Dissertation

IMPROVEMENTS AND ADAPTATIONS OF KNOWLEDGED-BASED ASSESSMENT APPROACHES:
Assessing land use activity impacts on ecosystem services

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“It always seems impossible until it’s done.”

Nelson Mandela

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CONTENTS

ABSTRACT

Humans place considerable demands on the environment for their well-being. Land use activities are intensifying worldwide and the impacts that such activities have on the natural environment are abundant. Land use activities contribute to a loss of the provisioning of many important ecosystem services. The provisioning of good quality water is a vital ecosystem service that is fundamental for a sustainable globe. Land use activities place an extensive amount of pressure on ecosystems to provide good quality water, especially since such activities are a major source of pollutants reaching water sources.

Land managers are confronted to fill the gaps in their knowledge regarding the impacts that land use activities have on ecosystem services. Simplified assessment approaches that incorporate land use/land cover (LULC) to assess the impacts of land use activities on ecosystem services and water quality are relative easy to apply compared to complex modeling tools. These knowledge-based assessment approaches rely on freely available public data, literature and expert knowledge. Their application is particularly useful for data scarce regions.

The aim of the thesis was to improve and adapt existing knowledge-based assessment approaches to assess the effects of LULC on (i) groundwater and (ii) river water quality, and (iii) certain ecosystem services based on available data and knowledge. The improved approaches were tested for regions under intense land use activities along the southern coast of the Western Cape Province located in South Africa.

The first approach used LULC parameters not considered before in the DRASTIC approach to assess the nitrogen pollution potential of groundwater. A spatial assessment approach was developed to delineate the submarine groundwater discharge areas that might contribute to the pollution potential of coastal waters. The findings indicated that the addition of the nitrogen related LULC parameters facilitate to determine if a land use activity are adapted to the physical conditions of a certain area.

The second approach incorporated landscape potentials into an ordinal rating approach that links LULC with water quality in order to assess the sediment and nutrient inputs on river reaches.

For the third approach scoring matrices that links LULC and landscape properties with ecosystem services were adapted to the study region's regional characteristics to determine the loss of ecosystem services.

The second and the third assessment approaches showed changes in the risk of river water pollution and the loss of ecosystem services from reference situations for specific areas in the landscape. This indicates that the inclusion of landscape potentials and properties needs to be considered.

The results showed that agricultural activities are an important contributor to the pollution potential of water sources and the loss of ecosystem service. The type of urban development that also contributed to such impacts was from the informal settlements, as point discharge pollution could not be considered for this study. Further development of the approaches is recommended as new and superior data become available and with increasing knowledge.

The improved assessment approaches made considerable contribution to existing knowledge regarding the complex interactions including the landscape, land use activities, and ecosystem services. The findings from this study can support with future decision-making to ensure improved management strategies.

ZUSAMMENFASSUNG

Für das Wohlbefinden stellt der Mensch erhebliche Anforderungen an seine Umwelt. Weltweit nehmen die Landnutzungsaktivitäten zu und führen zu steigenden Auswirkungen auf die natürliche Umwelt. Des weiteren tragen diese Landnutzungsaktivitäten dazu bei, dass viele wichtige Ökosystemdienstleistungen nicht mehr bereitgestellt werden können. Der Zugang zu qualitativ hochwertigem Wasser ist eine wichtige Ökosystemdienstleistung, die für eine nachhaltige Welt von grundlegender Bedeutung ist. Landnutzungsaktivitäten üben als Hauptquelle für Schadstoffe einen erheblichen Druck auf die Bereitstellung von qualitativ hochwertigem Wasser aus, sobald diese in die Gewässer des Ökosystems gelangen.

Landnutzungs-Manager sehen sich damit konfrontiert, Wissenslücken in Bezug auf die Auswirkungen von Landnutzungsaktivitäten auf Ökosystemdienstleistungen zu schließen. Vereinfachte Bewertungsansätze, welche die Landnutzung/Landbedeckung (LULC) zur Bewertung der Auswirkungen von Landnutzungsaktivitäten auf Ökosystemleistungen und Wasserqualität umfassen, sind im Vergleich zu komplexen Modellierungsinstrumenten relativ einfach anzuwenden. Diese wissensbasierten Bewertungsansätze stützen sich auf frei verfügbare öffentliche Daten, Literatur und Expertenwissen. Ihre Anwendung ist besonders nützlich in Regionen mit schlechter Datenverfügbarkeit.

Ziel der Arbeit war es, vorhandene Daten und Kenntnisse zu nutzen, um bestehende Bewertungsansätze zu verbessern und anzupassen und somit die Auswirkungen von LULC auf (i) Grundwasser und (ii) Wasserqualität in Flüssen sowie (iii) bestimmte Ökosystemdienstleistungen zu bewerten. Die verbesserten Ansätze wurden für Regionen mit intensiven Landnutzungsaktivitäten entlang der Südküste der in Südafrika gelegenen Westkap-Provinz getestet.

Im ersten Bewertungsansatz wurden LULC-Parameter verwendet, welche zuvor nicht im DRASTIC-Ansatz berücksichtigt wurden, um das Stickstoffbelastungspotenzial des Grundwassers zu bewerten. Weiter wurde ein räumlicher Bewertungsansatz entwickelt, um die Grundwasserabflussgebiete, die zum Verschmutzungspotenzial der Küstengewässer beitragen könnten, abzugrenzen. In den Ergebnisse zeigte sich, dass die Zugabe der stickstoffbezogenen LULC-Parameter eine Bestimmung der Anpassung der Landnutzungsaktivität an die physikalischen Bedingungen eines bestimmten Gebietes, erleichterte.

Der zweite Bewertungsansatz integrierte zusätzlich die Landschaftspotentiale zu einen ordinalen Bewertungsansatz, welcher die LULC mit der Wasserqualität verbindet, um die Sediment- und Nährstoffeinträge auf Flussläufe bewerten zu können.

Für den dritten Ansatz wurde eine Bewertungsmatrix, LULC und Landschaftseigenschaften mit Ökosystemdienstleistungen verknüpft und an die regionalen Merkmale der Untersuchungsregion angepasst, um den Verlust von Ökosystemdienstleistungen zu bestimmen.

Die Bewertungsansätze zwei und drei zeigten eine Veränderung des Risikos einer Verschmutzung des Flusswassers und des Verlustes von Ökosystemdienstleistungen in Referenzsituationen für bestimmte Gebiete in der Landschaft. Dies bedeutet, dass die Einbeziehung von Landschaftspotentialen und -eigenschaften berücksichtigt werden muss.

Die Ergebnisse zeigten, dass landwirtschaftliche Tätigkeiten einen wichtigen Teil zu potentiellen Verunreinigung von Wasserquellen und zum Verlust der Ökosystemdienstleistungen beitrugen. Die negativen Auswirkungen der Stadtentwicklung waren hauptsächlich auf informelle Siedlungen zurückzuführen, da die punktuelle Abwassereinleitungsdaten in dieser Studie nicht berücksichtigt werden konnten. Bei der Verfügbarkeit umfangreicherer Daten wird eine Weiterentwicklung der Bewertungsansätze als empfehlenswert erachtet.

Die verbesserten Bewertungsansätze lieferten einen bedeutenden Beitrag zum Wissenstand über die komplexen Wechselwirkungen, einschließlich Landschaft, Landnutzungsaktivitäten und Ökosystemdienstleistungen. Auf Grundlage der belastbaren Ergebnisse kann die Entscheidungsfindung zukünftig unterstützt werden, um verbesserte Managementstrategien sicherzustellen.

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LIST OF ABBREVIATIONS

ARC-ISCW	Agricultural Research Council-Institute for Soil, Climate, and Water
DEAP	Department of Environmental Affairs and Development Planning
DEM	Digital Elevation Model
DNS	Diffuse nitrogen surplus in the rooting zone
DWS	Department of Water and Sanitation
ER	Eastern region
FAO	Food and Agricultural Organization
GIS	Geographic Information Systems
HSWT	Weihenstephan-Triesdorf University of Applied Science
InVEST	Integrated Valuation of Ecosystem Services and Tradeoffs
LULC	Land use/land cover
MA	Millennium Ecosystem Assessment
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow Model
NC	Nitrogen concentration in the deep percolation
RUSLE	Revised Universal Soil Loss Equation
SGD	Submarine groundwater discharge
SGD-CA	Submarine groundwater discharge contribution area
SPACES	Science Partnerships for the Assessment of Complex Earth System Processes
SUDEM	Stellenbosch University Digital Elevation Model
SWAT	Soil and Water Assessment Tool
SWIM	Soil and Water Integrated Model

UFZ	Helmholtz Centre for Environmental Research
USLE	Universal Soil Loss Equation
WCDA	Western Cape Department of Agriculture
WCP	Western Cape Province
WR	Western region
WWAP	World Water Assessment Programme

LIST OF PUBLICATIONS

This cumulative thesis is based on the work published and submitted in the following three original articles. At the time of thesis submission, all three articles were published. The articles are attached in the appendix and reproduced with the permission of the publishers.

Paper 1: Malherbe, H., Gebel, M., Pauleit, S., Lorz, C. (2018). Land use pollution potential of water sources along the southern coast of South Africa. *Change and Adaptation in Socio-Ecological Systems,* 4(1), 7–20. https://doi.org/10.1515/cass-2018-0002

Summary

Since the 1990's, the groundwater quality along the southern coast of the Western Cape Province of South Africa has been affected by increasing land use activities. Groundwater resources have become increasingly important in terms of providing good quality water. Polluted coastal groundwater as a source of submarine groundwater discharge also affects the quality of coastal water. For this study, land use activities causing groundwater pollution and areas at particular risk were identified. An assessment approach linking land use/land cover, groundwater and submarine groundwater discharge on a meso-scale was developed and the methods applied to two study regions along the southern coastal area. Dryland and irrigated crop cultivation, and urbanized areas are subject to a "high" and "very high" risk of groundwater nitrogen pollution. Application of fertilizer must be revised to ensure minimal effects on groundwater. Practice of agricultural activities at locations which are not suited to the environment's physical conditions must be reconsidered. Informal urban development may contribute to groundwater nitrogen pollution due to poor waste water disposal. Groundwater monitoring in areas at risk of nitrogen pollution is recommended. Land use/land cover in the submarine groundwater discharge contribution areas was not found to have major effects on coastal water.

Author's contribution

The first author H. Malherbe developed the methodologies, completed the analysis, interpreted the results, and wrote the manuscript under the supervision of the co-authors. M. Gebel and C. Lorz supported with the research design. The co-authors contributed to the manuscript by scientific advice and language editing.

Paper 2: Malherbe, H., Le Maitre, D., Le Roux J., Pauleit, S., Lorz C. (2019). A simplified method to assess the impact of sediment and nutrient inputs on river water quality in two regions of the southern coast of South Africa. *Environmental Management,* 63(5), 658–672. https://doi.org/10.1007/s00267-019-01147-w

Summary

Many rivers in the southern coastal region of the Western Cape Province, South Africa, are known to be in a poor state. Since the 1990s, the river water quality of this coastal region has been affected by increasing populations and by intensifying land use activities. Simplified risk assessment approaches are critical to identify in a timely manner areas where land use activities may impact water quality, particularly for regions with limited data. For this study, a simple assessment approach to estimate the impacts of land use activities on river water quality was improved by incorporating landscape potentials that take into account environmental factors. The methods were applied to two regions experiencing intensive land use along the southern coast. The findings indicate that the incorporation of the landscape potentials, (i) the landscape sediment generation potential and (ii) the diffuse nitrate potential, to estimate the impacts of sediment and nutrient inputs on river water quality need to be considered. Agricultural activities and informal settlements contribute to the increasing sediment and nutrient inputs of the river reaches. Hotspot areas with high proportions of river reaches at increasing pollution risk need to be managed on a large scale to ensure that all the potentially affected sub-catchments are included.

Author’s contribution

The first author H. Malherbe developed the methodologies, completed the analysis, interpreted the results, and wrote the manuscript under the supervision of the co-authors. D. Le Maitre and C. Lorz supported with the research design. The co-authors contributed to the manuscript by scientific advice and language editing.

Paper 3: Malherbe, H., Pauleit, S., Lorz C. (2019). Mapping the loss of Ecosystem services in a region under intensive land use along the southern coast of South Africa. *Land,* 8(3), 51. https://doi.org/10.3390/land8030051

Summary

Intensive land use activities worldwide have caused considerable loss to many ecosystem services. The dynamics of these threats must be quickly investigated to ensure timely update of management strategies and policies. Compared with complex models, mapping approaches that use scoring matrices to link land use/land cover and landscape properties with ecosystem services are relatively efficient and easier to apply. In this study, scoring matrices are developed and spatially explicit assessments of five ecosystem services, such as erosion control, water flow regulation, water quality maintenance, soil quality maintenance, and biodiversity maintenance, are conducted for a region under intense land use along the southern coast of South Africa. The complex interaction of land use/land cover and ecosystem services within a particular landscape is further elucidated by performing a spatial overview of the high-risk areas that contribute to the loss of ecosystem services. Results indicate that both agricultural activities and urban development contribute to the loss of ecosystem services. This study reveals that with sufficient knowledge from previous literature and inputs from experts, the use of scoring matrices can be adapted to different regional characteristics. This approach can be improved by adding additional landscape properties and/or adapting the matrix values as new data become available.

Author's contribution

The first author H. Malherbe developed the methodologies, completed the analysis, interpreted the results, and wrote the manuscript under the supervision of the co-authors. The co-authors contributed to the manuscript by scientific advice and language editing.

1 INTRODUCTION

1.1 General introduction

The conversion of natural land cover is human-induced and causes major transformations of natural landscapes worldwide (Meyer and Turner 1994; De Fries et al. 2004; Foley et al. 2005). Land use activities vary across the globe but mostly include agricultural activities, livestock grazing, forestry and urban development (Meyer and Turner et al. 1994; De Fries et al. 2004; Foley et al. 2005; Rai et al. 2017). The ultimate outcome of land use activities is to meet the demands that humans place on the environment for resources such as food, fuel, fiber and water (Ojima et al. 2010). Land use activities have caused a substantial degradation of water, soil and natural habitats. The degradation of the environment has furthermore contributed to a significant decline in biodiversity (Pimm and Raven 2000; Newbold et al. 2015).

1.1.1 Land use activity impacts on ecosystem services

The environment provides numerous ecosystem services. A recognized definition of ecosystem services defined by the Millennium Ecosystem Assessment is "the benefits that humans derive from ecosystems to sustain human well-being" (MA 2005). Some well-known classification systems have categorized ecosystem services into provisioning, regulating and maintenance, and cultural services. Examples of ecosystem services include the provisioning of freshwater for human use (provisioning service), water flow regulation, erosion control, soil fertility maintenance (regulating and maintenance services), and recreation (cultural service) (MA 2005; Haines-Young and Potschin 2014). Another ecosystem service category, known as ecological integrity, describes the ability of ecosystems to provide various ecosystem services, including supporting services such as biodiversity (Burkhard et al. 2009).

Natural land cover plays an important role to maintain and provide many vital ecosystem services. For example, the natural vegetation "Fynbos" and grassland maintain water and soil related ecosystem services including water flow regulation, soil retention, soil accumulation, and carbon storage (Egoh et al. 2009, 2011). The physical, chemical and biological properties of soils are a good indication of soil quality and landscapes in their natural state maintain such properties (Mills and Fey et al. 2004). Natural land cover furthermore provides habitat that is crucial for biodiversity intactness (Scholes and Biggs 2005) and maintenance (Burkhard et al. 2009).

The decline in natural land cover as a result of land use activities are inevitable in order to meet the demands that humans place on the environment for their well-being. Land use activities that are needed to ensure the provisioning of ecosystem services such as food and energy are often at the expense of other vital ecosystem services (Burkhard and Kroll 2010). Agricultural activities and urban development especially contributes to the loss of ecosystem services. Critical source areas for sediment and nutrient inputs are from agricultural activities (Gebel et al. 2017). Increasing sedimentation due to agricultural activities presumably causes a loss of erosion control, whereas sediment, nutrient, and other harmful chemical inputs (Meybeck 2003; Foley et al. 2005; Vörösmarty et al. 2010) contribute to a loss of the capacity of landscapes to maintain water quality (Lima et al. 2017). Agricultural activities cause a loss of soil carbon (Collard and Zammit 2006; Polasky et al. 2011), soil erosion, and crusting of soils (Mills and Fey 2004). Crusting of soils in agricultural areas furthermore influence the infiltration rates (Robinson and Phillips 2001; Mills and Fey 2004). Therefore, there is a substantial loss of soil quality maintenance in areas that are subject to agricultural activities (Lima et al. 2017). Urban development also contributes extensively to a loss of soil quality maintenance (Lima et al. 2017). A decrease in water quality and quantity and an increase in flood risks can be a result of urbanization (Bello et al. 2017). The loss of natural habitats due to urbanization contributes to a loss of biodiversity (Sumarga and Hein 2014; Lima et al. 2017), water flow regulation, and water purification (Rojas et al. 2019).

1.1.2 Land use activity impacts on the provision of good quality water

The provisioning of good quality water is an ecosystem service that is fundamental for a sustainable globe (WWAP 2015). Polluted and scarce water resources significantly threaten human well-being and biodiversity (Vörösmarty et al. 2010). Growing populations and intensifying land use activities place greater pressure on ecosystems to deliver good quality water for human use and to support healthy aquatic habitats (Brauman et al. 2007, 2015). The supply of water is generated by terrestrial ecosystems and therefore subject to extensive impacts from land use activities (Brauman et al. 2007, 2015).

Water sources are vulnerable to anthropogenic pollutants such as pesticides, fertilizers, heavy metals, nutrients, organic compounds, and microbes resulting from land use activities (Lenat and Crawford 1994; Meybeck 2003; Geriesh et al. 2004; Foley at al. 2005; Vörösmarty et al. 2010; Lawniczak et al. 2016). Water sources in regions with the highest human-induced activities are the most polluted, especially because of intense agricultural activities and expanding urban development (Howarth et al. 1996; Shukla et al. 2018). Agricultural activities are a major source of nutrients reaching groundwater, streams, rivers, and coastal ecosystems (Foley et al. 2005). The nitrogen concentrations of groundwater and surface water are high in agricultural catchments, principally due to fertilizer applications (Lawniczak et al. 2016). Increasing dissolved nitrogen is present in the streams that are located in areas of agricultural activities and urban development, with metal concentration being particularly high for the streams in urban sites (Lenat and Crawford 1994). Pollution of water sources in urbanized regions mainly occurs in areas of wastewater disposal, especially if the wastewater treatment is ineffective or absent (Bennett et al. 2001; Foley et al. 2005). Furthermore, ammonium input from settlements (Lorz et al. 2012) and sediment input from agricultural activities (Gebel et al. 2017) and urban development (Franz et al. 2013) contribute to a decrease in river water quality.

Densely populated coastal regions are subject to a very high land use pressure. Areas of such coastal regions are located in the hydrological cycle water rich region and at the interface between freshwater and sea water systems. Polluted coastal groundwater can therefore contribute to the pollution of estuarine and marine ecosystems through submarine groundwater discharge (SGD). SGD involves the transfer of groundwater from land to sea (Church 1996) essentially connecting coastal groundwater with coastal marine and estuarine ecosystems (Figure 1). The anthropogenic impacts from land use activities may therefore increase the nutrient concentrations of SGD (Lapointe 1997; Bowen et al. 2007). Groundwater discharge into coastal zones containing high loads of nutrients leads to eutrophication and ultimately affects the coastal ecosystem dynamics negatively (Lapointe 1997; Bowen et al. 2007).

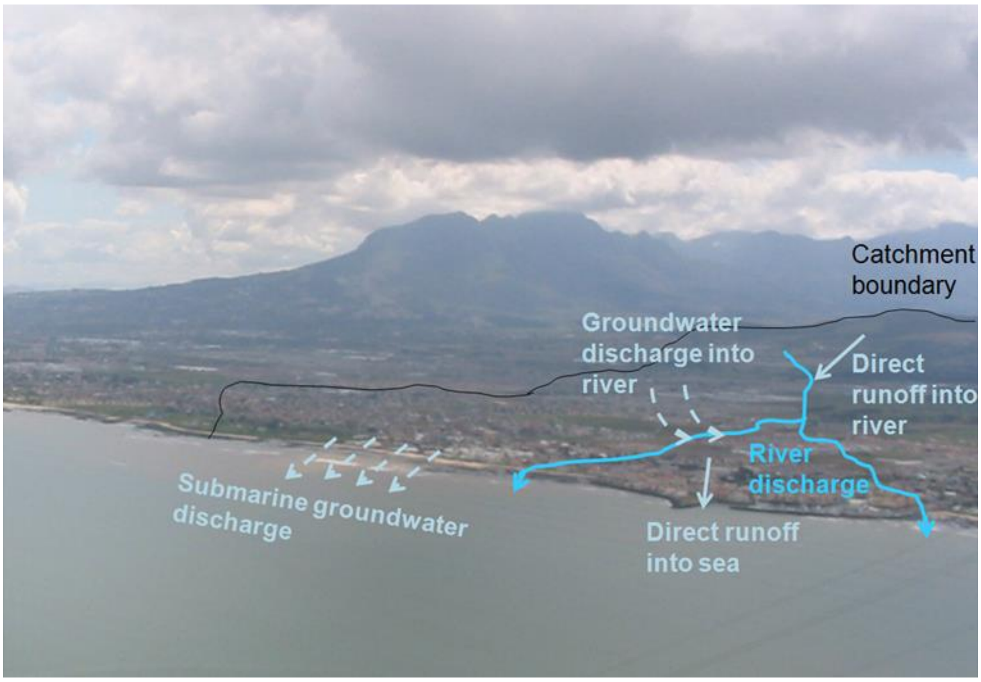

Figure 1: *Representation of submarine groundwater discharge in a catchment*

1.2 State of the art robust approaches to assess the impacts of land use activities on ecosystem services

Populations are growing worldwide (Bongaarts et al. 2009) along with associated intensification of land use activities. The undesirable impacts of land use activities on ecosystem services will continue to increase. Decision-makers are therefore continuously confronted to fill the critical gaps in their knowledge regarding the impacts that land use activities have on ecosystem services. Understanding the relationship between land use/land cover (LULC) and ecosystem services, and LULC and water quality is an important step to support managers with decision-making.

A number of modelling tools and assessment approaches incorporate LULC to assess and map the impacts of land use activities on ecosystem services and/or water quality. Mapping approaches are useful to recognize ecosystem services in decision-making and land management strategies (De Groot et al. 2010; Burkhard et al. 2012a; Crossman et al. 2012; Maes et al. 2016). Such approaches facilitate the quantification and visualization of spatial information related to the capacity of ecosystems to provide or maintain ecosystem services derived from complex systems (Crossman et al. 2012; Maes et al. 2016). Raster based mapping approaches that assess certain regulating services such as sedimentation retention (Lorz et al. 2013) and water purification

(Koschke et al. 2014) furthermore facilitate to identify the land areas and associated land use activities contributing to the potential pollution of water sources. Mapping of groundwater resources in order to determine the risk of groundwater pollution from land use activities facilitates to ensure the long-term protection of groundwater (Hadžić et al. 2015).

Table 1 lists models and assessment approaches that can be used to determine, visualize, and/or map the effects that LULC have on ecosystem services or water quality. The table is complemented with the required input data, the target ecosystem services and/or water source type to be assessed, their relative complexity and accuracy, and the methodology and or tools involved.

Table 1: *Models and assessment approaches to assess the effects of LULC on ecosystem services*

Name	Input	Output	Complexity	Accuracy	Methodology/ Tools	References
SWAT	Time-series data - LULC, climate, DEM, soil	Hydrological ecosystem services Water quality	High	High	Mathematical computational model	Duku et al. 2015 Dabrowski 2014
SWIM	Time-series data - LULC, climate, soil	Hydrology Water quality	High	High	Mathematical computational model GIS	Hesse et al. 2013 Krysanova et al. 1998
MODFLOW	Time-series data - water level and flow Measured contaminant data	Groundwater flow and quality	High	High	Mathematical computational model	Natesan and Deepthi 2012a,b
Statistical models	Measured contaminant and LULC data Spatial data - LULC, DEM, Geological	Water quality (Nutrient concentrations)	High	High	Statistical analyses GIS	Greene et al. 2013 Ali et al. 2017
USLE RUSLE	LandSat LULC Climate Soil DEM	Soil erosion	Moderate	Moderate to high – depending on public input data	Mathematical computational model GIS Public data	Blanco and Nadaoka 2006 Ashiagbor et al. 2012 Bouderbala et al. 2018
InVEST	LULC Biotic and abiotic parameters	Multiple ecosystem services	Low to high	Varies	Integrated approach Suite of models Vary in complexity GIS	Holfeld et al. 2012 Ochoa and Urbina-Cardona 2017

GISCAME LETSMAP	LULC DEM Soil map River network Lakes	Water purification Sediment retention Water retention Runoff control	Low to moderate	Low to moderate estimation	Web-based Raster-based Landscape properties and potentials Public data and published literature	Lorz et al. 2013 Koschke et al. 2014
Spatially explicit ecosystem service matrix approach	LULC DEM Soil map River network	Erosion control Runoff control Water quality Maintenance Water supply Biodiversity maintenance Soil quality maintenance	Low	Low to moderate estimation	GIS Landscape properties Public data and published literature	Lima et al. 2017
DRASTIC (modified)	LULC DEM Hydrogeo-logical map	Groundwater quality	Low	Low to moderate estimation	GIS Landscape properties Public data, published literature and expert knowledge	Secunda et al. 1998 Al-Adamat et al. 2003 Panagopoulos et al. 2006 Jayasekera et al. 2011 Shirazi et al. 2013 Vithanage et al. 2014
Spatially explicit ranking approach	LULC DEM Soil map Surface water network	Water quality (diffuse nitrate)	Low	Low to moderate estimation	GIS Landscape properties Public data, published literature and expert knowledge	Orlikowski et al. 2011
Ecosystem service matrix Approach	LULC	Multiple ecosystem services	Low	Low estimation	GIS Public data, published literature, and expert knowledge	Burkhard et al. 2009 Burkhard et al. 2012b Burkhard et al. 2014
Ordinal rating approach	LULC	River water quality	Low	Low estimation	GIS Public data, published literature and expert knowledge	O'Farrell et al. 2015

1.2.1 Applications of complex modelling tools

Complex models include the Soil and Water Assessment Tool (SWAT), the Soil and Water Integrated Model (SWIM), the Modular Three-Dimensional Finite-Difference Groundwater Flow Model (MODFLOW), and statistical models (Table 1). Even though the complexity among these models does vary, their complexity and accuracy compared to other assessment approaches listed in Table 1 are high. SWAT is a catchment-scale model developed to quantify and map hydrological ecosystem services (Duku et al. 2015; Ochoa and Urbina-Cardona 2017; Lüke and Hack 2018). The model also quantifies the transfer of pollutants from land to water (Dabrowski 2014). The SWIM model conducts detailed modelling of the chemical and nutrient pathways and fluxes in order to establish water quality (Hesse et al. 2013). The MODFLOW model determines the pollution of groundwater from watercourses (Natesan and Deepthi 2012ab). Statistical models are mainly used to relate data on measures of land use activity impacts to measures of water quality (Greene et al. 2013; Ali et al. 2017) in order to predict nutrients entering rivers (Greene et al. 2013) and to determine nutrient concentration discharge (Ali et al. 2007). Most models include the quantification of only one or two selected ecosystem services at a time. For example, the Universal Soil Loss Equation (USLE) and modifications thereof, the Revised Universal Soil Loss Equation (RUSLE) are well-known models to determine and map soil loss (Blanco and Nadaoka 2006; Ashiagbor et al. 2012; Bouderbala et al. 2018). The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model can however be implemented with low complexity but will be introduced here. The complexity and accuracy of the InVEST model varies from low to high (Table 1) because the needs of the user dictate the integrated models selected and therefore the extent and complexity of the input data and consequently the modelling process (Holfeld et al. 2012; Ochoa and Urbina-Cardona 2017). The model has been extensively used in order to spatialize multiple ecosystem services and to identify trade-offs among ecosystem services at the landscape level (Goldstein et al. 2012; Holfeld et al. 2012; Ochoa and Urbina-Cardona 2017).

1.2.2 Applications of knowledge-based assessment approaches

Various knowledge-based assessment approaches to assess and map the effects of LULC on ecosystem services and/or water quality exist. These assessment approaches are based on facts, existing information and assumptions. They can therefore be considered as simplified assessment approaches. Simplified assessment approaches include GISCAME, LETSMAP, the modified DRASTIC approach, the matrix approaches, and ordinal rating and ranking approaches.

Compared to the complex models, the application of the simplified assessment approaches are less complex (Table 1). Simplified assessment approaches rely on freely available public data, literature and expert knowledge. The accuracy of the results obtained from these approaches is therefore low in comparison to the complex models. To ensure spatially explicit assessments, approaches also include landscape properties and potentials. This increases the accuracy of the estimation results obtained when assessing the impacts of land use activities on ecosystem services and water quality (Table 1).

GISCAME and LETSMAP are web-based software developed assessment approaches that are used for the assessment of ecosystem services. These raster-based approaches calculate the contribution of LULC to the provisioning of ecosystem services on relative scales. The assessment of LULC vs ecosystem services are based on standardized indicator values. For a spatially explicit assessment, landscape properties and potentials that indicate the capacity of the natural ecosystem to provide certain ecosystem services are also considered. The methods that are used to assess the landscape potentials are relatively easy because they are based on qualitative standardization of the input parameters (Lorz et al. 2013; Koschke et al. 2014). In cases that the selected parameter values are not readily available, mathematical calculations are required in order to obtain such values (Lorz et al. 2013). The application of lengthy mathematical calculations therefore depends on the ecosystem services and related landscape potentials selected by the user. The GISCAME and LETSMAP approaches have been implemented for the Pipiripau river basin situated in the Cerrado biome of Brazil (Lorz et al. 2013; Koschke et al. 2014)

The matrix approach is a simplified and robust mapping approach that relates LULC classes to ecosystem services according to the capacity of the landscape to provide or maintain the ecosystem services (Burkhard et al. 2009, 2014). The assessment approach is based on the concept of ecological integrity and the indicators identified for ecosystem structures and processes. The scores to link LULC with ecosystem services are given by the authors based on an evaluation of available case studies and literature on the ecosystem service indicators as well as inputs from consulting experts in the field (Burkhard et al. 2009, 2012b, 2014). The relative scale of the scores are from “0” to “5,” where “0” indicates no capacity and “5” indicates the highest capacity of the landscape to provide or maintain an ecosystem service. These scores can be adapted as more exact modelling and measurement data become available. The approach facilitates to identify the land areas contributing to a loss and/or gain of ecosystem services due to land use activities (Burkhard et al. 2009, 2014). The final ecosystem service supply and budgets can also be determined by including a scoring matrix that relates LULC classes with ecosystem services according to the demands that humans place on ecosystems (Burkhard et al. 2012b). Case studies to visualize the provisioning of food (Burkhard et al. 2009), and the energy supply and demand budgets (Burkhard et al. 2012b) have been done in the Leipzig-Halle region in eastern Germany. A matrix approach developed by Lima et al. (2017) simply scores landscape properties relevant to each ecosystem service as an additional scoring matrix based on knowledge gained from the available literature and inputs from experts. The former approach is the most simplest to ensure a spatially explicit assessment and has been implemented for the Sarandi Catchment situated in the Cerrado biome of Brazil (Lima et al. 2017).

The DRASTIC approach, initially developed for the United States Environmental Protection Agency (Aller et al. 1987) is a standardized approach assessing groundwater vulnerability using Geographic Information Systems (GIS) software. The DRASTIC approach is generally used to gain a spatial overview of groundwater vulnerability based on the environment's physical conditions (Aller et al. 1987). The parameter classes include depth to water table, recharge, aquifer media, soil texture, topography, impact of vadose zone, and hydraulic conductivity. These classes are rated according to the hydrogeological settings of a particular region. Ratings may be done by referring to literature and/or using expert knowledge. The DRASTIC approach omits the potential contribution of anthropogenic impacts on groundwater vulnerability. This is considered a major shortcoming in regions subject to high human activity. Modifications of the DRASTIC approach include the incorporation of LULC to assess the groundwater pollution risk from land use activities. LULC classes are rated based on expert knowledge (Secunda et al. 1998), referring to literature (Al-Adamat et al. 2003; Panagopoulos et al. 2006; Musekiwa and Majola 2013; Shirazi et al. 2013), or, if available, using existing data (Jayasekera et al. 2011; Vithanage et al. 2014). The DRASTIC approach and modifications thereof consistently deliver reliable results and have been implemented in many regions worldwide.

A simplified and robust assessment approach to estimate the relative impacts of land use activities on river water quality on a reach-by-reach basis includes an ordinal rating system that links LULC with water quality. Scores are assigned using expert knowledge regarding land use management practices such as application of fertilizer, pesticides and herbicides, tillage and rotation practices, and the effectivity of wastewater treatment. LULC classes are given estimated impact scores according to the likelihood of freshwater sources being affected by chemical, sediment, and nutrient inputs. The impact scores are given on a scale from "1" to "3" to each of the previously mentioned variables, where "1" indicates a low impact and "3" indicates a high impact. The cumulative impact scores are calculated for buffers of different widths around the river reaches to assess the relative impacts of LULC per river reach. (O'Farrell et al. 2015). This approach facilitates to identify sub-catchments where the estimated impacts of land use activities on the river water quality are relatively high (O'Farrell et al. 2015). It has been applied to the Wilderness (Touws) River (O'Farrell et al. 2015), Berg River, and Olifants River network systems located in South Africa. Another approach identifies risk areas of potential diffuse nitrate reaching surface water for a catchment located in Côtes-d'Armor, France (Orlikowski et al. 2011). To identify the final risk areas, this approach simply classifies LULC and relevant landscape properties including soil, slope, riparian buffer strips, and distance to river network in three risk classes from low to high (Orlikowski et al. 2011).

1.2.3 Problem statement: Complex models vs knowledge-based assessment approaches

Complex modelling tools are rather time-consuming and difficult to apply (Lüke and Hack 2018). A major drawback of complex models is that they require a high amount of time-series data in order to calibrate the input parameters of a specific region (Duku et al. 2015). The application of such models is furthermore time-consuming because pre-processing of the input data is generally needed (Lüke and Hack 2018). A considerable amount of computing time is required to increase the spatial resolution of the input data, especially because high-resolution spatial data is not available for many regions of the world (Duku et al. 2015). The high level of expertise and training efforts to apply complex models make their application furthermore challenging and time-consuming (Lüke and Hack 2018). Applying complex models in some parts of the globe may be feasible; however, many regions lack sufficient expertise and suitable data that is freely available (Lüke and Hack 2018).

The high data, time, and expert requirements in order to use the complex approaches make it important to direct research to assessment approaches that are simpler and relatively fast to apply. The implementation of simplified assessment approaches is therefore especially important for data scarce regions (Burkhard et al. 2009; Viossange et al. 2018). As highlighted in the previous section, simplified and robust assessment approaches that are based on available data, literature, and if needed expert knowledge are relatively easier and more efficient to apply. Even though a disadvantage of such approaches are the relative low accuracy of the output results, the findings from such approaches will facilitate with timely decision-making in order to enhance management strategies (Secunda et al. 1998; Maes et al. 2016). Findings will also assist to identify the type and location of further in-depth research that requires costly resources.

Improvements and adaptations of already existing simplified assessment approaches might give results that are more reliable. Improving and adapting existing approaches are possible since the availability of data is not the same for all regions or new data may become available for a specific region. The increase in available knowledge furthermore facilitates to build on existing assessment approaches. It is also important to test the effectiveness of different versions of assessment approaches, especially since regions may differ considerably concerning LULC and the environment. Findings from the improved versions will enhance existing knowledge regarding the complex interactions including the landscape, land use activities, and ecosystem services. Obtaining results that are more reliable in a relatively fast manner will also facilitate management authorities and stakeholders to outline management strategies.

The southern coastal region of the Western Cape Province (WCP) situated in South Africa is subject to intense land use activities (DEAP 2005). The intensifying land use activities and the regional characteristics make this region suitable for developing and testing the effectiveness of improved simplified assessment approaches. The results from the improved versions will facilitate to identify the risk areas and the associated land use activities that contribute to the (i) loss of ecosystem services, and the (ii) potential pollution of groundwater and (iii) river water.

1.2.4 Shortcomings of existing knowledge-based assessment approaches

The loss of ecosystem services and the potential pollution of groundwater and river water as a result of land use activities can be assessed and mapped by implementing the selected simplified assessment approaches listed in Table 2. Table 2 gives a short overview of the shortcomings identified for the selected assessment approaches. Further information regarding the shortcomings is given in this section.

__Table 2:__ An overview of the shortcomings identified for selected simplified assessment approaches

Simplified assessment approach	**Output**	**Shortcomings**	**References**
Ecosystem service matrix approach	Multiple ecosystem services	Excludes landscape properties and potentials	Burkhard et al. 2009, 2012b, 2014
Spatially explicit ecosystem service matrix approach	Selected group of ecosystem services (Table 1)	Only implemented in one location Not tested for other ecosystem services	Lima et al. 2017
DRASTIC (modified with LULC)	Groundwater quality	No LULC parameter has been used to identify groundwater areas that are most likely already polluted No easy to apply spatial assessment linking LULC to delineated submarine groundwater discharge areas exist	Secunda et al. 1998 Al-Adamat et al. 2003 Panagopoulos et al. 2006 Jayasekera et al. 2011 Shirazi et al. 2013 Vithanage et al. 2014
Ordinal rating approach	River water quality	Excludes landscape properties and potentials	O'Farrell et al. 2015
Spatially explicit ranking approach	Water quality (diffuse nitrate)	Excludes a reach-by-reach assessment of rivers	Orlikowski et al. 2011

The original matrix approach does not include landscape properties and potentials and is not spatially explicit (Burkhard et al. 2009, 2012b, 2014). Landscape potentials based on relevant landscape properties have been developed as additional input data (Lorz et al. 2013; Koschke et al. 2014); however, depending on the selected ecosystem services the calculations required to develop the landscape potentials are lengthy. The simplest version that exists includes an additional scoring matrix that simply scores the relevant landscape properties with each ecosystem service (Lima et al. 2017). The effectiveness of using a landscape property scoring matrix to provide supplementary data has been implemented for the Cerrado Biome in Brazil but has not yet been adapted and tested in another region.

The DRASTIC approach has been subject to various modifications and improvements. The most commonly known modification is the addition of LULC to the DRASTIC index in order to assess the pollution risk of groundwater from land use activities (Secunda et al. 1998; Al-Adamat et al. 2003; Panagopoulos et al. 2006; Jayasekera et al. 2011; Musekiwa and Majola 2013; Shirazi et al. 2013; Vithanage et al. 2014). However, if available, a more accurate LULC parameter known as diffuse nitrogen surplus in the rooting zone (DNS) can be incorporated instead in order to describe increasing groundwater nitrogen pollution risk that is caused specifically by land use activities. In addition, the incorporation of a second LULC parameter known as nitrogen concentration in the deep percolation (NC) will facilitate to describe the groundwater areas that are most likely already polluted by nitrogen. Furthermore, the pollution risk of coastal marine and estuarine water from land use activities by means of SGD has been described (Umezawa et al. 2002; Basterretxea et al. 2010; Knee et al. 2010; Young et al. 2015). However, linking LULC with delineated areas of polluted groundwater that may contribute towards SGD using a spatial assessment approach that is relatively easy to apply has not been addressed thus far.

Lastly, one drawback of the ordinal rating system linking LULC with river water quality is that the approach also does not include landscape properties and is not spatially explicit. Other simplified raster-based tools that assess the impacts of land use activities on river water quality by determining, for example, sedimentation retention (Lorz et al. 2013; Koschke et al. 2014) and nitrogen loss control (Lorz et al. 2013) do include landscape potentials that are based on relevant landscape properties; however, these approaches do not show the estimated impacts on a reach-by-reach basis.

1.3 Objectives of the thesis

The overall aim of the thesis is to improve and adapt existing simplified assessment approaches in order to assess the effects of LULC on landscapes using existing data. The improved versions address the shortcomings related to existing simplified assessment approaches. The improved approaches are tested for regions under intense land use activities along the southern coast of the WCP, South Africa. Two objectives are identified in order to achieve the aim of the thesis. The first objective is to improve and adapt assessment approaches in order to assess the effects of LULC on groundwater quality (Paper 1) and river water quality (Paper 2). The second objective is to improve and adapt an assessment approach to assess the effects of LULC on ecosystem services (Paper 3).

Objective 1:

Improve, adapt and implement assessment approaches to assess the effects of LULC on water quality. Water sources of the southern coastal region in the WCP, South Africa are known to experience much pressure because of anthropogenic impacts and drought events. Therefore, two papers focus on the provision of good quality water as an ecosystem service. In addition, two land use dominant study regions were selected to implement the assessment approaches.

Paper 1: Land use pollution potential of water sources along the southern coast of South Africa (Malherbe et al. 2018)

- Implement an improved version of incorporating LULC parameters to the DRASTIC approach in order to determine the groundwater nitrogen pollution risk and the areas of groundwater most likely to be already polluted by nitrogen. Submarine groundwater discharge contribution areas (SGD-CA's) contributing to coastal marine and estuarine nitrogen pollution are furthermore described.

Paper 2: A simplified method to assess the impact of sediment and nutrient inputs on river water quality in two regions of the southern coast of South Africa (Malherbe et al. 2019a)

- Implement an improved version of an ordinal rating system linking LULC and landscape potentials with river water quality in order to assess the estimated impacts of the sediment input and the nutrient input on a reach-by-reach basis.

Objective 2:

Improve, adapt and implement a simplified assessment approach to assess the effects of LULC on ecosystem services. A land use dominant study region located along the southern coast of the WCP in South Africa was identified to implement the approach.

Paper 3: Mapping the loss of ecosystem services in a region under intensive land use along the southern coast of South Africa (Malherbe et al. 2019b)

- Implement an improved version of a simplified mapping approach to identify the high-risk areas that show a loss of ecosystem services as a result of land use activities.

1.4 Structure of the thesis

Section 1 includes the general background and the state of the art in order to identify the problem statement and shortcomings, and the objectives with and overview of three published papers. Section 2 highlights the overall methodologies to meet the aim and objectives of the thesis. The key methodologies for each paper are also given. Section 3 gives the summary of key results related to the improved assessment approaches for each paper. Section 4 gives an overall discussion of the land use activity impacts from the improved assessment approaches in relation to other research. Section 4 also includes the advantages and limitations of the improved and adapted assessment approaches. Section 5 gives a conclusion of the key results and the implications for land management (Figure 2).

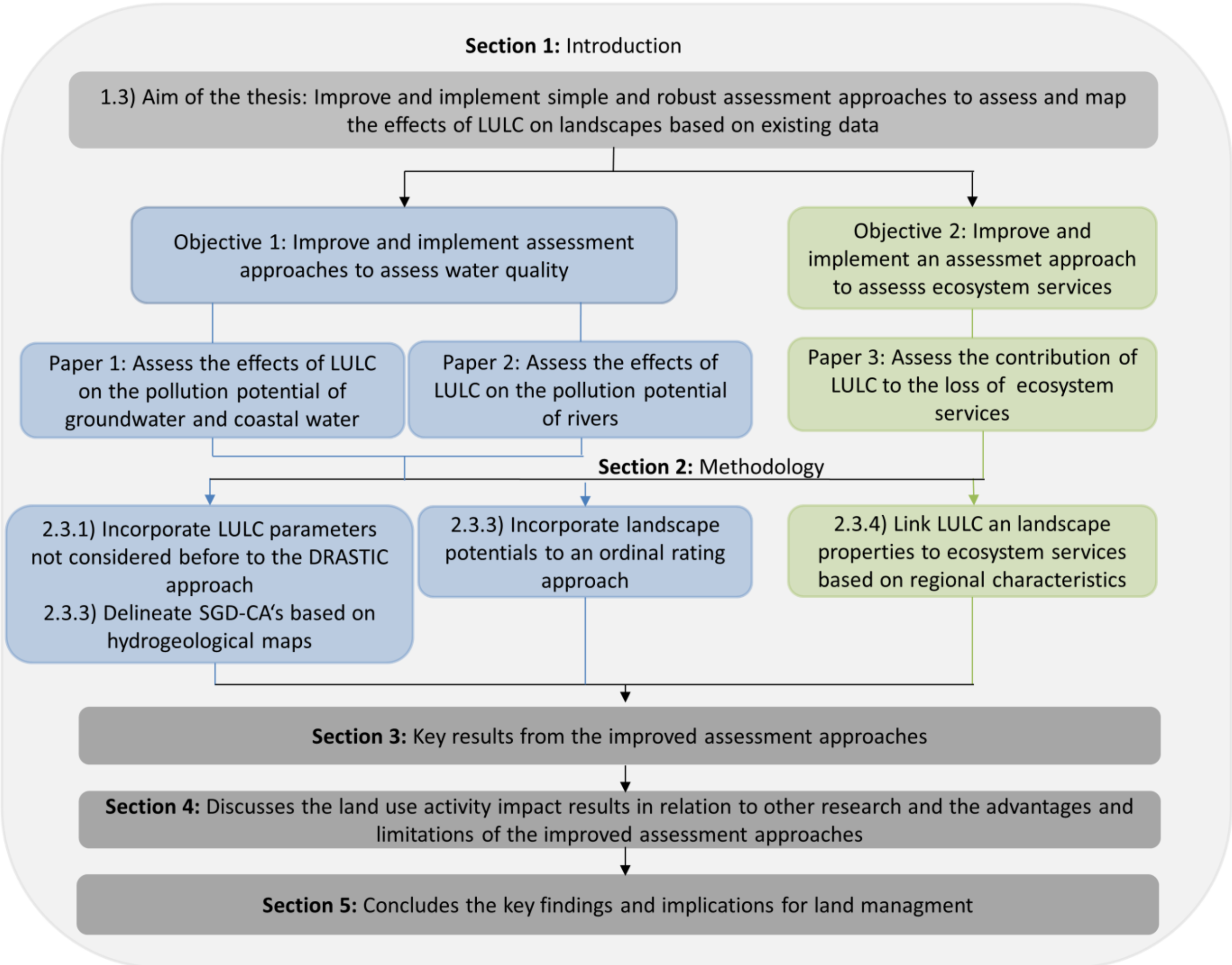

Figure 2: *Structure and overview of the thesis and related publications*
**SGD-CA - Submarine groundwater discharge contribution areas*

2 METHODOLOGY

This section presents the methodology applied to achieve the overall aim and objectives of this thesis. Firstly, the geographical focus and study regions are presented. Secondly, this section gives the overall research approach including data collection and data analysis. Thirdly, detailed methods to improve, adapt and develop the assessment approaches in order to achieve the aims and objectives of the three published papers are given. Water sources are experiencing much pressure along the southern coast of the WCP situated in South Africa and therefore two study regions were identified in order to assess the groundwater and river water quality. The study region that is subject to the most extensive land use activities was selected to assess the loss of ecosystem services.

2.1 Geographical focus

This study forms part of the Science Partnerships for the Assessment of Complex Earth System Processes (SPACES) project: groundwater/seawater interaction along the southern coast, WCP, South Africa and its effects on ecosystem services and sustainable water resource management. Project partners from the Helmholtz Centre for Environmental Research (UFZ) in Leipzig, Germany identified this coastal region because SGD-CA's were identified using remote sensing techniques. The selection of this coastal region favors this sub-project because of the intensification of land use activities experienced by the region and its regional characteristics. The variety of land use activities and the regional characteristics including the geology and topography make the southern coastal region ideal for the improvement, adaptation and implementation of the simplified assessment approaches in order to assess the region's water quality and selected ecosystem services.

The WCP has limited freshwater and has been experiencing water shortages due to prolonged drought events (Meissner and Jacobs-Mata 2016). The southern coastal region of the WCP experienced a significant population influx after, and presumably before, the political change in 1994. This has contributed to a considerable increase of urban development and land use activities (DEAP 2005). Dryland crop cultivation, irrigated vegetable cultivation, wine grapes and orchards are major land use activities covering extensive areas of this coastal region (DEAP 2011). These land use activities contribute to the pollution of water sources along the southern coast of the WCP (DEAP 2005). The demands placed on the environment to deliver good quality freshwater are increasing. Groundwater in the region has become an increasingly important source of freshwater for local scale irrigation and domestic use (Adams et al. 2015). Therefore, land managers place greater emphasis on protecting the groundwater (Meissner and Jacobs-Mata 2016). Knowledge of the impacts of land use activities on groundwater also lags behind that of surface water (Adams et al. 2015), and must be addressed. In addition, there is no information linking LULC, groundwater and SGD for this coastal region. Such a link will facilitate to identify the areas where polluted groundwater may contribute towards SGD and subsequently influence coastal waters. Large proportions of the river ecosystems in the region are known to be in a poor state and many river reaches are affected because of land use activities (Driver et al. 2004; Nel et al. 2007). It is therefore important to have a better understanding of the estimated impacts of land use activities on the water quality of the rivers located in this coastal region.

Nationally important soil- and water- related ecosystem services, including water flow regulation and soil retention are supported along the southern coast of the WCP (Egoh et al. 2008, 2009). Soil erosion does occur in areas of the southern coastal region (Gebel et al. 2017) and much of the water sources are known to be in a poor state (Nel et al. 2007). The loss of habitat in the region also threatens the biodiversity (Pool-Stanvliet et al. 2018). The ongoing increase in population along with intensifying land use activities might cause a potential loss of certain ecosystem services, including erosion control, water flow regulation, water quality maintenance, soil quality maintenance and biodiversity maintenance.

Two study regions situated along the southern coast of the WCP in South Africa were used for this research. The regions were described as the western region (WR) and the eastern region (ER). The methodologies for paper 1 and paper 2 were implemented for the WR and the ER, whereas the methodologies for paper 3 were only implemented for the WR. Figure 3 shows the locations of the two study regions.

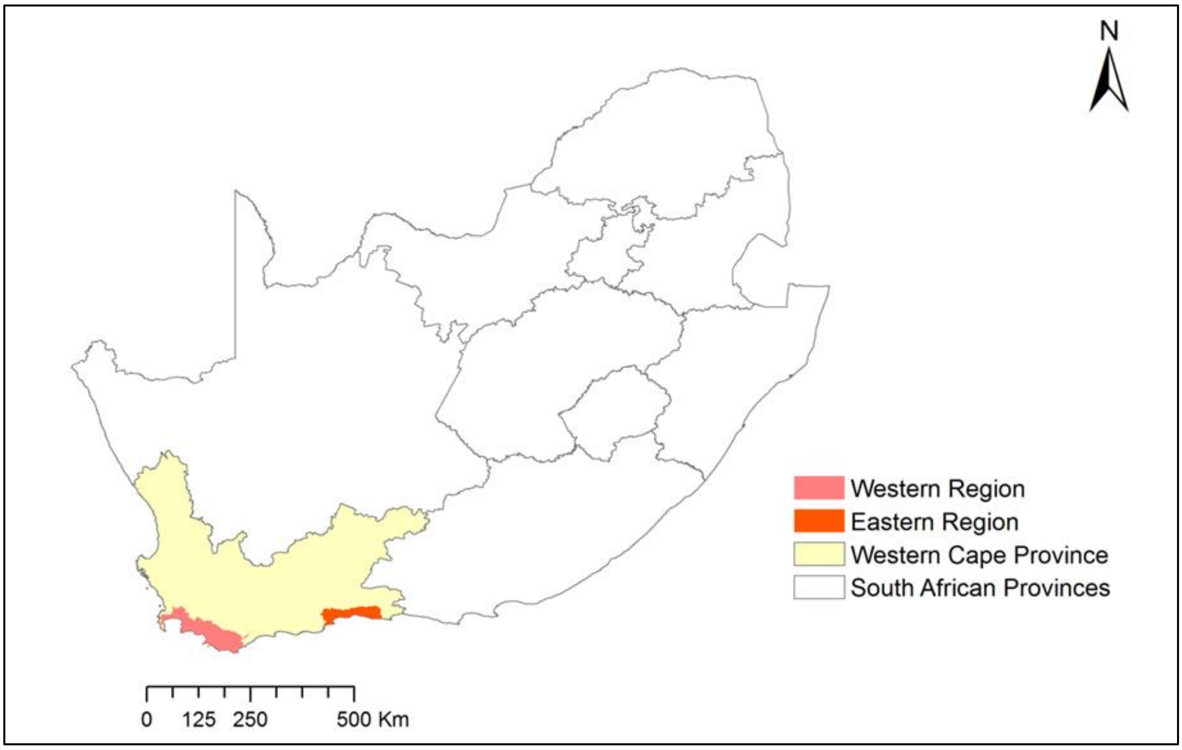

Figure 3: *Location of the study regions along the southern coast of the Western Cape Province, South Africa*

The WR extends along the coastline from Cape Point (34°21'S; 18°28'E) to 22 km east of Struis Bay (34°48'S; 20°03'E). It extends approximately 50 km inland and includes regions of the Cape Flats, the Cape Winelands District, and the Overberg District, covering a land surface area of 643,542 ha. The ER extends along the coastline, 15 km west of Mossel Bay (34°11'S; 22°8'E) to 12 km east of Knysna (34°04'S; 23°03'E). It is located in the Eden District, extending a maximum of 38 km inland and covering a land surface area of 285,735 ha.

The study regions are characterized by a Mediterranean climate of hot and dry summer seasons, rainy winter seasons, and mild to warm autumn and spring seasons. A mean annual precipitation gradient exists along the southern coastal region extending eastward. The highest mean annual precipitation in the coastal and mountainous regions is 1000–1200 mm, whereas the lowest mean annual precipitation is measured eastward along coastal areas and the inland region at 200–400 mm (Lynch 2004).

National Land Cover data (Van den Berg et al. 2008), incorporating the 2013 map of Agricultural Commodities in the WCP (WCDA 2013), were used to represent the LULC for the WR and the ER (Figure 4).

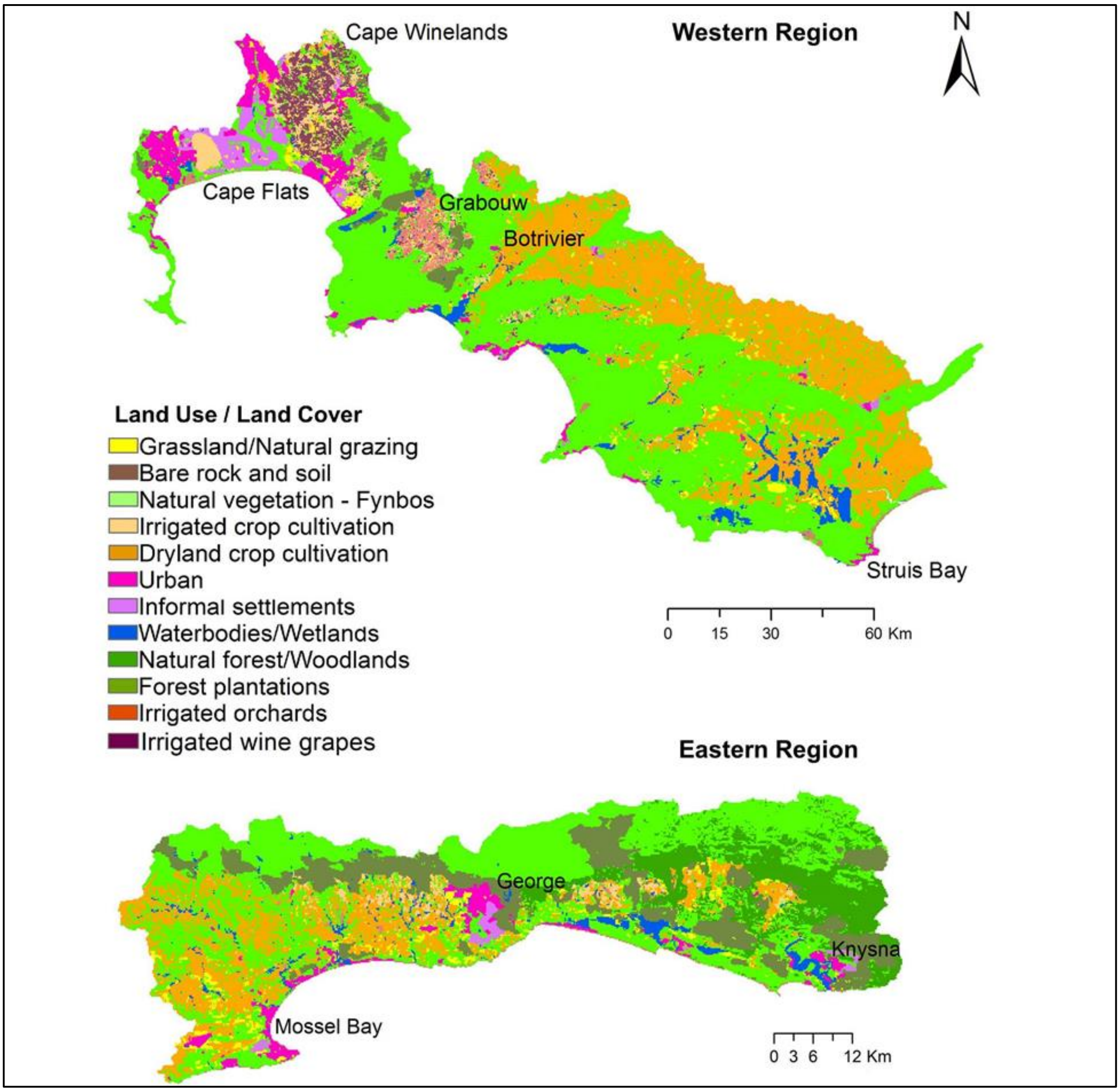

Figure 4: *Land use/land cover of the western region and the eastern region (Data sources: Van den Berg et al. 2018; WDCA 2013)*

Various land use types, including urban areas, agricultural land, forest plantations, and natural vegetation, are present in the study regions. The natural vegetation "Fynbos" is one of the biodiversity hotspots of the world (Goldblatt and Manning 2000). Fynbos covers much of the land surface along the coast and in the mountainous regions of both study regions. Natural vegetation in the ER also includes indigenous forests and woodlands. Other types of natural LULC include natural grassland, wetlands, and waterbodies.

Three major clusters of land use activities are evident for the WR (Figure 4). (i) The first cluster is in the Cape Flats/Winelands area in the western part of the study region. The Cape Flats portion primarily includes informal urban development and irrigated crop cultivation, and the Cape Winelands portion primarily includes formal urban development, irrigated production of wine grapes, and less extensively irrigated crop cultivation. (ii) The second cluster is in the Grabouw area and includes irrigated orchards and less extensively irrigated crop cultivation, whereas forest plantations border the irrigated orchards. (iii) The third cluster includes dryland crop cultivation covering much of the land surface from Botrivier extending eastward to Struis Bay.

The land use activity clusters of the ER can be divided into two large areas (Figure 4). (i) The first cluster extends towards the west from Mossel Bay to George. Dryland crop cultivation covers a large surface area. Irrigated crop cultivation are also practiced but less extensively. Urban development including formal and informal development includes Mossel Bay and other coastal towns east from Mossel Bay. Forest plantations are present in the mountainous areas. (ii) The second cluster extends from George eastward to Knysna. Dryland crop cultivation and irrigated crop cultivation are practiced less extensively. The principal urbanized area including formal and informal development is Knysna. Forest plantations are an important land use activity in this cluster.

2.2 Overall research approach

2.2.1 Data collection

To achieve the overall aim for this thesis freely available data was obtained and evaluated. A web-based literature review was done to collect and review all the available literature and case studies regarding simplified assessment approaches involving water sources and ecosystem services.

Table 3 gives an overview of the data sources, the institutes from which the data was collected, and additional details of the data that were required in order to meet the aims and objectives for each paper.

Table 3: *The data sources, the institutes from which the data was collected, and additional details of the data required for each paper*

Data source	**Institute**	**Additional detail**
Paper 1, 2 and 3		
LULC map	Weihenstephan-Triesdorf University of Applied Science (HSWT, data acquired 2014)	Modified after the 2000 National Land Cover data (Van den Berg et al. 2008) and the 2013 map of Agricultural Commodities (WCDA 2013)
Soil map	Harmonized World Soil Database (FAO 2012, data acquired 2014)	Extract the soil texture
DEM	Stellenbosch University Digital Elevation Model SUDEM (Van Niekerk 2015, data acquired 2015)	Create topography maps
Paper 1		
DEM Borehole data	Stellenbosch University Digital Elevation Model (SUDEM) (Van Niekerk 2015) National Groundwater Archive (DWS, data acquired 2014)	Create a depth to groundwater maps
Net groundwater recharge	Weihenstephan-Triesdorf University of Applied Science (HSWT, data acquired 2016)	WebGIS based model applying STOFFBILANZ (Gebel et al. 2017)
Hydrogeological map	1:500,000 hydrogeological map of South Africa (Meyer et al. 1999, 2001)	Crate aquifer media maps
Geological map	Helmholtz Centre for Environmental Research (UFZ unpublished material, data acquired 2015)	Modified after the Council for Geoscience 1990, 1993, 1997 Values assigned to post-processed lithologies Create hydraulic conductivity maps
Diffuse nitrogen surplus in the rooting zone	Weihenstephan-Triesdorf University of Applied Science (HSWT, data acquired 2015)	WebGIS based model applying STOFFBILANZ (Gebel et al. 2017)
Nitrogen concentration in the deep percolation	Weihenstephan-Triesdorf University of Applied Science (HSWT, data acquired 2015)	WebGIS based model applying STOFFBILANZ (Gebel et al. 2017)
Deep percolation rate	Weihenstephan-Triesdorf University of Applied Science (HSWT, data acquired 2015)	WebGIS based model applying STOFFBILANZ (Gebel et al. 2017)
Paper 2 and 3		
DEM	Stellenbosch University Digital Elevation Model SUDEM (Van Niekerk 2015, data acquired 2015)	Create river network and sub-catchment maps
Paper 2		
Rainfall intensity (R-factor) map	Department of Geography, University of the Free State, South Africa (Le Roux et al. 2006, 2008)	
Topsoil organic carbon content	Agricultural Research Council-Institute for Soil, Climate, and Water (ARC-ISCW) (Barnard 2000).	Create topsoil humus content maps
Soil map	Harmonized World Soil Database (FAO 2012, data acquired 2014)	Extract available soil water capacity

Paper 3		
Natural vegetation map	2006 natural vegetation map (Mucina and Rutherford 2006)	
Soil map	Harmonized World Soil Database (FAO 2012, data acquired 2014)	Create available water capacity in root zone maps according to the soil texture

2.2.2 Data analysis

From the literature, three simplified assessment approaches were selected and their shortcomings were identified. The methodologies applied in order to improve and adapt the selected assessment approaches were dependent on the available data.

Each of the three papers represents one of the selected assessment approaches. The methodological approaches for each of the papers were different. However, the basic principle for improving the assessment approaches was similar. This implies that the authors parameterized the input data based on available literature and knowledge.

The following three existing assessment approaches were selected:

- The DRASTIC approach (modified with LULC) in order to assesses the groundwater pollution risk as a result of LULC (Panagopoulos et al. 2006; Jayasekera et al. 2011; Shirazi et al. 2013; Vithanage et al. 2014) – Paper 1

- The ordinal rating approach that estimates the pollution risk of river water on a reach-by reach basis as a result of LULC (O'Farrel et al. 2015) – Paper2

- The spatially explicit ecosystem service matrix approach that is used to determine ecosystem service losses and gains as a result of LULC (Lima et al. 2017) – Paper3

2.3 Applied methodologies

The shortcomings of the three selected approaches are given in the introduction (Table 2). The required methods to meet the aims and objectives of each paper are given here. Data processing needed for each paper was done using ArcGIS version 10.1 software.

2.3.1 Groundwater quality assessment: Improving the DRASTIC approach

The DRASTIC approach is widely used to determine the groundwater vulnerability based on the following parameter classes; depth to water table, recharge, aquifer media, soil texture, topography, impact of vadose zone, and hydraulic conductivity (Aller et al. 1987). Modified DRASTIC approaches that incorporate LULC have been developed to assess the groundwater pollution risks (Panagopoulos et al. 2006; Jayasekera et al. 2011; Shirazi et al. 2013; Vithanage et al. 2014). This study incorporates nitrogen related LULC parameters not considered before in order to improve the DRASTIC approach. These LULC parameters include the DNS and the NC.

Firstly, a linear summation of the DRASTIC index with the DNS parameter was conducted (hereafter referred to as the D+DNS index). The product maps for each study region describe the groundwater nitrogen pollution risk. Secondly, a linear summation of the DRASTIC+DNS index with the NC parameter was conducted (hereafter referred to as the D+DNS+NC index). The product maps also known as the hotspot maps for each study region describe the groundwater areas that are most likely already polluted by nitrogen. A work flowchart representing the linear summation to create the groundwater vulnerability, groundwater nitrogen pollution risk, and hotspot maps are given in Figure 5.

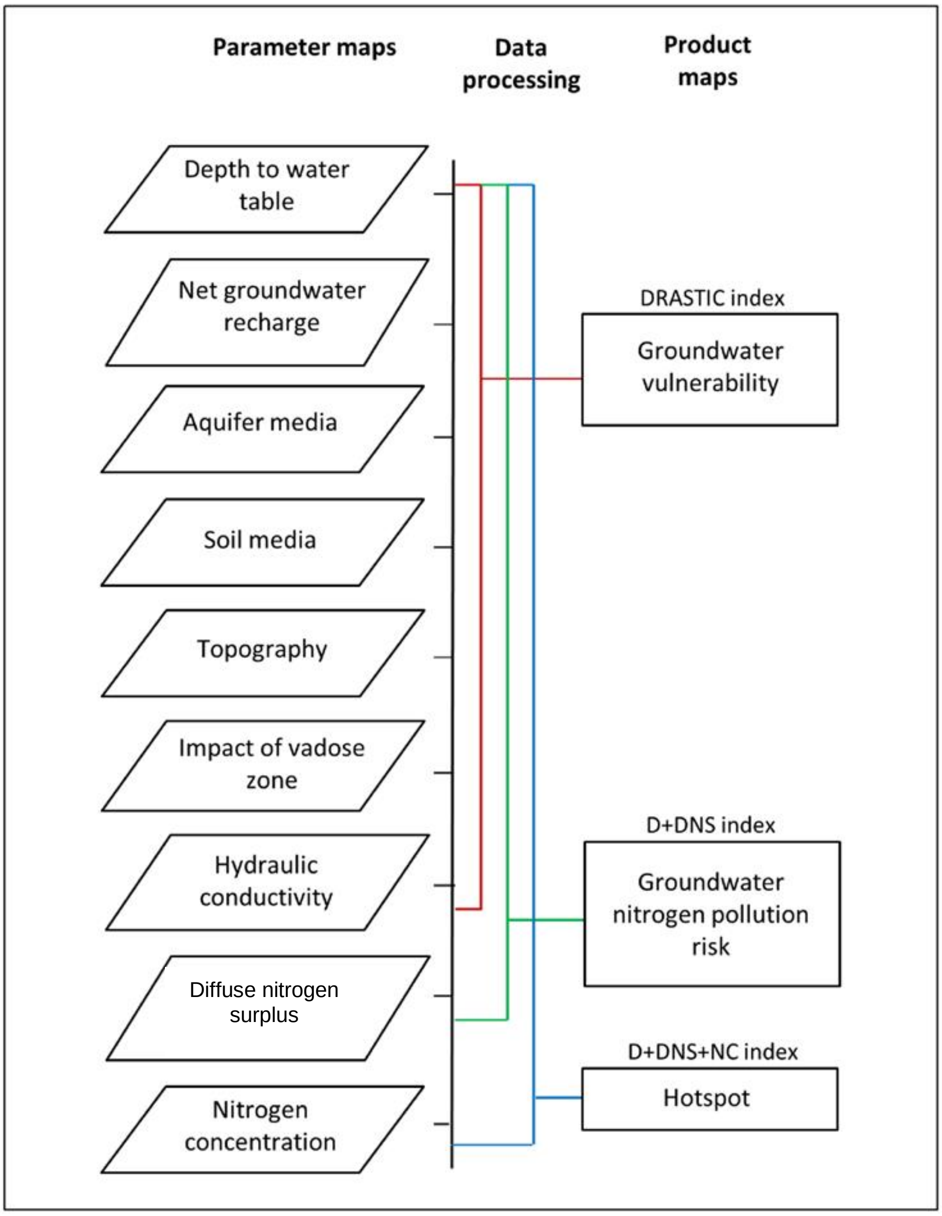

Figure 5: *Work flowchart representing the linear summation of the DRASTIC index with the LULC parameters*

Weights were allocated on a scale of “1” to “5” according to the contribution of each of the DRASTIC parameters to groundwater vulnerability, with “5” contributing the most and “1” contributing the least to groundwater vulnerability. The DNS and NC parameters were each allocated the highest weight of “5” because these parameters contribute the most to groundwater nitrogen pollution risk and nitrogen concentration in the groundwater. Each class or range given to the DRASTIC, DNS, and NC parameters were rated on a scale of “1” to “10.” Rating of each parameter describes the relative importance of each range or class in terms of groundwater vulnerability, nitrogen pollution risk and nitrogen concentration in the groundwater, with "10" being the most significant and "1" the least significant. Details regarding the allocation of weights and rates are given in appendix A, paper 1 (Malherbe et al. 2018).

The specified equations to determine the DRASTIC, D+DNS, and D+DNS+NC indices are given in appendix A, paper 1 (Malherbe et al 2018), where a high DRASTIC index indicates high groundwater vulnerability, a high D+DNS index indicates high groundwater nitrogen pollution risk and a high D+DNS+NC index indicates hotspot areas.

2.3.2 Delineating the submarine groundwater discharge contribution areas

To delineate the SGD-CA's the assumption was made that surface catchments located in the coastal intergranular areas represent subsurface catchments. Based on this assumption sandy aquifer areas were delineated from the 1:500,000 hydrogeological maps. The sandy aquifer areas that do not have river outlets contribute to SGD, and were identified as SGD-CA's. The SGD-CA's located in hotspot areas and that have a high groundwater contribution potential are likely to result in groundwater with increased nitrogen concentrations reaching marine and estuarine environments. The SGD-CA's with deep percolation rates greater than 50 mm a^{-1} were considered as areas with a high groundwater contribution potential to SGD.

2.3.3 River water quality assessment: Improving an ordinal rating approach

An ordinal rating approach has been applied to determine the relative impact scores of LULC on river water quality on a reach-by-reach basis (O'Farrell et al. 2015). This approach relies on expert knowledge about land management practices in order to assign LULC classes with estimated impact scores according to the likelihood of the water sources being affected by a) sediments, b) nutrients, and c) chemical pollutants. The cumulative impact scores per river reach for each of the latter pollutants can be calculated separately. For this study, the ordinal rating approach was improved by incorporating landscape potentials. This was achieved by incorporating (i) the landscape sediment generation potential to determine the improved sediment input, and (ii) the diffuse nitrate pollution potential to determine the improved nutrient input. A work flowchart for the development of the improved assessment approaches are given in Figure 6 followed by an overview of the three principle steps.

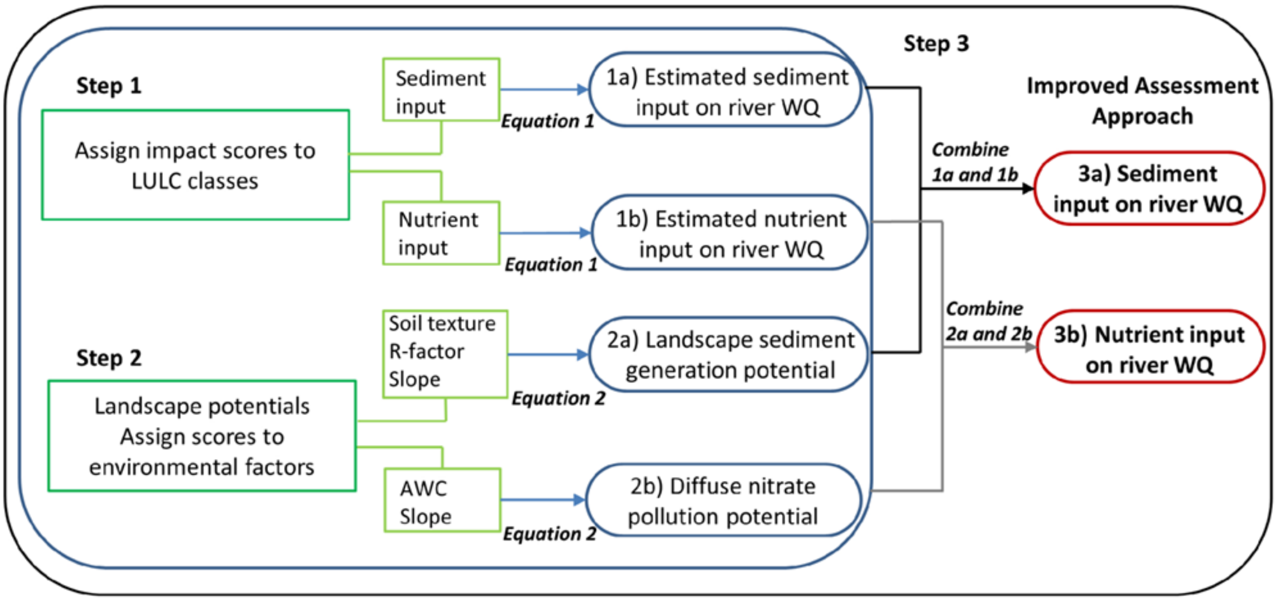

Figure 6: *Work flowchart for the development of the improved assessment approaches: sediment input on river water quality and nutrient input on river water quality*
**WQ – Water quality*

In Step 1, an assessment of the estimated impacts of 1a) the sediment input on the river water quality and 1b) the nutrient input on the river water quality based only on LULC was done. The impact scores for both the sediment and nutrient inputs were given to each LULC class on a scale from "1" to "3," where "1" indicates a low impact and "3" indicates a high impact. Details regarding the allocation of the estimated impact scores for each LULC class are given in appendix B, paper 2 (Malherbe et al. 2019a). Mean impact scores for the sediment and nutrient inputs were calculated for buffers of different widths around the river reaches. The equation that was used to combine and weight the mean impact scores in order to calculate the final impact scores of the sediment input and nutrient input on a reach-by-reach basis is given in appendix B, paper 2 (Malherbe et al. 2019a).

In Step 2, the landscape potentials, 2a) the landscape sediment generation potential and 2b) the diffuse nitrate pollution potential, were estimated using relevant environmental factors. The environmental factors were classified and scored according to the potential contribution of each class to the landscape potential. For this study, the environmental factors were rated on a scale from "1" to "5," where "1" indicates the lowest potential contribution and "5" indicates the highest potential contribution. The environmental factors used to determine the landscape sediment generation potential include soil texture, the slope, and rainfall intensity (Marks et al. 1999; Lorz et al. 2013; Koschke et al. 2014; Lima et al. 2017) and to determine the diffuse nitrate pollution potential include the available soil water capacity and slope (Orlikowski et al. 2011; Koschke et al. 2014). Details regarding the classification and the allocation of the rates for each environmental factor are given in appendix B, paper 2 (Malherbe et al. 2019a). The mean contribution potential scores for buffers around each river reach were determined for each of the landscape potentials using the relevant environmental factor scores. The equation that was used to combine and weight the mean contribution potential scores relevant to each landscape potential to calculate the final landscape sediment generation potential and diffuse nitrate pollution potential scores on a reach-by-reach basis is given in appendix B, paper 2 (Malherbe et al. 2019a).

In Step 3, two improved river water quality assessment approaches were presented by multiplying 3a) the landscape sediment generation potential with the sediment impact scores and 3b) the diffuse nitrate pollution potential with the nutrient impact scores.

2.3.4 Ecosystem services assessment: Improving a scoring matrix approach

A spatially explicit ecosystem service matrix approach that links LULC and landscape properties with ecosystem services in order to assess ecosystem service gains and losses has been applied (Lima et al. 2917). This approach is based on scoring matrices that are developed by evaluating available literature and knowledge from experts. For this study, the matrix scores were adapted in order to test the approach for another region. In addition, the approach was improved by considering water flow regulation as an ecosystem service not considered by Lima et al. (2017). Risk maps were generated to show the loss of soil erosion, water quality maintenance, water flow regulation, soil quality maintenance, and biodiversity maintenance from land use activities. To generate the risk maps, an ecosystem service assessment based on the most recent LULC map (LULC map) and the natural land cover reference map (reference map) was conducted. A work flowchart for the development of the risk maps are given in Figure 7 followed by an overview of the three principle steps.

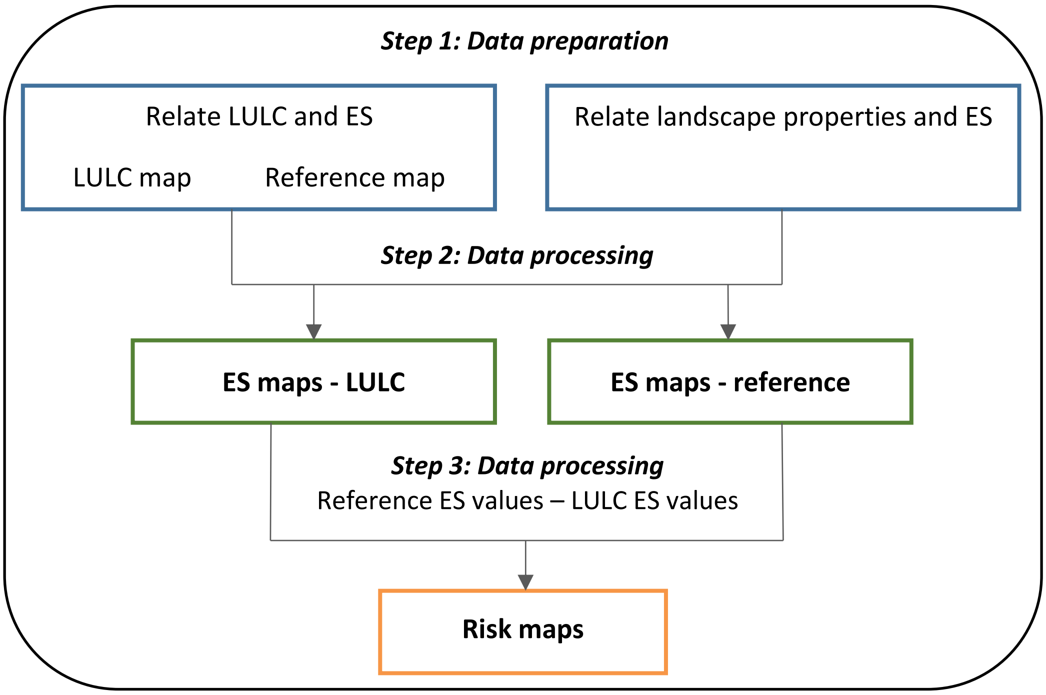

Figure 7: *Work flowchart for the development of the ecosystem service and risk maps*
**ES - ecosystem service*

In Step 1, two scoring matrices were developed. For the first scoring matrix, the LULC classes of the LULC and the reference maps were related to each ecosystem service based on certain criteria. The values were assigned according to the capacity of the landscape to provide or maintain the ecosystem services. The LULC were related to each ecosystem service on a scale from “0” to “5,” with “5” being the highest capacity to provide or maintain the ecosystem service and “0” indicating no capacity. An overview of the criteria, an interpretation of the relevant literature, along with detailed explanations for allocating the values and developing the scoring matrices are given in appendix C, paper 3 (Malherbe et al. 2019b). For the second scoring matrix, the landscape properties were related to each ecosystem service on a scale from “0” to “1”, where “1” does not impede and “0” fully impedes the ecosystem's capacity to provide or maintain the ecosystem service. The landscape properties included soil texture, slope, and distance from river network. Details of the literature used and the values allocated to develop the scoring matrix are given in appendix C, paper 3 (Malherbe et al. 2019b).

In Step 2, the ecosystem service maps for both the LULC and reference maps were generated. This was achieved by multiplying the values given for the LULC scoring matrix with the values given for the landscape property scoring matrix.

In Step 3, the risk maps were created by determining the ecosystem service difference values. This was done by subtracting the LULC ecosystem service values from the reference ecosystem service values.

3 SUMMARY OF RESULTS

This section summarizes the key results from improving the selected simplified assessment approaches presented in Paper 1 to 3.

3.1 Groundwater nitrogen pollution risk and hotspot maps: Potential nitrogen pollution of groundwater

The groundwater nitrogen pollution risk maps applying the DRASTIC+DNS index and the hotspots maps applying the DRASTIC+DNS+NC index are presented in Figures 8a, b for the WR and Figures 8c, d for the ER. The figures show the percentile intervals, which are the index values found within each interval. The high-risk land use activities (land use activities with DNS values greater than 30 kg/ha/yr.) located in the “high” and the “very high” groundwater nitrogen pollution risk areas are likely to have negative impacts on the groundwater. The LULC that are not high-risk but located in areas with “high” and “very high” groundwater nitrogen pollution risks indicate that the physical conditions of the environment rather than the land use activity itself makes the groundwater vulnerable to pollution.

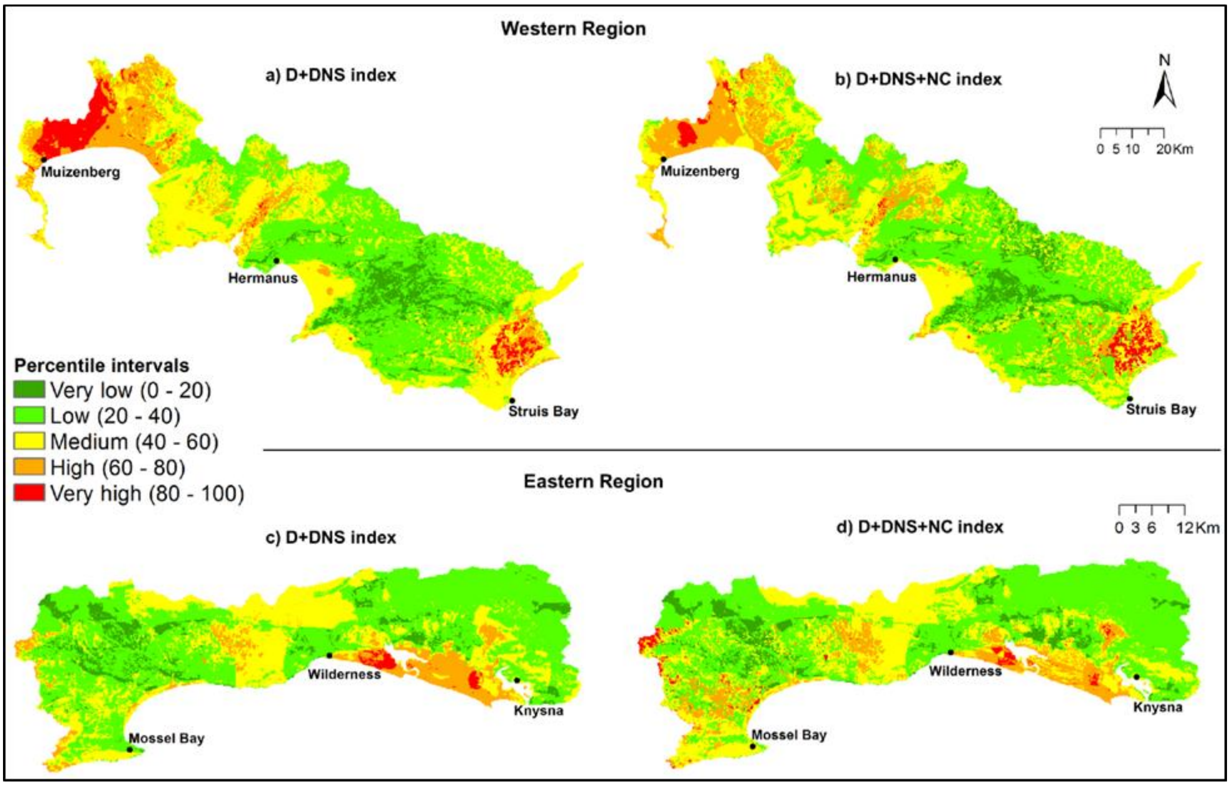

Figure 8: Groundwater pollution risk maps applying the DRASTIC+DNS index and hotspots maps applying the DRASTIC+DNS+NC index for the study regions (Reprinted from Malherbe et al. 2018, © [2018] De Gruyter. Open Access)

From analyzing the LULC maps given in Section 2.1 and the groundwater nitrogen pollution risk maps, it is evident that the agricultural activities, especially irrigated crop cultivation and dryland crop cultivation are important potential contributors to the increasing risk of groundwater nitrogen pollution. The hotspot maps furthermore support this finding. However, the area between Wilderness and Knysna in the ER has a “high” and “very high” groundwater nitrogen pollution risk and is the main hotspot area of this region. Fynbos and forest plantations are the principal LULC of this area and are not high-risk land use activities. Therefore, the physical conditions of this area contribute to increasing groundwater vulnerability and the area must remain free of high-risk land use activities.

3.2 Submarine groundwater discharge contribution areas: Potential nitrogen pollution of coastal water

Figure 9 shows the SGD-CA's located in hotspot areas. The SGD-CA of the WR potentially contributes to coastal nitrogen pollution. However, natural land cover is mainly present in the SGD-CA of the ER. This implies that this SGD-CA presumably do not contribute to coastal nitrogen pollution but must remain free from high-risk land use activities.

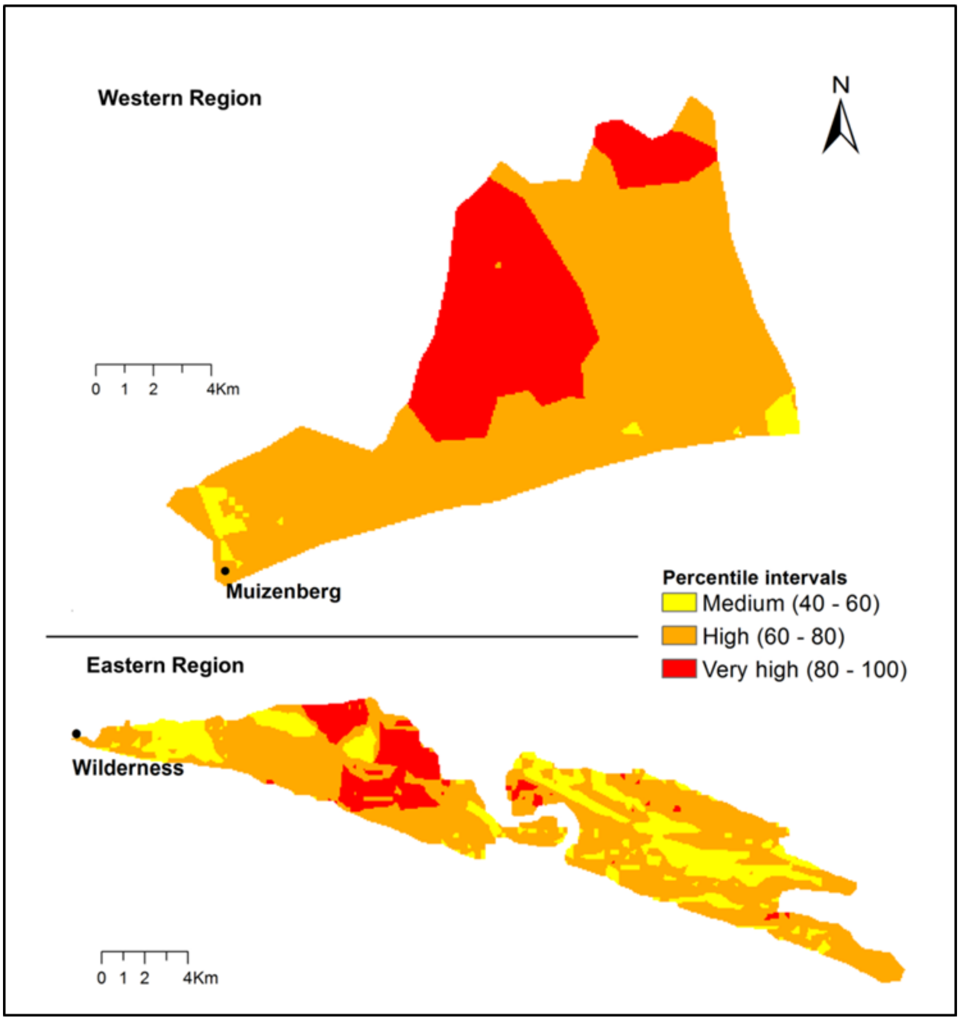

Figure 9: *Submarine groundwater discharge contribution areas located in the hotspot areas of the study regions (Reprinted from Malherbe et al. 2018, © [2018] De Gruyter. Open Access)*

3.3 Improved assessment approaches: Maps of sediment input and nutrient input on river water quality

Figures 10a,b show the improved assessment approaches in order to assess the sediment input and nutrient input on river water quality for the study regions. The percentile intervals, which are the impact scores found within each interval and their associated risk classes are given on the maps.

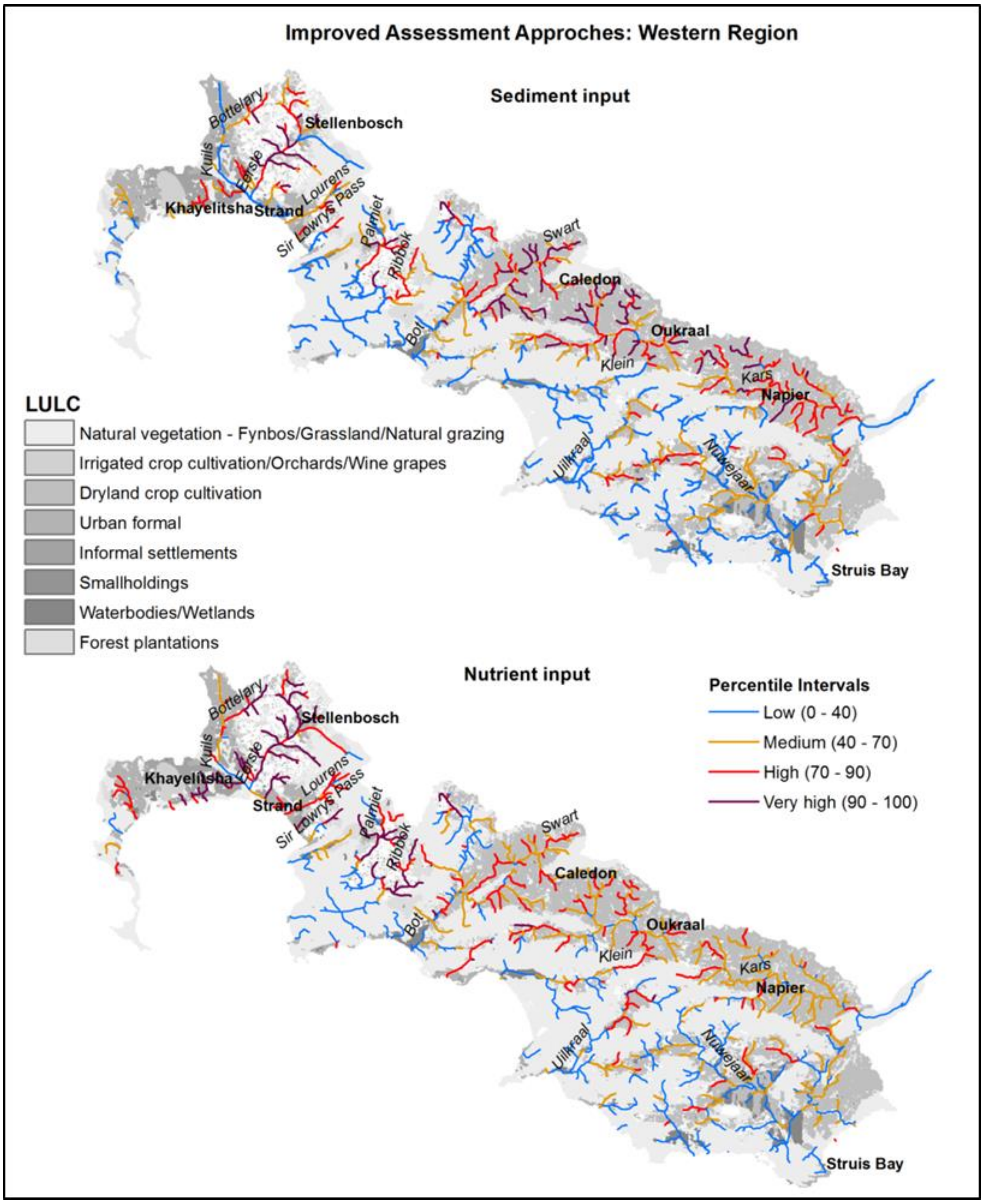

Figure 10a: The improved river water quality assessment approaches for the western region (Reprinted from Malherbe et al. 2019a, © [2019] SpringerNature license number 4546960542007)

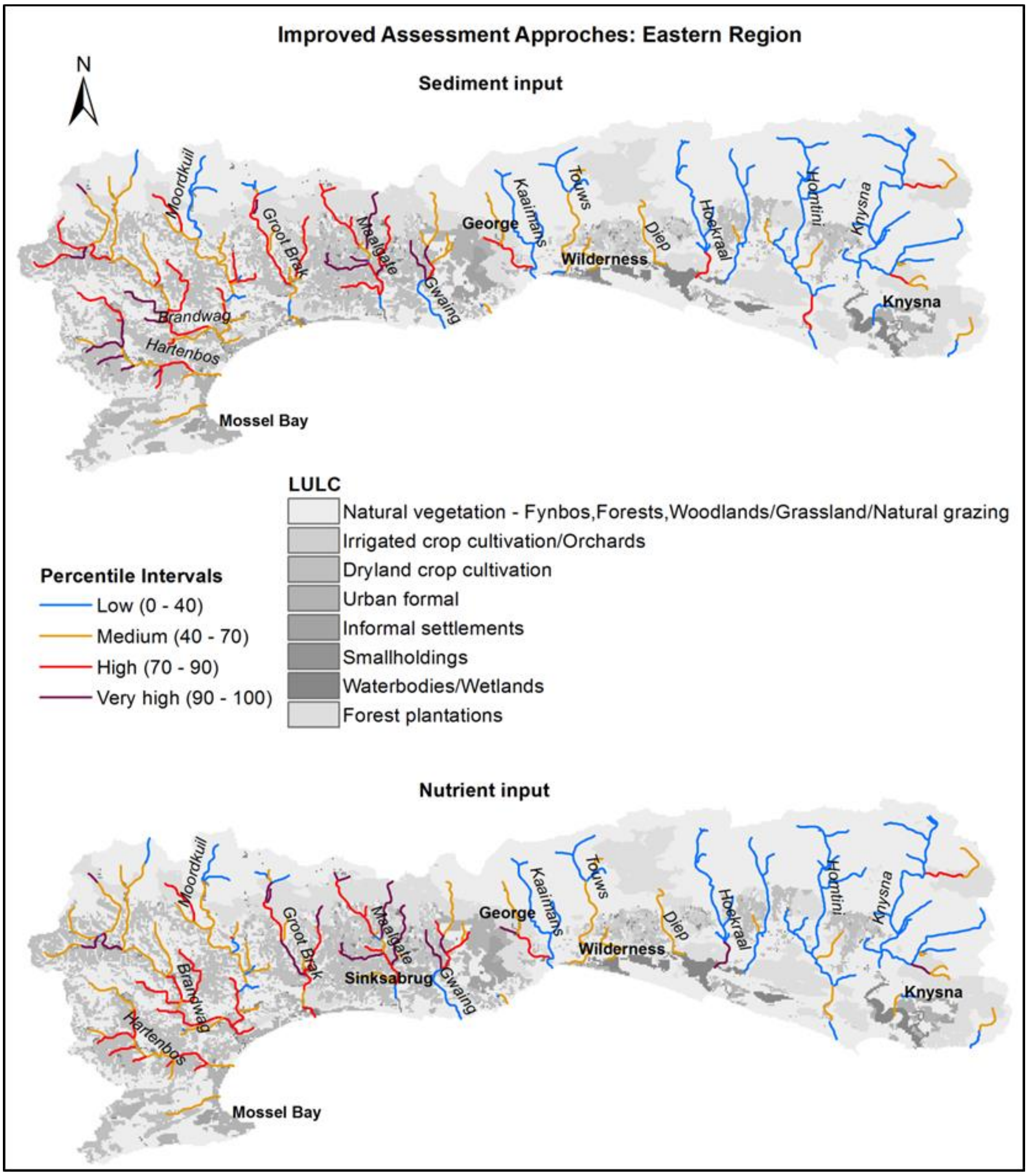

Figure 10b: *The improved river water quality assessment approaches for the eastern region (Reprinted from Malherbe et al. 2019a, © [2019] SpringerNature license number 4546960542007)*

From the improved assessment approaches, it is evident that the agricultural activities including irrigated production of wine grapes, irrigated orchards, irrigated vegetable cultivation, and dryland crop cultivation and informal settlements contribute to “high” and “very high” risks of sediment input and nutrient input on river water quality.

Percentage coverage differences of each risk class between the assessment approaches based only on LULC (maps not presented herein) and the improved assessment approaches for the assessment of the sediment input and nutrient input are evident for both study regions (Table 4).

This supports the importance of incorporating landscape potentials to assess the effects of LULC on river water quality.

Table 4: *Percentage coverage of each risk class for the assessment approaches based only on LULC and the improved assessment approaches (Reprinted from Malherbe et al. 2019a, © [2019] SpringerNature license number 4546960542007)*

Risk classes	**Western region**			
	Sediment input		**Nutrient input**	
	Assessment approach based on LULC only	**Improved assessment approach**	**Assessment approach based on LULC only**	**Improved assessment approach**
Low	40.35	39.21	40.20	35.42
Medium	29.75	27.35	29.67	31.54
High	20.20	21.92	19.83	21.69
Very high	9.88	11.52	10.30	11.35
Risk classes	**Eastern region**			
Low	36.64	38.85	36.5	37.77
Medium	31.76	29.6	34.55	33.55
High	22.89	22.70	18.47	18.76
Very high	8.71	8.84	10.48	9.92

3.4 Risk maps: The loss of ecosystem services

The total ecosystem service values for the LULC map and the reference map are given in Table 5.

Table 5: The total ecosystem service values for the LULC and reference maps (Reprinted from Malherbe et al. 2019b, © [2019] Land MDPI. Open Access)

Ecosystem service	**Total ecosystem service values**	
	LULC map	**Reference map**
Erosion control	1.82	3.06
Water flow regulation	1.15	1.72
Water quality maintenance	2.15	2.98
Soil quality maintenance	2.86	4.59
Biodiversity maintenance	3.30	5

The loss of ecosystem service values from the reference to the LULC situation is the highest for soil quality maintenance (4.59–2.86) and biodiversity maintenance (5–3.30). This is followed by erosion control (3.06–1.82) and water quality maintenance (2.98–2.15). Water flow regulation shows the lowest ecosystem service value loss from the reference to the LULC situation, decreasing from 1.72 to 1.15.

Figure 11 shows the risk maps in order to understand the extent that land use activities contribute to the loss of each of the selected ecosystem service.

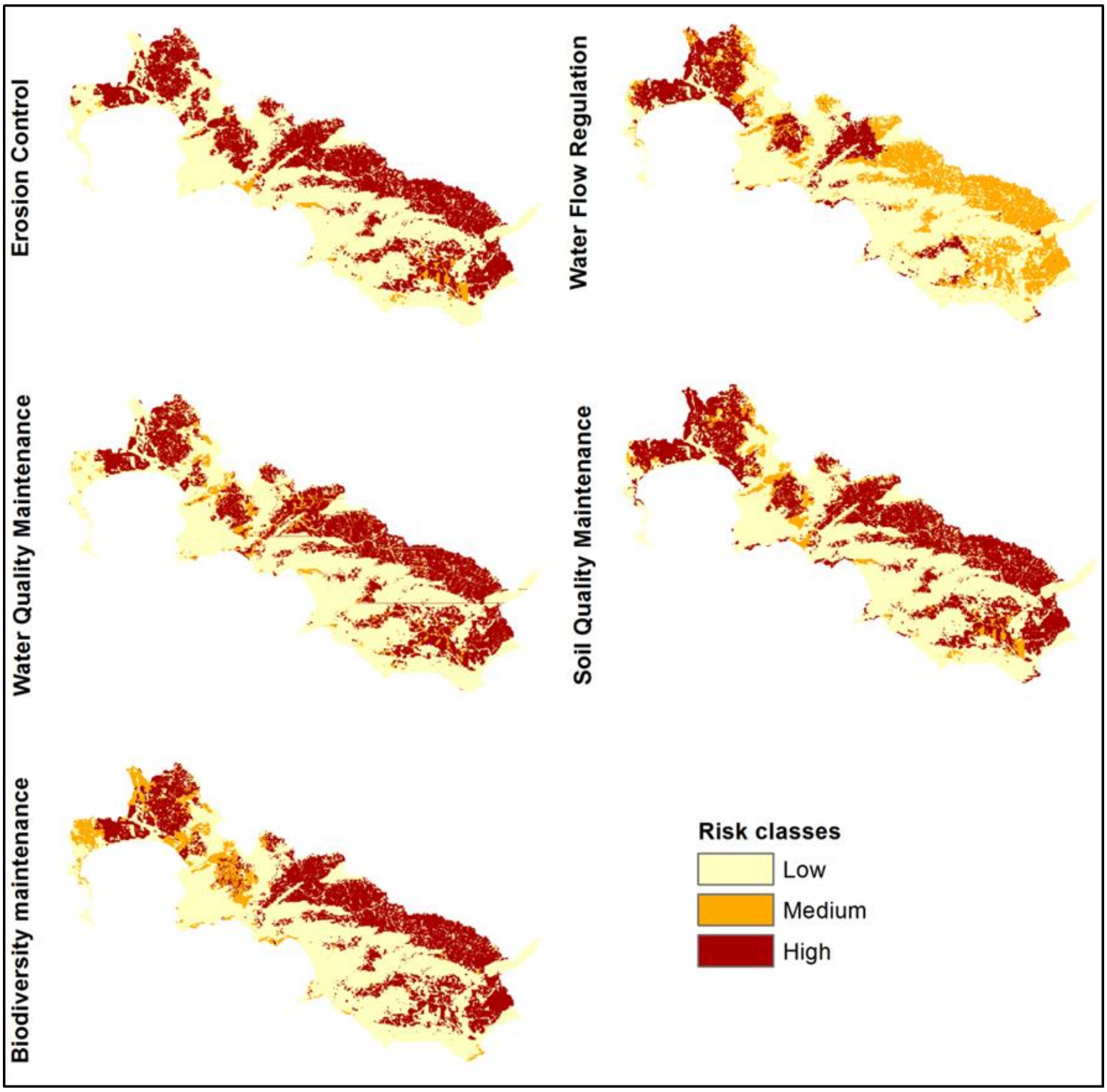

Figure 11: *Risk maps showing the loss of each ecosystem service for the western region (Reprinted from Malherbe et al. 2019b, © [2019] Land MDPI. Open Access)*

From analyzing the LULC maps given in Section 2.1 and the risk maps, it is evident that irrigated and dryland crop cultivation contribute the most to the loss of erosion control, followed by irrigated wine grapes and orchards, and informal settlements. As per erosion control, irrigated agricultural activities and informal settlements substantially contribute to the loss of water quality maintenance. However, the loss of water quality maintenance is lower for dryland crop cultivation and forest plantations. The contribution of agricultural activities to the loss of water flow regulation is similar to erosion control and water quality maintenance. However, for urban development (informal and formal) the loss of water flow regulation is substantial. Urban development (informal and formal), irrigated and dryland agricultural activities substantially contribute to the loss of soil quality, followed by forest plantations. Irrigated and dryland crop cultivation substantially contribute to the loss of biodiversity. However, irrigated orchards and forest plantations support biodiversity slightly more. Informal urban development is the largest contributors to the loss of biodiversity maintenance, whereas the formal urban development displays a medium contribution to such losses.

4 DISCUSSION

In this section, important results of the impacts that land use activities have on the pollution potential of water sources and the loss of certain ecosystem services are discussed. This is followed by a discussion of the advantages and limitations of the improved and adapted assessment approaches.

4.1 Land use activity impacts on water sources and ecosystem services

The results showed that agricultural activities including irrigated vegetable cultivation, irrigated orchards, irrigated production of wine grapes, and dryland crop cultivation were important contributors to the pollution potential of water sources with nitrogen. These agricultural activities and forest plantations contributed to increasing risks of sediment input on rivers. The agricultural activities and forest plantations also contributed to a considerable loss of ecosystem services. Furthermore, the negative impacts on the water sources and ecosystem services from urban development were mainly from the informal settlements considering that wastewater discharge data was not included in this study.

Findings from groundwater assessment studies conducted for regions worldwide showed that agricultural activities are major contributors of groundwater nitrogen pollution (Jayasekera et al. 20011; Shirazi et al. 2013; Vithanage et al. 2014). This study showed an increasing risk of groundwater nitrogen pollution for areas subject to agricultural activities. This was especially the case for the irrigated vegetable cultivation that receives an average rate of nitrogen fertilizer of 170 kg/ha (FAO 2005). The results are in accordance with similar groundwater assessment studies conducted for aquifers located in the southwest part of the Trifilia province in Greece (Panagopoulus et al. 2006) and in the northwest coast of Sri Lanka (Jayasekera et al. 2011). These studies indicated that intense fertilizer applications contributed to increasing risks of groundwater nitrogen pollution.

The results showed that urban development does not increase the risk of groundwater nitrogen pollution. This finding is because the simulation of the diffused nitrogen surplus parameter considered point source wastewater to flow directly into river systems (Gebel et al. 2017). However, groundwater assessment studies that were conducted for a coastal aquifer located in northwest Sri Lanka and the Chunnakam aquifer system located in the Jaffna Peninsula of Sri Lanka showed groundwater sources are subject to nitrogen loading from domestic sources (Jayasekera et al. 20011; Vithanage et al. 2014). Studies that were conducted for the Amman-Zerqa Basin in Jordan and the Sana's Basin in Yemen showed that point source pollution does contribute to groundwater pollution (Alwathaf et al. 2011; Al-Rawabdeh et al. 2014). Therefore, it is important to consider point source pollution in groundwater assessment studies. Furthermore, the informal settlements located in the study regions might contribute to high nitrogen concentrations from poor wastewater disposal (Mels et al. 2009), especially in the areas where these settlements cover flat sandy plains. However, gaining information on wastewater disposal in informal settlements is a major challenge in South Africa, particularly due to a variety of political and social aspects (Mels et al. 2009). The findings furthermore indicated that the groundwater from the SGD-CA's might increase the nitrogen pollution risk of coastal water. However, it was found that the nutrients that discharge into coastal water might disperse rapidly in a dynamic coastal environment.

A study that was conducted for various major deltas indicated that crop farming contributed to increasing river-sediment loads (Meade 1996). The findings from this study likewise indicated that the river reaches located in areas of irrigated vegetable cultivation and dryland crop cultivation of cereal crops were subject to increasing sediment input. These agricultural activities require frequent soil tillage contributing to the increasing sediment loss (O'Farrell et al. 2015). Long-lived crops, such as irrigated orchards and the production of wine grapes, require less frequent soil tillage (O'Farrell et al. 2015). These crops therefore contributed less extensively to sediment input of the river reaches.

For this study, the intensive fertilizer application used for the irrigated agricultural activities (FAO 2005) is an important contributor to the increasing risks of nutrient input on river reaches. The high fertilizer applications in agricultural catchments of central west Poland also showed high nitrogen concentrations in surface water (Lawniczak et al. 2016). This study however indicated that the river reaches located in areas with dryland crop cultivation were subject to a lower risk of nutrient input. This is because the average rate of nitrogen fertilizer applied to dryland crops in South Africa are much lower (FAO 2005).

River reaches that pass through forest plantations showed increasing risks of sediment and nutrient inputs. This supports the finding that clear-felled areas and improperly maintained roads of forest plantations contributed to an increasing loss of soil (O'Farrell et al. 2015).

Lake Paranoá located in the Distrito Federal of Brazil showed an increase in sediment input because of urban development (Franz et al. 2013). Increasing settlements also contributed to high ammonium inputs in the streams of two river basins located in the Distrito Federal (Franz et al. 2013). For this study, it was found that the river reaches flowing through the informal settlements were subject to increasing sediment and nutrient inputs. This was not the case for formal urban development. This finding is supported by the high sediment retention that was determined for formal urban development along the southern coast of South Africa (Gebel et al. 2017). The increasing nutrient input on river reaches in informal settlements is presumably because of the poor wastewater disposal (Mels et al. 2009).

From the for-mentioned findings, it is apparent that agricultural activities and forest plantations along the southern coast of South Africa influence water quality. The findings indicated that the irrigated agricultural activities substantially contributed to groundwater nitrogen pollution and to the increasing nutrient input on river water quality. In addition, irrigated and dryland crop cultivation and forest plantations contributed to increasing sediment input on river reaches. The findings for this study furthermore showed that irrigated agricultural activities substantially contributed to the loss of water quality maintenance; whereas the loss of water quality maintenance was slightly lower for dryland crop cultivation and forest plantations. Irrigated agricultural activities are known to be the most intensive agricultural activities in the WCP (FAO 2005; O’Farrell et al. 2015), therefore these activities were determined to have the highest impacts on water quality. Similarly, a high loss of water quality maintenance was determined for the Sarandi Catchment located in Brazil (Lima et al. 2017).

The assessment approach conducted by Lima et al. (2017) also showed that irrigated agricultural activities contributed to a loss of erosion control. In comparison, the findings from this study showed that the loss of erosion control was higher for irrigated agricultural activities, especially for irrigated vegetable cultivation. The physical limitations of the landscapes between the Sarandi Catchment in Brazil (Lima et al. 2017) and the southern coast of South Africa most likely contributed to the for-mentioned differences. Findings from other studies that used modelling approaches or field measurements furthermore indicated that agricultural activities contributed to soil erosion. García-Ruiz (2010) showed that the expansion of rainfed cereal crops and vineyards greatly contributed to soil erosion in Spain. Increasing soil erosion was evident for steep slopes that were converted to cropland in the Liupan Mountains located in the southern Ningxia Hui Autonomous Region of China (Quan et al. 2011). The highest erosion rate in the Mediterranean region was determined for vineyards, especially since the vineyards are mostly located in hilly areas (Kosmas et al. 1997). These findings coincide with the findings from this study because the agricultural activities located in hilly areas substantially contributed to the loss of erosion control.

The findings indicated that formal urban development has a greater capacity to support erosion control and water quality maintenance. This is most likely because of the high sediment retention that was determined for the formal urban development (Gebel et al. 2017). The formal urban development also have more efficient wastewater disposal (Mels et al. 2009). Other studies showed a decrease in water quality from domestic sources mainly because of point source pollution and septic tank leakages (Geriesh et al. 2004). Informal settlements in South Africa are associated with poor wastewater disposal. Based on local knowledge, the informal settlements along the southern coast of South Africa also have a limited number of paved roads and provide no green space. This supports the finding that such settlements contributed to the loss of erosion control and water quality maintenance.

A decline in natural vegetation for crop cultivation contributed to a loss of water flow regulation in South Africa (Egoh et al. 2009) and in Southeast Asia (Tarigan et al. 2018). Findings from this study also showed a loss of water flow regulation in cultivated areas. In comparison to the dryland crop cultivation, the irrigated agricultural activities contributed more extensively to the loss of water flow regulation. The frequent soil tillage of irrigated agricultural activities causes considerable soil degradation (O'Farrell et al. 2015). This decreases the ability of soil to retain water. The soil texture supporting the dryland crop cultivation presumably supports the capacity of soils to retain water more than sandier soils. The loss of water flow regulation was highest for formal urban development and informal settlements. This finding is presumably from the extensive degradation that urbanization has on soils (Mills and Fey 2004) and consequently water flow regulation.

Human interference has substantial impacts on soil quality and biodiversity (Matson et al. 1997; Mills and Fey 2004). This study showed substantial losses of soil quality maintenance and biodiversity maintenance. The loss of soil quality maintenance was presumably from intense agricultural activities, including the use of fertilizer and soil tillage and the extensive degradation of soils because of urban development. The findings showed that the loss of biodiversity maintenance is higher for cultivated areas than forest plantations. This was also found to be the case in a study that was conducted for southern Africa (Scholes and Biggs 2005). Green urban spaces are present in areas of formal urban development along the southern coastal region of South Africa and therefore, in comparison to the informal settlements, contributed less extensively to the loss of biodiversity maintenance.

4.2 Advantages of the improved and adapted knowledge-based assessment approaches

The approaches mostly require data extracted from freely available input layers, including LULC, soil maps, digital elevation models, hydrogeological maps and rainfall maps, and the evaluation of sufficient knowledge obtained from literature and/or the consultation of experts. This makes the approaches relatively easy to apply and particularly suitable for data scarce regions.

The linear summation of the DRASTIC approach with the DNS and NC parameters facilitates to identify if the land use activities itself or the physical characteristics of the environment contribute to an increase in groundwater nitrogen pollution for a specific area. If the nitrogen concentration in total runoff for an area is low, it can be concluded that land use activities contributing to high DNS values in the area is adapted to the physical conditions because the diffused nitrogen inputs are regulated (Gebel et al. 2017). On the other hand, areas with low percolation rates may contribute to increasing nitrogen concentrations reaching the groundwater (Gebel et al. 2017). Land use activities in such areas may therefore not be well adapted to the physical conditions of the landscape, even at low nitrogen fertilizer rates (Gebel et al. 2017). Furthermore, the addition of the NC parameter generates a map that can be used to identify the areas that are most likely already polluted with nitrogen. These findings will assist land use managers to determine if, for example, the intensity of agricultural activities needs to be adjusted to their foreseen environment.

Findings from this study also indicated that the incorporation of landscape potentials and properties is beneficial when assessing the impacts of land use activities on water sources and ecosystem services.

Results from the improved assessment approaches assessing the nutrient input and sediment input on river water quality were compared to the results from the assessment approaches based only on LULC. The findings indicated that the incorporation of the landscape sediment generation potential increased the risk of sediment input for a specific area. Furthermore, the incorporation of the diffuse nitrate pollution potential decreased the risk of nutrient input for another specific area. These findings highlight the importance of considering landscape potentials based on relevant environmental factors when assessing the estimated sediment input and nutrient input on river water quality. In addition, by incorporating the landscape potentials it is possible to determine if the increasing risks of sediment input and nutrient input are caused by the land use activities itself. For example, it was found that forest plantations made a low contribution to the nutrient input; however, for this study forest plantations were found to be present in areas that indicated increasing risks of nutrient input. This implies that these areas are rather vulnerable to increasing risks of nutrient input because of the environmental factors.

Similarly, findings from this study revealed that the capacity of the landscape to support a certain ecosystem service for the reference situation is not the same for all areas. Therefore, the addition of a landscape property scoring matrix has the potential to affect the capacity of landscapes to provide or maintain ecosystem services and must not be neglected. This also implies that the incorporation of a landscape property matrix will deliver a better overview of the loss of ecosystem services. The findings indicated that the approach can be easily adapted to the characteristics of other regions. It was also revealed that ecosystem services not yet considered before can be successfully assessed by using this approach. The approach can be further improved by adding additional landscape properties. Herein, the gravel content to the soil texture was added to assess erosion control.

4.3 Limitations of the improved and adapted knowledge-based assessment approaches

The improved and adapted assessment approaches give a good overview of the potential impacts of land use activities on water sources and ecosystem services. However, simplified assessment approaches do come with limitations. Simplified assessment approaches rely on freely available data. Therefore, there is a lack in data that might contribute to more optimal results. More detailed results are required to prioritize the high risk areas and to rank the land use activities from activities with the highest to lowest detrimental effects on water quality and ecosystem services. It is important that the results are therefore interpreted as potentials.

For example, the limited number and uneven distribution of boreholes to determine the depth to water table parameter may have caused irregularities in the output data influencing the final groundwater assessment results of this study. Insufficient information was also used for the simulation of the DNS and NC parameters and no validation of the nitrogen budgets was possible (Gebel et al. 2017). Furthermore, for the simulation of the nitrogen budgets no differentiation was made between the formal and informal settlements and point discharges from wastewater treatments were not considered (Gebel et al. 2017). Regardless, in comparison to the studies that rate LULC classes (Jayasekera et al. 2011; Vithanage et al. 2014), the incorporation of the DNS and NC parameters did deliver findings that are otherwise not possible.

For the improved assessment approaches a distinction was made between formal and informal urban development to determine the sediment input and nutrient input on river water quality. However, these approaches also do not incorporate point source pollution. The addition of data on point discharges or discharges from overflowing septic tanks can alter the final outcome of the results. For example, the lower river reaches of the Kuils River showed low and medium risks of sediment and nutrient inputs; however, it has been documented that storm water, litter, wastewater discharge, and spills from blocked sewage pump stations have major impacts on the water quality of the Kuils River (DWAF 2005). Another major limitation is that the impacts can only be determined for each river reach independently, which was also highlighted by a similar study conducted by O’Farrell et al. (2015). No method was developed to cumulate the impact scores longitudinally. This makes it problematic to identify and prioritize the most affected sub-catchments. From matching the estimated impact scores of the sediment input and nutrient input on river water quality with existing river water quality information, it was evident that some lower river reaches with low estimated impact scores are in fact in a poor state (DWAF 2003ab, 2005, 2007). Therefore, the development of a method that determines the cumulative impact scores will contribute to a better overview of the river water quality.

The limited knowledge regarding the complex interactions, including the landscape, land use activities, and ecosystem services, presents a certain limitation in the application of the improved scoring matrix approach. This implies that the actual effects of the land use activities on ecosystem services are not certain and, as stated previously, the loss of ecosystem services from land use activities must be regarded as potentials.

5 CONCLUSION

The results from the improved simplified assessment approaches applied herein indicated that agricultural activities considerably contributed to the increasing risks of water pollution and the loss of ecosystem services. The type of urban development that also contributed to such impacts was from the informal settlements, as point discharge pollution could not be considered for this study.

From the groundwater assessment approach, it can be concluded that the agricultural activities may not always be adequately adapted to the physical conditions of the environment. The intensity of these activities must therefore be adjusted to their foreseen environment. Groundwater pollution from poor wastewater disposal might be of concern for the informal settlements of the region, especially those settlements that are located on flat sandy plains. For future assessments, it is important to incorporate such information. However, information on poor wastewater disposal in informal settlements might not always be readily available. It can be concluded that the inclusion of the simulated nitrogen budgets did deliver a better overview of the relationship between LULC and groundwater pollution potential. However, simulated nitrogen budgets might not be available for most regions. In such cases, rating of LULC classes based on nitrogen loading is plausible.

This study is the first known attempt to delineate SGD-CA’s in order to assess the impacts that land use activities might have on coastal water. It can be concluded that the delineation of SGD-CA’s can be done using hydrogeological maps.

The results from the river water quality assessment study indicated that the incorporation of landscape potentials based on relevant environmental factors must be considered. The findings are useful because the distribution and origin of the probable river water quality are highlighted. The areas with a high probability of water pollution must be managed at a large scale. This will ensure that all the potentially affected sub-catchments of all the studied river networks are included. However, a simplified method to determine the cumulative effects of the impacts downstream along a river system need to be developed in order to prioritize the sub-catchments contributing the most to river water pollution

From the findings, it can be concluded that landscape properties have the potential to affect the capacity of the landscape to provide and maintain ecosystem services. The addition of a landscape property matrix is therefore essential. Adding additional landscape properties to improve the approach can be done. The approach can also be adapted to the regional characteristics of other study regions, especially since this was the first attempt to test the approach, originally developed by Lima et al. (2017), for a different region. Furthermore, ecosystem services not yet considered before can be assessed by implementing this approach.

The improved assessment approaches made considerable contribution to existing knowledge regarding the complex interactions including the landscape, land use activities, and ecosystem services. The knowledge obtained from implementing simplified assessment approaches furthermore gives a good overview about the areas and associated land use activities that contribute to increasing risks of water pollution and the loss of ecosystem services. However, due to the limitations of simplified assessment approaches it is important that the impacts of the land use activities must be interpreted as potentials. Regardless, an overview of the impacts of land use activities is important to make decisions regarding further in-depth research that requires costly resources. For future ference, testing different versions of the approaches developed herein is recommended based on further improvements and adaptations.

Gaining knowledge of the impacts that land use activities have on the environment is vital for land management worldwide. The application of simplified assessment approaches is essential to fill the gap between land use management and numeric modeling that uses complex tools. Simplified assessment approaches are the first step in gaining a critical understanding of how land use activities impact the environment, which is important to identify areas that require well-defined management strategies. The improved assessment approaches can be easily translated to other regions of interest. The approaches can be adapted to fit the regional characteristics of different regions. Only the basic input data, the evaluation of sufficient knowledge obtained from literature and/or the consultation of experts in the field, and knowledge of applying GIS or similar software packages are required. This is particularly important for data-scarce regions, including regions where the level of expertise using complex models is limited. Water sources and other ecosystem services of many regions are subject to high pressure from land use activities and require management solutions in a timely manner. The application of complex modelling is time-consuming and therefore simplified assessment approaches are of great importance because the results are delivered relatively fast.

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APPENDIX: PUBLISHED ARTICLES

Appendix A: Paper 1

Malherbe, H., Gebel, M., Pauleit, S., Lorz, C. (2018). Land use pollution potential of water sources along the southern coast of South Africa. Change and Adaptation in Socio-Ecological Systems, 4, 7-20.

Research Article

Hanlie Malherbe*, Michael Gebel, Stephan Pauleit, Carsten Lorz

Land use pollution potential of water sources along the southern coast of South Africa

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Abstract: Since the 1990's, the groundwater quality along the southern coast of the Western Cape Province of South Africa has been affected by increasing land use activities. Groundwater resources have become increasingly important in terms of providing good quality water. Polluted coastal groundwater as a source of submarine groundwater discharge also affects the quality of coastal water. For this study, land use activities causing groundwater pollution and areas at particular risk were identified. An assessment approach linking land use/land cover, groundwater and submarine groundwater discharge on a meso-scale was developed and the methods applied to two study regions along the southern coastal area. Dryland and irrigated crop cultivation, and urbanized areas are subject to a "high" and "very high" risk of groundwater nitrogen pollution. Application of fertilizer must be revised to ensure minimal effects on groundwater. Practice of agricultural activities at locations which are not suited to the environment's physical conditions must be reconsidered. Informal urban development may contribute to groundwater nitrogen pollution due to poor waste water disposal. Groundwater monitoring in areas at risk of nitrogen pollution is recommended. Land use activities in the submarine groundwater discharge contribution areas was not found to have major effects on coastal water.

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Keywords: land use/land cover, nitrogen, groundwater, DRASTIC, submarine groundwater discharge

1 Introduction

Population growth and increasing land use activities place greater pressure on ecosystems to deliver good quality water for human use and to support healthy habitats. The supply of water is generated by terrestrial ecosystems and therefore the quality is influenced by land use/land cover (LULC) [1-2]. Increasing global demand for good quality freshwater has shifted the focus on groundwater resources, which over recent years have experienced increasing pressure from human populations. Groundwater is vulnerable to anthropogenic pollutants such as pesticides, fertilizers, heavy metals, nutrients, organic compounds and microbes resulting from land use activities [3-7].

Mapping of groundwater resources is a useful tool to ensure long-term protection of potential groundwater pollution [8]. It delivers spatial overviews of groundwater vulnerability in data scarce regions [9]. Various groundwater assessments to identify areas at risk of groundwater pollution from land use activities have been conducted [10-17]. Agricultural activities, such as intense fertilizer application, greatly affect groundwater resources [10, 12-13, 15]. Point source pollution from wastewater discharge in urban areas also contributes to groundwater pollution [15, 18]. In addition, polluted coastal groundwater as a potential source of submarine groundwater discharge (SGD) may affect the quality of coastal marine and estuarine water essential to sustain healthy aquatic habitats [1-2]. The pollution risk of coastal water from land use activities by means of SGD has been addressed by several authors [19-22]. However, these studies applied measurements and analyses along shorelines which are cost-intensive.

In South Africa, groundwater has become an increasingly important source of freshwater for local scale irrigation and domestic use [23]. A greater emphasis on protecting groundwater resources has become evident in the Western Cape Province (WCP), which experienced significant population influx after the political change in 1994 [24]. People mainly settled along the southern coastal region, causing increased urban development and land use activities. Dryland cultivation, irrigated cultivation of vegetables, wine grapes and orchards are major land use activities covering extensive areas of this coastal region [25]. The southern coastal region has also been experiencing water shortages due to prolonged drought events, thereby increasing the importance of protecting the region's groundwater [26]. National scale groundwater vulnerability assessments for South Africa have been conducted [14, 27]. The vulnerability map presented by [14] indicated that the southern coast of the WCP is vulnerable to groundwater pollution. Although local scale studies, i.e. focusing on smaller basins of groundwater, exist for this region, no meso-scale assessment of nitrogen pollution of groundwater covering extensive land areas has been conducted so far. In addition, there is no spatial assessment approach identifying areas where polluted groundwater may contribute towards SGD. Filling the gaps in our knowledge regarding the relationship between LULC, groundwater and SGD will assist management authorities and stakeholders to give important land use recommendations and to outline management strategies.

The objective of this study is to identify land use activities causing groundwater nitrogen pollution and to determine hotspot areas of potentially polluted groundwater by nitrogen in a data scarce region. Furthermore, SGD contribution areas (SGD-CA's) contributing to coastal marine and estuarine nitrogen pollution will be described. This will be achieved by linking LULC, groundwater and SGD on a meso-scale and applying this approach to two study regions representing a variety of LULC types along the southern coast of the WCP, South Africa. The DRASTIC approach and linear summations of the DRASTIC index with diffuse nitrogen surplus in the rooting zone (DNS), and consecutively nitrogen concentration in the deep percolation (NC) were applied for the groundwater assessments. An approach was developed to delineate SGD contribution areas (SGD-CA's) and the groundwater contribution potential of such areas.

The remainder of the paper is organized in four parts: Section 2 introduces the DRASTIC approach and the linear summation of the DRASTIC approach with nitrogen related LULC parameters. The steps used to identify high-risk land use activities contributing to groundwater pollution are described and a simplified approach to identify SGD-CA's located in hotspot areas is presented. Section 3 presents the groundwater assessment results and the relevant SGD-CA's. In section 4, the results are discussed in light of other findings. Section 5 provides recommendations to assist with groundwater and coastal management of the study regions and globally.

2 Methods

2.1 Study regions

The assessment approach was applied to two study regions along the southern coast of the WCP, South Africa. These were described as the western and the eastern regions. The western region extends along the coastline from Cape Point (34°21'S; 18°28'E) to 22 km east of Struis Bay (34°48'S; 20°03'E). It extends approximately 50 km inland and includes regions of the Cape Flats, Cape Winelands District, and the Overberg District, covering a land surface area of 643,542 ha. The eastern region extends along the coastline, 15 km west of Mossel Bay (34°11'S; 22°8'E) to 12 km east of Knysna (34°04'S; 23°03'E). It is located in the Eden District, extending a maximum of 38 km inland and covering a land surface area of 285,735 ha (Figure 1a). The study regions are characterized by a Mediterranean climate of hot and dry summer seasons, rainy winter seasons, and mild to warm autumn and spring seasons. A mean annual precipitation gradient exists along the southern coastal regions extending eastwards. The highest mean annual precipitation in the coastal and mountainous regions is 1, 000 – 1, 200 mm, while the lowest mean annual precipitation is measured along coastal areas and for the inland at 200 - 400 mm [28].

The study regions were selected based on their physical conditions with regards to SGD and the diversity of LULC evident for both regions. The 2000 National Land Cover data [29], incorporating the 2013 map of Agricultural Commodities in the WCP [30] were used to represent the LULC for each study region (Figure 1b, c). The natural vegetation of the western region includes "Fynbos", with percentage coverage of 52.7%, while the eastern region includes Fynbos, and indigenous forests/woodlands covering 43.3% and 12.6% respectively. The Fynbos biome is rich in biodiversity and is recognized as one of the floral kingdoms of the world [31]. Dryland crop cultivation is the most important land use activity, covering 25.9% of the western region and 17.1% of the eastern region. The eastern region has high forest plantation coverage of 15.4%, compared to 2.2% coverage in the western region. Irrigated agricultural activities are practiced less extensively in both study regions. Informal urban development is present in both study regions, although it is most prevalent in the western part of the western region. Other LULC present in both study regions include natural grazing and grassland, bare rock and soil, water bodies and wetlands.

2.2 Groundwater assessments: DRASTIC approach / linear summation with LULC parameters

In order to describe the potential effects of land use activities on groundwater quality, an assessment of

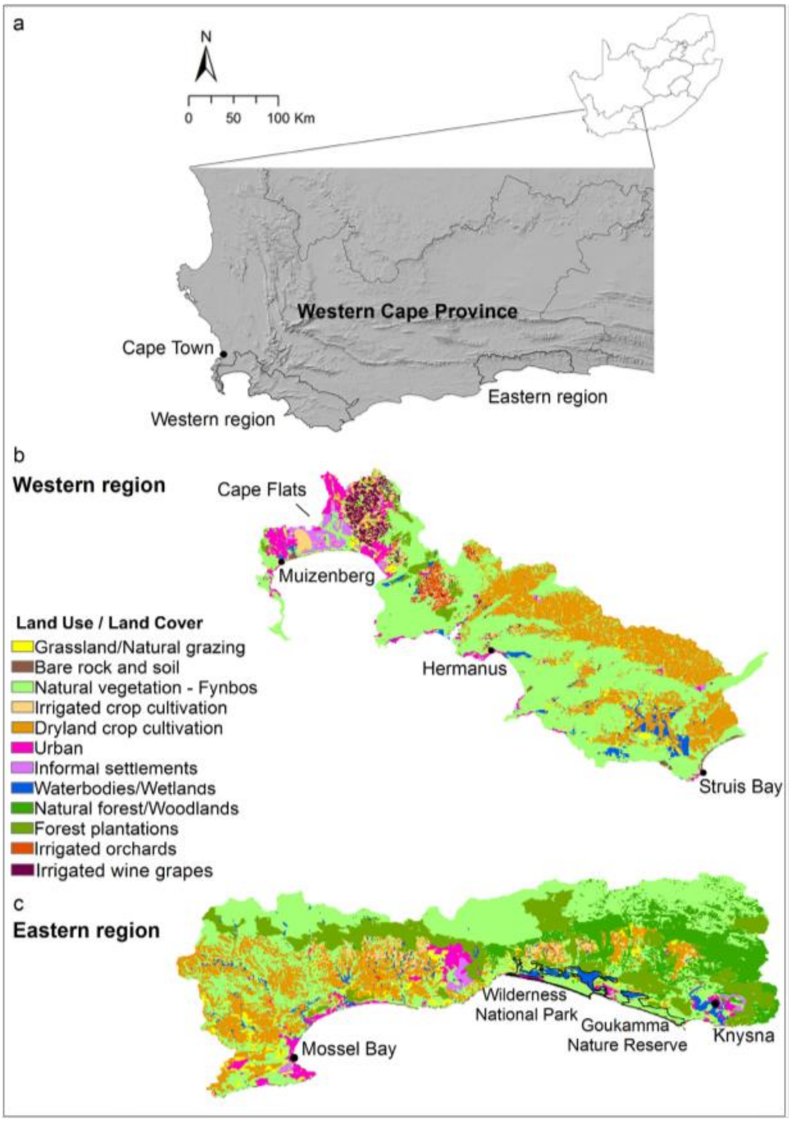

Figure 1a. Location of the study regions along the southern coast, Western Cape Province, South Africa [45]. **b.** Land use/land cover of the western region. **c.** Land use/land cover of the eastern region.

the groundwater and related formation processes was needed. The DRASTIC approach is a widely used approach used to assess the groundwater vulnerability of an area. It does not replace site-specific assessments, but rather aggregates relevant data in a spatially explicit manner, based on the environment's physical conditions [32]. The following hydrogeological settings, forming the acronym DRASTIC, are included in the approach: Depth to water table (D); Net recharge (R); Aquifer media (A); Soil media (S); Topography (T); Impact of the vadose zone (I); Hydraulic conductivity (C). The selection of parameters used for the DRASTIC approach can be reviewed in [32]. Details of the data sources used for the hydrogeological settings for this study are given in Table 1.

The DRASTIC approach may be used to incorporate LULC parameters. This is beneficial to assess the groundwater pollution risk from land use activities and to identify hotspot areas of potentially polluted groundwater. Linear summations of the DRASTIC index with a LULC parameter have been applied in several studies. For these studies LULC classes were rated according to their nitrogen pollution risk of groundwater. Ratings have been done using expert knowledge [10], surface nitrogen loads [13, 17], or referring to literature [11-12, 14-15]. This study used nitrogen related LULC parameters not considered before in the DRASTIC index. Firstly, the addition of diffuse nitrogen surplus (DNS) in the rooting zone was a more accurate LULC parameter to describe the groundwater nitrogen pollution risk from land use activities. Secondly, we assessed and mapped hotspot areas of potentially polluted groundwater by nitrogen by successively integrating nitrogen concentration (NC) in the deep percolation as a second LULC parameter.

A flowchart of the methods used to create the groundwater vulnerability, groundwater nitrogen pollution risk and hotspot maps using ArcGIS version 10.1 software [33] are given in Figure 2.

For the groundwater vulnerability assessment, the following specified equation was used, where a high DRASTIC index indicates high groundwater vulnerability [32]:

Equation 1:

DRASTIC index (henceforth referred to as the D index) = $D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w$ (r = rating and w = weight)

The weight of each parameter describes the relative effect on groundwater vulnerability. It includes values from 1 to 5, with 5 being the most significant and 1 the least significant. Rating of each parameter describes the relative importance of each range or class in terms of groundwater vulnerability. The values range between 1 and 10, with 10 being the most significant and 1 the least significant. The weights and rates allocated to each of the DRASTIC index parameters were mainly based on [32]. The classes and rates for the aquifer media and impact of vadose zone

Table 1. Data sources for the hydrogeological settings of the DRASTIC approach.

Data type	Detail of data	Additional detail	Output layer
Digital elevation models Borehole data	Stellenbosch University Digital Elevation Model (SUDEM) [45] National Groundwater Archive (data acquired 2014) [46]	Ground surface (m.a.s.l.) – depth to groundwater (m) = groundwater table (m.a.s.l.) Inverse distance weighting	Depth to groundwater (m)
Net groundwater recharge	Weihenstephan-Triesdorf University of Applied Science (HSWT, data acquired 2016)	WebGIS based model applying STOFFBILANZ [34]	Net groundwater recharge (mm/a)
Geological maps	Helmholtz Centre for Environmental Research (UFZ unpublished material, data acquired 2015)	Modified after the Council for Geoscience 1990, 1993, 1997	Aquifer media
Soil maps	Harmonized World Soil Database [47]	-	Soil media
Digital elevation models	SUDEM [45]	-	Topography (slope [%])
Hydrogeological maps	1:500,000 hydrogeological map of South Africa [36-37]	-	Impact of vadose zone
Geological maps	Helmholtz Centre for Environmental Research (UFZ unpublished material, data acquired 2015)	Modified after the Council for Geoscience 1990, 1993, 1997 Values assigned to post-processed lithologies	Hydraulic conductivity (m/s)

parameters were taken from [27] as these are adapted for South African settings.

For the groundwater nitrogen pollution risk assessment, DNS was added to the DRASTIC index. The simulation of DNS using the STOFFBILANZ model is based on a mass balance approach of nitrogen input and nitrogen output [34]. To describe the relative effects of LULC on groundwater nitrogen pollution risk, the DNS parameter was allocated the highest weight of 5. The following specified equation was used, where a high D+DNS index indicates high groundwater nitrogen pollution risk:

Equation 2:

D+DNS index = DRASTIC index + $DNS_r DNS_w$ (r = rating and w = weight)

Hotspot areas of potentially polluted groundwater by nitrogen were assessed by adding the nitrogen concentration in deep percolation (NC) to the D+DNS index. NC contributes mostly to groundwater nitrogen concentrations, and therefore the NC parameter was allocated the highest weight of 5. The rates for each of the NC parameter ranges were assigned based on the Water Research Commission's 1998 South African guideline values for nitrogen levels in drinking water [35]. Based on the guidelines, nitrogen levels in drinking water were divided into five ranges according to the potential effects on human health. These were presented on a scale from negligible health effects to increasing acute health risks in babies. The following equation was used, where a high D+DNS+NC index indicates potential hotspot areas:

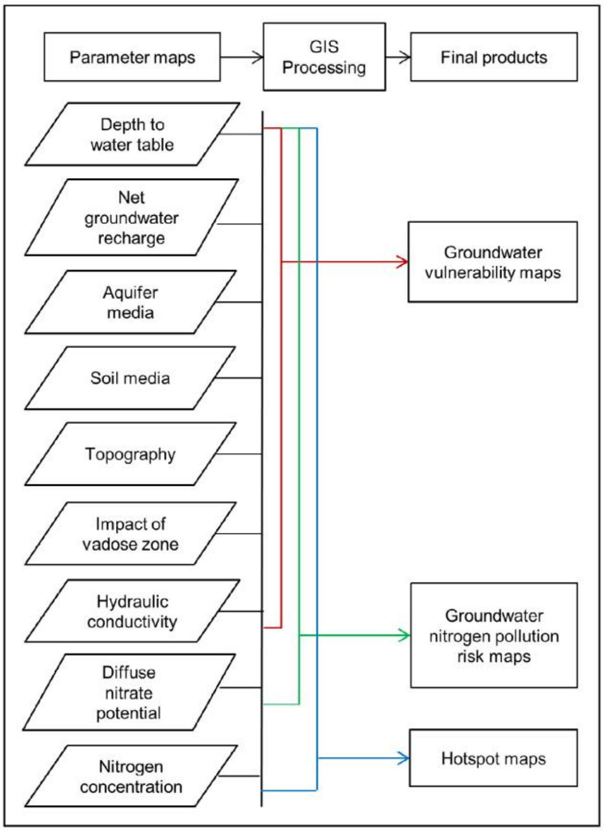

Figure 2. Flowchart of the DRASTIC approach including a linear summation with LULC parameters.

Equation 3:

$$\text{D+DNS+NC index} = \text{DRASTIC index} + DNS_r DNS_w + NC_r NC_w$$

(r = rating and w = weight)

The weight and rates allocated to the DRASTIC, DNS and NC parameters are given in Table 2. The DNS and NC maps were provided by HSWT [34]. The index values for each of the approaches were classified, on a scale of very low to very high in equal percentile intervals; very low (0 -20th), low (20 – 40th), medium (40 – 60th), high (60 – 80th), and very high (80 – 100th).

To determine the potential extent of groundwater nitrogen pollution due to land use activities, two steps were followed:

1) High-risk land use activities were identified. For the purpose of this study, high risk land use activities were defined as activities covering land areas with DNS values greater than 30 kg/ha/yr.
2) Percentage LULC coverage in "high" and "very high" (henceforth referred to as "H+VH") groundwater nitrogen pollution risk areas were calculated for each study region.

Table 2. Weights and rates of the DRASTIC parameters including diffuse nitrogen surplus in the rooting zone and nitrogen concentration in deep percolation.

Parameter	Weight	Classes/Ranges	Rates
Depth to groundwater (m)	5	<5	10
		5 – 10	7
		15 – 30	3
		>30	1
Net groundwater recharge (mm/a)	4	>100	9
		50 – 100	8
		10 – 50	6
		5 – 10	3
		<5	1
Aquifer media	3	Intergranular	8
		Fractured	6
		Fractured & Intergranular	3
Soil media	2	Loamy sand	7
		Sandy loam	6
		Sandy clay loam & Loam	5
		Clay loam	3
Topography (slope [%])	1	0 – 2	10
		2 – 6	9
		6 – 12	5
		12 – 18	3
		>18	1
Impact of vadose zone	5	Sandveld Group, Bredasdorp Groups	10
		Table Mountain Group, Witteberg Group, Cape Granite Suite	6
		Malmesbury Group, Bokkeveld Group	4
Hydraulic conductivity (m/s)	3	$>10^{-4}$	8
		10^{-4} - 10^{-5}	6
		10^{-5} - 10^{-6}	4
		10^{-6} - 10^{-7}	2
		$<10^{-8}$	1
Diffuse nitrogen surplus (kg/ha/yr)	5	0 – 10	2
		10 – 20	4
		20 – 30	6
		30 – 40	8
		>40	10
Nitrogen concentration in the deep percolation (mg/l)	5	<6	2
		6 – 10	4
		10 – 20	6
		20 – 40	8
		>40	10

High-risk land use activities located in H+VH groundwater nitrogen pollution risk areas are very likely to have a negative impact on the groundwater resources. LULC not identified as high-risk but located in H+VH groundwater nitrogen pollution risk areas, would indicate that the physical conditions of the environment rather than the land use activity itself makes the groundwater vulnerable to pollution.

2.3 Identification of submarine groundwater discharge contribution areas

Polluted coastal groundwater from hotspot areas which contributes to SGD is a good measure of the extent to which coastal marine and estuarine water is subjected to nitrogen pollution from land use activities. With limited available data, a simplified approach delineating SGD-CA's was developed. The coastal intergranular aquifers of the study regions are predominantly sandy sediments. Therefore, the assumption is that surface catchments located in the coastal intergranular areas represent subsurface catchments. Based on this assumption sandy aquifer areas were delineated from the 1:500,000 hydrogeological maps [36-37]. The sandy aquifer areas which do not have river outlets contribute to SGD, and were identified as SGD-CA's. SGD-CA's located in hotspot areas are likely to result in groundwater with increased nitrogen concentrations reaching marine and estuarine environments. This is particularly relevant for SGD-CA's which have a high groundwater contribution potential, i.e. high nitrogen flux. Deep percolation was simulated using STOFFBILANZ [34] and the maps were used to distinguish areas with high and low groundwater contribution potential to SGD. For the scope of this study, SGD-CA's with deep percolation rates greater than 50 mm a^{-1} were considered as areas with a high groundwater contribution to SGD.

3 Results

The analysis showed that high-risk land use activities include dryland crop cultivation, irrigated crop cultivation and the irrigated production of wine grapes. Dryland crop cultivation covers 88% of land areas with DNS values greater than 30 kg/ha/yr, followed by irrigated crop cultivation and irrigated wine grapes, covering 6% of such land areas respectively.

In both of the study regions, dryland crop cultivation and irrigated crop cultivation are present in the H+VH groundwater nitrogen pollution risk areas. These land use activities therefore do contribute to potential groundwater pollution.

3.1 Groundwater assessments: DRASTIC approach / linear summation with LULC parameters

The groundwater vulnerability, groundwater pollution risk, and hotspot maps for the western region are shown in Figure 3a, b, c.

The Cape Flats, located to the west of the study region, showed extensive H+VH groundwater vulnerability (Figure 3a) and H+VH groundwater nitrogen pollution risk (Figure 3b). This area is considered to be a hotspot area (Figure 3c). Irrigated crop cultivation covered 10% of the H+VH groundwater nitrogen pollution risk areas, with this area of overlap being concentrated in the Cape Flats.

The area towards the inland, east of the Cape Flats showed "medium" and "high" (henceforth referred to as "M+H") groundwater vulnerability (Figure 3a) and groundwater nitrogen pollution risk (Figure 3b). There is extensive irrigated production of wine grapes in this area.

The area east of Struis Bay represents M+H groundwater vulnerability (Figure 3a) and H+VH groundwater pollution risk (Fibure 3b). This area is considered to be a hotspot area (Figure 3c). Dryland crop cultivation had the highest coverage, covering 27% of H+VH groundwater pollution risk areas, mainly in the area east of Struis Bay.

Other LULC present in H+VH groundwater nitrogen pollution risk areas were mainly found in areas of the Cape Flats. These included the natural vegetation (Fynbos) (16%), urbanization (14%) and informal settlements (11%).

The groundwater vulnerability, groundwater pollution risk, and hotspot maps for the eastern region are shown in Figure 4a, b, c.

The area between Wilderness and Knysna showed H+VH groundwater vulnerability (Figure 4a) and H+VH groundwater nitrogen pollution risk (Figure 4b), and is the primary hotspot area of the eastern region (Figure 4c). The area is characterized by Fynbos and forest plantations. The latter LULC showed high coverage in H+VH groundwater pollution risk areas predominantly within this coastal area (Fynbos with 38% coverage and forest plantations with 16% coverage).

Extensive areas of the eastern region showed "medium" groundwater vulnerability (Figure 4a), but have "high" groundwater nitrogen pollution risk (Figure 4b). In these areas, dryland crop cultivation has the

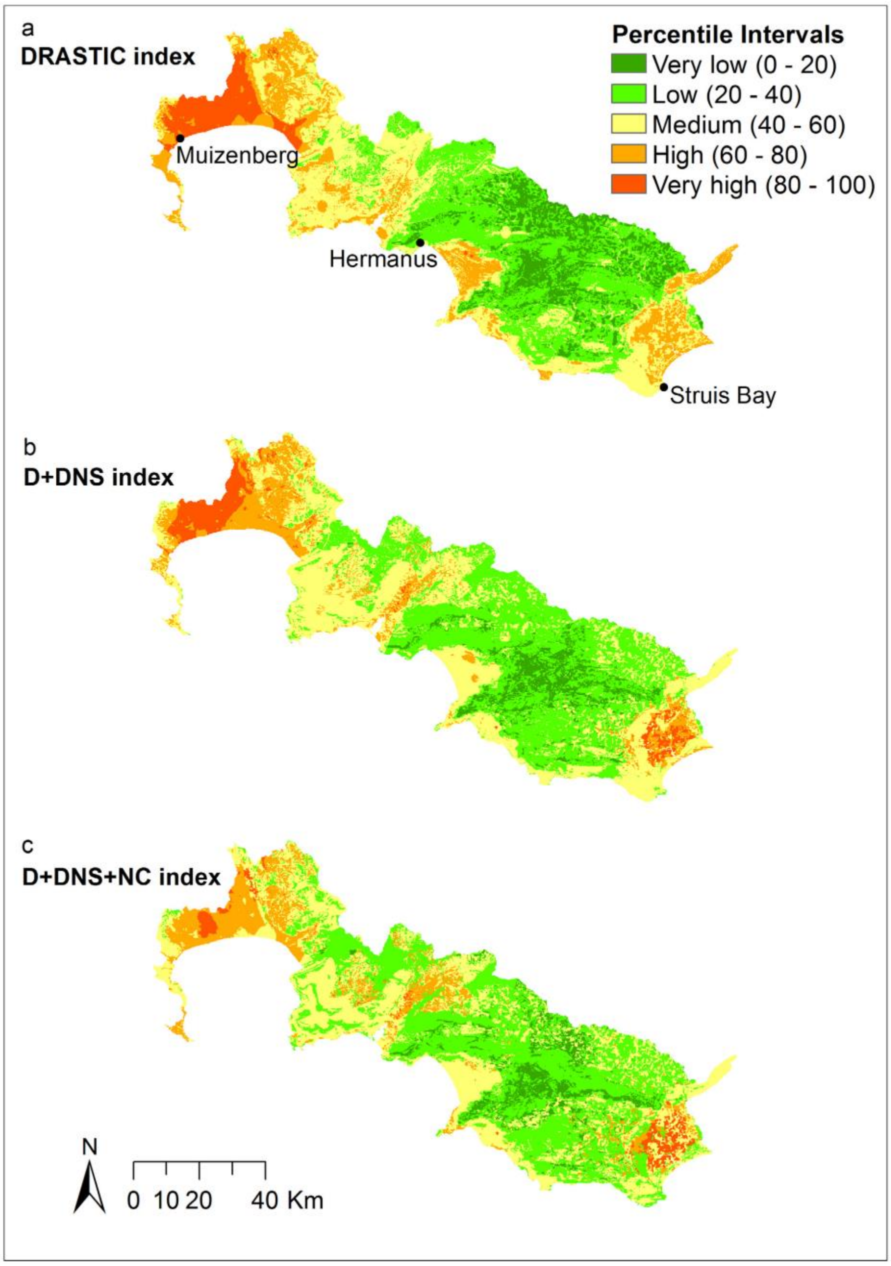

Figure 3. Groundwater assessment maps of the western region. a. Groundwater vulnerability map applying the DRASTIC index. b. Groundwater pollution risk map applying the D+DNS index. c. Hotspot map applying the D+DNS+NC index.

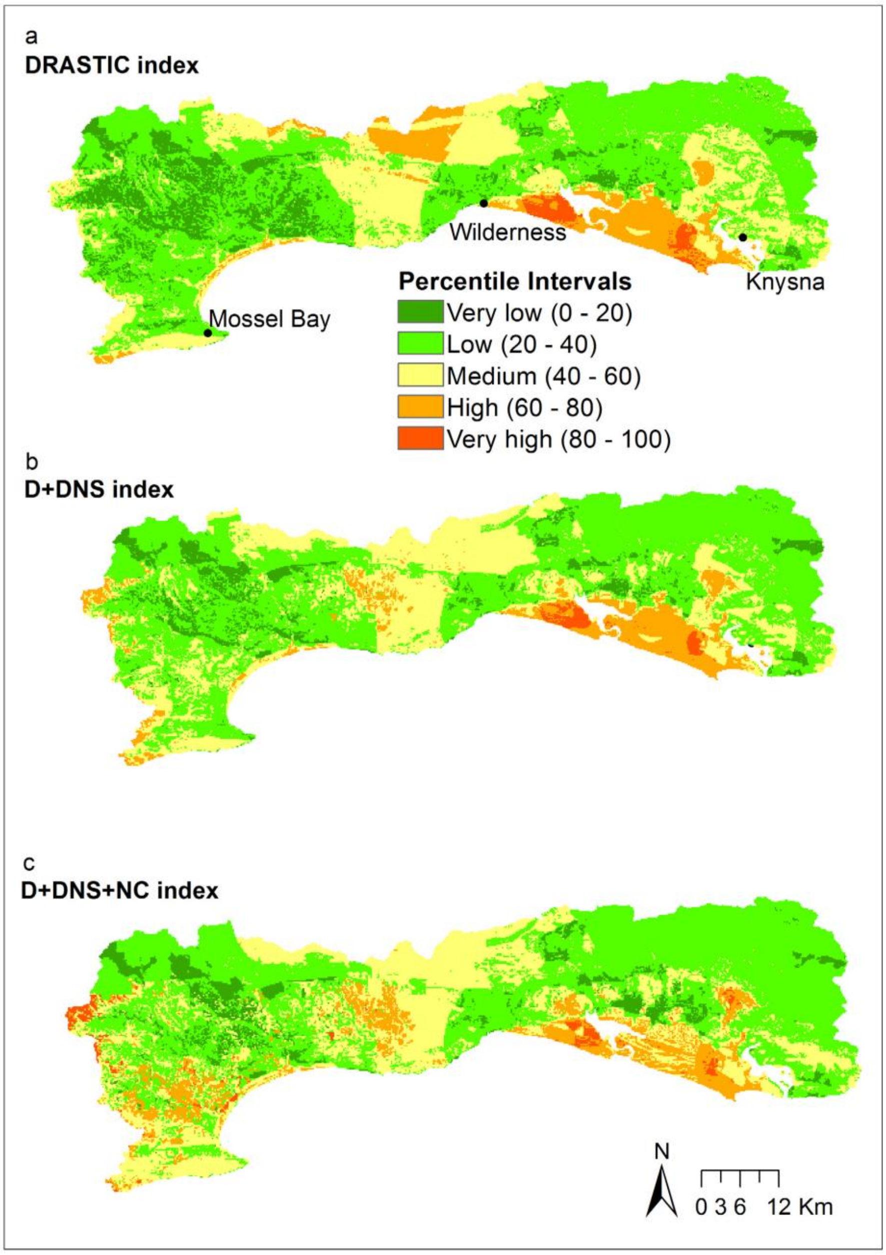

Figure 4. Groundwater assessment maps of the eastern region. a. Groundwater vulnerability map applying the DRASTIC index. b. Groundwater pollution risk map applying the D+DNS index. c. Hotspot map applying the D+DNS+NC index.

highest coverage (24% of H+VH groundwater pollution risk areas), followed by irrigated crop cultivation with a coverage of 5%.

3.2 Identified of submarine groundwater discharge contribution areas

The SGD-CA's located in hotspot areas for the study regions are shown in Figure 5.

The SGD-CA of the western region is located in the Cape Flats (Figure 5a). It is characterized by urbanization, mainly informal settlements, and irrigated cultivation of vegetables. This SGD-CA has a high groundwater contribution potential.

The SGD-CA of the eastern region is located in the area between Wilderness and Knysna (Figure 5b). Natural land cover is mainly present in this area.

4 Discussion

Our findings indicate that agriculture is an important potential contributor to groundwater nitrogen pollution. This corresponds with findings from other groundwater assessment studies conducted for various regions across the globe. These findings showed that agricultural activities, particularly from fertilizer application, were major contributors [10, 12-13, 15]. It was also found that agricultural nitrogen loading is higher than domestic nitrogen loading [13, 17]. The "very high" groundwater pollution risk area in the Cape Flats (Figure 3b), identified as a hotspot area (Figure 3c), might be influenced by the irrigated crop cultivation of intense multiple cropping of vegetables. The Fertilizer Association of South Africa states that the average rate of nitrogen fertilizer used for irrigated cultivation of vegetables is as high as 170 kg/ha [38]. The nitrogen surplus rate for the cultivation of

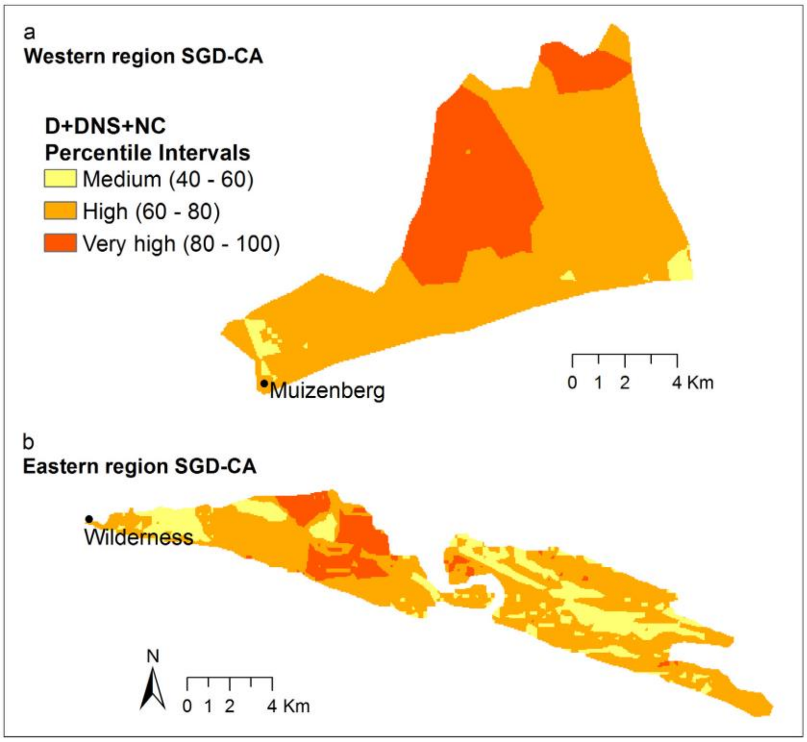

Figure 5. Submarine groundwater discharge contribution areas located in hotpot areas. a. Submarine groundwater discharge contribution area of the western region. b. Submarine groundwater discharge contribution area of the eastern region.

vegetables in this area is found to be high [34]. However, the Cape Flats has a high percolation rate which results in lower nitrogen concentrations reaching the groundwater. This suggests that nitrogen loads generated in such areas may be higher [34].

There was no irrigated production of wine grapes in the H+VH groundwater nitrogen pollution risk areas. The production of wine grapes in the western region is concentrated in an area east of the Cape Flats, which represents M+H groundwater vulnerability (Figure 3a) and groundwater nitrogen pollution risk (Figure 3b). Findings showed that the nitrogen surplus of irrigated wine grapes is high [34]. However, the nitrogen concentration in total runoff simulated for this area is low [34]. It may be concluded that the production of wine grapes in this area is adapted to the physical conditions regulating diffused nitrogen inputs.

The area east of Struis Bay shows an increase from M+H groundwater vulnerability (Figure 3a) to H+VH groundwater pollution risk (Figure 3b). This suggests that the dryland crop cultivation practiced within the area does influence the groundwater resources. The average rate of nitrogen fertilizer applied for dryland crops is 27 kg/ha [38]. Even at such low nitrogen fertilizer rates, the low percolation rates may contribute to increasing nitrogen concentrations reaching the groundwater [34], which supports the finding that this is a hotspot area (Figure 3c). The dryland crop cultivation practiced in this area does not seem well adapted to the physical conditions of the landscape.

Our findings indicate that urban development is not a high-risk activity as simulation of the diffused nitrogen surplus parameter for this study considers point source waste water to flow directly into river systems [34]. This suggests that the environment's physical conditions are an important contributor to the H+VH groundwater nitrogen pollution risk in the Cape Flats (Figure 3b). Groundwater assessment studies also indicate that domestic sources do not greatly influence groundwater resources [13, 17]. However, findings show that groundwater in the vicinity of point source pollution is subject to groundwater pollution [16, 18]. A large proportion of urban development in the Cape Flats is informal. Waste water disposal from informal settlements covering the flat sandy plains might contribute to high nitrogen concentrations and other organic and microbial contaminants reaching the groundwater [39]. Gaining information on waste water disposal from informal settlements is a major challenge, particularly due to a variety of political and social aspects [40].

The area between Wilderness and Knysna represents H+VH groundwater nitrogen pollution risk (Figure 4b). The land cover of this area is mainly natural ecosystems. Therefore it may be concluded that the groundwater is subjected to a high pollution potential due to the environments' physical conditions. The area was found to be a hotspot (Figure 4c), indicating that the groundwater is very susceptible to nitrogen pollution. The natural land cover must remain pristine and the area must remain part of the Wilderness National Park and the Goukamma Nature Reserve managed by South African National Parks under the 2009 Garden Route National Park management plan [41].

The SGD-CA located in the Cape Flats (Figure 5a) is characterized by urbanization, principally informal settlements, and irrigated cultivation of vegetables. This SGD-CA has a high groundwater contribution potential which could contribute to nitrogen pollution of the coastal environment, particularly from groundwater originating from irrigated agricultural activities. However, the offshore coastal marine environment of the southern Western Cape region is dynamic [42] and discharged nutrients should disperse rapidly. Groundwater from the SGD-CA located between Wilderness and Knysna (Figure 5b) mainly originates from natural land cover and should be of good quality minimizing nitrogen pollution of the coastal water. Long term data did not indicate a drastic decline in the water quality of the Swartvlei and Knysna estuaries [43-44].

Rating of selected DNS and NC classes as LULC parameters is an improved approach compared to rating LULC using expert knowledge or based on assumptions. This is supported by the finding that the nitrogen concentration in the deep percolation simulated for this study corresponds well to nitrate and nitrite hotspots in groundwater based on an interpolation of borehole sampling conducted for South Africa [34]. Although our approach gives a good overview of the potential groundwater nitrogen pollution from land use activities, it does have limitations. The limited data available for our study regions is challenging. The limited number and uneven distribution of boreholes to determine the depth to water table parameter caused irregularities in the data which may have contributed to less optimal results. Another limitation of our study was the insufficient information to simulate the nitrogen budgets using the STOFFBILANZ model [34]. Thus, no validation of the nitrogen budgets was possible, which implies that it is important to regard the DNS and NC results as potentials [34]. Also, due to a lack of sufficient information, no differentiation was made between formal and informal urban settlements for the simulation of the nitrogen budgets [34].

5 Conclusion

The objective of this study was to identify land use activities causing groundwater nitrogen pollution and to determine hotspot areas of potentially polluted groundwater by nitrogen in a data scarce region. Also, SGD-CA's contributing to coastal marine and estuarine nitrogen pollution was described. This was achieved by linking LULC, groundwater and SGD on a meso-scale to two study regions along the southern coast of the WCP, South Africa. From the findings, the groundwater assessment approaches and delineation of the SGD-CA's were successfully carried out. Groundwater assessment approaches are the first step in gaining a critical understanding of how LULC relate to the environment and to identify priority areas requiring well defined management strategies. Although data are limited, the assessment approach provides relevant results for our study regions and may be applied to other regions of interest. This is supported by various studies highlighting that the addition of LULC to the DRASTIC approach delivers a good spatial overview of areas at increased risk of groundwater nitrogen pollution. Simulated nitrogen budgets might not be available for most regions. In such cases, rating of LULC classes based on nitrogen loading is plausible. Findings from this study and other research indicate that agricultural activities are a major contributor of diffuse nitrogen groundwater pollution. With increasing pressure placed on the Cape Flats aquifer, it is important for land managers to not only improve management strategies for the small-scale irrigated cultivated area, but also for upstream agricultural activities beyond the boundaries of this study region. It is important that the land owners revise and monitor excessive use of fertilizer. Land rehabilitation of the area east of Struis Bay is most likely not viable for the land owners. Revision of fertilizer application in this area is also recommended. Globally, it is important that the intensity of agricultural activities must be reviewed. In regions with sufficient resources, in situ monitoring of groundwater is recommended. Agricultural activities may not always be adequately adapted to the physical conditions of the environment. It is important that the intensity of these activities is adjusted to their foreseen environment. For this study, urban development was not found to be high-risk. However, other research has shown groundwater pollution in areas of waste water treatment. Diffuse groundwater pollution from poor waste water disposal might be of concern for informal urban developments such as the Cape Flats. The groundwater of areas known to have poor waste water disposal, particularly areas where physical conditions contribute to infiltration, must be monitored and waste management strategies improved. It is recommended that waste water disposal in the Cape Flats is addressed by the government. Prevention of groundwater pollution is more viable than remediation, highlighting the importance that natural ecosystems must remain pristine in areas of high groundwater vulnerability. This study is the first known attempt to delineate areas contributing to SGD in order to assess the effects that land use activities might have on coastal water. Measurements and analysis of coastal water to identify areas of SGD are cost intensive. Instead, delineation of SGD-CA's can be done using hydrogeological maps. Land use activities in SGD-CA's, which might contribute to coastal pollution, must also be managed accordingly. Coastal water monitoring remains important due to pollution contribution from stream, rivers and waste water discharge. Water quality monitoring of the Swartvlei and Knysna estuaries is recommended.

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Appendix B: Paper 2

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A Simplified Method to Assess the Impact of Sediment and Nutrient Inputs on River Water Quality in Two Regions of the Southern Coast of South Africa

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Abstract

Many rivers in the southern coastal region of the Western Cape Province, South Africa, are known to be in a poor state. Since the 1990s, the river water quality of this coastal region has been affected by increasing populations and by intensifying land use activities. Simplified risk assessment approaches are critical to identify in a timely manner areas where land use activities may impact water quality, particularly for regions with limited data. For this study, a simple assessment approach to estimate the impacts of land use activities on river water quality was improved by incorporating landscape potentials that take into account environmental factors. The methods were applied to two regions experiencing intensive land use along the southern coast. The findings indicate that the incorporation of the landscape potentials, (i) the landscape sediment generation potential and (ii) the diffuse nitrate potential, to estimate the impacts of sediment and nutrient inputs on river water quality need to be considered. Agricultural activities and informal settlements contribute to the increasing sediment and nutrient inputs of the river reaches. Areas with high proportions of river reaches at increasing pollution risk need to be managed on a large scale to ensure that all the potentially affected sub-catchments are included.

Keywords LULC · Sediment input · Nutrient input · Landscape potentials · River water quality

Introduction

Many people worldwide are threatened by polluted and scarce water resources (Vörösmarty et al., 2010). High demands placed on water resources are a major challenge to maintain acceptable standard of freshwater supplies for human use and to support healthy aquatic habitats. Water sources experience negative impacts from increasing populations and intensifying land use activities. Rivers are the principal source of the globe's freshwater supply (World Water Assessment Programme WWAP (2009)). It is therefore critical to minimize the negative effects from land use activities on river reaches. Increasing sedimentation and nutrient inputs, and other harmful chemical pollutants, are known to affect river water quality (Meybeck 2003; World Water Assessment Programme WWAP, 2009; Vörösmarty et al., 2010).

Models are used to predict the impacts of land use/land cover (LULC) on water quality. The Soil and Water Integrated Model conducts detailed modeling of chemical and nutrient pathways, fluxes, and assimilation processes (Hesse et al., 2013). The Soil and Water Assessment Tool is a catchment-scale model that models hydrology and quantifies the transfer of pollutants from land to water by adding a water export coefficient (Dabrowski 2014). Statistical models are used to relate data on measures of land use activity impacts to measures of water quality (Greene et al., 2013;

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Ali et al., 2017). A drawback of such complex models is that they require a high level of expertise and detailed data.

Simpler assessment approaches based on available data are useful to gain a spatial overview of the effects of LULC on water sources. Such approaches are relatively easy for non-experts to use, and assessment results can be obtained in a timely manner. For example, raster-based tools have been used to assess the impacts of land use activities on erosion control and water quality maintenance (Lima et al., 2017), sedimentation retention (Lorz et al., 2013; Koschke et al., 2014), and nitrogen loss control (Lorz et al., 2013). Primary information includes the standardization of indicator values on a scale from 0 to 100 for each of the LULC classes based on literature and expert knowledge. Landscape potentials based on relevant environmental factors are also incorporated to make the assessments spatially explicit. The findings from these studies show the land areas contributing to the potential pollution of water sources but do not show the estimated river water quality on a reach-by-reach basis.

A simplified assessment approach (henceforth referred to as the SAA) to assess the relative impacts of LULC on river water quality on a reach-by-reach basis has been applied to the Wilderness (Touws) River (O'Farrell et al., 2015), Berg River, and Olifants River systems in South Africa. The SAA is based on an ordinal rating system. Expert knowledge about land management practices are used to assign LULC classes with estimated impact scores according to the likelihood of the water sources being affected by each of the following impacts: (a) sediments, (b) nutrients, and (c) chemical pollutants. The impact scores are given on a scale from 1 to 3, where 1 indicates a low impact and 3 indicates a high impact. The cumulative impact scores are calculated for buffers of different widths around the river reaches to assess the relative impacts of LULC per river reach. The findings help identify sub-catchments where the impacts of LULC on the river water quality are relatively high. One drawback of the SAA is that it does not incorporate environmental factors such as the soil texture, slope, and rainfall.

Humans place high demands on the water resources in South Africa (Driver et al., 2005). A large proportion of the country's river ecosystems are in a poor state, and many river reaches in the Western Cape Province (WCP) are affected by negative impacts from land use activities (Nel et al., 2007). After the political change in 1994, the WCP experienced a large population influx, causing increased urban development and land use activities along the southern coastal region (Department of Environmental Affairs and Development Planning (DEAP), 2005). Dryland crop cultivation, the irrigated cultivation of vegetables, and irrigated orchards and wine grapes are important land use activities covering extensive land areas of this coastal region (Department of Environmental Affairs and Development Planning (DEAP), 2011). Due to the increasing pressure placed on its water resources and intensifying land use activities, the southern coastal region of the WCP is relevant to assess the impacts of LULC on river water quality.

By applying the SAA, the cumulative impact scores per river reach can be calculated separately to assess the estimated impacts of (i) the sediment input and (ii) the nutrient input on the river water quality. The objective of this study is to improve the SAA for the sediment input and nutrient input by incorporating the landscape potentials. This approach was applied at a mesoscale for two study regions representing a variety of LULC types along the southern coast of the WCP, South Africa. Three principal steps were executed.

Step 1: The SAA was applied to assess the estimated impacts of (1a) the sediment input on the river water quality (henceforth referred to as the $SAA_{(sed)}$) and (1b) the nutrient input on the river water quality (henceforth referred to as the $SAA_{(nut)}$) based only on LULC.

Step 2: Two landscape potentials, (2a) the landscape sediment generation potential and (2b) the diffuse nitrate pollution potential, were estimated using relevant environmental factors.

Step 3: Improved assessment approaches were developed by incorporating the landscape potentials into the SAA (henceforth referred to as the SAAxLP) as follows: (3a) the landscape sediment generation potential was incorporated into the $SAA_{(sed)}$ (henceforth referred to as the $SAAxLP_{(sed)}$) and (3b) the diffuse nitrate pollution potential was incorporated into the $SAA_{(nut)}$ (henceforth referred to as the $SAAxLP_{(nut)}$).

Differences in the assessment results between the SAA and SAAxLP for each of the impacts, sediment input and nutrient input, are expected. These differences will indicate the importance of incorporating landscape potentials when assessing the impacts of LULC on river water quality. The assessment results from the $SAAxLP_{(sed)}$ and $SAAxLP_{(nut)}$ will help identify hotspot areas. For this study, hotspot areas are described as areas with high proportions of river reaches at increasing risk of sediment and/or nutrient inputs. From the hotspot areas, the associated land use activities impacting the river water quality will be identified. Knowledge of the land use types and areas threatening river water quality is important for management strategies and the planning of remedial actions (Vörösmarty et al., 2010).

Methods

Study area

The SAA and SAAxLP assessment approaches were applied to two study regions along the southern coast of the

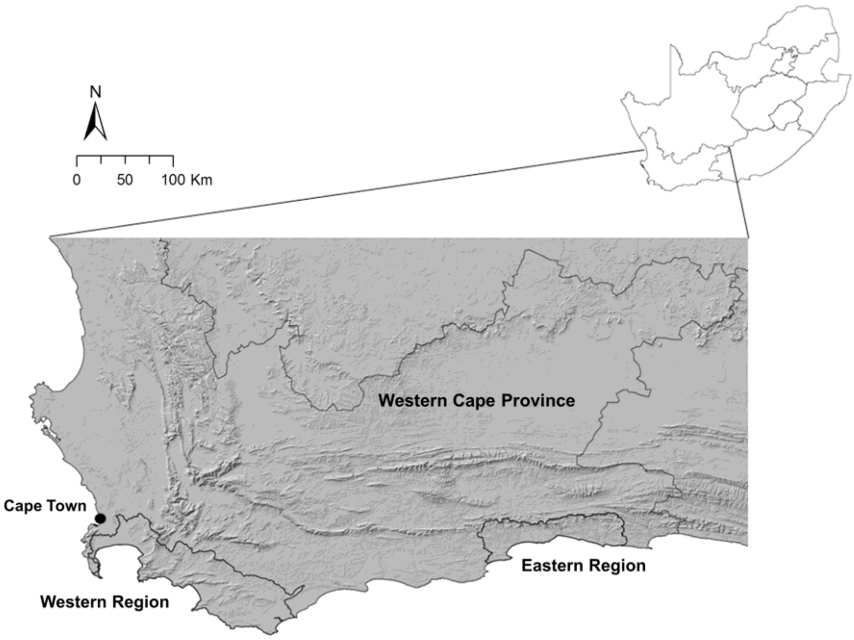

Fig. 1 Location of the study regions along the southern coast of the Western Cape Province, South Africa (based on van Niekerk 2015)

WCP, South Africa, referred to as the western and the eastern regions. The western region extends along the coastline from Cape Point (34° 21' S, 18° 28' E) to 22 km east of Struis Bay (34° 48' S, 20° 03' E) and extends approximately 50 km inland, covering a land surface area of 643,542 ha. It includes regions of the Cape Flats, the Cape Winelands District, and the Overberg District. The eastern region extends along the coastline, 15 km west of Mossel Bay (34° 11' S, 22° 8' E) to 12 km east of Knysna (34° 04' S, 23° 03' E). It is located in the Eden District, extending a maximum of 38 km inland and covering a land surface area of 285,735 ha (Fig. 1). The study regions are characterized by a Mediterranean climate of hot and dry summer seasons, rainy winter seasons, and mild to warm autumn and spring seasons. A mean annual precipitation gradient exists along the southern coastal regions extending eastwards. The highest mean annual precipitation in the coastal and mountainous regions is 1000–1200 mm, while the lowest mean annual precipitation is measured along the coastal areas and inland at 200–400 mm (Lynch 2004).

The two study regions were selected based on their diversity of LULC classes. The 2000 National Land Cover data (van den Berg et al., 2008), incorporating the 2013 map of Agricultural Commodities in the WCP (Western Cape Department of Agriculture (WCDA), 2013), were used to represent the LULC for the western region (Fig. 2a) and the eastern region (Fig. 2b). The natural vegetation in both regions includes "Fynbos." The Fynbos biome is rich in biodiversity and is recognized as one of the world's floral kingdoms (Goldblatt and Manning 2000). Natural vegetation in the eastern region also includes indigenous forests and woodlands. Dryland crop cultivation is the most important land use activity in both study regions, while irrigated agricultural activities and forest plantations are practiced less extensively. The irrigated production of wine grapes is only present in the western region. Urban development is present in both study regions, even though informal urban development is most prevalent in the western part of the western region. Other LULCs present in both study regions include natural grazing and grassland, water bodies, and wetlands.

General workflow

A general workflow of the three principal steps given in the introduction is shown in Fig. 3. Details of the methods used to achieve these steps are given in the sections below. Data processing was performed using ArcGIS version 10.1 software (ArcGIS 2012).

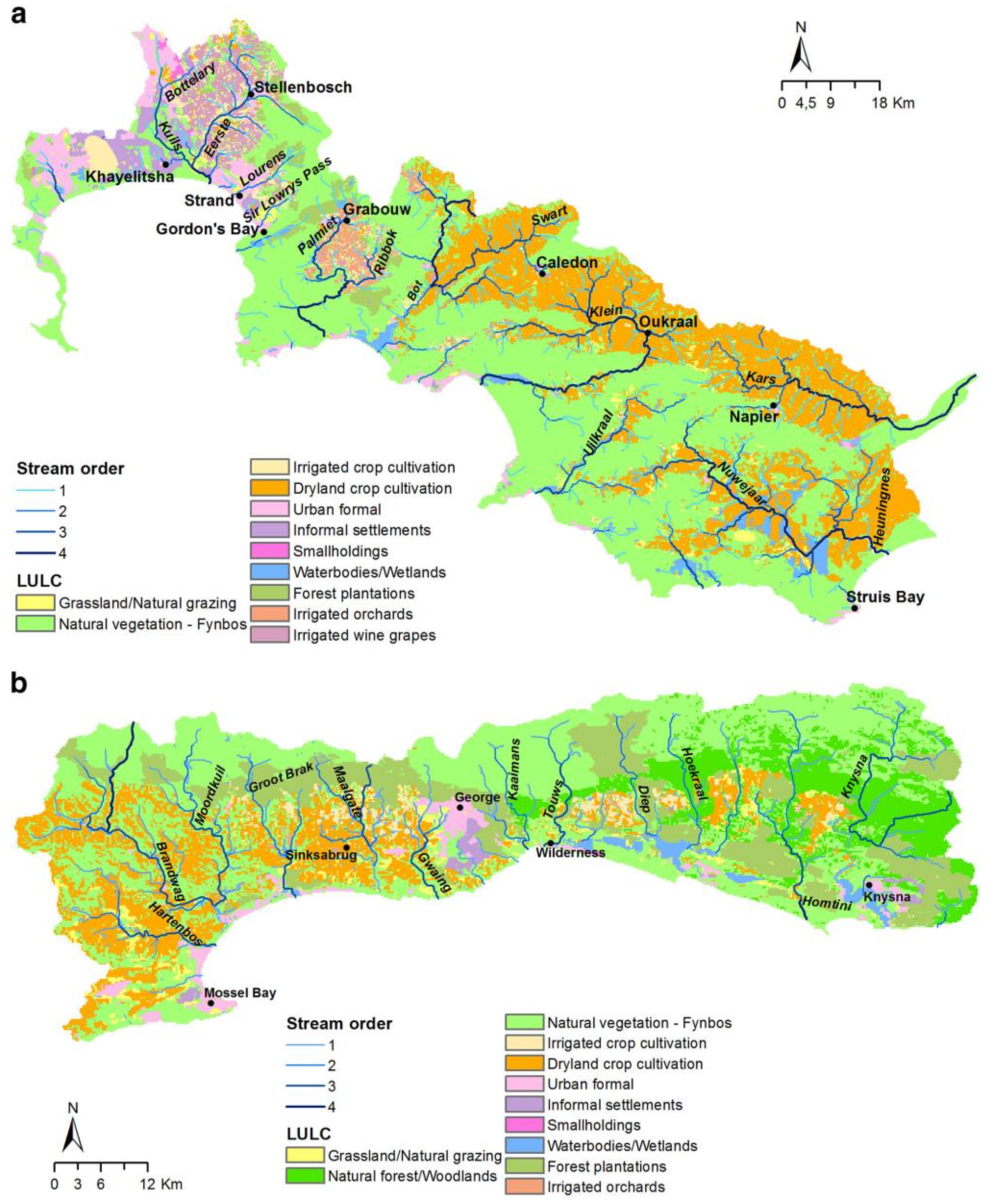

Fig. 2 **a** Land use/land cover and important rivers in the western region (Western Cape Department of Agriculture (WCDA), 2013; van den Berg et al., 2008). **b** Land use/land cover and important rivers in the eastern region (Western Cape Department of Agriculture (WCDA), 2013; van den Berg et al. 2008)

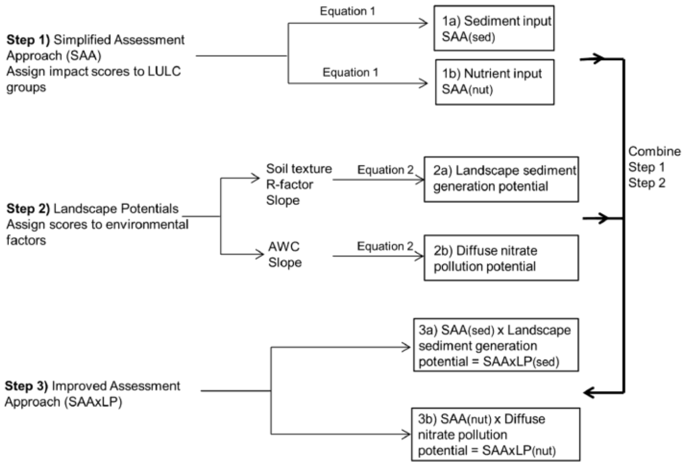

Fig. 3 Work flowchart for the development of the improved assessment approaches

Table 1 Estimated impact scores for sediment input and nutrient input from LULC (O'Farrell et al., 2015)

LULC classes	Sediment input	Nutrient input
Natural vegetation: Fynbos/forest/woodlands, waterbodies/wetlands, grassland, and natural grazing	0	0
Forest plantations and smallholdings	2	1
Irrigated orchards and wine grapes	2	3
Irrigated crop cultivation and informal settlements	3	3
Dryland crop cultivation	3	1
Urban formal	1	1

Step 1: River water quality assessment applying the SAA approach

In Step 1, the SAA was applied to assess the estimated impacts of (1a) the sediment input on the river water quality ($SAA_{(sed)}$) and (1b) the nutrient input on the river water quality ($SAA_{(nut)}$) based only on LULC (Fig. 3). Accordingly, the estimated impact scores were first given to the LULC classes for both the sediment and nutrient inputs and were primarily taken from O'Farrell et al., (2015). The impact scores were given on a scale from 1 to 3, where 1 indicates a low impact and 3 indicates a high impact (O'Farrell et al., 2015). Even though natural vegetation, water bodies, and wetlands do undergo some soil loss (O'Farrell et al., 2015), it was decided to give a score of 0 to these land cover classes. Relative to other land use activities, the sediment and nutrient inputs from natural grazing can be regarded as negligible and were therefore also given scores of 0 (Table 1).

Second, river networks and sub-catchments for each study region using digital elevation models provided by the Stellenbosch University, SUDEM–2015 (van Niekerk 2015), were created. A raster analysis of the SUDEM data was performed to obtain the flow direction and flow accumulation. A stream grid was computed based on the flow accumulation. The stream grid and flow direction were processed together to obtain a grid of the stream segments. Catchment grid delineation was performed to create a sub-catchment of each stream segment (henceforth referred to as river reaches) (ArcTutorial, 2011).

Buffer strips with the same distance as those used for the Olifants River System were created from either side of each river reach: 0–25, 25–50, 50–125, 125–500, and 500–1000 m. Mean impact scores were determined for the sediment input and the nutrient input for each buffer width using the relevant scores given in Table 1. The mean impact scores were combined and weighted to calculate the final impact scores of the sediment input ($SAA_{(sed)}$) and nutrient input ($SAA_{(nut)}$) on a reach-by-reach basis using the following equation.

Equation 1: $SAA_{(sed)}$ or $SAA_{(nut)}$ impact scores = {25 m buffer (mean impact score)} + 0.95 {25–50 m buffer (mean impact score)} + 0.85 {50–125 m buffer (mean impact score)} + 0.50 {125–500 m buffer (mean impact score)} + 0.25 {500–1000 m buffer (mean impact score)}

The weights indicate the decline in the potential impact on the river reaches as the distance of the successive buffers

Table 2 Classification and scoring of the environmental factors for the landscape sediment generation potential and the diffuse nitrate pollution potential

Sedimentation contribution potential					
Soil texture Topsoil gravel content >2 mm (%volume)	Rate	R-factor (MJ mm ha^{-1} h^{-1} yr^{-1})	Rate	Slope (%)	Rate
Loamy sand, clay loam, and sandy clay loam	**1**	400–600	**1**	<1	**1**
Topsoil gravel 11–30%		600–1200	**2**	1–5	**2**
Loamy sand, clay loam, and sandy clay loam	**3**	1200–2500	**4**	5–10	**3**
Topsoil gravel < 10%		2500–5000	**5**	10–20	**4**
Sandy loam Topsoil gravel 11–30%				>20	**5**
Sandy loam Topsoil gravel <10%	**5**				
Nitrate pollution potential					
AWC (mm m^{-1})	**Rate**	**Slope (degree)**	**Rate**		
150	**1**	0–2.5	**1**		
100	**3**	2.5–8.0	**3**		
50	**4**	>8.0	**5**		
15	**5**				

from the river channel increases. The used weights follow a negative exponential function because it fits the non-linear decrease in the impact with increasing distance (Weller et al., 1998).

The $SAA_{(sed)}$ and $SAA_{(nut)}$ impact scores were classified on a scale of very low to very high in equal percentile intervals, which are the index values found within each interval: low (0–40th percentile), medium (40–70th percentile), high (70–90th percentile), and very high (90–100th percentile).

Step 2: Generation of the landscape sediment generation potential and diffuse nitrate pollution potential

In Step 2, two landscape potentials, (2a) the landscape sediment generation potential and (2b) the diffuse nitrate pollution potential, were estimated using relevant environmental factors (Fig. 3). The environmental factors were classified and given scores according to the potential contribution of each class to the landscape potential. Classifying and scoring were conducted with reference to literature (Marks et al., 1999; Orlikowski et al., 2011; Lorz et al., 2013; Koschke et al., 2014; Lima et al., 2017). For this study, the environmental factors were rated on a scale from 1 to 5, where 1 indicates the lowest potential contribution and 5 indicates the highest potential contribution (Table 2). All areas of the study regions with >80% rock outcrops were given an overall landscape potential score of 0.

The environmental factors used to determine the landscape sediment generation potential include soil properties, the slope (Marks et al., 1999; Lorz et al., 2013; Koschke et al., 2014; Lima et al., 2017), and rainfall intensity (Marks et al., 1999). The soil texture and the topsoil gravel content (>2 mm) were retrieved from the Harmonized World Soil Database (HWSD) (Food and Agricultural Organization (FAO), 2009). The topsoil organic carbon content (%) was retrieved from the Agricultural Research Council-Institute for Soil, Climate, and Water (ARC-ISCW) (Barnard 2000). The carbon content was multiplied by the van Bemmelen factor of 1.7324 for the conversion to topsoil humus content (%). The percentage of topsoil humus is <2 for all areas of the study regions and therefore was not used to determine the landscape sediment generation potential. Three classes including soil texture and topsoil gravel content, were scored according the contribution that the soil properties have on the erodibility (Table 2).

The rainfall intensity (MJ mm ha^{-1} h^{-1} yr^{-1}) (R-factor) map for South Africa was obtained from Le Roux et al., (2006, 2008). Four R-factor classes were scored according to the effect that the rainfall intensity has on the erosivity (Table 2).

The slope steepness in percentage rise was calculated using the 2015 SUDEM data (van Niekerk 2015). Five classes were scored according to the effect that the slope steepness has on the landscape sediment generation potential (Table 2).

The environmental factors used to determine the diffuse nitrate pollution potential include the available soil water capacity and slope (Orlikowski et al., 2011; Koschke et al., 2014). For this study, the rating of the riparian buffer strips was not performed because the decreasing risk of nutrients reaching river water due to the LULC is already included in the $SAA_{(nut)}$.

Soil texture and depth are known to be major controlling factors of the diffuse nitrate pathway to the surface water. These parameters can be used to determine the root zone available soil water capacity (RZAWC). The lower the RZAWC, the less water will be retained in the root zone. This indicates that more nitrate leaching may occur, causing increasing nitrate pollution of the surface water (Orlikowski et al., 2011). For this study, the available water storage capacity (AWC) of the HWSD (Food and Agricultural Organization FAO (2009)) was used because no RZAWC data are available for the study regions. The AWC was estimated by accounting for the soil textural classes and reference depths of the soil units (Food and Agricultural Organization FAO (2009)). Four AWC classes were scored according to the contribution that AWC has on nitrate leaching (Table 2).

The slope steepness in degrees was calculated using the 2015 SUDEM data (van Niekerk 2015). The main pathway for nitrate to reach the surface water is via the subsurface; however, nitrate may also reach river water as surface runoff (Mayer et al., 2005). For this study, slope classifications different from those of Orlikowski et al., (2011) were used. The three classes that best fit the study regions were scored according to the effect that the slope steepness has on the diffuse nitrate pollution of river water (Table 2).

The same buffer strips created in Step 1 were used to determine the landscape potential scores. For each buffer width, the mean contribution potential scores were determined for each of the landscape potentials using the relevant environmental factor scores given in Table 2. The mean contribution potential scores relevant to each landscape potential were combined and weighted to calculate the final landscape sediment generation potential scores and the diffuse nitrate pollution potential on a reach-by-reach basis using the following equation.

Equation 2: Landscape sediment generation potential or diffuse nitrate pollution potential scores = {25 m buffer (mean contribution potential score)} + 0.95 {25–50 m buffer (mean contribution potential score)} + 0.85 {50–125 m buffer (mean contribution potential score)} + 0.50 {125–500 m buffer (mean contribution potential score)} + 0.25 {500–1000 m buffer (mean contribution potential score)}

Step 3: Improved river water quality assessment applying the SAAxLP approach

In Step 3, two improved river water quality assessment approaches were presented by multiplying the landscape potential contribution scores calculated in Step 2 by the SAA impact scores calculated in Step 1 as follows: (3a) the landscape sediment generation potential was multiplied by the $SAA_{(sed)}$, referred to as the $SAAxLP_{(sed)}$, and (3b) diffuse nitrate pollution potential was multiplied by the $SAA_{(nut)}$, referred to as the $SAAxLP_{(nut)}$ (Fig. 3).

The $SAAxLP_{(sed)}$ and $SAAxLP_{(nut)}$ impact scores were classified on a scale of very low to very high in equal percentile intervals, which are the index values found within each interval: low (0–40th percentile), medium (40–70th percentile), high (70–90th percentile), and very high (90–100th percentile).

Results and discussion

Risk class differences between the simplified and improved assessment approaches

Table 3 gives the percentage coverage of each risk class for the $SAA_{(sed)}$ and $SAAxLP_{(sed)}$ and for the $SAA_{(nut)}$ and $SAAxLP_{(nut)}$ for each study region. The percentage coverage differences between the $SAA_{(sed)}$ and $SAAxLP_{(sed)}$ and between the $SAA_{(nut)}$ and $SAAxLP_{(nut)}$ are evident. This supports the importance of incorporating landscape potentials to assess the effects of LULC on river water quality. Compared to the $SAA_{(sed)}$ and $SAA_{(nut)}$, the $SAAxLP_{(sed)}$ and $SAAxLP_{(nut)}$ tend to put more land area in the high- and very high-risk classes in the western region, which is not the case in the eastern region. Important differences in the risk classes between the $SAA_{(sed)}$ and $SAAxLP_{(sed)}$ and between the $SAA_{(nut)}$ and $SAAxLP_{(nut)}$ for two areas located in the western region are discussed below.

Figure 4a shows a risk class map applying the simplified assessment approach, $SAA_{(sed)}$, and Fig. 4b shows a risk class map applying the improved assessment approach, $SAAxLP_{(sed)}$, for the western region. The Eerste River and its tributaries flowing through Stellenbosch to the coast in

Table 3 Percentage coverage of each risk class for the $SAA_{(sed)}$ and $SAAxLP_{(sed)}$ and for the $SAA_{(nut)}$ and $SAAxLP_{(nut)}$ for each study region

Risk classes	$SAA_{(sed)}$	$SAAxLP_{(sed)}$	$SAA_{(nut)}$	$SAAxLP_{(nut)}$
Western region				
Low	40.35	39.21	40.20	35.42
Medium	29.75	27.35	29.67	31.54
High	20.20	21.92	19.83	21.69
Very high	9.88	11.52	10.30	11.35
Eastern region				
Low	36.64	38.85	36.5	37.77
Medium	31.76	29.6	34.55	33.55
High	22.89	22.70	18.47	18.76
Very high	8.71	8.84	10.48	9.92

the western part of the western region mostly indicate a high risk of sediment input in terms of the $SAA_{(sed)}$ (Fig. 4a) but a very high risk in terms of the $SAAxLP_{(sed)}$ (Fig. 4b). This is due to the increasing contribution of the sediment input related to the soil textures (loamy sand and a sandy loam area with topsoil gravel < 10%) and the increasing slope toward Stellenbosch.

Figure 5a shows a risk class map applying the simplified assessment approach, $SAA_{(nut)}$, and Fig. 5b shows a risk class map applying the improved assessment approach, $SAAxLP_{(nut)}$, for the western region. The river reaches and tributaries of the Kars and Heuningnes rivers located in the far eastern part of the western region mostly indicate a high risk of nutrient input in terms of the $SAA_{(nut)}$ (Fig. 5a) but a medium risk in terms of the $SAAxLP_{(nut)}$ (Fig. 5b). This finding is due to the decreasing nitrate pollution of the river water caused by the areas' low slope and high AWC.

Hotspot areas for the estimated impact of sediment and nutrient inputs on river water quality

For this discussion refer also to the $SAAxLP_{(sed)}$ and $SAAxLP_{(nut)}$ risk class maps for the western region presented in the section above. Figure 6 shows a risk class map applying the improved assessment approach, $SAAxLP_{(sed)}$, and Fig. 7 shows a risk class map applying the improved assessment approach, $SAAxLP_{(nut)}$, for the eastern region. For each of the identified hotspot areas, the sediment input and nutrient input risk classes for the main rivers and associated land use activity patterns are given in Table 4.

The irrigated crop cultivation of vegetables is highly intensive and requires frequent soil tillage, which contributes to increasing sediment loss. Long-lived crops, such as irrigated orchards and wine grapes, require less frequent soil tillage, but also contribute to sediment loss (O'Farrell et al., 2015). Irrigated agricultural activities also require intensive fertilizer application (O'Farrell et al., 2015). The Fertilizer Association of South Africa (FSSA) states that the average rate of nitrogen fertilizer used for the irrigated cultivation of vegetables is as high as 170 kg ha^{-1}, while the rate for irrigated orchards and wine grapes is as high as 80 kg ha^{-1} (Food and Agricultural Organization (FAO), 2005). The irrigated production of wine grapes and the small-scale irrigated cultivation of vegetables are therefore the primary contributors to the high and very high risks of sediment and nutrient inputs for river reaches of the Bottelary and lower Eerste rivers in hotspot area "1" and the upper Sir Lowrys Pass and Lourens rivers in hotspot area "2." Wastewater disposal in informal settlements in the study regions is poor (Mels et al., 2010). The main rivers mentioned in Table 4 do not flow through informal settlements. However, Figs. 4b and 5b indicate that tributaries of the main rivers and other smaller rivers flowing through the informal settlements in hotspot areas "1" and "2" are subject to high and very high risks of sediment and nutrient inputs.

River reaches of the Kuils River and at the confluence of the Kuils and Eerste rivers in hotspot area "1" are surrounded by natural vegetation, which reflects their low and medium risks of sediment and nutrient inputs.

The river reaches and tributaries of the Palmiet and Ribbok rivers in hotspot area "3" in the Grabouw region are subject to very high risks of sediment input and high risks of nutrient input, presumably from the irrigated orchards and the small-scale irrigated cultivation of vegetables.

Dryland crop cultivation of cereal crops requires frequent tillage contributing to increasing sediment loss (O'Farrell et al., 2015). The average rate of nitrogen fertilizer applied to dryland crops is documented to be 27 kg ha^{-1} (Food and Agricultural Organization FAO (2005)). River reaches and tributaries of the Swart, Klein, and Kars rivers in hotspot area "4" therefore show high and very high risks of sediment input. The Swart and Klein rivers, including their tributaries near Caledon and Oukraal and extending southwards, are subject to medium and high risks of nutrient input.

From the extensive practice of dryland crop cultivation in hotspot area "5," it is not surprising that many river reaches and tributaries of the Hartenbos, Brandwag and Moordkuil, rivers are subject to medium and high risks of sediment and nutrient inputs. Irrigated cultivation of vegetables is also practiced to the west of George. This explains the high and very high risks of sediment and nutrient inputs for the middle reaches and tributaries of the Groot Brak, Maalgate, and Gwaing rivers.

Lastly, river reaches that are not located in hotspot areas but pass through forest plantations in the eastern region also show high and very high risks of sediment (Fig. 6) and nutrient (Fig. 7) inputs. Clear-felled areas of forest plantations mostly contribute to soil loss increasing the risk of sediment input; however, improdperly maintained roads also cause soil loss (O'Farrell et al., 2015). Forest plantations make a low contribution to the nutrient input (O'Farrell et al., 2015); therefore, the high and very high risks of nutrient input are most likely caused by the environmental factors.

Performance of the assessment approach

The state of rivers reports (Department of Water Affairs and Forestry (DWAF) 2003a, b, 2005, 2007) used nitrogen, ammonia, and other water chemistry data to categorize the water quality categories of main rivers in the study regions. Herdien et al. (2005) also indicated the water quality for important rivers referring to the total nitrogen and total phosphate conditions. Table 5 shows how the results of this study match with the above mentioned water quality

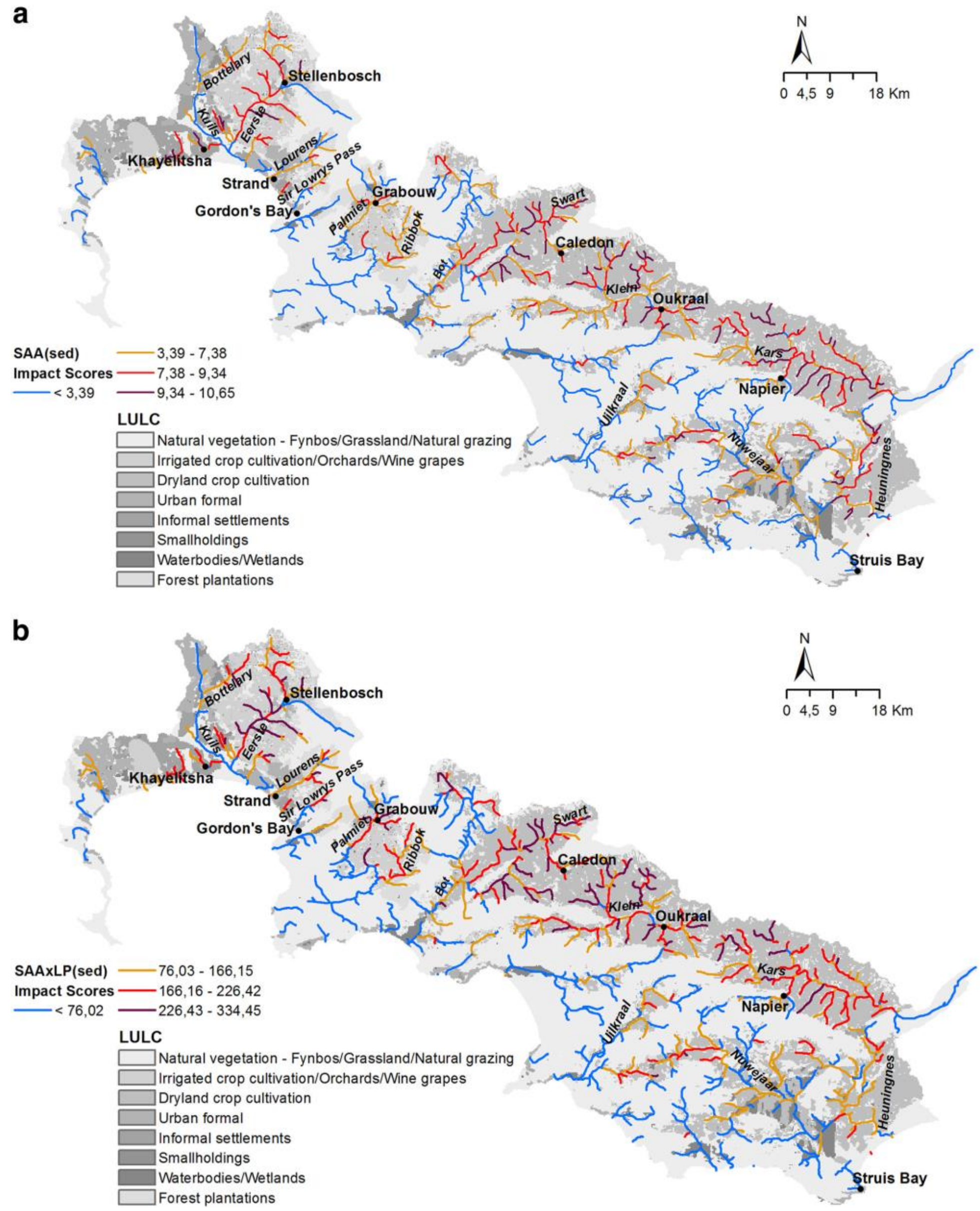

Fig. 4 **a** A risk class map of the estimated impacts of the sediment input on the river water quality for the western region applying the $SAA_{(sed)}$. **b** A risk class map of the estimated impacts of the sediment input on the river water quality for the western region applying the $SAAxLP_{(sed)}$

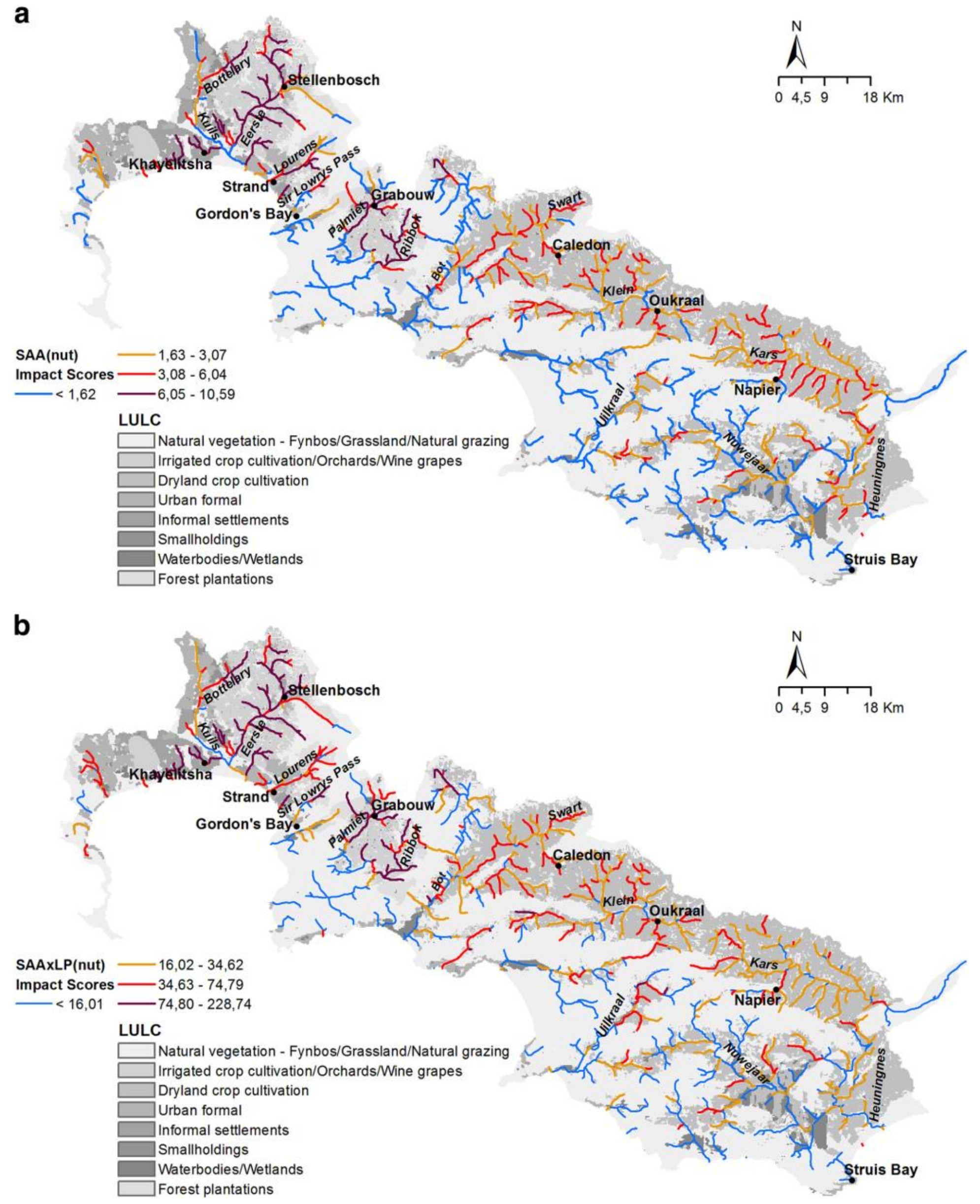

Fig. 5 **a** A risk class map of the estimated impacts of the nutrient input on the river water quality for the western region applying the $SAA_{(nut)}$. **b** A risk class map of the estimated impacts of the nutrient input on the river water quality for the western region applying the $SAAxLP_{(nut)}$

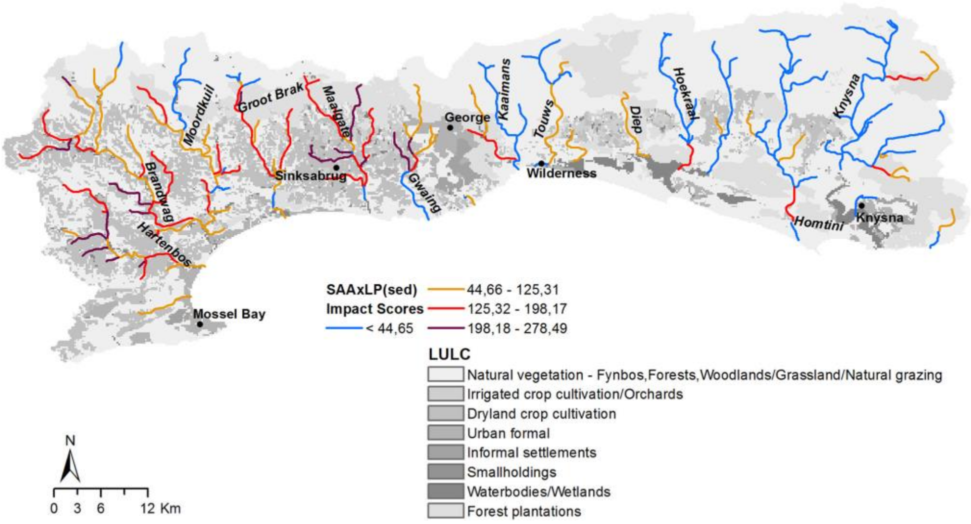

Fig. 6 A risk class map of the estimated impacts of the sediment input on the river water quality for the eastern region applying the $SAAxLP_{(sed)}$

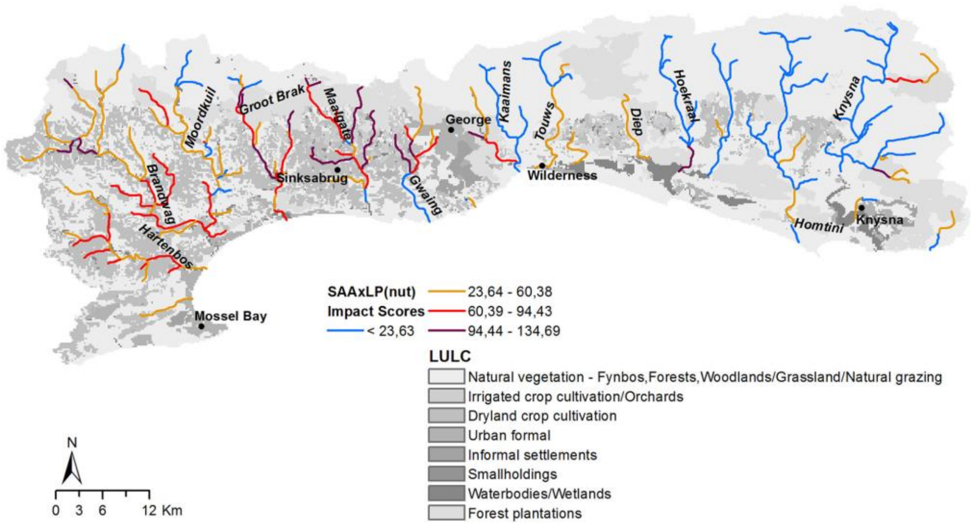

Fig. 7 A risk class map of the estimated impacts of the nutrient input on the river water quality for the eastern region applying the $SAAxLP_{(nut)}$

reports. The findings are discussed further in this section to determine the performances of the $SAAxLP_{(sed)}$ and $SAAxLP_{(nut)}$.

Our results coincide with the poor water quality category reported for the Bottelary, middle Palmiet, and middle Gwaing rivers. Agricultural activities are most likely the reason for the poor water quality reported for these rivers. However, the wastewater treatment works of Grabouw discharge directly into the Palmiet River and could also contribute greatly to the decreasing water quality of this

Table 4 Sediment input and nutrient input risk classes for the main rivers and associated land use activity patterns of the hotspot areas

Hotspot areas	Land use activity patterns	Rivers	Sediment input risk classes	Nutrient input risk classes
Western region				
1 Area extending from Stellenbosch to Khayelitsha	Irrigated wine grapes Small-scale irrigated cultivation of vegetables Urban Informal settlements	Upper Bottelary	High	Very high
		Lower Bottelary	Medium	High
		Middle Kuils	Low	Medium
		Confluence of Kuils and Eerste	Low	Low
		Lower Eerste	High, Very high	Very high
2 Area of Gordon's Bay and Strand	Small-scale irrigated cultivation of vegetables Small-scale irrigated wine grapes Urban Informal settlements	Lourens	Medium	High
		Upper Sir Lowrys Pass	High	Very high
		Lower Sir Lowrys Pass	Low	Medium
3 Surroundings of Grabouw extending southwards	Irrigated orchards Small-scale irrigated cultivation of vegetables	Middle Palmiet	High	Very high
		Ribbok	High	Very high
4 Extensive areas from Caledon to Napier extending southwards	Dryland crop cultivation of wheat and barley	Confluence of Swart and Bot	High, Very high	Medium, High
		Klein	High, Very high	Medium, High
		Kars	High	Medium
Eastern region				
5 Complete western part extending from Mossel Bay beyond George	Dryland crop cultivation of wheat and barley Small-scale irrigated cultivation of vegetables	Upper Hartenbos	Medium, Very high	Medium, High
		Lower Hartenbos	Medium, High	Medium, High
		Brandwag	Medium, High	High
		Moordkuil	Medium	Medium
		Groot Brak	High	High, Very high
		Maalgate	High, Very high	High, Very high
		Middle Gwaing	High, Very High	High, Very high
		Lower Gwaing	Low	Low

river (Department of Water Affairs and Forestry (DWAF), 2003a). Our results show high and very high risks of sediment input from dryland crop cultivation for river reaches and tributaries of the Swart, Klein, and Kars rivers. This reflects the very high concentration of total phosphates determined for the Klein and Kars rivers (Herdien et al., 2005). Increased nutrient input where the Swart and Bot rivers meet has greatly affected the water quality of the Swart River (Herdien et al., 2005). This reflects the high risk of nutrient input determined at the confluence in this study.

In some cases, our results do not compare well with the existing river water quality categories. Our results show low and medium risks of sediment and nutrient inputs for the Kuils River and at the confluence of the Kuils and Eerste rivers. However, it has been documented that storm water, litter, wastewater discharge, and spills from blocked sewage pump stations greatly impact the water quality of the Kuils River, which is categorized as unacceptable (Department of Water Affairs and Forestry (DWAF), 2005).

The Lourens River is reported to be in a fair condition (Department of Water Affairs and Forestry (DWAF), 2003a, 2005), and the upper Sir Lowrys Pass River is reported to be in a natural condition (Department of Water Affairs and Forestry (DWAF), 2005). However, sectors of Somerset West and Gordon's Bay have expanded since these rivers were assigned their water quality categories in 2005. In particular, the increase in informal settlements along the Lourens River and the intensification of the irrigated production of wine grapes along the upper Sir Lowrys Pass River might explain the increased risks of sediment and nutrient inputs calculated for these rivers.

The river water quality categories were reported some years before the compilation of the LULC data used for this study. The high and very high sediment and nutrient input results are an indication that the lower Eerste, Hartenbos,

Table 5 Matching of the study results with existing river water quality reports

	Sediment input risk	Nutrient input risk	Existing river water quality
Study results and existing water quality matches			
Hotspot area 1			
Upper Bottelary	High	Very high	Poor (Department of Water Affairs and Forestry (DWAF), 2005)
Lower Bottelary	Medium	High	
Hotspot area 2			
Lower Sir Lowrys Pass	Low	Medium	Fair (Department of Water Affairs and Forestry (DWAF), 2005)
Hotspot area 3			
Middle Palmiet	High	Very high	Poor (Department of Water Affairs and Forestry (DWAF), 2003a)
Hotspot area 4			
Confluence of Swart and Bot	Very high. High	Medium, High	Greatly affected (Herdien et al., 2005)
Klein	Very high, High	Medium, High	High concentrations: total phosphate (Herdien et al., 2005)
Kars	High	Medium	High concentrations: total phosphate (Herdien et al., 2005)
Hotspot area 5			
Middle Gwaing	High, Very high	High, Very high	Poor (Department of Water Affairs and Forestry (DWAF), 2007)
Study results and existing water quality do not match			
Hotspot area 1			
Middle Kuils	Low	Medium	Unacceptable (Department of Water Affairs and Forestry (DWAF), 2005)
Lower Eerste	High, Very high	Very high	Fair (Department of Water Affairs and Forestry (DWAF), 2005)
Confluence of Kuils and Eerste	Low	Low	Unacceptable (Department of Water Affairs and Forestry (DWAF), 2005)
Hotspot area 2			
Lourens	Medium	High	Fair (Department of Water Affairs and Forestry (DWAF), (2003a, 2005)
Upper Sir Lowrys Pass	High	Very high	Natural (Department of Water Affairs and Forestry (DWAF), 2005)
Hotspot area 5			
Upper Hartenbos	Medium, Very high	Medium, High	Good (Department of Water Affairs and Forestry (DWAF), 2003b)
Lower Hartenbos	Medium, High	Medium, High	Fair (Department of Water Affairs and Forestry (DWAF), (2003b, 2007)
Brandwag	Medium, High	High	Good (Department of Water Affairs and Forestry (DWAF), 2007)
Moordkuil	Medium	Medium	Natural (Department of Water Affairs and Forestry (DWAF), 2005)
Maalgate	High, Very high	High, Very high	Fair (Department of Water Affairs and Forestry (DWAF), 2007)
Lower Gwaing	Low	Low	Poor (Department of Water Affairs and Forestry (DWAF), 2007)

Brandwag, and Moordkuil rivers could also now be in a poorer state than previously reported.

The lower Gwaing has a low risk of sediment and nutrient inputs but is reported to be in a poor state (Department of Water Affairs and Forestry (DWAF), 2007). The confluence of the Kuils and Eerste rivers also has a low risk of sediment and nutrient inputs but is reported to be in an unacceptable state. Furthermore, the upper reaches of the Bottelary, Sir Lowrys Pass, and Gwaing rivers show higher risks of sediment and nutrient inputs than the lower reaches. These findings may be due to the fact that cumulative effects were not considered in this study.

A major limitation of these approaches is that the impacts can only be determined for each river reach independently. The methods do not accumulate the impacts longitudinally, which makes it problematic to identify and prioritize the most affected sub-catchments. Even though a distinction is made between formal and informal urban development, the approaches do not take point discharges from wastewater treatments in urban areas into account. Regardless, the assessment results give a good spatial overview of hotspot areas requiring more detailed land use and water related research.

Conclusions

The findings show that the landscape sediment generation potential increases the risk of sediment input for the western part of the western region and the diffuse nitrate pollution potential decreases the risk of sediment input for the eastern part of the western region. It is therefore recommended that landscape potentials based on relevant environmental factors be considered when assessing the potential impacts of LULC on river water quality. Findings from the assessment approaches are useful because the distribution and origin of the probable river water quality are highlighted. The insight gained from this study is a good starting point that can assist with management strategies to protect rivers. High proportions of river reaches with increasing risks of sediment and nutrient inputs are located in areas where the principal land use activities include irrigated crop cultivation, irrigated wine grapes, irrigated orchards, dryland crop cultivation, informal settlements, and forest plantations. However, more detailed results are required to prioritize the hotspot areas and to rank the land use activities from activities with the highest to lowest detrimental effects on river water quality. It is important to ensure that the hotspot areas are managed at a large scale to ensure that all the potentially affected sub-catchments of all the studied river networks are included. To maintain the approaches' simplicity with more detailed results to prioritize sub-catchments, further development of the methods is recommended to determine the cumulative effects of the impacts downstream along a river system.

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Authors' contributions HM (Technical University of Munich; University of Applied Science Weihenstephan-Triesdorf) designed and carried out the methodologies, interpreted the results, and wrote the manuscript. DLM (Council for Scientific and Industrial Research) assisted with the methodologies and co-prepared the manuscript. CL (University of Applied Science Weihenstephan-Triesdorf) assisted with the methodologies and co-prepared the manuscript. JLR (University of the Free State) co-prepared the manuscript. SP (Technical University of Munich) co-prepared the manuscript.

Compliance with ethical standards

Conflict of interests All authors explicitly reveal all potential financial, personal or professional conflicts of interest. All authors explicitly state that there is no such conflict regarding the publication of the article.

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Appendix C: Paper 3

Malherbe, H., Pauleit, S., Lorz C. (2019). Mapping the loss of Ecosystem services in a region under intensive land use along the southern coast of South Africa. Land, 8(3), 51.

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Mapping the Loss of Ecosystem Services in a Region Under Intensive Land Use Along the Southern Coast of South Africa

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Abstract: Intensive land use activities worldwide have caused considerable loss to many ecosystem services. The dynamics of these threats must be quickly investigated to ensure timely update of management strategies and policies. Compared with complex models, mapping approaches that use scoring matrices to link land use/land cover and landscape properties with ecosystem services are relatively efficient and easier to apply. In this study, scoring matrices are developed and spatially explicit assessments of five ecosystem services, such as erosion control, water flow regulation, water quality maintenance, soil quality maintenance, and biodiversity maintenance, are conducted for a region under intense land use along the southern coast of South Africa. The complex interaction of land use/land cover and ecosystem services within a particular landscape is further elucidated by performing a spatial overview of the high-risk areas that contribute to the loss of ecosystem services. Results indicate that both agricultural activities and urban development contribute to the loss of ecosystem services. This study reveals that with sufficient knowledge from previous literature and inputs from experts, the use of scoring matrices can be adapted to different regional characteristics. This approach can be improved by adding additional landscape properties and/or adapting the matrix values as new data become available.

Keywords: Land use/land cover; scoring matrix; landscape properties; spatially explicit

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1. Introduction

The Millennium Ecosystem Assessment defines ecosystem services as "the benefits that humans derive from ecosystems to sustain human well-being" [1]. Some well-known classification systems have categorized ecosystem services into provisioning services (provisioning of freshwater for human use); regulation and maintenance services (water flow regulation, erosion control, and soil fertility maintenance); and cultural services (recreation) [2]. Another ecosystem service category, known as ecological integrity, describes the ability of ecosystems to provide various ecosystem services, including supporting services, such as biodiversity [3].

The contribution of the natural environment to human well-being can be better understood by mapping ecosystem services [4], which facilitate the quantification and visualization of spatial information related to the capacity of ecosystems to provide or maintain ecosystem services derived from complex systems [4,5]. Mapping approaches are therefore useful to recognize and implement ecosystem services in decision making and land management strategies [4–7]. These approaches incorporate land use/land cover (LULC) to assess the effects of land use activities on ecosystem services. Many mapping approaches use complex models and extensive geodatabases [8–11], which make their application challenging and time-consuming. However, mapping approaches that rely on available data, literature, and the knowledge of experts are useful to ensure timely decision making [3,12–17]. Simple and robust mapping approaches that relate LULC classes to ecosystem services using a scoring matrix [3,14,17] are useful, particularly in data-scarce regions wherein expert knowledge may be used [3]. For the matrix approach, the values to link LULC with ecosystem services are given by the authors on the basis of an evaluation of available case studies and literature on ecosystem service criteria, as well as inputs from consulting experts in the field [3,14,17]. To ensure a spatially explicit assessment of the effects of LULC on ecosystem services, the capacity of the natural ecosystem to provide certain ecosystem services are considered [12,15,16] and the landscape potentials developed for each studied ecosystem service are parameterized [15,16]. The landscape potentials are based on existing methods that require lengthy calculations; however, Lima et al. [12] simply scored landscape properties relevant to each ecosystem service as an additional scoring matrix based on knowledge gained from the available literature and inputs from experts.

Mapping approaches employed in South Africa have primarily focused on identifying ecosystem service priority areas and determining the correspondence of ecosystem services with natural vegetation and biodiversity hotspots [18–21]. These approaches require the integration of proxy datasets, which are occasionally available. Furthermore, only two studies have evaluated the effects of LULC on various ecosystem services using mapping approaches [22,23]. Reyers et al. [22] indicated the loss of ecosystem services, due to the degradation and transformation of land cover, whereas O'Farrell et al. [23] assessed the effects of more refined LULC classes on ecosystem services. Applying matrix approaches to assess the effects of LULC on ecosystem services in South Africa is needed, especially since such approaches are less data-intensive, and the evaluation of expert knowledge may be incorporated. After the South African political change in 1994, the southern coastal region of the Western Cape Province (WCP) began experiencing a considerable population influx, thereby increasing urban development and agricultural activities [24] and causing a potential loss of certain ecosystem services. A simplified scoring approach can be applied to effectively identify high-risk areas that are contributing the most to the loss of ecosystem services from land use activities in the region. The regional characteristics make this region suitable for testing the effectiveness of using a landscape property scoring matrix to provide supplementary input data.

This study aims to use a simple and robust mapping approach to identify the high-risk areas that show a loss of ecosystem services, due to land use activities in a specific study region located along the southern coast of the WCP in South Africa. Available literature and knowledge from experts were evaluated to develop the scoring matrices by linking LULC and landscape properties with ecosystem services. The values from the scoring matrices were used to map the ecosystem service values for the most recent LULC situation (including land use activities) and a natural land cover reference situation (excluding land use activities). To identify the high-risk areas, risk maps were created using the ecosystem service difference values derived from the reference and LULC situations.

2. Methods

2.1. Study Region

The mapping approach was applied to a particular study region (Figure 1a) along the southern coast of the WCP, South Africa. The study region extends along the coastline from Cape Point (34°21′ S; 18°28′ E) to 22 km east of Struis Bay (34°48′ S; 20°03′ E). It extends approximately 50 km inland and includes regions of the Cape Flats, the Cape Winelands District, and the Overberg District, covering a land surface area of 643,542 ha. The study region is characterized by a Mediterranean climate with hot and dry summer seasons, rainy winter seasons, and mild to warm autumn and spring seasons. A mean annual precipitation gradient exists along the southern coastal region extending eastward. The highest mean annual precipitation in the coastal and mountainous regions is 1000–1200 mm, whereas the lowest mean annual precipitation is measured eastward along coastal areas and the inland region at 200–400 mm [25].

The 2000 National Land Cover data [26], incorporating the 2013 map of Agricultural Commodities in the WCP [27], were used to represent the LULC and the percentage coverage of each class (Figure 1b). Various land use types, including urban areas, agricultural land, forest plantations, and natural vegetation, are present in the study region. The natural vegetation "Fynbos" is one of the biodiversity hotspots of the world [28]. Fynbos covers much of the land surface along the coast and in the mountainous regions. Three major clusters of land use activities are evident (Figure 1b). (i) The first cluster is in the Cape Flats/Winelands area in the western part of the study region. The Cape Flats portion primarily includes informal urban development and irrigated crop cultivation, and the Cape Winelands portion primarily includes formal urban development, irrigated production of wine grapes, and less extensively irrigated crop cultivation. (ii) The second cluster is in the Grabouw area and includes irrigated orchards and less extensively irrigated crop cultivation, whereas forest plantations border the irrigated orchards. (iii) The third cluster includes dryland crop cultivation covering much of the land surface from Botrivier extending eastward to Struis Bay. Other types of LULC include natural grassland, wetlands, and waterbodies.

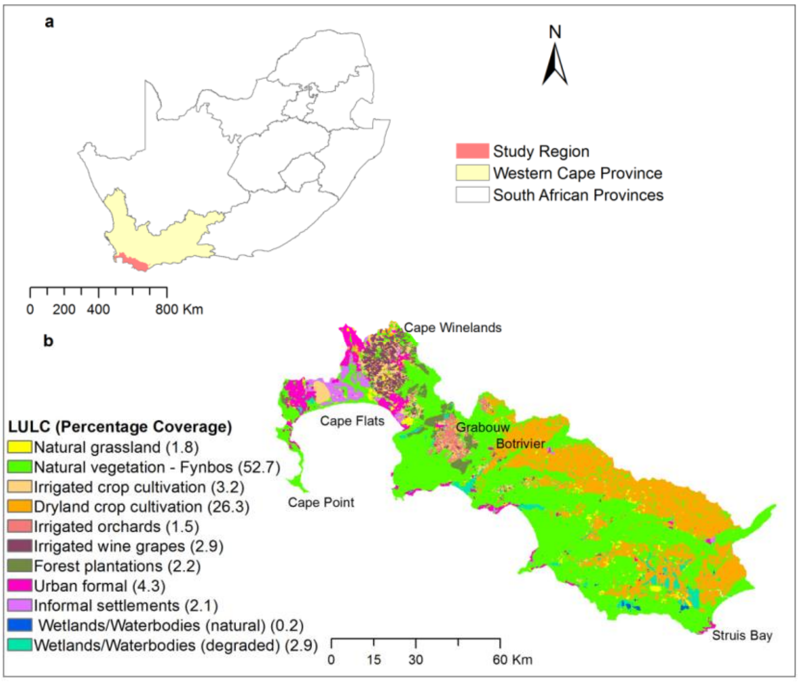

Figure 1. (**a**) Location of the study regions along the southern coast, Western Cape Province, South Africa. (**b**) Land use/land cover of the study region, including the percentage coverage of each class [26,27].

2.2. Generating Ecosystem Service and Risk Maps

The study region supports nationally important water- and soil-related ecosystem services, including water flow regulation and soil retention [20,21]. The WCP indicates a particularly high potential risk of soil erosion [29] and soil erosion occurs in areas of this region [30]. Water sources in the region are also documented to be in a poor state [31]. The region is a biodiversity hotspot that underpins the provisioning of most ecosystem services [3,19]. Furthermore, the loss of habitat threatens the biodiversity in the region [32]. The selected ecosystem services therefore include (1) erosion control, (2) water flow regulation, (3) water quality maintenance, (4) soil quality maintenance, and (5) biodiversity maintenance.

To generate risk maps that show the loss of ecosystem services from land use activities, an ecosystem service assessment based on the most recent LULC map (henceforth referred to as the LULC map) (Figure 1b) and the natural land cover reference map (henceforth referred to as the reference map) was conducted. The 2006 map of the potential natural vegetation [33] was used as the reference map for the study region, which includes different Fynbos biomes, wetlands, and waterbodies (Figure 2).

Figure 3 shows the general workflow used to generate the ecosystem service and risk maps. Three principal steps were employed:

(i) First, two scoring matrices were developed and used as input data. Using the values from the scoring matrices, less-intensive data input is required, and maps can be obtained in a timelier manner; this process is beneficial because it allows evaluating and using the knowledge gained from literature and experts in the field [3,12,14,17]. For the first scoring matrix, the LULC was related to each ecosystem service based on certain criteria. For a spatially explicit assessment, a second scoring matrix was developed that relates landscape properties (soil texture, slope, and distance to the river network) to each ecosystem service. The study region is suitable for using a landscape property scoring matrix given by flat plains and mountainous terrains with variable soil textures. Further details for developing the scoring matrices are discussed in Section 2.3.

(ii) Second, the ecosystem service maps for both the LULC and reference maps were generated. This was accomplished by multiplying the values given for the LULC scoring matrix with the values given for the landscape property scoring matrix.

(iii) Finally, risk maps were created by subtracting the LULC ecosystem service values from the reference ecosystem service values. The differences in the ecosystem service values were classified in risk classes as low, medium, and high in percentile intervals, including low (0–50th percentile), medium (50–80th percentile), and high (80–100th percentile).

From the risk maps, the high-risk areas of land use activity clusters that contribute the most to decreases in ecosystem service values were identified. Data were processed using ArcGIS version 10.1 software [34].

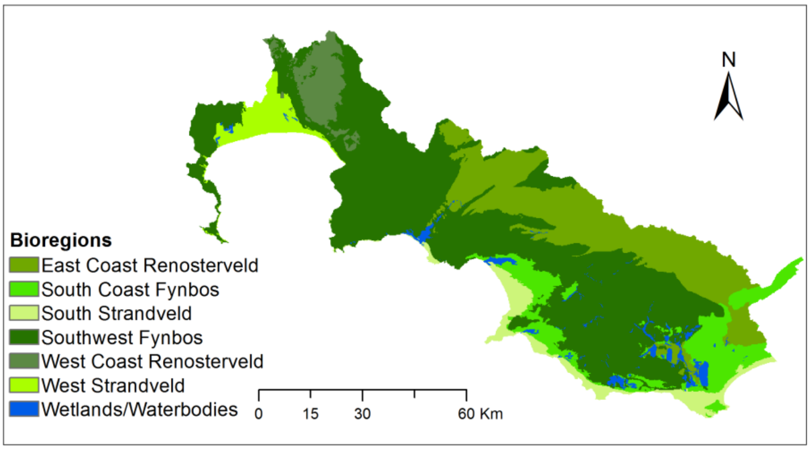

Figure 2. The 2006 natural vegetation map for the study region [33].

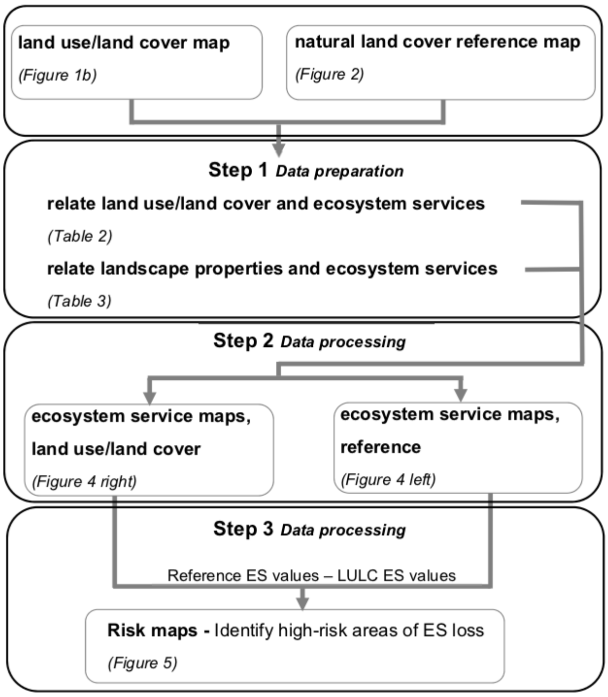

Figure 3. The three principal steps of the general workflow required to generate the ecosystem service and risk maps. (*ES: Ecosystem service). Figure created by authors.

2.3. Relating LULC and Landscape Properties to Ecosystem Services

To relate the LULC and landscape properties to each ecosystem service, values were assigned by the authors on the basis of an evaluation of the available literature and knowledge obtained from expert consultations. Lima et al. [12] and Burkhard et al. [14] provided a comprehensive list of ecosystem service criteria that served as a basis to search for relevant literature. This section overviews the literature; an interpretation of the relevant literature is provided in Section 3.1, along with detailed explanations for assigning the values and developing the scoring matrices.

To relate the LULC to each ecosystem service for the LULC and reference maps, values were assigned according to the capacity of the landscape to provide or maintain the ecosystem services. For this study, the LULC were related to each ecosystem service on a scale from 0 to 5, with 5 being the highest capacity to provide or maintain the ecosystem service and 0 indicating no capacity. From reviewing the selected literature, LULC classes that have little or no impacts on a certain ecosystem service or its related criteria support the capacity of the landscape to provide or maintain the ecosystem service; these classes were given high scores. The LULC classes that were identified to impact a certain ecosystem service or its related criteria cause a loss in the capacity of the landscape to provide or maintain the specific ecosystem service; these classes were given low scores.

The literature on ecosystem services and related criteria specific to the study region and similar regions of South Africa is somewhat limited, but received the most consideration in value assignment [28,30,35–38]. For example, Gebel et al. [30] identified the land use activities that mostly contribute to sediment and nutrients reaching river networks in the same study region. For the same study region, Malherbe et al. [35] assigned the LULC classes with impact scores to indicate the nutrient, sediment, and chemical inputs from LULC. Such impact scores were also developed by O'Farrell et al. [36] for a similar study region situated further east along the southern coast of the WCP. These references were helpful in the development of values that link LULC with erosion control and water quality maintenance. A review published by Mills and Fey [37] regarding the effects of agricultural activities on soil properties in South Africa was also utilized to develop these values for soil quality maintenance. Scholes and Biggs [38] presented a biodiversity intactness index under different land conditions, specifically for southern Africa. Although they did not differentiate between cultivated lands and types of urban development, their research was useful in the development of the biodiversity maintenance scores. Other literature also highlights that natural vegetation of South Africa plays an important role to provide and maintain water- and soil-related ecosystem services [18,20]. Information gained from Egoh et al. [18,20] was useful in the linking of natural vegetation with erosion control, water flow regulation, and soil quality maintenance.

Due to a limited amount of information about the study region, the knowledge gained from the available literature, which includes global information regarding the consequences of land use activities on ecosystem services, and related criteria were also evaluated [39,40]. Moreover, values given to scoring matrices for other regions of the globe [3,12,14] were adjusted using local knowledge gained from literature and by consulting experts. Local knowledge from literature includes information about the use of fertilizer [41] and wastewater disposal [42] and that gained by consulting experts includes information about the infrastructure.

Table 1 lists the references used to link the LULC with each ecosystem service. Different Fynbos biomes (Figure 2) represent the natural vegetation of the study region and are not considered to affect the selected ecosystem services. The Fynbos biomes were therefore given the highest capacity to provide or maintain the ecosystem services. The same values given for Fynbos and wetlands and waterbodies (natural) from the LULC map were used for the reference map.

The landscape properties were related to each ecosystem service on a scale from 0 to 1, where 1 does not impede and 0 fully impedes the ecosystem's capacity to provide or maintain the ecosystem service. The landscape properties included soil texture, slope, and distance from the river network. Values that relate landscape properties to erosion control and water flow regulation were adapted according to our study region based on a study reported by Marks et al. [43]. The humus content of the study region was <2%. Such low percentages have little to no effect on erosion resistance [43] and were not considered in this study. The gravel content of the study region affects the erosion resistance. The gravel content was therefore included when relating the soil texture to erosion control [43]. The root zone available water capacity (RZAWC) affects water flow regulation, and Marks et al. [43] provided RZAWC values based on soil texture. Values for relating landscape properties to water quality maintenance, soil quality maintenance, and biodiversity maintenance were adapted according to our study region based on the findings of Lima et al. [12].

The soil texture and topsoil gravel content were obtained from the Harmonized World Soil Database at a resolution of 30 arc seconds of longitude and latitude (~1 km) [44]. The slope was calculated using the Stellenbosch University Digital Elevation Model for South Africa at a resolution of 5 m [45]. Distances to river network (buffer strips), with the same distances as those used by Malherbe et al. [35] for the same study region, were created on both sides of each river reach at 0–25, 25–50, 50–125, 125–500, and 500–1000 m.

Table 1. References used to assign the values of land use/land cover (LULC) and ecosystem services.

LULC	Erosion Control	Water Flow Regulation	Water Quality Maintenance	Soil Quality Maintenance	Biodiversity Maintenance
Natural grassland	Egoh et al. [18] Egoh et al. [20] Malherbe et al. [35]	Egoh et al. [18] Egoh et al. [20]	Malherbe et al. [35]	Egoh et al. [18] Egoh et al. [20]	Scholes and Biggs [38]
Natural vegetation–Fynbos	Egoh et al. [20] Malherbe et al. [35] O'Farrell et al. [36]	Egoh et al. [20]	Malherbe et al. [35] O'Farrell et al. [36]	Egoh et al. [20] Mills and Fey [37]	Manning [28] Scholes and Biggs [38]
Irrigated crop cultivation	Gebel et al. [30] Malherbe et al. [35] O'Farrell et al. [36] Foley et al. [39]	Foley et al. [39]	Gebel et al. [30] Malherbe et al. [35] O'Farrell et al. [36] Foley et al. [39] Matson et al. [40] FAO et al. [41]	Mills and Fey [37] Matson et al. [40]	Burkhard et al. [3] Scholes and Biggs [38] Matson et al. [40]
Dryland crop cultivation	Gebel et al. [30] Malherbe et al. [35] Foley et al. [39]	Burkhard et al. [14] Foley et al. [39]	Gebel et al. [30] Malherbe et al. [35] Foley et al. [39] Matson et al. [40] FAO et al. [41]	Mills and Fey [37] Matson et al. [40]	Burkhard et al. [3] Scholes and Biggs [38] Matson et al. [40]
Irrigated orchards	Gebel et al. [30] Malherbe et al. [35] O'Farrell et al. [36]	Burkhard et al. [14]	Gebel et al. [30] Malherbe et al. [35] O'Farrell et al. [36] FAO et al. [41]	Mills and Fey [37]	Burkhard et al. [3] Scholes and Biggs [38]
Irrigated wine grapes	Gebel et al. [30] Malherbe et al. [35]	Burkhard et al. [14]	Gebel et al. [30] Malherbe et al. [35] O'Farrell et al. [36] FAO et al. [41]	Mills and Fey [37]	Burkhard et al. [3] Scholes and Biggs [38]
Forest plantations	Malherbe et al. [35] O'Farrell et al. [36]		Malherbe et al. [35] O'Farrell et al. [36]	Mills and Fey [37]	Scholes and Biggs [38]
Urban formal	Malherbe et al. [35] O'Farrell et al. [36]	Burkhard et al. [14]	Malherbe et al. [35] O'Farrell et al. [36]	Lima et al. [12]	Burkhard et al. [3] Scholes and Biggs [38]
Informal settlements	Malherbe et al. [35]		Malherbe et al. [35] Mels et al. [42]		
Wetlands/Waterbodies (natural)	Malherbe et al. [35] O'Farrell et al. [36]	Burkhard et al. [14]	Malherbe et al. [35] O'Farrell et al. [36]		Burkhard et al. [3]
Wetlands/Waterbodies (degraded)	O'Farrell et al. [36]		O'Farrell et al. [36]		

2.4. *Reference Threshold*

For this study, LULC is related to ecosystem services based on ecosystem service criteria. Methodological errors are observed when measuring ecosystem service criteria [46]; therefore, reference thresholds exist because of the methods used to measure ecosystem service criteria. A reference threshold showing lower and upper threshold values for the ecosystem services can be used in order to establish if the differences between the ecosystem service values calculated for the reference and LULC maps can be assigned to particular land use activities. A range of reference thresholds with lower and upper threshold values was determined for each ecosystem service. Changes from the reference to the LULC ecosystem service values that fall outside the range of thresholds were most likely associated with land use activities. Range factors were combined with each reference ecosystem service value to determine the lower and upper threshold values for each ecosystem service.

Range factors are defined on the basis of methodological errors, which exist when measuring ecosystem service criteria [12]. The range factors were determined using expert knowledge regarding the complexity of generating reliable ecosystem service criteria data. The knowledge regarding the processes that support biodiversity is somewhat limited, and transferring soil quality point data to spatial data leads to very high uncertainties. Measuring criteria for biodiversity maintenance and soil quality maintenance is therefore quite complex and were given a high range factor of 0.4 [12]. Generating sediment flow data and other water quality measurements are also rather complex. Erosion control and water quality maintenance were given a range factor of 0.3 [12]. Water flow regulation was given the lowest range factor of 0.1 as baseflow can be measured with a higher degree of accuracy [12].

3. Results

3.1. Development of Scoring Matrices Including LULC and Landscape Properties

This section provides more detailed examples of the relation between ecosystem services and (i) LULC and (ii) landscape properties. The values linking LULC classes to each ecosystem service are presented in Table 2. Findings for South Africa indicated that natural vegetation, including Fynbos and grassland, plays an important role in erosion control, water flow regulation, and water quality maintenance [18,20,35,36] (value = 5), which is also the case for wetlands and waterbodies in their natural state [35,36] (value = 5 for erosion control and water quality maintenance, but 3 for water flow regulation). Degraded wetlands and waterbodies lose their ability to support erosion control, water flow regulation, and water quality maintenance to their full potential (value = 3, but 2 for water flow regulation). Biological, physical, and chemical properties of soil are good indications of soil quality and are maintained by landscapes in their natural state [37] (value = 5). Natural vegetation, wetlands, and waterbodies in their natural state are important for biodiversity maintenance [3,28,38] (value = 5).

Table 2. Assigned values of LULC classes and ecosystem service (5 = the highest capacity and 0 = no capacity).

LULC	Erosion Control	Water Flow Regulation	Water Quality Maintenance	Soil Quality Maintenance	Biodiversity Maintenance
Natural grassland	5	5	5	5	5
Natural vegetation–Fynbos	5	5	5	5	5
Irrigated crop cultivation	0	1	0	1	1
Dryland crop cultivation	0	2	2	1	1
Irrigated orchards	1	2	1	1	2
Irrigated wine grapes	1	1	1	1	1
Forest plantations	1	2	3	2	2
Urban formal	4	1	4	0	2
Informal settlements	0	0	0	0	0
Wetlands/Waterbodies (natural)	5	3	5	5	5
Wetlands/Waterbodies (degraded)	3	2	3	3	3

Agricultural activities considerably impact the selected ecosystem services and related ecosystem service criteria. For example, simulation results for the same study region indicate that the critical source areas for sedimentation and nutrient inputs are from irrigated crop cultivation of vegetables, irrigated orchards, irrigated wine grapes, and dryland crop cultivation [30]. In addition, for the same study region, impact scores given for sediment input are the highest for irrigated crop cultivation and dryland crop cultivation, followed by irrigated orchards, irrigated wine grapes, and forest plantations [35]. The impact scores given for nutrient input are highest for all the previously mentioned irrigated agricultural activities [35]. Low sediment retention is also determined for irrigated crop cultivation, irrigated orchards, and forest plantations for a similar region situated further east along the coast [36]. Based on the previously mentioned literature, irrigated crop cultivation of vegetables do not support erosion control and water quality maintenance (value = 0); however, irrigated wine grapes and irrigated orchards support these ecosystem services to a very small extent (value = 1). Dryland crop cultivation also does not support erosion control (value = 0). Considering the low amount of fertilizer used for dryland crop cultivation [41], landscapes subject to this activity have a slightly higher capacity to maintain water quality compared with that of the other agricultural activities (value = 2). Erosion control is limited for forest plantations (value = 1); however, compared with other agricultural activities, the water quality maintenance for forest plantations is higher (value = 3). Agricultural activities are widely known to have significant impacts on soil properties [37,40] and biodiversity [3,38,40]. Landscapes subject to agricultural activities therefore have a low capacity to maintain soil quality (value = 1, but 2 for forest plantations) and biodiversity (value = 1, but 2 for forest plantations and irrigated orchards).

Wastewater disposal in the informal settlements of South Africa is relatively poor [42]. Based on local knowledge, the region's informal settlements also have a limited number of paved roads and provide no green space. This supports the high impact scores for nutrient and sediment inputs attributed to informal settlements [35]. This suggests that informal settlements impede the capacity of the landscape to provide or maintain the selected ecosystem services (value = 0). The sediment retention is determined to be high [36] and the wastewater disposal is more efficient [42] for formal urban development in the region. The impact scores given for nutrient and sediment inputs are therefore low for formal urban development [30]. For this study, formal urban development was found to have a greater capacity to support erosion control and water quality maintenance (value = 4). Green space in formal urban areas supports biodiversity maintenance to some extent [3] (value = 2).

The values linking landscape properties to each ecosystem service are listed in Table 3. Under natural conditions, soil texture does not impede soil quality maintenance and biodiversity maintenance [12] (value = 1) and slope does not impede biodiversity maintenance [12] (value = 1). As the slope increases, the capacity of the landscape to support erosion control, water flow regulation, water quality maintenance, and soil quality maintenance decreases [12,43] (decreasing values are represented by an increasing slope). The distance to the river network was only considered for water quality maintenance [12]. Riparian zonation minimizes pollutants entering rivers and streams [47]. The closer land use activities are to river networks, the higher is the potential impact (increasing values are given with increasing distance).

Table 3. Assigned values of landscape properties and ecosystem services.

Soil Texture	**Erosion Control**	**Water Flow Regulation**	**Water Quality Maintenance**	**Soil Quality Maintenance**	**Biodiversity Maintenance**
Loamy sand		0.9	0.6	1	1
Sandy loam		0.7	0.7	1	1
Sandy clay loam/Loam		0.5	0.8	1	1
Clay loam		0.5	0.9	1	1
Loamy sand, Clay loam, Sandy clay loam—Topsoil gravel 11–30%	0.8				
Loamy sand, Clay loam, Sandy clay loam—Topsoil gravel <10% & Sandy loam—Topsoil gravel 11–30%	0.7				
Sandy loam—Topsoil gravel <10%	0.5				
Soil (Available water capacity in root zone nFk in l/m^3)					
Sandy loam (140–200)		0.9			
Sandy clay loam/loam (90–140)		0.7			
Loamy sand (50–90)		0.5			
Slope (%)					
<3	1	1	1	1	1
36	0.9	0.9	0.9	1	1
6–12	0.8	0.9	0.8	0.9	1
12–26	0.7	0.7	0.7	0.8	1
26–60	0.5	0.5	0.5	0.7	1
>60	0.4	0.3	0.4	0.6	1
Distance (m)					
<25			0.4		
25–50			0.6		
50–125			0.7		
125–500			0.8		
>500			1		

3.2. Ecosystem Service and Risk Maps

Figure 4 shows the total ecosystem service values for the reference and LULC maps. Comparing the reference and LULC ecosystem service values, an overall loss for each ecosystem service is evident. The highest losses were found to be associated with soil quality maintenance and biodiversity maintenance, followed by erosion control, water quality maintenance, and water flow regulation.

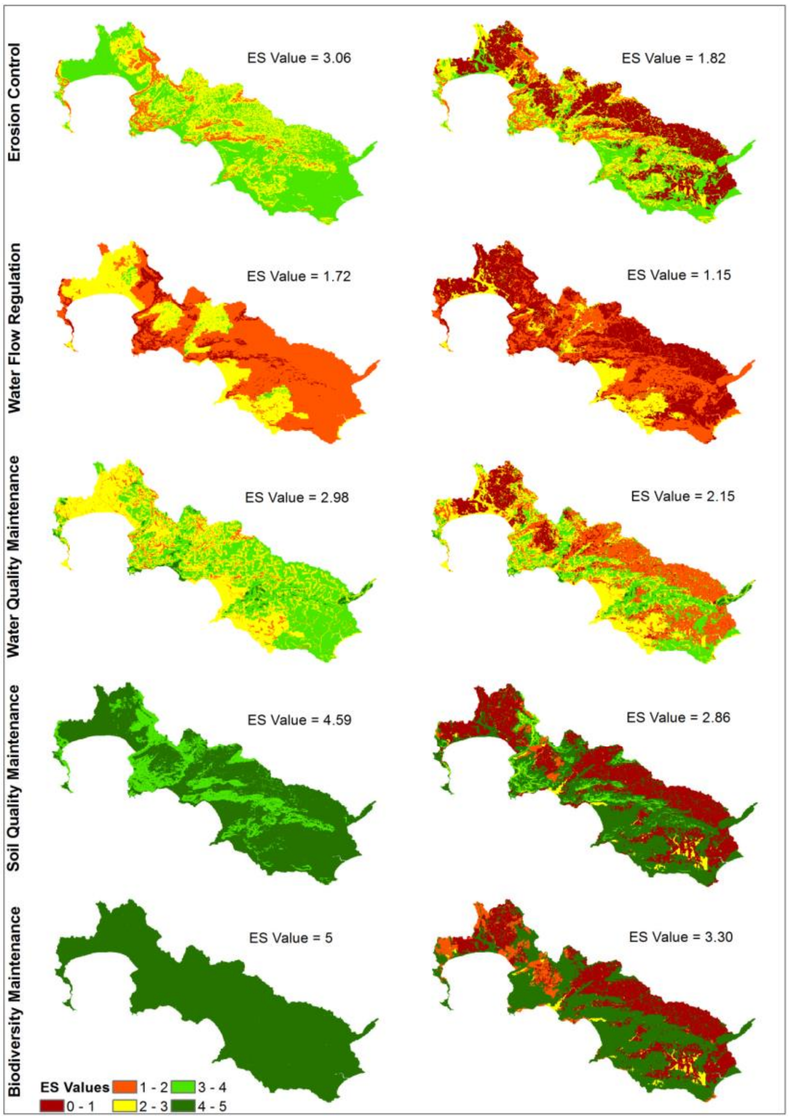

Figure 4. The values for different ecosystem services, reference (left) and LULC (right) maps.

To understand the extent that land use activities contribute to ecosystem service loss, risk maps of each ecosystem service are presented in Figure 5. Three high-risk areas of land use activity clusters that contribute the most to the loss of each ecosystem service are evident. These include the Cape Flats/Winelands cluster, Grabouw cluster, and Botrivier to Struis Bay cluster.

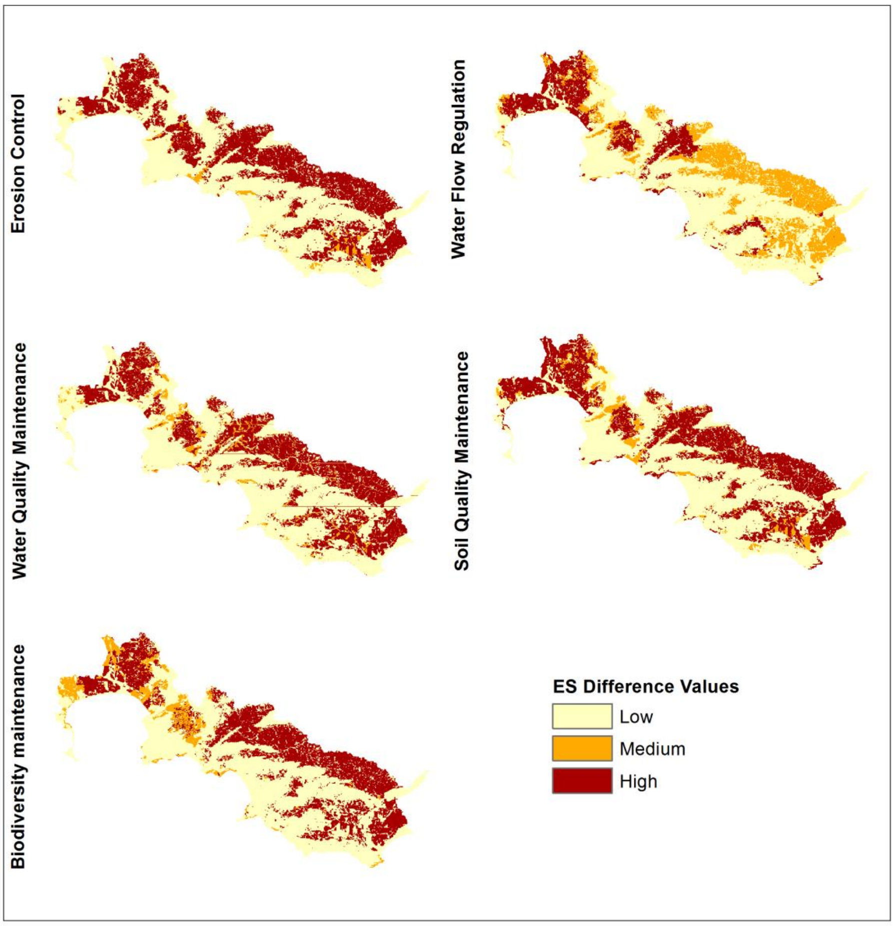

Figure 5. Risk maps showing the ecosystem service difference values from the reference to the LULC situation.

There was a high loss of erosion control from the reference to the LULC situation, resulting in a decrease of the ecosystem service value from 3.06 to 1.82 (Figure 4). High-risk areas displaying a loss of erosion control included all three clusters (Figure 5). The irrigated crop cultivation of vegetables in the Cape Flats/Winelands and Grabouw clusters and the dryland crop cultivation in the Botrivier to Struis Bay cluster were largely responsible for the loss of erosion control (value = 0) (Table 2). This was followed by the irrigated production of wine grapes in the Cape Winelands and the irrigated orchards and forest plantations in the Grabouw cluster (value = 1) (Table 2). Vineyards in the Cape Winelands, the irrigated agricultural activities in the Grabouw cluster, and the dryland crop cultivation in the

Botrivier to Struis Bay cluster are located in hilly areas, which reduce the capacity of the landscape to control erosion (Table 3). Informal settlements in the Cape Flats also contributed to substantial losses of erosion control (value = 0) (Table 2). These settlements cover vast sandy areas that also decrease erosion control (Table 3).

Although not as influential as erosion control, there is a loss of water quality maintenance from the reference to the LULC situation (i.e., from 2.95 to 2.15) (Figure 4). The high-risk areas also included all three clusters (Figure 5). As per erosion control, irrigated agricultural activities and informal settlements substantially contributed to the loss of water quality maintenance (value = 0) (Table 2). However, the loss of water quality maintenance was lower for dryland crop cultivation in the Botrivier to Struis Bay cluster (value = 2) and forest plantations in the Grabouw cluster (value = 3) (Table 2), which explains the reason for the lower overall loss of water quality maintenance than erosion control. Water quality maintenance for the reference situation had a lower value closer to river networks (Figure 4) because buffers limit the potential of pollutants to reach waterways (Table 3).

Water flow regulation shows the lowest ecosystem service value loss from the reference to the LULC situation, decreasing from 1.72 to 1.15 (Figure 4). The soil texture (clay loam and sandy clay loam) that underpins much of the natural vegetation contributes to the low water flow regulation values in such areas (Table 3). The two primary high-risk areas include the Cape Flats/Winelands and Grabouw clusters. The area surrounding Botrivier was also a high-risk area, whereas the area extending further east from Botrivier provided a medium contribution to the loss of water flow regulation (Figure 5). The contribution of agricultural activities to the loss of water flow regulation is similar to erosion control and water quality maintenance (Table 2). However, for urban development, particularly in the Cape Flats/Winelands cluster, the loss of water flow regulation was substantial (value = 1 for formal and 0 for informal urban development) (Table 2).

The loss of ecosystem service values from the reference to the LULC situation was the highest for soil quality maintenance (4.59–2.86) and biodiversity maintenance (5–3.30) (Figure 4). The high-risk areas for soil quality maintenance included all three clusters (Figure 5). Irrigated agricultural activities and dryland crop cultivation were found to substantially contribute to the loss of soil quality (value = 1), followed by forest plantations (value = 2) (Table 2) whereas urban development (informal and formal) destroys soils, which is largely responsible for the loss of soil quality (value = 0) (Table 2). The reference situation fully supports biodiversity maintenance (Figure 4) because natural vegetation provides habitat. The high-risk areas include the Cape Flats/Winelands and the Botrivier to Struis Bay clusters, whereas the Grabouw cluster provided a medium contribution to the loss of biodiversity maintenance (Figure 5). Agricultural activities in high-risk areas substantially contribute to the loss of biodiversity (value = 1) (Table 2). However, irrigated orchards and forest plantations in the Grabouw cluster support biodiversity slightly more (value = 2) (Table 2). Informal urban development in the Cape Flats cluster is the largest contributor to the loss of biodiversity maintenance, whereas the formal urban development displayed a medium contribution to such losses (value = 0 for informal and 2 for formal urban development) (Table 2).

The total ecosystem service values of the reference and LULC maps, including the lower and upper threshold values, are presented in Table 4 and Figure 6. A wide range of threshold values was evident for soil quality maintenance and biodiversity maintenance. The range of threshold values was not much lower for erosion control and water quality maintenance. Water flow regulation displayed the lowest range of threshold values (Table 4 and Figure 6).

The net loss of erosion control and water flow regulation falls outside the range of the threshold values (Figure 6). It can be assumed that land use activities do have an impact on erosion control and water flow regulation. In contrast, the loss of water quality maintenance, soil quality maintenance, and biodiversity maintenance fall inside the range of threshold values (Figure 6), and the effects of land use change from the reference to the LULC situation on these particular ecosystem services are not completely known.

Table 4. Total ecosystem service values for the LULC and reference situations, range factors, and the calculated lower and upper threshold values for each ecosystem service. The lower and upper threshold values indicate the range of threshold values for the reference situation.

Ecosystem Service	Total Ecosystem Service Values		Range Factors	Thresholds of Ecosystem Service Values	
	LULC	Reference		Lower	Upper
Erosion control	1.82	3.06	0.3	2.14	3.98
Water flow regulation	1.15	1.72	0.1	1.55	1.89
Water quality maintenance	2.15	2.98	0.3	2.09	3.87
Soil quality maintenance	2.86	4.59	0.4	2.75	5
Biodiversity maintenance	3.30	5	0.4	3	5

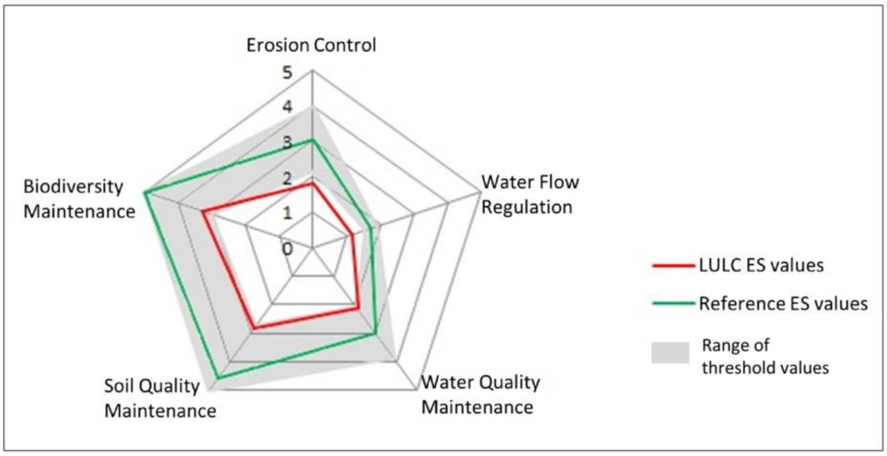

Figure 6. Visualization of the total ecosystem service values for the LULC and reference situations and the range of threshold values for the reference situation with lower and upper threshold values for each ecosystem service.

4. Discussion

The inclusion of environmental data provides meaningful refinements to ensure spatially explicit assessments of the effects of LULC on ecosystem services [15]; however, existing approaches that exclude complex modeling still rely on lengthy calculations [15,16]. Findings of this study strengthen the credibility of the approach developed by Lima et al. [12], which includes a landscape property scoring matrix by simply scoring relevant landscape properties with each ecosystem service. Results reveal that landscape properties have the potential to affect the capacity of landscapes to provide or maintain ecosystem services. For example, the reference situations, particularly erosion control, water flow regulation, and water quality maintenance, clearly indicate that the capacity of the landscape to support a specific ecosystem service is not the same for all areas. This is consistent with the reference situation maps for erosion control and water quality maintenance reported by Lima et al. [12]. Lima et al. [12] did not assess water flow regulation; however, water flow regulation is successfully assessed in this study. This highlights the simplicity of the approach to expand its use in the evaluation of other ecosystem services. To do so, only the basic input layers, including LULC, soil texture and digital elevation models, and the evaluation of sufficient knowledge obtained from literature and/or the consultation of experts are necessary. This approach is further developed herein by considering the gravel content of soils to assess for erosion control. Another advantage is that the hypothesized values in such studies can be adjusted as more accurate and comprehensive data become available in the future.

Based on the range of threshold values, the land use activities appear to contribute to the loss of erosion control and water flow regulation. The loss of the other studied ecosystem services, due to land use activities is not completely clear, but must not be disregarded. Although the actual effect of land use changes from the reference situation cannot be determined, the findings of this study fill critical gaps in our knowledge regarding the complex interaction of LULC and ecosystem services within a particular landscape by performing a spatial overview of high-risk areas contributing to the loss of ecosystem services that can be used for making decisions regarding the implementation of more effective management strategies. The high-risk areas identified in this study show that both agricultural activities and urban development contribute to the loss of ecosystem services.

As mentioned previously, the WCP indicates a particularly high potential risk of soil erosion [29]. The findings show that the irrigated and dryland agricultural activities and forest plantations in the Cape Winelands, Grabouw cluster, and Botrivier to Struis Bay cluster are mainly located in elevated areas that contribute to an increase in erosion. Lorz et al. [16] reported an increase in sediment input in agricultural areas for the Cerrado biome in Brazil that was also increased by elevated slopes. The irrigated crop cultivation of vegetables in the Cape Flats is located on erodible sandy soils, which increase the risk of soil erosion. Another substantial loss of erosion control is associated with the cultivation of irrigated vegetable crops and informal settlements in the Cape Flats. The informal settlements cover vast sandy areas that presumably contribute to the loss of erosion control.

Widespread impacts of land use activities on water quality primarily include increased sediment, nutrient, and chemical inputs [39,48,49], and the agricultural activities and urban development along the southern coast of the WCP greatly contribute to such impacts [35,36,50]. The findings show that irrigated and dryland agricultural activities in the Cape Flats/Winelands, Grabouw, and Botrivier to Struis Bay clusters contribute to the loss of water quality maintenance. One reason is presumably associated with the previously mentioned increase in erosion and the use of fertilizer. Informal settlements also contribute to a loss of water quality maintenance, which is most likely a result of poor wastewater disposal practices [42]. Similar to the finding from Lima et al. [12], a decreasing contribution to water quality maintenance for areas closer to river networks was evident.

In the tropical regions of Southeast Asia, the decline of natural forest has drastically decreased water flow regulation [51]. A loss of water flow regulation was also evident in regions of South Africa, where a decline in the amount of natural vegetation in favor of crop cultivation is prevalent [20]. For example, land degradation in the Little Karoo is indicative of a decrease in water flow regulation [22]. Our findings also revealed a loss of water flow regulation in cultivated regions, especially for irrigated agricultural activities. The soil texture supporting the dryland crop cultivation between Botrivier and Struis Bay most likely supports water flow regulation more than sandier soils. Water flow regulation displayed a profound loss in both formal and informal urban developed areas of the Cape Flats, which was presumably intensified by the sandy soils in the area.

Under natural conditions, soil properties mostly remain undisturbed, which maintains soil quality and is evident for the reference situation of this study. Natural conditions provide the maximum potential for biodiversity maintenance [12], which is also evident for the reference situation for biodiversity maintenance. Human interference has a significant impact on soil quality and biodiversity [37,40]. The agricultural activities and urban development in the Cape Flats/Winelands, Grabouw, and Botrivier to Struis Bay clusters substantially contribute to the loss of soil quality maintenance, biodiversity maintenance, or both of these ecosystem services. For soil quality maintenance, the loss can be attributed to the use of fertilizer or the total destruction of soils from urban development, regardless of it being formal or informal development. The impacts on biodiversity in cultivated areas is slightly more than for forest plantations in southern Africa [38], which is also evident based on the results for this study. Although urbanization usually causes the total destruction of habitats, the formal urban development in the Cape Flats/Winelands cluster has green urban spaces and explains the medium contribution of formal urban development to the loss of biodiversity maintenance.

5. Conclusions

Findings of this study indicate that landscape properties have the potential to affect the capacity of the landscape to provide and maintain ecosystem services. Applying a matrix approach to assess the effects of LULC on ecosystem services must therefore not neglect the addition of landscape properties. Results further reveal that, with sufficient knowledge from previous literature and the inputs from experts, the approach can be adapted to the characteristics of other regions, particularly regions with limited data and resources. The approach can be further improved by adding additional landscape properties. Herein, the approach is improved by adding the gravel content to the soil texture for the assessment of erosion control. The values given for the matrices can also be changed and improved as new data become available. For future reference, testing different versions of the approach is recommended based on further improvements.

Compared to complex modeling, the application of the approach is also relatively fast because it involves inputs from experts. However, limited knowledge regarding the complex interactions, including the landscape, land use activities, and ecosystem services, presents a certain limitation in its application. The actual effects of the land use activities on the ecosystem services are therefore not certain, and it is difficult to provide recommendations. Regardless, the approach does deliver a good spatial overview to understand the extent and magnitude of impact that land use activities have on the loss of ecosystem services by highlighting high-risk areas. Obtaining knowledge about the areas and associated land use activities that contribute to increasing risks of the loss of ecosystem services is important to make decisions regarding further in-depth research that may require costly resources.

Global policies and strategies focus on the conservation of biodiversity because conserving biodiversity targets the protection of ecosystem services [52]. However, since the establishment of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services [53], there is a trend of focusing on the conservation and sustainable use of both biodiversity and ecosystem services [52,53]. To ensure the continuity of the delivery of ecosystem services, it is important to enhance the global knowledge of the threats to ecosystem services. It is therefore important to direct research toward simple and relatively fast assessment approaches, such as this study, to understand and tackle the negative effects of land use activities on ecosystem services. This will facilitate the improvement of management strategies and policies that focus on biodiversity conservation and ensure the continuous delivery of ecosystem services threatened by human interference and the restoration of lost ecosystem services.

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