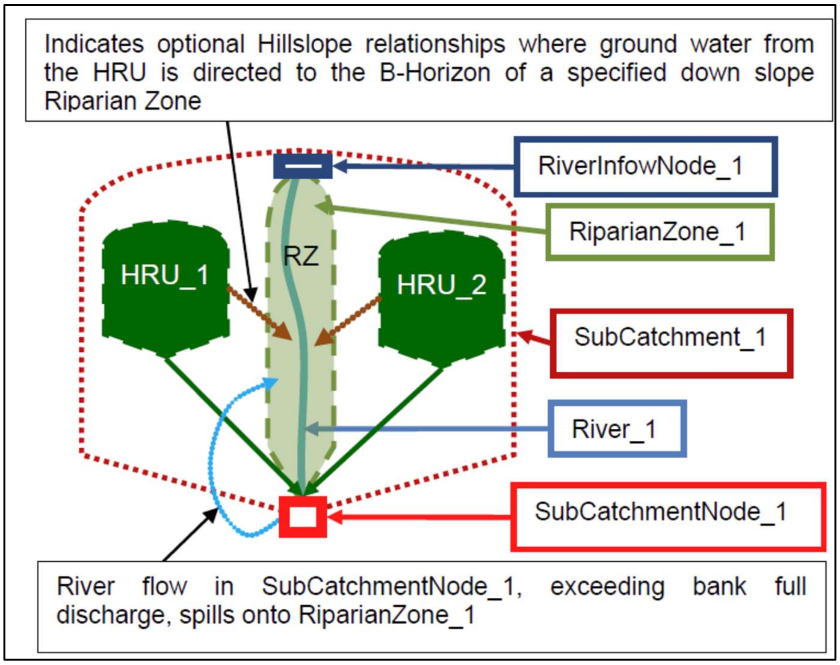

Figure 10: Illustration of the structure of a single Riparian Zone HRU in the *ACRU4* model (Thornton-Dibb et al., 2010)

Model Input and Parameterisation

Climatic input variables, including daily rainfall, temperature as well biophysical information needed as input and to parameterise the model were extracted from the aforementioned South Africa's Quinary catchment database (Table 2).

An important aspect of this study was the selection of an appropriate baseline against which stormflow and baseflow volumes from degraded landscapes could be assessed. Following the established approaches described by Gush et al. (2002) and Jewitt et al. (2009) for the assessment of potential Streamflow Reduction Activities in South Africa, naturally occurring vegetation types according to Acocks (1988) were selected as the baseline (Appendix A). Schulze (2004) developed a set of rules to link the monthly values for various parameters (water use coefficients [CAY], interception per rainday [VEGINT], root mass distribution in the topsoil [ROOTA], coefficient of infiltration [COIAM] and the index of suppression of soil water evaporation by a litter/mulch layer [PCSUCO]) to climatically derived variables (MAP, monthly heat units, frost occurrence, soil water status in wet, average and dry years) and crop physiological characteristics for the Acocks Veld Types (Warburton et al. 2011). It has been suggested that more recent natural vegetation maps such as that by Mucina and Rutherford (2006) may provide more realistic baseline vegetation types. However there are, as yet, no established hydrological parameters available for these.

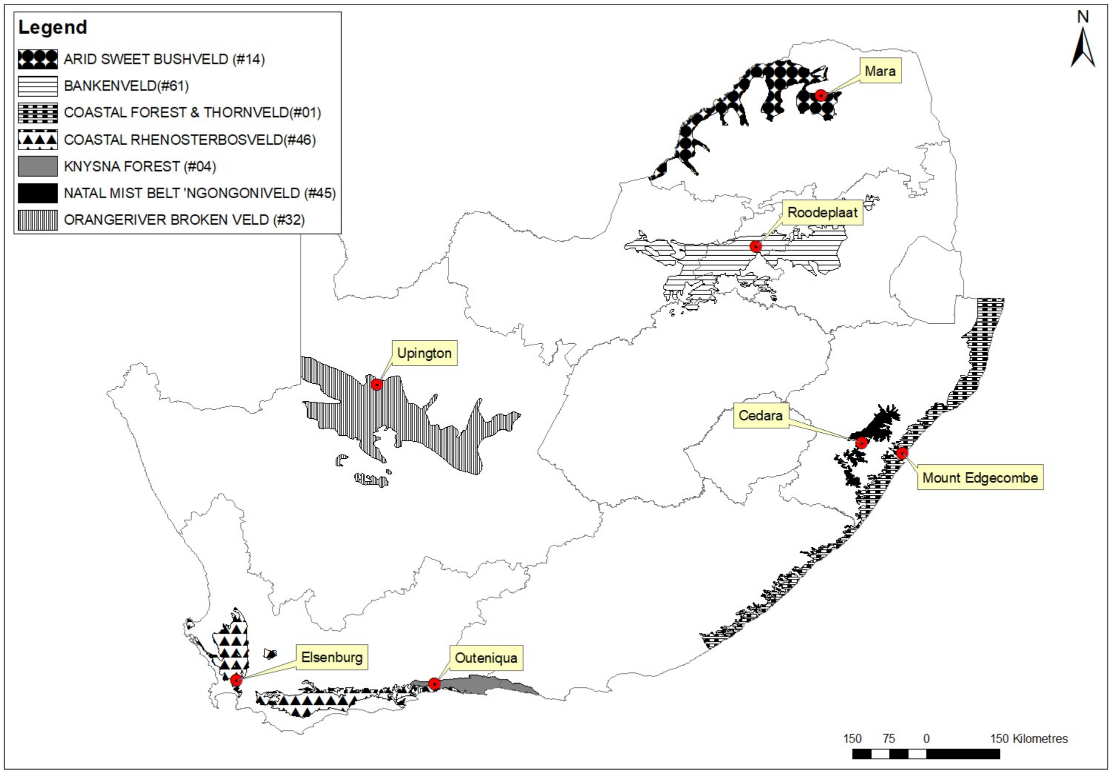

Figure 11: Location of the seven representative regions and their rainfall stations (selected after Smithers and Schulze 2004). The Acocks's Veld Type (1988) of each chosen station is shown[7].

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[7] See note below for explanation of choice of Acocks (1998) information as vegetation cover.

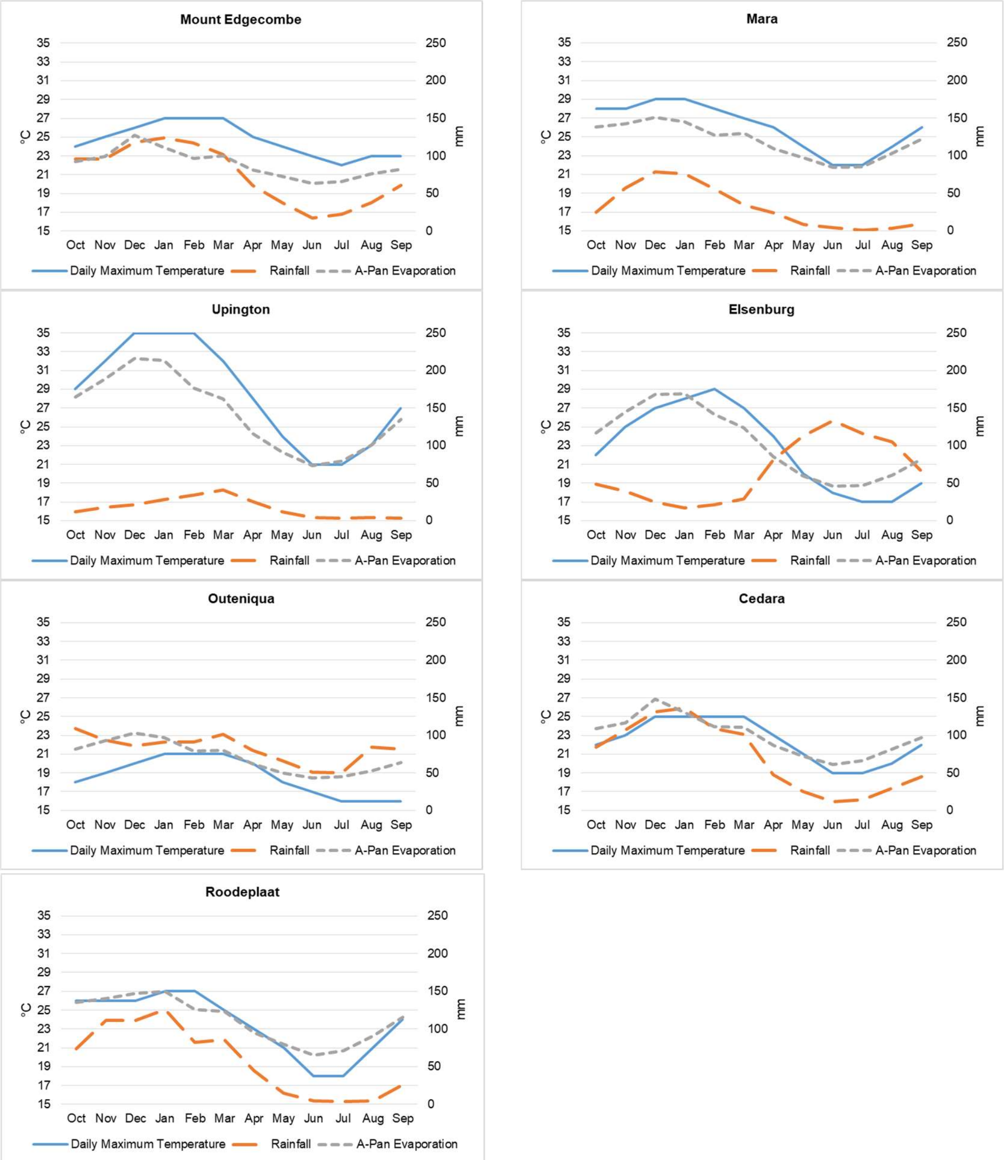

Figure 12: Monthly means of daily maximum temperature (˚C), as well as mean rainfall (mm) and of A-Pan equivalent evaporation (mm) per month for the period 1950-1999 for seven selected locations (calculated from Lynch 2003, Kunz 2014) as provided in the Quinary catchment database (Schulze et al. 2010)

Table 2: Quinary catchments and their characteristics for each location used for the analysis (Schulze et al. 2010)

Name	Representative Quinary Catchment	Elevation (masl)	Latitude	Longitude	Acocks (1988) vegetation type	Description (Acocks 1988)	Dominant Soil
Mount Edgecombe	U20M3	82.9	29˚42’S	31˚02’E	Coastal Forest and Thornveld (#01)	Open thornveld with numerous or extensive patches of forest. Grassveld is scrubby, with tall herbs, shrubs and coarse grasses.	Loam
Mara	A71D3	918.8	23˚09’S	29˚33’E	Arid Sweet Bushveld (#14)	Heterogeneous vegetation type, Adansonia-Mixed Thornveld with underlying granite and deeper soils. Typical trees are *Grewia flava*, *Ziziphus mucronata* and *Acacia dulcis*. Grasses include *Schmidtia bulbosa*, *Eragrostis* spp. And *Digitaria eriantha*.	Loamy Sand
Upington	D73E3	851.6	28˚27’S	21˚25’E	Orange River Brokenveld (#32)	Characterized by *Aloe dichotoma* and *Euphorbia avasmontana*, occurring on a variety of rock types. Shrubs and grasses are also important, and include *Barleria rigida* (shrub) and *Aristida diffusa* (grass).	Loamy Sand
Elsenburg	G22G3	181.4	33˚51’S	18˚50’E	Coastal Rhenosterbosveld (#46)	Clayey soils, with little natural vegetation due to cultivation for dryland crops and grazing. Originally scrub vegetation, very dense and thorny, with *Olea africana* and *Sideroxylon inerme* dominant. Renosterveld species which have replaced the scrub include *Relhania squarrosa*, *R. genistifolia* and *Selago corymbosa*.	Loam
Outeniqua	K30B1	965.5	33˚55’S	22˚28'E	Knysna Forest (#04)	Region of high, well distributed rain, sandy soils, vigorous vegetation. Succession of Fynbos from forest likely due to exploitation.	Loam
Cedara	U20E1	1101.5	29˚31’S	30˚17’E	Natal Mist Belt Ngongoni Veld (#45)	Transitional type between Ngongoni Veld and Highland Sourveld. Misty country, with favourable agricultural soils. Grassland (which has largely replaced forest species) is dominated by *Themeda* and *Aristida*.	Loam
Roodeplaat	A21A3	1541.7	25˚55’S	28˚21’E	Bankenveld (#61)	Soils mainly quartzite, shale, dolomite, chert and granite, with poor, acid soils which are stony or sandy. Sour, wiry grassveld. Rocky hills and ridges dominated by *Protea caffra*, *Acacia caffra*, *Celtis kraussiana* and *Protea hirta*. Grassland species include *Trachypogon capensis* and *Tristachya hispida*.	Loam

Cedara and Mount Edgecombe in the province of KwaZulu-Natal are characterized by the highest rainfall of the seven locations selected for this analysis, with a marked summer rainfall pattern (Table 2; Figure 12). At Cedara there is higher potential evaporation than rainfall almost throughout the year, whereas at Mount Edgecombe rainfall exceeds evaporation in the summer months. The lowest rainfall of the seven zones is at Mara and Upington in the more arid western and northern parts of the country, and these are also summer rainfall areas with very high evaporation. In terms of major differences in rainfall patterns, there is rainfall almost throughout the year at Outeniqua, with this rainfall almost always exceeding potential evaporation. Elsenburg in the Western Cape is the most unique of the seven zones, with a wet winter and a dry summer, a high mean annual rainfall and potential evaporation lower than rainfall in winter. It is important to note that in the Western Cape, where rain mainly falls during the cooler part of the year, sustained low flows are vital for sustained water supply to society and ecosystems during the drier, hotter summer months (Schulze et al. 2011).

Once the baseline responses had been established, the model was used to explore the hydrological effects of IAPs at each location, and the effects of overgrazing at the two Grassland Biome sites). It must be noted that although it is recognized that certain vegetation species may differ between riparian zones and upland vegetation, this is a hypothetical modelling exercise and there is no differentiation between exact riparian species and the natural vegetation of the area described by Acocks (1988), and the associated characteristics assigned to it within the *ACRU* model.

The parameters used to simulate baseline and degraded vegetation types are shown in Appendix A. Although the characteristics (soil properties, vegetation cover and historical climate data from 1950 to 2000) are taken from the Quinary catchments database and are appropriate for each of the seven specified locations, a standard catchment size (197 km^2 – the size of the Cedara catchment) was used for the modelling exercise to normalize the results and ensure that they were comparable. For each standardized catchment, the following model simulations were carried out:

Scenario 1: To assess the change in hydrological responses across the seven locations due to the presence of IAPs within the riparian zone

This was carried out for three common invasive genera separately, and represented by *A. mearnsii*, *E. grandis* and *P. patula*[8], the hydrological attributes of which are provided in Appendix A. The land cover within the riparian zone (using a hillslope relationship) was altered from that of the natural vegetation of the area to that of an IAP of "intermediate age", i.e. 5 years for *A. mearnsii* and *E. grandis,* and 8 years for *P. patula*, given that each species has a different growth cycle. It is understood that not all species are likely to proliferate in all locations (e.g. *P. patula* is unlikely to grow in Upington; Henderson 1991), and as such not all species are reported for each zone.

Scenario 2: To assess the change in hydrological responses due to overgrazing in the two Grassland Biome locations

For each of the areas dominated by grassland vegetation (e.g. Cedara, Roodeplaat) the *ACRU* model rules and hydrological attributes for overgrazed lands which were developed by Schulze et al. (2007) for Maloti Drakensberg Transfrontier Project (2007) in the grasslands of KwaZulu-Natal and Eastern Cape were used to simulate impacts of severe degradation. Model input details of these attributes are given in Appendix A.

When modelling the responses of IAPs, parameter values derived for use in the *ACRU* model through many years of field experimentation in forestry plantations were used for assessment of the hydrological responses of *A. mearnsii*, *E. grandis* and *P. patula* (e.g. Schulze and George 1987, Tarboton and Schulze 1991, MBB 1997, Jewitt and Schulze 1999, Gush et al., 2002; Warburton et al. 2010). In the case of *A. mearnsii* the values derived by Schulze and Schütte (2014) and Bulcock and Jewitt (2012) for landscape and riparian invasion were applied. These values are given in Appendix A and each of the parameters are included in the sensitivity analysis undertaken.

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[8] Although it is noted that not all of these species necessarily occur in all of the locations, they have been selected as representative of the most dominant woody alien genera nationally.

Parameter sensitivity analysis

The parameters used for this modelling study were selected based on published literature, expert opinion and workshop outcomes. However, although these parameters have been well utilized in earlier studies, it is important to understand the potential errors and uncertainties which may be introduced to the modelling process. The sensitivity analysis serves to indicate which parameters are the most important in the model, and also provide a range of results – indicating to the user the risk of a "false result". A sensitivity analysis was therefore carried out for each of the important vegetation-related parameters which were varied during this study, namely CAY, ROOTA, PSCUCO, VEGINT and COIAM to provide an indication of their various responses to the specified land cover changes. This was done using the natural vegetation for the non-riparian portion of the catchment. For each month, each parameter was increased by 10% and 20%, and decreased by 10% and 20%, with the original value plotted between them.

Results

For each scenario and where relevant, simulated changes in baseflow and stormflow when land cover is changed are illustrated in the following series of figures[9], and reasons for the changes are explored in the Discussion section which follows.

Scenario 1: To assess the change in hydrological responses across the seven locations due to the presence of IAPs within the riparian zone

The largest reductions in baseflows (Figure 13) are apparent in the Elsenburg area (Western Cape), particularly in winter and spring (with a maximum reduction of nearly 5 m^3/ha/day in July by *E. grandis*), followed by Cedara, which has summer rainfall and is located in the central eastern part of the country, and Mount Edgecombe on the coast of KwaZulu-Natal, both of which are affected in late summer and autumn (with a maximum reduction of nearly 2 m^3/ha/day in April by *E. grandis*).

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[9] If the change is greater than 100%, the change is shown as 100%.

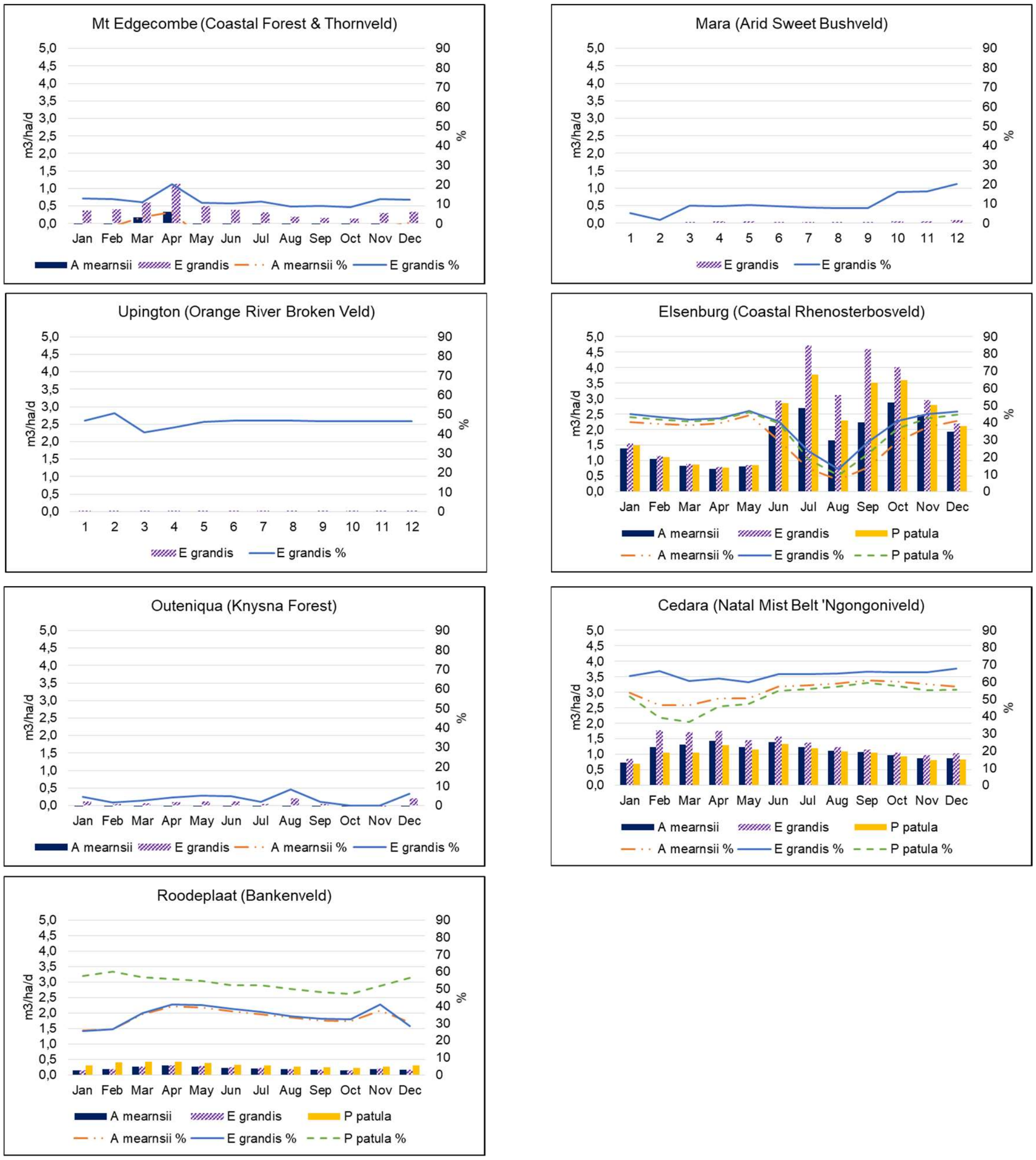

Figure 13: Modelled reductions, for the period 1950-1999, in average baseflow in both m^3/ha/d and as a percentage when different IAPs replace natural vegetation in the riparian zone of each of the seven selected locations

In terms of the modelled changes in stormflow response when various IAPs replace natural vegetation in the riparian zone, the pattern of results is less clear, and the changes are relatively minor.

Scenario 2: To assess the changes in hydrological responses due to overgrazing across two grassland-dominated locations

The following figures present the modelled changes in baseflow and stormflow when the model simulates the hydrological effects of overgrazing of an upslope HRU. The results indicate that the highest volumetric reduction per hectare in baseflow under overgrazing is at Cedara, where the natural vegetation is Natal Mist Belt Ngongoni Veld (Acocks 1988; Figure 14). Results show an average baseflow reduction of 68%, while the average reduction at Roodeplaat is 34% (Bankenveld - a grass-dominated natural vegetation type; Acocks 1988).

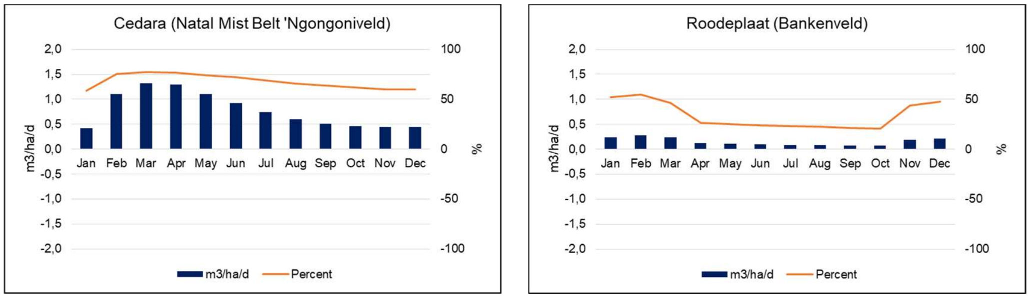

Figure 14: Modelled reductions, for the period 1950-1999, in average baseflow in both m^3/ha/d and as a percentage when different grassland vegetation is overgrazed at Cedara and Roodeplaat

Overgrazing increases stormflow (high energy runoff) during the wet season (Figure 15), which is likely to cause and increase sediment and nutrient transport.

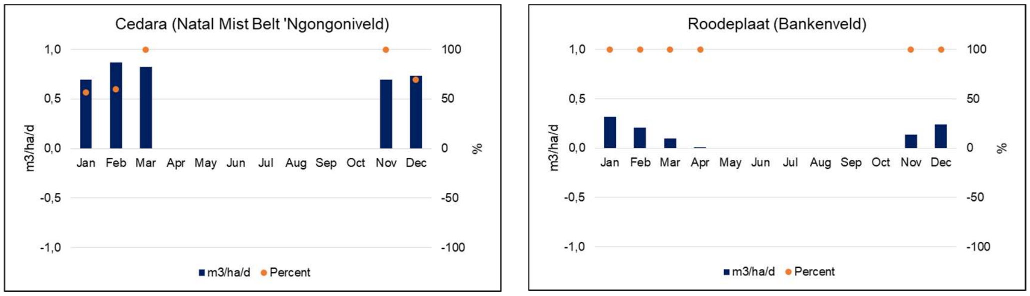

Figure 15: Modelled increases, for the period 1950-1999, in average stormflow in both m^3/ha/d and as a percentage when different grassland vegetation is overgrazed at Cedara and Roodeplaat

Discussion

Scenario 1: To assess the change in hydrological responses across the seven locations due to IAPs within the riparian zone

In this study, the modelled reductions in baseflow due to IAPs are strongly linked to the rainfall patterns in each catchment, with the greatest reductions taking place following the respective rainy seasons. There is a marked reduction in baseflow particularly at Elsenburg (winter rainfall). As mentioned previously, this area is highly dependent on baseflow for year-round water supply, and the importance of prevention of establishment of invasive woody species in this part of South Africa is emphasized.

Of the three IAPs considered, the highest individual modelled reduction in baseflow per hectare in the Western Cape is caused by *E. grandis*. In the summer rainfall regions, the highest modelled reduction in baseflow also results from *E. grandis*, which has a high crop coefficient (the model parameter used to estimate its evapotranspiration) and high evaporation potential (see Appendix A). The Upington catchment appears to experience high reductions in baseflow when the riparian zone is infested with *E. grandis*, owing to the small amount of rainfall received in the catchment and this IAP's large vegetation interception potential (see Appendix A). Given that this is a particularly arid area of the country, water loss through IAPs is of major concern. A caveat here is that that there are other species which are particularly problematic in this part of South Africa, such as *Prosopis* spp. (Dzikiti et al. 2013), but for which model parameter values have not yet been determined and tested.

Previously published results on runoff reduction as a consequence of IAP infestation vary greatly according to site location, rainfall, technique, species and measurement units (e.g. Dye et al. 2001, Blignaut el al. 2007). Le Maitre et al. (2000) however estimate that *Acacia* spp. have a Mean Annual Runoff (MAR) reduction factor of between 86 and 90%, *E. grandis* a MAR reduction factor of 72 - 90%, and *Pinus* spp. 57 – 87%, although these reductions are for dryland and not riparian systems. The authors indicate that the riparian invading taxon specific reduction factor could be as much as 2.0 or 1.5 times the dryland reduction, based on Dye and Jarmain (2004) and Clulow et al. (2011), (Le Maitre et al. 2016). Although the impact of *A. mearnsii* is not the highest in this study, it is consistent across each site, and as reported in Le

Maitre et al. (2016), the *Acacia* taxon (Wattle) is the group of the IAPs with the greatest estimated impact on South Africa's water resources, with 34% of the total reduction in flows.

Scenario 2: To assess the changes in hydrological response due to overgrazing across two grassland-dominated locations

The increase in stormflow (and associated sediment losses) and reduction in baseflow volumes due to overgrazing is a major concern, particularly in communal areas where overstocking with cattle and other livestock can be common (Dlamini et al. 2014, Maloti Drakensberg Transfrontier Project 2007). A large reduction in baseflow is estimated in the months following the rainy season at Roodeplaat and Cedara, which could affect streamflow and water supply later in the year. Stormflow during the rainy season is increased in overgrazed areas, implying that rainfall is less likely to infiltrate to lower soil layers and recharge baseflow and groundwater supplies for the dry season.

It is also likely that in high intensity rainfall areas, high stormflows will result in increased sediment transport and movement of fertile topsoil into streams, which could result in sedimentation of dams and soil infertility in degraded areas (Dlamini et al. 2014, Mander et al. 2016). This is an important factor when considering the warmer future which is projected under climate change, which could mean a change in rainfall characteristics (Hewitson and Crane 2006).

Baseflow volumes are determined by rainfall intensity, as this affects the partitioning of rainfall at the surface (with lower intensity rainfall being able to infiltrate to lower soil layers), and antecedent moisture. Sustained baseflow allows the ecosystem to maintain a variety of water-related services (such as dilution and purification), and therefore catchment's water quality depends greatly on the efficient function of these services (Jewitt et al. 2015). It is important to ensure the maintenance of baseflows for assurance of runoff (and thus streamflow supply) for domestic, ecological and commercial use.

Parameter sensitivity analysis

A sensitivity analysis for each key vegetation-related parameter (CAY, ROOTA, PSCUCO, VEGINT and COIAM) was carried out for two of the catchments, namely Cedara and

Elsenburg, which have contrasting rainfall patterns and very different vegetation. From the original analysis, it was noted that quickflow is a far more responsive and volumetrically higher output for the Cedara (summer rainfall) catchment than for Elsenburg (winter rainfall), in which baseflow is volumetrically higher.

Figure 16 provides a comparison of the differences in baseflow and quickflow when the five parameter values are reduced or increased by 10-20%, compared with the original baseline parameter values at Cedara and Elsenburg. More explicitly, for each parameter, the first column in the figures below indicates the difference between the baseline flow output and that with a 10-20% reduction in the parameter, and the second column indicates the difference between the baseline flow output and that with a 10-20% increase in the parameter. These are presented for the maximum value ("Max") and average value ("Ave") of the baseflow and quickflow values, in mm. In some cases, the increase in ROOTA for the maximum value by 10-20% has been omitted, due to the need to cap the ROOTA fraction at 1.

The overall findings for the sensitivity analysis are shown in Table 3, which also lists the most influential/sensitive parameter at each site for baseflow and quickflow, as well as the relationship (+ve or –ve) between the output flow and each parameter.

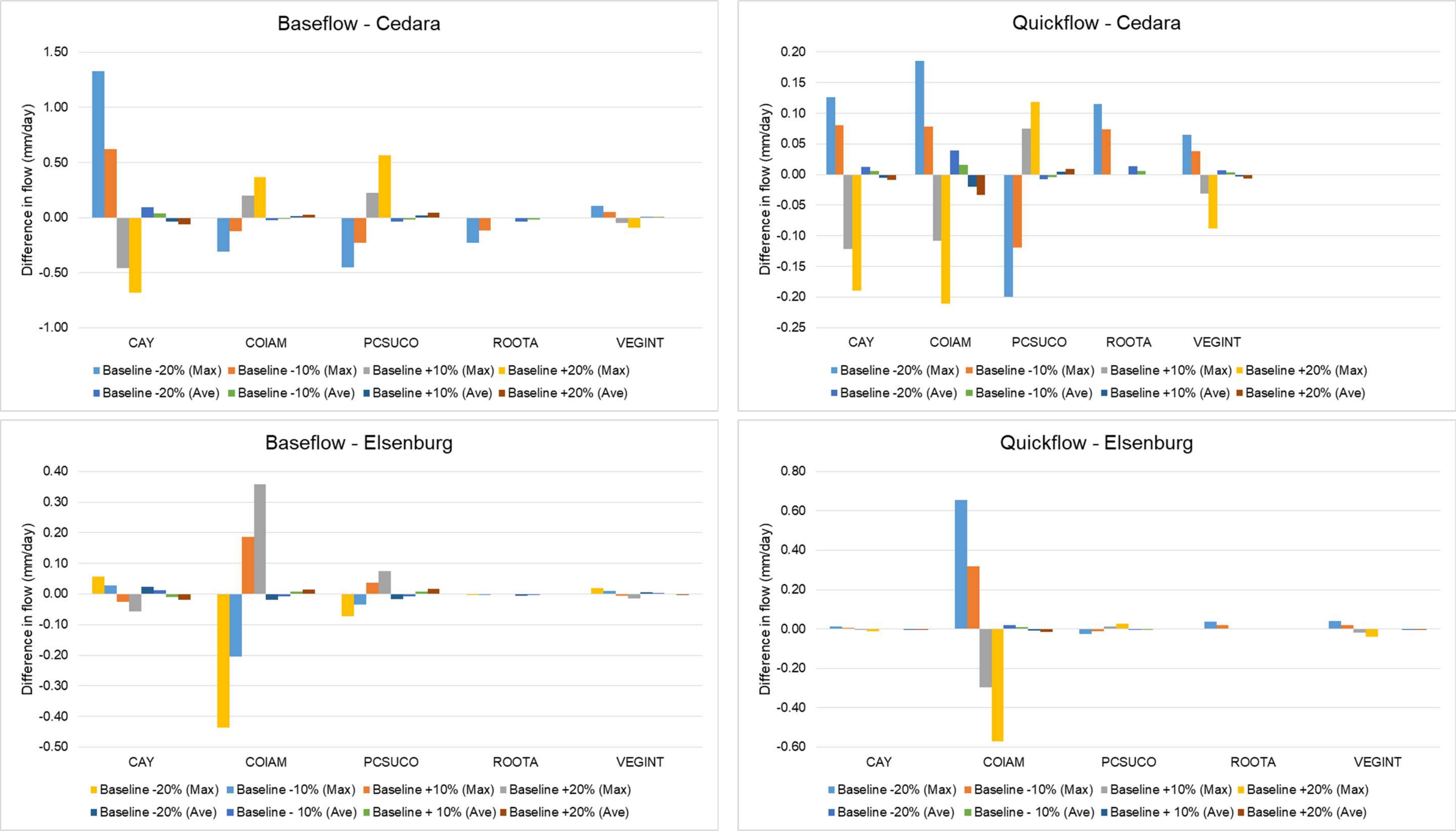

Figure 16: Sensitivity analysis for baseflow and quickflow at Cedara and Elsenburg. Columns indicate the difference between the baseline flow and flow with a 10-20% reduction/increase in the vegetation-related parameters (CAY, COIAM, PCSUCO, ROOTA or VEGINT). Results are presented for the maximum flow values in mm ("Max") and average flow values ("Ave") in mm/day.

Table 3: Findings from sensitivity analyses for the 5 key vegetation-related parameters for Cedara and Elsenburg. The most influential parameter at each site is indicated for baseflow and quickflow for maximum and average daily flows, as well as the relationship (- or +) between the parameter and the output flow

***ACRU* Parameter**	**Cedara**				**Elsenburg**			
	Baseflow		**Quickflow**		**Baseflow**		**Quickflow**	
	Parameter influence	**Relationship**	**Parameter influence**	**Relationship**	**Parameter influence**	**Relationship**	**Parameter influence**	**Relationship**
CAY[10]	Most influential (Max, Ave)	-		-	Most influential (Ave)	-		-
COAIM[11]		+	Most influential (Max, Ave)	-	Most influential (Max)	+	Most influential (Max, Ave)	-
PCSUCO[12]		+		+		+		+
ROOTA[13]		+		-		+		-
VEGINT[14]		-		-		-		-

The most influential vegetation-related parameter for determination of baseflow at Cedara (summer rainfall region) is CAY, for the maximum and average flow values. A negative relationship exists between the baseflow/quickflow for CAY, i.e. as the crop coefficient (essentially the water used by the plant) increases, the amount of baseflow/quickflow decreases. This is consistent with the literature mentioned above, in which degradation is expected to lead to a reduction in above-ground biomass, an in turn a decrease in transpiration, as well as a decrease in canopy interception. Quickflow at Cedara is most influenced by COIAM - i.e. as e rainfall abstracted by interception, surface storage and infiltration increases, there is lower quickflow from the surface as less water is made available for stormflow.

At the Elsenburg catchment (winter rainfall region), there is a contrasting relationship between the COIAM value for baseflow (positive, i.e. as abstraction increases, baseflow increases due to more infiltration into the soil) and quickflow (negative). This is the most influential parameter at this site.

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[10] Crop coefficient – water used by the plant

[11] Rainfall abstracted before stormflow begins

[12] Percentage surface cover - surface cover is able to retain water for surface flow and infiltration to the soil profile

[13] Percentage of roots in the A soil horizon - a 10-20% increase raises the value of the fraction above 1, and therefore this result was omitted. As ROOTA is increased, baseflow increases, meaning that more water is absorbed by the roots in the soil's upper layer

[14] Interception loss

The highest difference apparent with the 10-20% variation in modelled parameters was found to be for the CAY parameter (for baseflow at Cedara). This implies that the water used by the plant has the strongest influence on changes in baseflow/quickflow, with the percentage of root stock in the A-horizon, coefficient of initial abstraction and percentage surface cover having less of an influence on flow. The interception of water at the surface by vegetation (VEGINT) is one of the least influential parameters. Interception by the plant is therefore a less significant determinant of how much water volume reaches the soil surface and is converted to baseflow and stormflow when compared to the volume of water taken up by the plant itself.

At both sites, ROOTA (the percentage of roots in the A soil horizon) is increased, baseflow increases, meaning that more water is absorbed by the roots in the soil's upper layer and is therefore made available for baseflow. The opposite is true with quickflow, as less water runs off the surface with a higher ROOTA value.

This sensitivity analysis indicates that the CAY and COIAM are critical parameters within the *ACRU* model. Water use by the vegetation (above surface) plays a key role in determining baseflow particularly. Rainfall intensity (for which COAIM is a surrogate in the model), and therefore soil/water interactions at the surface, i.e. infiltration and storage, plays a key role in determining quickflow volume. It is important to note that if these parameters are not appropriate for the modelling exercise concerned, there is potential for error in the findings.

Conclusion

This study provides an indication of where key types of degradation, and the rehabilitation thereof, can have the greatest relative impact on surface and below-ground water flows in South Africa. These types of results can be valuable to the country's natural resource management programmes in terms of making investments in ecological infrastructure for improved water supply.

The importance of the crop coefficient (CAY) and coefficient of initial abstraction (COIAM, which is used as a surrogate for rainfall intensity in the model) parameters was highlighted by the sensitivity analysis. This indicates that the type of vegetation and its level of water use, as well as the infiltrability into the soil (i.e. the rainfall abstracted by interception, surface storage and infiltration before stormflow commences) are key determinants of baseflow and quickflow volumes. Further validation of these results and parameters as the most important in determining the effects of changes in vegetation through overgrazing and non-indigenous plant invasion on surface and sub-surface flow is recommended. Furthermore, uncertainties with regard to parameter values, particularly in terms of CAY and COIAM, could influence the model results.

The largest volumetric baseflow reduction due to the establishment of IAPs for any particular month (July) was found to be in the Western Cape, which experiences low intensity rain which falls on high antecedent soil water conditions, and hence high infiltrability. In terms of relative change, however, the presence of IAPs in the Northern Cape was estimated to reduce average baseflow by approximately 50% - important for this arid area, and in KwaZulu-Natal the presence of *E. grandis* could potentially affect baseflow volumes by up to 65%. The model indicates that *E. grandis* has the most profound negative effect on baseflow per hectare per day in the Western Cape and KwaZulu-Natal. *Acacia* spp., although not indicated as the most significant IAP in this study, has a consistent negative effect on baseflow at most locations – which is consistent with its reported impact as the most problematic invasive genus in the country.

In highly degraded grasslands, a large volumetric increase in surface runoff was simulated when compared to grasslands in pristine condition. This is likely to result in a decrease in baseflow (as more rainfall runs off the surface and does not infiltrate to lower layers of soil), and higher levels of sedimentation as topsoil is eroded and mobilized.

Catchment managers should aim to control the spread of woody IAPs into riparian zones to ensure sustainability of baseflow. In parts of the country where grasses dominate, and where stormflows, particularly delayed stormflows, are an important source of streamflow, the spread of *P. patula* and *E. grandis* trees in particular should be prevented, due to their higher canopy interception and interception at the soil surface, as well as high evapotranspiration rates (see Appendix A). This study also supports the findings of other studies (e.g. Le Maitre et al. 2014), that the responsible and systematic removal of these species from riparian zones, coupled with soil stabilization and rehabilitation, could improve water-related ecosystem service delivery.

Overgrazing in grassland-dominated areas leads to increased runoff from the soil surface, and reduced infiltration of water to the lower soil layers. It is acknowledged that rehabilitation efforts (through reduced stocking rates, for example) are very unlikely to return overgrazed lands to their pristine state. However, as has been shown in several plot-scale experiments (Dlamini et al. 2014), the benefits of rehabilitation of these lands are likely to be significant, with improved basal cover (and in turn soil stability, interception and infiltration) leading to higher recharge to the lower soil layers and sustainability of baseflow into the dry season, which is vital for the maintenance of water-related ecosystem services (such as dilution and purification) for overall water and ecosystem health.

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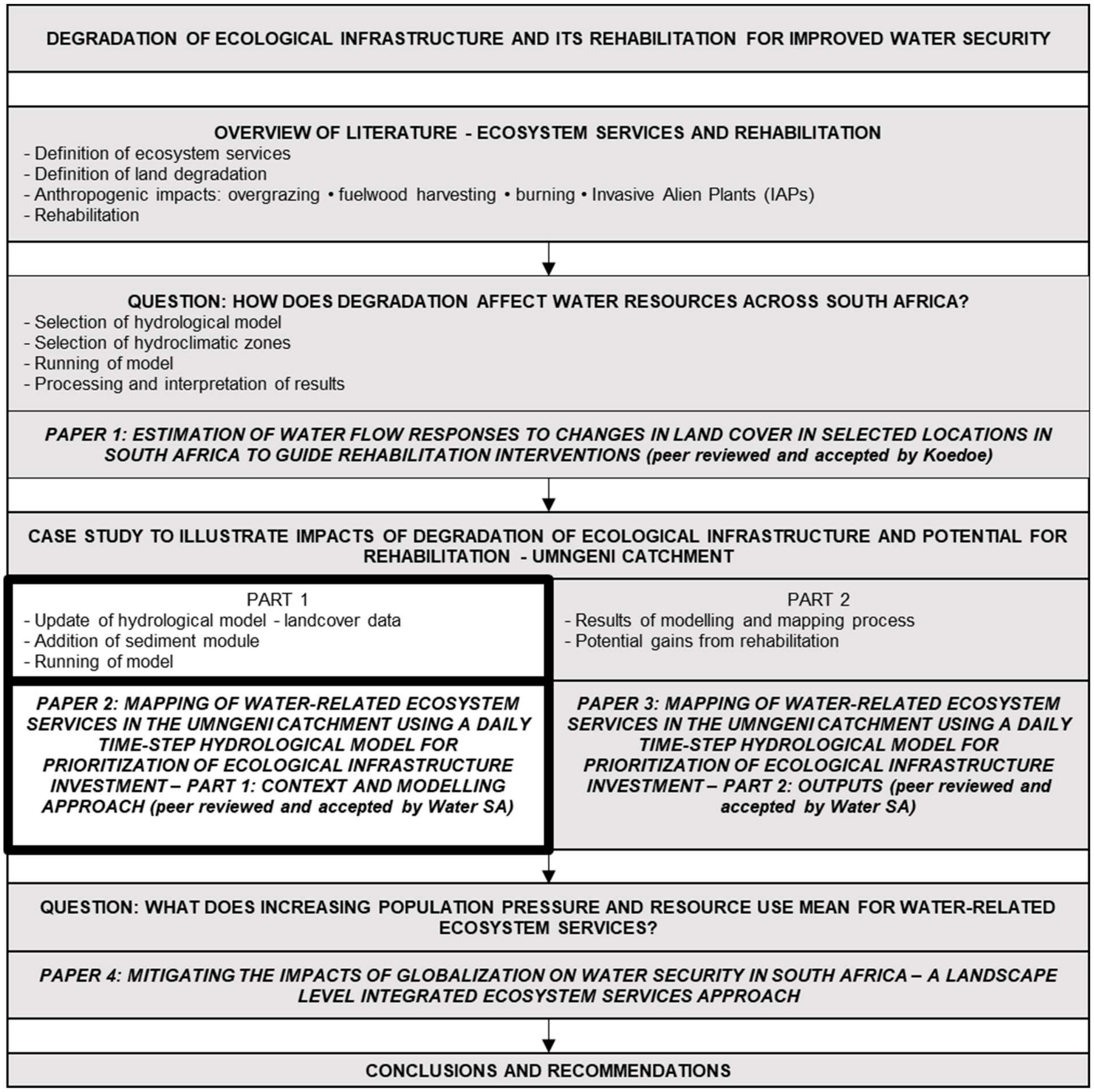
Appendix A

Table A: Monthly values of average crop coefficients (CAY), interception loss (VEGINT, mm.rainday^{-1}), fraction of roots active in the topsoil (ROOTA), coefficient of initial abstraction (COIAM, which determines infiltrability into the soil and is used to estimate the rainfall abstracted by interception, surface storage and infiltration before stormflow commences) and percentage (%) of surface cover (mulch etc., PCSUCO) which controls soil water evaporation. These parameters are provided for the Acocks Veld Types (1988) and land cover changes occurring in the seven locations (Schulze 2004, Warburton 2011)

Land Cover	***ACRU* Parameter**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Acocks Veld Type													
Coastal Forest and Thornveld, Mt Edgecombe	CAY	0.85	0.85	0.85	0.85	0.75	0.65	0.65	0.75	0.85	0.85	0.85	0.85
	VEGINT	3.1	3.1	3.1	3.1	2.5	2	2	2.5	3.1	3.1	3.1	3.1
	ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
Arid Sweet Bushveld Mara	CAY	0.75	0.6	0.5	0.45	0.35	0.3	0.2	0.2	0.4	0.55	0.65	0.75
	VEGINT	1.6	1.6	1.6	1.5	1.3	1.2	1.1	1.1	1.2	1.4	1.6	1.6
	ROOTA	0.8	0.8	0.8	0.85	0.9	0.95	1	1	0.95	0.9	0.8	0.8
	COAIM	0.15	0.15	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15
	PCSUCO	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3	82.3
Orange River Brokenveld Upington	CAY	0.25	0.3	0.3	0.25	0.25	0.2	0.2	0.2	0.25	0.3	0.3	0.3
	VEGINT	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	ROOTA	0.8	0.8	0.8	0.8	0.9	1	1	1	1	0.9	0.8	0.8
	COAIM	0.2	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2
	PCSUCO	10	10	10	10	10	10	10	10	10	10	10	10
Coastal Rhenosterbosveld Elsenburg	CAY	0.4	0.4	0.4	0.45	0.5	0.5	0.5	0.5	0.5	0.45	0.4	0.4
	VEGINT	0.8	0.8	0.8	1	1.2	1.2	1.2	1.2	1	0.8	0.8	0.8
	ROOTA	0.95	0.95	0.95	0.9	0.9	0.9	0.9	0.9	0.95	0.95	0.95	0.95
	COAIM	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
	PCSUCO	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8	37.8
Knysna Forest Outeniqua	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.8	0.85	0.85	0.85	0.85	0.85
	VEGINT	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2	3.2
	ROOTA	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75	0.75
	COAIM	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
Natal Mist Belt Ngongoni Veld, Cedara	CAY	0.7	0.7	0.7	0.5	0.35	0.25	0.2	0.2	0.55	0.7	0.7	0.7
	VEGINT	1.5	1.5	1.5	1.3	1.1	1.1	1.1	1.1	1.4	1.5	1.5	1.5
	ROOTA	0.9	0.9	0.9	0.94	0.96	1	1	1	0.95	0.9	0.9	0.9

	COAIM	0.15	0.15	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15
	PCSUCO	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4
Bankenveld Roodeplaat	CAY	0.65	0.65	0.65	0.5	0.35	0.2	0.2	0.2	0.25	0.5	0.65	0.65
	VEGINT	1.3	1.3	1.3	1.3	1.1	1	1	1	1.1	1.2	1.3	1.3
	ROOTA	0.9	0.9	0.9	0.9	0.95	1	1	1	0.95	0.9	0.9	0.9
	COAIM	0.15	0.15	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.25	0.15
	PCSUCO	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5	64.5
Invasive alien plant species													
Acacia mearnsii	CAY	0.9	0.9	0.9	0.88	0.85	0.86	0.89	0.9	0.92	0.92	0.9	0.9
	VEGINT	2.0	2.0	2.0	2.0	1.9	1.85	1.85	1.85	1.9	1.95	2.0	2.0
	ROOTA	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83
	COAIM	0.25	0.25	0.25	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.25	0.25
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
Eucalyptus grandis	CAY	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
	VEGINT	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50	2.50
	ROOTA	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
Pinus patula	CAY	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
	VEGINT	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50	3.50
	ROOTA	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66	0.66
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	100	100	100	100	100	100	100	100	100	100	100	100
Degraded Natural Vegetation													
Coastal Forest and Thornveld, Mt Edgecombe	CAY	0.65	0.65	0.65	0.65	0.65	0.65	0.6	0.65	0.65	0.65	0.65	0.65
	VEGINT	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	ROOTA	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	COAIM	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	PCSUCO	40	40	40	40	40	40	40	40	40	40	40	40
Arid Sweet Bushveld Mara	CAY	0.54	0.43	0.36	0.32	0.25	0.21	0.20	0.20	0.29	0.39	0.46	0.54
	VEGINT	0.80	0.80	0.80	0.75	0.65	0.60	0.55	0.55	0.60	0.70	0.80	0.80
	ROOTA	0.80	0.80	0.80	0.85	0.90	0.95	1.00	1.00	0.95	0.90	0.80	0.80
	COAIM	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.10	0.10
	PCSUCO	10	10	10	10	10	10	10	10	10	10	10	10
Orange River Brokenveld Upington	CAY	0.20	0.21	0.21	0.20	0.20	0.20	0.20	0.20	0.20	0.21	0.21	0.21
	VEGINT	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15
	ROOTA	0.80	0.80	0.80	0.80	0.90	1.00	1.00	1.00	1.00	0.90	0.80	0.80
	COAIM	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.10	0.10
	PCSUCO	10	10	10	10	10	10	10	10	10	10	10	10
Coastal Rhenosterbosveld Elsenburg	CAY	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	VEGINT	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	ROOTA	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
	COAIM	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.15

	PCSUCO	10	10	10	10	10	10	10	10	10	10	10	10
Knysna Forest Outeniqua	CAY	0.65	0.65	0.65	0.65	0.65	0.65	0.6	0.65	0.65	0.65	0.65	0.65
	VEGINT	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	ROOTA	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90	0.90
	COAIM	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
	PCSUCO	40	40	40	40	40	40	40	40	40	40	40	40
Natal Mist Belt Ngongoni Veld, Cedara	CAY	0.50	0.50	0.50	0.36	0.25	0.20	0.20	0.20	0.39	0.50	0.50	0.50
	VEGINT	0.75	0.75	0.75	0.65	0.55	0.55	0.55	0.55	0.70	0.75	0.75	0.75
	ROOTA	0.90	0.90	0.90	0.94	0.96	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COAIM	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.10	0.10
	PCSUCO	10	10	10	10	10	10	10	10	10	10	10	10
Bankenveld Roodeplaat	CAY	0.46	0.46	0.46	0.36	0.25	0.20	0.20	0.20	0.20	0.36	0.46	0.46
	VEGINT	0.65	0.65	0.65	0.65	0.55	0.50	0.50	0.50	0.55	0.60	0.65	0.65
	ROOTA	0.90	0.90	0.90	0.90	0.95	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COAIM	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.10	0.10
	PCSUCO	10	10	10	10	10	10	10	10	10	10	10	10



DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND ITS REHABILITATION FOR IMPROVED WATER SECURITY

OVERVIEW OF LITERATURE - ECOSYSTEM SERVICES AND REHABILITATION

- Definition of ecosystem services
- Definition of land degradation
- Anthropogenic impacts: overgrazing • fuelwood harvesting • burning • Invasive Alien Plants (IAPs)
- Rehabilitation

QUESTION: HOW DOES DEGRADATION AFFECT WATER RESOURCES ACROSS SOUTH AFRICA?

- Selection of hydrological model
- Selection of hydroclimatic zones
- Running of model
- Processing and interpretation of results

PAPER 1: ESTIMATION OF WATER FLOW RESPONSES TO CHANGES IN LAND COVER IN SELECTED LOCATIONS IN SOUTH AFRICA TO GUIDE REHABILITATION INTERVENTIONS (peer reviewed and accepted by Koedoe)

CASE STUDY TO ILLUSTRATE IMPACTS OF DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND POTENTIAL FOR REHABILITATION - UMNGENI CATCHMENT

PART 1	PART 2
- Update of hydrological model - landcover data - Addition of sediment module - Running of model	- Results of modelling and mapping process - Potential gains from rehabilitation
PAPER 2: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 1: CONTEXT AND MODELLING APPROACH (peer reviewed and accepted by Water SA)	***PAPER 3: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 2: OUTPUTS (peer reviewed and accepted by Water SA)***

QUESTION: WHAT DOES INCREASING POPULATION PRESSURE AND RESOURCE USE MEAN FOR WATER-RELATED ECOSYSTEM SERVICES?

PAPER 4: MITIGATING THE IMPACTS OF GLOBALIZATION ON WATER SECURITY IN SOUTH AFRICA – A LANDSCAPE LEVEL INTEGRATED ECOSYSTEM SERVICES APPROACH

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 4: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 1: CONTEXT AND MODELLING APPROACH[15]

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Keywords: water, ecosystem services, hydrological modelling, ecological infrastructure, water security

Abstract

South Africa is a semi-arid country which frequently faces water shortages, and experienced a severe drought in the 2016 and 2017 rainfall seasons. Government is under pressure to continue to deliver clean water to the growing population at a high assurance of supply. Studies now show that the delivery of water may be sustained not only through built infrastructure such as dams and pipelines, but also through investment in Ecological Infrastructure (EI).

A daily time-step hydrological model was used to map areas which should be prioritised for protection or rehabilitation to sustain the delivery of water-related ecosystem services within the uMngeni catchment. We focused on three water-related ecosystem services, i.e.:

- water supply;
- sustained baseflow; and
- erosion control/avoidance of excessive sediment losses.

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[15] Format: WaterSA journal

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The two key types of degradation were modelled, namely overgrazing and the invasion of upland areas by Black Wattle (*Acacia mearnsii*).

This, Part 1 of a paper in 2 parts, provides a discussion on the role of EI in delivering water-related ecosystem services, describes the motivation for the study, and the methods used in modelling and mapping the catchment. The results of this modelling exercise are presented in Part 2, which also explores and illustrates the potential hydrological benefits of rehabilitation and protection of EI in the uMngeni Catchment.

Introduction

South Africa, as a semi-arid country, frequently faces water shortages and in the 2016 and 2017 rainfall seasons experienced a severe drought. Government is under pressure to continue to deliver clean water to the growing population at a high assurance of supply. Several studies have suggested that the delivery of water may be sustained not only through built infrastructure such as dams and pipelines, but also through investment in ecological infrastructure.

Ecological infrastructure (EI) is defined as "naturally functioning ecosystems that produce and deliver valuable services to people[16]" (Jewitt, Zunckel et al., 2015). Delivery of water-related ecosystem services is highly dependent on healthy EI (Brauman et al., 2007), which plays a key role in determining the catchment's capacity to firstly receive precipitation, and in turn the distribution of water through varying soil/water responses. The condition of the catchment (e.g. pristine vs overgrazed) therefore determines the partitioning of rainfall above and below the earth's surface, as well as the distribution of water within a catchment. Healthy vegetation cover protects, and its root system binds, the topsoil, reducing its exposure and mobilisation by wind, rainfall and surface runoff.

The role of Ecological Infrastructure (EI) in delivering water-related ecosystem services is well recognised (Brauman et al., 2007, Guswa et al., 2014, Elmqvist et al., 2015). These services include, amongst others, flood attenuation, water purification through biophysical and biological processes, i.e. retention of sediments and nutrients, pollution dilution, sustaining

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[16] Similar to the widely used term Natural Capital, which is defined as "the world's stocks of natural assets which include geology, soil, air, water and all living things" (Natural Capital Forum, 2017).

baseflows during dry periods and provision of water supply of high quality (Elmqvist et al., 2007, Guswa et al., 2014), see Figure 17).

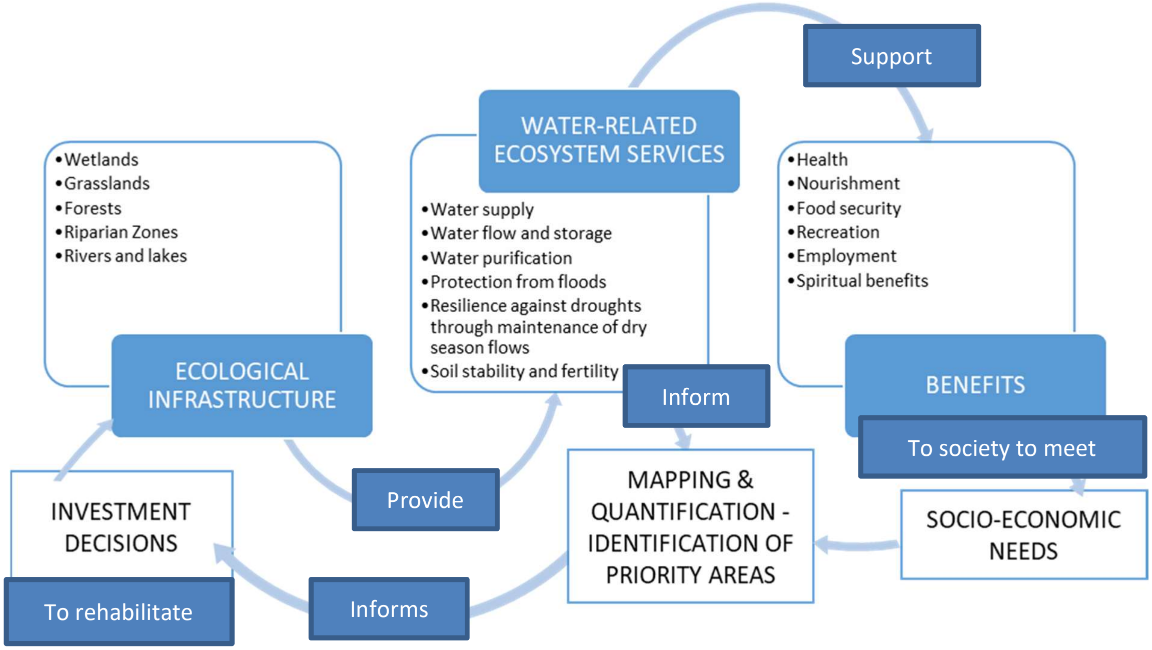

Figure 17: Water-related ecosystem services and benefits provided by ecological infrastructure

Degradation of EI through various human-induced processes such as overgrazing, inappropriate burning regimes, poor agricultural practices (livestock and cropping) and the proliferation of invasive alien plants (IAPs)[17] reduces its capability to deliver water-related ecosystem services of the highest quality. In this study, we have concentrated on the outputs from the modelling of two key anthropogenic drivers of degradation, namely overgrazing and the proliferation of IAPs.

Degradation can have a marked effect on catchment hydrology (Figure 18), such as reducing streamflows (water supply), causing high-energy runoff which mobilises excessive amounts of sediments, and reducing infiltration of precipitation to the lower layers of soil with associated lower volumes of baseflow and groundwater recharge. These effects lead to negative impacts on water-related ecosystem services, such as reducing flood attenuation capacity, water supply and water quality. Additionally, all of these can affect human communities in terms of health,

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[17] See definitions of "invasive" and "alien" in Richardson et al., 2000

agricultural productivity and safety. This is particularly important in rural and peri-urban areas where people are immediately dependent on run-of-river water supply and quality. The effective rehabilitation of degraded areas, when taking into account the need for considering the entire ecosystem and the reinstatement of ecological processes, can improve the delivery of water-related ecosystem services.

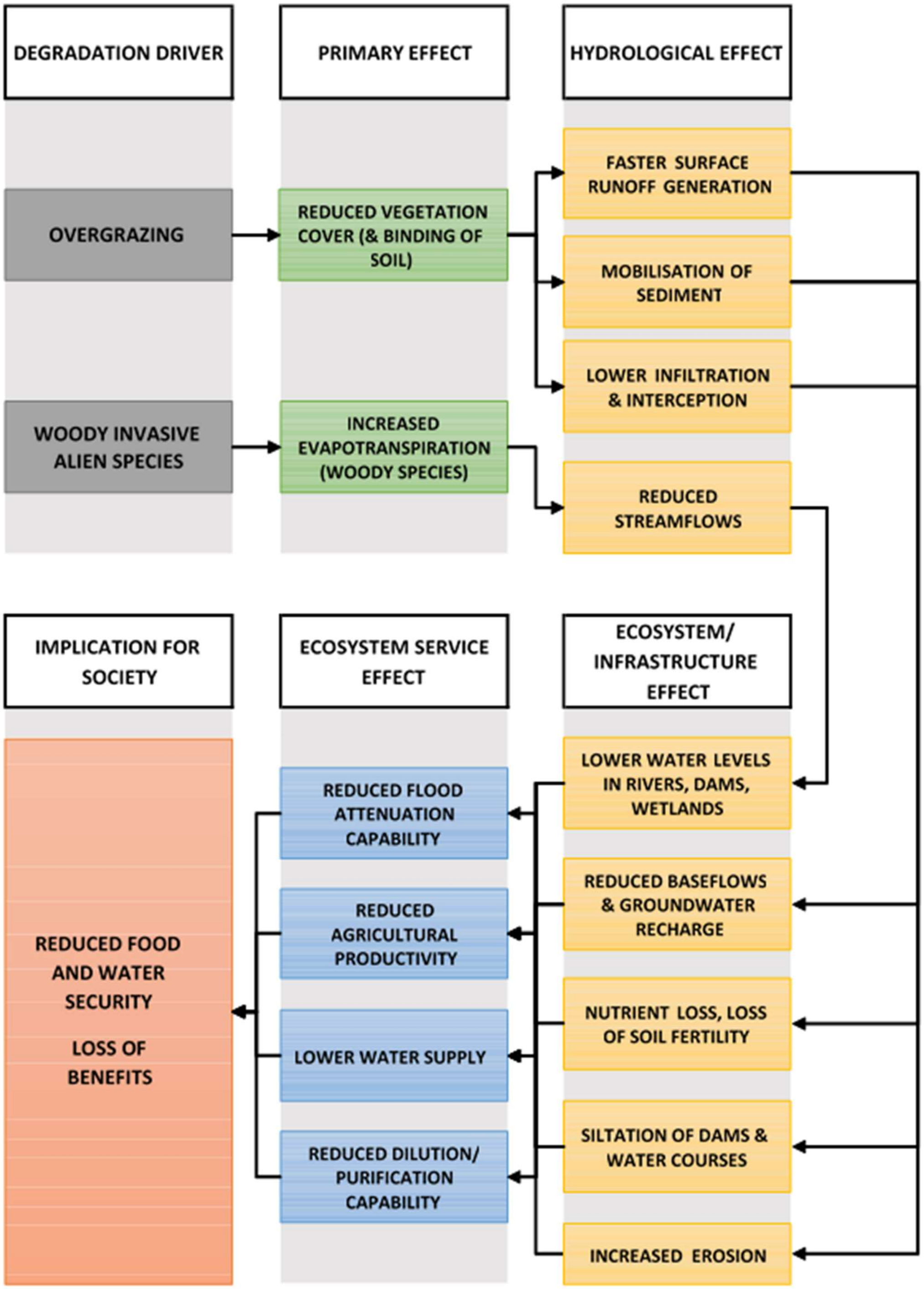

Figure 18: Degradation effects of overgrazing and woody IAPs

Perhaps the most important aspect of water distribution is the partitioning of water into surface and sub-surface water, the latter often being derived from infiltration and percolation through the soil profile, as a result of which rainfall becomes shallow or deep groundwater which contributes to sustained baseflows and thus water supply (Kosgei et al., 2007, Wenninger et al., 2008, Van Tol et al., 2010). Dilution of pollutants through a sufficient and sustained water supply has a direct bearing on water quality. This, in turn, has a marked effect on a number of ecosystem service benefits to society, including human health (Keeler et al. 2012). Identification of socio-economic needs such as human health (and hence desired benefits derived from ecosystem services) can drive the mapping of ecosystem services and in turn the identification of priority areas for investment into ecological infrastructure protection and/or rehabilitation. Such investments could include the securing and rehabilitation of naturally functioning ecosystems, including grasslands, riparian zones and wetlands.

In naturally perennial systems, baseflow is maintained by healthy ecological infrastructure through providing steady infiltration and percolation. Baseflow drives the functionality of many water-related ecosystem services (see **Figure 19**), notably water quality and run-of-river abstraction in the dry season (both of which are key considerations in times of drought) and for aquatic ecosystem function throughout the year to support the Ecological Reserve, and ensure that primary water users have sustained access to sufficient, good quality water

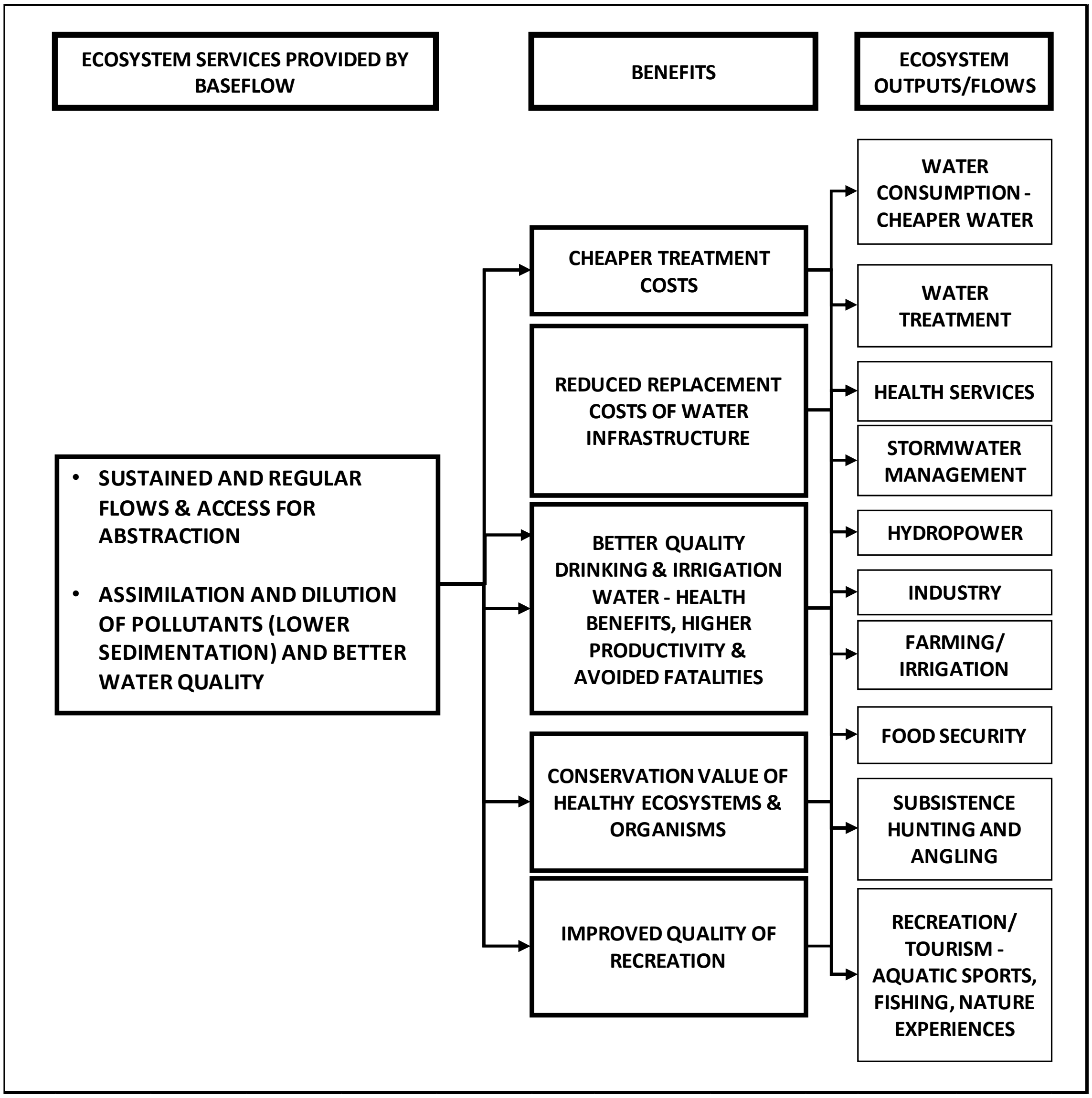

Figure 19: Interrelationships between baseflow, changes in ecosystem services and human benefits

In contrast to baseflow, surface or near-surface runoff (referred to as quickflow), i.e. the water which runs off the surface or near-surface following a rainfall event, does not infiltrate to the lower layers of soil (Le Maitre et al. 2014). While it contributes to the water supply of the river, should the natural balance between quickflow and baseflow be disrupted, too much quickflow can mobilise excessive sediments and nutrients from the surface (Dlamini et al. 2014). Sediments and nutrients are moved downslope and deposited in lower-lying areas and water courses, changing the area's geomorphological structure and potentially compromising the quality of the water in the river. Prevention of excessive sediment mobilisation is therefore another key ecosystem service. Generation of higher amounts of sediment than are characteristic of the system results in degradation, and this sediment is likely to be transported towards, and within, water courses, altering natural flow paths and ecosystem processes, and/or be deposited in dams. Man-made dams are designed to contain and consistently supply water to domestic, industrial and agricultural users. Sedimentation may thus reduce their capacity and lifespan (Csiki and Rhoads, 2010) and lead to more frequent spilling and/or the need for costly dredging, and a loss of storage capacity.

Mapping of ecosystem services

Decision making based on the concept of ecosystem services has gained academic and political traction over recent years, and it is important that these services are able to be mapped and quantified (Daily et al., 2009, Seppelt et al., 2011). Brauman et al. (2007) identified the potential knowledge gaps of water-related ecosystem services in terms of location, scale and connectivity, and the likelihood that mapping could make a useful contribution to ecosystem service assessments. A common approach to assessing ecosystem services is the use of proxy variables, or surrogates, particularly of land cover, to represent ecosystem processes and to map services using a Geographical Information System or GIS (Egoh et al., 2008, Seppelt et al., 2011, Burkhard et al., 2012).

Focusing on water-related ecosystem services in South Africa, Egoh et al. (2008, 2009, 2011) mapped surface water supply (using runoff) and water flow regulation services (using groundwater) across South Africa. Spatially, results of these studies are presented at the spatial scale of Quaternary catchments (i.e. delineated to the fourth level of disaggregation, average area of ~ 650 km^2), as well as at the temporal scale of annual averages, which is appropriate for national scale assessments and comparisons, but may not be adequate for municipal/catchment planning.

Although the spatial unit of analysis of many ecosystem service studies may be at a small enough scale to allow for catchment-scale development or rehabilitation planning, Table 1 shows that the temporal scale is generally presented as an annual average, which does not take inter-annual variability, seasonality, nor impacts of individual hydrological events, into account. For catchment and municipal-scale planning, seasonality and inter- as well as intra-annual variability are vital aspects to consider with regard to South Africa’s naturally discrete dry and wet seasons, and also the variations in summer rainfall which are associated with the cycle of the El-Niño Southern Oscillation (Malherbe et al., 2016).

Relatively few studies have been reported which use simulation models to map ecosystem services (Seppelt et al., 2011), and many rely on expert opinion to provide links to land cover data. The application of models that operate according to the biophysical principles and feedback mechanisms of the hydrological cycle that represent the water flow through the landscape over long time periods provides an advance in the way that maps of water-related ecosystem services can be derived. The value of daily time-step models in the valuation of water-related ecosystem services, particularly with respect to land use[18] change and feedback mechanisms, has been specifically recognised (Seppelt et al., 2011., Keeler et al., 2012), but has seen little application, particularly in South Africa. In this study a daily time-step hydrological model which has a hydrological "memory" which carries through water volumes and states by way of a day to day water balance, taking feedback mechanisms/complexity into account, is applied at a small spatial resolution, providing information appropriate to catchment level decision making and providing a significant advance on previous studies.

Motivation for the study of the uMngeni catchment

Throughout South Africa, water engineers from large municipalities and water boards face ongoing pressure in terms of water service delivery. Stakeholders such as these are, however, beginning to show a willingness to invest in the rehabilitation of upstream catchments for improved water availability and security downstream (e.g. eThekwini Municipality, 2012). It is, therefore, important for scientists and water resource managers to be able to guide potential investors in terms of where their money may be best spent, i.e. where the largest gains in water could be made through rehabilitation actions. Thus, our aim was to use a spatially explicit method for the prioritisation of areas for investment into EI assets in the uMngeni Catchment. This paper describes the motivation for the use of the uMngeni Catchment as a case study, as well as the methods used to prioritise areas for investment, and Part 2 describes the results and outputs.

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[18] Lambin et al. (2001) describe land cover as the "biophysical attributes of the earth's surface" and land use as the "human purpose or intent applied to these attributes".

The uMngeni Catchment provides an excellent case study for the exploration of the potential value of EI rehabilitation interventions for several reasons. From an institutional perspective, the uMngeni Ecological Infrastructure Partnership (UEIP), which is made up of 23 signatories including both government and non-government agencies and tertiary institutions, all of whom recognise the role that investments in EI can play in the enhancement of water and sanitation services in the uMngeni catchment, has made a case for incorporating EI solutions into catchment management (Jewitt, Zunckel, et al., 2015). The South African National Biodiversity Institute (SANBI) has laid considerable groundwork in terms of the role of EI in delivering water-related ecosystem services (e.g. Blignaut et al., 2010, Holness and Skowno, 2013, SANBI, 2014). These studies have found a strong link between healthy EI, delivery of ecosystem services and socio-economic development, and have attracted investment into South Africa to reduce the risks associated with water scarcity and water-related natural disasters such as droughts and floods (SANBI, 2014).

Study area

The uMngeni catchment (±4,400 km^2, 921 mm rainfall per annum; Umgeni Water 2016) is located in the province of KwaZulu-Natal, South Africa, and hosts the country's second largest economic hub, and its largest trade port. It is a summer rainfall region mostly characterised by grassland, although much of this area has been cultivated. There are also areas of thicket and bushland, with forest patches (Umgeni Water 2016). Mean annual temperatures range between 14 and 22°C. There is a current focus on trade, investment, imports and exports in the following key sectors: manufacturing (automotive, chemical, metals and maritime), agriculture, tourism, transport and logistics, and the green economy (KZN Provincial Planning Commission, 2012). However, economic growth and rapid immigration from rural areas (known as urbanization; United Nations, Department of Economic and Social Affairs, Population Division 2014) which exceeds the growth in employment, places increasing pressure on the catchment's natural resources. The emphasis for delivery of water to the catchment's people is currently aimed at more investment into built infrastructure. However, the extent of degradation of EI and loss of natural land cover through transformation within the uMngeni catchment over time has compromised the system's natural ability to perform optimally in delivering strategically important water-related ecosystem services (Jewitt, Zunckel, et al., 2015).

The local water authority states that the uMngeni River catchment, supported by a transfer scheme from the adjacent Mooi River catchment, is able to yield approximately 1,050 Ml per day at a 99% level of assurance of supply from its various major supply dams, viz. Midmar, Albert Falls, Nagle and Inanda (Umgeni Water, 2015). In the 2013/2014 financial year, however, the demand exceeded this amount by over 75 Ml per day. Demand is projected to increase to 1,800 Ml per day by 2043/2044 owing to further economic development (Umgeni Water, 2015), which will lead to a lower assurance of supply and a high risk of shortfall. The degradation of natural land (and loss of EI) in the uMngeni catchment over recent decades also implies a change in the partitioning of rainfall, as well as a reduction in the catchment's ability to sustain water-related ecosystem services. This is likely to have led to an increase in surface runoff from areas overgrazed/trampled by livestock, or from hardened roads and roofs, which means that baseflow and groundwater recharge is reduced, and may not be adequate to sustain the catchment in the dry season. In as little as six years (2005-2011), the KwaZulu-Natal province, in which the uMngeni catchment lies, has lost as much as 7.6% of its natural land due to anthropogenic transformation (mainly due to agriculture, timber plantations, the built environment, dams and mines; Jewitt, Goodman, et al., 2015), which brings the total of natural land lost in the catchment to almost 48%.

Materials and methods

This project used established hydrological modelling and GIS techniques to map and model water-related ecosystem service delivery from land cover within the catchment. The following water-related ecosystem services were the focus of the initial mapping process, and they were selected on the basis of previous research elsewhere (e.g. Brauman et al., 2007), discussions with various experts in the field, and available data:

- *Water supply*: Provision of water throughout the year for domestic, industrial, ecological and recreational use (modelled and mapped as streamflow);
- *Sustained baseflow*: Maintenance of water supply during dry periods, and associated water quality maintenance due to assimilation and/or dilution of excess nutrients and waste; and
- *Erosion control and avoidance of excessive sediment losses*: Avoidance of the mobilisation of excessive sediments from upslope land areas to watercourses and dams,

thus affecting the nutrient distribution in the landscape and reducing dam storage capacity, as well as resulting in turbidity in water courses. This includes the transport of soluble nitrates as well as phosphates – the latter, importantly, being sediment-bound (Pettersson et al., 1988).

The ACRU *model*

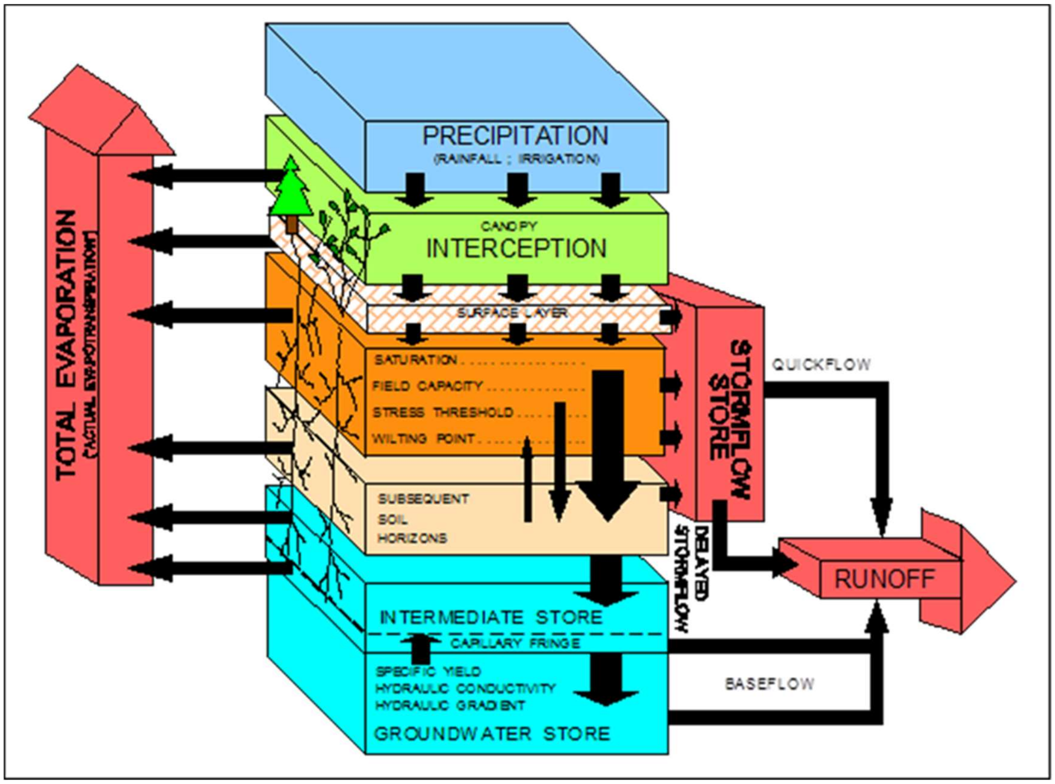

Figure 20: Schematic representation of the *ACRU* model's water budget (Schulze, 1995)

The *ACRU* (Agricultural Catchments Research Unit) model (Figure 20), a detailed, daily time-step hydrological model which is able to operate at an appropriate spatial scale for planning, has been widely used for land use impact studies in South Africa, Eritrea, Zimbabwe, United States of America, Germany, New Zealand and Canada.

The model has been used in the Upper Thukela and Baviaanskloof in South Africa for similar ecosystem service-based studies (Maloti Drakensberg Transfrontier Project, 2007, Blignaut et al., 2010, Mander et al., 2010). Importantly, Warburton et al. (2010) undertook a comprehensive simulation study of the hydrology of the uMngeni catchment with the *ACRU* model and confirmed the ability of the model to represent the high, low and total flows, with satisfactory comparison statistics (Table 4). They concluded that the model was able provide a satisfactory simulation of streamflow from the range of climates and diversity of land uses present within the catchment.

Table 4: Statistics of performance of the *ACRU* model in various Water Management Units within the uMngeni catchment: Comparison of daily observed and simulated values (from Warburton et al., 2010)

Water Management Unit (1987 – 1998)	**Mpendle**	**Lions River**	**Karkloof**	**Henley**
Total observed flows (mm)	3,444	2,507	3,456	2,636
Total simulated flows (mm)	3,171	2,258	3,006	2,534
Average error in flow (mm/day)	-0.063	-0.058	-0.105	-0.024
Mean observed flows (mm/day)	0.796	0.582	0.803	0.629
Mean simulated flows (mm/day)	0.733	0.524	0.698	0.605
% Difference between means	7.91	9.95	13.05	3.86
Standard Deviation of observed flows (mm)	1.823	1.734	1.228	1.246
Standard Deviation of simulated flows (mm)	2.011	1.947	1.305	1.541
% Difference between Standard Deviations (%, <15% indicating a satisfactory result)	-10.34	-12.31	-6.26	-23.67
Correlation Coefficient : Pearson's R (value of 1 indicating a satisfactory result)	0.915	0.939	0.844	0.886
Regression Coefficient (slope, value of >0 indicating a satisfactory result)	1.009	1.055	0.897	1.095
Regression Intercept (value of 0 indicating a satisfactory result)	-0.070	-0.090	-0.022	-0.084
Coefficient of Determination: R^2 (value of 0.7 indicating a satisfactory result)	0.836	0.882	0.713	0.785
Nash-Sutcliffe Efficiency Index (E_f) (value of 1 indicating a satisfactory result)	0.802	0.847	0.655	0.654

Flow modelling in **ACRU**

Outputs from the *ACRU* model were used to derive maps of the areas of ecological infrastructure that generate water-related ecosystem services. In the model, processes directly affected by land cover, i.e. canopy interception loss, evaporation from vegetated surfaces and soil water extraction by plant roots all directly contribute to total evaporation (Schulze, 1995). These processes are controlled by a range of parameters including those which control the magnitude of interception and transpiration for different plants in their different stages of growth, rooting pattern and depth and those which affect the composition of the soil and its infiltrability. This affects the amount of water available in each of the soil horizons, which in turn affects the amount of runoff (in the form of quickflow or baseflow) generated. The key output parameters from the model as they relate to the water-related ecosystem services, as already mentioned above, include:

- Runoff (water supply/streamflow);
- Quickflow (non-delayed stormflow, i.e. water available at or near to the surface on the same day as the rainfall event; water supply);
- Baseflow (water which has infiltrated to lower soil layers and provides recharge to the groundwater store which then discharges into rivers and sustains flows in the dry season); and
- Sediment yield (soil mobilised/eroded from the landscape part of the catchment and entering the stream).

Baseflow is modelled explicitly within *ACRU*, with the value derived from soil water which has percolated out of the base of the sub-soil (B) horizon, and into a baseflow store (Smithers and Schulze, 2004). The store which collects baseflow is connected in the model to the stream channel, and releases water into the stream at a rate which depends on the quantity of water in the groundwater store (Smithers and Schulze, 2004). Technically, quickflow in the *ACRU* model represents the portion of stormflow generated from a rainfall event on a given day that exits the catchment on the same day on which it was generated, plus an amount of quickflow that has been accumulated from preceding days (Smithers and Schulze, 2004).

Sediment yield was calculated within the *ACRU* model using the Modified Universal Soil Loss Equation (MUSLE; Williams, 1975) and modified Soil Conservation Service (SCS) techniques which are used to calculate stormflow (Smithers and Schulze, 2004). The sediment yield functions used in the *ACRU* model consider, *inter alia*, stormflow (as the surrogate for sediment yield transport), peak discharge (used as an indicator of soil particle dislodgement), erodibility characteristics of soils, slope length and a vegetation cover factor that considers both above-ground and surface protection characteristics.

Setting up the sub-catchments and Hydrological Response Units

Building from Warburton et al. (2010), the catchment has been delineated into 145 sub-catchments (**Figure 21**). These sub-catchments range in area from 37 to 11,000 hectares, and are differentiated on the basis of soils, altitude, topography, land cover, water management practices and gauging stations within the uMngeni catchment. The catchments are in turn grouped into 13 Quaternary catchments. For the current study, the 13 Quaternaries were further grouped into six "Dam" catchments to analyse different user groupings based on population clusters and areas supplied by each of the dams and, in turn, the demand for ecosystem services from EI within each Dam catchment (

Table 5). The assessment of ecosystem service requirements and benefits formed part of a separate process of interactions with catchment stakeholders and information gathering on water use, water users and built infrastructure mapping, and is described by Mander et al. (2017).

The 145 sub-catchments have each been further sub-delineated into 11 Hydrological Response Units (HRUs), i.e. representative land areas with similar hydrological characteristics/responses, based on vegetation types, specific land uses and classes of urbanisation. Although the sub-catchment boundaries are spatially explicit, the HRUs are not. Within each sub-catchment, the non-irrigated land uses are linked to the areas of natural vegetation, which in turn are linked to the areas of commercial agriculture and riparian zones, such that each HRU's individual streamflows are logically routed through each sub-catchment (**Figure** 22).

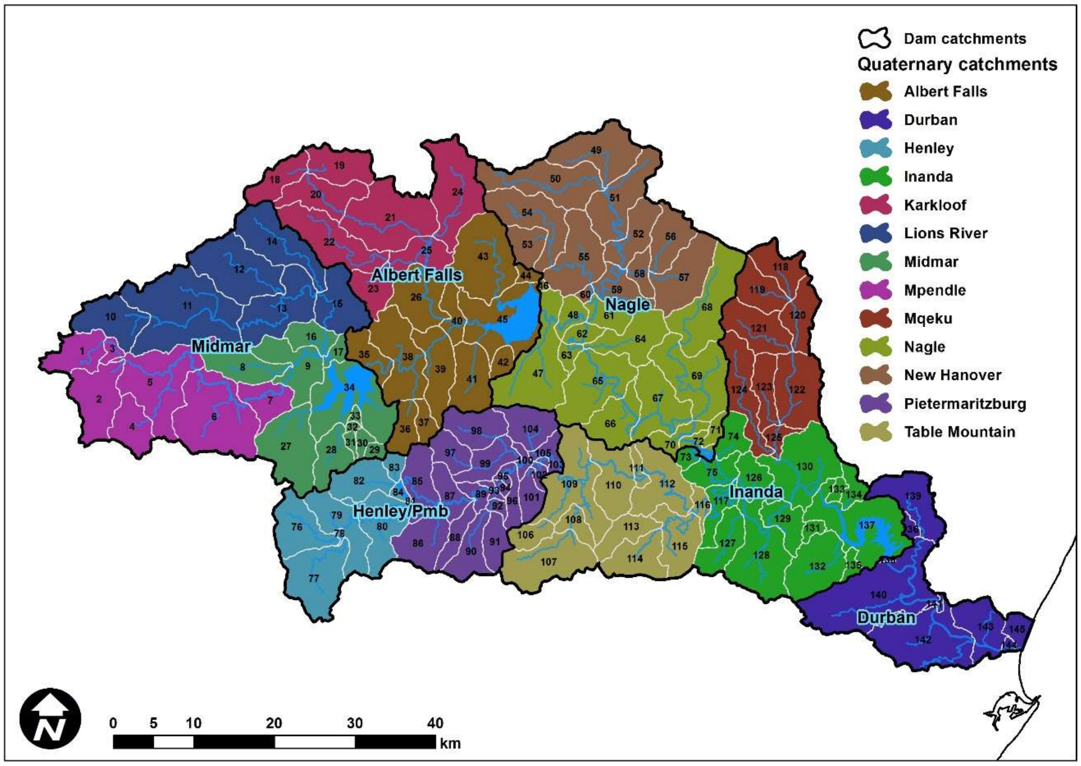

Figure 21: Dam Catchments, Quaternary Catchments and Sub-Catchments within the uMngeni catchment used for this study

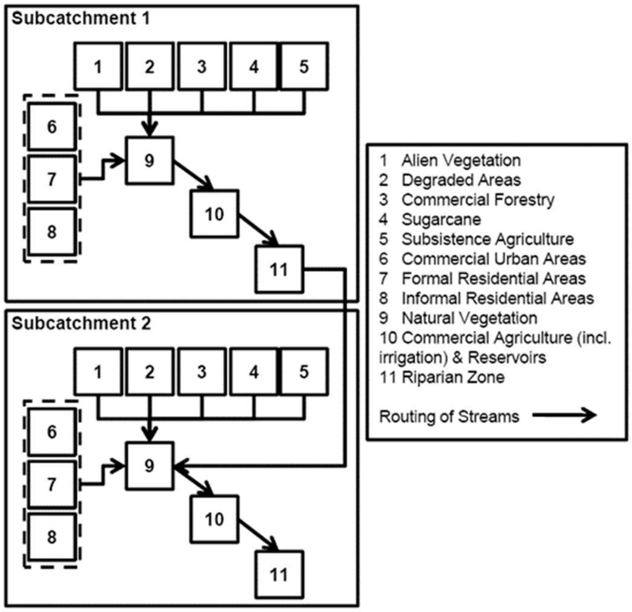

Figure 22: An example of flow paths between each sub-catchment and HRUs within each (Warburton et al. 2010)

Table 5: List of Dam catchments, Quaternary catchments and Sub-Catchments

Dam catchment	Quaternary catchments*	Number of sub-catchments
Midmar	Mpendle (U20A)	7
	Midmar (U20C)	12
	Lions River (U20B)	6
Albert Falls	Albert Falls (U20E)	12
	Karkloof (U20D)	8
Nagle	New Hanover (U20F)	12
	Mqeku (U20K)	8
	Nagle (U20G)	15
Henley/Pietermaritzburg[19]	Henley (U20H)	9
	Pietermaritzburg (U20J)	21
Inanda	Table Mountain (U20J)	11
	Inanda (U20L)	15
Durban[20]	Durban (U20M)	9

*(approximate corresponding Department of Water and Sanitation catchment in brackets)

Land cover classes and parameterisation

Within each of the 145 sub-catchments, each of the 11 land cover types making up the sub-catchment is modelled individually as a HRU. The outputs from the model can therefore quantify and indicate the relative degree of delivery of each service from each land cover type in the various sub-catchments.

The original model configuration (Warburton et al., 2010) was set up using information from the year 2000 National Land Cover imagery (NLC, 2000) and individual sub-catchments, with soils information (Schulze et al., 2008), together with default input values obtained from the *ACRU* User Manual (Smithers and Schulze, 2004) where no better information was available. This project, however, made use of more recent land cover data available at the time of writing, *viz*. the 2011 KwaZulu-Natal provincial land cover map (EKZNW and GTI, 2013). Thus, the

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[19] Henley/Pietermaritzburg is not a dam catchment *per se*, but was included owing to the need to incorporate the large city of Pietermaritzburg as a user group. It is recognised that streamflow from the city ultimately feeds the Inanda Dam.

[20] The Durban catchment feeds the uMngeni estuary.

area of each HRU was updated to reflect this. The land cover classes which were translated into HRUs for the modelling process are summarised for each sub-catchment in Table 6).

Three HRUs were targeted during this study to highlight hydrological differences between degraded and healthy EI, namely the HRUs with Invasive Alien Plants (IAPs), degraded vegetation (which was modelled as overgrazed land using the *ACRU* model hydrological attributes for overgrazed lands developed by Schulze et al. [2007] for the grasslands of KwaZulu-Natal and the Eastern Cape) for Maloti Drakensberg Transfrontier Project [2007], and untransformed natural vegetation (grassland or forest areas which were not considered by the mapping team to be degraded). Figure 23 shows their distribution and extent, and these HRUs are highlighted in bold in Table 6. Full details of the *ACRU* parameters used for the modelling process are provided in Appendix 1.

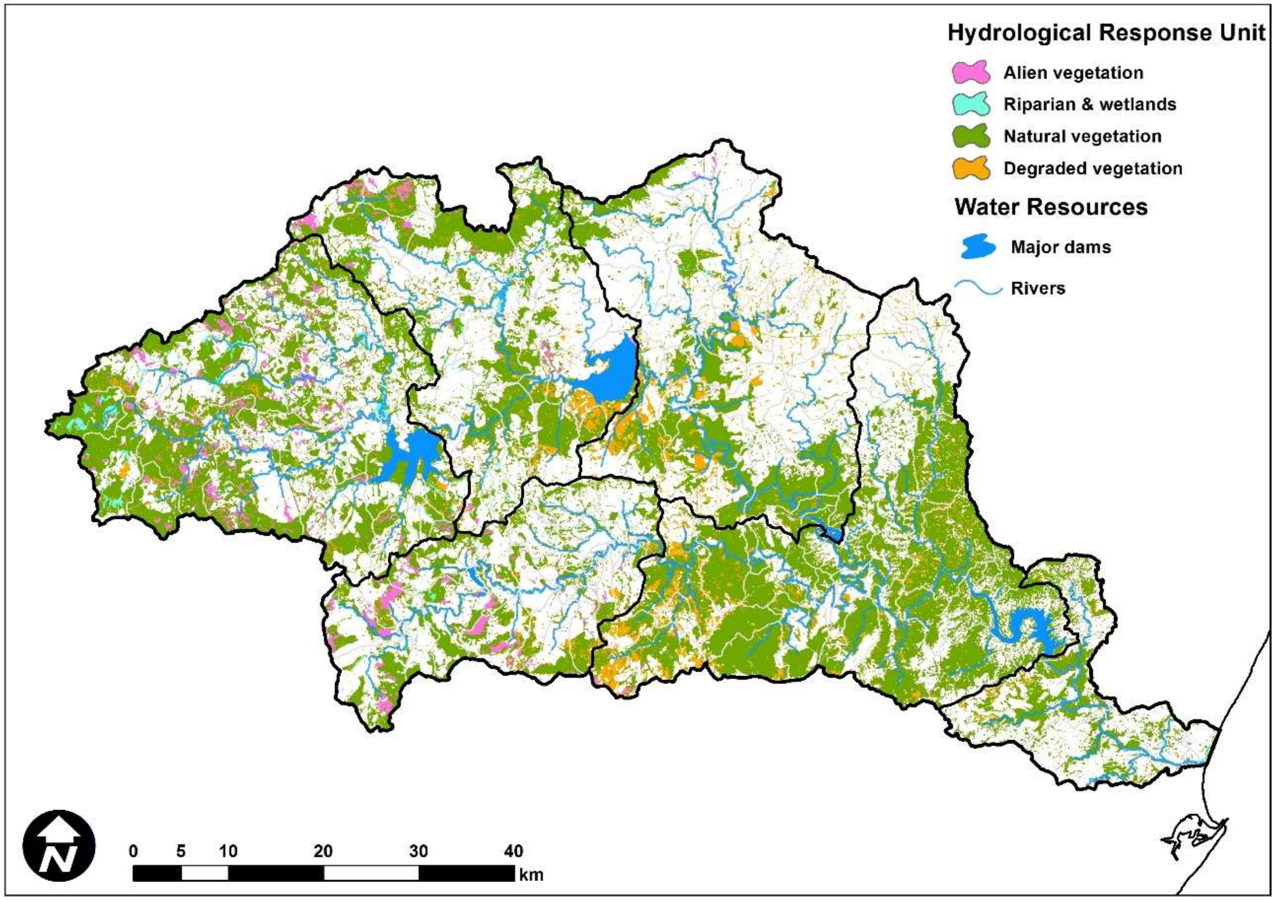

Figure 23: Map of targeted land uses used to model the delivery of water-related ecosystem service outputs in the uMngeni catchment[21]

Table 6: Accumulated HRU extent for each Dam catchment (ha)

ACRU HRU (after Warburton et al. 2010)	Midmar	Albert Falls	Henley/ Pietermaritzburg	Nagle	Inanda	Durban	Land cover data (from various sources)	Data Source
Invasive alien vegetation (Wattle), *Acacia mearnsii*	**2,835**	**846**	**1,860**	**153**	**84**	**22**	**Coverage of *Acacia mearnsii* infestation**	**Umgeni Water *Acacia mearnsii/ dealbata* coverage (2007)**
Built-up	2,445	3,011	17,295	2,690	7,765	14,305	Mines and Quarries, Built-up/dense settlement, KZN National Roads, KZN Main and District Roads, KZN Railways, Natural hard rock	KZN Province land cover mapping classes (EKZNW and GTI, 2013)
Commercial agriculture/dams	22,598	12,059	724	3,082	3,998	92	Orchards (permanent, irrigated, bananas and citrus), Cultivation (commercial, annual crops, dryland), Cultivation (commercial, annual crops, irrigated), Water (dams)	
Commercial forestry	15,058	25,063	4,885	25,259	2,270	135	Plantation and Plantation (clear-felled). The dominant species (*Eucalyptus grandis*, *Pinus patula* or *Acacia mearnsii*) were assigned using the original *ACRU* menu classification	
Degraded vegetation	**2,955**	**3,113**	**1,810**	**5,444**	**7,191**	**368**	**Bare Sand, Degraded Forest, Degraded Bushland (all types), Degraded Grassland, Old Fields (previously**	

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[21] White areas represent other land uses, e.g. residential, plantations, etc.

							grassland), Old Fields (previously bushland), Erosion, Airfields	
Informal residential	1,783	1,303	6,613	3,090	9,687	2,241	Low density settlements	
Natural vegetation	**42,291**	**24,068**	**16,552**	**23,126**	**51,725**	**8,617**	**Forest (indigenous), Dense thicket and bush (70 – 100% canopy cover), Medium bush (< 70% canopy cover), Woodland and Wooded Grassland, Bush Clumps/Grassland, Grassland, Forest glade**	
Pasture grass	109	77	357	11	17	412	Golf courses	
Riparian and wetlands	2,497	1,176	514	720	362	376	Natural water, Wetland, Wetland (mangrove), Water (estuarine)	
Subsistence agriculture	116	281	3,001	995	7,532	679	Cultivation (subsistence, dryland), Smallholdings	
Sugarcane (generalized)	0	1,631	242	23,755	9,278	250	Sugarcane (commercial, irrigated and dryland), Sugarcane (semi-commercial, emerging farmer, irrigated and dryland)	

The 2011 land cover data do not contain a mapped coverage of IAPs. A mapped and ground-truthed coverage of invasive alien wattle species (notably *Acacia mearnsii* and *A. dealbata*) provided by Umgeni Water (dated 2007) was thus used to represent this HRU. We acknowledge that these data are outdated and limited, and that our estimates indicate that they are far more extensively distributed at the time of the research than in 2007. However, it was the most reliable dataset of IAPs available at the time of the study. Furthermore, wattle trees are acknowledged to be the most problematic alien plant species in South Africa at present (Le Maitre et al., 2013), and give an indication of hydrological responses to woody IAP species.

Parameters used for the HRUs infested by *Acacia mearnsii* are shown in Table 7. The default parameters provided within *ACRU* were used – however the key parameter of canopy and interception loss (VEGINT) was increased to a value of 3.3 based on Schulze and Schütte (2014) and Bulcock and Jewitt (2012). This value was determined using fieldwork based on cultivated wattle trees and may thus be higher than might be expected for an IAP infestation. Furthermore, anecdotal evidence suggests that IAPs "thin out" when they have been established for many years (as opposed to newly established trees), and this may imply a lower water use than for cultivated plantations.

Table 7: *ACRU* parameters used for the modelling of *Acacia mearnsii*

HRU	***ACRU* Parameter***	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Acacia mearnsii	CAY	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	VEGINT	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ROOTA	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	80	80	80	80	80	80	80	80	80	80	80	80
	COLON	60	60	60	60	60	60	60	60	60	60	60	60
	COVER	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**	**0.08**

* Monthly values of average crop coefficients (CAY), interception loss (VEGINT, mm.rainday^{-1}), fraction of roots active in the topsoil (ROOTA), coefficient of initial abstraction (COIAM, which determines infiltrability into the soil and is used to estimate the rainfall abstracted by interception, surface storage and infiltration before stormflow commences), percentage (%) of surface cover (mulch etc., PCSUCO) - the maximum evaporation from the soil can be suppressed by surface cover such as mulch, litter and surface rock, percentage root colonisation in the subsoil horizon (COLON), and cover factor (C) in M.U.S.L.E. (COVER).

The effects of severe overgrazing

The hydrological effects of overgrazing, according to Maloti Drakensberg Transfrontier Project (2007), and based on the literature (e.g. Trimble and Mendel [1995], Sahin and Hall [1996], Illius and O'Connor [1999]), are summarised below:

- A reduction in above-ground biomass, which in turn results in a decrease in transpiration, with the decrease dependent on whether the original natural veld had a relatively high or low biomass, as well as a decrease in canopy interception and the canopy's protective properties in regard to soil loss;
- A reduction in litter or mulch on the soil surface, which results in increases in the rate of soil water evaporation, thus drying out the topsoil horizon more rapidly and exposing the soil to more severe erosion; and
- A possible compaction of the more exposed soil surface through rainfall compaction during convective events and trampling by livestock, which can result in a reduction in the infiltration of rain into the soil.

A sensitivity analysis was carried out for each varied parameter (see Chapter 3). Quickflow is far more responsive to changes in parameters for grassland catchments (of which the uMngeni is largely made up), and the most important parameters were found to be the crop coefficient, the percentage of root stock in the A horizon and the percentage of surface cover. Therefore, the changes in these three parameters to simulate overgrazing are key. ROOTA is not varied as this below-ground factor is not vastly altered with overgrazing, but a reduction of the crop coefficient by a factor of 1.4 aligns with the loss of biomass as vegetation is denuded by grazing animals (a symptom of "Step 3" in the stepwise degradation of arid/semi-arid rangelands as described by Milton et al. [1994] is "perennial biomass reduced"). Milton and Dean (1995) refer to the fact that grazing reduces vegetation cover, doubling runoff, increasing evapotranspiration, and reducing plant biomass production by 75%, and a reduction by a factor of 1.4 for the CAY parameter may in fact underestimate this. Reducing the percentage of surface cover to 10% is also a likely consequence of severe overgrazing (as a symptom of "Step 4" in the stepwise degradation as described by Milton et al. [1994] is "bare ground"), and denudation of the ground surface. **Table 8** provides an example of how the parameters for degraded vegetation were derived based on the above for the Natal Mist Belt Ngongoniveld natural vegetation type. *ACRU* parameters to be changed for the simulation of runoff from degraded areas relative to natural conditions include the following monthly parameters, based on Schulze et al. (2007) as developed for Maloti Drakensberg Transfrontier Project (2007) using expert opinion:

- The water use (crop) coefficient (CAY) is reduced by a factor of 1.4, because overgrazed areas have less above-ground biomass, but with a minimum CAY value of 0.2 in any month;
- The interception loss per rainday (VEGINT), is consequently reduced by 50%;
- The coefficient of initial abstraction (COIAM[22]) is assigned a value of 0.10 for November to March (when thunderstorms occur), 0.15 for April, May and October and 0.20 for June to September, as a result of assumed trampling of grazing areas;
- The percentage litter/mulch (PCSUCO), is reduced to 10 % for all months of the year;
- The root colonisation in the subsoil (COLON), with reduced above-ground biomass, reduces to 60% in all months (**and reduced to 50% if already lower than 60%); and
- The fraction of surface cover protection is reduced and with the resultant enhanced sediment losses the COVER–factor is increased accordingly to 0.24 in all months and for all Veld Types.

Table 8: *ACRU* parameters used for the modelling of healthy (pristine) and degraded Ngongoniveld as an example (Acocks, 1988)

HRU	***ACRU* Parameter***	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Natal Mist Belt Ngongoniveld (Healthy/ pristine)	CAY	0.70	0.70	0.70	0.50	0.35	0.25	0.20	0.20	0.55	0.70	0.70	**0.70**
	VEGINT	1.50	1.50	1.50	1.30	1.10	1.10	1.10	1.10	1.40	1.50	1.50	**1.50**
	ROOTA	0.90	0.90	0.90	0.94	0.96	1.00	1.00	1.00	0.95	0.90	0.90	**0.90**
	COAIM	0.15	0.15	0.20	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.20	**0.15**
	PCSUCO	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	**73.4**
	COLON	60	60	60	60	60	60	60	60	60	60	60	**60**
	COVER	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03	**0.03**
Natal Mist Belt Ngongoniveld (Degraded)	CAY	0.50	0.50	0.50	0.36	0.25	0.20	0.20	0.20	0.39	0.50	0.50	**0.50**
	VEGINT	0.75	0.75	0.75	0.65	0.55	0.55	0.55	0.55	0.70	0.75	0.75	**0.75**
	ROOTA	0.90	0.90	0.90	0.94	0.96	1.00	1.00	1.00	0.95	0.90	0.90	**0.90**
	COAIM	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.10	**0.10**
	PCSUCO	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	10.0	**10.0**
	COLON	50	50	50	50	50	50	50	50	50	50	50	**50**
	COVER	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**	**0.24**

* Monthly values of average crop coefficients (CAY), interception loss (VEGINT, mm.rainday-1), fraction of roots active in the topsoil (ROOTA), coefficient of initial abstraction (COIAM, which determines infiltrability into the soil and is used to estimate the rainfall abstracted by interception, surface storage and infiltration before stormflow commences), percentage (%) of surface cover (mulch etc., PCSUCO) - the maximum evaporation from the soil can be suppressed by surface cover such as mulch, litter and surface rock, percentage root colonisation in the subsoil horizon (COLON), and cover factor (C) in M.U.S.L.E. (COVER).

Climatic data

The *ACRU* model was run using daily historical climate data from 1961 – 1999 (Lynch, 2004), which at the time of the study was the most readily available, consistent and quality controlled

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[22] an index of infiltrability of rainwater into the soil

dataset. It is recognised that the latest climate data have not been included in the model, but the available record is considered to be sufficiently representative of the catchment's climate, including periods of floods and droughts. Owing to the focus on EI, i.e. terrestrial HRUs such as grasslands, and to allow for more efficient running of the model, each sub-catchment was run individually, and results therefore derived and analysed for each. As explained above, the study focused on the quantification and mapping of two water-related ecosystem services, namely water supply (in the form of baseflow, surface runoff and total streamflow) and sediment yield.

Conclusion

There is a growing recognition that investment in ecological infrastructure through rehabilitation and responsible land management can improve delivery of ecosystem services, and thus create a strong platform for socio-economic development. This requires hydrological modelling at spatial and temporal scales which are adequate for planning to allow planners to align potential ecosystem service delivery with stakeholder needs.

The *ACRU* model was set up to map the delivery of water-related ecosystem services associated with three broad land cover types in the uMngeni catchment. We incorporated recent available land cover data into an existing catchment configuration, and set up the model to calculate components of runoff and sediment yield for each HRU in the catchment. The model incorporates hydrological feedback mechanisms, and responds to wet and dry spells in the rainfall record, thus proving extremely useful for identifying inter- and intra-seasonal catchment response characteristics. It is recognized that certain parameters have been updated between this version of the model and the validated version (Warburton et al., 2010). However, given the improvement in field-based and expert knowledge (e.g. Milton et al. 1994, Milton and Dean 1995, Bulcock and Jewitt, 2012) introduced in this version, we consider these changes to strengthen the model. We acknowledge the lack of direct field-based measurements for each type of land use, change and parameter. However, for a short-term, large-scale, comparative study such as this, we consider the model setup to be sufficiently reliable for water resource analysis.

The results of this modelling exercise are presented in Part 2 of this paper (*Mapping of water-related ecosystem services in the uMngeni catchment using a daily time-step hydrological model for prioritization of ecological infrastructure investment – Part 2: Outputs* (Hughes et al., 2018), which also discusses the identification of priority areas for each water-related ecosystem service within the catchment, and illustrates the useful contribution that can be made by detailed hydrological modelling towards achieving desirable socio-economic outcomes, such as the provision of a cleaner and more sustained supply of water to South Africa's people.

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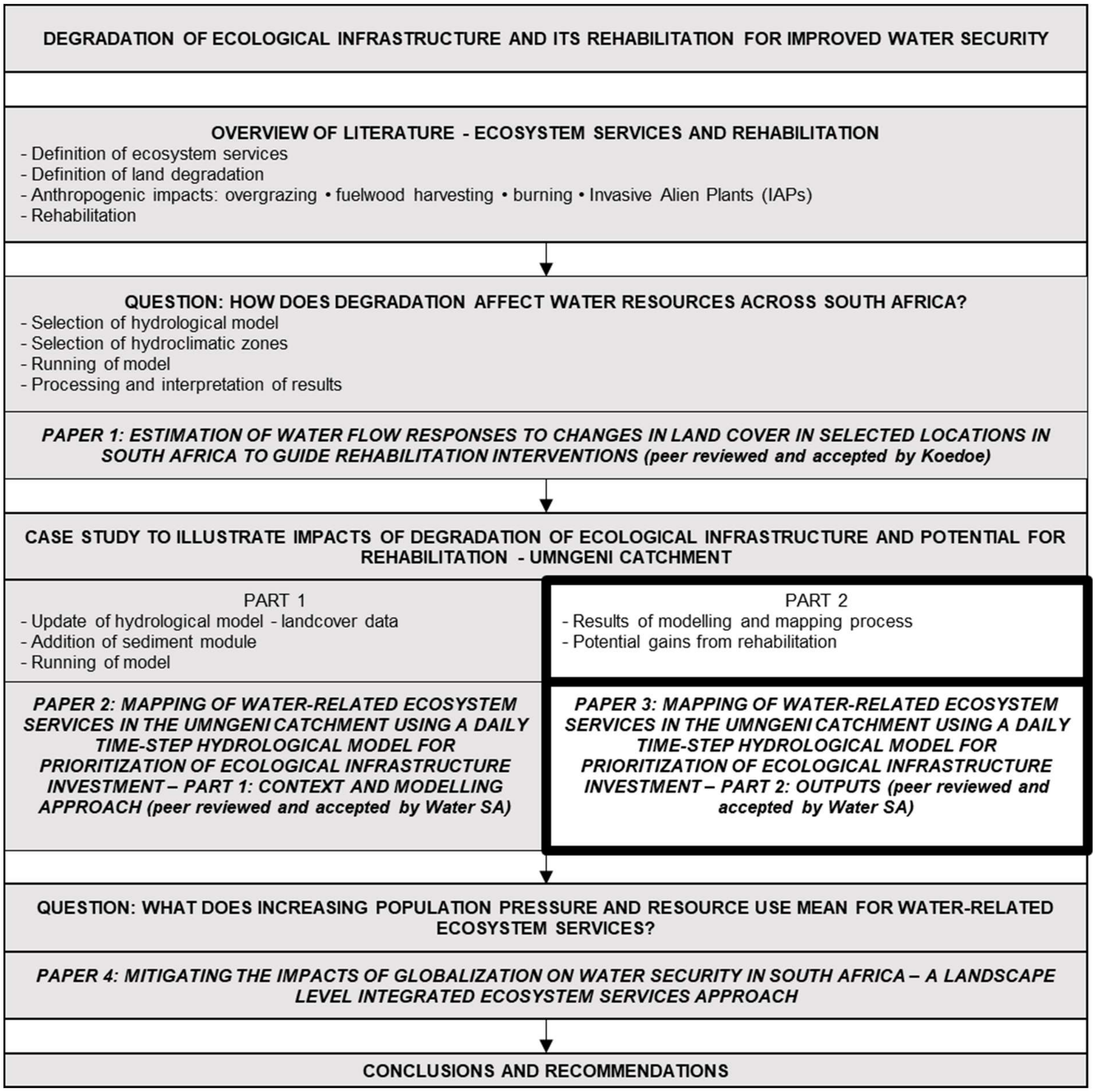
Appendix I

Table A: Monthly values of average crop coefficients (CAY), interception loss (VEGINT, mm.rainday^{-1}), fraction of roots active in the topsoil (ROOTA), coefficient of initial abstraction (COIAM, which determines infiltrability into the soil and is used to estimate the rainfall abstracted by interception, surface storage and infiltration before stormflow commences) and percentage (%) of surface cover (mulch etc., PCSUCO) - the maximum evaporation from the soil can be suppressed by surface cover such as mulch, litter and surface rock. These parameters are provided for the healthy (pristine) and degraded Ngongoniveld HRU as an example (Acocks, 1988), and for *Acacia mearnsii*. The *ACRU* model rules and hydrological attributes for overgrazed lands which were developed by Schulze et al. (2007) in the grasslands of KwaZulu-Natal and Eastern Cape for Maloti Drakensberg Transfrontier Project (2007), were used.

		Monthly values											
Land Cover	***ACRU* Parameter**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Natal Mist Belt Ngongoniveld (healthy/pristine)	CAY	0.7	0.7	0.7	0.5	0.35	0.25	0.2	0.2	0.55	0.7	0.7	0.7
	VEGINT	1.5	1.5	1.5	1.3	1.1	1.1	1.1	1.1	1.4	1.5	1.5	1.5
	ROOTA	0.9	0.9	0.9	0.94	0.96	1	1	1	0.95	0.9	0.9	0.9
	COAIM	0.15	0.15	0.2	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.2	0.15
	PCSUCO	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4	73.4
Natal Mist Belt Ngongoniveld (Degraded)	CAY	0.50	0.50	0.50	0.36	0.25	0.20	0.20	0.20	0.39	0.50	0.50	0.50
	VEGINT	0.75	0.75	0.75	0.65	0.55	0.55	0.55	0.55	0.70	0.75	0.75	0.75
	ROOTA	0.90	0.90	0.90	0.94	0.96	1.00	1.00	1.00	0.95	0.90	0.90	0.90
	COAIM	0.10	0.10	0.10	0.15	0.15	0.20	0.20	0.20	0.20	0.15	0.10	0.10
	PCSUCO	10	10	10	10	10	10	10	10	10	10	10	10
Acacia mearnsii	CAY	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	VEGINT	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
	ROOTA	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
	COAIM	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35	0.35
	PCSUCO	80	80	80	80	80	80	80	80	80	80	80	80


DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND ITS REHABILITATION FOR IMPROVED WATER SECURITY
OVERVIEW OF LITERATURE - ECOSYSTEM SERVICES AND REHABILITATION
- Definition of ecosystem services
- Definition of land degradation
- Anthropogenic impacts: overgrazing • fuelwood harvesting • burning • Invasive Alien Plants (IAPs)
- Rehabilitation
QUESTION: HOW DOES DEGRADATION AFFECT WATER RESOURCES ACROSS SOUTH AFRICA?
- Selection of hydrological model
- Selection of hydroclimatic zones
- Running of model
- Processing and interpretation of results
PAPER 1: ESTIMATION OF WATER FLOW RESPONSES TO CHANGES IN LAND COVER IN SELECTED LOCATIONS IN SOUTH AFRICA TO GUIDE REHABILITATION INTERVENTIONS (peer reviewed and accepted by Koedoe)
CASE STUDY TO ILLUSTRATE IMPACTS OF DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND POTENTIAL FOR REHABILITATION - UMNGENI CATCHMENT
PART 1
- Update of hydrological model - landcover data
- Addition of sediment module
- Running of model
PART 2
- Results of modelling and mapping process
- Potential gains from rehabilitation
PAPER 2: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 1: CONTEXT AND MODELLING APPROACH (peer reviewed and accepted by Water SA)
PAPER 3: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 2: OUTPUTS (peer reviewed and accepted by Water SA)
QUESTION: WHAT DOES INCREASING POPULATION PRESSURE AND RESOURCE USE MEAN FOR WATER-RELATED ECOSYSTEM SERVICES?
PAPER 4: MITIGATING THE IMPACTS OF GLOBALIZATION ON WATER SECURITY IN SOUTH AFRICA – A LANDSCAPE LEVEL INTEGRATED ECOSYSTEM SERVICES APPROACH
CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 5: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 2: OUTPUTS

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Keywords: water, ecosystem services, hydrological modelling, ecological infrastructure, rehabilitation

Abstract

South Africa is a semi-arid country which frequently faces water shortages, and experienced a severe drought in the 2016 and 2017 rainfall seasons. Government is under pressure to continue to deliver clean water to the growing population at a high assurance of supply. Studies now show that the delivery of water may be sustained not only through built infrastructure such as dams and pipelines, but also through investment in Ecological Infrastructure (EI).

Part 1 of this paper in 2 parts concentrated on the role of EI in delivering water-related ecosystem services, as well as the motivation for this study, and the methods used in modelling and mapping the catchment. Part 2 explores and illustrates the current level of delivery of water-related ecosystem services in different parts of the catchment, with potential hydrological benefits of rehabilitation and protection of EI in the uMngeni Catchment.

The Mpendle, Lions River, Karkloof, Inanda and Durban sub-catchments are important areas for the generation of streamflows which accumulate downstream (i.e. water yield in the catchment) when annual totals are considered. Modelled annual sediment yield (in tonnes) from naturally vegetated areas is most severe in the lower catchment areas with steeper slopes such

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as Inanda, and in the high altitude areas which have both steeper slopes and higher rainfall. The central and eastern parts of the uMngeni Catchment were found to contribute the greatest yield of sediment from degraded areas with low protective vegetation cover.

This combined modelling and mapping exercise highlighted areas of priority ecosystem service delivery, such as higher altitude grassland areas, which could be recommended for formal conservation, or protection under private partnerships. Generally, these areas confirm the intuitive sense of catchment stakeholders, but provide a robust and more defendable analysis through which water volumes are quantifiable, and potential investment into catchment interventions are justified.

Introduction

There is growing concern over the sustainability of water supply for various uses to the large economic centres of Durban and Pietermaritzburg in the province of KwaZulu-Natal (KZN) in South Africa. Southern Africa experienced a severe drought associated with an El Niño event in 2015/6, with exceptionally high temperatures and the lowest rainfall in 35 years in parts of the region, which has significant implications for water resources and for agriculture in particular – a key sector in KZN (SADC, 2016), and alternative methods of achieving water security are being sought.

This study is reported in two companion papers (Figure 1). Part 1 describes the setting up of a daily time-step hydrological model and land cover parameterisation (Hughes et al., 2018). The focus of this paper is to investigate which areas within the catchment currently supply high levels of water-related ecosystem service delivery, and will continue to do so if sustainably managed, as well as those areas which would provide the most significant service delivery improvements should they be rehabilitated. The key rehabilitation interventions could include grassland rehabilitation through improved management practices (livestock management, fire regime maintenance) and control of IAPs.

Materials and Methods

The methods used for hydrological modelling and mapping for the identification of priority areas for water-related ecosystem service delivery are described in full by Hughes et al. (2018) and summarised below.

Model setup

The *ACRU* (Agricultural Catchments Research Unit) model (Schulze, 1995 and updates), which has been developed and used extensively in the uMngeni catchment by the University of KwaZulu-Natal and others, was used to model and map water-related ecosystem services. *ACRU* is a detailed process-based, daily time-step hydrological model, which is able to operate at an appropriate spatial scale for catchment and sub-catchment level water resources planning.

The uMngeni catchment was delineated into 145 sub-catchments by Warburton et al., 2010) and their delineation was followed in this study (Hughes et al. 2018). These sub-catchments range in area from 37 to 11,000 hectares (i.e. 0.37 to 110 km^2), and are differentiated on the basis of soils, altitude, topography, land cover, water management practices and gauging stations within the uMngeni catchment. The sub-catchments were all grouped within 13 Quaternary catchments, largely aligning with the operational Quaternary catchments used by the South African Department of Water and Sanitation for water resource planning purposes (Figure 24, Part 1).

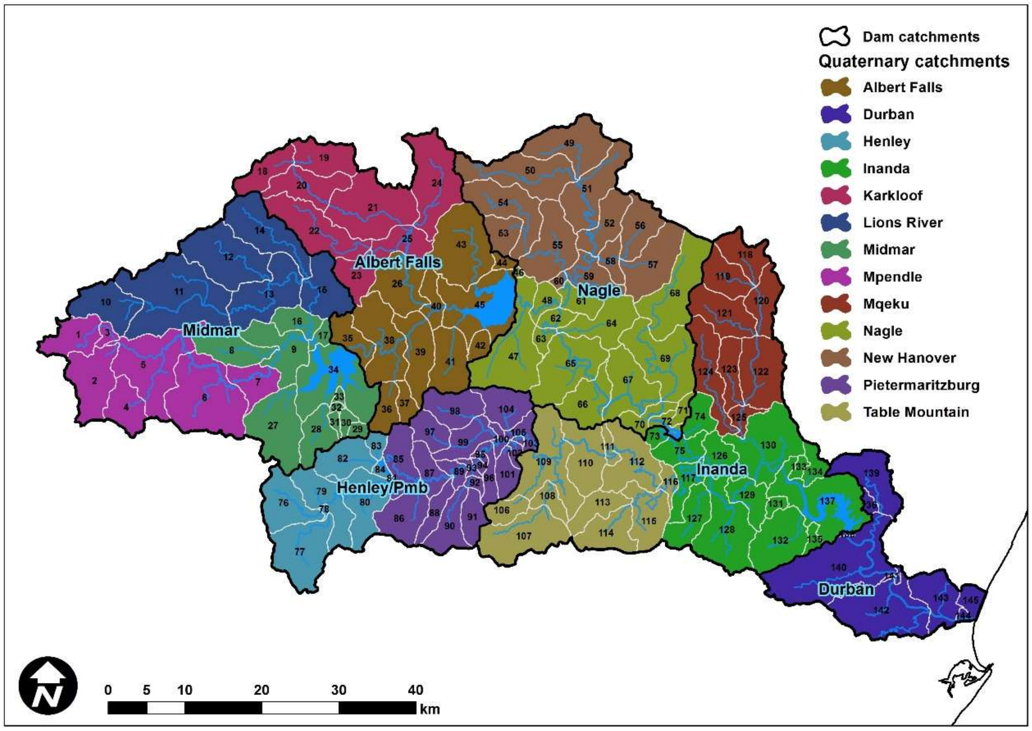

Figure 24: Catchments and sub-Catchments within the uMngeni catchment used for this study

Each of the 145 sub-catchments was, in turn, further sub-delineated into Hydrological Response Units (HRUs), primarily on the basis of discrete land cover types, including healthy natural vegetation, degraded lands and areas under IAPs. The 13 Quaternaries were further grouped into six "Dam" catchments to analyse different user groupings based on population clusters and areas supplied by each of the dams and, in turn, the demand for ecosystem services from EI within each Dam catchment. Daily time series outputs from the *ACRU* model allow the user to analyse the delivery of water-related ecosystem services for each HRU within the sub-catchments over time (See Part 1 of this study).

Selection of outputs

The *ACRU* model produces a daily time series of a wide range of outputs. These time series can then be analysed to assess and map water-related ecosystem services for each HRU within each catchment. The following outputs were selected for detailed analysis, with reasons for their selection also given:

- Runoff, which provides/supplies water within a year for domestic, industrial, ecological and recreational use, and is made up of the quickflow and baseflow from a sub-catchment (see below), and which when accumulated downstream is modelled and mapped as streamflow;
- Baseflow, which maintains water supply during dry periods and maintains water quality by dilution of excess nutrients and waste and/or sustaining the ecosystems that assimilate pollutants; baseflow is the water which has infiltrated through the soil layers to recharge to the groundwater store which then discharges into the rivers to sustains their flows, particularly during the dry season);
- Quickflow is the non-delayed stormflow, i.e. water available from the surface or near-surface on the same day as the rainfall event; much of this is captured by dams and sustains water supplies; and
- Sediment yield, which is the soil mobilised/eroded from the landscape portion of the catchment and deposited/transported in the channel portion of the catchment; high sediment loads can degrade river ecosystems and fill dams, reducing their storage capacity and reducing water security.

The potential improvements in water-related ecosystem service delivery following rehabilitation, were calculated from the difference between the quantity of water or sediment generated per hectare for each degraded HRU (overgrazed or IAP-infested), and that from the same HRU under un-degraded natural vegetation. The results were than summarised for each HRU within the catchment and represented spatially using GIS. Complete restoration to pristine natural vegetation is unlikely or impossible, but this does give an indication of the quantity of benefits and where they are the greatest.

Results and Discussion

Analysis of the land cover data indicated that the Inanda and Midmar Dam catchments have the highest proportion of healthy ecological infrastructure (i.e. intact grasslands, riparian zones, wetlands), covering approximately 60% of each respective area. The most transformed areas are Nagle and Durban. The relative presence of degraded vegetation and invasive alien wattle is highest within the Henley/Pietermaritzburg and Inanda Dam catchments (7%), according to the available dataset provided by Umgeni Water (see Part 1 of this study).

Dry-season Baseflow

Since there is a lag in baseflow response, the winter dry season lows are only apparent later in the year. Thus, the average volumes have been accumulated for the months of August, September and October, which is the dry winter season in this region. The most important sub-catchments for sustained, dry-season, baseflow delivery are the far west and higher altitude areas of the Mpendle and Lions River Quaternary catchments, as well as the lower areas of the Nagle and Inanda Quaternary catchments (Figure 25a). Conservation and/or maintenance of these areas could assist in the delivery of water supply to ecosystems and especially communities who are reliant on run-of-river abstractions throughout the year, i.e. the Ecological Reserve.

The overall volume of dry-season baseflow and delivery per hectare is highest from natural vegetation (Figure 25b), and much lower from degraded vegetation and IAP infested areas (Figure 25d&f). Owing to the loss of vegetation from the surface of degraded lands, interception and infiltration are reduced, and precipitation is likely to flow more directly off the surface as quickflow (see the next section), rather than infiltrating to the lower soil layers and becoming baseflow. In general, the model's simulation of higher water use by IAPs is consistent with other studies (Le Maitre et al., 2013; Everson et al., 2014), implying that less water is able to reach the lower soil layers, with the dry-season baseflow per hectare thus being lower (Figure 25f) than for natural vegetation (Figure 25b). However, as explained in Part 1, our assumption is that in their invasive form in the catchment, IAPs occur in stands that are less dense than those in managed plantations (as reported by Schulze and Schütte, 2014) and this is reflected in these results. Everson et al. (2014) found that wattle trees dried up the riparian zone entirely in their case study catchment, although this was in a small catchment entirely infested by wattles.

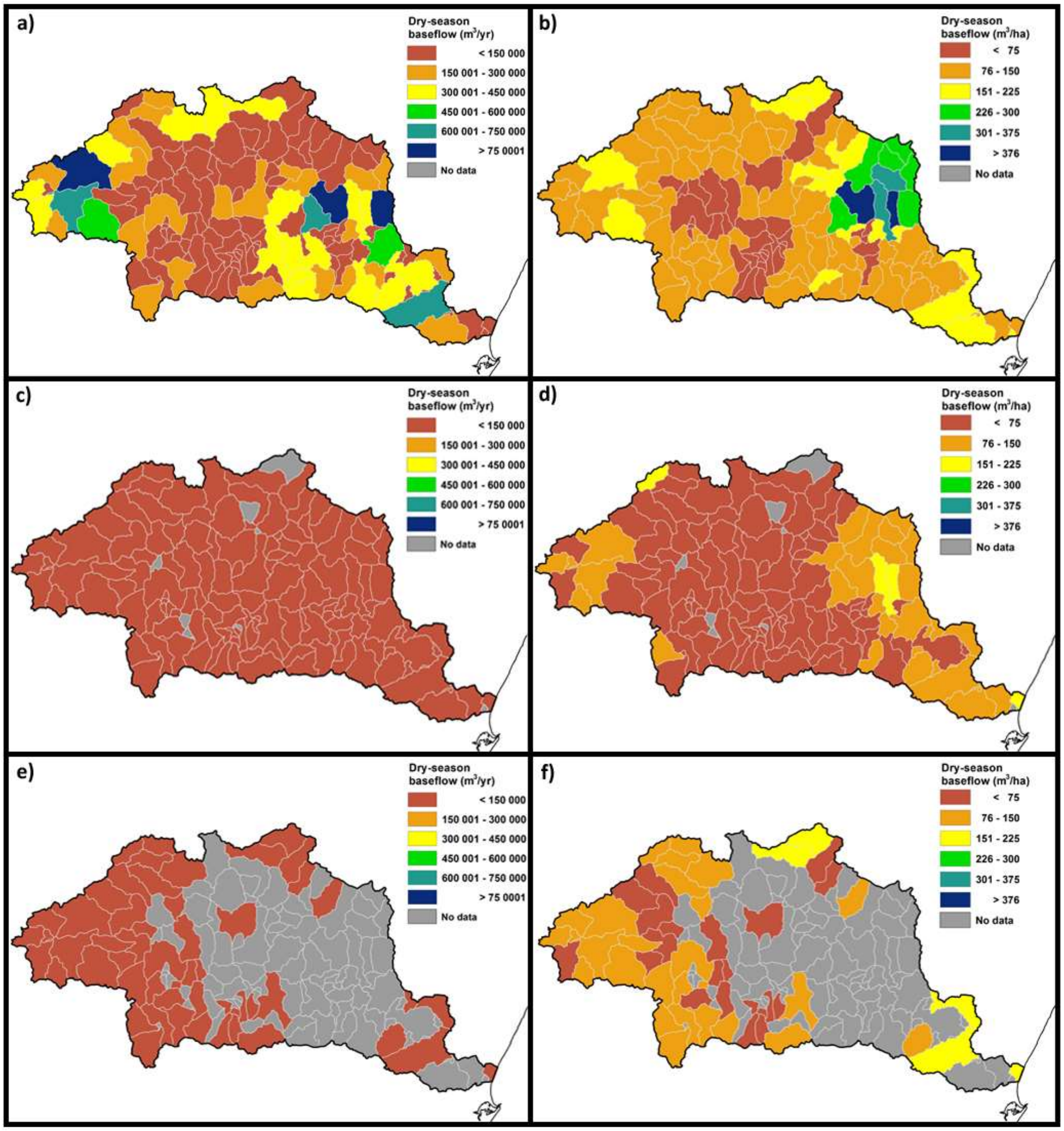

Figure 25: Average dry-season baseflows from 2011 natural vegetation a) in m^3/yr per HRU for each sub-catchment and b) in m^3/ha, from 2011 degraded vegetation c) in m^3/yr per HRU for each sub-catchment and d) in m^3/ha, and from 2011 invasive alien wattle e) in m^3/yr per HRU for each sub-catchment and f) in m^3/ha[23]

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[23] Catchments which are labelled with "no data" (greyed out) did not have areas of degraded vegetation or invasive alien wattle recorded on the land cover map.

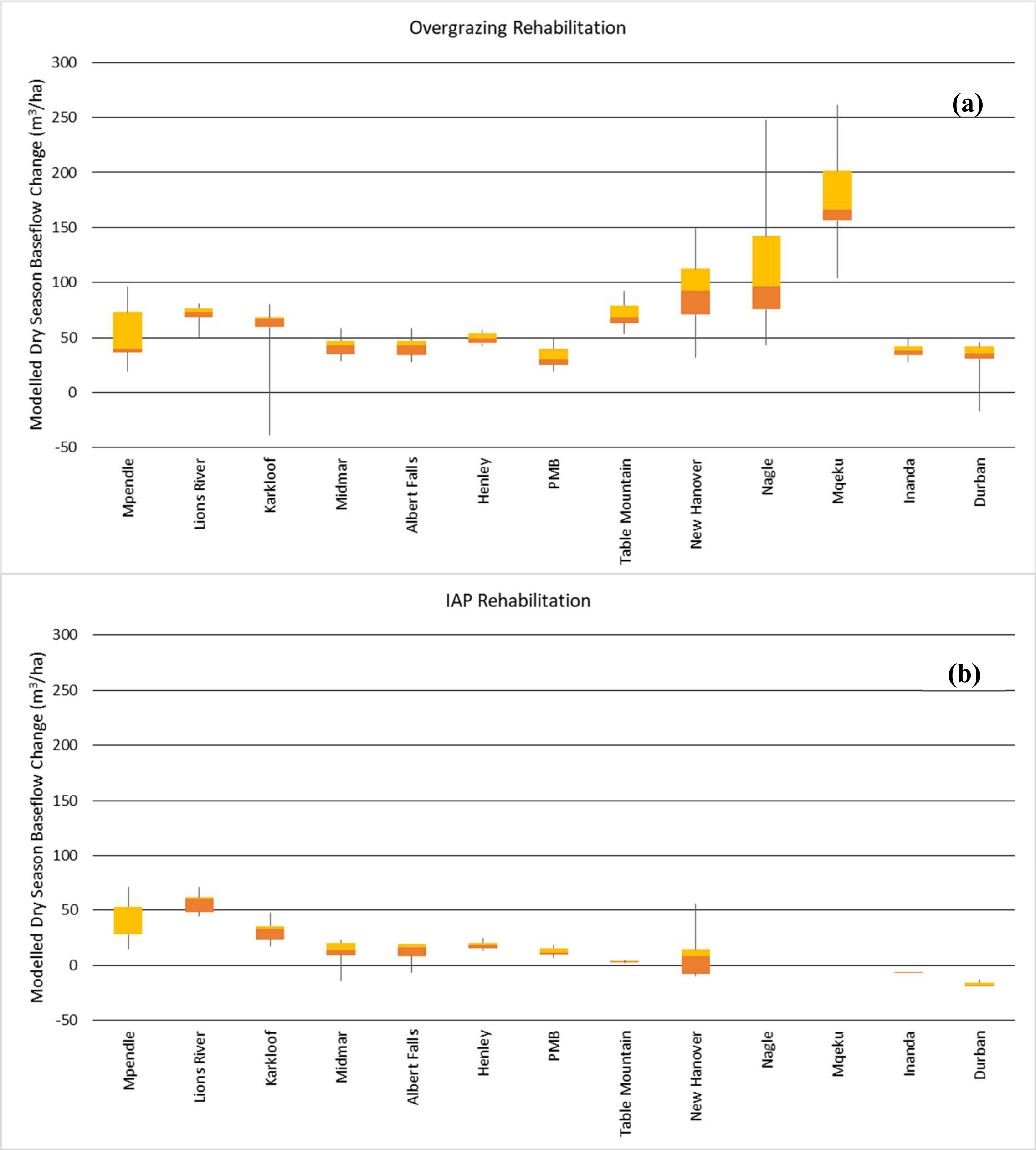

Figure 26: Box and whisker plots illustrating modelled changes in dry season baseflow per sub-catchment (m^3/ha) upon rehabilitation of overgrazed vegetation (a) and IAPs (b)

Following the hypothetical effective rehabilitation of the entire HRU to natural vegetation, the greatest benefits are to be gained in New Hanover, Mqeku and Nagle, which are in the lower altitude parts of the catchment (in the Savanna Biome), with a maximum potential gain of 260 m^3/ha during the dry season. Following the rehabilitation of IAPs, the largest modelled benefits are to be gained in the high altitude, north-western parts of the catchment, although it should be noted that the coverage of wattle trees in the catchment used for this study is mainly concentrated in this area. The maximum potential gain is estimated to be 260 m^3/ha (Figure 26).

Although the improvements in dry season baseflow volumes per hectare do not appear large, it is important to note the value of this ecosystem service. Dry season baseflow, i.e. the sustained flow of water during the dry season, ensures that there is adequate water supply for ecosystem function, as well as human users during the months in which rain does not generally fall (winter in the uMngeni catchment). Baseflow is vital for the health of the ecosystem in terms of maintaining ecological processes such as the provision of animal habitats and refugia, assimilation of pollutants and nutrient cycling (Bauman et al. 2007).

The effective rehabilitation of degraded grasslands implies that there is improved vegetation cover, which results in increased interception of precipitation, but especially higher infiltration of precipitation and then percolation into the lower soil layers. This allows for baseflow accumulation and recharge of the groundwater store, which contributes to the sustainability of dry season water supply.

Quickflow

Annual quickflow volume is particularly high in the steeper, higher altitude areas of Karkloof, Mpendle and Lions River where rainfall is relatively high (Figure 27a/b). It is also high in the lower parts of the uMngeni catchment such as in the Inanda and Durban Quaternaries, again where rainfall is relatively high. Important areas for quickflow generation are also located around the Albert Falls and Inanda Dams. This has implications, *inter alia*, for sediment delivery to these impoundments and loss of dam capacity, probably leading to an inability for dams to continue delivering water to a growing society in the long-term, as stated in Part 1 of this study. Regulation of quickflow volumes through preservation of a healthy vegetation cover not only reduces excessive sediment generation and associated loss of nutrients (Brauman et al. 2007), but can also prevent flooding and associated risk to life and infrastructure.

Quickflow is higher per hectare from degraded vegetation (Figure 27d) than from natural vegetation (Figure 27b), highlighting that areas which have been denuded of vegetation do not allow for adequate retention of precipitation through infiltration, and that water flows in greater volumes off the surface, potentially also resulting in soil erosion and soil nutrient losses. The modelling and mapping also indicate that invasive IAPs reduce quickflow from the surface when compared with natural vegetation (Figure 27f), potentially due to higher interception as well as higher transpiration rates resulting in surface soil moisture deficits which must first be replenished by rain before they lead to runoff, and higher canopy/litter interception.

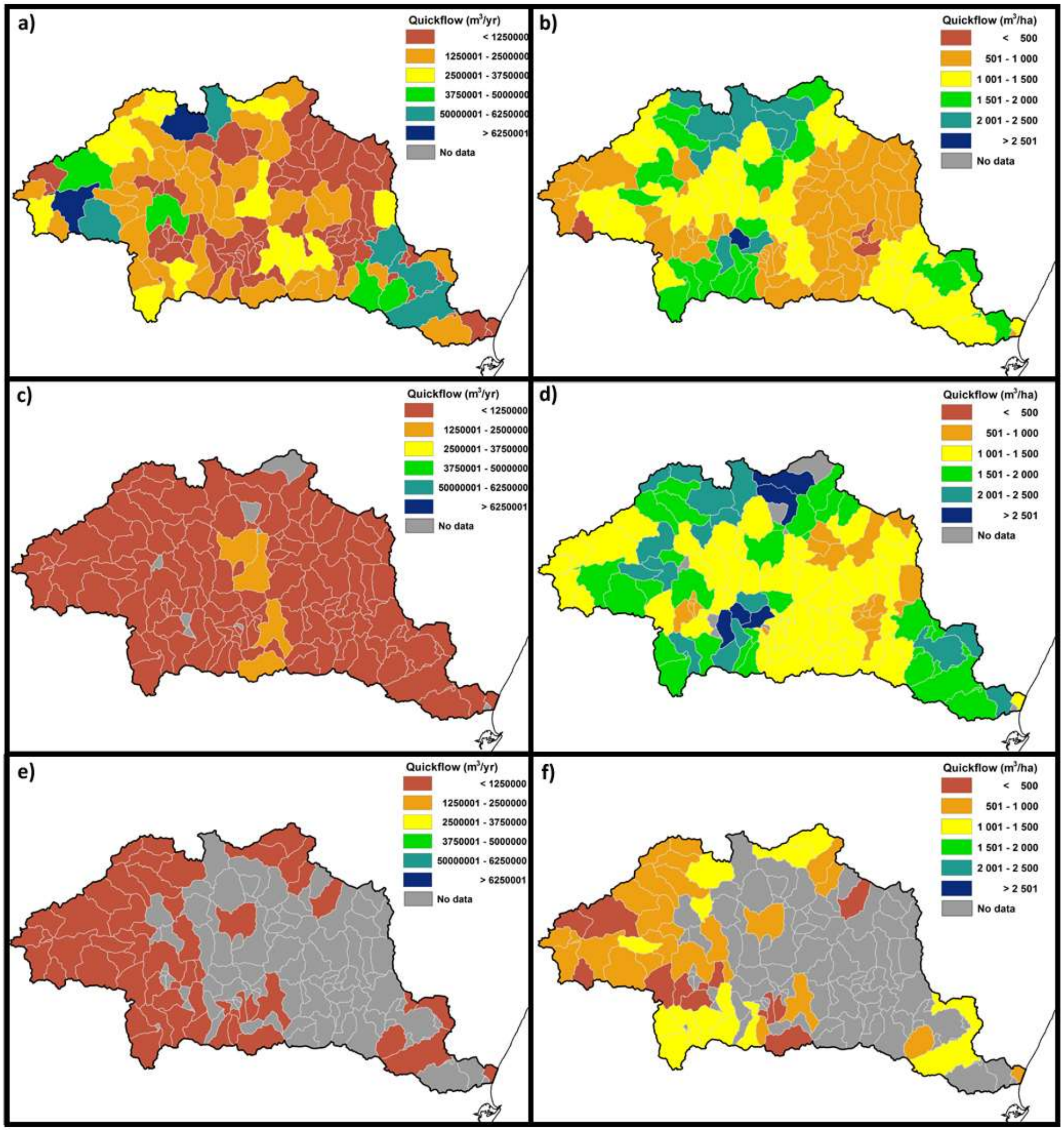

Figure 27: Average annual quickflow from 2011 natural vegetation, a) in m^3/yr per HRU for each sub-catchment and b) in m^3/ha, from 2011 degraded vegetation c) in m^3/yr per HRU for each sub-catchment and d) in m^3/ha, and from 2011 invasive alien wattle e) in m^3/yr per HRU for each sub-catchment and f) in m^3/ha

(a)

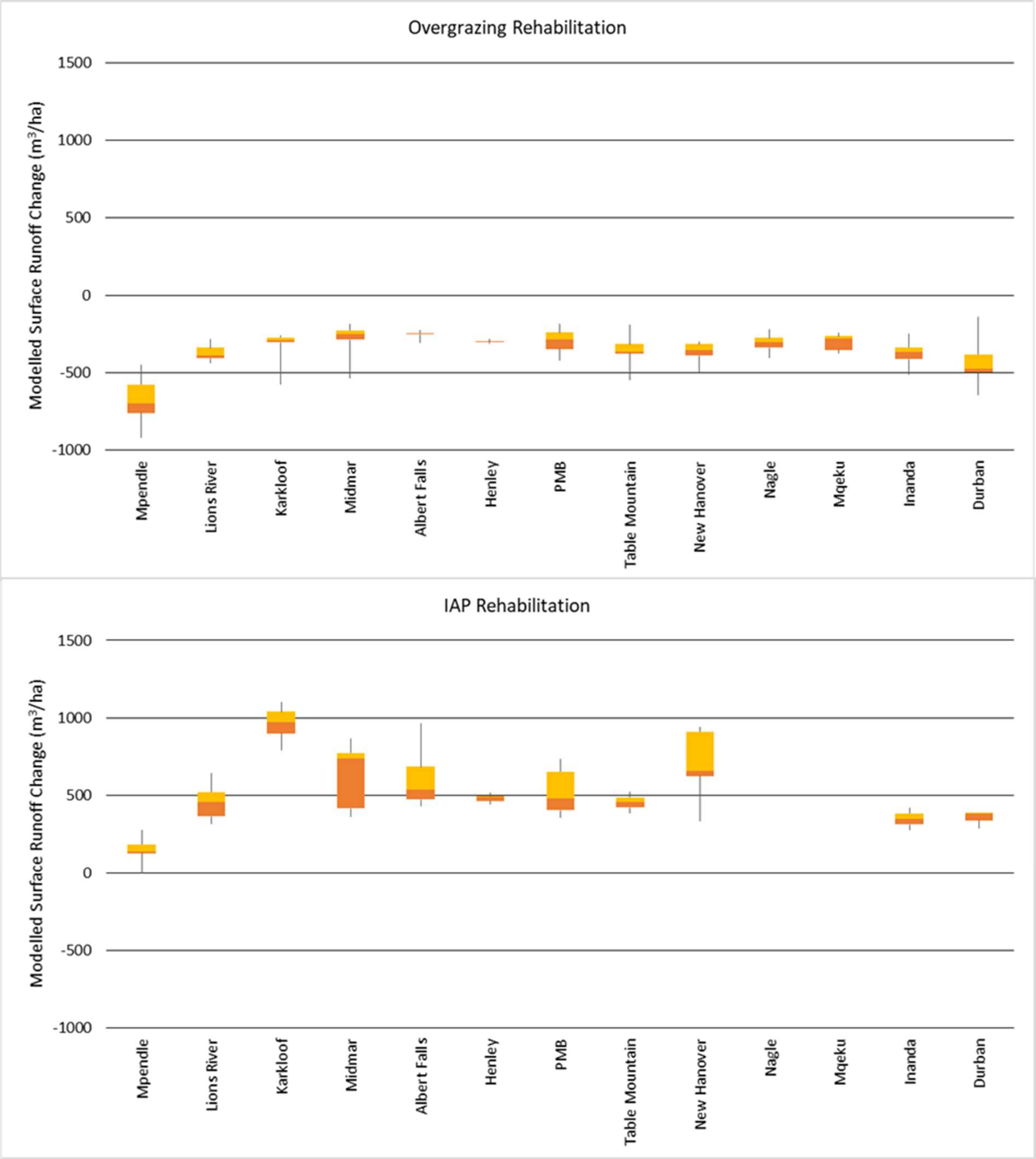

Figure 28: Box and whisker plot illustrating modelled changes in annual surface runoff per sub-catchment (m^3/ha) upon rehabilitation of overgrazed vegetation (a) and IAPs (b)

The amount of surface runoff increases with overgrazing due to the lack of vegetation, and as such, upon the rehabilitation of denuded areas the amount of surface runoff is reduced. This implies that upon rehabilitation, less precipitation will run off the surface, and more will be infiltrated and percolate to the lower layers of soil. The largest modelled reduction in surface runoff upon rehabilitation was found to be in the high altitude grassland areas of Mpendle (median value of 900 m^3/ha per year). Rehabilitation is furthermore likely to reduce the amount of high energy runoff from the catchment, and as such excessively high levels of sediment and nutrient mobilisation.

Rehabilitation of IAPs reduces the high rate of evapotranspiration, increasing the amount of available water and, in turn, the surface runoff (Figure 28b) by up to 1,100 m^3/ha per year. The greatest benefits are in the high altitude areas of the Karkloof catchment.

Streamflow

The streamflow exiting into the river channel at the outlet of each sub-catchment is an indication of the water that is available for use for ecosystem function, domestic use and drinking water or irrigation. In the *ACRU* model, streamflow is a combination of the volumes of baseflow and quickflow produced within a sub-catchment together with any runoff accumulated from upstream within a catchment based on the upstream to downstream sub-catchment flow paths.

As was the case for dry season baseflow and annual quickflow, the Mpendle, Lions River, Karkloof, Inanda and Durban Quaternary catchments are also important areas for the generation of accumulated streamflows when annual totals are considered (Figure 29a). The Pietermaritzburg and Henley catchments are also sources of higher streamflow generation per hectare (Figure 29b). Total streamflow volumes per month (Figure 29c) appear to be low for the degraded catchments. However, this is due to their small size, which is why it is also important to view the results on a unit area basis (per hectare) (Figure 29d). In certain parts of the uMngeni catchment, degraded vegetation provides a higher streamflow per hectare than healthy vegetation. However, the negative effects associated with higher quickflow from degraded vegetation (erosion, nutrient mobilisation, flooding risk) may outweigh the positive gains in streamflow. It may therefore be preferable to restore degraded vegetation to natural vegetation given the potential gains in baseflow and associated improvement in sustained water supply and quality during the dry-season.

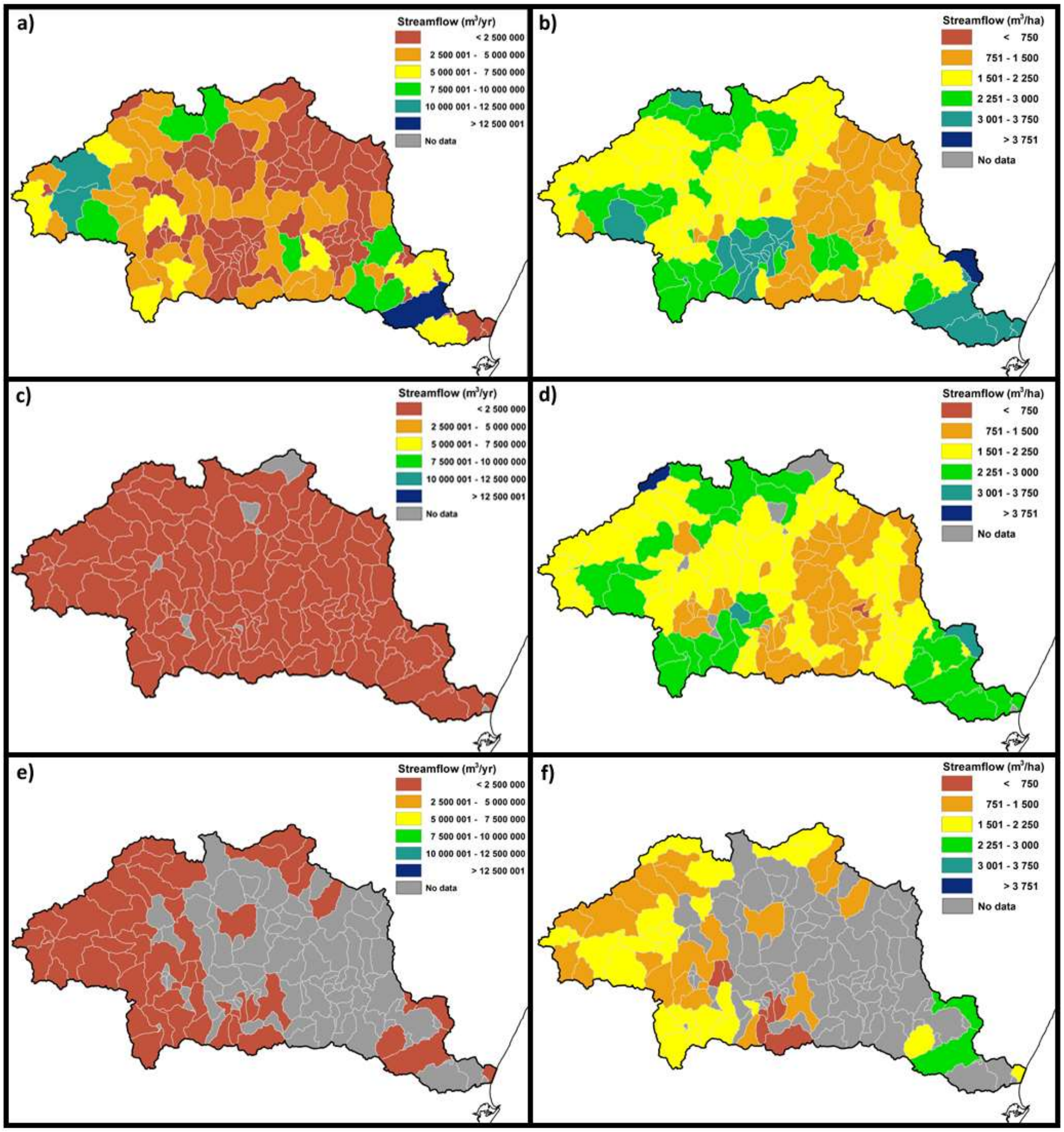

Figure 29: Annual average streamflow from 2011 natural vegetation, a) in m^3/yr per HRU for each sub- catchment and b) in m^3/ha, from 2011 degraded vegetation c) in m^3/yr per HRU for each sub-catchment and d) in m^3/ha, and from 2011 invasive alien wattle e) in m^3/yr per HRU for each sub- catchment and f) in m^3/ha

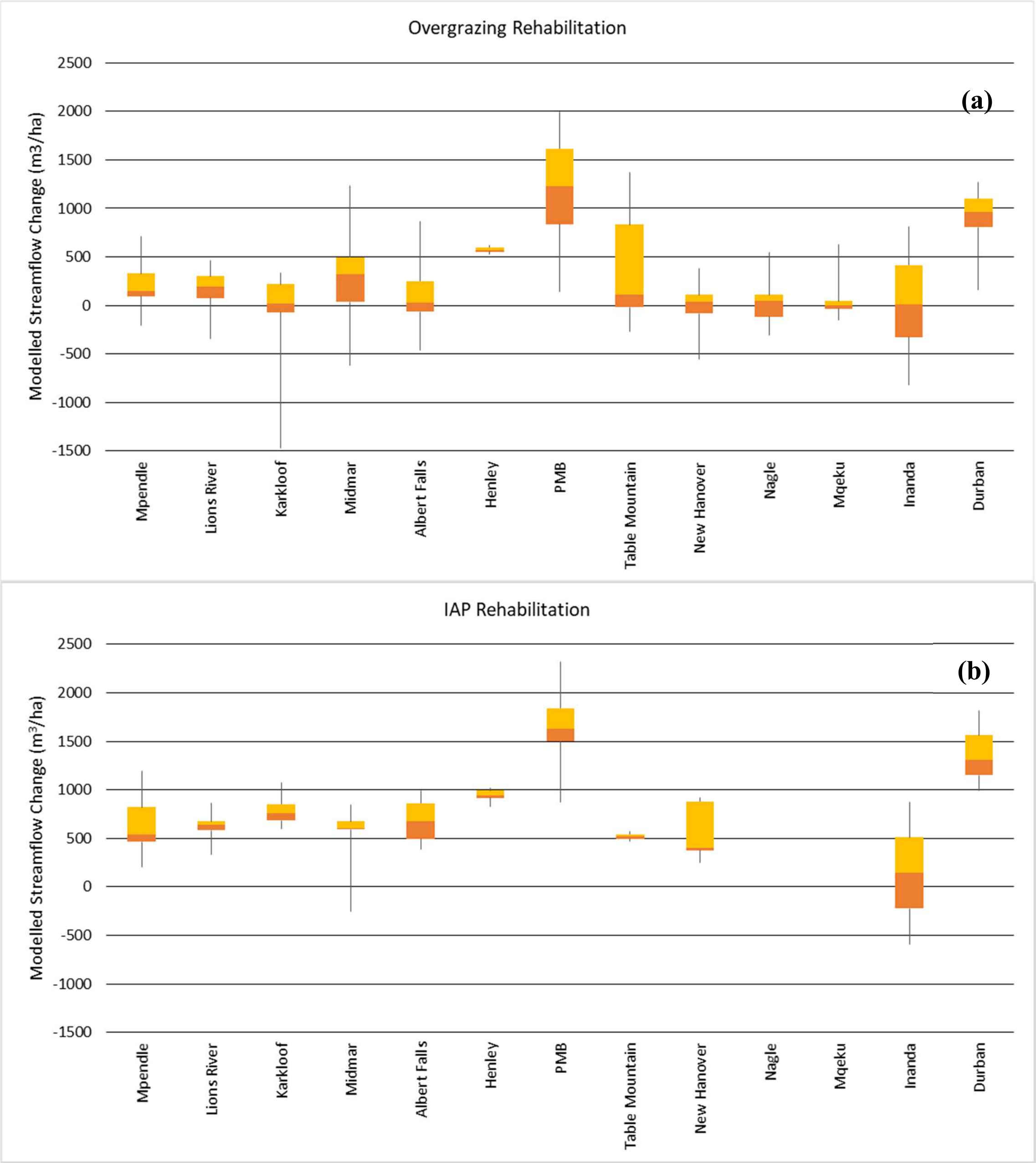

Figure 30: Box and whisker plot illustrating modelled changes in annual streamflows per sub-catchment (m3/ha) upon rehabilitation of overgrazed vegetation (a) and IAPs (b)

Owing to the high water use by woody IAPs, as well as the reduction in the amount of available water in the catchment due to overgrazing (mainly in the below ground layers of soil), the rehabilitation of these two forms of degradation is likely to result in an increase in overall water availability in the catchment. The greatest improvements in streamflow upon rehabilitation of overgrazed lands were found to be in the rapidly urbanising catchments around Pietermaritzburg and Durban (median values of around 1,000 m^3/ha per year, Figure 30). In terms of rehabilitation of IAP-infested areas, a similar pattern is evident, with a potential median increase of up to 1,600 m^3/ha.

Sediment yield

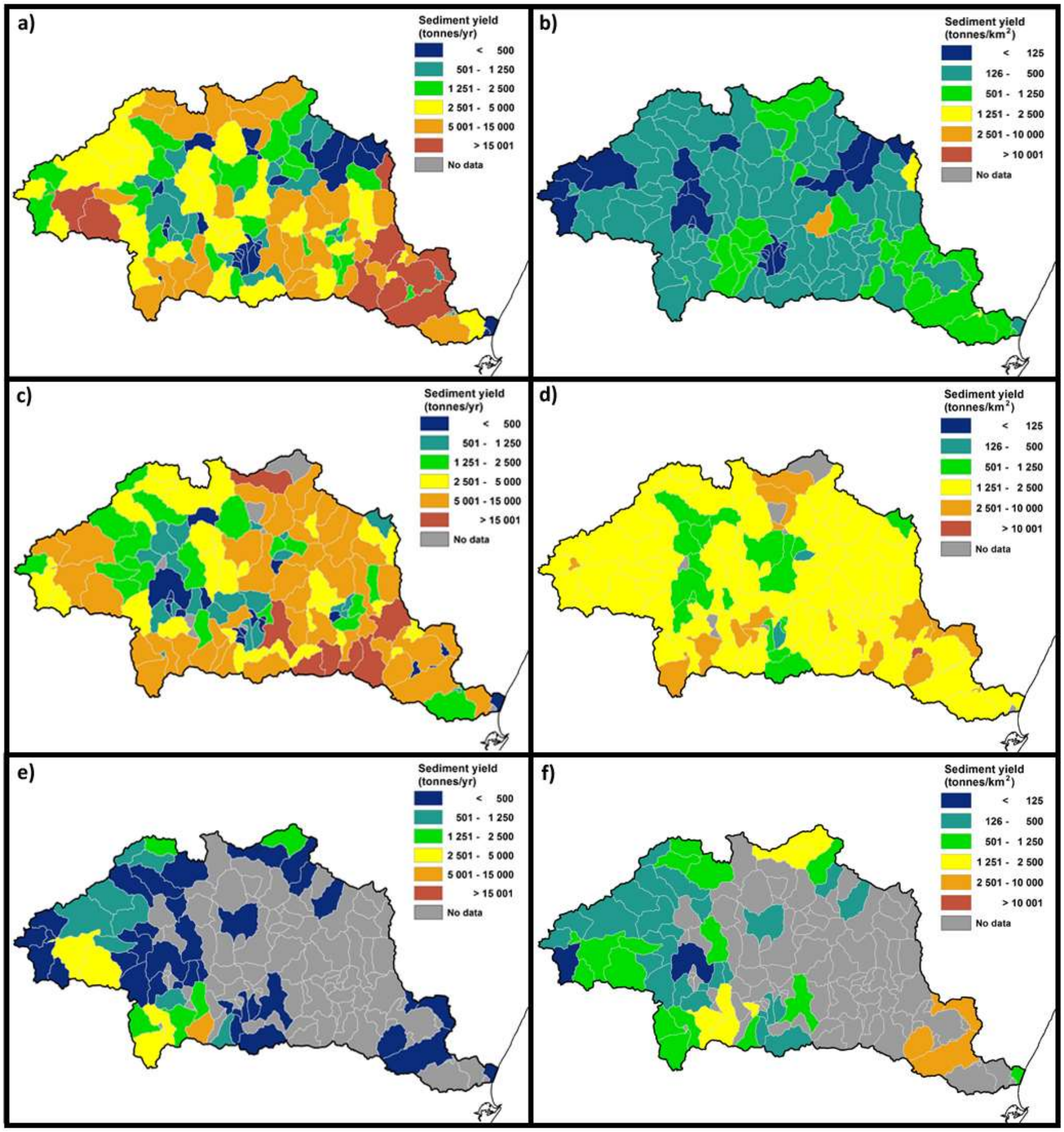

Figure 31: Annual average sediment yield (tonnes/yr) from 2011 natural vegetation, a) in t/yr per HRU for each sub-catchment and b) in t/km^2, from 2011 degraded vegetation c) in t/yr per HRU for each sub-catchment and d) in t/km^2, and from 2011 invasive alien wattle e) in t/yr per HRU for each sub-catchment and f) in t/km^2

According to Msadala et al. (2010), measured natural sediment yield values for KwaZulu-Natal vary between 30 tonnes/km^2 per year and 1,037 tonnes/km^2 per year. This large range is based on geological variations within the region, with varied land uses from cattle farming to sugar cane farming (Msadala et al., 2010). Most of the uMngeni catchment had previously been mapped as having high, very high or extremely high erodibility according to the Revised Sediment Yield Map of Southern Africa (Rooseboom et al., 1992) and Le Roux et al. (2008). Modelled annual sediment yield (in tonnes) with the *ACRU* model from naturally vegetated areas is most severe in the lower catchment areas with steeper slopes such as Inanda, and in the high altitude areas which have steeper slopes and higher rainfall (Mpendle - Figure 31a). The central and eastern parts of the uMngeni catchment were found to contribute the greatest yield of sediment from degraded areas with low protective vegetation cover (Figure 31c).

Degraded land (Figure 31d) produces considerably higher sediment yields per km^2 when compared with natural vegetation and wattle-infested lands. Sediment yield per unit area is particularly severe towards the lower part of the catchment, notably around the urbanising areas of Pietermaritzburg and Durban. Wattle-infested areas produce slightly higher sediment yield per unit area than naturally vegetated areas, according to the modelling results. This indicates that IAPs, while reducing quickflow overall in a catchment, also cause a drying of the upper soil layer and associated mobilisation of soils, leading to higher sediment yields (Dye and Jarmain, 2004). Furthermore, *A. mearnsii* trees have been found to leave little ground cover in dense invasive stands (van der Waal et al., 2012), which leads to a low lower basal cover - an important parameter in the Modified Universal Soil Loss Equation which is used within the *ACRU* model to generate sediment yields.

Based on the modelling results, the greatest reduction in sediment generation through rehabilitation of overgrazed land could be achieved near the coast, in the Inanda and Durban catchments (Figure 10; median reduction of approximately 6,000 tonnes/km^2). This is highly pertinent as this area is undergoing extensive transformation in terms of industry and residential developments, and it is important that the sediment and nutrient balance be maintained to ensure natural ecosystem functionality and the health of the estuary downstream (Adams et al., 2016; Cooper 1993). Upon removal of IAPs, benefits can be achieved, particularly in the coastal catchments, although these are not as high as those to be gained upon the rehabilitation of overgrazed lands.

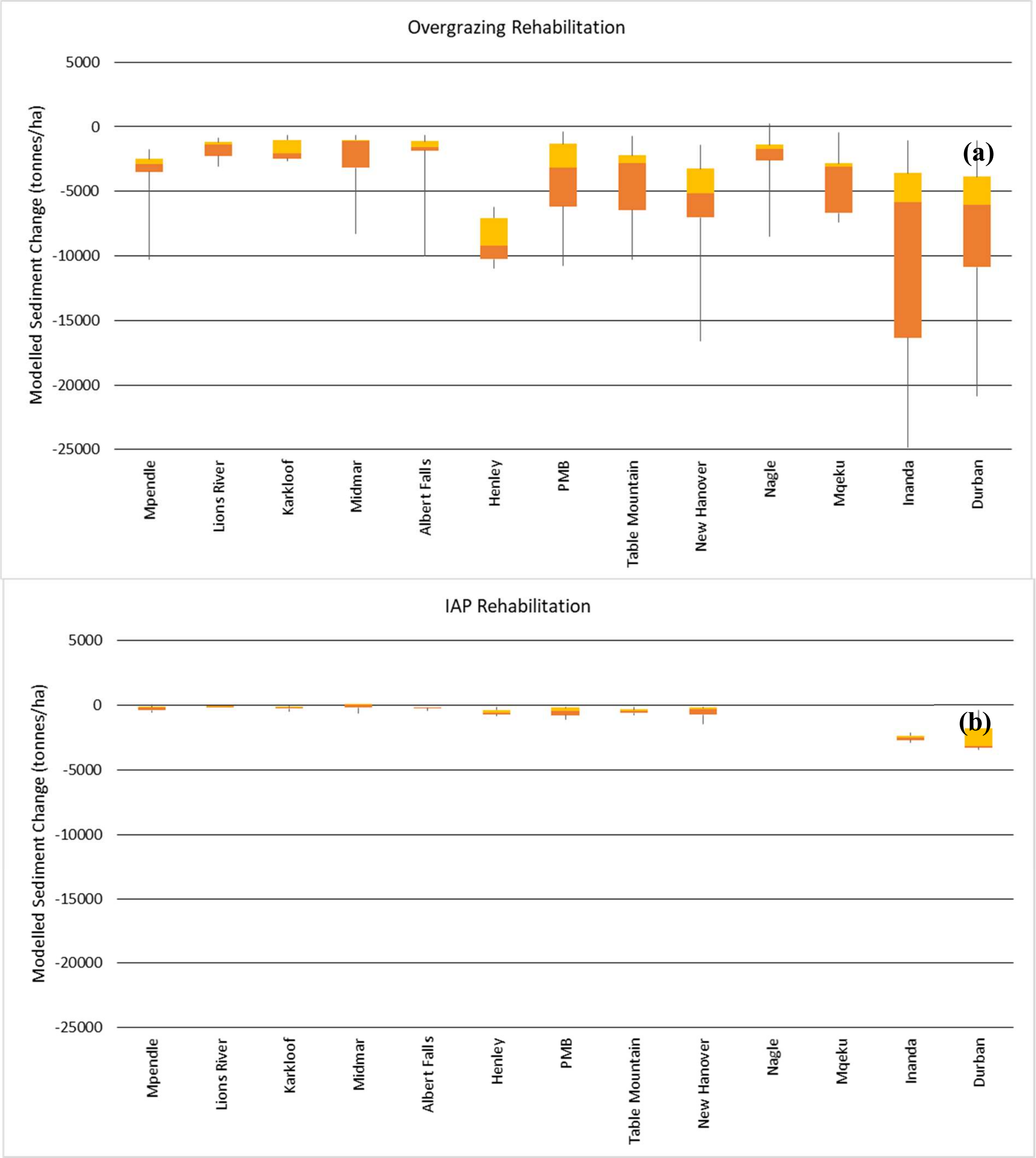

Figure 32: Box and whisker plots illustrating modelled changes in annual sediment yield per sub-catchment (tonnes/km^2) upon rehabilitation of overgrazed vegetation (a) and IAPs (b)

Limitations of the Study

The time and budget constraints did not allow for the explicit modelling of riparian zones and wetlands. In addition, the study was limited by the outdated spatial data related to the extent of

IAP infestations in the catchment, but we did use the most reliable data available at the time. These factors are likely to have resulted in an underestimation the reductions in flows due to IAPs and the impacts of factors like sedimentation and reduced baseflows on floodplains and the benefits of their rehabilitation..

Conclusion

Water resources researchers are seeking to establish whether healthy ecological infrastructure in water-stressed catchments can be used to augment water supply and to protect vulnerable water source areas from further degradation and transformation. This combined modelling and mapping exercise highlighted areas of priority ecosystem service delivery such as higher altitude grassland areas, which could be recommended for conservation through various mechanisms such as Biodiversity Stewardship or land partnerships. In many cases, these areas confirm the intuitive sense of those familiar with the catchment, but provide a robust and more defendable analysis through which water volumes are quantifiable. It is also important to view these results in conjunction with water demand information and to hold a thorough, inclusive stakeholder interaction process such that the true benefits of water-related ecosystem service delivery may be assessed, and appropriate steps be taken in policy and planning processes, as well as that more detailed return on investment analyses can be undertaken.

According to the modelling results, significant gains in terms of water-related ecosystem services can be made upon rehabilitation of overgrazed lands, and those which have been invaded by *Acacia mearnsii* in particular. Dry season baseflow in the catchment could potentially be increased by up to 260 m^3/ha for rehabilitation of overgrazed land (more than double), and accumulated streamflows by up to approximately 1,600 m^3/ha per annum (~80% increase for the sub-catchment). The results indicate that for dry season baseflow volume improvements, the rehabilitation of overgrazed land produces the best results. In terms of streamflow, the removal of alien plants is likely to improve the delivery of water to the catchment most effectively, and for the entire catchment could significantly increase the annual streamflow. Bearing in mind that the coverage used in this study underestimates the current extent of IAPs, the gains provided through rehabilitation may be even higher. Rehabilitation of overgrazed lands provides land managers with a far better chance of reducing excessive sediment generation within the catchment when compared to IAP clearing, which, however, could retain valuable nutrients and topsoil and prevent sedimentation of water courses, thereby extending the longevity of dams.

This study approach enabled us to spatially and quantitatively explore the primary, hydrological and ecosystem effects of overgrazing and IAP proliferation (as outlined in **Figure 18** in Part 1) within the uMngeni catchment. Comparisons were possible at both sub-catchment scale (for different land covers) and across the entire catchment, thus allowing potential investors in EI to make informed decisions across different scales. Informed by stakeholder needs, such a comparative and spatial approach is recommended for catchment-wide infrastructure and land use planning for the sustained delivery of sufficient clean water to society.

Acknowledgements

This work was funded and supported by the Development Bank of South Africa's Green Fund and the South African Department of Environmental Affairs. The final report for this project was compiled is Jewitt, et al. (2015), and this paper is drawn predominantly from Chapter 3 of this report. The authors wish to acknowledge the support for the wider project from the Water Research Commission through project K5/2354, the South African National Biodiversity Institute (SANBI), FutureWorks, Umgeni Water, the Institute of Natural Resources, Kevan Zunckel, members of the Centre for Water Resources Research at the University of KwaZulu-Natal and Ezemvelo KZN Wildlife.

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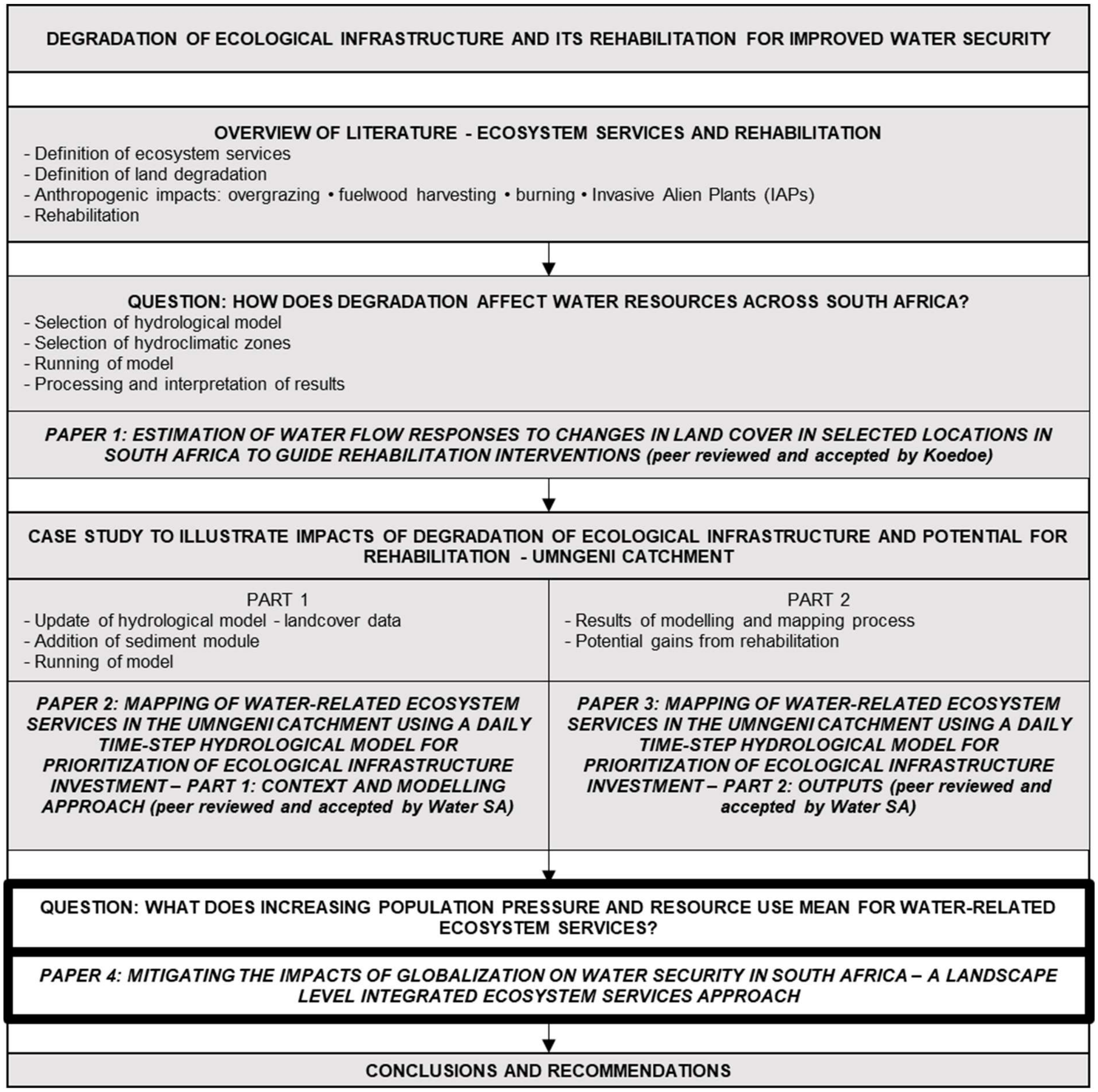
DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND ITS REHABILITATION FOR IMPROVED WATER SECURITY
OVERVIEW OF LITERATURE - ECOSYSTEM SERVICES AND REHABILITATION
- Definition of ecosystem services
- Definition of land degradation
- Anthropogenic impacts: overgrazing • fuelwood harvesting • burning • Invasive Alien Plants (IAPs)
- Rehabilitation
QUESTION: HOW DOES DEGRADATION AFFECT WATER RESOURCES ACROSS SOUTH AFRICA?
- Selection of hydrological model
- Selection of hydroclimatic zones
- Running of model
- Processing and interpretation of results
PAPER 1: ESTIMATION OF WATER FLOW RESPONSES TO CHANGES IN LAND COVER IN SELECTED LOCATIONS IN SOUTH AFRICA TO GUIDE REHABILITATION INTERVENTIONS (peer reviewed and accepted by Koedoe)
CASE STUDY TO ILLUSTRATE IMPACTS OF DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND POTENTIAL FOR REHABILITATION - UMNGENI CATCHMENT
PART 1
- Update of hydrological model - landcover data
- Addition of sediment module
- Running of model
PART 2
- Results of modelling and mapping process
- Potential gains from rehabilitation
PAPER 2: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 1: CONTEXT AND MODELLING APPROACH (peer reviewed and accepted by Water SA)
PAPER 3: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 2: OUTPUTS (peer reviewed and accepted by Water SA)
QUESTION: WHAT DOES INCREASING POPULATION PRESSURE AND RESOURCE USE MEAN FOR WATER-RELATED ECOSYSTEM SERVICES?
PAPER 4: MITIGATING THE IMPACTS OF GLOBALIZATION ON WATER SECURITY IN SOUTH AFRICA – A LANDSCAPE LEVEL INTEGRATED ECOSYSTEM SERVICES APPROACH
CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 6: MITIGATING THE IMPACTS OF GLOBALIZATION ON WATER SECURITY IN SOUTH AFRICA – A LANDSCAPE LEVEL INTEGRATED ECOSYSTEM SERVICES APPROACH

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Abstract

With South Africa's re-entry into the global markets post-apartheid, the trend of globalization has led to increased urbanization. This has in turn influenced the size and impact of the economy's ecological footprint. Environmental degradation in and around the country's urban and peri-urban centres due to population and economic growth has direct impact on the health of its natural systems, the delivery of water-related ecosystem services, and ultimately water security.

The uMngeni catchment provides the setting for a national Strategic Integrated Project, one of several linked projects outlined in South Africa's National Infrastructure Plan (2012), which will have concomitant associated increased trade and industry impacts. A DBSA Green Fund project carried out under the uMngeni Ecological Infrastructure Partnership (Chapters 4 and 5) provides a case study that illustrates the potential value of rehabilitation for improved water security in important catchments which are targeted for development. As the study indicates, enhancing stakeholder frameworks at a catchment scale, as well as integrated hydrological modelling to identify key areas for rehabilitation, can help maintain the resilience of water-related ecosystem service delivery by ecological infrastructure – securing water quality and quantity for people, animals and ecosystems.

A discussion is provided on globalization and urbanization which aims to bring together previous studies to illustrate the importance of ecological infrastructure in providing resilience to ecosystems and society in the face of globalization.

Keywords: South Africa, Ecological Infrastructure, Water security, Globalization, Urbanization, Catchment, Ecosystem Services.

Introduction

Globalization is defined as "the act or process of globalizing: the state of being globalized; especially: the development of an increasingly integrated global economy marked especially by free trade, free flow of capital, and the tapping of cheaper foreign labor markets" (Merriam-Webster 2017). Globalization is therefore framed within four processes: trade and transactions, capital and investment movements, migration and movement of people, and the dissemination of knowledge (IMF 2017). Furthermore, there is a strong element of deregulation: Harper Collins (2012) define globalization as the "process enabling financial and investment markets to operate internationally, largely as a result of deregulation and improved communications." This is similar to the concept of neoliberalism, which refers to an economic system in which there is widespread adoption of the "free" market, often facilitated by policies such as cutting trade tariffs and barriers (Birch 2017). Al-Rodhan (2006) emphasizes the outcome – the global market can be free from political or social control.

When South Africa was re-integrated into the global economy after sanctions were lifted in 1994, there was a marked growth in the economy and in particular, industrialization (Green 2009). The "KOF" Globalization Index[24] incorporates three main dimensions, i.e. economic integration, social integration, and political integration, and indicates that globalization does indeed promote growth (Dreher 2006). South Africa's KOF Globalization Index (2017) rose from below 40 in 1993 to above 60 in 2003 and is now the third highest in Africa. As such, globalization is playing an increasing role in the development of South Africa. This has resulted in growth in the tourism, telecommunications and the financial services sectors.

Referring to the IMF definition above (2017), the impacts of globalization on the environment can most obviously be linked to the "migration and movement of people". As people migrate to urban and peri-urban centres to take advantage of (or merely to seek) job opportunities, there is an increase in development from a residential, service provision and industrial perspective,

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[24] Developed by Axel Dreher at the Konjunkturforschungsstelle of ETH Zurich, in Switzerland (Dreher 2006)

which places heavy pressure on natural resources such as water, soil for agricultural products and land for livestock. The sustainable delivery of ecosystem services to support South Africa's rapidly urbanizing communities is highly dependent on healthy natural capital, or Ecological Infrastructure (EI). EI is defined as "naturally functioning ecosystems that produce and deliver valuable services to people" (Jewitt et al. 2015). Importantly, in a water-scarce country like South Africa, the water-related ecosystem services provided by EI are vital. These include water supply and purification, sediment and nutrient balance, recreation and cultural uses, and flood and drought attenuation.

Less tangible but equally important is the growth of trade under globalization, including manufacturing of goods and use of energy, which implies the increased exploitation of raw materials and fossil fuels, and for which large-scale transformation of the wider environment is often required, placing additional pressure on EI. The deregulation of markets can also lead to more diverse opportunities for manufacturing, services and trade, which is likely to expand requirements for natural and human resources. Environmental issues which have been linked with globalization (e.g. unsustainable fishing and climate change) are often considered to be inadequately addressed due to the lack of regulation of the global market (Sonnenfeld and Mol 2002). Becker (2005) and Ehrenfeld (2003) conclude that a higher overall index of globalization implies an increased ecological footprint of consumption, exports and imports (Najam et al. 2007).

Urbanization impacts on South Africa's EI

Concurrent with globalization, there is a trend of urbanization (Carmody and Owusu 2016). This process is not only driven by the migration of work seekers and densification of residential areas, but also by the location of industries near trade ports and transport networks. The increased use of space both vertically and horizontally within existing urban areas and new developments, accompanied by an increased population and number of buildings, leads to increasing pressure on existing infrastructure and service delivery, ranging from water and sanitation to transport and communications (Schäffler and Swilling 2013), and a concurrent increased reliance on existing EI.

Much of South Africa's traditionally rural population is migrating to the large cities of Johannesburg, Pretoria, Cape Town and Port Elizabeth (United Nations, Department of Economic and Social Affairs, Population Division 2014; Figure 33). The urbanization trends in South Africa are reportedly higher than those for the southern African region, and are furthermore higher than average urbanization rates in the rest of Africa ("SA population flocking to cities" 2014).

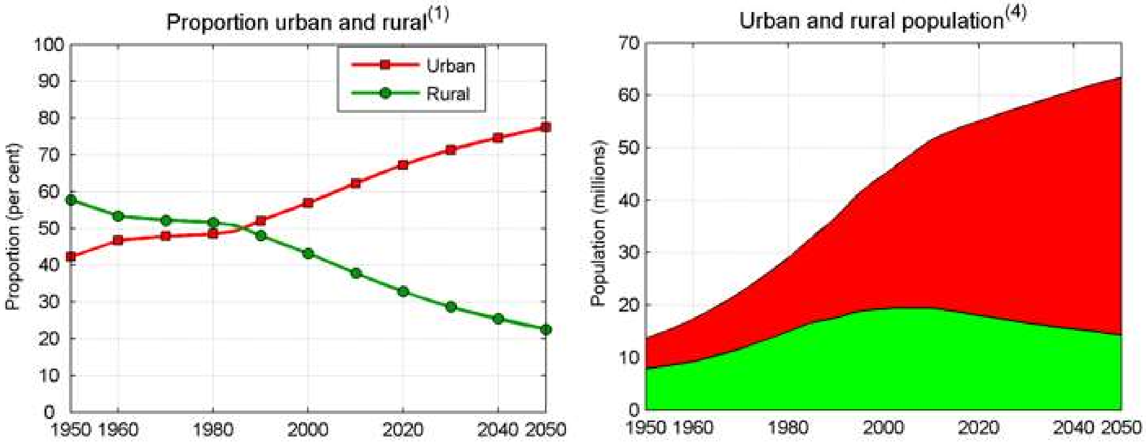

Figure 33: South Africa's urbanization profile (United Nations, Department of Economic and Social Affairs, Population Division, 2014)

The increasing number of people in South Africa's urban and peri-urban areas, and their need for raw materials and energy, has had a severe effect on EI in the country, with more and more land being cleared for agriculture, mining, manufacturing and residential properties. This has resulted in permanent impacts on functioning natural systems such as grasslands, natural forests, wetlands and riparian zones, as well as numbers and diversity of organisms, ranging from microscopic invertebrates to megafauna.

The traditional cultural value of cattle as an indication of wealth is an important factor which adds to the pressure of increased peri-urban populations on natural resources in South Africa (Salomon et al. 2014). Although overgrazing occurs throughout the country, it has been a notable feature of lower income areas of South Africa for many years, particularly due to the inequalities of land distribution during the apartheid era (in which previously disadvantaged communities were often limited to making use of less productive agricultural lands), the effects now being referred to as "environmental apartheid" (Stull et al. 2016).

Steffen et al. (2006) explore human influences as a “complex hierarchical cascade of drivers from proximate to ultimate”. An example is the clearing of land for agricultural practices (proximate driver), which has resulted from an ultimate/underlying driver of demand for food, recreation etc.; or fossil fuel burning (proximate driver) which has come about as a consequence of a demand for mobility, consumer products, etc. These underlying/ultimate drivers are almost certainly a consequence of globalization – all of which lead to transformation of the Earth and impacts on ecosystem services. Table 9 further explores some of the proximate and ultimate drivers (Steffen et al. 2006) of land degradation caused by globalization and urbanization.

Table 9: Proximate and ultimate drivers due to urbanization and the associated impacts on ecosystem services (adapted from Ngcobo and Jewitt 2017)

Theme	Proximate drivers	Ultimate drivers	Ecosystem service impact/response
Increased populations in urban and peri-urban areas	Land clearing and overgrazing	People in search of employment, urban lifestyle, consumption	• Increased stormflow from roads, roofs, disruption to ecological corridors • Increased vulnerability to floods and droughts • Overgrazing and cattle pathways - Erosion, topsoil and sediment-bound nutrient loss, increased sedimentation (see Chapter 2, Moore 2001, Snyman and Du Preez 2005, Pettersson et al. 1988, Peden 2005). • Eutrophication (Nlela et al. 2016) • Disrupted soil profile (stability and structure) • Poor water quality due to waste, spills and overflows, as well as leaks and non-revenue water due to failing/aging infrastructure • Loss of water storage capacity in dams (Jaiyeola 2016)
	Disruption of wetlands, grasslands, riparian zones (by humans and livestock)		
	Residential and industrial development – poor or inadequate sewerage and stormwater infrastructure		
	Chemical and waste pollution		
	Non-sustainable harvesting of indigenous plants and animals		• Loss of viable indigenous populations of plants and animals • Potential loss/failure of traditional indigenous knowledge and resources • Loss of genetic diversity, inbreeding, extinction • Disruption of predator/prey relationships
Increased trade	Construction of infrastructure corridors	Increasing manufacturing/economic growth	• Increased stormflow from roads, roofs • Disruption to ecological corridors for species movement
	Opportunity for invasive species spread (see Chapter 2, Moran et al. 2013, Richardson and Rejmánek, 2011)		• Disruption of indigenous species' ecological processes and increased water use by woody IAPs
Transformation of ecological infrastructure	Land clearing (e.g. forest/grassland clearing and cutting, see Chapter 2	Increased demand for agricultural produce/forestry products	• Increased sedimentation • Poor water quality

	and definition of “land degradation” below)	to supply human needs – often driven by volatile international markets (Meyfroidt et al. 2013)	• Lower infiltration (Le Maitre et al. 2007), reduced baseflow (and water supply during the dry season) • Disruption of pollination processes • Disruption of natural purification processes (by algae etc.) • Disruption of natural food chain • Reduced flood attenuation (protection of human life through natural wetland and riparian zone buffering)
	Increased demand for raw materials and natural resources for processing	Increased demand for minerals	
	Stormwater/irrigation management/dam building/inter-basin transfers	Increased requirement for access to water (under an unpredictable climate)	• Decline in available, good quality water resources • Disruption of natural ecosystem service provision by existing systems, and flows

The impacts of globalization and urbanization on EI in South Africa can further be explored through an adaptation of Noss’s illustration of the interconnected nature of natural systems at four levels of organization, (i.e. “biodiversity”, Noss 1990). Development associated with globalization and urbanization transforms the functional, structural and species composition of ecosystems in a variety of ways which are expanded upon in Figure 3. Ecosystem services delivered by EI (such as water production) to support urban populations are often located beyond the city and at a landscape scale, operating therefore at the levels of community-ecosystem and regional landscapes – both of which can be significantly influenced by the effects of globalization through urban expansion and large-scale exploitation of natural resources. Examples of these impacts include the establishment of agricultural farmlands to support livestock to feed city residents (which includes large-scale transformation of natural vegetation), the spread of Invasive Alien Plants (IAPs) through increased road networks and trade mechanisms from foreign countries, and the destruction of EI (wetlands, grasslands) for residential and industrial expansion.

The disruptions to ecosystem services caused by globalization and urbanization as explored in Figure 3 and Table 9 can result in the need for humans to take action to provide these services in other ways. These could include construction of flood barriers, dredging to remove sediment from dams, or installing expensive facilities to ensure security of water supply, and/or treat water to potable standard. The alternative to these, often costly, anthropogenic actions is that society can attempt to rehabilitate natural systems to reinstate ecosystem service delivery, such as rehabilitating wetlands to improve flood attenuation capacity, and reinstating natural populations of microorganisms to encourage natural processes of waste dilution and water purification. It is however important that, when planning rehabilitation interventions, society focuses on restoring the *functionality* of the ecosystem to ensure the persistence of ecosystem services (ultimately aiming for restoration rather than just rehabilitation - see Bradshaw 1996, Chapter 2). Rehabilitation of structural and compositional aspects (Figure 3) are part of this process, but rehabilitation goals should not only focus on these – functionality needs to be reinstated to ensure that ecosystem service delivery persists.

Mitigating globalization impacts on the environment

Many of the drivers of globalization's environmental impacts can be ascribed to the lack of a global regulatory framework to manage the use of ecological resources across countries, political systems and cultures in a vast 'tragedy of the commons' scenario (Hardin 1968). Mechanisms such as the Millennium Development Goals (the MDGs, which were aimed at reducing poverty in developing countries), and the Sustainable Development Goals (SDGs), which are aimed more at social, economic and environmental sustainability (Spaiser et al. 2017, Loewe 2012) aim to drive the global development and equality agenda. These can often lead to some exhibit of global unity, and the MDGs have seen some success. However, the success of the SDGs, adopted in 2016, remains to be seen (Solberg 2015), and some critics have expressed the opinion that the SDGs present a direct conflict of interest between human/economic growth and the resilience of the natural environment (Spaiser et al. 2017). It is therefore worth considering how one can develop an approach to managing overarching ecological degradation by addressing those drivers at a wider scale. River catchments which cross man-made borders provide useful case studies to explore the potential interventions for building resilience against the national and global negative consequences of globalization, such as lack of water security[25], poor resource use regulation, urbanization impacts, migration and associated ecological consequences.

The broader goals, model and implications of a catchment-scale demonstration project located within the uMngeni catchment (spanning metropolitan, local and district municipalities) which aimed to ensure water security for the catchment's people is explored in the following sections.

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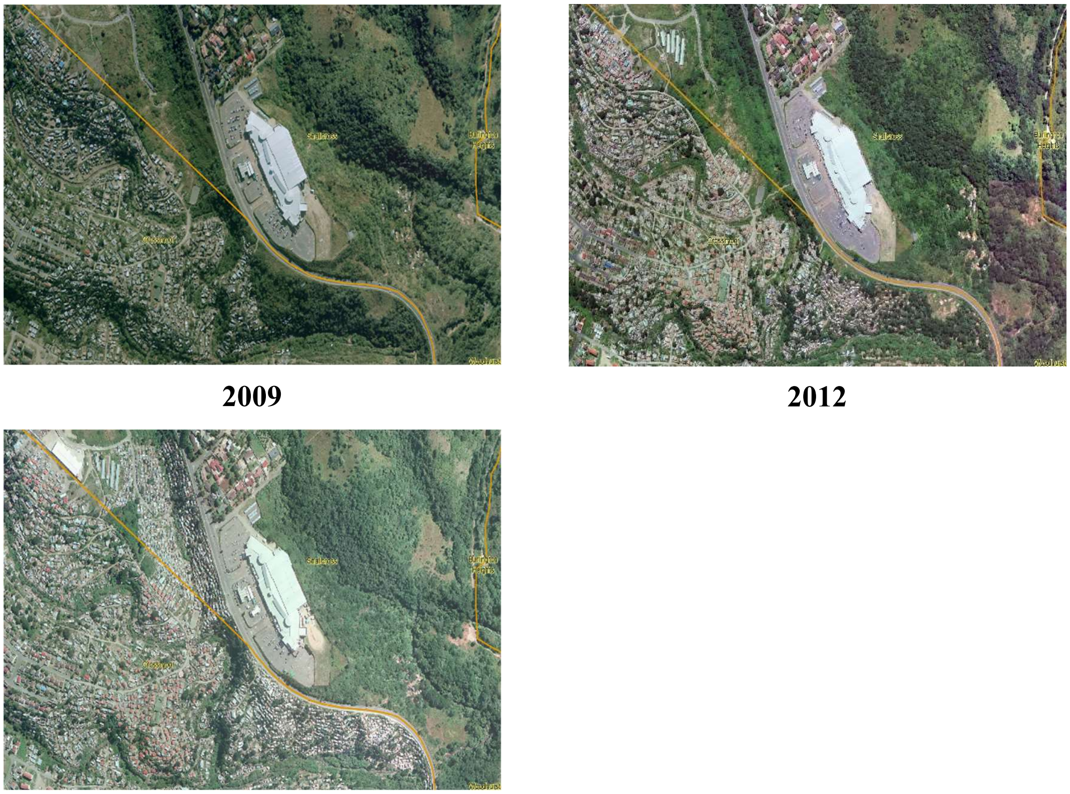
[25] The United Nations consider "water security" to be the ability of a society to ensure access to sufficient good quality water to safeguard livelihoods, health, wellbeing, ecosystems and development in a politically stable setting (UN-Water 2013).

Case study: Potential for rehabilitation to support growing development and urban centres in South Africa

South Africa’s largest trade port, Durban (which lies within the eThekwini Municipality and the province of KwaZulu-Natal, KZN), is the busiest in southern Africa (Roberts et al. 2016). This area is also a key corridor for South Africa’s second Strategic Integrated Project (SIP), the “Durban-Free State-Gauteng Logistics and Industrial Corridor”. This project aims to strengthen the logistics and transport route between South Africa’s main industrial hubs, and improve access to Durban’s export and import facilities (thus increasing exposure to globalization and enhancing trade, finance and transport flows, Presidential Infrastructure Coordinating Commission 2012).

Durban and Pietermaritzburg (the capital of KwaZulu-Natal), are located within the uMngeni catchment. The catchment is approximately 4,400 km^2 in size, ranging from higher altitude areas in the west and north to sea level (Durban) in the east. Although South Africa is a semi-arid country, the average Mean Annual Precipitation (MAP) of the uMngeni catchment (921 mm per annum; Umgeni Water 2016) is higher than in many other parts of the country. However, the population of the two major cities is growing significantly, and there is increasing pressure on the catchments that provide water-related ecosystem services to their communities and businesses.

Urbanization in the area has been further exacerbated by the development of vast new residential areas which have been built, in some cases, without adequate planning, compliance and/or coordination between various authorities, which has affected the adequacy of sewerage, water supply infrastructure and/or roads (see example in Figure 34). The area’s apartheid history, recent urbanization and densification of surrounding areas and continued lack of viable livelihoods maintains a large degree of inequality, and many people are still reliant on run-of-river water supply, which, due to pollution caused by industrialization and poor sanitation upstream, is in many places not potable (Stull et al. 2016). Furthermore the lack of co-ordination between regulating authorities has exacerbated over-abstraction of water by multiple sector users.



2009

2012

2015

Figure 34: Example of densification over a short time period within the uMngeni catchment, in the Shallcross area (Photos: N McLeod)

The uMngeni catchment, supported by a transfer scheme from the adjacent Mooi River catchment, yields approximately 1,050 Ml per day at a 99% level of assurance of supply from its various major supply dams, viz. Midmar, Albert Falls, Nagle and Inanda (Umgeni Water 2015). Some of the catchment's dams originally designed for water supply have already been rendered useless in terms of their purpose due to sedimentation (although still fulfilling some ecosystem service functions such as recreation and flood attenuation; Umgeni Water 2016). With an increasing number of people in the catchment, and the recent problems with drought, the dilution service normally provided by plentiful water in the catchment is becoming less and less reliable.

This case study is set in an evolving policy context (Costanza et al. 2017, Kubiszewski et al. 2017) that, whilst recognizing the grave need for improvement of resource management, development planning and equality, is also beginning to acknowledge that the maintenance of natural capital is a key instrument that can assist with the support of a growing human population (Cumming et al. 2017). The rehabilitation and protection of natural capital can therefore support the provision of basic needs such as food and water security, as well as recreation and tourism, key facets of the South African economy, which also bring many global citizens to its shores.

Case study model

The uMngeni Ecological Infrastructure Partnership (UEIP)[26] represents 36 organizations in the greater catchment area, and is a multi-stakeholder alliance of public and private sector stakeholders sharing knowledge, responsibilities and resources in order to achieve a common goal – protecting and enhancing the state of EI in the uMngeni and therefore water security in the catchment.

In order to explore the value and use of EI in the catchment, a hydrological modelling exercise was carried out in order to identify areas of priority in terms of water-related ecosystem service delivery within the uMngeni catchment (see full method and results in Chapters 4 and 5, Hughes et al. 2017a, Hughes et al. 2017b and summarized in Jewitt et al. 2015). The model also allowed the researchers to identify areas in which to undertake rehabilitation to improve water-related ecosystem service delivery, and therefore water security. Building from Warburton et al. (2010), the catchment was delineated into 145 sub-catchments (Figure 35). The catchments are in turn grouped into 13 Quaternary catchments, which align with the South African Department of Water and Sanitation's Quaternary catchments. The 13 Quaternaries were further grouped into six "Dam" catchments to analyze different user groupings based on population clusters and areas supplied by each of the dams and, in turn, the demand for ecosystem services from EI within each Dam catchment.

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[26] http://www.sanbi.org/news/umngeni-ecological-infrastructure-partnership-ueip-strengthening-collaborative-water-governance

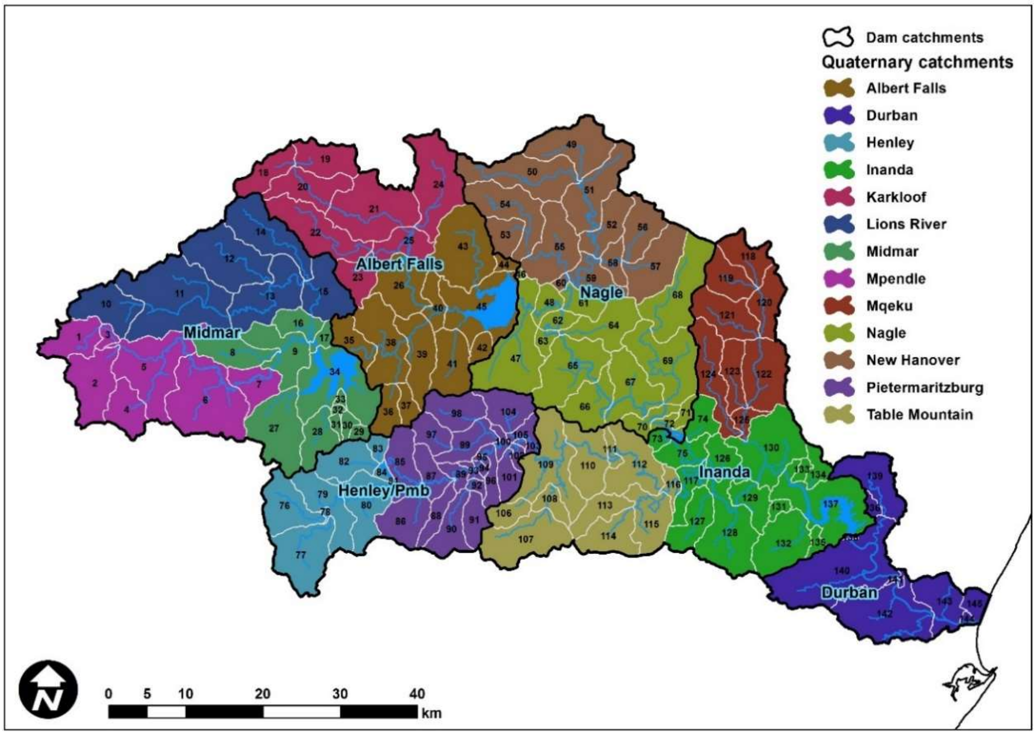

Figure 35: Dam Catchments, Quaternary Catchments and Sub-Catchments within the uMngeni catchment used for this study

Mander et al. (2017) further expanded on this work, and included economic modelling to estimate both the hydrological and economic costs and benefits associated with scenarios of degradation and rehabilitation of land. Fine-scale land cover mapping, combined with hydrological modelling, allowed the study to generate and analyze water flow information to identify important catchment areas from both a water supply and demand perspective, taking into account streamflow, surface runoff, sustained baseflow during the dry season and sediment generation, as influenced by EI (Mander et al. 2017).

The hydrological model simulated the current level of delivery of these water-related ecosystem services as well as the implementation of rehabilitation projects. It accumulated the results to a sub-catchment scale to provide water resource planning level comparisons as outlined in Table 10. Baseflow and streamflow gains were optimized by Mander et al. (2017) according to the requirements of water demand, and can be achieved with the same rehabilitation intervention.

Table 10: Modelled changes in average water yield (m^3 per year) or sediment yield (m^3 per year) given management options that seek to increase water yield, or reduce sediment yield, compared to a current-state baseline, in the sub-catchments of the uMngeni catchment. Note these values are the changes in annual streamflow, not total annual streamflow, and represent accumulations across multiple sub-catchments.

	Midmar	**Albert Falls**	**Henley**	**Inanda**	**Nagle**	**Durban**	**TOTAL**
Gain in streamflow	2 153 600	305 679	3 400 544	863 384	84 468	379 465	7 187 139
Gain in baseflow	311 048	172 538	101 404	529 951	525 911	12 337	1 653 189
Sediment reduction	-99 419	-69 017	-146 440	-205 794	-488 631	-42 448	-1 051 749

The results of this study indicate that specific interventions to rehabilitate, maintain and protect priority EI could result in significant hydrological gains (estimated gains in water supply), and thus gains in the water-related ecosystem services that support water security. If rehabilitation and other management interventions are successfully implemented, increased baseflow volumes are estimated to in the order of 1.6 million m^3 per year (60% increase), and increased streamflow volumes up to 7 million m^3 per year, which is an overall increase of 16% (Table 10; Mander at al. 2017).

Jewitt et al. (2015) further documented a part of the study which assessed which catchments were important from the perspective of flood attenuation by EI of small to medium flood events. This is extremely important in an urban context, as flooding can cause loss of human life, render people homeless and disrupt business and industry. Following swift urbanization (which can be poorly planned), the laying down of roads (hard surfaces) with inadequate stormwater drainage, and impermeable surfaces and roofs which do not incorporate rainwater harvesting systems, heavy rainfall events can pose great risks to downstream settlements, people and ecosystems (Schäffler and Swilling 2013).

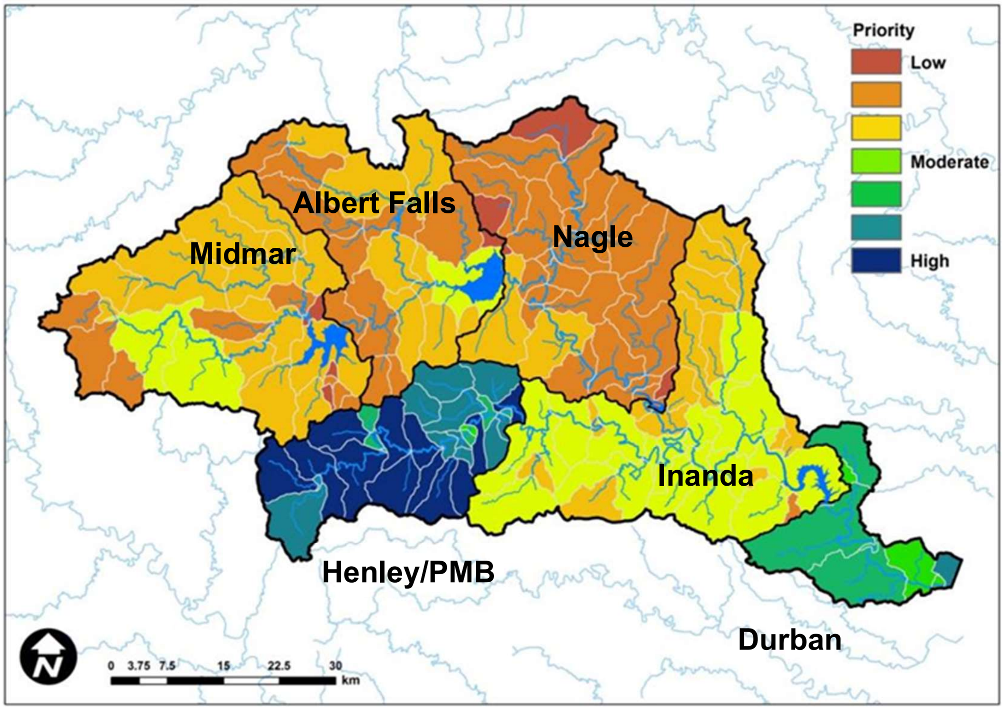

Figure 36: Priority catchments to enhance flood attenuation in the uMngeni catchment (Jewitt et al. 2015)

As shown in Figure 36, priority catchments in the uMngeni catchment which, if EI is protected and/or rehabilitated could provide improved flood attenuation services, were found to be in the Henley Dam area (shown in blue colours, location shown in Figure 37), and could protect the densely populated areas downstream and in Pietermaritzburg. Near the Henley Dam area there has been significant densification (Figure 38). In order to prevent infrastructure damage and potential loss of life during small and medium storms in this area, it is important that the EI (in the form of wetlands, riparian zones and grasslands) are kept in tact. EI has the ability to slow water flow (due to the presence of indigenous riparian and wetland vegetation which slows stormflow), and the spreading of water volumes across floodplains to dissipate the energy of a storm.

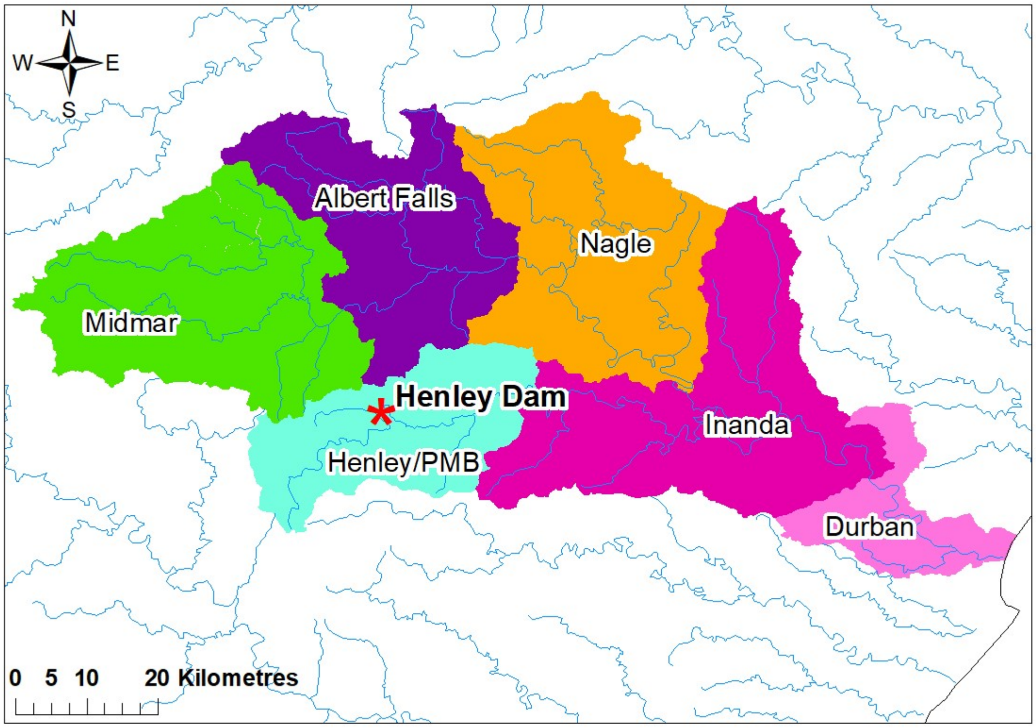

Figure 37: Location of Henley Dam within the uMngeni catchment

Figure 38: Densification of settlements in the Henley Dam area compared between 2006 and 2017 (Google Earth 2018)

Discussion

Viewing the interrelationships between the Earth's ecosystems and its inhabitants, i.e. the socio-ecological system, as a biosphere (Folke et al. 2016) which crosses man-made borders should allow for more effective consideration of ecosystem structure, composition and function (Noss 1990, Figure 3). Folke et al. (2016) indicate the biosphere as the very foundation of the sustainability concept, which includes (as related to the Sustainable Development Goals), life on land, life below water, clean water and sanitation, and climate action. These elements are all key to ecosystem resilience (and that of society), and should also be considered when planning rehabilitation of degraded land, as explored in Chapter 2.

The recognition of the dependency of people on resources not only for exploitation and global competitiveness, but also on ecosystem composition and functionality for survival, e.g. the purification of water, should be used to develop techniques for environmental management, or, preferably, biosphere management for ecosystem, population and economic resilience. This should facilitate more collaborative, cross-border (municipal in this case) and cross-sector governance as illustrated by the UEIP, as well as adaptive management.

In order to mitigate the overarching negative influence of globalization on EI as explored in Figure 3 and Table 9, and improve the management thereof, buy in from stakeholders at all levels is important. Within the uMngeni catchment, stakeholder co-operation has been strong, and the necessary suite of skills and expertise to manage a problem of such complexity and interactions driven by urbanization is available as a result. The UEIP includes private companies, government, non-government agencies and tertiary education institutions, all of whom recognize the role that investments in EI can play in the enhancement of water and sanitation services in the uMngeni catchment. Some of these organizations are furthermore directly influenced by the global impact of trade, such as the forestry companies, and government entities.

There are several research and implementation projects in progress under the UEIP. These include the integration of models to target those areas in which EI rehabilitation will effectively increase water flows to support the growing population and economic activities in the catchment, as well as to inform investment in catchment interventions such as removal of IAPs, rehabilitation of wetlands, citizen science projects and social change programmes. The initial success of this partnership illustrates the importance of communicating the direct but not always tangible link between ecosystem services provided by healthy EI (such as grasslands, wetlands, forests and riparian zones), economic success in the global arena and human survival. It also encourages the enhancement of a broader scale of governance and regulation, undertaken by the users themselves in partnership with public organizations.

Linked to the requirement for buy-in from all forms of stakeholders in order to protect EI, it is important to note that in South Africa, many important EI assets are found outside of protected areas, on privately owned land. Compounding this issue are the budget and resource challenges faced by the country's provincial government environmental management departments. This implies that the resilience of EI (which is outside of cities but delivers valuable ecosystem services to urban areas) relies heavily on strong, collaborative partnerships with private and communal landowners. South Africa has developed an approach known as Biodiversity Stewardship (Rawat 2017), which allows for the formal proclamation of privately or communally owned protected areas. As part of this process, and in collaboration with the respective landowner so as not to compromise agricultural productivity and food security, environmental managers can promote land management techniques which not only minimize disturbance and transformation of remaining intact EI, but also facilitate catchment management interventions such as IAP clearing, reduced cattle numbers (and thus reduced overgrazing) and wetland rehabilitation. Intact farmland can thus be secured in priority EI areas through voluntary agreements with private and communal landowners, municipalities and other government entities, which are supported by provincial authorities. Owner benefits can include fiscal incentives like income tax deductions and property rates exclusions. This type of innovation, as an example of a successful private-public partnership, can also contribute to rural development goals and discourage urban migration through the creation of green jobs and the upliftment of formerly marginalized communities (Rawat 2017). There are several international examples of investment in EI through the Payment for Ecosystem Services concept (PES), and may also be studied to inform EI planning in South Africa, and adapted to our circumstances (e.g. Deng et al., Sgroi et al. 2016).

In addition, cities themselves are also dependent on (and can benefit from) the EI within their borders - utilizing green spaces and urban riparian zones. However, there is a lack of knowledge around delivery and valuation of ecosystem services in cities, with a large degree of socio-ecological complexity (Schäffler and Swilling 2013), and perhaps an insufficient recognition of the benefits that these areas may generate for a city's residents.

The shared nature of a river catchment also provides opportunities for 'shared value creation' by businesses and private investors, in which they can advance their competitive advantage through collaboration with other stakeholders (Colvin et al. 2015) to improve the value of the shared resource, i.e. the river and its associated EI. Furthermore, Nel et al. (2011) demonstrated the justification for private sector stakeholders to share in the cost of rehabilitation of EI, as this type of investment reduces business, reputational and regulatory risk.

Conclusion

As is illustrated by this case study, in order to protect South Africa's ecological infrastructure, and in turn the survival and health of the rapidly increasing population of urban centres due to globalization and urbanization, robust hydrologically-informed research, as well as strong private-public partnerships at regional or catchment scales, are vital. As the uMngeni study has shown, there is a need for stakeholders and decision-makers to ensure that EI is valued at all levels of society – in public, academic, business and governmental spheres - and that when stakeholders fail to cover the damages they inflict on common goods like natural resources, these costs do not fall upon the broader community.

Only through making the connection between nature and human survival clear to the public at large (Folke et al. 2016), as well as potential private sector investors, can we hope to ensure resilience of EI and its services to society. If we achieve this, we may be able to ensure resilience of the country's continued economic growth, population, built infrastructure and biodiversity in the long term.

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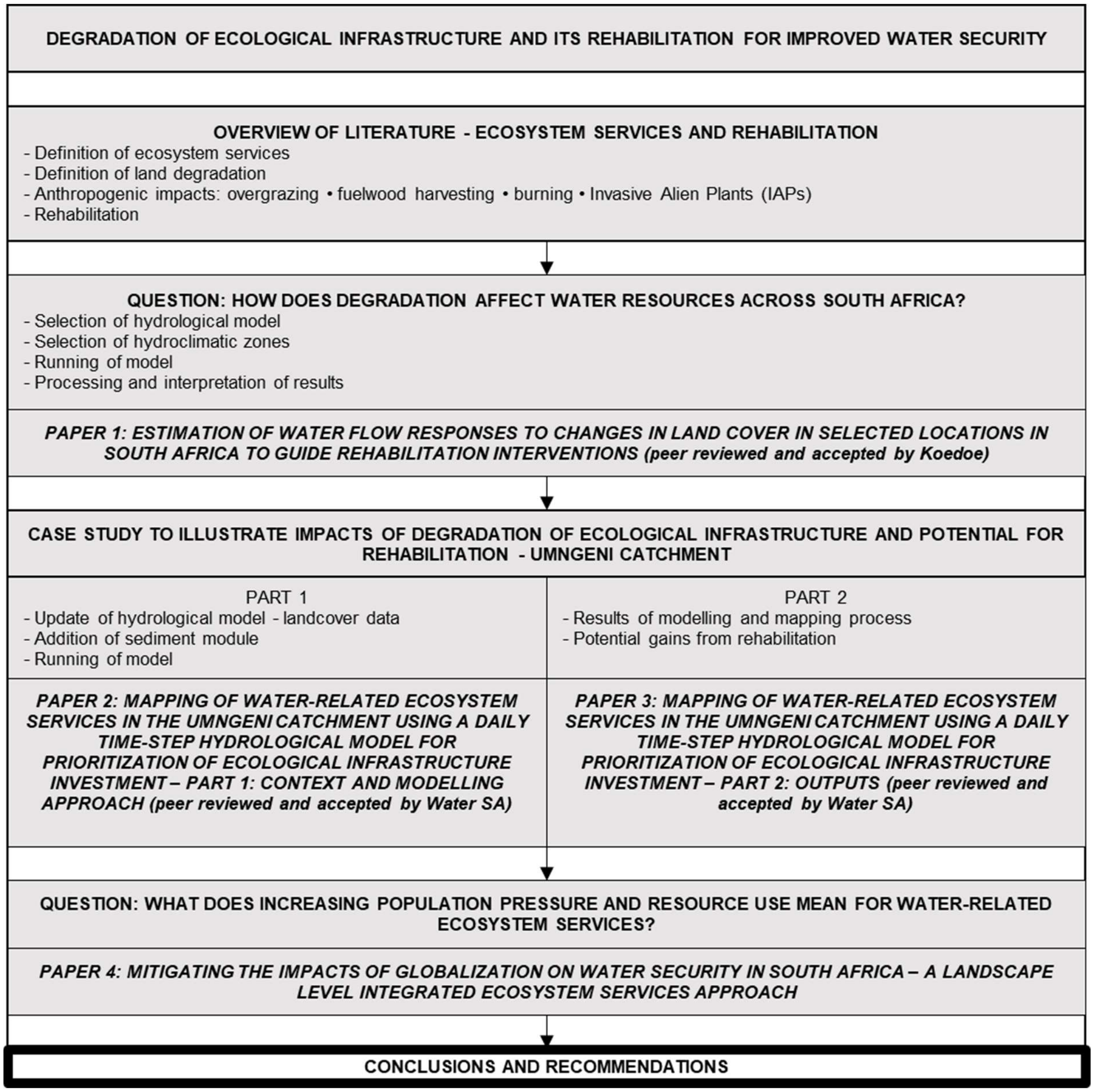

DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND ITS REHABILITATION FOR IMPROVED WATER SECURITY

OVERVIEW OF LITERATURE - ECOSYSTEM SERVICES AND REHABILITATION

- Definition of ecosystem services
- Definition of land degradation
- Anthropogenic impacts: overgrazing • fuelwood harvesting • burning • Invasive Alien Plants (IAPs)
- Rehabilitation

QUESTION: HOW DOES DEGRADATION AFFECT WATER RESOURCES ACROSS SOUTH AFRICA?

- Selection of hydrological model
- Selection of hydroclimatic zones
- Running of model
- Processing and interpretation of results

PAPER 1: ESTIMATION OF WATER FLOW RESPONSES TO CHANGES IN LAND COVER IN SELECTED LOCATIONS IN SOUTH AFRICA TO GUIDE REHABILITATION INTERVENTIONS (peer reviewed and accepted by Koedoe)

CASE STUDY TO ILLUSTRATE IMPACTS OF DEGRADATION OF ECOLOGICAL INFRASTRUCTURE AND POTENTIAL FOR REHABILITATION - UMNGENI CATCHMENT

PART 1

- Update of hydrological model - landcover data
- Addition of sediment module
- Running of model

PART 2

- Results of modelling and mapping process
- Potential gains from rehabilitation

PAPER 2: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 1: CONTEXT AND MODELLING APPROACH (peer reviewed and accepted by Water SA)

PAPER 3: MAPPING OF WATER-RELATED ECOSYSTEM SERVICES IN THE UMNGENI CATCHMENT USING A DAILY TIME-STEP HYDROLOGICAL MODEL FOR PRIORITIZATION OF ECOLOGICAL INFRASTRUCTURE INVESTMENT – PART 2: OUTPUTS (peer reviewed and accepted by Water SA)

QUESTION: WHAT DOES INCREASING POPULATION PRESSURE AND RESOURCE USE MEAN FOR WATER-RELATED ECOSYSTEM SERVICES?

PAPER 4: MITIGATING THE IMPACTS OF GLOBALIZATION ON WATER SECURITY IN SOUTH AFRICA – A LANDSCAPE LEVEL INTEGRATED ECOSYSTEM SERVICES APPROACH

CONCLUSIONS AND RECOMMENDATIONS

CHAPTER 7: CONCLUSIONS AND RECOMMENDATIONS FOR FURTHER RESEARCH

Introduction

After several years of working in the field of ecosystem services - in industry, academia and the conservation world - it has become clear to me that there is a disconnect between the consciousness of human beings and their dependence on natural resources. People are often unaware of their reliance on clean air, fertile soil, structurally sound ecological infrastructure and, above all, clean and plentiful water. They are also often unaware that everything is interlinked - a short term action to plant an extra hectare of maize, exploit a coal seam, or create a profit in manufacturing, can have lasting and permanent consequences on the ability of the natural environment to sustain human and animal life. Only in moments of crisis, such as the recent and current droughts in South Africa, do people seem to realize that their immediate actions and impacts on natural resources have consequences. However, if the real value of water, in particular, is communicated (through effective education) and enforced (through compliance and in monetary terms), perhaps South Africa’s people would not be waiting until the eleventh hour to prevent disaster, and turning to highly costly, risky and energy intensive infrastructure solutions.

Due to the above situation, and during my past decade of work in the environmental field, I have become increasingly convinced of the value of the concept of ecosystem services Costanza et al. 1997). It is something tangible not only for scientists (hydrologists and ecologists in particular), but also for the general public and for business people. It talks directly to the value that ecosystems provide to society – i.e. ultimately for society’s use. Personally, through my work in industry and with people to undertake activities which sustainably make use of natural resources, I have realized that it is preferable to work with these stakeholders to secure natural resources, whatever the motivation – whether for business continuity or something as simple as a spiritual or recreational benefit - rather than opting for a preservationist attitude based on keeping things in their natural state which aims to exclude not only industry, but many rural communities as well.

It is now twenty years since the value of ecosystem services was first globally estimated (Costanza et al. 2017). The concept has been used extensively for research, the development of large-scale programs and institutions, as well as integrated modelling to explore the various interactions that lead to ecosystem services delivery. It has also assisted with the development of innovative governance mechanisms, and to business decision making. Businesses both depend and have an impact on natural resources, throughout their supply chain. There is immense potential for scientists to assist businessmen in making investments into, and recognizing the value of natural capital, and to derive significant benefits from it.

Notwithstanding the benefits of the ecosystem services concept, Seppelt et al. (2011) provided a summary of the shortcomings thereof, which include the often inconsistent and widely varied nature of ecosystem services approaches, a lack of data at appropriate scales, a lack of knowledge of institutional decision making and implementation, as well as a lack of effective models for aligning economic aspects with the more biophysical or conservation-related factors.

This study, conceptualized out of an interest in water-related ecosystem services, their vital role in provision of water security, and the impacts that land degradation has on these – invasive alien plants in particular – initially aimed to build on previously validated techniques to quantify the amount of water which could be derived through effective rehabilitation activities. These activities are likely to form the backbone of private sector or government investment into ecological infrastructure protection or repair aimed at improving water security. Fortunately, I was able to develop this high level concept into a full, detailed case study, and finally synthesize the ideas which emanated from this process into a bigger picture view of the implications of this work.

Aims, objectives and contributions of this study

This study aimed to illustrate, through review of literature, interaction with experts in the field, and hydrological modelling – both at a high level and within a case study catchment in significant detail - that improvement in water security can be achieved through rehabilitation of degraded ecological infrastructure. I also aimed to illustrate that the conservation and rehabilitation of ecological infrastructure can prevent or delay the need for the construction of costly infrastructure for clean and sufficient water delivery.

My literature review synthesized the following:

- An understanding of water-related ecosystem services;
- An understanding of land degradation, and exploration of several types of human-induced degradation, with an emphasis on overgrazing and invasive alien plants;
- An understanding of the concepts of land rehabilitation and restoration with a view to reinstating water-related ecosystem services in degraded catchments.

The investigation into water flow responses to changes in land cover in selected locations in South Africa provided a high level, spatial insight into differing responses to key human-induced land cover changes (overgrazing by livestock and presence of invasive alien plants) across the country, taking into account different climatic and soil characteristics. This provides a general reference for water resource managers in different parts of the country, particularly in terms of three specific problematic invasive alien plant species. This work was inspired by the Working for Water program (Department of Environmental Affairs 2014).

The detailed hydrological modelling case study (set in the uMngeni catchment) allowed for the application of the above principles to a specific area. The uMngeni is highly relevant and topical at present, with this catchment being used to pioneer the ecological infrastructure approach to ensure water security in South Africa by a number of stakeholders. The research team used a validated hydrological model (Warburton et al. 2010) to map and illustrate priority areas of ecological infrastructure in the uMngeni. My work specifically contributed an update of land cover data for each hydrological response unit (Ezemvelo KZN Wildlife and GeoTerraImage 2013), as well the addition to the model of sediment yield, which allowed us to not only explore water quantity (baseflow and quickflow), but also water quality, and infer the impacts of degradation of topsoil and nutrient loss, as well as sedimentation of dams – all requiring potentially costly interventions. We were able to note the significant gains in streamflow, as well as sustainability of flow during the dry season to ensure ecological function and year-round water supply, which can be obtained through rehabilitation interventions. This was further explored and compared to another catchment study (Baviaanskloof) in Mander et al. (2017) – for which I was a co-author.

The overall implications of this work for ecological infrastructure in South Africa, as driven by urbanization and globalization, were explored in the final paper contributing to this thesis. This chapter aims to provide a more holistic view of the case study, and how its approach could potentially influence governance at a broader level. This paper allowed me to draw on direct experience of working in the conservation field in South Africa, a country in which the provincial capacity for nature conservation and protected area management is rapidly diminishing with a loss of training, resources and institutional capacity. The role of the private landowner (and the private sector in general), as well as collaboration between all catchment stakeholders, is becoming more and more key to the persistence of ecological infrastructure, ecosystem services and water security.

Challenges

The main challenges of this study were associated with the time consuming nature of hydrological modelling. For the first part of the study, a process of assessing the ability of the *ACRU* model to simulate the riparian zone was undertaken as part of Water Research Commission project K5/2156. In the uMngeni catchment model, the update to each and every hydrological response unit based on the KZN land cover (Ezemvelo KZN Wildlife and GeoTerraImage 2013) was time consuming. Due to the short-term nature of the project funding it was also not possible to explore all types of ecological infrastructure, such as wetlands and riparian zones, which require different and complex modelling routines. However, if a study aims to inform an investment plan, for example, there is often insufficient time to allow for such detailed research. This is acknowledged as a limitation of the study, but it has been received nevertheless as a useful and pioneering project.

Availability of data, particularly with regard to alien plant coverage, was a challenge. The team working on the Green Fund project were not able to obtain an updated coverage of alien plants (as this is not documented on the KZN land cover layer). We therefore had to use the most up to date, validated coverage provided by Umgeni Water of Black Wattle (*Acacia mearnsii*). Unfortunately, this data was several years older than the 2011 land cover. This highlights the need to maintain validated and groundtruthed datasets of alien plant species. Unfortunately, the lack of resources and continuously diminishing institutional memory at government departments compounds this issue. The high quality and detail provided by the land cover data (Ezemvelo KZN Wildlife and GeoTerraImage 2013) must however be acknowledged as providing an excellent basis for the study.

Despite its power, the parameterized nature of a hydrological model such as *ACRU* leads to some uncertainty, particularly given the variability of physical and climatic parameters across South Africa. I was able to rely on the many years of field experiments carried out by the Centre for Water Resources Research (CWRR) and its preceding department, the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal, as well as the immense experience of my colleagues and supervisors in the CWRR. It cannot be emphasized enough how important it is to document this wealth of information in an accessible manner such that new generations of hydrologists can benefit from this validated information.

The apparent importance of certain parameters in the *ACRU* model, as highlighted by the sensitivity analysis in Chapter 3, also indicated the possible uncertainties with regard to parameter value selection. If selected incorrectly, sensitive parameters could falsely influence the model results. Further validation of parameter values within the *ACRU* model for detailed hydrological scenario analysis is recommended.

A further challenge experienced by most scientists in the field of environmental management and during the uMngeni case study project (Chapters 4 and 5) is stakeholder participation, particularly from government role-players. It is becoming increasingly difficult to ensure the attendance and engagement of appropriate (and well informed) people at stakeholder meetings, which should lead to investment planning or joint decision making. This brings into question not only the validity of decisions being taken, but also the potential uptake of innovative concepts such as that of investment into ecological infrastructure for water security by decision makers, particularly at a political level.

Future possibilities

Throughout my research, as well as during my current work in the conservation field, the lack of evidence for nature-based solutions has been continually emphasized. There is a need for a wide range of scalable pilot studies to be instituted across different sites to prove the usefulness of ecological infrastructure in preventing water-related disasters and ensuring water security, as well as the gains to be made in water-related ecosystem service delivery across varying environments with conservation and rehabilitation, as well as cumulative and interactive impacts, such as the combined effect of IAPs and overgrazing. This should enable planners to establish a standard set of numbers to be taken forward when planning EI investment projects. Given the variability of climates and ecosystems across the country, this is no easy undertaking.

Despite the research still required, and particularly in the realm of policy, there is a need for ecological scientists to raise their voices. In many other fields (economics for example), professionals do not always strive for the same degree of accuracy and confidence - their decisions are taken practically and confidently. Particularly in the area of ecological infrastructure, practitioners have not come close to quantifying or even conceptualizing the *additional* benefits to be gained through proper care of these assets, nor rehabilitating them, and yet we sometimes doubt the value of such interventions. Perhaps we will derive 10% less water through a catchment intervention (such as rehabilitating a grassland) than our models have indicated, but we will have gained innumerable further services to society such as habitat for various organisms, more fertile soil, lower sedimentation, more carbon storage and scenic beauty. Having confidence and gaining political will for pursuing greener solutions and thus ensuring these added benefits is absolutely imperative.

Final comments and summary conclusions

Many environmental scientists and activists wish to preserve the value of natural resources “just as they are”, and not to “commodify nature”. In order to convince society at large of this value however, now more than ever, it is necessary for the full value of water in particular, and its contribution to human life, livelihoods and business success, to be recognized by society. This does not diminish the intrinsic value of natural resources in any way - in fact it increases it. Society must at the same time recognize that a sustainable supply of clean water is regulated by ecosystems and healthy ecosystems mediate the delivery of those benefits.

Costanza et al. (2017) state, in an assessment of the need for valuation of ecosystem services, that in the many cases in which trade-offs are required for decision making about development opportunities and potential sacrifice of natural capital, being more explicit in terms of the value of ecosystem services can help society make more prudent decisions. Scientists should use whatever means necessary to ensure that society values and protects natural resources - whether it is for recreational or cultural needs, for supporting our modern requirements for manufacturing and food security, or for the basic delivery of water for our own survival and that of future generations.

I would like to end with a quote from Costanza et al. (2017), which encapsulates the value of the ecosystem services derived from our ecological infrastructure:

"the substantial contributions of ecosystem services to the sustainable wellbeing of humans and the rest of nature should be at the core of the fundamental change needed in economic theory and practice if we are to achieve a societal transformation to a sustainable and desirable future."

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